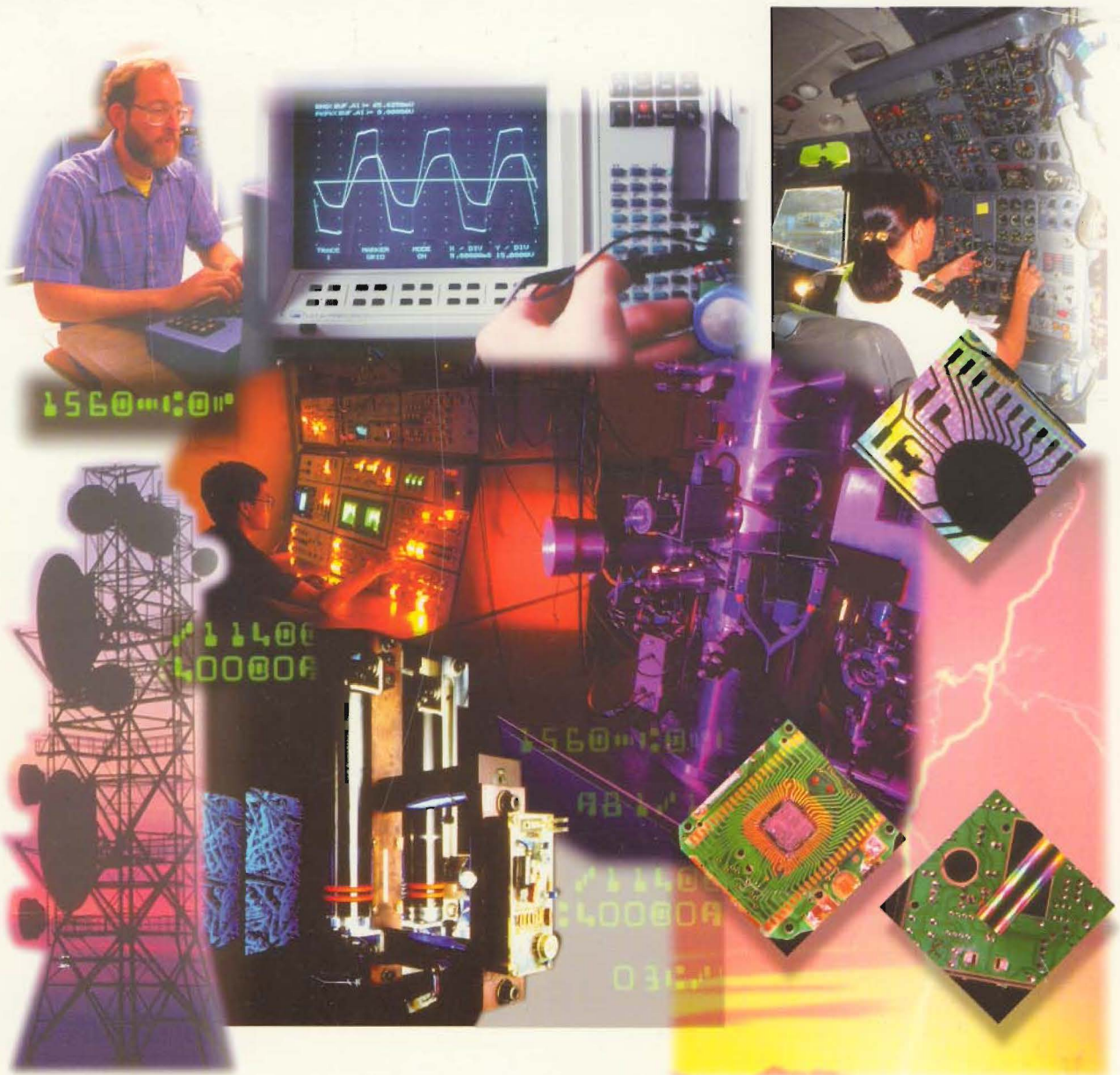


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AC ELECTRONICS



AC ELECTRONICS

TEXTBOOK



Model EB-6102A
HEATHKIT COMPANY, INC.
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Contents

Introduction	IV	Unit 4	
Course Objectives	V	Inductive Circuits	4-1
Course Outline	VII	Unit 5	
Unit 1		Tuned Circuits	5-1
Alternating Current	1-1	Unit 6	
Unit 2		Transformers	6-1
AC Measurements	2-1	Unit 7	
Unit 3		Motors and Motor Controls	7-1
Capacitive Circuits	3-1	Unit 8	
		AC Home Applications	8-1
		Index	I-1

Introduction

This textbook on AC (alternating current) Electronics is designed as a training tool for students requiring a practical, concise and complete treatment of the subject. The text along with its accompanying AC Electronics Student Workbook, is field proven and has been successfully used in a wide range of technical training programs worldwide. Prerequisites for the study of AC Electronics include an understanding of the principles of DC Electronics, as well as an understanding of the basic mathematical concepts of algebra and trigonometry typically associated with the subject.

The text has been divided logically into eight separate learning units. Each unit begins with an introduction and a listing of learning objectives. The introduction is included to provide some background, and aid student understanding of the reasons why the material in the unit is important. The unit objectives provide a detailed list of specific learning goals to be reached by the student after studying the unit. Immediately following this Introduction is a listing of course objectives. These are much broader than the unit objectives and provide an indication of the proficiencies to be gained upon completion of the course.

A complete summary is also included at the end of each unit. By paying close attention to the introduction and objectives; then carefully studying the material in the unit and relating the summary back to the objectives, the student will gain a solid understanding of the information. Also to assist in this process, self-test reviews are included at the end of each main section within each unit. These should be used to test your understanding of the most important concepts presented in the section: they can also be viewed as “practice quizzes.” Practice “unit examinations” covering each unit in its entirety are included in the Student Workbook.

Upon successfully completing this course the student will be well acquainted with the main concepts and principles of AC Electronics. For some programs and disciplines this may be a terminal course in electronics; for many others this will provide the prerequisite knowledge necessary for subsequent courses in semiconductor electronics, digital electronics, electronic circuits, and more.

Course Objectives

When you have completed this course on AC electronics you should be able to:

1. State the difference between alternating and direct current.
2. List the advantages that alternating current has over direct current.
3. Describe the operation of a basic AC generator.
4. Determine the effective value, peak value, peak-to-peak value, frequency, and period of an AC sine wave.
5. Measure AC voltages using an AC voltmeter.
6. Analyze series and parallel AC circuits that contain only resistance, and solve these circuits for voltage, current, and power.
7. Define the term capacitor and explain the electrical property known as capacitance.
8. State how capacitors are formed.
9. Define the term inductor and explain the electrical property called inductance.
10. Explain how inductors are formed.
11. Analyze inductive circuits and determine the resistance, inductive reactance, current, voltage, true power, reactive power, phase angle, and power factor of the circuit.
12. Analyze capacitive circuits and determine the resistance, capacitive reactance, current, voltage, true power, reactive power, phase angle, and power factor of the circuit.
13. Analyze RLC circuits and determine the resistance, inductive reactance, capacitive reactance, true power, reactive power, current, voltage, phase angle, power factor, power factor correction, and resonant frequency.
14. List the characteristics of both series and parallel resonant circuits.
15. Explain the term impedance and calculate the impedance of simple RC, RL, and RLC series and parallel circuits.
16. Explain transformer action.
17. Determine the current, voltage, impedance, and power ratios for a given transformer.
18. Determine the turns ratio necessary for an impedance match.
19. List the electrical properties of a transformer and name five general uses of the transformer.
20. Explain the term remote control.
21. Explain the difference between a generator and a motor.

-
22. List the basic types of motors.	29. Explain the term service drop.
23. State the type of AC motor most used in industrial applications.	30. Convert power requirements between horsepower, watts, and current.
24. Explain the term universal motor.	31. List 4 safety devices that should be in every home.
25. State the advantages and disadvantages of series type motors when compared to shunt type motors.	32. Explain the difference between reference ground and earth ground.
26. Explain the term compound motor.	33. Draw a block diagram complete with current requirements for the electrical loads in your home.
27. State the advantage of a servosystem over a synchrosystem.	
28. Calculate AC currents for specified appliances .	

VI AC ELECTRONICS

Course Outline

UNIT 1 **Alternating Current**

Introduction

Unit Objectives

The Importance of AC

What is AC?

Why is AC Used?

Where is AC Used?

Generating AC

Electromagnetic Induction

A Simple AC Generator

The Sinusoidal Waveform

The Basic Sine Wave

The Cycle

AC Values

Peak Value

Peak-To-Peak Value

Average Value

Effective Value

Period

Frequency

Nonsinusoidal Waveforms

The Square Wave

The Triangular Wave

The Sawtooth Wave

Fluctuating DC Waves

Desk-Top Experiment 1

Analyzing A Simple AC Series Circuit

Unit Summary

UNIT 2 **AC Measurements**

Introduction

Unit Objectives

AC Meters

Rectifier-Type, Moving-Coil Meters

Moving-Vane Meters

Thermocouple Meters

Clamp-On Meters

Using AC Meters

Oscilloscopes

Oscilloscope Operation

Using The Oscilloscope

Resistance In AC Circuits

Basic AC Circuit Calculations

Series AC Circuit Calculations

Parallel AC Circuit Calculations

Power in AC Circuits

Desk-Top Experiment 2

Analyzing A Simple AC Parallel Circuit

Unit Summary

UNIT 3 **Capacitive Circuits**

Introduction

Unit Objectives

Review of Capacitors and Capacitance

- Units of Capacitance**
- Factors Affecting Capacitance**
- Types of Capacitors**
- Capacitor Ratings**
- Capacitor Defects**
- Capacitors in Series and Parallel**
- Capacitors in DC Circuits**

Capacitors in AC Circuits

- Current-Voltage Relationships in Capacitive AC Circuits**
- Capacitive Reactance**
- Ohm's Law in Capacitive Circuits**

RC Circuits

- Series RC Circuits**
- Vector Diagrams**
- Impedance**
- Power in AC Circuits**
- Phase Shift**
- Parallel RC Circuits**

Applications of Capacitive Circuits

- Capacitive Voltage Dividers**
- RC Filters**
- Circuits Combining AC and DC**
- Phase Shift Networks**

Desk-Top Experiment 3

Analyzing RC Circuits

Unit Summary

Appendix A:

Solving Right Triangles

Appendix B:

Introduction to Trigonometry

Appendix C:

Table of Trigonometric Functions

UNIT 4

Inductive Circuits

Introduction

Unit Objectives

Review of Inductors and Inductance

- Self-Induction**
- Inductors and Inductance**
- Unit of Inductance**
- Factors Affecting Inductance**
- Types of Inductors**
- Inductors in DC Circuits**
- Inductive Time Constant**

Inductors in AC Circuits

- Current-Voltage Relationship**
- Inductive Reactance**
- Ohm's Law For Inductive Circuits**
- Mutual Inductance**
- Inductors in Series and in Parallel**

RL Circuits

- Series RL Circuits**
- Vector Diagrams**
- Impedance**
- Phase Shift**
- Power in an Inductive Circuit**
- Parallel RL Circuits**

Applications of Inductive Circuits

- Inductive Filters**
- Inductive Phase Shifters**

VIII AC ELECTRONICS

Desk-Top Experiment 4
Analyzing LR Circuits

Unit Summary

UNIT 5 Tuned Circuits

Introduction

Unit Objectives

RLC Circuits
 Series RLC Circuits
 Parallel RLC Circuits

Resonance

Series Resonance

Desk-Top Experiment 5
Analyzing RLC Circuits

Q and Bandwidth in Series Resonant
Circuits
 Q in Series Resonant Circuits
 Bandwidth and Q
 Measuring Bandwidth

Parallel Resonance
 Ideal Circuit
 Flywheel Effect
 Practical Tank Circuits
 Q in Parallel Resonant Circuits
 Bandwidth in Parallel Resonant Circuits
 Distributed Capacitance and Self
 Resonance of Coils
 Power Factor and the Parallel Resonant
 Circuit

LC Filters

Types of Filters
Band-Pass Filter
Band-Stop Filter
Low-Pass Filter
High-Pass Filter

Desk-Top Experiment 6
Analyzing RLC Series-Parallel Circuits

Unit Summary

Appendix A: Resonance Nomograph

UNIT 6 Transformers

Introduction

Unit Objectives

Transformer Action
 Mutual Inductance
 Transformer Action
 Transformer Construction

Transformer Theory
 Transformer With No Load
 Transformer With Load

Transformer Ratios
 Voltage Ratio
 Power Ratio
 Current Ratio
 Solving Transformer Problems
 Impedance Ratio

Transformer Losses

- Core Losses
- Copper Loss
- External Induction Loss
- Transformer Efficiency

Transformer Applications

- Power Distribution
- Electronic Applications
- Autotransformer

Unit Summary

UNIT 7

Motors And Motor Controls

Introduction

Unit Objectives

Review Of DC Motors

- Induction Principles
- Right-Hand Motor Rule
- DC Motor Problems

Types Of Induction Motors

- Series Motor
- Shunt Motor
- Compound Motor
- Universal Motor

AC Motors

- Single-Phase Motors
- Two-Phase Motors
- Polyphase Motors

Motor Speeds

- RPM
- Motor Regulation
- Synchronous Speed
- Asynchronous Speed
- Percent of Regulation

Motor Control Circuits

- DC Control Circuits
- Remote Controls

Motor Control Systems

- Remote Control System
- Synchro System
- Servo Systems
- Comparing Synchro and Servo Systems

Desk-Top Experiment 7

Identifying Motor Symbols

Unit Summary

UNIT 8

AC Home Applications

Introduction

Unit Objectives

The Service Drop

- Transformer
- Power Meter
- Power Distribution Box
- Grounding The Power Box

Paralleling Loads
Current Paths
Home Appliances
Combining Loads
Load Power

Safety
Safety Grounds
Safety Devices
Unit Summary

Desk-Top Experiment 8
Designing AC Loads



Unit 1

Alternating Current

Contents

Introduction	1-3	AC Values	1-35
Unit Objectives	1-4	Nonsinusoidal Waveforms	1-49
The Importance of AC.....	1-5	Desk-Top Experiment 1	
Generating AC	1-13	Analyzing A Simple AC Series Circuit ...	1-53
The Sinusoidal Waveform	1-27	Unit Summary	1-57

Introduction

It is essential that anyone who plans to work within the field of electronics have a thorough understanding of the theory and principles of alternating current. Not only does alternating current (AC) play an important role in the field of theoretical electronics, but it is also used much more extensively than direct current (DC) in practical applications. In fact, it is virtually impossible to avoid using it or at least being affected by it.

Today, you are surrounded by the miracles of the electronic age. Appliances, tools, and communication equipment simplify every day living and contribute to a comfortable lifestyle. It is hard to imagine what life would be like without these conveniences.

In this unit, you will begin your study of the principles that have such an impact on your everyday life. You will learn how alternating current is produced and study its electrical characteristics.

Unit Objectives

When you have completed this unit, you should be able to:

1. Define: alternating current (AC), sine wave, cycle, alternation, positive alternation, negative alternation, instantaneous value, peak value, peak-to-peak value, effective value, average value, period, frequency, and hertz.
2. State the difference between alternating current and direct current.
3. Name three advantages of AC current over DC current.
4. Name six general applications of alternating current.
5. Describe the operation of the basic AC generator.
6. State the four factors that affect the voltage or current induced in a conductor.
7. Determine the peak value of a sine wave.
8. Determine the peak-to-peak value of a sine wave.
9. Determine the effective value of a sine wave.
10. Calculate the frequency of an AC signal.
11. Calculate the average value of a sine wave.
12. Determine the period of a sine wave.
13. Name three types of AC waveforms (other than the sine wave).

The Importance of AC

Because of its characteristics, alternating current is suitable for a variety of commercial and industrial applications. To understand why AC is used, you must understand its advantages and characteristics. We will begin by telling you what AC is, how it is used, and why it is used. This brief discussion on the significance of AC will prepare you for the more detailed discussions that follow.

What is AC?

Unlike direct current (DC) which flows only in one direction, alternating current periodically changes its direction of flow. In other words, alternating current flows first in one direction and then in the opposite direction.

This difference between DC and AC is illustrated in Figure 1-1. Figure 1-1A shows a resistor that has direct current flowing through it. The current that flows only in one direction is the result of the fixed or constant voltage that is applied to the circuit. This fixed voltage source (referred to as a DC voltage) could be a storage battery or a dry cell. The DC voltage source and the resistor form an elementary DC circuit.

Since the voltage source is fixed, the polarity of the source does not change. Therefore, the polarity of the voltage drop across the resistor in the circuit is also unchanged. The current through this circuit flows only in one direction because the DC voltage source remains fixed.

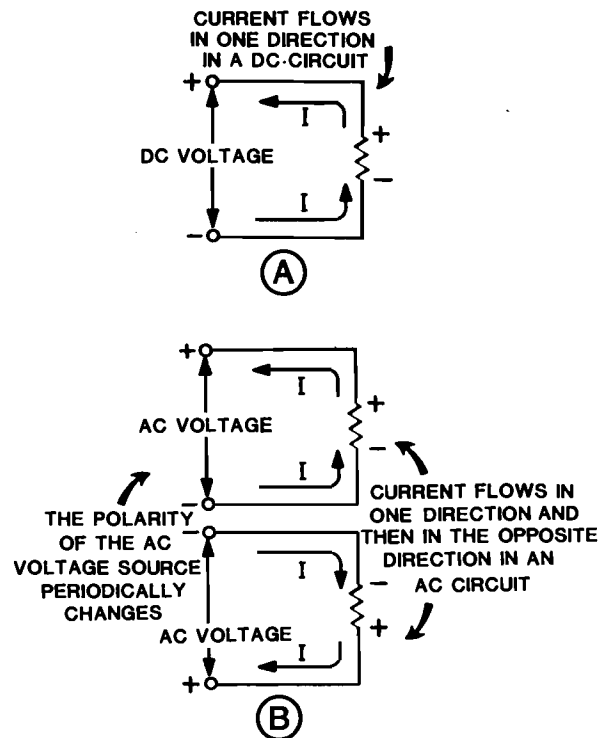


Figure 1-1 Current flow in AC and DC circuits.

Figure 1-1B shows how alternating current flows through a resistor. In the top figure, current flows in a counterclockwise direction while, in the bottom figure, current flows clockwise. Notice also that the polarity of the source voltage as well as the polarity of the voltage drop across the resistor changes in these illustrations. The change in the polarity of the voltage applied to the circuit results in a change in the direction of current flow and a change in the polarity of the voltage drop. The voltage source shown here is generally referred to as an AC voltage. The resistor and the voltage source form a basic AC circuit

Remember, in this **HEATHKIT COURSE** current flow means electron flow. Electrons always flow from a negative to a positive potential.

It is also important to note that a direct current usually has a steady or constant value since it is usually produced by a DC voltage that has a fixed value. However, momentary changes may result if, for example, the DC voltage is adjusted to a higher or lower value or when the circuit resistance changes in value. However, in most DC circuits we are concerned with a steady current which always flows in one direction. By comparison, an alternating current changes in both value and direction. In other words, the current in an AC circuit will increase from zero to some maximum value and then drop back to zero as it flows in one direction and then vary in the same manner in the opposite direction. The exact manner in which the current increases and decreases in each direction can be controlled. This makes it possible to produce various types of AC signals. In fact, a variety of AC voltage sources are used to generate different types of AC voltages that are suitable for a variety of applications. In this unit you will examine some of the basic types of AC signals that are commonly used.

Why is AC Used?

Alternating current is widely used because of its versatility. Since AC changes in both value and direction, it has characteristics which can be uti-

lized in a wider range of applications than is possible with DC currents.

For example, when a large amount of electrical energy is required for a particular application, it is much easier to generate and transmit alternating current instead of direct current. In applications where large amounts of power are required, devices such as batteries (which produce DC voltages suitable for low power applications) cannot be used. In these applications, electromechanical devices known as **generators** are used to generate the high voltages and currents required.

A generator is defined as a device that converts mechanical motion into a voltage. Generators will be discussed in more detail later in this course. Generators can be used to produce both DC and AC electricity. AC generators, when compared to DC generators are less complex, can be constructed in larger sizes, and are often more economical to operate. Therefore, AC electrical power is simpler, easier, and cheaper to produce than DC electrical power.

You can easily change an AC voltage to a higher or lower voltage by passing it through a device known as a **transformer**. The transformer is an AC component and it will be explained in detail later. For now it is sufficient to say that the transformer is made by using inductors to induce a current into another inductor. The inductors are called the transformer's primary and secondary winding. The primary winding is connected to an AC source

voltage. The secondary winding is connected to the load.

By passing a current through the primary winding a magnetic field is generated that cuts the windings (turns) of the secondary. This cutting of the secondary causes current to flow in the secondary to the load. When the secondary contains more turns than the primary, the secondary voltage is higher (stepped up) than the source voltage. When the number of turns in the secondary are less than the number of turns in the primary (stepped down) the secondary voltage will be less than the source voltage.

Using transformer action the increase (step up) or decrease (step down) in voltage can be achieved with very little loss of power. In other words, the new voltage will provide approximately the same power to a load as could be obtained from the initial voltage. This is an important feature which is used to advantage in many applications. Although it is true that DC voltages may also be stepped up or down, the process is much more complex and costly. Also, additional power is lost in the step up or step down of DC voltages. This makes the conversion (step up or step down) of DC voltages less efficient than the step up or step down of AC voltages using transformer action.

When needed, the alternating current can be easily converted into direct current by a process called **rectification**. The basic rectification process is accomplished using a solid state component called a diode. A variety of diodes will be explained later

in your studies of **SEMICONDUCTOR DEVICES**.

While it is true that DC power can be converted into AC power, the process is much more complex, more expensive, and less efficient than converting AC into DC. Therefore, when AC is used as the primary source of electrical power, DC can be obtained.

The characteristics and features just described may seem to indicate that AC is useful only because it can serve as a source of electrical power to operate electronic equipment. However, this is not the case. Alternating current is also used extensively to transmit information from one location to another. This information carrying ability results because the characteristics of an alternating current or voltage can be made to vary in a desired manner. In other words, the magnitude or amplitude (maximum value in each direction) can be varied to represent intelligence or information. Even the rate at which the alternating current changes direction can be varied to represent intelligence. In this way, information can be inserted within an alternating current or voltage, thus making it possible for the AC to carry information. When alternating currents or voltages are used to carry information they are often referred to as **AC signals**. AC signals are widely used in electronics to carry information from one point to another within an electronic circuit. These signals can also be transmitted over long distances by using long wires or transmission lines.

Alternating current may also be converted into electromagnetic waves (also called radio waves) which can radiate or travel through space. This action is possible because a conductor which carries alternating current is surrounded by a magnetic field. The field expands and collapses as the intensity and direction of the current changes. If the current changes at a sufficiently high rate of speed, the magnetic field will actually radiate outward and the radiated energy will vary in accordance with the alternating current. This means that AC signals (which contain information) can be transmitted from one location to another, without the use of wires or transmission lines. This action cannot be performed with direct current.

The points just discussed illustrate just a few of the reasons why AC is used. Although there are many additional factors to consider, we can summarize by saying that AC is primarily used to provide electrical power or to provide a means of transmitting information or intelligence from one point to another.

Where is AC Used?

In any application where large quantities of power are needed, alternating current is generally used. In fact, most electrical energy supplied for domestic and commercial purposes is alternating current.

Large amounts of AC power can be generated at the power plant by extremely large genera-

tors which are driven by turbines that are in turn powered by steam or falling water. Power stations that utilize falling water are referred to as **hydroelectric** stations and are usually located near a dam where the water can be stored and its rate of flow can be controlled. When steam is used in the generation process, a source of heat is required to produce the steam. This heat may be produced by the burning of coal, although many of the newer stations use nuclear energy. At one time, wind mills were widely used in some of the more remote areas, to generate AC power. Many wind mills are still in operation today, but they are not considered suitable for supplying large amounts of power.

The AC electrical power produced by a power plant is distributed as shown in Figure 1-2. The generators at the plant produce a relatively high AC voltage (often 2,300 volts or more), and this voltage is passed through power transformers which step it up to an even higher voltage (often as high as 275,000 volts). This extremely high AC voltage is applied to long distance transmission lines. These lines carry the voltage to the various cities and towns that are serviced by the power plant. At each location where the power is to be used, it is then passed through power transformers which step it back down to a lower voltage (typically 2,300 volts). The AC voltage is then distributed through wires which are strung on utility poles that are located along roadways, streets and alleys. This relatively high AC voltage may be directly used to power high voltage motors and equipment used in industry.

The AC voltage must be reduced even further before it can be used in the home. This final step-down is accomplished by a transformer which is usually located on one of the utility poles. This transformer steps the voltage down to 240 and 120 volts, which is then distributed to the nearby homes.

Most of your household wall plugs and light fixtures are 115/120 AC volts at 60 hertz (Hz). Some of the major appliances like stoves, wall heaters, electric furnaces, electric dryers, and some air conditioners use the 220/240 AC voltage source. Wall plugs that are rated as other

than 115/120 should require a special plug. The special plug requirement eliminates the possibility of mistakenly plugging an appliance into an improper supply voltage.

In the home, AC power is used for heating, cooking, and illumination. It is used to operate appliances such as clothes dryers, refrigerators, electric ranges, microwave ovens, dishwashers, and vacuum cleaners. In fact all of the large electrical appliances used in your home depend on the 240 or 120 volt AC power provided by the electric power company.

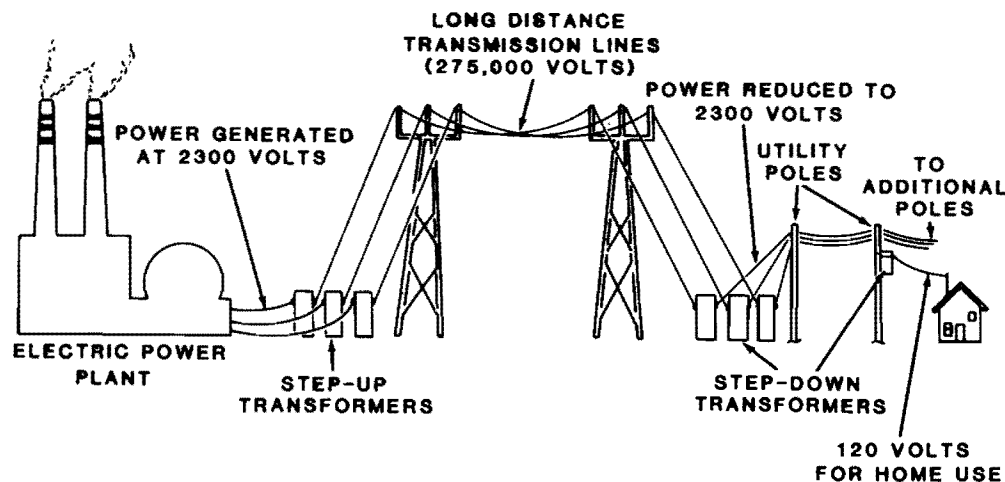


Figure 1-2 A typical electrical power distribution system.

CAUTION

Power cords should be inspected periodically for signs of wear and bare wire. A bare wire can be caused by wearing away a portion of the insulation material that coats the power cord. Keep power cords out of exposed areas. Don't route a power cord or extension cord across a doorway or any place where it might be stepped on or run over by other objects. Most wall receptacles (wall plugs) are rated at 15 amperes. Make sure that you **do not** demand more current than a receptacle can supply. Besides blowing a fuse, it could start a fire.

If you have an electrical fire **do not** pour water on the fire. To put out an electrical fire use a carbon dioxide fire extinguisher or sand.

Many industries rely on AC power to operate the electric motors that drive their machinery. AC motors are used much more extensively than DC motors because of the readily available AC power source. AC motors are also less expensive, more rugged, more efficient, and require less maintenance than comparable DC motors. In the relatively few applications where DC motors are required, such as the types used to operate elevators and certain machine tools, AC power is converted to DC power which is then used to drive the equipment.

In other industrial applications, AC is used to heat various materials. In these applications, rapidly varying AC currents are allowed to flow

through specially shaped coils of wire. The electromagnetic fields produced by the AC currents, will cause heat to be generated within any metal object that is placed within its coils. This process is often used to heat-treat metals. A similar process is also used in the medical profession where AC currents are used to produce heat within body tissue.

Without alternating current, radio or television communication would not be possible. This is because AC is used to carry the sound as well as the picture information that is transmitted from one location to another. A typical television broadcasting system is shown in Figure 1-3. The sound and picture information is converted into electrical signals by the microphone and television camera respectively. These signals are applied to the sound and picture transmitters, as shown, where they are used to vary the characteristics of the high power alternating currents which are produced by the transmitters. The resulting high power AC signals contain the sound and picture information and are applied to the transmitting antenna.

The antenna converts the signals into electromagnetic waves and radiates the waves into space. When these waves intercept the antenna on a television set. They produce AC signals within the antenna that are identical to the signals applied to the transmitting antenna. These AC signals are separated and processed by the television set so that the sound and picture information is extracted and converted into an audible and visual display.

AC signals also play an important role in many applications where information must be transmitted from one location to another. For example, the generation and transmission of AC signals are utilized in modems, two-way radio communication systems, as well as AM and FM radio broadcast systems. The various telephone systems across the country utilize AC signals, although these signals are carried by wires or transmission lines. Many of the telephone company's transmission lines have been replaced with low loss fiber optic cables.

In addition, AC signals are used in many short range applications. Such applications include cordless telephones, radio control systems used

to control model airplanes, toys, and boats. Remote television channel selectors which change the channels on television sets from several yards away, and the electronic garage door opener which allows you to open a garage door without getting out of your car are also types of remote control devices.

As you can see, there are many applications for alternating current. In fact, there are so many that it would be impossible to consider all of them at this time. However, this brief review will help you to understand the important role that AC plays in electronics. AC is used to provide comfort, convenience, and entertainment for a large number of people.

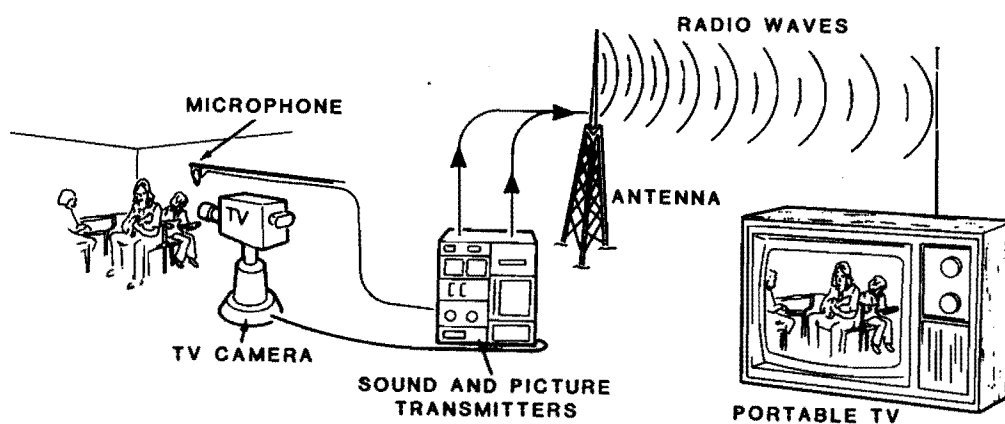


Figure 1-3 A typical television broadcast system.

Self-Test Review

1. Alternating current (AC) periodically changes its:
_____ and _____.
2. An alternating current usually increases from zero to a:
_____ value.
3. How many alternations does a sine wave contain?
_____.
4. Which type of current is most often used?
_____.
AC/DC
5. List 3 advantages of AC current over DC current.
 1. _____.
 2. _____.
 3. _____.
6. What is meant by the term step up?

_____.
7. Alternating current may be used to carry information or intelligence?
A. True
B. False
8. AC radio waves can be transmitted and received through space?
A. True
B. False
9. When AC is routed over power lines from the electric company, the value of the voltage transmitted is:
_____.
120/240/very high
10. The two 60 Hz voltages used in most homes are:
_____ and _____.
11. When a transformer's secondary contains twice as many turns as its primary, it is a:
_____ transformer.
12. Radio waves traveling through space have:
_____ properties.

Generating AC

Although alternating current may be generated in a number of ways, the most basic means of obtaining AC is by using an electromechanical device known as an **AC generator** or **alternator**. An AC generator produces an alternating voltage which in turn develops an alternating current through any load (resistor, lamps, etc.) that is connected to the generator's output terminals. Basically an AC generator produces an AC voltage by turning a loop of wire within a magnetic field. The relative motion between the wire and the magnetic field causes a voltage to be induced within the wire. This voltage changes, in magnitude and polarity, as the speed and direction of the wire changes, in relation to the magnetic field.

Now let's look at the conditions that are necessary to produce a voltage within a conductor. You will see how a simple AC generator is capable of producing an alternating voltage.

Electromagnetic Induction

An AC generator produces an alternating voltage because it makes use of a fundamental but important process known as **electromagnetic induction**. Electromagnetic induction is the process of inducing a voltage within a wire or conductor by moving it through a magnetic field.

In Figure 1-4, notice that a short wire or conductor has been inserted into the magnetic field that exists between the north (N) and

south (S) poles of two magnets. When the conductor is moved upward, through the magnetic field, it cuts across the magnetic lines of force (also called flux lines) produced by the magnets. As the magnetic flux lines pass through the conductor, the free electrons in the conductor are forced to move. These free electrons will move towards one end of the conductor, thus leaving a deficiency of electrons at the other end. This excess and deficiency of electrons causes the opposite ends of the conductor to take on negative (–) and positive (+) charges as shown. In other words, a difference of potential or voltage is developed across the conductor.

The voltage developed across the conductor shown in Figure 1-4 results because of the relative motion between the conductor and the magnetic lines of force. This relative motion must exist in order for a voltage to be produced. The conductor may move while the field remains stationary or the conductor could be held stationary while the field is moved. Either condition would cause a voltage to be produced. If there is no relative motion, no voltage is produced.

The voltage produced within the conductor is generally referred to as an **induced** voltage. This voltage is induced within the conductor regardless of whether there is current flowing through the conductor or not. In fact, a continuous current cannot flow through the conductor unless there is a **complete** circuit. You might form such a circuit by connecting a load

(such as a resistor) across the conductor as shown by the dashed lines in Figure 1-4. Current could then flow through the load resistance as shown.

The polarity of the voltage induced within the moving conductor is determined by the direction that the conductor is moving and the direction of the magnetic field. Notice the direction of conductor motion and the direction (north to south) of the magnetic flux shown in Figure 1-4. Note the polarity of the induced voltage and the direction that current will

travel when a complete current path is provided. If either the direction of conductor motion or the direction of the magnetic flux is reversed, the polarity of the induced voltage will be reversed, and current will flow in the opposite direction.

You can use the left-hand generator rule, illustrated in Figure 1-4, to determine the direction of current flow or the polarity of induced voltage, within a conductor. When your left hand is positioned as shown, your thumb indicates the direction of conductor motion, your index finger points in the direction of magnetic flux, and your middle finger, which is bent out from the palm at a 90 degree angle, points in the direction of the induced current.

The amount of voltage induced in a conductor is determined by several factors. First the induced voltage is affected by the strength of the magnetic field. A stronger magnetic field will result in more lines of force per unit area. This means that there are more lines to cut and the induced voltage is increased. When the field strength is reduced, fewer lines of force exist, and the induced voltage decreases.

Induced voltage also depends on the speed of conductor movement. The faster the conductor moves, the greater the induced voltage. This is because the faster moving conductor cuts more lines of force in a given period of time. When the speed of the conductor is reduced, fewer lines of force are cut per unit of time and the induced voltage decreases.

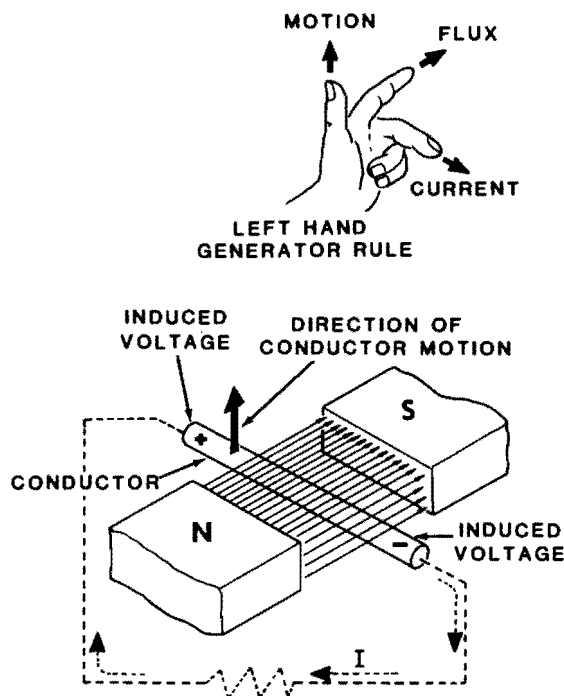


Figure 1-4 Voltage induced in a conductor by movement in a magnetic field.

The length of the conductor within the magnetic field also affects the induced voltage. The longer the conductor, the greater the induced voltage. The longer conductor cuts more lines of force as it moves through the magnetic field. A shorter conductor intercepts (cuts) fewer lines of force, and induced voltage is decreased.

The angle at which the conductor cuts the magnetic field also affects the induced voltage. When a conductor moves at a right angle (90 degrees) with respect to the magnetic field, as shown in Figure 1-4, maximum voltage is induced. When the angle between the field and the direction of conductor motion decreases, induced voltage decreases. This relationship is true regardless of the direction of the induced voltage.

The relationship between the direction of the field and the direction of conductor motion is shown in Figure 1-5. If the conductor (viewed edgewise) moves straight up from the starting position (direction A), it moves at a right angle (90 degrees) with respect to the field. At this time, the conductor is cutting the maximum number of lines per unit of time and the induced voltage is maximum. The voltage induced in the conductor would cause current to flow out of the page or toward you (according to the left-hand rule). The same condition exists when the conductor moves in the opposite direction (direction E). In this case, the conductor is still moving at a right angle with respect to the field. The change in direction still induces a maximum current, which develops a maximum voltage. The only difference

caused by reversing the direction of conductor motion is that the induced current flows into the page. In other words, the direction of current flow reverses.

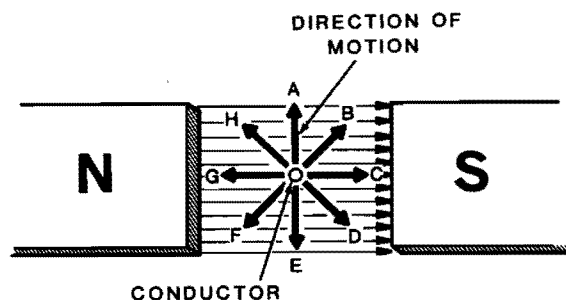


Figure 1-5 Cutting magnetic lines of force.

When the conductor moves in direction B, at the same speed, the cutting angle decreases, below 90 degrees. This means that the conductor must travel further between lines of force. This results in fewer lines being cut for the same distance of travel. The induced voltage would be less than it is at points A or E. This is also true when the conductor moves in direction H.

In either direction, B or H, the cutting angle will be the same and the induced voltage will be the same. In each case, the induced current flows out of the page. The same cutting angle is obtained, when the conductor moves in the direction of D or F. The amount of induced voltage is the same in both examples. However, in direction D or F the induced current would flow into the page.

When the conductor moves in the direction of C or G, the cutting angle is effectively zero. At this time, the conductor is moving parallel with the lines of force and no lines are cut. Under these conditions, no voltage is induced in the conductor and no current flows.

Remember, the amount of voltage induced in a conductor is affected by the following four factors:

1. The strength of the magnetic field.
2. The speed of conductor movement.
3. The length of the conductor in the field.
4. The angle at which the conductor cuts the field.

Although these four factors effectively state the conditions which affect the voltage induced in a conductor, it is possible to formulate one simple rule which takes all of these factors into account. This simple rule is stated as follows:

The voltage induced in a conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force.

The word rate in this rule is used to indicate the number of lines of force cut per second. The rule indicates that the induced voltage is proportional to the number of lines of force cut

per second. When more lines of force are cut per second, the induced voltage increases. When fewer lines are cut per second, the voltage decreases. The number of lines of force cut per second (the rate) can be increased by increasing the strength of the field, the speed of conductor motion, the length of the conductor, or the cutting angle.

A Simple AC Generator

A simple AC generator may be formed by bending a wire or conductor, in the form of a loop, and then mounting the loop so that it can rotate within a magnetic field. When the wire loop rotates, an AC voltage is induced into the loop. The only other considerations are to provide a convenient means of extracting the AC voltage generated within the rotating loop and applying this voltage to the load.

Generator Construction

An AC generator is shown in Figure 1-6. It consists of a wire loop called an armature, which is mounted so that it rotates within a magnetic field. The magnetic field exists between the north and south poles of a magnet. The magnet used for this purpose is commonly referred to as a field magnet. The field magnet is constructed so that it produces a strong, concentrated magnetic field between its poles. It can be either a permanent magnet or an electromagnet.

The electromagnet is preferred in applications where a high field strength is required to produce substantial output power.

The AC voltage induced in the rotating armature must be extracted at the ends of the wire loops which form the armature. However, the armature constantly turns, thus making it impossible to permanently attach any wires or leads directly to the armature. For this reason, it is necessary to use some type of sliding contact at each end of the wire loop. As you can see in Figure 1-6, two cylindrical metal rings are attached to the opposite ends of the loop. These metal rings are called **slip rings**. An external circuit, or load, is connected to these slip rings through contacts which are held against the rings.

The contacts are made from a soft but highly conductive material (usually carbon), and are called **brushes**. The brushes slide against the slip rings as the armature turns. The brushes serve as two stationary contacts to which an external load can be connected. The brushes are the output terminals of the generator. Simply stated, the AC output voltage is applied from the armature, through the brushes, to the load.

Generator Operation

In order to function properly, an AC generator must be operated so that its armature rotates at a constant speed. As the armature rotates in the magnetic field, one side moves down through the magnetic field while the other side

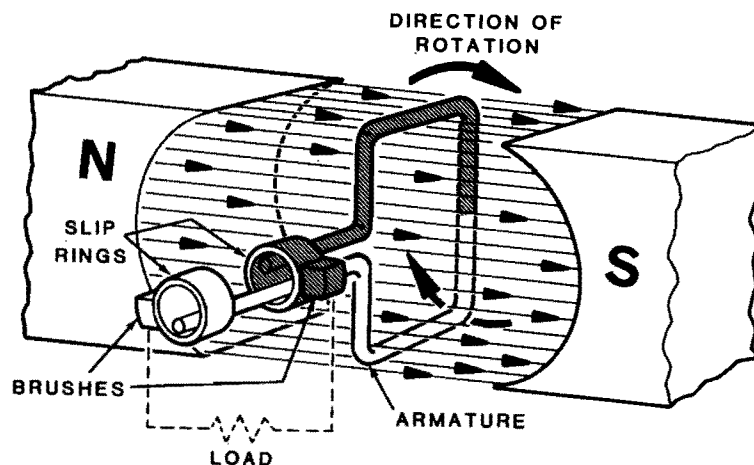


Figure 1-6 A basic AC generator.

moves up. It is important to note, during each complete revolution of the armature, each side must move down and then up through the field. Furthermore, each side of the armature always remains in contact with its respective brush through a slip ring. Keeping these considerations in mind, we will now examine the basic action that takes place during one complete revolution of the armature.

An armature is shown in four specific positions in Figure 1-7. These are intermediate positions

which occur during one complete revolution of the armature. Notice that one side of the armature and its associated slip ring and brush are black, the other side is white. The two colors are used to help you keep track of each side of the armature. Also, a resistive load is connected to the brushes so that a complete circuit is formed. The complete circuit allows current to flow through the armature to the load. The output voltage is monitored by a voltmeter. Notice that the voltmeter is connected across the load.

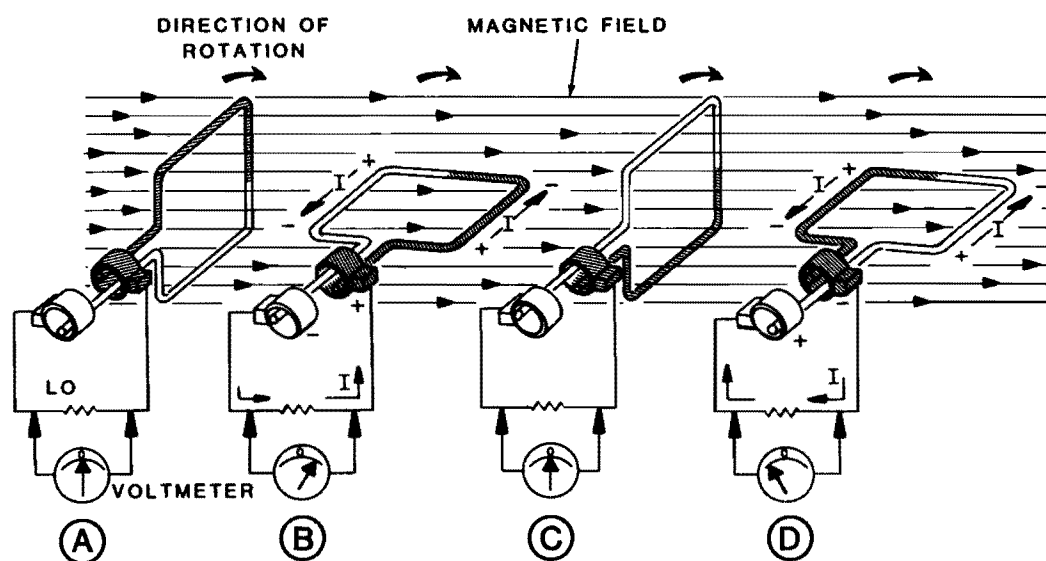


Figure 1-7 Generating an AC voltage.

Assume that the armature starts rotating in a clockwise direction from the initial position shown in Figure 1-7A. Notice that initially the black side of the armature is on top and the white side is on the bottom. As the armature moves from this starting position, the black side moves from left to right, and the white side moves from right to left. However, both sides are moving parallel to the lines of force (no lines are cut). When a conductor moves parallel to the field the induced voltage is zero. Notice that the voltmeter, which is connected to the brushes, indicates zero at this time.

As the armature rotates from the position shown in Figure 1-7A, to the position shown in Figure 1-7B, the black side moves down through the field while the white side moves up. The opposite side of the armature therefore cuts the magnetic lines of force in opposite directions. The polarity of the voltage induced in the black side will be opposite the polarity of the voltage induced into the white side. However, the voltages induced in each side are series-aiding and the two sides of the armature form a complete loop. These induced voltages are equal in value. Therefore, the voltage which appears at the brushes, is equal to the sum of the voltages, induced in each side.

The polarity of these voltages are shown in Figure 1-7B, along with the resulting currents. Notice that the series-aiding voltages produce a current that circulates through the armature and the load.

As you examine Figure 1-7B, notice that the armature is horizontal. In other words, the black and white sides of the armature are cutting the magnetic lines of force at right angles (the fastest cutting rate), resulting in the maximum induced voltage. At this time, the output voltage applied to the load is at its maximum value, as indicated by the voltmeter. It is important to note, that the output voltage does not suddenly jump from zero to maximum. The output voltage increases at a specific rate. As the armature rotates from the position shown in Figure 1-7A, to the position shown in Figure 1-7B, it cuts the magnetic lines of force, at an ever-increasing angle, until maximum voltage is obtained. This causes the output voltage to increase smoothly from zero to its maximum value.

When the armature rotates from the position shown in Figure 1-7B to the position shown in Figure 1-7C, it cuts the magnetic lines of force at a slower and slower rate. When the armature reaches the position shown in Figure 1-7C, the opposite sides of the armature are moving parallel to the lines of force and no flux lines are cut. This means that the output voltage decreases from maximum to zero as the armature moves to the position shown in Figure 1-7C. The corresponding load current also decreases to zero as the output voltage decreases.

At this point in the discussion the armature has completed one-half of a revolution and produced an output voltage that has increased

from zero to a maximum value and back to zero. The corresponding load current also varied in the same manner. It is important to note that up to this point the output voltage has changed only in value and not in polarity. This is defined as an alternation. To be more specific, from zero to maximum and back to zero is described as the positive alternation of an AC waveform. Later, this will be described as being one-half of a sine wave.

As the armature continues its rotation from the position shown in Figure 1-7C, to the position shown in Figure 1-7D, the opposite sides of the armature move across the magnetic lines of force, in opposite directions. However, the black side of the armature now moves up and the white side moves down. This is exactly opposite to the situation which occurred during the first one half revolution. Therefore, the voltages induced into each side of the armature, have polarities which are opposite to those induced earlier. These induced voltages series-aid, as before, to produce an output voltage.

The output voltage now has a polarity exactly opposite to the polarity that was produced earlier. As the armature moves to the position shown in Figure 1-7D, the new output voltage (of opposite polarity) increases to maximum because the armature cuts the lines of force at the fastest rate in this position. This maximum voltage is indicated on the voltmeter which is connected across the load. The load current is also maximum at this time and it flows in

the direction shown. The amplitude or value is exactly the same as before but the polarity of the voltage is opposite its initial direction.

The armature completes a full revolution by returning to its initial position as shown in Figure 1-7A. As the armature continues rotating toward its initial position, the armature cuts the lines of force at a decreasing rate, until no lines are cut. This causes the induced voltage within the armature and the resultant output voltage to decrease to zero. The corresponding load current is also zero at this time.

As you can see, one complete revolution of the armature produces a voltage (and corresponding load current) that changes in both magnitude and direction. Therefore, the output voltage and current are AC values. This discussion is not a full description of exactly how these AC quantities vary. We have only shown what an AC output is and that an AC output voltage is produced by generator action.

Let's look again at the generator action that was just described and consider exactly how an AC output voltage is generated. We will again rotate the armature one complete revolution (360 degrees) through the magnetic field. This time, instead of examining only the maximum and minimum points, we will consider the action that takes place at a number of intermediate armature positions.

Since the voltage induced in each side of the armature is series-aiding, it is necessary to observe only the voltage that is induced in one side of the armature. The one-half armature loop will rotate through 16 different positions as depicted in Figure 1-8. The conductor is rotating through the magnetic field in a clockwise direction.

At position A the wire moves parallel with the lines of force and no voltage is induced. However, as it moves through positions B, C, D, to E, it cuts lines of force at a faster and faster rate. At position E, the wire is moving at a right angle (90 degrees), with respect to the field. The voltage induced in the wire is proportional to the rate at which the lines of force are cut. Since the cutting rate increases in a nonlinear manner, the voltage increases in the same way.

This increasing nonlinear voltage is shown graphically in Figure 1-8. The voltage graph is plotted by marking off the angular rotation of the wire (in degrees) along a horizontal line. This horizontal line is calibrated for one complete revolution of the wire (360 degrees). The value or amplitude of the voltage that is induced within the wire is plotted vertically as shown. Notice that five voltage values have been plotted that correspond to wire positions A through E. Each successive value is higher and corresponds to the rate at which the magnetic lines of force are cut. These values are then connected to form a continuous line. The resulting curve shows how the induced voltage varies when the armature rotates one quarter of a revolution which is 90 degrees. Notice that the voltage value increases rapidly from zero (at zero degree rotation) and tapers off to a maximum value (at 90 degrees of rotation).

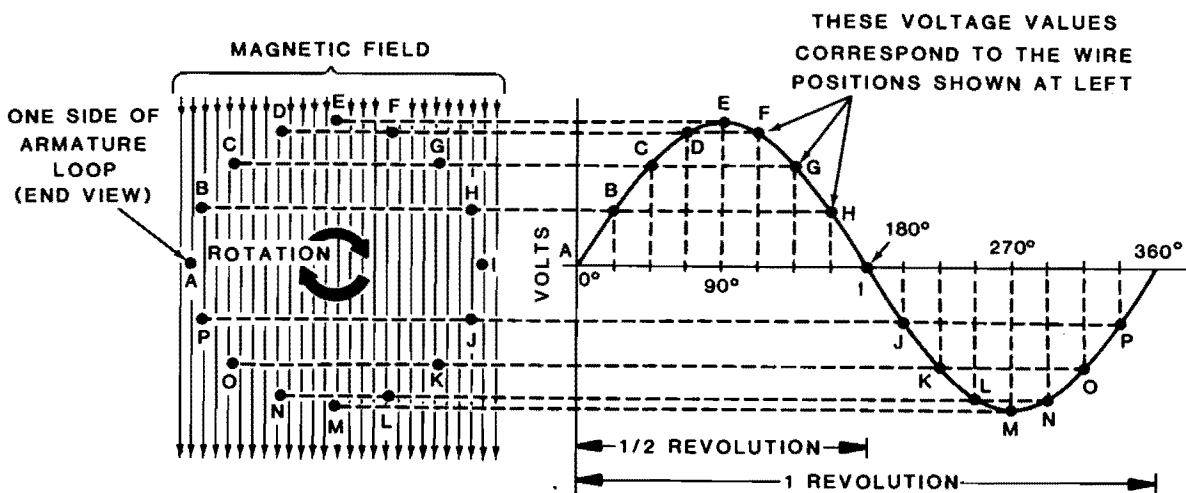


Figure 1-8 Plotting an AC output.

As the wire continues its rotation past position E and moves through positions F, G, H, and I, it cuts lines of force at a slower and slower rate. This causes the value of the induced voltage to decrease from a maximum value (at 90 degrees) to a minimum value (at 180 degrees). At position I, the wire is moving parallel to the magnetic flux lines. At this time, no lines are cut and the induced voltage is again zero.

The induced voltage values which correspond to wire positions F through I are plotted on the voltage graph as shown. Notice that these values (F through I) are successively lower, with the value at I being equal to zero. When these voltage values are joined with a continuous line, you can see that the voltage decreases slowly from its maximum value, at a faster and faster rate, until it reaches zero. The voltage curve, between values E and I, show how the voltage varies when the armature rotates an additional 90 degrees, which is the second quarter of one revolution.

To this point, the armature has rotated one half of one revolution (180 degrees) and has produced a voltage that varies from zero to a maximum value and back to zero. When the armature moves past position I, it starts cutting flux lines. This time the armature loop is moving in the opposite direction, through the magnetic field. Therefore, the polarity of the voltage induced in the armature during this alternation is opposite the polarity of the voltage produced during the first one-half revolution (positive alternation).

As the armature moves from position I through positions J, K, L, and M, it cuts the lines of force at an increasing rate. The amplitude of the induced voltage is the same as it was when the armature moved from position A to position E. The only difference is that the induced voltage now has the opposite polarity. To show that the polarity is opposite, the voltage values which occur at positions J, K, L, and M are plotted below the horizontal line as shown. This portion of the curve shows that the voltage varies from zero to a maximum value in the opposite direction as the armature wire rotates from the 180 degree position to the 270 degree position (M).

When the armature moves to positions N, O, and P, it cuts the lines of force at a decreasing rate. When it reaches position A (its initial starting position), it has completed one complete revolution (360 degrees). At this point, the armature is again moving parallel to the lines of force and no flux lines are cut. The voltage drops from its maximum value back to zero, as shown. The voltage produced during the second half of rotation (between 180 degrees and 360 degrees), increases from zero to a maximum negative value and back to zero.

One complete revolution of the armature produces an AC voltage that varies in both amplitude and direction. This is shown in Figure 1-8. During one-half of the revolution (the positive alternation), the voltage increases from zero to maximum and back to zero. During the next half of a revolution (the negative alternation), the voltage increases from zero to a negative maximum and back to zero.

When this AC voltage is applied to a load, the resulting current through the load varies in the same manner. In other words, the current will increase and decrease in one direction and then increase and decrease in the opposite direction.

One complete revolution (360 degrees) is made up of a positive (0 to 180 degrees) and a negative (180 to 360 degrees) alternation. These two alternations comprise what is called a cycle of AC. A cycle of AC is the combined time that it takes to generate the positive and negative alternations. This is also defined as the **period** of an AC waveform.

Since the armature of an AC generator rotates at a constant speed, the AC output voltage produced by the device continually changes in value and direction, as shown in Figure 1-8.

The AC generator just described is the simplest device that can be used to generate AC voltages. The AC generators used to produce electrical power for commercial applications are more complex in construction. However, all AC generators operate on the principles just described. Practical AC generators utilize many loops of wire, within their armatures, to increase the induced voltage to a much higher value. These generators may also contain more than one pair of north-south magnetic poles.

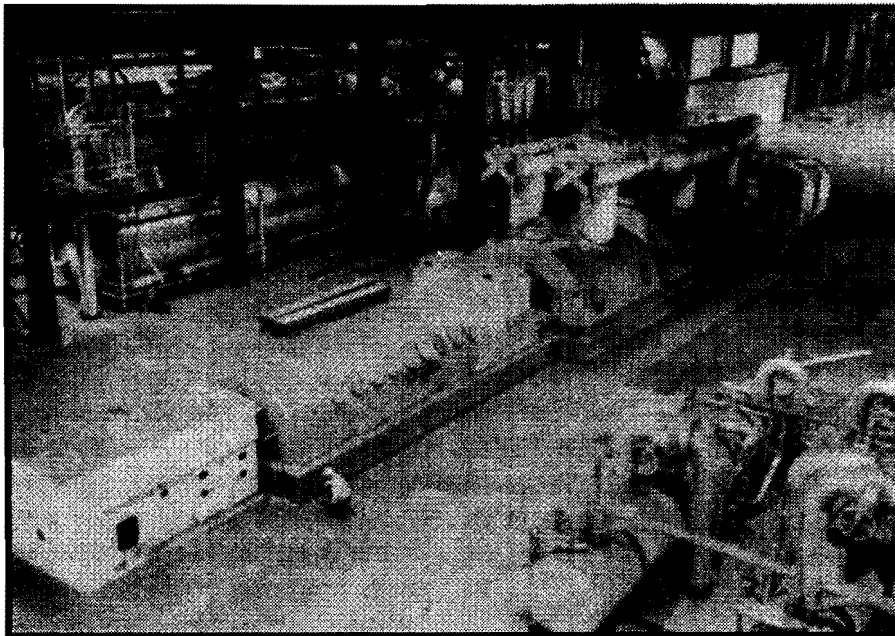
When more than one pair of poles are used, one revolution of the armature can produce more than one AC voltage variation.

Some AC generators that are designed for low power applications can be very small. For example, alternators that are used on most automobiles are small AC generators that are only six or seven inches in diameter. These small AC generators can produce a few hundred watts of output power. These alternators (generators) are powered by the car's engine and used to produce an AC voltage that is converted to a DC voltage. The DC voltage is then used to operate the car's electrical system. The newer alternators are used in place of DC generators (which were once widely used) because they are more efficient and require less maintenance. The process of converting AC to DC is relatively easy and inexpensive. The process of converting AC to DC is called **rectification** and will be explained in detail later in this course.

Some AC generators are designed to produce large amounts of electrical power and are extremely large. For example, an AC generator that is used by an electric power company might be too large to fit into the living room of your house. Such a generator might produce as much as 1,000,000 watts of output power. This would be enough power for an entire community.

In the photograph below the extremely large AC generator, next to the man, is powered by the large turbines shown at the right. This generating system produces up to 609,000

watts of output power. It is just one type of AC generator that is used by electric power companies to generate electrical power for homes and for industry.



Self-Test Review

13. The generator converts _____
_____ to:

_____ energy.

14. List the 3 methods most commonly used
by power companies to generate electrical power.

1. _____.

2. _____.

3. _____.

15. The process in which a voltage is induced
within a wire that cuts magnetic flux lines
is commonly referred to as:

_____.

16. The cutting of magnetic flux lines is
caused by moving a conductor through
a:

_____.

17. The polarity of the induced voltage is de-
termined by the direction of conductor
motion and the direction of the mag-
netic:

_____.

18. Magnetic flux lines travel outside the
magnet from the:

_____ pole to the _____
pole.

19. If the magnetic field becomes stronger, the
induced voltage will:

_____.
increase/decrease

20. If the speed of conductor motion increases,
the induced voltage will:

_____.
increase/decrease

21. When the length of a conductor is in-
creased, the induced voltage will:

_____.
increase/decrease

22. Induced voltage can also be increased by
increasing the:

_____.

23. The induced voltage is directly propor-
tional to the rate at which the conductor
cuts the magnetic:

_____.

24. When the conductor is moving parallel to
the field, the induced voltage will be:

_____.
maximum/minimum

25. The AC generator's rotating loop is called
the:

_____.

26. External loads may be connected directly to the AC generator's:

_____.

27. The armature in an AC generator produces two voltages that are equal in amplitude but have opposite:

_____.

28. The two voltages induced into the armature are:

_____ -aiding.

29. The armature begins its rotation at a point parallel to the magnetic lines of force. After one-half revolution the induced voltage will be:

zero/positive/negative

30. The part of a car that converts mechanical motion into electrical energy is the:

_____.

31. One complete revolution of the armature produces an AC voltage that varies in both:

_____ and _____.

32. The time of one complete revolution is defined as the waveforms:

_____.

33. AC can be converted to DC by a process called:

_____.

The Sinusoidal Waveform

In the previous section you learned how an AC voltage could be produced by a simple AC generator. This AC voltage was graphically plotted in Figure 1-8 so that you could see exactly how it varies throughout one complete revolution of the generator's armature. When voltage (or current) values are plotted to form a continuous curve, they form a picture or pattern which is referred to as a **waveform**. The waveform shows exactly how the voltage varies over a period of time as the armature rotates. You may examine the waveform to determine the exact value and polarity of the AC voltage at any particular instant when the armature is at a specific point.

The waveform shown in Figure 1-8 varies in a unique manner and is given a special name. It is called a **sinusoidal waveform** or simply a **sine wave**. The sine wave is the most basic and widely used AC waveform. It can be produced by an AC generator as previously shown or it can be produced by various types of electronic circuits.

The AC voltage that you use in your home to provide heat, light, and operate appliances, varies in a sinusoidal manner. The radio and television signals which carry sound and picture information are basically sine waves whose characteristics have been modified. A variety of waveforms that are more complex than the basic sine wave can be proven to be mathematically equivalent to combinations of sine waves.

The Basic Sine Wave

The sine wave is referred to as a **sine** wave because it changes in value according to the trigonometric function known as sine. Sine is a trigonometric function that describes the relationship between the sides of a right triangle. A right triangle is a triangle in which one of the angles equals 90 degrees. A triangle is defined as a three sided figure that contains 3 angles. The sum total of all three angles in a triangle is 180 degrees.

An angle has a sine value that is equal to the ratio of the length of the opposite side (the side opposite the working angle) to the length of the hypotenuse (the side opposite the right angle). This relationship is shown in Figure 1-9. Notice that the sine of angle A is equal to the opposite side (side Y) divided by the hypotenuse (side Z). Angle B would have a sine value that is equal to its opposite side (side X) divided by the hypotenuse (side Z). Notice also that the hypotenuse is always larger than either of the other sides. Therefore, the value of the sine varies from 0 to 1, for angles between zero and 90 degrees.

The sine of angle A (or angle B) will vary as the angle varies. This is because the length of the opposite side and the length of the hypotenuse both change as the angle changes. Angle A or angle B can be any value between 0 degrees and 90 degrees. These are the extreme

limits which can occur within the right triangle. Remember, the sum of angles A, B, and C must always equal 180 degrees.

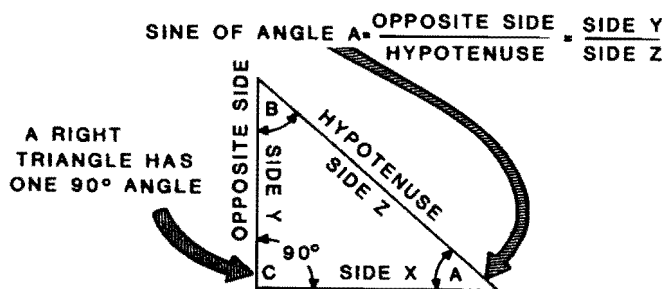


Figure 1-9 The sine (SIN) function.

As angle A (or B) varies from a minimum of 0 degrees to a maximum of 90 degrees, its sine value will vary from zero (when side Y is infinitely small) to 1 (when side Y and side Z are equal). The various sine values for all of the angles between 0 degrees and 90 degrees (in increments of 1 degree) are shown in Figure 1-10. This table of sine values is a portion of the standard table of trigonometric functions. These functions can be found in almost any textbook on trigonometry.

<i>Angle</i>	<i>Sine</i>	<i>Angle</i>	<i>Sine</i>	<i>Angle</i>	<i>Sine</i>
0°	0.000	31°	.515	61°	.875
1°	.018	32°	.530	62°	.883
2°	.035	33°	.545	63°	.891
3°	.052	34°	.559	64°	.899
4°	.070	35°	.574	65°	.906
5°	.087				
6°	.105	36°	.588	66°	.914
7°	.122	37°	.602	67°	.921
8°	.139	38°	.616	68°	.927
9°	.156	39°	.629	69°	.934
10°	.174	40°	.643	70°	.940
11°	.191	41°	.656	71°	.946
12°	.208	42°	.669	72°	.951
13°	.225	43°	.682	73°	.956
14°	.242	44°	.695	74°	.961
15°	.259	45°	.707	75°	.966
16°	.276	46°	.719	76°	.970
17°	.292	47°	.731	77°	.974
18°	.309	48°	.743	78°	.978
19°	.326	49°	.755	79°	.982
20°	.342	50°	.766	80°	.985
21°	.358	51°	.777	81°	.988
22°	.375	52°	.788	82°	.990
23°	.391	53°	.799	83°	.993
24°	.407	54°	.809	84°	.995
25°	.423	55°	.819	85°	.996
26°	.438	56°	.829	86°	.998
27°	.454	57°	.839	87°	.999
28°	.470	58°	.848	88°	.999
29°	.485	59°	.857	89°	1.000
30°	.500	60°	.866	90°	1.000

Figure 1-10Table of sine values.

Let's see how this applies to the voltage output from an AC generator. As you know, the output voltage from an AC generator varies in a sinusoidal manner. Figure 1-11A is a representation of the output of an AC generator 30 degrees through the armature's rotation. In this illustration, the maximum output voltage for the generator is shown as the hypotenuse of the right triangle, 100 volts. The actual output voltage, at any instant, is represented by the length of the side opposite the angle of rotation.

Since the sine of any angle is the relationship of the opposite side divided by the hypotenuse, you can determine the output voltage of the generator, 30 degrees through the armature's rotation. This is done by multiplying the length of the hypotenuse (100 volts) by the sine of 30 degrees (.5). In this case, the output voltage of the generator, 30 degrees through the armature's rotation, is 50 volts.

Figure 1-11B illustrates values for a number of armature positions. Notice that specific voltage values are shown at 15 degree intervals, between 0 degrees and 90 degrees, along the horizontal base line. Keep in mind that the horizontal line indicates the number of degrees of armature rotation.

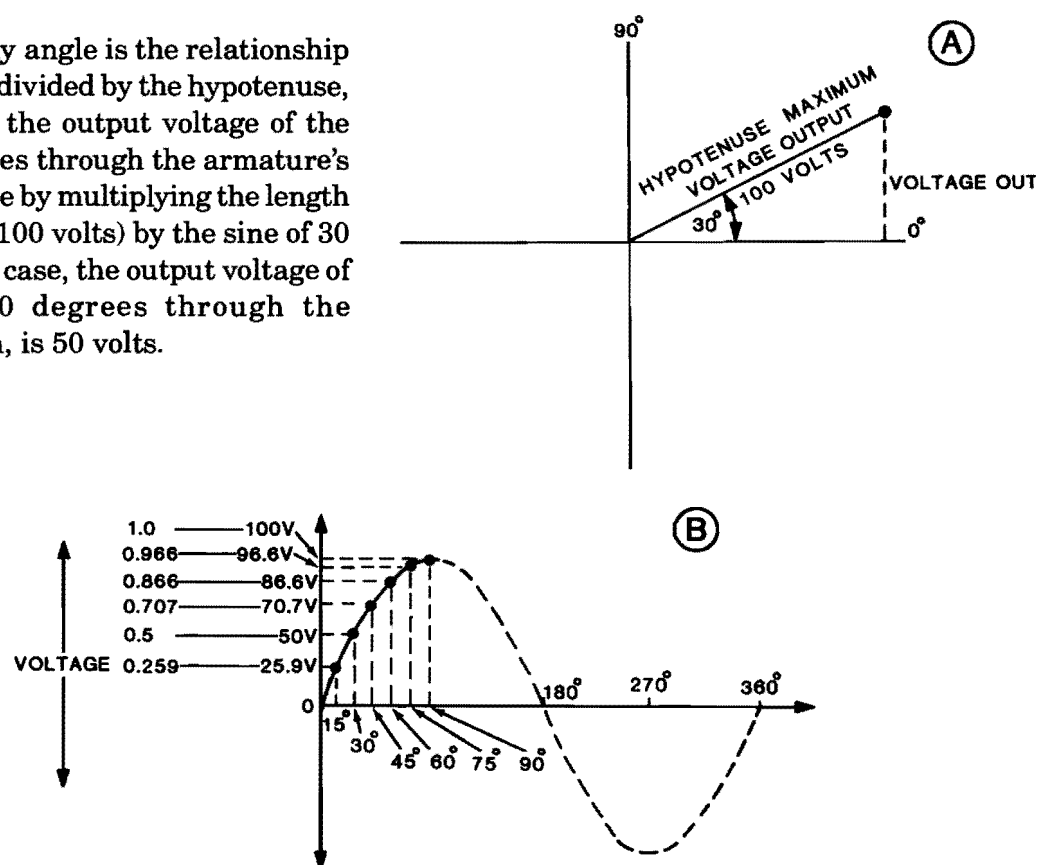


Figure 1-11 Amplitude plotted as a function of rotation.

The voltage is zero at the beginning of the waveform when the armature is at 0 degrees (parallel to the field). When the armature rotates 15 degrees, the voltage increases to a value equal to the sine of 15 degrees (.259) times the generator's maximum output voltage. Therefore, the output voltage after 15 degrees of rotation is 25.9 volts.

The output voltage continues to rise for the first 90 degrees of rotation. The sign of the angles along with the voltages present at the output are shown in Figure 1-11B. At 30 degrees the output is 50 volts; at 45 degrees the output is 70.7 volts, and so on. At 90 degrees, the sine of the angle is 1 and the voltage output at this time is the maximum voltage output for the generator.

When you compare the angular position of the armature with the corresponding output voltage, you will find that the voltage increases according to the sine of the angle of rotation.

Between the 90 and 180 degree points on the waveform, the voltage drops from its maximum value to zero. During this portion of the waveform, the voltage decreases in the exact opposite manner that it increased. In other words, the sine is maximum at 90 degrees and decreases to zero at 180 degrees. Between the 180 and 360 degree points, the voltage varies in the same manner as it did between 0 degrees and 180 degrees. The only difference is that the polarity of the voltage is opposite. This is why the curve extends below the horizontal line.

From 0 to 180 degrees is the positive alternation of the waveform. From 180 to 360 degrees is the negative alternation. The positive and negative alternations make up one complete sine wave. The time of one complete sine wave (cycle) is the waveforms period.

The Cycle

Each time the armature of an AC generator rotates through one complete revolution, it generates an output voltage that increases and decreases in value in first one direction and then in the opposite direction, as shown in Figure 1-12. When the armature rotates one complete revolution, it completes one cycle of events. In other words, it produces one complete change in voltage values. If the armature rotates another 360 degrees, it will simply repeat the cycle or sequence of output voltages. The output voltage produced during one complete revolution of the armature is therefore referred to as one **cycle** of output voltage as indicated in Figure 1-12. The armature will also produce one cycle of output current when there is a complete circuit through which current can flow.

During the generation of one cycle of output voltage, there are two changes or alternations in the polarity of the voltage. In other words, the voltage has one polarity during the first half of the cycle and the opposite polarity during the second half. These equal but opposite halves of a complete cycle are referred to as **alternations**. To further distinguish one-half

of the cycle from the other, we generally call one the **positive alternation** and the other the **negative alternation**. These two alternations are identified in Figure 1-12. The terms positive and negative are used arbitrarily to distinguish one alternation from the other. During the positive alternation the output voltage will be of a specific polarity, and during the negative alternation the polarity of the voltage is reversed.

The voltage sine wave in Figure 1-12 is made up of an infinite number of voltage values which have been plotted and joined together. At any particular point on the waveform, the

voltage is generally referred to as an **instantaneous** value, a value that occurs at a specific instant of time.

The instantaneous value is equal to the maximum value times the sine of the angle, at any instant. You may recognize this equation from the previous discussion of the sine wave.

It takes a specific amount of time to generate the sine wave shown in Figure 1-12. For this reason the horizontal line on which the waveform is plotted can be thought of as a time line, or a time base. The horizontal line can be calibrated in units of time, as well as in degrees of armature rotation.

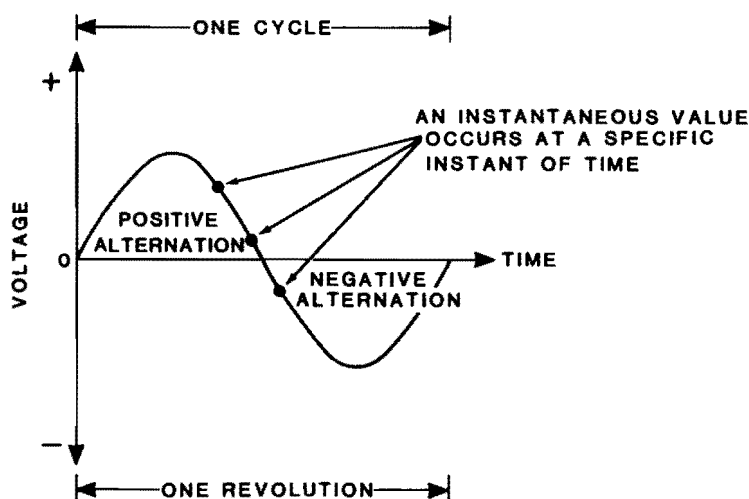


Figure 1-12 One complete revolution provides one cycle.

The horizontal line in Figure 1-12 also serves as a zero reference line. Any voltage value that is plotted on this line will have a value of zero. Above the line, all values are assumed to be positive. Below the line, all values are assumed to be negative. Therefore, all of the instantaneous voltage values which make up the positive alternation have positive values, and all of the instantaneous values which form the negative alternation have negative values. This is indicated by the plus (+) and minus (-) signs on the vertical axis of the graph shown in Figure 1-12.

The terms described in this discussion are extremely important. If you want to understand AC electronics, you must become familiar with them. These terms describe the various characteristics of one cycle of a sine wave. You must understand the exact meaning of these terms, since they will be used throughout your study of electronics.

It is also important to note that the sine wave shown in Figure 1-12 could represent one complete cycle of output current as well as a cycle of output voltage. When current is represented, the positive and negative alternations represent current that is flowing in first one direction and then the opposite direction.

Self-Test Review

34. The basic AC waveform is the:

_____.

35. The sine function has a maximum value of:

_____.

36. The sine wave is maximum at:

_____ and _____ degrees.

37. How many degrees are contained in a triangle?

_____.

38. The decimal value of the sine function can be calculated by dividing the opposite side by the:

_____.

39. State two facts about the hypotenuse of a right triangle.

_____.

_____.

40. Each time the armature makes one complete revolution (360 degrees), it completes one:

_____.

41. The part of a sine wave that appears above the reference line is the:

_____.

42. The AC waveform is a plot of value and:

_____.

43. The reference line on which a sine wave is plotted can be labeled in both:

_____ and _____.

44. The value of a sine wave, at any specific instant of time, is called an:

_____ value.

45. Any value which is plotted directly on the horizontal line has a value of:

_____.

46. The sine of 30 degrees is equal to:

_____.

47. The sine of 45 degrees is equal to:

_____.

48. The time of one cycle of a waveform is defined as its:

_____.

49. Sine waves can vary in value, direction, and:

_____.

AC Values

Since the value of a sine wave of voltage or current continually changes, you must be specific when describing the value of the waveform. In other words, you cannot simply state that a voltage sine wave has a value of 100 volts. You must specify that this is the maximum value of the voltage waveform, or some value at a specific point between zero and maximum. There are several ways of expressing the value of a sine wave and you must be familiar with each of them.

Peak Value

Each alternation of a sine wave is made up of an infinite number of instantaneous values. These values are plotted at various heights above and below the horizontal line to form a continuous waveform. It is the height (amplitude) of each instantaneous value above, or

below the line, that represents the sine wave's actual value. The greater the amplitude, the higher the value. The points on the waveform which have the greatest height, distance from the horizontal line, are defined as **peak** values.

There are two peak values in one cycle of a sine wave. This is clearly shown in Figure 1-13. One peak occurs during the positive alternation when the waveform reaches its maximum height. This point is appropriately identified as the **positive peak**. The positive peak is the maximum positive value that occurs during one cycle.

The second peak value occurs during the negative alternation when the waveform again reaches its maximum height, but this time the peak is below the line. This point is referred to as the **negative peak**.

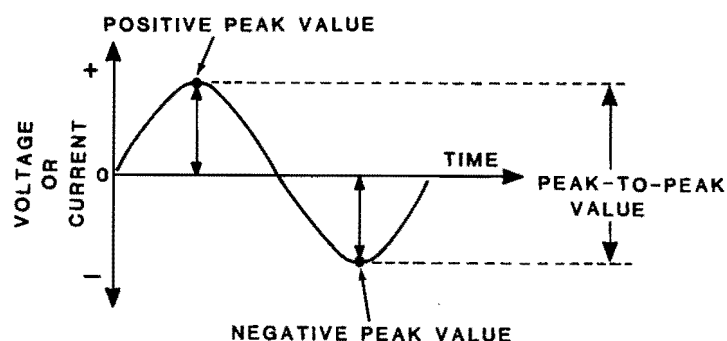


Figure 1-13 Peak and peak-to-peak values.

The positive and negative peak values of a sine wave are equal in value. In other words, the positive and negative peaks are an equal distance from the zero reference line and require the same amount of time to generate. For example, a voltage sine wave which has a positive peak value of + 5 volts, would have a negative peak value of - 5 volts, and the widths of the alternations would be the same. Only the polarity of the voltage is different and is indicated by the + and - signs. The same relationship is also true for a sine wave of current. The peak value of the current during the positive alternation is equal to the peak value during the negative alternation. The only difference is that current does not have a negative polarity. In the case of current, the minus means that the current reverses (flows in the opposite direction). Current flows in opposite directions on the positive and negative alternations.

Peak values are sometimes described by using other terms which have the same meaning. For example, the peak value is sometimes called the **peak amplitude** or the **maximum amplitude**. Any of these terms used to describe maximum value or amplitude can be applied to any type of waveform.

Peak-To-Peak Value

Sometimes it is necessary to know the total height or value of a sine wave. The overall value of the sine wave (from one peak to the other) is called its **peak-to-peak** value and can be written as $E_{p.p.}$. The peak-to-peak value of a sine wave is indicated in Figure 1-13.

The peak-to-peak value can be determined by adding the positive and negative peak values. Since two peaks are equal in value, it necessary to know only one peak value. The peak-to-peak value can be determined by simply multiplying the peak value by 2. This relationship is shown mathematically as follows:

$$\text{peak-to-peak value} = 2 \times \text{peak value}$$

For example, if the peak value of a voltage sine wave is equal to 5 volts, the peak-to-peak value must be equal to 2×5 volts or 10 volts. A current sine wave with a peak value of 10 amperes would have a peak-to-peak value that is equal to 2×10 amperes or 20 amperes. In the case of voltage, the difference of potential would be 10 volts and the peaks would be labeled + 5 volts and - 5 volts.

To determine peak value, when the peak-to-peak value is known, simply divide the peak-to-peak value by 2. For example, a sine wave with a peak-to-peak value of 18 volts would have a peak value of $18\text{V}/2$ or 9 volts. A current sine wave with a peak-to-peak value of 5 amperes would have a peak value of $5\text{A}/2$ or 2.5 amperes.

It is necessary to understand the meaning and relationship of the peak and peak-to-peak values, of a voltage or current sine wave. You will need these values, often when analyzing the characteristics of waveforms, and when measuring waveforms. Various test instruments such as oscilloscopes and certain types of AC meters are used to directly measure the peak-to-peak value of a waveform.

The oscilloscope is the most common instrument used to measure peak-to-peak values. The oscilloscope measures the value of the peaks, and displays them on its vertical axis. The vertical axis is divided into squares, each square is 1 centimeter wide and 1 centimeter high. Each square (CM) represents a specific amplitude. The oscilloscope also contains a vertical range switch (V/CM). The V/CM range switch can be used to change the value of the squares on the vertical axis. The range switch is used to expand or decrease the space required to display a waveform.

The oscilloscope can be used to display an AC waveform above and below the zero reference

line. This is accomplished by selecting AC coupling. The coupling switch can be set to reference AC, DC, or ground on most oscilloscopes. In the AC position, the sine wave will be displayed with the center line on the scope as the zero reference line. The positive and negative alternations will then appear above and below the reference

The oscilloscope is also capable of displaying the time of a waveform. Remember, that the time of a waveform is defined as its period, and is the combined time of the positive and negative alternations. Time is displayed on the horizontal axis and is controlled by a TIME/CM switch. The horizontal squares are 1 square centimeter, and can be used to expand or compact the waveform in terms of the space required to display the time of one cycle. The TIME/CM function provides a variable horizontal time base reference line.

Using the vertical and horizontal squares together, it is possible to measure and observe the complete waveform and evaluate any point on the waveform in terms of amplitude (value) and time. This allows you to measure a waveform's period, peak, and peak-to-peak values. You can also measure the rate of change in amplitude as time increases. The oscilloscope allows you to see the actual waveform. This will be especially valuable when we discuss phase and distortion later in your studies. At this time, we are only concerned with amplitude, time, and the rate of change.

Average Value

When we examine one alternation of a voltage or current sine wave, we find that it increases from zero to a peak value and back to zero as shown in Figure 1-14. The voltage or current remains at its peak value for only an instant. Except for this one instant of time, the voltage or current is always lower than its peak value. Since the voltage or current remains at the peak value for only an instant, the average voltage for the entire alternation must be less than the peak value. This average voltage can be determined by taking a large number of the instantaneous values, which occur during one alternation, and computing their average value. The average can also be calculated using integral calculus. Integral calculus is the branch of mathematics used to find volumes, areas, and equations of curves. In either case, you will find that the average value of one alternation is approximately equal to 0.636 of its maximum or peak value. This relationship between peak and average is shown in Figure 1-14. It can also be expressed by the following equation:

$$\text{average value} = 0.636 \times \text{peak value}$$

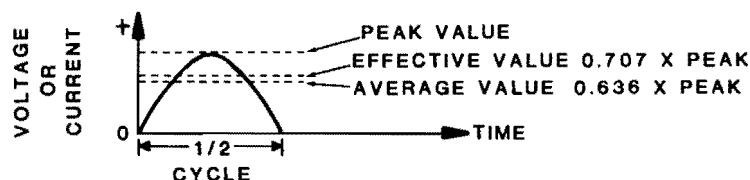


Figure 1-14 Average and effective (RMS) values.

For example, a voltage sine wave which has a peak value of 100 volts will have an average value of $0.636 \times 100 \text{ V}$ or 63.6 volts. This equation is used to determine the average value of either a voltage or current sine wave. For example, a current sine wave with a peak value of 10 amperes would have an average value of $0.636 \times 10 \text{ A}$ or 6.36 amperes.

The equation may also be transposed so that the peak value can be determined, when the average value is known. In this case, the equation becomes:

$$\text{peak value} = \frac{\text{average value}}{0.636}$$

Suppose the average value of a voltage sine wave is 50 volts. Its peak value will be equal to $50 \text{ V}/0.636$ or 78.6 volts. A current sine wave, with an average value of 1 ampere, would have a peak value of $1 \text{ A}/0.636$ or 1.57 amperes.

It is important to note that we have considered the average value of only one alternation or one-half cycle, we must add the average value of one alternation to the average value of the other alternation. Since each alterna-

tion has the same average value ($0.636 \times \text{peak value}$) and because one value is positive when the other is negative, you can see that the two averages cancel. Therefore, the average value of a sine wave is zero.

When the average value of a sine wave is discussed, it is common practice to assume that the discussion concerns only one of the alternations. The true average of a sine wave (zero) is most commonly referred to as the sine wave's reference line.

Average values are not used extensively when dealing with voltage and current sine waves, but they do have certain special applications. As you proceed with your study of AC Electronics you will find it beneficial to have a knowledge of how these average values are determined.

Effective Value

When a direct current (DC) flows through a resistor, a certain amount of power is dissipated by the resistor, in the form of heat. A certain amount of heat is also produced if an alternating current is allowed to flow through the same resistance. However, the heat produced by an alternating current, with a peak value of 1 ampere, will not be as great as the heat produced by a DC current of 1 ampere. The alternating current produces less heat because it stays at its peak value of 1 ampere for only a short period of time. Therefore, an alternating current with a peak value higher

than 1 ampere must be used to produce the same amount of heat that is produced by 1 ampere of direct current.

The AC current that will produce the same amount of heat in a specified resistance as a DC current that has a value of 1 ampere is considered to have an **effective value** of 1 ampere. In other words, a DC current of 1 ampere is equivalent to an AC current which has an effective value of 1 ampere, as far as their ability to produce heat is concerned. For this reason, the AC current must have a peak value higher than 1 ampere, in order to be equivalent to the DC current.

The effective value of a sine wave of current can be determined by a mathematical process known as the **root-mean-square or rms value**. The rms method is lengthy and will not be examined at this time. However, by using this process it can be shown that the effective value of a sine wave of current is equal to 0.707 times its peak value. The relationship between peak and effective values, of a sine wave, is shown in Figure 1-14. The same relationship is shown in the following equation:

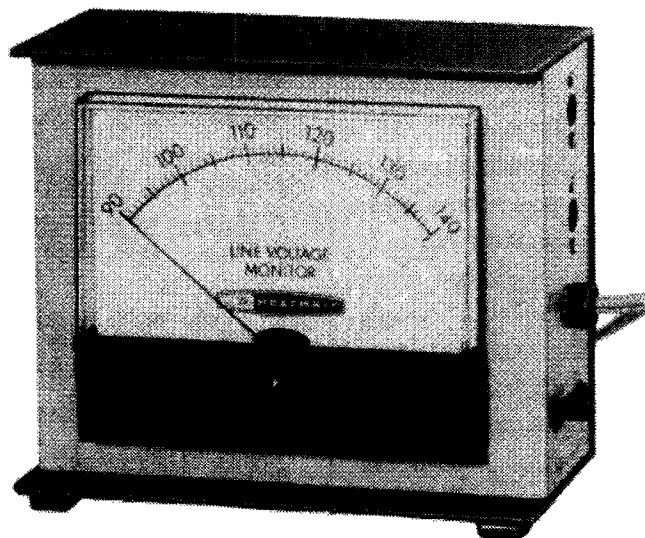
$$\text{effective value} = 0.707 \times \text{peak value}$$

For example, a current sine wave with a peak value of 10 amperes would have an effective value of $0.707 \times 10 \text{ A}$ or 7.07 amperes. This AC current, which has a peak value of 10 amperes, will produce the same heating effect as a direct current of 7.07 amperes.

Since an AC current is produced by an AC voltage, you may express the AC voltage in terms of its effective value. The effective value of a voltage sine wave is determined by using the equation ($0.707 \times \text{peak value}$). For example, a voltage sine wave with a peak value of 40 volts would have an effective value of $0.707 \times 40 \text{ V}$ or 28.28 volts.

Most AC voltmeters are calibrated to measure effective (rms) values. They measure only one alternation's effective voltage. The AC voltmeter shown is a special type meter used to monitor line voltage. This AC voltmeter is used to continuously monitor the 120 volt AC voltage that is used in most homes. It is calibrated to

read the effective or rms value of an AC sine wave. It can be plugged into any convenient electrical outlet. Notice that there are no meter leads. It is a special purpose meter and has very limited uses. The peak-to-peak AC voltmeter is also considered to be a special purpose voltmeter. The more common voltmeters are used to measure effective voltage. They have test leads so that the difference of potential, between two points, can be measured. The more common AC meters are multi-function meters. That means, that they have selectable ranges and functions such as measuring voltage, current, and resistance that have a variety of values. This type of meter can be either a VOM or an electronic type.



The peak value of a sine wave can be determined when its effective value is known by using the equation that follows:

$$\text{peak value} = 1.414 \times \text{effective value}$$

The number (1.414) is the reciprocal of 0.707, and 0.707 is the number used to change peak values to effective (rms) values.

This equation may be used to determine the peak value of either a current sine wave or a voltage sine wave. For example, a current sine wave with an effective value of 7 amperes would have a peak value of $1.414 \times 7 \text{ A}$ or approximately 10 amperes. A voltage sine wave with an effective value of 30 volts would have a peak value of $1.414 \times 30 \text{ V}$ or 42.4 volts.

Effective (or rms) values are used extensively when working with AC sine waves. It is important that you understand the relationship between effective and peak values of a sine wave. In most cases, when an AC voltage or current is specified, it is the effective value that is specified. In fact, effective values are used so extensively that they are often not specifically identified. For example, it is common practice to express an effective voltage value of 100 volts as simply 100 volts AC or an effective current value of 10 amperes as simply 10 amperes AC. When the alternating current or voltage value is specified, but not specifically identified, the effective value is usually implied. For example, the 120 volt AC electrical power that is used in your home has an effective

value of 120 volts. Its peak value is approximately 170 volts.

Most AC voltmeters and ammeters are calibrated to read effective (rms) values. The ability to accurately measure these effective values is very important, since the effective values are most often used in AC calculations.

Period

When you are analyzing an AC sine wave, it is often necessary to know exactly how much time is required to generate one complete cycle. The time required to produce one complete cycle is called the **period** of the waveform. The period of a sine wave is shown in Figure 1-15. The period is usually measured in seconds although other units of time can be used. Furthermore, the period is often represented by the letter T as shown.

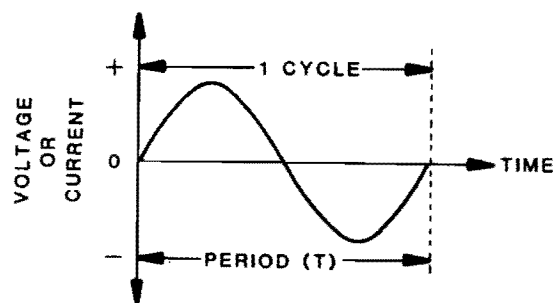


Figure 1-15 The period of a sine wave.

If a generator produces 1 cycle of output voltage in 1 second, the output sine wave has a period of 1 second. However, if 4 cycles are produced in 1 second, the output sine wave will have a period of 1/4 of a second ($T = 0.25$ seconds). It is important to remember, that the period is the time of one cycle, and not the total time required to generate a given number of cycles.

Time of a cycle is also expressed in angular notation. Remember that an armature is rotated through 360 degrees, to produce a complete sine wave. The output voltage started at zero and increased to maximum at 90 degrees. This portion is equal to 1/4 of one revolution. From maximum back to zero completes one alternation which is 1/2 of one cycle. The other 1/2 cycle is the other alternation.

Angular motion is measured in radians. A radian is equal to approximately 57.3 (57.295317254) degrees. A circle (360 degrees) contains exactly 2π radians.

As π is a constant used in electronic calculations and is equal to 3.141618, then

$$2\pi \text{ radians} = 360$$
$$(2)(3.141618)(57.295317254) = 360$$

For our purposes, π can be rounded off to 3.14. Then, $(2)(3.14)(57.3) = 359.844$. Here it is not exactly equal to 360 because both π and radians have been rounded.

Now that you have some of the basics for angular measurements, angular velocity can be discussed. In AC the term most often used for rate of change is frequency.

Frequency

It is often necessary to know how rapidly an AC waveform is changing in value. In other words, it may be important to know how many cycles of the waveform occur in a given period of time. The number of cycles that occur in a specified period of time is called the **frequency** of the waveform.

Each time the armature of the simple AC generator completes one revolution, one cycle is produced. This means that the frequency of an AC waveform is determined by the speed at which the armature rotates. As the speed of rotation increases, more cycles are generated for each unit of time. Therefore, the frequency is increased.

The frequency of an AC sine wave is usually expressed in terms of the number of cycles generated per second. For example, an armature, rotating 1 complete revolution each second, produces 1 cycle of AC each second. The AC voltage would have a frequency of 1 cycle per second.

Although the frequency is the number of cycles produced each second, it is expressed in **hertz** (abbreviated Hz). A generator which produces

an AC voltage that completes 1 cycle per second, is said to be operating at a frequency of 1 hertz. The term hertz is simply used in place of cycles per second.

If the AC generator produces 30 cycles of AC output voltage each second, it is operating at a frequency of 30 hertz or 30 Hz. Likewise, an output of 60 cycles each second is expressed as 60 hertz or 60 Hz.

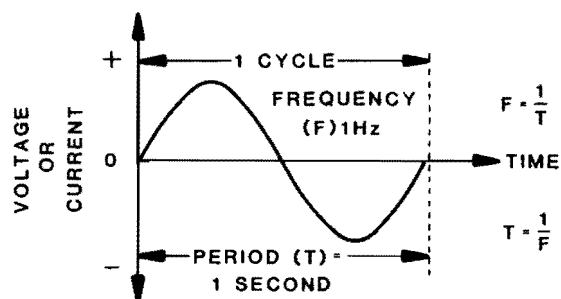


Figure 1-16 The frequency of a sine wave.

There is a definite relationship between the frequency and the period of a sine wave. When the period of a sine wave is equal to 1 second, the frequency will be equal to 1 hertz as shown in Figure 1-16. If the period decreased to 0.5 seconds or one-half of its original value, the frequency would double or increase to 2 hertz. This is because exactly twice as many cycles would occur each second. Likewise, if the period doubled, the frequency would be cut in half.

Frequency is the reciprocal of time. This relationship is shown in the following equation:

$$F = \frac{1}{T}$$

The equation simply states that frequency, represented by the letter F, is equal to 1 divided by the period, T. Furthermore, if the period is expressed in seconds, the frequency will be in hertz. For example, when the period of a sine wave is equal to 0.05 seconds, the frequency of the waveform will be equal to:

$$F = \frac{1}{0.05 \text{ s}} \text{ or } 20 \text{ hertz}$$

A period of 0.05 seconds would therefore correspond to a frequency of 20 hertz. However, if the period was cut in half or reduced to 0.025 seconds, the frequency would be:

$$F = \frac{1}{0.025 \text{ s}} \text{ or } 40 \text{ hertz}$$

In other words, the frequency would increase to 40 hertz or double. The equation shows that F and T are inversely proportional. When one increases, the other decreases proportionally.

The equation can be transposed so that T can be determined when F is known. This transposed equation is shown below.

$$T = \frac{1}{F}$$

The equation states that T is equal to 1 divided by F. If F is expressed in hertz, the value of T will be in seconds. For example, when F is equal to 100 hertz, T can be determined as follows:

$$T = \frac{1}{100 \text{ Hz}} \text{ or } 0.01 \text{ seconds}$$

The period (T) is equal to 0.01 seconds or 10 ms.

Frequencies that range from just a few hertz to many millions of hertz are widely used in the electronics industry. For example, the 120 volt AC electrical power used in your home has a frequency of 60 hertz. This 60 hertz power is used to operate your lights and appliances and it may even provide heat. In many electronic applications, much higher frequencies are required. This is because high frequencies are needed to carry information or intelligence. The higher frequencies are easier to convert into electromagnetic (radio) waves. The higher frequencies can be transmitted more easily over long distances.

These higher frequencies cannot be produced by mechanical AC generators. Mechanical generators cannot rotate at the very high speeds required to produce frequencies such as 10 kHz. To produce a frequency equal to 10 kHz requires a waveform with a period of (1 divided by 10,000). The generator would have to turn at the rate of 600,000 revolutions per minute (RPM). Therefore, electronic generators are used to produce the required high frequencies

which would be necessary. Electronic circuits do not require moving parts and are easily capable of producing frequencies many times greater than 10 kHz.

When working with frequencies that extend up to many millions of hertz, you must work with very large numbers. However, these large numbers can be reduced to a manageable size by using various metric prefixes and positional notation (powers of ten). The metric prefixes most commonly used for this purpose are defined in Table 1-1.

Metric Prefix	Symbol	Powers of Ten Value
kilo	k	1000 or 10^3
mega	M	1,000,000 or 10^6
giga	G	1,000,000,000 or 10^9
milli	m	.001 or 10^{-3}
micro	u	.000,001 or 10^{-6}
pico	p	.000,000,000,001 or 10^{-12}

Table 1-1

The negative prefixes are included in the table because they are commonly used in electronics. However, the negative prefixes are not used to represent frequency. Remember, time and frequency are closely related.

Prefixes can be placed before a word to change its meaning. For example, the prefix, **kilo** means 1,000 and when it is placed before the word hertz, we obtain the word kilohertz which means 1,000 hertz. Generally we express 1,000 hertz as simply 1 kilohertz or we use the symbol k to represent kilo and the symbol Hz to represent hertz and express the quantity as 1 kHz. In a similar manner we use **mega** (M) to represent 1,000,000. Therefore, 1,000,000 hertz (an be expressed as 1 megahertz or 1 MHz. The prefix **giga** (G) represents 1,000,000,000. Therefore, 1,000,000,000 hertz can be expressed as 1 gigahertz or 1 GHz. Also, a frequency of 10,000 hertz could be expressed as 10 kilohertz or a frequency of 1,000,000,000 hertz could be expressed as 1,000 megahertz.

The frequencies that are most commonly used in electronic applications are shown in Figure 1-17. As shown in this Figure, the frequencies between 15 hertz and 300 GHz (300,000,000,000 hertz) are the ones that are most widely used. The frequencies between 15 hertz and 20 kHz (20,000 hertz) are referred to as audio frequencies (AF) as shown. The AC current that has a frequency in this range will produce an audible tone. An audible tone is a tone to which the human ear will respond. In many cases, the AC current must be applied to a device, such as a speaker, which will convert the AC waveform into sound waves that can be detected by the human ear.

The frequencies between 3 kHz (3,000 hertz) and 300 GHz are referred to as radio frequencies (RF) since they are used extensively in radio communications. This band of frequencies is further divided into eight smaller bands. The band with the lowest frequencies is called the very low frequency (VLF) band and each higher band is appropriately named. The highest band is called the extremely high frequency (EHF) band. The frequencies within the various RF bands are widely used to transmit information or intelligence from one location to another. Once these frequencies are produced, in the form of electrical currents and voltages, they are converted to radio waves which are suitable for transmission through space.

The frequencies within the eight RF bands are further divided into smaller bands which are allocated for specific applications. As shown in Figure 1-17, a small band of frequencies within the medium frequency (MF) band is identified as the standard broadcast band. This band of frequencies is used by commercial AM radio stations. Also note, that the television channels (2 through 6 and 7 through 13) and the FM band (used by FM radio stations) are within the very-high frequency (VHF) band. The higher television channels (14 through 83) are transmitted at higher frequencies which fall within the ultra-high frequency (UHF) band. In the United States, these frequency assignments (as well as others which have not been discussed) are controlled by an agency of the U.S. Government known as the **Federal Communications Commission (FCC)**.

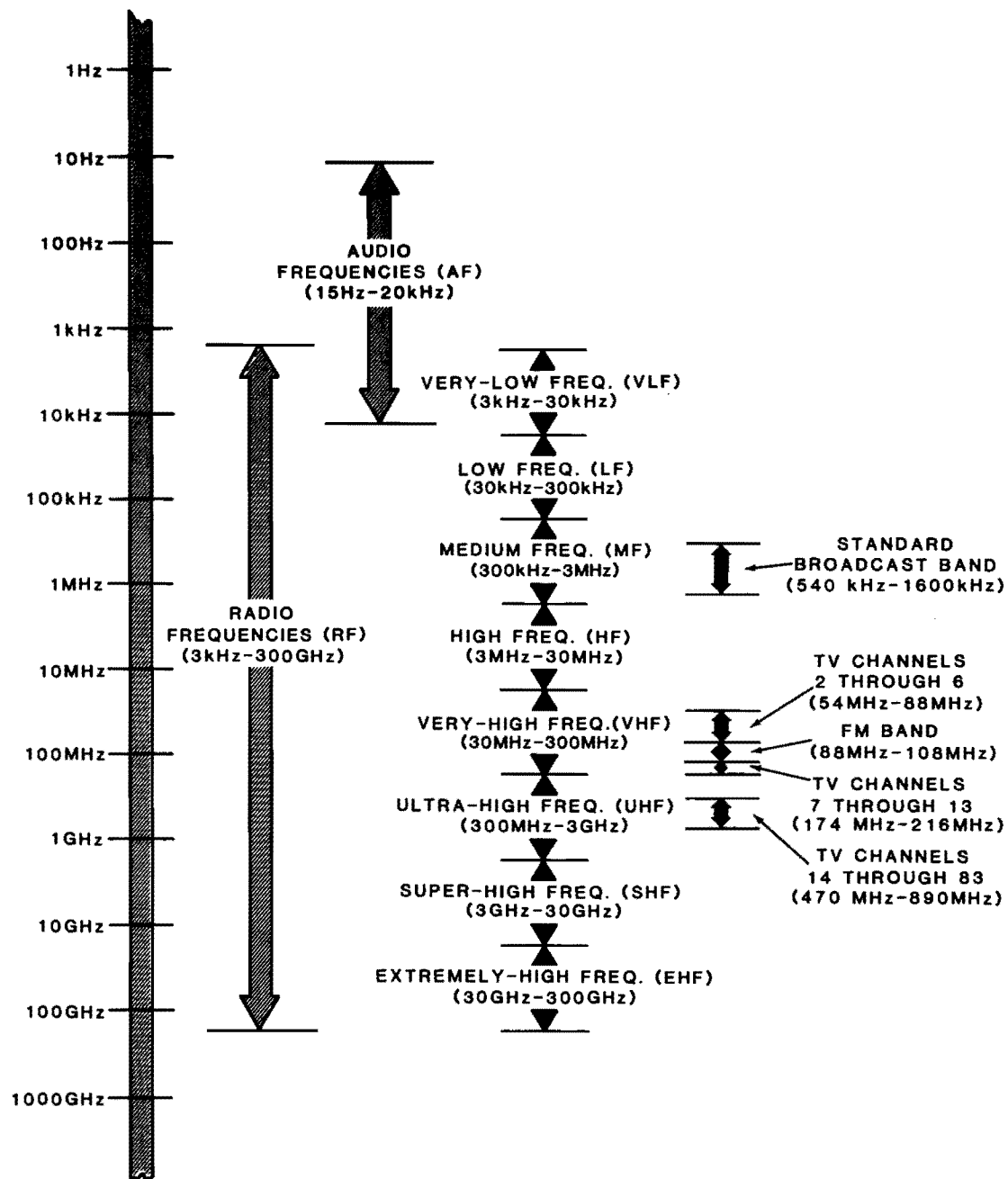


Figure 1-17 Frequency bands used in electronic applications.

Self-Test Review

50. The points on an AC waveform that have the greatest height or amplitude, are referred to as:

_____ values.

51. During one cycle the highest points occur:

_____.

52. The reference line of an AC waveform is measured in:

_____.

53. The peak-to-peak value of a waveform may be determined by multiplying:

_____ by 2.

54. A voltage sine wave has a peak value of 25 volts. What are its average, rms, and peak-to-peak values?

$E_{avg} =$ _____ volts.

$E_{rms} =$ _____ volts.

$E_{p-p} =$ _____ volts.

55. Most AC voltmeters are calibrated to measure:

_____ values .

56. A current sine wave with a peak value of 3 amperes would have an effective value of:

_____ amperes.

57. When an AC voltage is written, unless otherwise labeled, it is assumed that the voltage is an:

_____ value.

58. An rms voltage of 120 volts has a peak to-peak value of:

_____ volts.

59. The time of 10 cycles is 100 ms. What is the period of the waveform:

_____.

60. The unit hertz is a measure of:

_____.

61. What is the equation that defines the relationship between the frequency and time of a waveform?

_____.

62. When frequency is equal to 5 kHz, the period of the waveform is equal to:

_____ seconds .

63. Frequencies are generally classified as either audio frequencies (AF) or:

_____ frequencies .

64. The upper limit placed on the audio frequency range is approximately:

_____.

Nonsinusoidal Waveforms

Although the sine wave is the most basic and widely used AC waveform, it is not the only type of waveform that is used in electronics. In fact, many different types of AC waveforms are used and these waveforms may have very simple or extremely complex shapes.

We will now briefly examine some of the more common AC waveforms that are used in electronic equipment, for a variety of applications. These nonsinusoidal AC waveforms cannot be produced by the mechanically operated AC generators previously discussed. Nonsinusoidal waveforms are generated by electronic circuits utilizing a variety of semiconductor devices such as diodes and transistors. The actual semiconductor devices will be explained later in your studies of electronics. They were mentioned only to provide a prospective of how AC waveforms are utilized in the field of electronics. In this section, we are concerned with the actual types of waveforms, and how they relate to the sine wave.

The Square Wave

Figure 1-18 shows four different types of nonsinusoidal waveforms which represent either current or voltage. In each case, only one cycle of the waveform is shown. The waveform shown in Figure 1-18A is commonly referred to as a **square wave**. The name was selected because its positive and negative alternations are square in shape. The square shape of each alternation indicates that the voltage, or current, immediately increases to its maximum or peak value, at one polarity and remains there throughout that alternation. Then the voltage waveform immediately changes its polarity, or the current waveform reverses its direction. Notice that the waveform jumps to a peak value almost instantly, and remains there for the duration of the second alternation. When a continuous train of these square waves is produced, the voltage or current simply continues to fluctuate back and forth between its peak values.

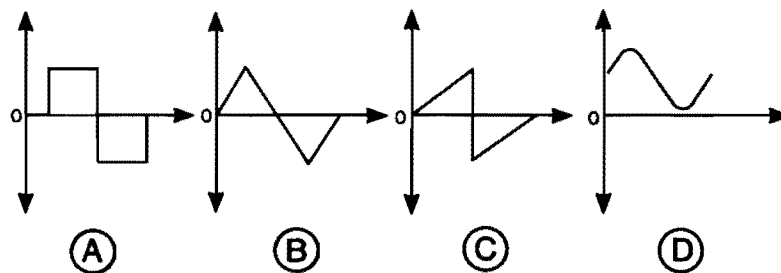


Figure 1-18 Nonsinusoidal waveforms.

Not all square waves are symmetrical, as shown in Figure 1-18A. In some cases, the positive half may be wider or narrower (longer or shorter time duration) than the negative half. Also, some square waves may have a positive peak value that is higher or lower (amplitude variations), than its negative peak value.

Although electrical power can be generated as square waves, the square wave is more useful as an electronic signal. The square wave is used to represent electronic data because its characteristics can be easily varied.

The Triangular Wave

The waveform shown in Figure 1-18B is called a **triangular wave** because its positive and negative alternations are triangular in shape. Notice that during the positive alternation the waveform rises at a linear rate from zero to a peak value and then decreases linearly back to zero. Then, on the negative alternation its polarity, or direction, reverses.

Triangular waves may have peak values that are higher or lower than those shown in Figure 1-18B. In other words, the positive and negative alternations may not always form a perfect triangle which has three equal sides. Triangular waves are used as electronic signals and are seldom used to provide electrical power.

The Sawtooth Wave

The waveform shown in Figure 1-18C is called a **sawtooth wave**. The sawtooth wave is similar to the triangular wave but there are important differences. The sawtooth wave is formed when a voltage or current increases from zero to its positive peak value at a linear rate and then rapidly changes to its negative peak value and then decreases back to zero at a linear rate. This sequence of events represents one complete cycle of the waveform. When a number of cycles are graphically plotted, the waveform has a sawtooth appearance. The sawtooth waveform has a shape that has some of the characteristics of both the square wave and the triangle waveform.

The sawtooth waveform may vary slightly from the shape shown in Figure 1-18C. For example, the change from the positive peak value to the negative peak value may not occur almost instantaneously, as shown. The change may require a small, but discernible, amount of time. Thus, the waveform appears to more closely resemble a triangular waveform than a square wave.

Fluctuating DC Waves

There are many instances when an electronic signal does not change direction. Instead the signal varies or fluctuates, at a specific rate.

These waveforms cannot be truly defined as AC waveforms, but they still behave as if they were signals. For example, the waveform in Figure 1-18D actually represents a DC voltage or current which fluctuates in value, in the same manner as the sine wave. The DC voltage fluctuates or rides above the horizontal line which serves as a time base and a zero reference line. This fluctuating DC waveform can produce the same effect as an AC sine wave in certain applications. Such a waveform might appear at an intermediate point within an electronic circuit, but it may be converted into a true AC signal before it reaches the output of the circuit.

The waveforms shown in Figure 1-18A, B and C might also appear as fluctuating DC voltages within the circuits that generate them, and then converted to AC. In many applications, either an AC or a fluctuating DC signal can be used to perform a specific function. This is true, when the manner in which they change is more important than their specific voltage or current values.

The function generator shown below produces AC sine waves, square waves, and triangular waves over a frequency range of 0.1 hertz to 1 megahertz. The waveforms produced by this instrument are used to test the operation and calibration of electronic circuits and electronic equipment.



Self-Test Review

65. Nonsinusoidal AC waveforms are produced by:
_____.
66. The type of AC waveform that has positive and negative alternations which are square in shape is called a:
_____.
67. When a waveform's positive and negative alternations change at a linear rate the waveform is called a:
_____.
68. The waveform that changes in value at a linear rate and then suddenly jumps to its other peak is a:
_____.
69. A pulsating waveform that varies in value, but not in polarity or direction, is referred to as a:
_____.
70. An AC or a pulsating DC waveform is used to perform the same function. This type of waveform is called an:
_____ signal.
71. The test instrument that provides sine, square, and triangle waveforms is commonly referred to as a:
_____ generator.
72. The type of waveform most likely to be used to control the time base of an oscilloscope is a:
_____.

Desk-Top Experiment 1

Analyzing A Simple AC Series Circuit

Introduction

This experiment provides practice in analyzing a simple series AC circuit. The principles learned in DC electronics can be applied to AC circuits. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

It is recommended that you do all of your calculations on scratch paper. Once you are satisfied with your calculations, they can be recorded in the spaces provided in this experiment. This makes your work more presentable and easier to verify.

Objectives

1. To calculate the parameters of a series resistive AC circuit.
2. To gain confidence in using Ohm's Law.
3. To prove that Kirchhoff's Voltage Law applies to AC circuits.
4. To review the characteristics of a sine wave.

Procedure

On a separate sheet of paper, draw the circuit shown below. Make all of your calculations on your drawing. The circuit is a series resistive circuit. The input sine wave has a peak-to-peak amplitude of 340 volts, at a frequency of 60 hertz.

There are several procedures for solving this problem, and you may use any of them. Depending on your approach to the problem, you may or may not, want to make your calculations in the order presented. You should round off your answers to two decimal places, for ease of calculations. When calculations are rounded off, the answers will be approximate values.

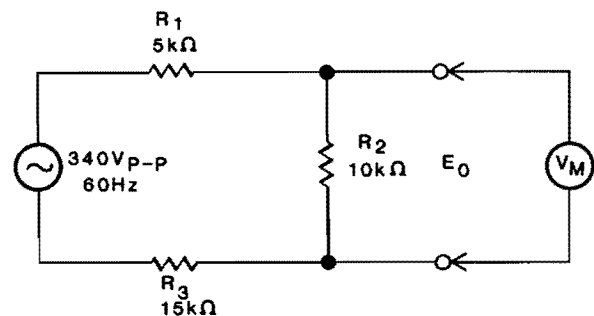


Figure 1-19 Desk-Top Experiment 1.

- $$\mathbf{E}_{\text{OUT}} = \underline{\hspace{2cm}}.$$

$P_{\text{SOURCE}} =$ _____

7. What minimum size resistors does the circuit require?

_____ watt.

Discussion

Since current is constant in a series circuit, the same current flows through all of the resistors. The formula for power dissipation is I^2R . Resistor size and resistor value are not the same thing.

8. What is the period of the waveform?

_____.

9. What is the phase angle between the voltage and current associated with R_1 ?

_____.

10. In Figure 1-20 draw the output waveform and label the following points.

Peak values = _____.

Reference value = _____.

E_{AVG} = _____.

E_{RMS} = _____.

Period = _____.

Time of positive alternation = _____.

11. What is the value of the voltage waveform at $(\pi/2)$ radians?

_____ volts.

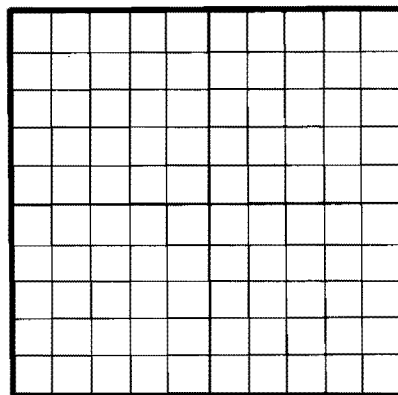


Figure 1-20 Grid Square

Discussion

The period of a waveform is the time of one cycle. Time is the reciprocal of frequency. In a purely resistive circuit, voltage and current are in phase.

The waveform starts at a zero reference and increases to a positive peak and then returns to the reference 180 degrees later. The sine wave then varies from the reference to a negative peak and back to the zero reference at 360 degrees.

The time of one cycle, 360 degrees, is the period of the sine wave. Both the positive and

negative alternations represent 180 degrees of rotation for a pure sine wave. Points to remember are:

Effective values (RMS) are equal to $.707 \times E_{PEAK}$.

Average values are equal to $.637 \times E_{PEAK}$.

π radians/2 is another way of expressing 90 degrees.

The sine wave is maximum at 90 degrees.

Summary

Your first step should have been to find the value of E_p . Then you should have found the effective (RMS) value.

Next, you should have known that all of the voltage is dropped across a closed loop. Then you should have known that since R_2 is twice as large as R_1 , and R_3 is three times as large as R_1 , the source effective voltage could be divided into 6 equal parts.

Since the voltage drop is proportional to a resistor's value, the smallest resistor has the lowest voltage drop.

The output terminals parallel R_2 , therefore, the output voltage is the same as the voltage dropped across R_2 .

Current according to Ohm's Law is E/R . Since you are asked for effective current, the formula is:

$$I = \frac{E_{RMS}}{R_T}$$

The formula for power dissipation is I^2R . Since the largest power dissipation is 240 mW, 1/4 watt resistors should be used in this circuit.

$$T = t_1 + t_2 = \frac{1}{F}$$

$$\begin{aligned} \pi \text{ radians}/2 &= \frac{(3.14 \times 57.3 \text{ degrees})}{2} \\ &= 90 \text{ degrees} \end{aligned}$$

The sine wave is maximum (E_p) at 90 degrees.

Unit Summary

Unlike direct current (DC), which flows in only one direction and has a constant value, an alternating current (AC) flows first in one direction, and then reverses direction. The value or magnitude of an AC waveform varies as it flows in each direction.

AC is used more extensively than DC because it is more versatile. Alternating current may be used as a source of electrical power, or energy. AC can also be used to carry information or intelligence.

The electrical power that is produced for use in the home is actually alternating current. This power is produced by large generators at the power plant. It is then distributed through a network of transmission lines to various homes and industries. Most houses have two AC sources of power available. They are 120 volts at 60 hertz and 240 volts at 60 hertz.

Alternating current is used instead of direct current in applications where large amounts of electrical power are required because it is easier and cheaper to produce and transport. AC voltage can be converted to a higher or lower value very easily. AC is also easily converted into DC by a process called rectification.

Alternating current may be used as an electronic signal, to carry information from one point to another. The AC signal may be carried by wires or transmission lines. It may be converted to electromagnetic waves which can be transmitted through space without the aid of wires and transmission lines.

An AC generator is able to produce an alternating current because it makes use of a process known as electromagnetic induction. Electromagnetic induction is the process of inducing a voltage in a conductor. The induced voltage appears when the conductor moves through a magnetic field.

The voltage induced within a conductor is affected by the strength of the magnetic field, the speed of conductor movement, the length of the conductor in the field, and the angle at which the conductor cuts the field. When all of these factors are considered, a rule is formed that states, that the voltage induced into a conductor, is directly proportional to the rate at which the conductor cuts the magnetic field. Maximum voltage is induced when the conductor is perpendicular to the field (90 and 270 degree positions).

The polarity of the induced voltage is determined by the direction of conductor motion and the direction of the magnetic field. Positive at 90 degrees and negative at 270 degrees.

A simple AC generator is formed by bending a wire into a loop (called an armature) and rotating the armature within a magnetic field. Slip rings and brushes are used to extract the AC voltage that is induced within the armature.

The AC output voltage produced by the AC generator, varies from zero to maximum and back to zero again as the armature completes one-half of a revolution. Then during the next one-half revolution, the voltage value is the

same, but its polarity is reversed. One complete revolution of the armature, produces an AC voltage, that changes in both amplitude and polarity. If a load resistance is connected to the generator, the AC output voltage will cause a corresponding AC current to flow through the load.

When the output voltage values are graphically plotted with respect to armature position or time, a curve is formed which shows how the AC voltage varies. Such a curve is called a waveform.

The AC voltage produced by the simple generator varies from zero to its maximum value according to the sine function and then decreases to zero in the exact opposite manner. The AC voltage changes in this manner in each direction. For this reason, the AC voltage is said to vary in a sinusoidal manner. When this AC waveform is graphically plotted, it is called a sinusoidal waveform or simply a sine wave.

One complete revolution of the armature produces one cycle of output voltage. One cycle is further divided into two alternations. One is called the positive alternation and corresponds to the first one-half revolution of the armature. The other is called the negative alternation and corresponds to the second one-half revolution of the armature.

The maximum value reached during each alternation is called a peak value. The total value of a waveform, between its peak values, is called its peak-to-peak value.

The average value of one alternation is equal to 0.636 times the peak value. The actual average of a sine wave is zero.

The effective value of a sine wave is equal to 0.707 times its peak value. A current sine wave with an effective value of 1 ampere will produce the same amount of heat in a given resistance as a direct current of 1 ampere. The effective value is also called the root-mean-square or rms value.

The period of a sine wave is the time required to produce one complete cycle. The number of cycles that occur in a specified period of time is called the frequency. The period is usually measured in seconds and the frequency is measured in hertz (Hz) which stands for cycles per second.

A variety of nonsinusoidal waveforms are also used in electronics. These waveforms are usually named for their shape. Such waveforms include the square wave, triangular wave, and sawtooth wave.

Unit 2

AC Measurements

Contents

Introduction	2-3	Resistance in AC Circuits.....	2-41
Unit Objectives	2-4	Desk-Top Experiment 2	
AC Meters	2-5	Analyzing A Simple AC	
Oscilloscopes	2-30	Parallel Circuit	2-52
		Unit Summary	2-56

Introduction

If you plan to operate, repair, or design electronic equipment, you should fully understand their use, and to some extent the creation of electronic test instruments. By this time, you are already familiar with the use and operation of DC voltmeters, ammeters, and ohmmeters. You have also had a basic introduction to oscilloscopes, AC voltmeters, and function generators. However, there are a number of test

instruments designed specifically for AC measurements.

In this unit, you will study a variety of test equipment. You will learn how the equipment operates and how to use it. Since it is necessary that you understand current and voltage relationships in AC electronics, you will also examine these relationships in AC resistive circuits.

Unit Objectives

When you have completed this unit, you should be able to:

1. Define: Lissajous pattern, CRT, graticule, and in-phase.
2. Explain the operation of the basic rectifier-type, moving-coil meter.
3. State how to increase either the current or voltage range of a meter movement.
4. Explain the operation of a thermocouple meter.
5. State the proper way to use a clamp-on meter and its principles of operation.
6. Explain the operating principles of a watt-meter and state how and why it is used.
7. Explain the advantages of an oscilloscope when compared to an AC voltmeter.
8. Explain how the oscilloscope is used to measure a waveform's pulse width, period, amplitude, rate of change, and phase relationships.
9. Analyze both series and parallel resistive AC circuits and determine their current and voltage values.
10. State the phase relationship between current and voltage in a resistive circuit.

AC Meters

A variety of meters are used to measure alternating current and voltage values. Most of these meters are electromechanical devices. They depend on induced magnetism for operation. We will now examine some of the most commonly used AC meters to see how they operate, and how they should be used. Many of the meters that we will discuss you have already used in your study of DC Electronics.

Rectifier-Type, Moving-Coil Meters

One popular type of AC meter consists of a **moving-coil** meter movement in conjunction with a group of rectifier diodes. Actually, the meter movement is designed to measure direct current rather than alternating current. The diodes, or rectifiers, are used to convert the incoming AC into a DC that can be measured by the meter movement.

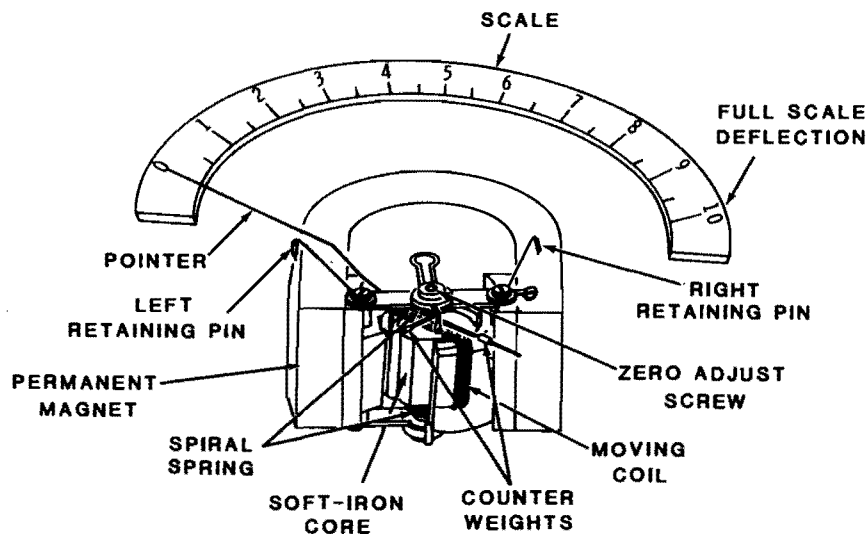


Figure 2-1 Moving-coil meter movement.

The Basic Meter Movement

The moving-coil meter movement is also commonly referred to as a d'Arsonval meter movement in honor of its inventor, Arsene d'Arsonval. This meter movement is essentially the heart of the rectifier-type, moving coil meter.

A typical moving-coil meter movement is shown in Figure 2-1. A horseshoe magnet is used to produce a stationary magnetic field which cuts across a moving coil. The moving coil consists of many turns of fine wire on an aluminum frame and the coil is mounted so that it can rotate within the magnetic field much like the armature of a mechanical AC generator. However, the coil cannot rotate 360 degrees which is one complete revolution. Instead, the frame can only move between specific limits. This is because a pointer (indicator needle) is attached to one end of the coil.

The pointer moves as the coil rotates. The pointer is allowed to swing between the left and right retaining pins. The moving coil rotates around a soft iron core which is fixed in place. The iron core helps maintain a uniform magnetic field between the opposite poles of the magnet.

The spiral springs force the coil to the extreme left so that the pointer is near the left retaining pin. In this position, the pointer rests above the zero calibration mark on the meter's scale.

The spiral springs are also used as current paths to the moving coil. The two ends of the moving coil connect to the inner ends of the spiral springs. The outer end of the rear spring is fixed in place but the outer end of the front spring connects to a zero adjust screw. By adjusting this screw, the tension on the spring is controlled and the pointer can be mechanically repositioned. Normally, the screw is adjusted so that the pointer rests over the zero position.

Counterweights are attached to the pointer so that it will be perfectly balanced and rotate smoothly on its pivots.

The action that takes place in the moving-coil meter movement is illustrated in Figure 2-2. Figure 2-2A shows a front view of the basic meter movement. As shown, the moving coil rotates around the soft-iron core and remains within the magnetic field. This illustration also shows the relative position of the pole pieces which are attached to the opposite poles of the magnet. These pole pieces help maintain a uniform magnetic field through which the moving coil is to be rotated.

The meter movement in Figure 2-2 has been simplified so that only one turn of the moving coil is shown. This single conductor is viewed from one end. This is a cross sectional view of the moving coil. When current is forced through the coil, it flows into the upper right conductor, and out of the lower left conductor.

The current through the conductor creates a magnetic field which surrounds the conductor. The created field interferes with the stationary field, produced by the magnet. The interaction of the fields causes the coil to move. This action is exactly opposite the generator action described in Unit 1. Remember, that in an AC generator, the armature moves through a magnetic field and a voltage (and corresponding current) is induced into the armature loop. In this case, a current is forced through a loop of wire, and the loop turns. This is caused by the interaction of the fields and electrical energy is converted to mechanical energy.

In Unit 1 we defined a generator as a device that converted mechanical motion (energy) into electrical energy. The action described

above converts electrical energy into mechanical motion. This is defined as **motor** action.

The moving-coil meter movement operates on the same basic principle as an electric motor. The moving-coil responds to current just like the armature in a motor. It is possible to analyze the exact manner in which the fields interact to determine the direction of conductor motion. However, a simple rule can be used to determine the same result. This rule is commonly referred to as the **right-hand motor rule**. This rule is illustrated in Figure 2-2B. When the right hand is positioned as shown, the forefinger points in the direction of the magnetic field, the middle finger (which is bent out from the palm at 90 degrees) points in the direction of current flow, and the thumb points in the direction of conductor motion.

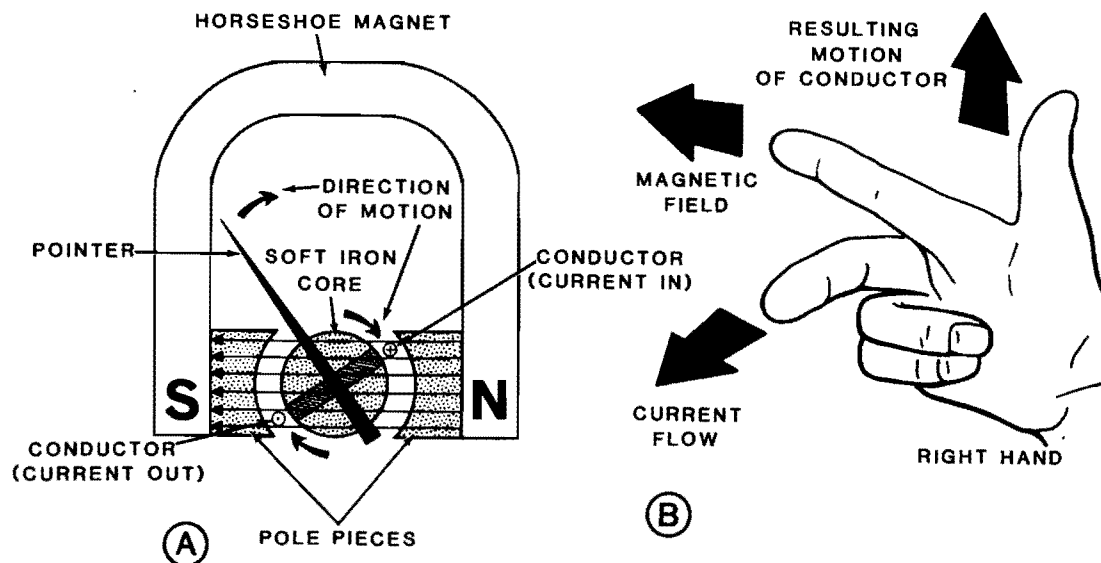


Figure 2-2 Motor action of moving coil.

When the right hand rule is applied to the coil in Figure 2-2A, we find that the upper right side of the coil is forced down and the lower left side is forced up. Therefore, the pointer is forced to move clockwise (CW). CW movement is up scale from left to right. The coil must move against the tension provided by the spiral springs. The resulting pointer deflection is proportional to the amount of current flowing through the coil. The higher the current, the greater the deflection.

Like all meter movements, the moving-coil meter movement is rated according to the amount of current required to produce full scale deflection. For example, a 1 milliamperemeter movement would deflect full scale when 1 milliamperes of current flows through it. Some meters are designed to be more sensitive than others. For example, a meter with a 200 microampere rating would be more sensitive than one with a 1 milliampererating. Other commonly used meters which are even more sensitive, have ratings of 100 and 50 microamperes.

It is also important to note that all moving-coil meter movements are designed to operate using only direct current. These meters will not respond properly when alternating current is applied directly to them.

Rectifiers

The moving-coil meter movement may be used to measure alternating current if the AC is converted to DC, before it is applied to the meter movement. This can be accomplished using a semiconductor device called a diode. A diode is a 2 element device that is used to convert AC to pulsating DC (rectification process). These rectifier components are connected between the input AC and the meter. They allow current to pass through the meter in one direction and then block current during the reversing alternation.

One of the earliest rectifier diodes used in conjunction with meter movements is illustrated in Figure 2-3A. It consists of a copper disk which has a layer of copper oxide on one side. A lead disk is placed against the copper oxide layer and the entire unit is compressed between two metal pressure plates. The pressure plates are held in place by a bolt. This type of rectifier diode is commonly referred to as a **copper oxide rectifier**.

The copper oxide rectifier will allow current to flow readily from the copper to the copper oxide, but will allow only a small current to flow in the reverse direction. Therefore, it is essentially a unidirectional conductor of elec-

trical current. An ideal rectifier would act as a short in one direction and an open in the opposite direction. Since this ideal situation does not exist, most practical rectifiers have small resistances when operated in the shorted condition, and small currents still flowing when operating in the open condition. However, the difference between a diode's shorted and open conditions are extremely large, and unmistakable.

The copper oxide rectifier has been replaced in most applications by a more efficient device known as a **junction diode rectifier** or more commonly a **junction diode**. The junction diode is made from a semiconductor material (a material which is not a good conductor or a good insulator) such as germanium or silicon. The semiconductor material is processed so that it takes on unidirectional characteristics. The semiconductor device is then mounted in a glass, metal, or plastic package which protects it from environmental hazards.

A typical junction diode is shown in Figure 2-3B. The device shown has two metal leads which extend from opposite ends of a plastic case. The leads are internally connected to the opposite ends of the junction diode rectifier. Current can readily flow into one lead and out of the other lead in the direction shown but

only a small leakage current can flow in the opposite direction.

One end of the rectifier shown in Figure 2-3B is marked with a band. This end of the diode is referred to as the **cathode** and the opposite end is called the **anode**. Current always flows from the cathode end to the anode end as shown.

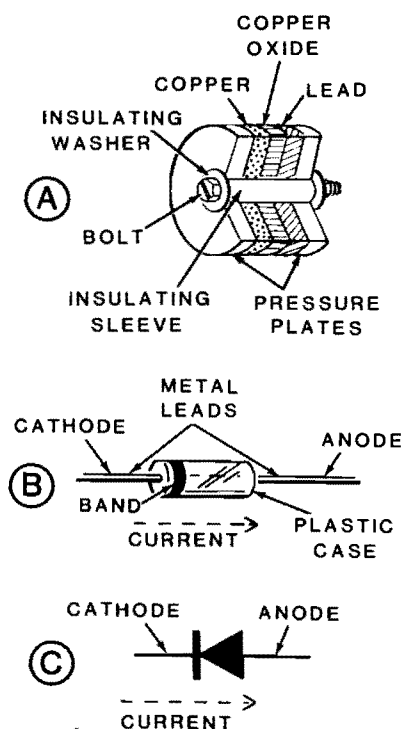


Figure 2-3 Rectifiers and their symbol.

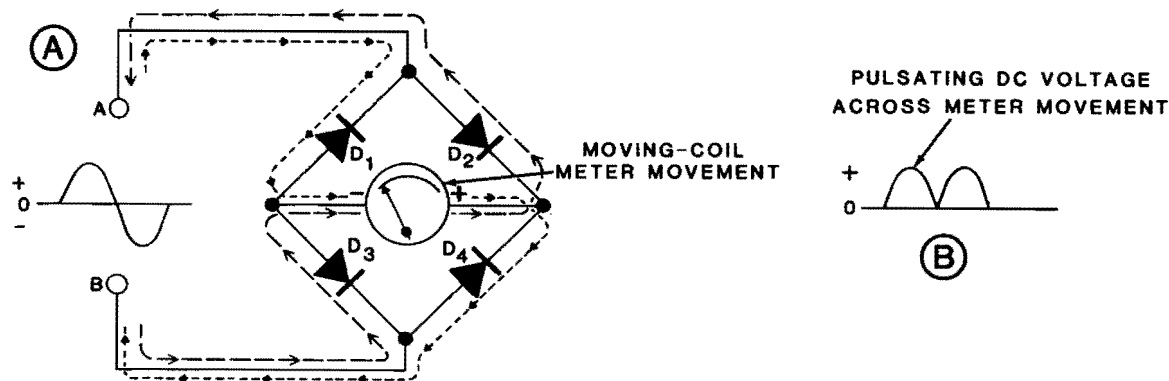


Figure 2-4 Rectifier-type, moving-coil meter.
 A. Bridge rectifier.
 B. Rectified input to meter movement.

The schematic symbol commonly used to represent a rectifier is shown in Figure 2-3C. Notice that the symbol consists of a bar and an arrow, and that current (electron) flow is always against the direction that the arrow is pointing. In other words, current can flow from the bar to the arrow but not in the opposite direction.

The Complete AC Meter

The schematic diagram of a rectifier-type, moving-coil meter is shown in Figure 2-4A. Notice that four rectifiers are used in conjunction with one meter movement. The four rectifiers are identified as D_1 , D_2 , D_3 , and D_4 and are arranged in what is called a **bridge recti-**

fier configuration. The two input terminals of the circuit are identified as A and B.

Let's assume that an AC generator is connected to input terminals A and B, and that this generator is supplying a continuous alternating current that varies in a sinusoidal manner. We will also assume that during each positive alternation of the sine wave, terminal A is positive with respect to terminal B. During each positive alternation the circuit current flows along the path indicated by the long dashed lines. Current flows from terminal B, through D_3 , the meter movement, D_2 , and out terminal A. During each negative alternation, B is positive with respect to A and current flows along the path indicated by the short dashed lines.

In other words, current flows from terminal A, through D_1 , the meter movement, D_4 , and out terminal B. Notice that even though the input current changes direction, the current through the meter movement is always in the same direction. The four rectifiers therefore convert the input AC into pulsating DC, as shown in Figure 2-4B.

Later in your study of electronic circuits you will learn that when the sine wave is converted to 2 pulses of the same polarity, either positive (as shown in Figure 2-4B) or negative, the term rectifier is changed to full-wave rectifier. A bridge rectifier provides full-wave rectification. The polarity of the output pulses is determined by the positioning of the diodes. The direction of current flow can be reversed by reversing all of the diodes in the bridge circuit.

The process of converting AC to DC is referred to as **rectification** and this is why the diodes used in this application are referred to as simply rectifiers. Furthermore, the rectifiers in this circuit convert both halves of the sine wave into a pulsating direct current and are therefore said to be providing **full-wave** rectification. Less complicated circuits, which use only one or two rectifiers, may also be used to provide **half-wave** rectification. In this last process, only one of the alternations is allowed to flow through the meter movement.

The current through the meter movement flows in pulses since each alternation rises from zero to a peak value and drops back to zero. Unless the frequency of the input is ex-

tremely low, the meter movement will not follow the variations in the pulsating current. Instead, the meter's pointer responds to the average value of the AC alternation. The average of an alternation is equal to 0.636 times the peak value. However, the scale on the meter is usually calibrated in effective or rms values.

In other words, the numbers on the meter scale represent effective values. The effective value is equal to 0.707 times the peak value. The effective value of a sine wave is much more important than the average value since effective values are used in most calculations involving current and voltage. The effective values are also used to compute the power dissipated by the resistors in electronic circuits.

Electrical Characteristics

A variety of rectifier-type, moving-coil meters are available which are capable of measuring a wide range of alternating currents. Each meter is designed to measure up to a certain maximum current. For example, some meters may have calibrated scales which extend from 0 to 1 milliamperere, 0 to 10 milliamperes, or 0 to 100 milliamperes.

Most rectifier-type, moving-coil meters have an accuracy of $\pm 5\%$. This accuracy measurement is based on the percentage of error in the meter reading at full-scale deflection. For example, a 100 milliamperere meter which has an accuracy of $\pm 5\%$ might be off by as much as ± 5 milliamperes when it is indicating a

current of 100 milliamperes. However, this same full scale accuracy of $\pm 5\%$ will pertain to any other meter reading. For example, if the meter indicates 50 milliamperes, the true reading could still be off by as much as ± 5 milliamperes.

The scale used with the rectifier-type, moving-coil meter is linear. This means that the numbers or values on the scale are equally spaced. Therefore, the pointer's deflection is always directly proportional to the current flowing through the meter movement. A typical scale used with this type of meter is shown in Figure 2-5.

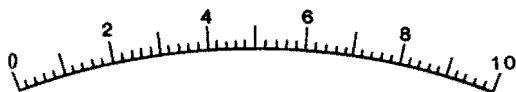


Figure 2-5 Typical linear scale.

The rectifier-type, moving-coil meter is useful for measuring alternating currents over a specific frequency range. This type of meter is usually quite accurate over a frequency range that extends from approximately 10 hertz to as much as 10,000 to 15,000 hertz. Below a lower limit of approximately 10 hertz, the

meter's pointer tends to fluctuate in accordance with the changes in input current. Since the meter's pointer is never stationary it is difficult to accurately read the meter.

Above the upper frequency limit (10 kHz), the meter readings are usually too inaccurate to be usable. In fact, the accuracy of the meter progressively gets worse as frequency increases beyond a few hundred hertz. This is because the rectifiers have a certain amount of internal **capacitance** and the moving-coil meter movement has a certain amount of internal **inductance**. These two internal properties present a certain amount of opposition to the flow of alternating current through the meter. The opposition that capacitance and inductance has to current flow is not constant, but varies as the frequency changes.

Later when inductors and capacitors are utilized and fully explained you will see that inductive reactance (X_L) increases as frequency increases. Capacitive reactance (X_C) decreases as frequency increases. The term reactance is used instead of resistance to differentiate between DC and AC opposition. DC opposition is resistance and is measured in ohms. AC opposition is also measured in ohms, but the proper term for the opposition is impedance. The symbol for impedance is Z and in circuits where components other than resistors are used it is a vector relationship.

Moving-Vane Meters

Some meter movements are capable of responding directly to AC inputs. One of these types is the **moving-vane** meter or a **moving iron** meter. This type of meter contains a movable iron vane and depending on the shape of the vane, it may be classified as either a **radial-vane** or a **concentric-vane** meter. We will examine both of these basic types and then consider their important electrical characteristics.

The Radial-Vane Meter Movement

The radial-vane mechanism is shown in Figure 2-6. It contains the same basic components as the meter movements. But they are arranged differently. A coil is stationary. It surrounds a moving iron vane which is attached to the meter's pointer. A stationary iron vane is mounted inside the coil, parallel to the moving vane. When current flows through the coil (in either direction) a magnetic field is produced that surrounds the coil. This field passes through the moving and stationary vanes and magnetizes both in the same direction. Therefore, the vanes will always have north and south poles directly adjacent to each other. Since like poles repel, the movable vane is pushed away from the stationary vane, and

the meter's pointer is forced to rotate against the tension provided by the springs. Figure 2-6 shows the tops of the vanes as north poles and the bottoms as south poles. This condition occurs when current flows in one direction. When current flow reverses, the poles reverse. However, in either case, the two vanes are pushed apart.

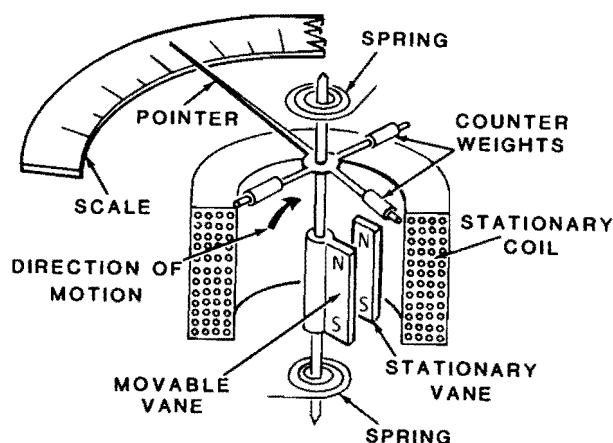


Figure 2-6 Radial-vane meter movement.

A higher current through the coil, produces a stronger magnetic field around the coil. This results in greater induced magnetism within the vanes. The increased magnetism causes the pointer to deflect further. In other words, the higher the current the greater the pointer deflection. As shown, the scale must be appro-

proportionately calibrated so that the pointer indicates the amount of current applied to the meter movement. Like most AC meters, the scale is usually calibrated in effective values. The scale extends from zero to the maximum value that the meter movement is designed to measure.

Most AC meters have range select scales the same as DC meters. This is accomplished by switching multiplier resistors in series with the meter movement for the voltage scales. Current ranges can be extended by routing the excess current around the meter movement. This is called shunting a meter. When a meter is shunted, a small valued resistor is placed across the meter movement.

The Concentric-Vane Meter Movement

The concentric-vane meter movement is shown in Figure 2-7. Notice that it is similar to the radial-vane movement, except that its stationary and moving iron vanes are semicircular in shape. The moving vane is mounted inside the stationary vane and it is attached to the pointer. The moving vane has square edges but the stationary vane is tapered along one edge.

When current flows through the coil, a magnetic field is produced around the coil. The magnetic field passes through both vanes causing them to become magnetized in the same direction. However, the magnetic lines of force are not distributed uniformly through the stationary vane because of its tapered edge. Fewer lines of force will pass through the narrow end

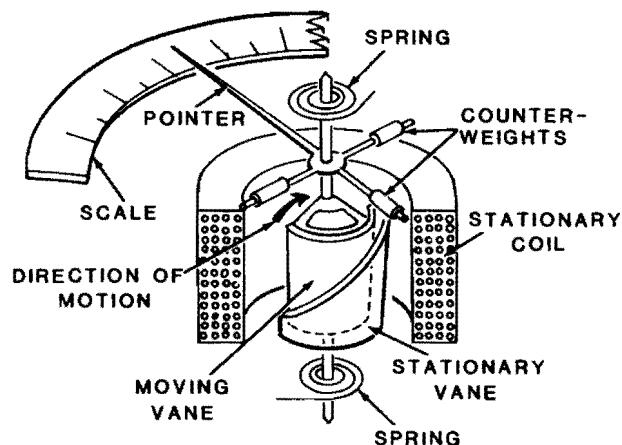


Figure 2-7 Concentric-vane meter movement.

than the wide end. This is because the narrow end offers higher opposition to the magnetic lines of force. The wider end provides an easier path for the lines of force, thus allowing more lines of force to be produced.

Therefore, the wider end of the vane is more strongly magnetized than the narrow end. The strongest repulsion will occur between the wide end of the stationary vane and the moving vane. Since the repulsion at the narrow end of the stationary vane is less, the movable vane is forced to rotate toward the tapered end of the stationary vane. This force is against the tension, provided by the springs, and causes the pointer to deflect up scale. The higher the current through the meter movement, the greater the pointer deflection.

Electrical Characteristics

Moving-vane meters are primarily used to measure AC values. They can also be used to measure DC values when their scales are appropriately calibrated. This is possible because the moving and stationary vanes always repel, regardless of which direction current flows.

Moving-vane meters require more current to produce full-scale deflection, than the rectifier-type moving-coil meters. Therefore, moving-vane meters are seldom used in low power circuits. They are more suited for measuring the relatively high currents in AC power circuits.

Most moving-vane meters have a full scale accuracy of approximately $\pm 5\%$. Moving vane meters do not provide accurate readings at frequencies above 100 hertz. Therefore, they are usually used to measure 60 hertz AC.

The scale used with the moving-vane meter is usually nonlinear. In other words, the values on the meter's scale are not equally spaced. In fact, these meters usually provide a pointer deflection that increases with the square of the change in current. For example, suppose that

10 milliamperes of current causes the pointer to deflect a distance of 1 inch on the meter's scale. When the current is increased to 20 milliamperes, or doubled, the pointer would not deflect 2 inches (twice as far). Instead, the pointer would deflect four times as far or 4 inches. Likewise, if the current increased to 3 times its initial value, the pointer would deflect 9 times as far (9 is the square of 3). If the input current becomes 4 times as great, the pointer would deflect 16 times its initial distance. Any meter that is calibrated in this manner is said to have a **square-law** scale.

A typical scale for a moving-vane meter is shown in Figure 2-8. Notice that the values near the zero end of the scale are more closely spaced. With this type of scale it is difficult to accurately measure current values that fall near the zero end.

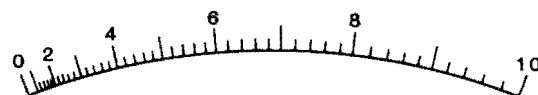


Figure 2-8 Typical nonlinear scale.

Thermocouple Meters

The thermocouple meter is also commonly used to measure AC. This instrument uses a device known as a **thermocouple** to generate the current needed to drive the meter movement. We will now briefly examine this meter and consider its important electrical characteristics.

Meter Operation

The thermocouple meter consists of a thermocouple and a moving-coil meter movement as shown in Figure 2-9. The thermocouple is two dissimilar metal strips or wires that are joined at one end. When this junction is heated, the two metals produce a difference of potential across their open ends. The thermocouple converts heat into an electrical voltage. This is very similar to the battery action studied in DC electronics, except heat, instead of chemical action, is used to produce a voltage.

A short heater wire is placed against the thermocouple's junction as shown in Figure 2-9. The AC input is applied directly to the heater wire. The wire heats to a temperature that is determined by the amount of current flowing through the wire. The heat produced by the wire causes the thermocouple to produce a DC output voltage. The DC voltage causes current to flow through the moving-coil meter movement. This current causes the pointer to deflect, indicating the AC effective value of the input.

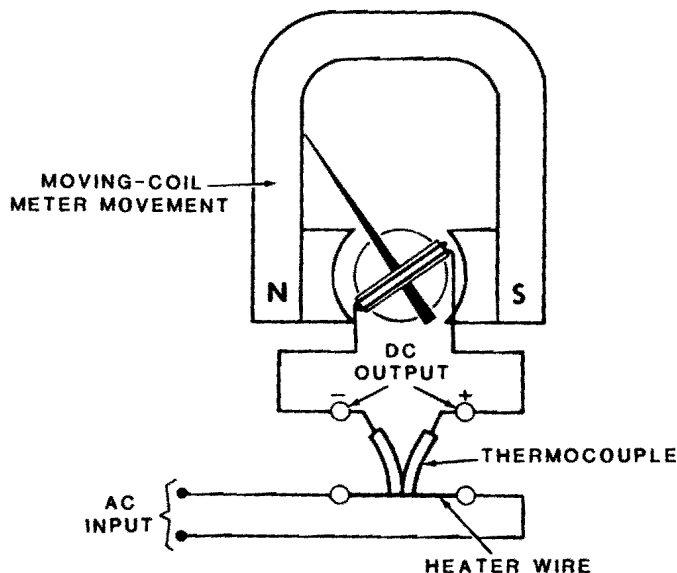


Figure 2-9 Thermocouple meter.

Electrical Characteristics

The thermocouple meter can measure alternating currents over an extremely wide frequency range. In fact, its upper frequency limit extends well up into the radio frequency (RF) range. These meters are often used at frequencies as high as several gigahertz. They may also be used to measure DC when their scales are appropriately calibrated. This is because thermocouple meters are completely insensitive to the rate at which the input current varies. They respond only to the amount of heat that is produced by the AC or DC input.

When a thermocouple meter is used to measure an alternating current that has an extremely high frequency, it is necessary to calibrate the instrument at that particular frequency. In other words, the meter should be calibrated to indicate the correct AC value at a particular frequency. This is because a phenomenon known as **skin effect** occurs at extremely high frequencies. Skin effect occurs because high frequency AC currents tend to flow near the outer surface of a wire. The higher the frequency, the higher the skin effect. This means that most of the conductor's interior is not used to support current (the effective diameter of the conductor is reduced) and its resistance is higher than it would normally be. Therefore, the effective resistance of the wires within the meter vary with frequency. This change in internal resistance affects the meter's response, making it necessary to calibrate the meter, at the frequency that is to be measured.

When properly calibrated, thermocouple meters provide accurate AC measurements. Typical meters will usually have a full scale accuracy of $\pm 2\%$ or $\pm 3\%$ and certain types of laboratory instruments may have an accuracy of $\pm 1\%$. Furthermore, the thermocouple meter provides a pointer deflection which varies as the square of the change in AC input current. Therefore, the thermocouple meter must also have a square law scale.

Clamp-on Meters

All of the meters previously described must be connected directly into an electronic circuit to measure current. However, there is an instrument that does not have to be physically connected into the circuit to measure current. This instrument can be clamped over a conductor to measure the current flowing through the conductor. These meters are sometimes referred to as field strength meters because they measure the strength of the magnetic field around a conductor. These clamp-on type meters are also referred to as **split-core** meters, **hook-on** meters, or **snap-around** meters.

Meter Operation

A clamp-on meter consists of a transformer and a rectifier-type moving-coil meter, as shown in Figure 2-10. The instrument is usually mounted within a small plastic case and can be held in one hand.

This meter utilizes a split-core transformer. One side of the transformer core is hinged and is movable. This section of the core may be opened by pressing a trigger which is attached

to it. To measure the AC current in a conductor, the core (which is made of soft iron) must be opened and the conductor inserted inside the core. Then the core is closed so that it completely surrounds the conductor. It is important to ensure that the core is completely enclosed and that no air gap is present.

The AC current flowing in the conductor produces a circular magnetic field around the conductor. The strength of this field is proportional to the current flowing through the conductor. This magnetic field expands and collapses as the AC increases and decreases in value. The field polarity reverses as the current changes

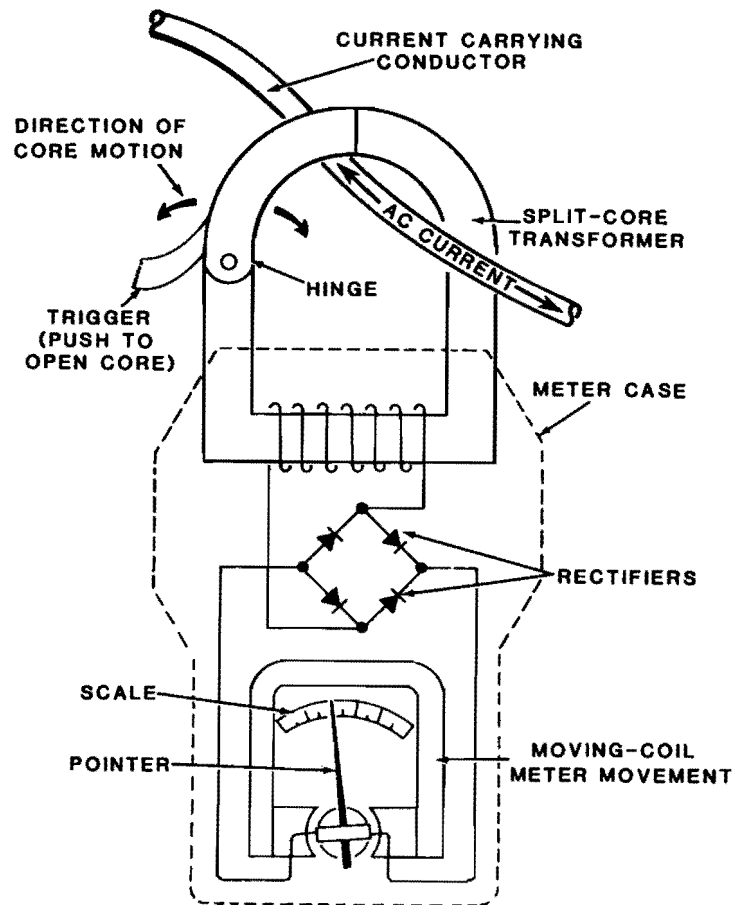


Figure 2-10 Clamp-on meter.

direction. The iron core offers little opposition to the magnetic field (much less than air). This means that most of the lines of force pass through the core.

In order for this to happen, the magnetic lines of force must cut across the coil that is wound around the opposite side of the core. When this happens, a voltage is induced into the coil which causes an induced current to flow through the coil. The conductor, the core, and the coil, form a **transformer**. The conductor is the input or **primary** winding even though it contains only one turn. The coil is the output or **secondary** winding of the transformer.

The current induced in the secondary is an alternating current just like the current in the conductor. This AC is applied to the rectifiers which convert AC to DC. The DC is then used to operate the moving-coil meter movement causing its pointer to deflect. The meter is calibrated to indicate the effective AC value of current that is flowing through the conductor.

Electrical Characteristics

Since the clamp-on meter depends on transformer action for operation, it can be used to measure AC only. The moving magnetic field produced by AC in the conductor, is necessary to induce a voltage into the secondary of the transformer. The magnetic field produced by a direct current is constant, and therefore cannot be coupled using transformer action.

In general, the clamp-on meter is useful for measuring only relatively high alternating currents. This is because the current in the conductor must be high in order to produce a magnetic field strong enough to induce a significant amount of current into the secondary coil. These meters are often used to measure currents as high as several hundred amperes. They are usually used by electricians for power line checks rather than by electronic technicians.

Using AC Meters

Now that you have examined some of the basic types of AC meters, it is time to consider how these meters are used in typical applications. Although there are no complicated rules governing their use, there are some important points which must be considered. The basic AC meter is essentially a current measuring device. It is also used to measure voltage and power. Let's see how these instruments are used to measure various quantities and the important precautions that must be observed when they are used.

Measuring Current

With the exception of the clamp-on meter, current is measured by inserting the ammeter into

the circuit, in series with the component whose current is to be measured. In the case of DC currents, proper polarity must be observed. When using an AC current meter, the meter will only respond to one of the alternations and polarity is not a problem.

AC meters are current measuring instruments. They are available for measuring alternating currents over a variety of ranges. In general, any meter which is used to measure current, either AC or DC, is referred to as an **ammeter**. However, the terms **microammeter** and **milliammeter** are also used to specifically identify meters that measure currents in the microampere and milliamperere ranges.

Many AC ammeters are designed to measure current over one specific range. For example, a meter may be calibrated to measure currents from 0 to 50 milliamperes, while another meter may have a scale which extends from 0 to 100 milliamperes. These two meters could be used to measure currents as high as 50 and 100 milliamperes respectively. If these values are exceeded by a substantial margin, even momentarily, sensitive meter movements could be damaged.

The amount of current required to deflect the meter's pointer to its full scale position is called the **meter's sensitivity**. The two meters just mentioned would have meter sensitivities of 50 and 100 milliamperes respectively. Meter sensitivity and meter movement sensitivity

should not be confused. Meter sensitivity is the maximum current that the meter can measure on any given scale. Meter movement sensitivity is the maximum current that can pass directly through the meter movement. Meter movement sensitivity is fixed at the time of manufacture and is usually printed on the face of the meter movement.

Certain types of ammeters are designed to have more than one current range. Such meters are usually equipped with a range switch which effectively changes the sensitivity of the meter and its operating range. A typical multirange ammeter circuit is shown in Figure 2-11A. Notice that the instrument utilizes a 1 mA (1 milliamperere) AC meter movement, three resistors, and a range switch. When the range switch is in the 1 mA position, only the meter movement is connected to the input terminals thus giving the instrument a current range that extends from 0 to 1 milliamperere.

When the range switch is moved to the 10 mA position, a resistor, R_1 , is connected in parallel with the meter movement. When the switch is in this position, it can measure currents up to 10 milliamperes. The meter movement itself can only handle 1 milliamperere of current. R_1 shunts the additional 9 milliamperes of current around the meter movement. In other words, when 10 milliamperes of current flow through the meter, the shunt resistor, R_1 , must route all of the current except 1 milliamperere around the meter movement.

When the range switch is moved to the 100 mA position, the meter measures up to 100 milliamperes. Resistor, R_2 , shunts up to 99 milliamperes of current around the meter movement. When the range is set to the 1 A position, the meter measures up to 1 ampere (1,000 milliamperes). Resistor, R_3 , shunts up to 999 milliamperes of current around the meter movement. Resistors R_1 , R_2 , and R_3 are referred to as **shunt resistors**.

The complete AC meter is shown in Figure 2-11B. Notice that only one scale is used and it is calibrated from 0 to 1. This scale is used on each range. You must mentally adjust the decimal point on the scale to correspond to the range that is used. Some meters have more

than one scale. When this is the case, read the scale that you selected with the range selector switch.

When using an ammeter to measure current, you should be sure that the current that you are measuring is not beyond the range of your ammeter. Initially play it safe and use the highest possible range. Then work down in range until you obtain a reading that is slightly higher than midscale. Be sure that your meter is properly calibrated. You should always check the pointer to ensure that it is on zero before inserting the meter into the circuit. If it is not, readjust the meter for a zero reading. Most meter movements have a mechanical zero adjustment that is used to reposition the pointer.

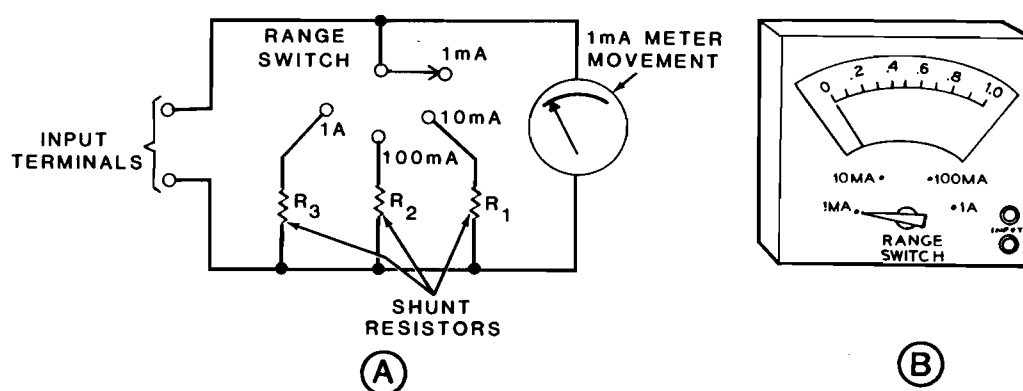


Figure 2-11 Typical multirange ammeter.

When using any type of ammeter, except the clamp-on type, to measure AC current, the meter must always be connected in series with the current to be measured. This means that it is necessary to break the circuit under test so that the ammeter can be inserted. For example, if you wish to measure the current flowing through a resistor, it is necessary to break the circuit on one side of the resistor and insert the ammeter as shown in Figure 2-12A. With the ammeter connected in series, a complete circuit is again formed and the current flows through the meter. When measuring the current through a component that is connected in series or parallel with other components, extreme caution must be exercised to be sure that the ammeter is in series with the correct component. For example, if you wish to measure the current through R_2 in Figure 2-12B, you must be sure that the meter is in series with R_2 . When the circuit is broken and the meter is installed at points A or C, you will measure the total current flowing through R_1 . When the ammeter is inserted at point B, it measures the current through R_3 .

Since the alternating current periodically changes its direction, it makes no difference which direction the meter is connected. In other words, the wires connected to the meter's input terminals (shown in Figure 2-12) could be reversed and the meter would still function

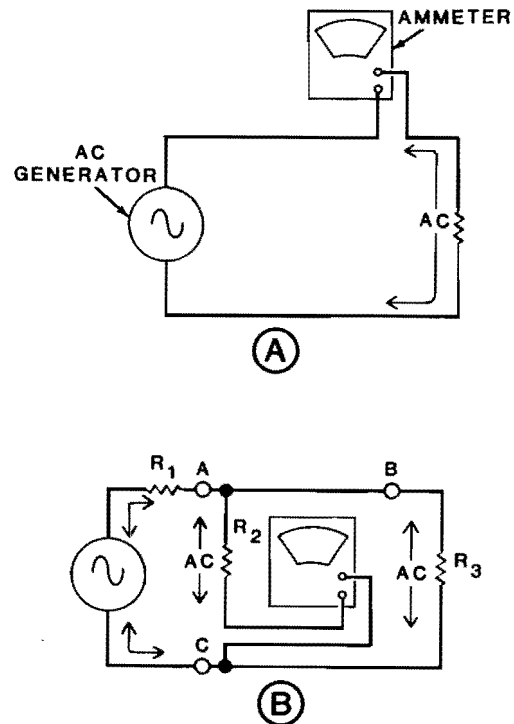


Figure 2-12 Measuring current with an ammeter.

properly. It is only necessary to ensure that the meter is in series with the alternating current. In this respect, AC meters are much easier to use than DC meters. DC meters must be connected so that the current flows through them in the proper direction. In other words, you must observe proper polarity.

Measuring Voltage

Although AC meters are current measuring instruments, they can also be used to indicate voltage. When they are used to measure voltage, additional components are required. The additional components limit the current flowing through the meter to the proper value. Meters that are used to measure voltage, either AC or DC, are referred to as **voltmeters**.

Some voltmeters are designed to measure one specific range of voltages that extend from zero to some maximum value. However, many voltmeters are capable of measuring voltages over several ranges. These multirange meters are more versatile and are therefore more practical in applications where a wide range of voltage values must be measured.

A typical multirange voltmeter circuit is shown in Figure 2-13A. Notice that the instrument uses a meter movement, three resistors, and a range switch. When the range switch is set to the 1 V position, the instrument is capable of measuring AC voltages from 0 to 1 volt. When the range switch is in this position, a resistor (R_1) is connected in series with the meter movement. This resistor has a resistance value that will limit the current flowing through the meter movement to its full-scale value when the AC voltage across the input terminals has an effective (rms) value of 1 volt. The internal

resistance of the meter movement (although it is usually very low) is also taken into consideration when this resistor value is determined. This is necessary in order to ensure that the total resistance of the meter circuit will have the proper value.

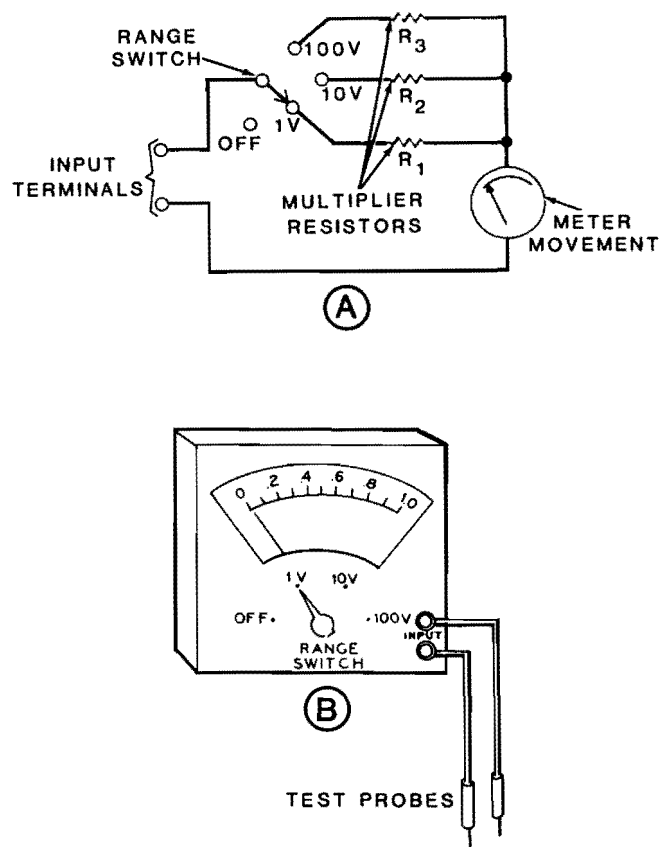


Figure 2-13 Typical multirange voltmeter.

When the range switch is set to the 10 V position, the meter can measure effective voltages up to 10 volts. In this case, resistor R_2 is in series with the meter movement. This resistor has a higher value than R_1 and it limits the current through the meter movement to its full-scale value when the input voltage is 10 volts. When the range switch is set to the 100 V position, R_3 is switched into the circuit. This resistor is larger than R_2 and it limits the current through the meter movement to its full-scale value when the input value is 100 volts. Resistors R_1 , R_2 , and R_3 multiply or extend the meter's voltage range by a factor of 10 in each case. These resistors are commonly referred to as multiplier resistors. Notice that as the applied voltage is increased, the value of the multiplier resistor is increased, and the maximum current allowed to flow is limited to a safe value for the meter movement.

The complete AC voltmeter is shown in Figure 2-13B. Notice that only one scale is used for all three ranges. The instrument is also equipped with test probes which are used to connect it to a circuit. The test probes are simply placed in contact with the circuit under test and they allow voltage measurements to be made very quickly and efficiently.

When measuring a voltage, the voltmeter must always be connected in parallel with the voltage to be measured. It is not necessary to break the circuit to obtain a voltage measurement. To measure the voltage produced by the AC voltage source shown in Figure 2-14A, you would connect the meter in parallel with the source as shown. Since a resistor is also connected across the voltage source, the voltmeter is measuring the voltage across the resistor as well. Remember, voltage is constant

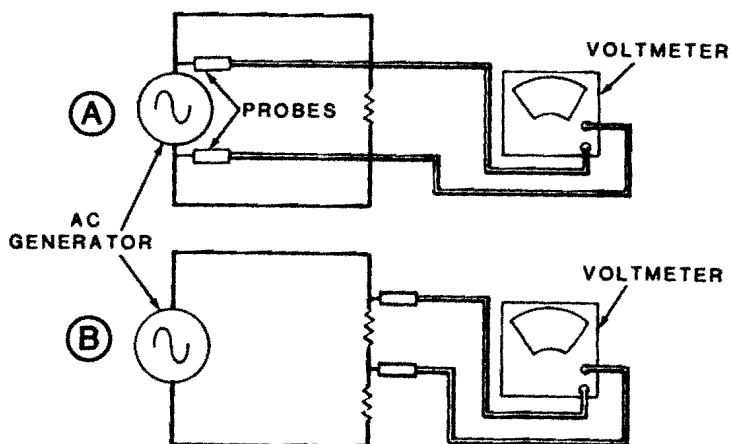


Figure 2-14 Measuring voltage with a voltmeter.

across a parallel branch circuit. If two resistors were connected in series and then connected across a voltage source, to measure the voltage across one of the resistors, connect your meter in parallel with the single resistor as shown in Figure 2-14B. The voltage measurement is made by connecting (touching) the test probes to each side of the resistor. The voltage measured will be the voltage dropped across the single resistor.

When measuring an AC voltage, in most cases, it makes no difference which direction the meter is connected. The test probes shown in Figure 2-14 could be reversed and the voltage readings would not change. The AC voltage continually changes direction or polarity thus making it unnecessary to observe polarity.

CAUTION

One exception to this is when you are measuring voltages with a meter that has an earth grounded reference lead. For example, electronic trainers that are earth grounded (3-prong line cords) and meters that are earth grounded. It is possible to insert a ground into the circuit under test. The point where the meter's reference lead is connected becomes earth ground.

Always be sure that the voltage is within the meter's capability. When in doubt, use the highest range possible and work your way down to a range that provides a midscale read-

ing. In the case of a DC voltage, observe proper polarity.

Measuring Power

AC electrical power can be measured by using special types of AC meters. These instruments measure the effective (rms) values of current and voltage and internally compute the amount of power ($I \times E$). The power is then indicated on a calibrated scale. Electrical power is the rate at which electrical energy is used. Power is measured in units called watts. The calculation of power in AC circuits is more complex than with DC circuits. In DC circuits, the power consumed by a component, in the form of heat, is determined by multiplying the current through the component by the voltage dropped across the component. This relationship is shown mathematically as:

$$P = I \times E$$

Using this equation, the power in watts, is equal to the current, in amperes, times the voltage, in volts. AC Power is usually represented as true power (effective-rms).

This same equation is also applicable to AC circuits as long as the circuit contains only resistance. In a purely resistive circuit, the product of I and E will always equal P . However, AC circuits often contain properties such as inductance and capacitance. The properties of inductive and capacitive reactances will be fully explained in a later unit.

When these properties exist, the product of I and E will not provide a true indication of power. The resulting power can appear to be much higher than is actually the case. Since the power **appears** to be consumed by the inductive or capacitive components, it is called apparent power. **Apparent power is expressed in units called volt-amperes.**

A meter that measures AC or DC power is called a **wattmeter**. Most wattmeters utilize a special type of meter movement called an **electrodynamometer** movement. This type of instrument always measures the true AC power that is used by a component or circuit. In other words, it can distinguish true power from apparent power.

A simple wattmeter is shown in Figure 2-15. Notice that the meter uses two stationary coils in series, and a moving coil. When this instrument is used to measure the AC power consumed by a load, its stationary coils are connected in series with the load. Remember, in order to measure the load current, the meter movement must be connected in series.

The stationary coils are wound around two iron cores. The iron cores become magnetized when current flows through the coils. The stationary coils perform essentially the same functions as the permanent magnet pole pieces, that are used in the moving-coil meter movement, previously described.

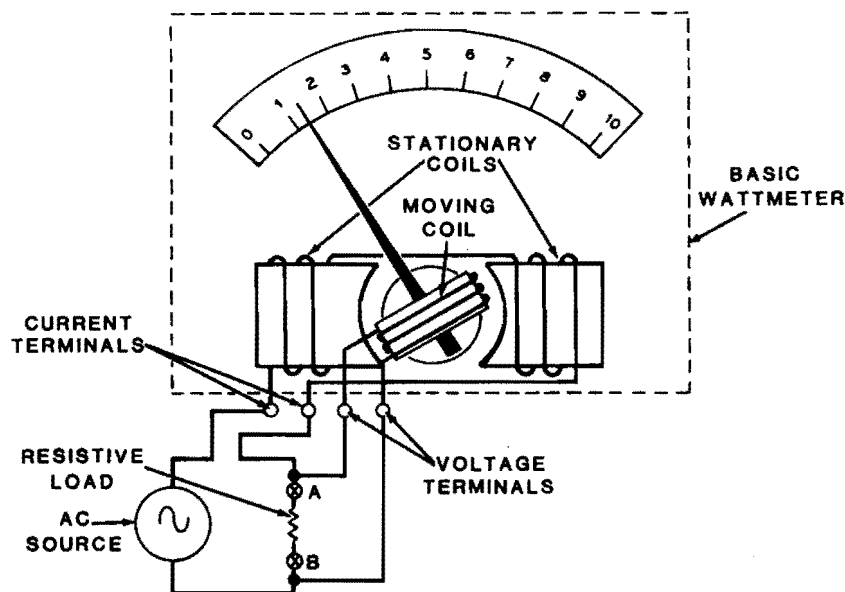


Figure 2-15 Measuring power with a wattmeter.

The moving coil is similar to the type used in the moving-coil meter movement. This coil is connected in parallel with the load in order to measure the voltage dropped across the load. When the stationary and moving coils are properly connected as shown in Figure 2-15, they both produce magnetic fields which interact and cause the moving coil and its attached pointer to deflect. The amount of deflection is proportional to the product of the load voltage and the load current. Therefore, the meter actually monitors the voltage and the current, and provides a scale reading calibrated in watts.

Most wattmeters provide reasonably accurate measurements and some are accurate to within $\pm 1\%$. These meters, like the ammeters and voltmeters, have internal resistance. Since they have resistance properties they consume a certain amount of power.

Some wattmeters are calibrated to take their internal power loss into consideration. When using meters that do not compensate for their own loss, it is necessary to subtract the power used by the meter, from the meter's reading. Manufacturers of these instruments sometimes indicate how much power is used by the

meter. This information is in the form of correction data and is usually provided on a graph for a variety of power ratings at specific frequencies.

When using an instrument that is not compensated and the manufacturer does not indicate the internal power loss, a simple test can be performed to determine the meter's internal loss. This is done by disconnecting the load at points A and B as shown in Figure 2-15. When this is done, the stationary and moving coils are effectively in series and the meter measures its own internal power loss. This internal power reading is subtracted from the reading obtained with the load connected. After correction, the actual true power dissipated by the load is known.

The stationary and moving coils in a watt meter have specific current and voltage ratings respectively. Therefore, when using a wattmeter you must be sure that you do not exceed the individual maximum current and voltage ratings of the device. Also, you must be careful not to exceed the maximum power that the device is designed to measure. If either of these ratings are exceeded, the instrument can be permanently damaged.

Self-Test Review

1. Alternating currents and voltages may be measured by electromechanical devices called AC:
_____.
2. A meter that internally converts AC to pulsating DC is called a:
_____ type moving-coil meter.
3. The moving-coil meter movement responds only to:
_____.
4. The moving coil in the meter movement operates on the:
_____ principle.
5. When the pointer is attached to the moving coil, the pointer's deflection is proportional to:
_____.
6. Most AC meters are calibrated to display:
_____ values.
7. When the numbers or values marked on a meter's scale are equally spaced, the meter has a:
_____ scale.
8. A moving-vane meter utilizes either a radial or a concentric iron vane that moves inside a stationary:
_____.
9. When current flows through the coil of a radial-vane meter, the two vanes become magnetized in the same direction, and the moving vane is:
_____.
10. Springs are used to provide tension to oppose the action caused by current flow. They are also used to adjust the meter to:
_____.
11. How are ammeters connected into circuits?
_____.
12. Moving-vane meters provide a pointer deflection that increases with the square of the change in current. This type of scale is referred to as a:
_____ scale.
13. A thermocouple meter uses two metal strips which are:
_____.

14. The thermocouple operates by measuring the DC voltage potential caused by:

_____.

15. The thermocouple meter movement has a scale that is calibrated as a:

_____ scale.

16. The AC meter that measures current without being wired into the circuit is a:

_____ type.

17. AC meters that are used to measure milliamperes of current are classified as:

_____.

18. The range of an ammeter can be extended by bypassing a portion of the current, around the meter. This is done by using components known as:

_____ resistors.

19. The sensitivity of an ammeter is its:

_____.

20. When an AC meter is used to measure voltage it is connected in:

_____.

21. The range of a voltmeter can be extended by using:

_____ resistors.

22. The range of a voltmeter is to be extended using a resistor. In relation to the meter movement, the resistor is added in:

_____.

23. The meters that are used to measure power are commonly referred to as:

_____ meters.

24. The unit of measure for power meters is the:

_____.

25. Power meters usually measure:

_____ power.

Oscilloscopes

AC meters can provide reasonably accurate measurements of current and voltage, but these instruments do not allow you to see what the AC quantities actually look like. In most cases, they are calibrated to indicate the effective or rms value of a sine wave. When used to measure nonsinusoidal waveforms, they do not provide true rms readings.

When you are troubleshooting or analyzing electronic equipment, it is often helpful or even necessary to know exactly what an AC waveform looks like. In many cases, it is necessary to know the peak and peak-to-peak values, instantaneous values, and the waveform's period. These measurements as well as others can be performed, using a device known as an **oscilloscope**.

The oscilloscope may be used to analyze any type of AC waveform and measure its most important electrical characteristics. The oscilloscope, or **o'scope** as it is commonly called, is one of the most important test instruments used to measure AC quantities. The oscilloscope is also used to measure DC currents and voltages.

We will examine the operation of a basic oscilloscope and then consider some of the ways it is used to measure and analyze AC waveforms. Although this discussion will be brief, it contains background information that should prove helpful.

Oscilloscope Operation

Oscilloscopes do not contain moving parts like the AC meters, previously described. They are electronic test instruments that use a wide variety of electronic circuits.

An oscilloscope is capable of measuring AC or DC voltages and displaying the voltage on a graph. The AC or DC voltage appears as a picture on a screen similar to the type of screen used in a television set or a computer monitor. The main difference in the screen is that it is divided into equally spaced 1 centimeter squares. The oscilloscope contains a number of controls that are used to adjust the size and the number of complete waveforms that are displayed. Most oscilloscopes are calibrated so that the waveform can be visually analyzed, and its most important characteristics easily determined.

A simplified block diagram of an oscilloscope is shown in Figure 2-16. The device has two input terminals which are connected across the voltage that is to be measured. They are generally referred to as the **vertical input terminals**. The AC voltage at these terminals is applied to an amplifier circuit. The amplifier increases the amplitude of the voltage before it is applied to the **cathode ray tube** or CRT. The CRT is the device which graphically displays the waveform being measured.

As shown in Figure 2-16, the CRT contains an electron gun and two sets of deflection plates. These components are mounted inside a glass tube which fans out at one end to form a screen. The air is pumped out of the tube and the end is sealed. The components within the CRT operate within a vacuum. The electron gun

produces a stream of electrons which are focused into a narrow beam and aimed at the CRT screen. When the beam strikes the screen, it illuminates a phosphorus coating on the inside of the screen and a spot of light is produced. The electron beam passes between the two sets of deflection plates.

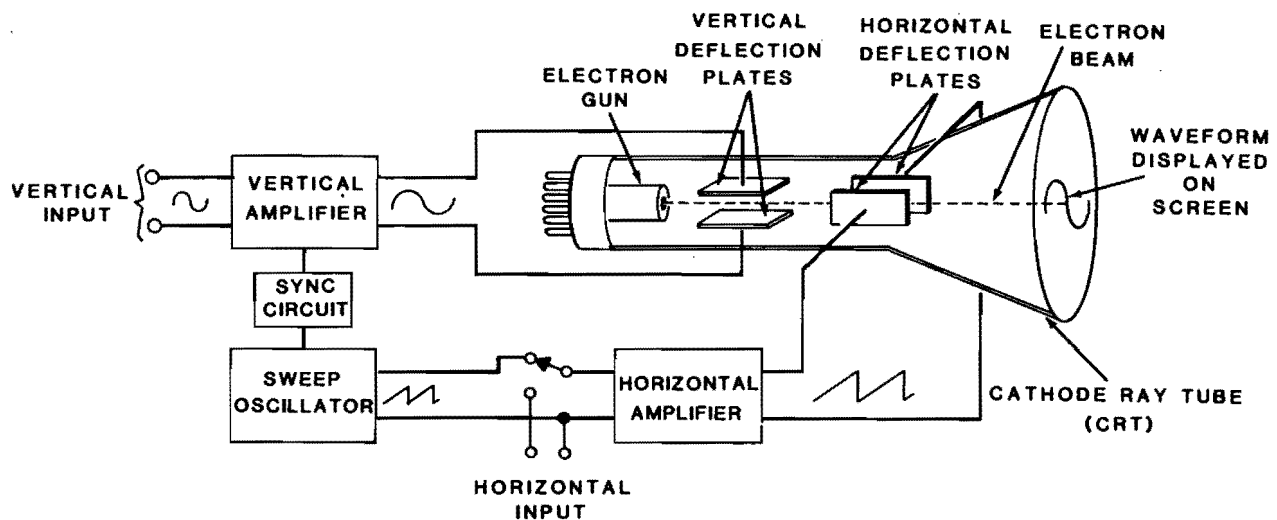


Figure 2-16 Basic oscilloscope.

The AC voltage from the vertical amplifier is applied to the **vertical deflection plates**. This alternating voltage causes the plates to become positively and negatively charged. The polarity of these charges is continually reversed. The electrons in the beam are negatively charged and tend to deflect toward the positive plate and away from the negative plate. Like charges repel and unlike charges attract. This constant change causes the electron beam to bend. Since the charges on the vertical plates continually change direction, the electron beam is deflected up and down. The beam movement causes a vertical trace to appear on the CRT screen. The height of the vertical trace is the amplitude of the applied AC voltage being measured and the amount of amplification provided by the oscilloscope's vertical amplifier circuit.

When the electron beam is moved up and down, only a vertical line or trace appears on the screen. Such a display could indicate the peak-to-peak amplitude of a waveform but still not the exact shape of the waveform. In order to show the waveform's variations, the electron beam must also be deflected horizontally across the screen.

This is accomplished by a circuit known as a **sweep oscillator**. This circuit generates an AC sawtooth waveform, the waveform is then amplified by a **horizontal amplifier** and applied to the **horizontal deflection plates**. The sawtooth voltage increases at a linear rate from a negative peak value to a positive peak value and then almost instantly changes back

to a negative value again. The positive and negative charges on the horizontal deflection plates varies at the sawtooth's linear rate. This causes the electron beam to move from left to right across the screen at a linear rate and then immediately jump back to the left side and start over again.

When the sawtooth waveform is applied to the horizontal plates, with no voltage on the vertical plates, only the horizontal trace will appear on the screen. This trace is the **horizontal time base** that is used to measure the time of a waveform. The electron beam moves from left to right in a specific period of time. The horizontal trace is continually repeated. A waveform that is generated and occurs continuously is the definition of the output of an **oscillator** circuit.

When the vertical signal voltage and the horizontal sawtooth voltage are both applied to the CRT, the signal waveform is displayed on the screen of the CRT. As the beam moves from left to right, at a linear rate, the vertical AC voltage causes the beam to move up and down following the AC variations. When the time required for the beam to move across the screen, from left to right, is equal to the time of one cycle of the AC input voltage, one cycle of the AC waveform will be displayed on the screen.

The relationship between the input AC sine wave, the sawtooth wave, and the displayed waveform is further illustrated in Figure 2-17. Notice that one completed cycle of the

sine wave (Figure 2-17A) occurs in the time required to generate one complete cycle of the sawtooth wave (Figure 2-17B) . When these conditions are met, one complete AC sine wave is displayed. This is shown in Figure 2-17C. In other words, the time ($1/F$) of the input AC waveform must be equal to the time ($1/F$) of the sawtooth waveform.

Another important condition is that the sine wave and sawtooth wave must begin their cycles at the same time. If the two waveforms are not properly synchronized, the displayed waveform might appear as shown in Figure 2-17D, or Figure 2-17E. Although these waveforms are complete AC cycles, they are not properly oriented sine waves. Figure 2-17D is shifted right by 90 degrees and Figure 2-17E is shifted by 180 degrees. Note that 180 degrees is the opposite polarity. This is easily seen when Figures 2-17C and 2-17E are compared.

To ensure that the input AC waveform and the sawtooth waveform are properly synchronized, a synchronization or **sync** circuit is included in the oscilloscope circuit. This circuit samples the incoming AC signal and produces a control signal that is applied to the sawtooth oscillator to make sure that the sawtooth generator begins its cycle at the proper time.

The input AC waveform and sawtooth waveform must occur repeatedly, to produce a display on the screen. In other words, the electron beam follows the pattern of the waveform again and again. This results in a sine wave

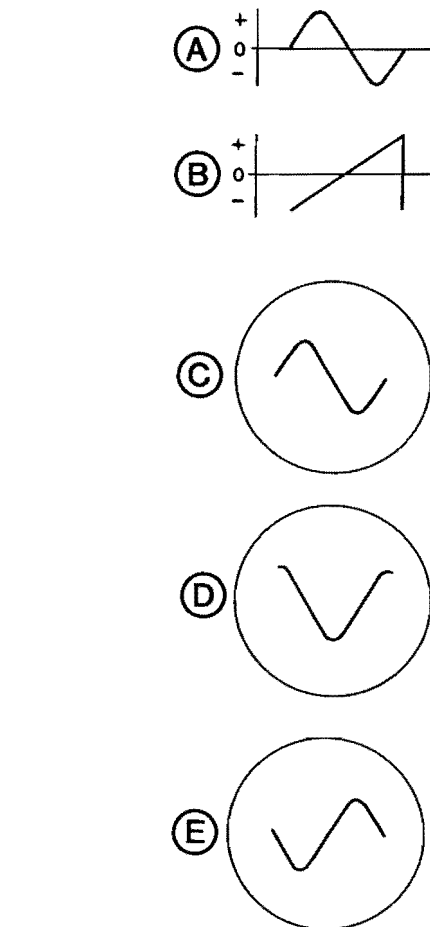


Figure 2-17 Typical oscilloscope waveforms.

being displayed on the screen. The phosphor on the screen produces light for only an instant after the electron beam strikes it. Therefore, constant repetition (sweeping of the electron beam) is required to produce a pattern that is constantly illuminated.

Using the Oscilloscope

The oscilloscope can be used to observe and measure various types of AC waveforms. We will discuss some of the ways in which this important test instrument is used.

Measuring Voltage

Since the oscilloscope displays an entire AC waveform, it can be used to determine instantaneous values as well as peak and peak-to-peak values.

A typical oscilloscope display is shown in Figure 2-18. Notice that the screen of the oscilloscope is marked with vertical and horizontal lines which form squares. This grid pattern is commonly referred to as a **graticule**. The squares are usually 1 centimeter high and 1 centimeter wide and represent a sheet of graph paper.

When observing an AC waveform as shown in Figure 2-18, the amplification of the vertical amplifier can be controlled. Vertical control means that the vertical height (amplitude) of the waveform can be adjusted. The vertical amplifier controls are usually calibrated so that a given input voltage will produce a specific amount of vertical deflection on the screen. Vertical amplification is usually adjusted by a **vertical sensitivity** control or **vertical attenuator** control. For example, suppose the vertical sensitivity control is set to the 10 volts per centimeter position, as shown in Figure 2-18. Each centimeter of vertical height represents 10 volts at the vertical input terminals. The waveform being observed in Figure 2-18 is 4 centimeters high. Therefore, it has a peak-to-peak amplitude of 4 times 10 or 40 volts. The peak value of the waveform is equal to one half of 40 volts, or 20 volts.

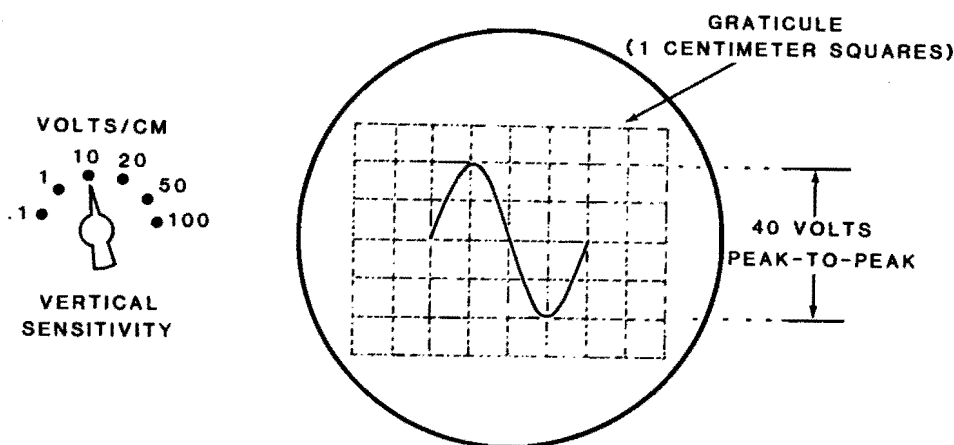


Figure 2-18 Measuring voltage with an oscilloscope.

The value at any point on the waveform can be determined by referring to the squares on the graticule. The vertical sensitivity control can be reset to other positions, to increase or decrease the vertical gain of the oscilloscope. When this is done, the squares represent values of voltage which are either lower or higher than 10 volts per square.

Some of the less expensive oscilloscopes are not calibrated as shown in Figure 2-18. When using an oscilloscope of this type, it is necessary to apply a known DC or AC reference voltage to the vertical terminals and adjust the vertical amplifier for a specific amount of deflection. In other words, you calibrate the oscilloscope by using a known voltage source. Then you may apply the unknown voltage and compare the two to determine the unknown voltage value.

Measuring The Period

One of the most important uses of the oscilloscope is to measure the period of an AC waveform. The period, or time for 1 cycle, is determined by observing the horizontal width of the waveform. The oscilloscope's sawtooth oscillator can usually be adjusted so that the electron beam will move, from left to right across the screen, at a specific speed. The time required for the beam to move horizontally across the screen is referred to as the **sweep time**. The sweep time can be adjusted by a control that is mounted on the oscilloscope. This control sets the amount of time, in seconds, milliseconds, or microseconds, required for the trace

to move horizontally a distance of 1 centimeter.

Let's assume that the oscilloscope's sweep time control (TIME/CM) is set to the 5 milliseconds per centimeter position as shown in Figure 2-19. Each centimeter of horizontal deflection represents a time interval of 5 milliseconds. The waveform being displayed in Figure 2-19 is 4 centimeters wide. In other words, one complete cycle occupies 4 centimeters of the trace. The period of the waveform is equal to 4 times 5 milliseconds or 20 milliseconds.

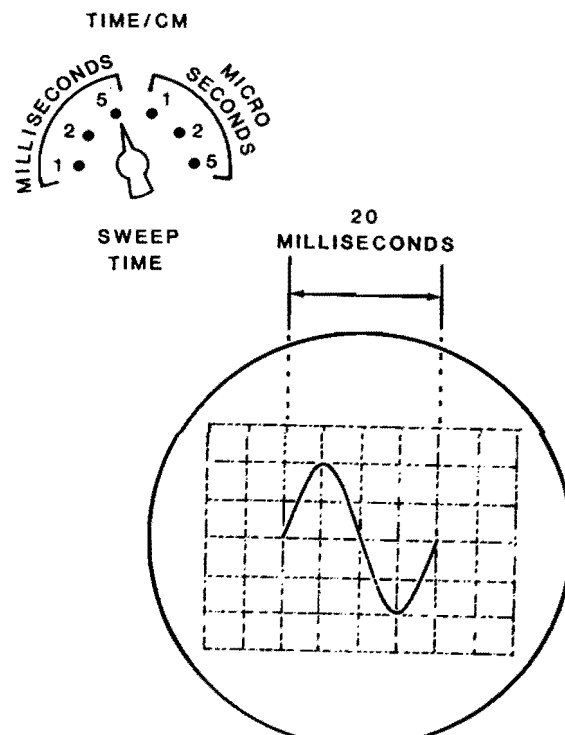


Figure 2-19 Measuring time with an oscilloscope.

The horizontal sweep control can be set to a variety of positions. This allows you to use the oscilloscope to measure waveforms that have very long or very short cycle times. In many cases, it is desirable to display only one cycle of the waveform as shown. However, the oscilloscope is capable of displaying many complete AC cycles at the same time. This is accomplished by adjusting the sweep control to produce one complete sweep of the trace that is equal to the time required to produce the desired number of input AC cycles. In other words, if 4 cycles of the input AC signal occur during the time required to generate one cycle of the sawtooth waveform, then 4 cycles of the input waveform will be displayed.

The oscilloscope can be used to display a number of AC input cycles. When a number of cycles are displayed on the screen, it is only necessary to determine the time of one cycle in order to determine the period of the waveform.

Measuring Frequency

In order to determine the frequency of an AC waveform, you must know the period of the waveform. The frequency of an AC waveform is equal to 1 divided by the period of the waveform. In other words, time and frequency are reciprocal functions. Time is measured in seconds and frequency is measured in cycles per second. The unit of measure for frequency is

the hertz. Frequency is expressed mathematically as:

$$F = \frac{1}{T}$$

For example, the waveform in Figure 2-19 has a period (T) of 20 milliseconds (0.02 seconds). This waveform has a frequency (F) of:

$$F = \frac{1}{.02 \text{ s}} \text{ or } 50 \text{ Hz}$$

The oscilloscope is used to measure time. You must then convert time to frequency mathematically. Another piece of test equipment called the frequency counter is used to measure frequency directly. The frequency counter may have a period mode and a frequency mode. In the period mode, the counter displays the time of 1 cycle. In the frequency mode, the period is internally converted, and the frequency is displayed.

Measuring Phase Relationships

In some cases, it is necessary to compare two AC waveforms, of the same frequency, to determine if the two waveforms coincide (occur at the same time). In many cases, two AC waveforms within the same circuit will be displaced in time, or by a given number of degrees. For example, an AC signal may be shifted by approximately 90 degrees across a capacitor.

If two AC waveforms are in coincidence, they are said to be **in phase** with each other. When the two waveforms are displaced (do not occur at the same time), they are said to be **out of phase**. The amount of phase displacement is usually measured in degrees. For example, the AC sine wave shown in Figure 2-20B is in phase with the waveform in Figure 2-20A. The waveform in Figure 2-20C is 90 degrees out of phase with the waveform in Figure 2-20A. The waveform in Figure 2-20D is 180 degrees out of phase with the waveform in Figure 2-20A. Remember, that 180 degrees out of phase is the same thing as polarity inversion.

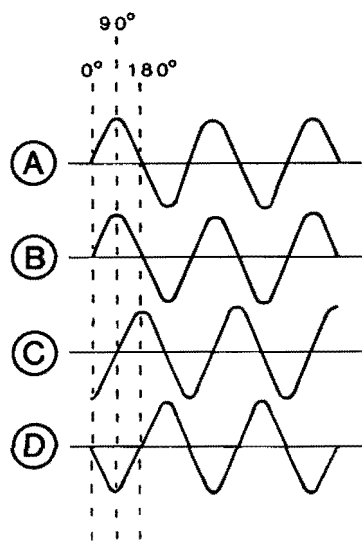


Figure 2-20 Phase relationships between AC sine waves.

An oscilloscope can be used to compare two AC sine waves and determine their phase relationship. This is done by applying one sine wave to the oscilloscope's vertical deflection plates and the other sine wave to the scope's horizontal deflection plates. That is, we apply one waveform to the vertical input terminals and the other to a set of horizontal input terminals. A switch is usually provided, as shown in Figure 2-16, which disconnects the sweep oscillator and connects the horizontal input terminals directly to the horizontal amplifier.

When both AC sine waves are applied to the scope, and the vertical and horizontal controls are properly adjusted, the electron beam will be deflected by both AC waveforms. The resulting patterns displayed on the screen are referred to as **Lissajous patterns**. The phase relationship between the two waveforms can be determined by properly interpreting these unique patterns.

Several common Lissajous patterns are shown in Figure 2-21. These patterns occur at phase difference intervals of 45 degrees, starting at 0 degrees and extending to 360 degrees. The pattern shown in Figure 2-21A occurs when both sine waves are in phase. This pattern is a diagonal line that extends from the lower left hand portion of the screen to the upper right hand portion. The pattern in Figure 2-21B occurs when two waveforms are 45 degrees out of phase. It is an oval or an ellipse.

At a phase difference of 90 degrees, a perfect circle is formed as shown in Figure 2-21C. Then at 135 degrees and 180 degrees an ellipse and diagonal line are again formed as shown in Figure 2-21D and Figure 2-21E. However, these last two patterns are slanted in the opposite direction.

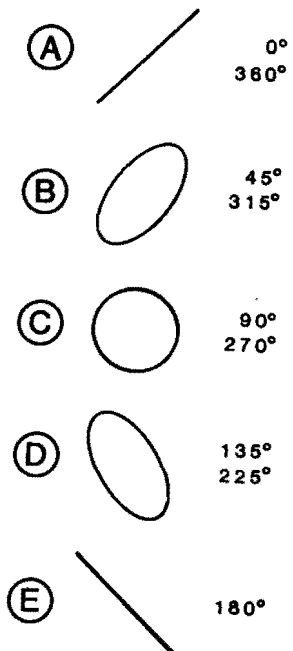


Figure 2-21 Typical Lissajous patterns.

Phase differences other than the values shown in Figure 2-21, will produce elliptical patterns that have shapes midway between the various shapes shown. It is important to realize that the Lissajous pattern changes from a diagonal line, to an ellipse, to a circle, then back to an ellipse, and finally back to a diagonal line as the phase difference increases from 0 degrees to 180 degrees. For phase differences between 180 degrees and 360 degrees, the sequence is repeated but in the opposite direction as shown in Figures 2-21D and 2-21E. These phase difference displays were produced, using two sine waves that are equal in amplitude and frequency, but separated in phase.

By using Lissajous patterns, the oscilloscope becomes a reasonably accurate phase measuring device. However, the accuracy of the measurements taken, will depend largely on the skill of the individual using the scope. Also, the waveforms must be sinusoidal in shape to produce the patterns shown in Figure 2-21. Nonsinusoidal waveforms will produce irregular shaped patterns which are extremely difficult to analyze.

Many oscilloscopes have two vertical input channels. The two channels can be used to evaluate or compare two signals at the same time. This is especially helpful when monitoring the input to a circuit on one of the channels and observing the various outputs of the

different circuits that the input is driving. The output waveform can be instantly compared to the input as to gain, polarity inversion, and phase shift all at the same time. Later in your studies, you will use all of the oscilloscope's capabilities just mentioned.

Self-Test Review

26. The display component of an oscilloscope is its:
_____.
27. The signal (AC waveform) to be measured is applied to the oscilloscope's:
_____ deflection plates.
28. The oscilloscope's screen is usually divided by a graticule. The graticule is divided into:
_____ squares.
29. A sawtooth waveform is generated within the scope and applied to the:
_____.
30. The sawtooth waveform establishes the oscilloscope's:
_____ base.
31. The time of one cycle is its:
_____.
32. The reciprocal of time is:
_____.
33. Amplitude or value is measured using an oscilloscope's:
_____ axis.
34. The TIME/CM switch is also known as the:
_____ control.
35. When are two signals said to have coincidence?
_____.
36. A scope is adjusted to have a vertical sensitivity of 20 volts per centimeter. The waveform on its screen has a total height of 6 squares. The peak-to-peak value of the waveform is:
_____ volts.
37. A signal takes up 4 squares horizontally. The TIME/CM control is set to 2 ms. The waveform's frequency is:
_____ Hz.
38. The scope is adjusted so that the beam requires 2 ms to move 1 centimeter. Four cycles have a combined width of 8 centimeters. The frequency of the waveform is:
_____ Hz.
39. It is also possible to determine phase relationships between sine waves using an oscilloscope. The scope produces:
_____ patterns.

Resistance In AC Circuits

Now that you have examined some of the basic test instruments that are used to measure AC values. It is time to analyze some fundamental AC circuits, and the rules which apply to these circuits.

For now we will confine our discussion to AC circuits which contain only resistance. We will discuss the relationship between current, resistance, and voltage, in these purely resistive circuits and compare them with similar DC circuits. Later in this course, we will examine more complex AC circuits. The complex circuits will take into consideration additional properties such as inductance and capacitance. You must have a complete understanding of simple resistive circuits. The relationship between voltage, current, and resistance must also be fully understood before you can move to more complex concepts.

Basic AC Circuit Calculations

A basic AC circuit can be formed by connecting a load resistance across an AC voltage source. This is shown in Figure 2-22A. Although a resistor is used in this circuit, any resistive component such as a lamp or heating element will have the same effect. Such devices are considered purely resistive and have a negligible amount of inductance or capacitance.

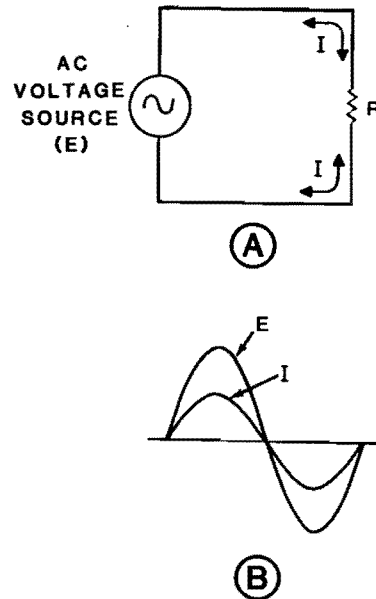


Figure 2-22 Current and voltage in an AC resistive circuit.

The voltage source could be an AC generator or an electronic circuit that produces an AC voltage. When this voltage is applied across the resistor, a corresponding AC current is produced that flows through the resistor. This current varies in amplitude and direction and is in phase with the AC voltage applied. In other words, the current is zero when the voltage is zero and it reaches its maximum when the voltage is maximum. When the voltage changes its polarity, the current changes its direction. The voltage and current in a purely resistive AC circuit are **in phase**.

This phase relationship, between the voltage and current, is shown graphically in Figure 2-22B. The illustration shows that the voltage (E) waveform and the current (I) waveform pass through zero and maximum at the same time. Both E and I change direction at the same time. The two waveforms do not have exactly the same peak amplitude because they represent different quantities. The quantities are also measured in different units. E is measured in volts and I is measured in amperes. They are drawn together only to show that they occur simultaneously.

The value of current flowing through the resistor in Figure 2-22A, at any given instant, depends on the voltage at that instant, and the circuit resistance. The current at any instant can be determined by using Ohm's Law. This is the same Ohm's Law that you used in DC Electronics. In other words, the same rules and laws that apply to DC circuits are used in AC circuits that are purely resistive.

Ohm's Law states that the voltage, current, and resistance are mathematically related as follows:

$$E = I \times R$$

This equation states that voltage, which is measured in volts, is equal to current, which is measured in amperes, times the resistance, which is measured in ohms.

This basic equation can be rearranged to show that current is equal to voltage divided by resistance. This is expressed mathematically as:

$$I = \frac{E}{R}$$

It may also be rearranged to show that resistance is equal to voltage divided by current and expressed mathematically as:

$$R = \frac{E}{I}$$

When working with AC circuits, instantaneous values of voltage and current are seldom used in AC calculations. In most cases, effective values are used. The effective value of an AC voltage or current sine wave is equal to 0.707 times its peak or maximum value. An AC current sine wave with an effective value of 1 ampere effectively produces the same amount of heat, in a given resistance, as a DC current of 1 ampere. When we use effective values we are expressing the AC quantity in terms of its DC equivalent value.

Ohm's Law can be used with effective values just as easily as with instantaneous values. In other words, the effective value of E is obtained, if the effective value of I is multiplied by R. Likewise the effective value of I is determined when the effective value of E is divided by R. Also, R is equal to the effective value of E divided by the effective value of I. Peak and average values of current, voltage, and power can be calculated when all of the instantaneous values are in the same reference.

Let's consider a typical circuit that has an AC voltage source with an effective value of 100 volts and a resistance of 100 ohms, as shown in Figure 2-23. According to Ohm's Law, the effective value of current (I) is equal to:

$$I = \frac{E}{R} = \frac{100 \text{ volts}}{100 \text{ ohms}} \text{ or } 1 \text{ ampere}$$

Therefore an effective voltage of 100 volts will cause an effective current of 1 ampere to flow through a resistance of 100 ohms.

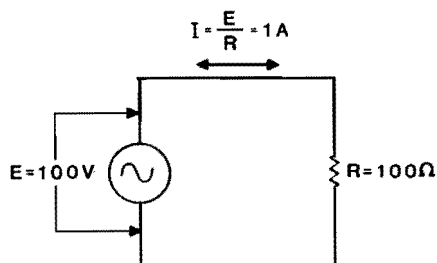


Figure 2-23 Calculating the effective value of AC current.

Let's consider a circuit in which resistance and current are known and the voltage must be determined. For example, in Figure 2-24 the current has an effective value of 3 amperes and a resistance equal to 50 ohms. According to Ohm's Law, the applied voltage must have an effective value of:

$$E = IR = (3 \text{ A}) (50 \text{ ohms}) = 150 \text{ volts.}$$

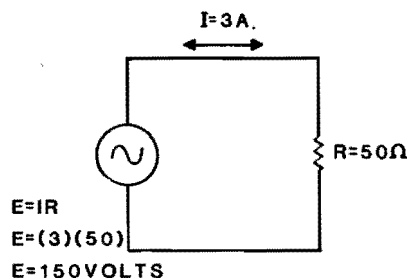


Figure 2-24 Calculating the effective value of AC voltage.

Series AC Circuit Calculations

The current in a purely resistive circuit is always in phase with the applied voltage. The current flowing through a circuit is limited by the total resistance of the circuit. Current has the same value, at any given instant, at all points in a series circuit. The in phase relationship between applied voltage, E_A and circuit current is shown in Figure 2-25B.

Since the current flows through both R_1 and R_2 , a voltage is dropped across each resistor. The voltage dropped across each resistor, at any given instant, is equal to the product of the circuit current at that instant and the resistor's value. The two voltages, designated as E_1 and E_2 , are in series. Their instantaneous values, when added together, equal the applied voltage at that specific instant. In other words,

E_1 and E_2 are in phase with E_A because they are developed at the same time and vary in the same direction. The combined values, $E_1 + E_2$, will always be equal to E_A . This in phase relationship between E_A , E_1 , and E_2 is shown in Figure 2-25B. Notice that all three of these voltages are in phase with each other and they are also in phase with the circuit current.

It is common practice to use effective values of current and voltage when analyzing AC circuits. To illustrate this point, let's consider a typical series AC circuit. Suppose that the AC voltage source has an effective value of 150 volts and that R_1 and R_2 have values of 50 ohms and 100 ohms respectively. This is shown in Figure 2-26. The total resistance of the circuit, R_T is equal to $R_1 + R_2$. Therefore, R_T equals 50 ohms + 100 ohms or 150 ohms. The current equals E_A divided by R_T or:

$$I = \frac{150 \text{ volts}}{150 \text{ ohms}} = 1 \text{ ampere}$$

This current value of 1 ampere represents the effective value of circuit current. The current flowing through R_1 produces a voltage drop equal to the current times the resistance of R_1 or:

$$E = IR_1 = (1 \text{ A})(50 \text{ ohms}) = 50 \text{ volts}$$

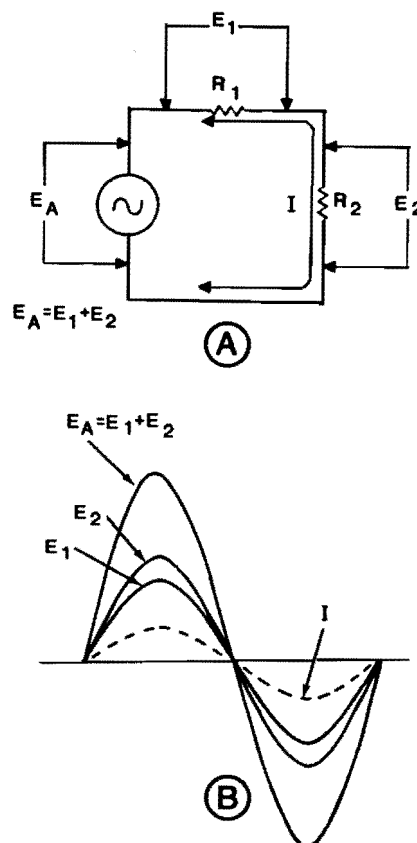


Figure 2-25 Current and voltage in a series circuit.

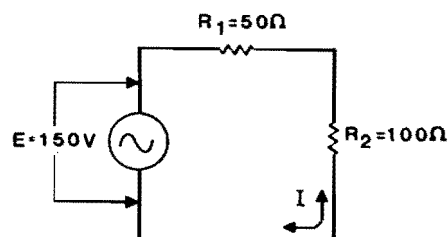


Figure 2-26 Calculating current and voltage in a series circuit.

Since current everywhere in a series circuit is the same, it also flows through R_2 . This produces a voltage across this resistor that is equal to:

$$E = IR_2 = (1 \text{ A}) (100 \text{ ohms}) = 100 \text{ volts}$$

Notice that these voltage drops are proportional to the resistor's values. In other words, the larger resistor drops the most voltage in a series circuit. The sum of these two effective voltages is equal to the effective value of the applied voltage. This is expressed mathematically as:

$$E_A = E_1 + E_2 = 50 \text{ V} + 100 \text{ V} = 150 \text{ volts}$$

As you can see, AC effective values are used in the same way that DC values are used. The same rules apply to a series DC or AC circuit that contains only resistors.

Parallel AC Circuit Calculations

Two resistors are connected in parallel and an AC voltage is applied. This is shown in Figure 2-27A. The total current (I_T) supplied by the voltage source will be in phase with the applied voltage (E_A). The in phase relationship between E_A and I_T is shown in Figure 2-27B. In this case, total current divides and two separate currents flow through the two resistors. These currents are designated as I_1 and I_2 . In parallel circuits the separate currents are

called **branch** currents. In a parallel circuit I_T is equal to the sum of all of the branch currents ($I_T = I_1 + I_2$).

The branch currents are in phase with I_T . Their instantaneous values are added to produce I_T . This is shown in Figure 2-27B.

The applied voltage is dropped across each resistor. The applied voltage is in phase with currents I_T , I_1 , and I_2 as illustrated in Figure 2-27B.

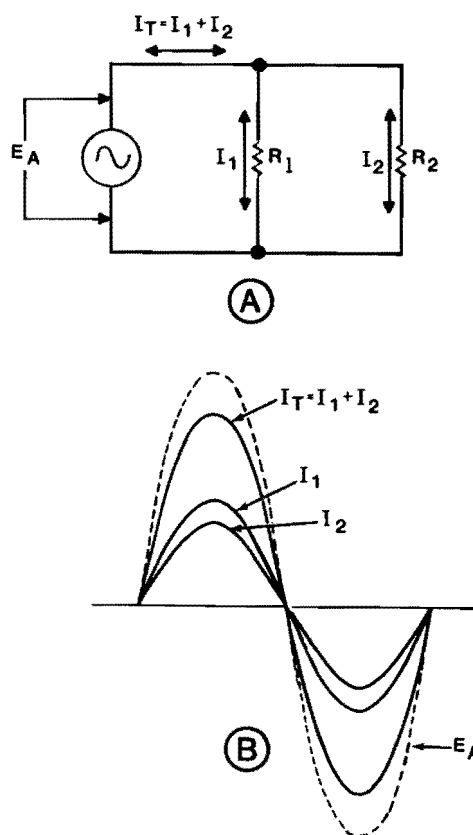


Figure 2-27 Current and voltage in a parallel circuit.

Now to illustrate how effective values are used in analyzing parallel circuits. Suppose that the applied voltage is equal to 150 volts and that R_1 and R_2 have values of 50 ohms and 100 ohms respectively. The circuit described is shown in Figure 2-28.

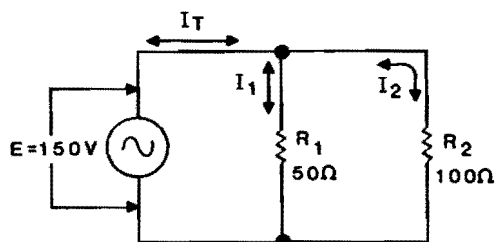


Figure 2-28 Calculating current and voltage in a parallel circuit.

You can determine the value of branch current I_1 , by dividing the applied voltage by the branch resistance (R_1). The value is equal to:

$$I_1 = \frac{150 \text{ volts}}{50 \text{ ohms}} = 3 \text{ amperes}$$

The current through R_2 is equal to the same applied voltage divided by R_2 .

$$I_2 = \frac{150 \text{ volts}}{100 \text{ ohms}} = 1.5 \text{ amperes}$$

Total current (I_T) is equal to the sum of the branch currents.

$$I_T = I_1 + I_2 = 3 \text{ A} + 1.5 \text{ A} = 4.5 \text{ amperes}$$

Since total current is 4.5 amperes and the applied voltage is 150 volts, total resistance is equal to:

$$R_T = \frac{150 \text{ volts}}{4.5 \text{ amperes}} = 33.3 \text{ ohms}$$

The circuit functions as if it contained one resistor that has a value of 33.3 ohms. If such a resistor were connected across the voltage source, the same total current would result. In a parallel circuit, R_T is the equivalent resistance that results from combining all of the individual resistors into a single value.

All of the current and voltage values just used are effective values. They are used exactly the same as DC current and voltage values are used in DC parallel circuits.

The total resistance of a parallel circuit can be calculated using the reciprocal formula for resistors connected in parallel. The formula is:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_N}}$$

The reciprocal formula for parallel resistors can be used regardless of the number of resistors that are connected in parallel.

Another method of calculating the value of R_T in a parallel circuit is called the product over the sum method. Using this method only 2

resistances can be combined in a single calculation. The formula for the product over the sum is:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

When all of the resistors that are connected in parallel have the same value, an alternate method is used to shorten the process of calculating R_T . This short cut method is accomplished by dividing the value of one resistor by the total number of resistors that are connected in parallel.

$$R_T = \frac{\text{the value of one resistor}}{\text{number of resistors in parallel}}$$

The last method that is used to calculate total resistance in a parallel circuit is called the assumed voltage method. In this method it is not necessary to know the actual value of the applied voltage or the branch currents. You assume a voltage (make it a voltage that is evenly divided by each of the resistors that are in parallel whenever practical). Next, divide the assumed voltage by each branch resistance to obtain the individual assumed branch currents. Now add the calculated branch currents to obtain an assumed value for I_T . The last step in determining R_T , using the assumed method, is to divide the assumed voltage by the assumed total current. This results in the actual total resistance of the paralleled resistors.

Power in AC Circuits

In an AC resistive circuit, power is consumed by the resistive component, in the form of heat. Power is measured in units called **watts**.

In a DC circuit, power is equal to current times voltage. This is shown mathematically as:

$$P = IE$$

The same relationship applies to AC circuits, which contain only resistance. In other words, the current at a specific instant can be multiplied by the voltage of that instant to determine the instantaneous power. When all of the instantaneous values are multiplied for a complete cycle of voltage and current, we find that the power curve follows the voltage and current changes. In other words, AC power is proportional to the product of voltage and current at any point on their curves.

A simple AC circuit is shown in Figure 2-29. The power consumed by the resistor in this circuit varies with the product of the current through the resistor and the voltage dropped by the resistor. The relationship between power, current, and voltage is shown in Figure 2-29B. Notice that the power curve, or waveform, does not extend below the zero axis (horizontal line). This is because the power is

effectively dissipated in the form of heat, no matter which direction current flows, it is assumed to have a positive value. Notice that power reaches its peak value when both E and I are maximum. Likewise, power drops to zero when both E and I equal zero.

Since the power fluctuates between a peak value and zero, the average power used by the circuit is midway between these two extremes. In other words, you draw a line midway between the peak and zero values, the line indicates the average power used. It is average power that is most important in AC circuits. Average power is the power that is actually used in AC circuits.

The average power dissipated in an AC circuit can be calculated by multiplying the effective value of current times the effective value of voltage. Therefore, the power equation, $P = IE$, can be used in AC calculations as long as effective values of I and E are used. For example suppose that the resistor in Figure 2-29 has a value of 100 ohms and the applied voltage has an effective value of 100 volts. The current in the circuit would be equal to:

$$I = \frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere}$$

This effective current value of 1 ampere is multiplied by the effective value of the applied voltage as follows:

$$P = IE = (1 \text{ A}) (100 \text{ V}) = 100 \text{ watts}$$

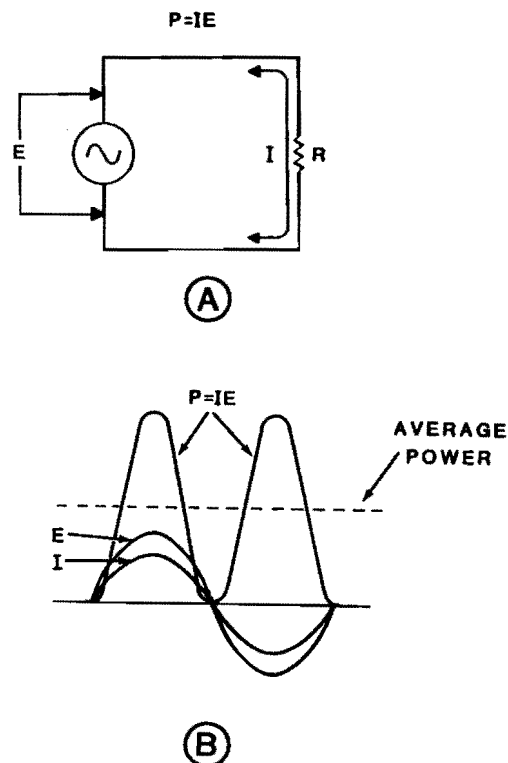


Figure 2-29 Power in an AC circuit.

The resistor would consume (dissipate in the form of heat) 100 watts of power.

At times, it is convenient to use another form of the power equation that expresses power in terms of voltage and resistance. This equation states that power is equal to the voltage squared (E^2) divided by the resistance. This is stated mathematically as:

$$P = \frac{E^2}{R}$$

This form of the power equation could have been used to solve the previous problem. It would have eliminated the step used to calculate the current through the resistor.

The power equation can also be expressed in terms of current and resistance as:

$$P = I^2R$$

This equation simply states that power is equal to the current squared times the resistance.

The various forms of the power equation provide several means of calculating power. You can use combinations of known values of current, voltage, and resistance to find unknown values. These equations are also used for DC circuit calculations.

Self-Test Review

40. In a purely resistive AC circuit current and voltage are:
_____ phase.
41. The voltage and current values used in AC calculations are:
_____ values.
42. Current in an AC circuit is always assumed to have a:
_____ polarity.
43. When an effective voltage (E) of 100 volts is applied to a 25 ohm resistor, the current through the resistor will have an effective value of:
_____ A.
44. In a series circuit containing more than one resistor, the current in the circuit
_____.
_____.
45. The voltage dropped across each resistor in a series circuit is proportional to the
_____ value.
46. At any given instant, the sum of the voltage drops in a series circuit is equal to the:
_____.
47. A series circuit contains a 10 ohm resistor and a 20 ohm resistor. When an effective voltage of 90 volts is applied across the resistors, the circuit current is:
_____ A.
48. When the two resistors in question 47 are connected in parallel, and 90 volts is applied across them, the circuit current is:
_____ A.
49. An AC peak voltage of 200 volts is applied to two 10 k ohm resistors, connected in parallel. The circuit current is equal to:
_____.
50. The circuit described in question 49 has a total resistance (R_T) of:
_____ ohms.

51. Power in an AC circuit is dissipated in the form of:

_____.

52. Effective voltage is multiplied times effective current to calculate power. This calculation results in:

_____ power.

53. Power is measured in:

_____.

Desk-Top Experiment 2

Analyzing A Simple AC Parallel Circuit

Introduction

This experiment provides practice in analyzing a simple parallel AC circuit. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

It is again recommended that you do your calculations on scratch paper. Once you are satisfied with your calculations, they can be recorded in the spaces provided in this experiment.

Objectives

1. To calculate the parameters of a parallel resistive AC circuit.
2. To demonstrate that Kirchhoff's Current Law applies to AC circuits.
3. To review the characteristics of AC meters.
4. To review the proper use of the ammeter and voltmeter to measure values in AC circuits.

Procedure

On a separate sheet of paper, draw the circuit shown below. The circuit shown is a parallel resistive circuit. The input AC sine wave has a peak-to-peak amplitude of 85 volts at a frequency of 60 hertz. Round off your calculations to two decimal places. There are several procedures for solving this problem, and you may use any of them. Depending on your approach to the problem you may, or may not, want to make your calculations in the order listed.

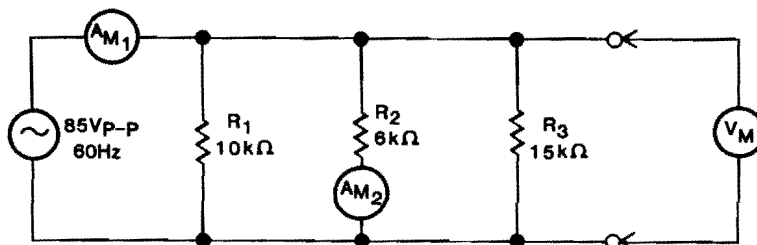


Figure 2-30 Desk-Top Experiment 2.

Unit 3

Capacitive Circuits

Contents

Introduction	3-3	Unit Summary	3-71
Unit Objectives	3-4	Appendix A:	
Review of Capacitors and Capacitance.....	3-5	Solving Right Triangles	3-75
Capacitors in AC Circuits	3-25	Appendix B:	
RC Circuits	3-35	Introduction to Trigonometry	3-80
Applications of Capacitive Circuits	3-54	Appendix C:	
Desk-Top Experiment 3		Table of Trigonometric Functions	3-90
Analyzing RC Circuits	3-65		

Introduction

In this unit you will study capacitors, capacitance, and the effects of capacitance in an AC circuit. You should already be familiar with capacitors from your study of DC electronics. However, to refresh your memory, the first part of this unit is devoted to a review of capacitors and capacitance.

In the remainder of the unit you will study the effects of capacitance on an AC circuit.

The relationship between voltage and current in a capacitive circuit is discussed in detail. In addition, some practical applications of basic capacitive circuits are presented.

The concepts presented in this unit are very important to your understanding of AC electronics. Study this unit carefully.

Unit Objectives

When you have completed this unit, you should be able to:

1. Identify capacitors and capacitor symbols.
2. Explain how a capacitor operates.
3. List the basic parts of a capacitor.
4. Explain the factors that affect capacitance.
5. List the most commonly used types of capacitors.
6. Calculate the total capacitance of capacitors connected in series and in parallel.
7. Explain the most common ways in which capacitors fail.
8. Define the term phase shift as it relates to capacitors.
9. Draw a diagram illustrating the phase relationship between current and voltage in a purely capacitive circuit.
10. Define capacitive reactance and compute its value in ohms when the capacitance in farads and the operating frequency are known.
11. Explain the phase relationship between voltage and current in a series RC circuit.
12. Explain the phase relationship between voltage and current in a parallel RC circuit.

Review of Capacitors and Capacitance

Before you learn how capacitors are used in alternating current circuits, it is desirable to review the basic operation and characteristics of a capacitor. It is easier to understand the operation of a capacitor in an AC circuit, when you are familiar with the operation of capacitors in DC circuits. This section will review the key facts about capacitors .

A capacitor is a passive electronic component that stores electrical energy in the form of an electrostatic field. In its simplest form, a capacitor consists of two conducting plates separated by an insulator called the dielectric. Figure 3-1 shows a simple capacitor. It has two square metal plates that are separated by an air dielectric.

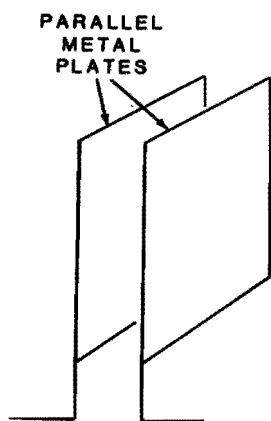


Figure 3-1 A simple capacitor.

When a DC voltage is applied to the plates of a capacitor, the capacitor becomes charged. Figure 3-2A shows a battery (DC source) connected to the capacitor. The positive terminal of the battery attracts electrons from the left-hand plate of the capacitor. This leaves the left hand plate with a positive potential. Electrons from the negative terminal of the battery move on to the right hand plate, causing it to be at negative potential. In this state, the capacitor is charged. Since the positive and negative electrical potentials on the plates attract one another, a force field is set up in the dielectric, between the two plates. However, there is no current flowing through the capacitor. The only time current flows is when the DC potential is initially connected. Current flow, or the movement of electrons, takes place only during the time it takes to charge the capacitor. Once the capacitor is charged to a value approximately equal to the DC source voltage current ceases to flow.

Most capacitors can be charged in either direction. Figure 3-2B shows how the two plate capacitor can be charged in the opposite direction by reversing the battery's leads. In this state, the left-hand plate takes on a negative charge and the right-hand plate takes on a positive charge. When a capacitor starts to charge, current is maximum. As the difference of potential between the battery and capacitor charge becomes less and less, current decreases until the capacitor's charge equals the applied voltage. At this instant there is no difference of potential and current ceases to flow.

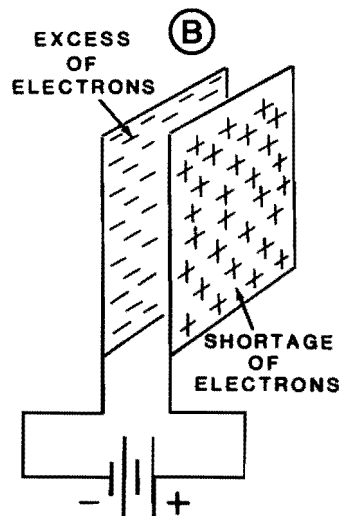
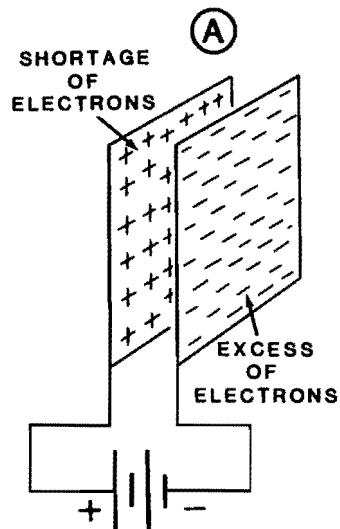


Figure 3-2 Charging a capacitor with a DC source.

When the battery in the circuits shown in Figure 3-2 is removed from the capacitor, the electrical charges on the plates remain. The attraction of the positive and negative charges on the two plates across the dielectric holds the charges in place and the capacitor remains charged. As long as the two plates are insulated from one another, the capacitor will remain charged.

The capacitor can be discharged by shorting the plates together. This is accomplished by connecting a wire between the plates as shown in Figure 3-3. When a capacitor is shorted in this way, electrons flow from the negative plate through the short to the positively charged plate.

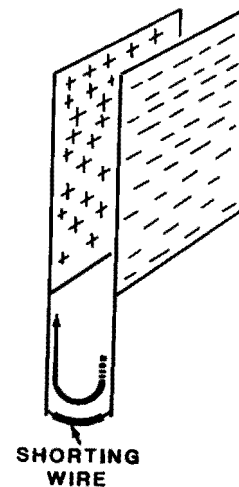


Figure 3-3 Discharging a capacitor by shorting the plates.

The excess of electrons on the right-hand plate will neutralize the positive charge on the left-hand plate. This discharge action gives the capacitor a neutral or zero charge. When a capacitor discharges, initially current flow is maximum and decreases as the charge (difference of potential between the plates) decreases. Once the plates are neutralized current ceases to flow.

As you can see, a capacitor can store electrical energy in the form of a charge. The capacitor is charged by an external voltage source, then retains that charge because of the attraction of the opposite charges on the two plates across the dielectric. The capacitor can be discharged by connecting the two plates (providing a complete path for current flow). Current **does not** flow through the capacitor itself. Current does flow in a capacitive circuit during the time the capacitor is being charged or discharged. Figure 3-4 shows the symbols used to represent capacitors in schematic diagrams of electronic circuits.

The ability of an electronic component to store an electrical charge is referred to as capaci-

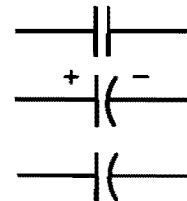


Figure 3-4 Schematic symbols for capacitors.

tance. Components that exhibit this characteristic are known as capacitors. Most capacitors have two leads, each attached to a plate, which are separated by a dielectric.

However, capacitance can exist in any situation where two conductors are separated by an insulator. For example, capacitance exists between an insulated wire running near a metal chassis. The chassis represents one plate of the capacitor while the wire represents the other plate. The insulation of the wire and any air space between the two conductors is the dielectric. Capacitance not in the form of a physical component is generally referred to as distributed or stray capacitance. It exists in all electronic circuits and greatly affects their operation, especially at high frequencies.

Units of Capacitance

The measure of a capacitor's ability to store an electrical charge is its capacitance. The unit of capacitance is the farad. One farad of capacitance indicates that a capacitor will store one coulomb of charge when the voltage applied to the capacitor is one volt. This relationship is expressed below:

$$C = \frac{Q}{E}$$

C equals the capacitance in farads, Q equals the quantity of the electrical charge expressed in coulombs (one coulomb = 6.25×10^{18} electrons), and E represents the applied voltage in volts. This expression tells us that the larger the quantity of electrons that a capacitor stores for a given applied voltage, the greater its capacitance. A large capacitor is one that is capable of storing a large charge even when a small voltage is applied. A small capacitor is one that can not hold a large charge even when a large voltage is applied to it. The capacitance is a function of the physical characteristics of the capacitor.

The farad is a very large unit of measure. A one farad capacitor would be physically very large. A capacitor of this size is much larger than is required in most electronic applications. Most capacitors used in electronic circuits have capacitances in the microfarad range. Typical capacitors have a capacitance of one millionth of a farad or less. One millionth of a farad is called a microfarad. An-

other commonly used unit of capacitance is the picofarad. The picofarad is one millionth of a microfarad.

Table 3-1 shows the relationship between the farad, microfarad and picofarad. Table 3-2 shows how to convert from one unit to the other.

1 farad = 1,000,000 or 10^6 microfarads
1 farad = 1,000,000,000,000 or 10^{12} picofarads
1 microfarad = .000001 or 10^{-6} farad
1 microfarad = 1,000,000 or 10^6 picofarads
1 picofarad = .000000000001 or 10^{-12} farad
1 picofarad = .000001 or 10^{-6} microfarad
microfarad = μF
picofarad = pF or $\mu\mu F$

Table 3-1 Units of capacitance.

The examples below illustrate the use of Table 3-2 in converting from one unit of capacitance to another.

1. To convert 25 μF to farads, move the decimal point 6 places to the left:

$$25 \mu\text{F} = .000025 \text{ farads}$$

2. To convert 470 pF to farads, move the decimal point 12 places to the left:

$$470 \text{ pF} = .00000000047 \text{ farads}$$

3. To convert 1,000 pF to microfarads, move the decimal point 6 places to the left:

$$1,000 \text{ pF} = .001 \mu\text{F}$$

4. To convert .00082 μF to pF, move the decimal point 6 places to the right:

$$.00082 \mu\text{F} = 820 \text{ pF}$$

To Convert	To	Action
Farads	Microfarads	Multiply by 1,000,000 (10^6) or move the decimal point 6 places to the right.
Farads	Picofarads	Multiply by 1,000,000,000,000 (10^{12}) or move the decimal point 12 places to the right.
Microfarads	Farads	Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}) or move the decimal point 6 places to the left.
Microfarads	Picofarads	Multiply by 1,000,000 (10^6) or move the decimal point 6 places to the right.
Picofarads	Farads	Divide by 1,000,000,000,000 (10^{12}) or multiply by .000000000001 (10^{-12}) or move the decimal point 12 places to the left.
Picofarads	Microfarads	Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}) or move the decimal point 6 places to the left.

Table 3-2 · Converting units of capacitance.

Factors Affecting Capacitance

The ability of the capacitor to store an electrical charge is capacitance. The capacitance of a capacitor is determined by its physical characteristics. Specifically, capacitance is determined by the total area of its plates, the distance separating the plates, and the type of dielectric.

The larger the plates in a capacitor, the greater the charge that the capacitor can store. Larger plates can store more electrons and have more electrons to give up than smaller plates. The greater the charge (Q), the greater is the capacitance (C) for a given applied voltage. Therefore, increasing the plate area, or decreasing the distance between the plates, of a capacitor, increases its capacitance. Physically moving the plates is the most common method used to vary capacitance.

The spacing between the plates of a capacitor also determines the amount of charge that it can store. Decreasing the distance between the two plates increases the intensity of the attraction of the charges on the two plates. The greater this attraction, the greater the quantity of electrons stored in the capacitor, for a given applied voltage. Moving the plates closer together increases the capacitance. Separating the plates by a greater distance causes the capacitance to decrease. In most capacitors, the distance between the two plates is a function

of the thickness of the dielectric material used in the capacitor.

The type of insulating material used between the two plates of the capacitor also greatly affects the amount of charge that a capacitor can store. Generally, the better the insulator, the greater is the capacitance.

Many different types of insulating materials are used as a dielectric in capacitors. Insulators such as air, oil, paper, glass, and various types of plastics are widely used. Each type of insulator has a specific dielectric constant (K), that affects the amount of charge that a capacitor stores for a given applied voltage. Table 3-3 shows the dielectric constants for typical insulating materials.

Type Material	Dielectric Constant (K)
Air	1
Paper	3.5
Mica	6
Glass	6 to 10

Table 3-3 Dielectric constants.

The formula below shows the relationship between the factors affecting the capacitance of a capacitor. C is the capacitance in picofarads. A is the plate area in square inches, D is the distance between the plates in inches, and K is the dielectric constant. If all of these factors are known, the capacitance can be computed.

$$C = \frac{0.2248 (A) (K)}{D}$$

As you can see by the formula, capacitance is directly proportional to plate area and the dielectric constant. Capacitance is inversely proportional to the distance separating the plates

Example: What is the capacitance of a paper capacitor with a plate area of 18 square inches and spacing of .005 inches?

$$C = \frac{0.2248 (18) (3.5)}{0.005} = 2,832.5 \text{ pF}$$

Types of Capacitors

There are two basic types of capacitors (fixed and variable) used in electronic circuits. A fixed capacitor is one that has a constant capacitance. Its physical construction is such that the capacitance remains at the same value under all conditions. A variable capacitor is designed so that its capacitance is adjustable.

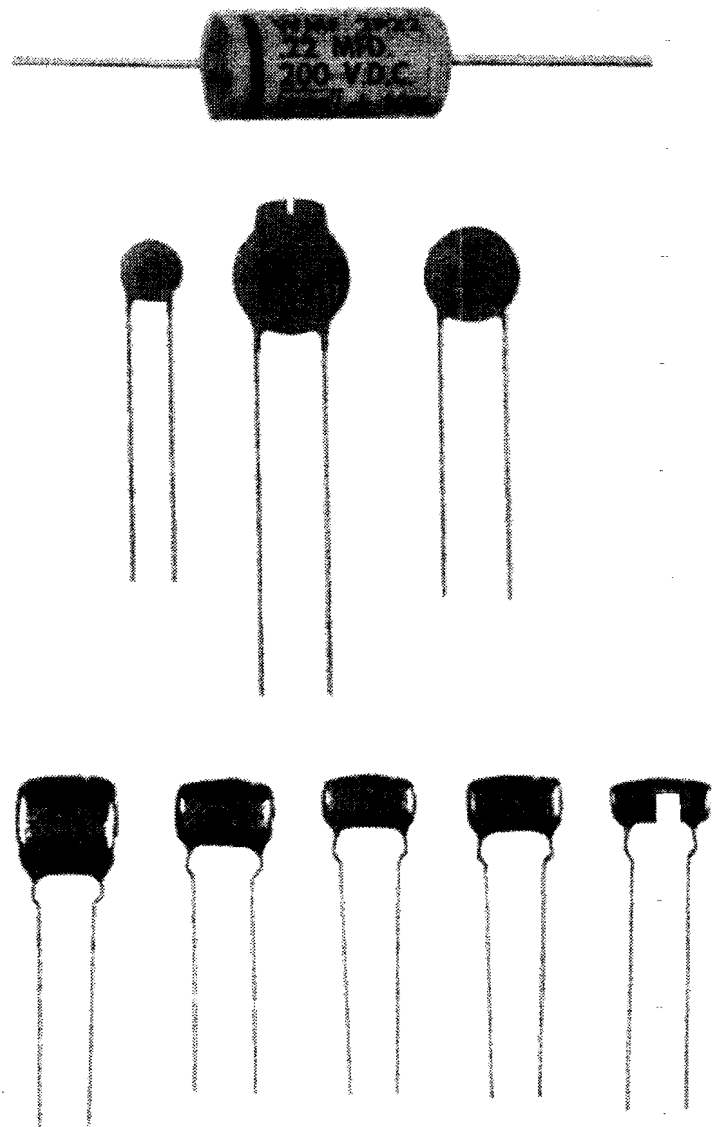


Figure 3-5 Typical fixed capacitors.

Another method of classifying capacitors is by the type of dielectric used. The most commonly used dielectric materials are mica, ceramic, paper, and plastic films such as Mylar*. Oil is also used as a dielectric in some large capacitors for high power applications. Another type of capacitor widely used in electronic applications is the **electrolytic** capacitor. Electrolytic capacitors have aluminum plates. The dielectric is a thin layer of aluminum oxide that is deposited on the plates during the manufacturing process. The dielectric is formed by an electro-chemical process on the plates so that plate spacing is extremely small. This permits very high values of capacitance to be contained within a relatively small package.

Capacitors can be either polarized or nonpolarized. Electrolytic capacitors are polarized capacitors. The term polarized means that the capacitor has a definite polarity and its polarity must be observed when installing the electrolytic capacitor into a circuit.

When a polarized capacitor is installed incorrectly (reversed in the circuit) it may short, get excessively hot, or even explode. The capacitor's positive or negative plate may be marked with a + or - sign and have an arrow pointing to the lead it refers to. The plus (+) side of the capacitor must be connected to the most positive potential.

Likewise the negative side of the polarized capacitor must be connected to the most negative potential. An improperly installed polarized capacitor can cause bodily harm (when it explodes) or destroy components and complete circuit boards when it shorts or over heats. All polarized capacitors have the polarity markings stamped on their bodies.

Various fixed value capacitors have been developed to meet the wide range of electronic applications. For example, mica and ceramic capacitors are excellent for very high frequency applications. Paper and plastic film capacitors are used in lower frequency applications where higher values of capacitance are required. Figure 3-5 shows several types of fixed capacitors used in electronic circuits.

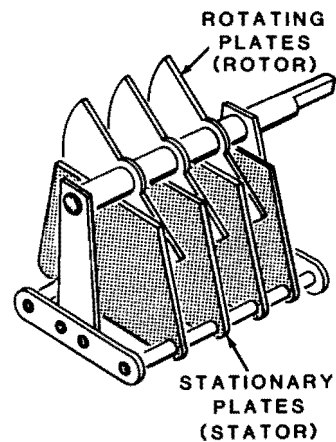


Figure 3-6 A typical variable capacitor.

*DuPont registered trademark.

Most variable capacitors have an air dielectric and are therefore referred to as air capacitors. Figure 3-6 shows a typical variable capacitor. Note the fixed plates (stator) and the variable plates (rotor). The capacitance increases as the variable plates are rotated to mesh with the fixed plates. Maximum capacitance occurs with full mesh, minimum capacitance occurs when the plates are not overlapped.

Another type of variable capacitor called a trimmer uses a mica dielectric to obtain a relatively high value of capacitance in a small size. Trimmer capacitors with a ceramic dielectric are also available. Figure 3-7 shows the symbol used to represent a variable capacitor in a schematic diagram. Trimmer capacitors are used to adjust the higher frequencies in a band of frequencies.



Figure 3-7 Schematic symbol for a variable capacitor.

One old phrase that was widely used in the audio communication field was to trim them on the top and pad them on the bottom, when a piece of equipment contained capacitors to adjust (balance) the gain over a range of frequencies. The trimmer capacitors adjusted the high frequencies and the padder capacitors adjusted the lower end of the frequency band.

When properly adjusted, the gain was relatively stable across the frequency band.

Capacitor Ratings

All capacitors are rated according to two basic characteristics: capacitance and working voltage. Capacitors come in a variety of standard capacitance values. Standard ranges cover from as high as several thousand microfarads to as low as one picofarad. Working voltage is listed as a DC voltage.

Another capacitor characteristic is its voltage rating. All capacitors are designed to withstand a maximum voltage. This voltage rating is a function of the type of dielectric used and its thickness. When the voltage rating of a capacitor is exceeded, it is possible to rupture the dielectric and cause the plates of the capacitor to short together. In some very high value capacitors, the dielectric material is extremely thin. A very thin dielectric is used for its high capacitance value, but it is also easier to damage a thin dielectric with high voltage.

Capacitors are generally rated in terms of an operating or working voltage. This is the maximum voltage that can be safely applied to the capacitor on a continuous basis. For example, a capacitor with a 200 volt rating can operate continuously with any value of DC voltage less than 200 volts. Applying a voltage greater than 200 volts may damage the capacitor. The 200

volt capacitor, operates satisfactorily at 50 volts DC. You will often see working voltage abbreviated WV.

Another capacitor voltage rating is peak voltage. The peak voltage is the maximum voltage that a capacitor can withstand when used with an AC voltage. For example, assume that a capacitor has a peak voltage rating of 1,000 volts. This means the peak AC value applied to the capacitor must never exceed 1,000 volts. If a 1,000 volt rms sine wave is applied to the capacitor, its voltage rating would be exceeded, and the capacitor may be damaged. The peak value of a 1,000 volt rms sine wave is 1,000 divided by 0.707 or 1,414 volts.

Both the capacitance and voltage ratings of a capacitor must be considered in terms of their tolerance ratings. It is extremely difficult and expensive to design components which have capacitance and voltage ratings exactly as specified. Therefore, most practical electronic components have a tolerance range on their ratings. A typical capacitance value might have a tolerance of plus and minus 10% ($\pm 10\%$). This means that the actual value of the capacitor could be 10% higher or 10% lower than the actual rated value. While 10% is a typical capacitance tolerance, capacitors with wider tolerance ranges and narrower ranges are also available. For example, one percent tolerance capacitors are available. However, closer tolerances are more expensive, this is partly true because of the additional expense to make, but just as important is that the number of appli-

cations for the component is reduced. Therefore, precision components are manufactured in smaller quantities than standard components. Some very large capacitors have tolerances as great as 80%.

The voltage ratings of capacitors are generally very conservative. That is the actual voltage rating is generally higher than the stated working value. While this is true, it is still a poor practice to use a capacitor in a circuit where the voltage exceeds its rated value.

Capacitor Defects

Like any electronic component, capacitors are subject to defects. Defects may occur in the manufacturing process or may be caused by an improper electrical condition in the circuits in which they are used. There are four common ways that capacitors fail. A capacitor can become shorted or open. The capacitor can have excess leakage or it can change in value.

A shorted capacitor is one where the plates either touch, or where a very low resistance path is formed between the plates. A low resistance path may cause arcing between the plates. Internal shorts usually occur when the dielectric is punctured. A capacitor that is shorting has a very low resistance, sometimes as low as zero ohms, and can often cause damage to other components in the circuit.

An open capacitor occurs when one or possibly both of the leads become disconnected from the plates. An open capacitor has a very high resistance and causes an open in the circuit.

A capacitor with excessive leakage is one where a resistive path is formed between the two plates. A good capacitor should be an open circuit to direct current (capacitors block DC currents) and should measure infinite (or extremely high) resistance between the two leads. A low resistance is sometimes developed when the dielectric fails. The resistance that develops between the two plates is referred to as leakage. It has the effect of an external resistor connected across the capacitor's leads. Leakage is sometimes detected by measuring the capacitor with an ohmmeter. When an ohmmeter is connected across a capacitor the meter reading constantly increases as the capacitor charges to the ohmmeter's internal voltage source. When the capacitor is fully charged the meter reading is stable. If the meter reading starts decreasing or the reading fluctuates, the capacitor is charging and discharging. This is an indication of changing internal capacitor resistance and is referred to as leakage.

Capacitors also change in value. A fixed capacitor has a specific given value. Later when used in a circuit, the capacitor may no longer have that specific value of capacitance. The capacitance value can change because of an incorrect applied voltage, excessive temperature conditions, or as in the case of electro-

lytic capacitors, expired shelf life. Electrolytic capacitors actually hold their values better when used in circuits than they do on the shelf.

Capacitors in Series and Parallel

Capacitors are often connected in series or parallel to form new values of capacitance. When two or more capacitors are connected in series or parallel, the capacitance of the combination is greater than or less than the values of the individual capacitors. Because such combinations occur so frequently in electronic circuits, it is desirable to know how to compute the total capacitance of the various combinations.

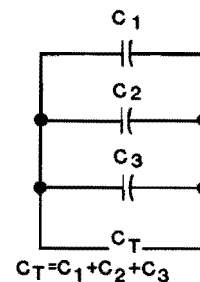


Figure 3-8 Capacitors connected in parallel.

Capacitors In Parallel

When two or more capacitors are connected in parallel as shown in Figure 3-8, the total capacitance of the combination is equal to the

sum of the individual capacitances. If the total capacitance of the combination is designated C_T the total capacitance is the sum of the individual capacitors.

$$C_T = C_1 + C_2 + C_3$$

For example, if $C_1 = .015 \mu\text{F}$, $C_2 = .002 \mu\text{F}$, and $C_3 = 1,000 \text{ pF}$, total capacitance is equal to:

$$C_T = .015 \mu\text{F} + .002 \mu\text{F} + .001 \mu\text{F} \\ \text{or } .018 \mu\text{F}.$$

In a parallel circuit configuration, total capacitance is always greater than any single value in the combination. Remember, capacitors in parallel are added like resistors in a series circuit.

The most important thing to note in making capacitance calculations such as this, is that all values of capacitance must be expressed in the same units. In this example, C_1 and C_2 are given in μF . C_3 is expressed in pF. In order to make the proper calculation, all values were changed to μF . A 1,000 pF capacitor is the same as a .001 μF capacitor. Remember, to convert pF to μF , the capacitance value in pF is divided by 1,000,000 (10^6)

Capacitors In Series

When two or more capacitors are connected in series as shown in Figure 3-9, the total capacitance of the combination will be less than the

capacitance of the smaller capacitor in the combination.

This is the same relationship that applies to resistors connected in parallel.

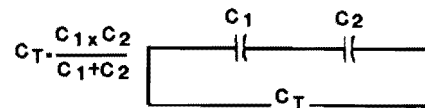


Figure 3-9 Capacitors connected in series.

The formula for calculating total capacitance, C_T , of two capacitors connected in series is illustrated below:

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

For example, assume that two capacitors, $C_1 = .001 \mu\text{F}$ and $C_2 = 390 \text{ pF}$, are connected in series. The total capacitance is:

$$C_T = \frac{1,000 \text{ pF} \times 390 \text{ pF}}{1,000 \text{ pF} + 390 \text{ pF}} \\ = \frac{390,000 \times 10^{-24}}{1,390 \times 10^{-12}} \\ = 280.6 \text{ pF}$$

Note that C_1 is expressed in μF while C_2 is expressed in pF. In order to compute the proper value of capacitance, the values of both capacitors are expressed in the same units. Here both were expressed in picofarads. A .001 μF capaci-

tor is equal to 1,000 pF. Note that the total capacitance of the combination is less than the smallest capacitor's value.

When more than two capacitors are put in series, the formula given above can be used to compute the total by combining the capacitors two at a time. For example, in a circuit with three capacitors in series, the combination capacitance of two of them would first be computed. This combination capacitance would then be combined with the third value of capacitor in the same formula to arrive at the correct total. This method is the same as the product over the sum formula used for paralleled resistors. The reciprocal method that is used for resistors in parallel also applies to capacitors in series .

Capacitors in DC Circuits

When capacitors are used in DC circuits, they exhibit certain properties and operational characteristics. When used in AC circuits, the capacitor has different properties and characteristics. Since the capacitor is usually considered to be an AC component most of this unit is devoted to the operation of capacitors in AC circuits. However, many AC circuits also use DC voltages. For that reason, we will first review the operation of capacitors in DC circuits.

Since there is no direct electrical connection between the plates of a capacitor, a capacitor

represents an open circuit (infinite resistance) to a DC voltage. There is no direct path for electrons to flow through the capacitor. However, when a capacitor is charging or discharging, movement of electrons takes place within the circuit. This movement of electrons constitutes current flow, but this charging or discharging action is transient (short time duration) in nature.

Once the capacitor is charged or discharged, current ceases to flow. While electrons do not cross between the plates of a capacitor, the charging and discharging action does cause movement of electrons in the external circuit. A component connected in series with the capacitor, such as a resistor, will have a voltage drop developed across it as the capacitor charges and discharges. The voltage dropped across the resistor will reverse polarities due to current moving in one direction during charging and moving in the opposite direction during the discharge cycle.

Figure 3-10 shows a simple series resistor-capacitor (RC) circuit connected to a DC voltage source. With the switch open and the capacitor initially discharged, no current flows in the circuit. However, when the switch is closed, the capacitor starts to charge. Electrons from the negative terminal of the battery flow through the switch and the resistor to the right hand plate of the capacitor. Electrons are drawn from the left hand plate of the capacitor by the positive terminal of the battery, leav-

ing the left plate positively charged. Once the capacitor is fully charged, current flow ceases. During the charging time, electrons flow through resistor (R) in the direction shown. This causes a voltage drop across the resistor with the polarity as indicated. This voltage appears only momentarily as the capacitor is charged. When the switch is initially closed, electrons begin to flow immediately and a peak voltage appears across the resistor. As the capacitor charges, the voltage drop across the resistance decreases. The voltage across the resistor is zero when the capacitor is fully charged or completely discharged.

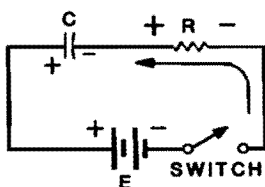


Figure 3-10 A series RC circuit.

The series combination of resistance and capacitance shown in Figure 3-10 is a common configuration. There are many variations and applications for this simple circuit. The most important characteristic of this RC combination is the time that it takes to charge or discharge the capacitor. This time is referred to as the time constant, T . The time constant is the time it takes for a capacitor to charge to approximately 63.2% of the applied voltage.

This time is the product of the circuit's resistance and capacitance value.

$$T = RC$$

The time constant in seconds is equal to the capacitance in farads, multiplied by the resistance in ohms. One time constant in seconds is also equal to the resistance in megohms, multiplied by the capacitance in microfarads.

For example: What is the time constant of a 25 microfarad capacitor and a .47 megohm resistor? The applied voltage is 12 volts.

$$T = 25(10^{-6}) \times .47(10^6) \text{ or } 11.75 \text{ seconds}$$

In other words, it takes the 25 microfarad capacitor 11.75 seconds to charge to 63.2% of 12 volts ($.632 \times 12 = 7.584$) or 7.584 volts through a .47 megohm resistor.

After one time constant, the voltage across a capacitor will be equal to 63.2% of the applied voltage. It takes approximately five time constants for the capacitor to charge to the full applied voltage. In the example above, it would take $5 \times 11.75 = 58.75$ seconds for the capacitor to charge to 12 volts.

The time constant relationship also holds true for the discharge of a capacitor. See Figure 3-11. A capacitor is initially charged to an applied voltage by closing the switch. When the

switch is opened, the capacitor discharges through the resistor. The time constant (T), is the time it takes the capacitor to discharge to 36.8% of the initial voltage. This is another way of saying that in one time constant, the capacitor's charge decreases by 63.2%. It takes approximately five time constants for the capacitor to discharge completely. If the capacitor is initially charged to 36 volts, after one time constant its voltage is $36 \times .368 = 13.25$ volts.

For each time constant, the capacitor changes its charge by 63.2%. As you can see, if the capacitor changes its charge by 63.2% each time constant, the capacitor never fully charges to the applied voltage or never fully discharges to zero. However, after 5 time constants the charge is so close to either the supply voltage or zero that it is appropriate to assume the capacitor changed its charge by 100%.

For example, assume that a capacitor is charging to 100 volts.

After 1 time constant the charge on the capacitor is 63.2 volts. The difference between the applied voltage and the charge on the capacitor is now:

$$100 \text{ V} - 63.2 \text{ V} = 36.8 \text{ V}.$$

During the second time constant, the capacitor charges to 63.2% of this remaining voltage. Therefore:

After 2 time constants, the charge on the capacitor is:

$$(.632 \times 36.8 \text{ V}) + 63.2 \text{ volts}.$$

$23.26 \text{ V} + 63.2 \text{ V} = 86.46 \text{ V}$. At this time, the difference between the applied voltage and the charge on the capacitor is only:

$$100 - 86.46 \text{ V} = 13.54 \text{ V}.$$

After 3 time constants, the charge on C is:

$$(.632 \times 13.54 \text{ V}) + 86.46 \text{ volts}.$$

$$8.56 \text{ V} + 86.46 \text{ V} = 95.02 \text{ V}.$$

After 4 time constants, the charge is:

$$(.632 \times 4.98 \text{ V}) + 95.02 \text{ volts}.$$

$$3.15 \text{ V} + 95.02 \text{ V} = 98.17 \text{ V}.$$

After 5 time constants, the charge is:
 $(.632 \times 1.83 \text{ V}) + 98.17 \text{ volts}.$

$$1.16 \text{ V} + 98.17 \text{ V} = 99.33 \text{ V}.$$

Since there are tolerances in all electronic circuits it was decided that 99.33% or 5 time constants is close enough to call it 100%. Therefore, a capacitor is considered to be fully charged after 5 time constants.

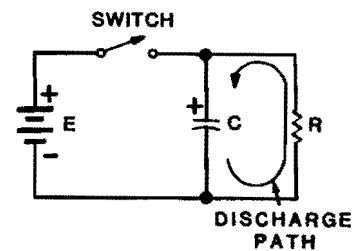


Figure 3-11 A parallel RC circuit.

Self-Test Review

1. A capacitor is an electronic component made up of two metal:
_____.
2. The insulator material in a capacitor is called its:
_____.
3. When a DC voltage is applied to a capacitor, electrons build up on one side and are drawn from the other. In this state, the capacitor is said to be:
_____.
4. The charge on a capacitor is stored in the form of a/an:
_____ field.
5. A capacitor's charge can be released by:
_____ its plates together.
6. Current flows in a capacitive circuit when the capacitor is:
_____ or _____.
7. Current does not flow between the capacitor's plates because the dielectric materials acts as a/an:
_____.
8. Capacitance in a circuit does not have to be a physical capacitor. This capacitance is called:
_____ capacitance.
9. The unit of capacitance is the:
_____.
10. A charge of one coulomb contains:
_____ electrons.
11. One farad is a common value for capacitors.
_____.
yes/no
12. To convert microfarads to picofarads the decimal point is moved 6 places to the:
_____.
13. An example of a polarized capacitor is the:
_____ capacitor.
14. It is often necessary to convert from one unit of capacitance to another. For example, a 2,200 picofarad capacitor expressed in microfarads is:
_____ μF .

-
15. A value of 0.47 microfarads in picofarads is equivalent to:

_____ pF.

16. The three basic factors that affect capacitance are:

_____, _____,

and _____.

17. When the diameter of the capacitor's plates is increased, capacitance:

_____.

18. The better the insulating capabilities, the higher the dielectric constant. If the dielectric constant decreases, capacitance:

_____.

19. When the separation between a capacitor's plates is increased, capacitance:

_____.

20. An adjustable capacitor is classified as a:

_____ capacitor.

21. Fixed capacitors are usually classified according to their:

_____.

22. A special type of fixed capacitor that has an aluminum oxide dielectric is called a/an:

_____ capacitor.

23. In most variable capacitors (the types used in tuners) the dielectric material is:

_____.

24. When mica, ceramic, paper, air, and glass dielectric constants are compared, the one with the highest dielectric constant is:

_____.

25. Capacitors are also rated by applied voltage. The working voltage stamped on a capacitor is usually specified as a:

_____ voltage.

26. A capacitor will not function properly if the applied voltage is more than 10% below its working voltage.

A. True
B. False.

27. Capacitors usually fail by either:

_____ or _____.

28. When an ohmmeter is connected across a capacitor's leads, the meter initially measures zero and then increases to a very high value and remains there. The capacitor is probably:

_____.

29. When an ohmmeter is connected across a capacitor's leads the meter initially measures zero, and remains at zero. The capacitor is probably:

_____.

30. A capacitor is connected to a 100 volt source and allowed to charge for 3 time constants. The difference of potential between its plates is:

_____ volts.

31. When capacitors are connected in parallel, the total capacitance always:

_____.
increases/decreases

32. When two capacitors that have values of 680 pF and 750 pF are connected in parallel. C_T is equal to:

_____ pF.

33. When capacitors are connected in series, total capacitance

_____.
increases/decreases

34. The method used to find the total capacitance of two capacitors connected in series is called the:

_____.

_____ method.

35. A capacitor is connected to a 100 volt DC source in a series RC circuit. The voltage difference, between the capacitor's charge and the source voltage, after 1 time constant is:

_____.

36. In 1 time constant the capacitor can change its charge by:

_____ %.

37. Decreasing either R or C will decrease

_____.

38. A series RC circuit has a source voltage of 10 volts DC. R is equal to 1.2 megohms and C is equal to 0.68 microfarads. The instant the circuit is turned on the voltage drop across the capacitor is:

_____ volts.

39. The time constant for the circuit described in question 38 is:

_____ seconds .

40. After 3 time constants, the voltage drop across the resistor (in the circuit described in question 38) will be:

_____ volts.

Capacitors in AC Circuits

When an AC voltage is applied to a capacitor, alternating current flows in the circuit. Figure 3-12 shows a sine wave generator, connected to a capacitor. As the AC voltage varies, the current in the circuit follows a sinusoidal path. Electrons do not pass through the dielectric, from one plate of the capacitor to the other. However, electrons do flow in the circuit external to the capacitor. As the applied AC voltage rises and falls, the capacitor charges and discharges. The charge and discharge rate of the capacitor is determined by the frequency of the input voltage. Note also the arrow in Figure 3-12. It indicates that current flows first in one direction and then reverses, and flows in the other direction. This oscillating current is also the definition of a sine wave.

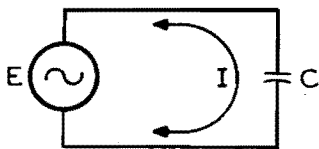


Figure 3-12 An AC voltage source applied to a capacitor.

Figure 3-13 illustrates the action of an electron in the dielectric of a capacitor. The illustration also shows the effect an applied AC

voltage has on the atoms within the dielectric of a capacitor. In Figure 3-13A, the applied voltage is zero. At this time, the electrons contained in the atoms of the dielectric rotate normally about their nuclei. Note what happens to the orbit of the electron, when the capacitor is charged. This is shown in Figure 3-13B. In this example, the upper plate is made negative with respect to the lower plate. The electrons orbiting in the dielectric, are repelled by the negative plate and attracted by the positive plate. This distorts the orbit of the electrons. The amount of voltage applied to the capacitor determines the amount of orbit distortion. Figure 3-13C shows the orbit distortion when the capacitor is charged in the opposite direction.

When an AC voltage is applied to the capacitor, the polarity of the applied voltage alternates. This causes the electrons in the dielectric to shift in their orbits. While the amount of electron shift is small, it nevertheless constitutes a movement of electrons within the dielectric. While it's true that none of the electrons actually break loose from their orbits and flow in the external circuit, we can say that the movement of electrons constitutes current flow. As the capacitor is charged and discharged by the AC voltage, the movement of electrons onto one plate and off the other, in the external circuit, is current flow. When the applied voltage is a sine wave, current flow in the circuit is also sinusoidal.

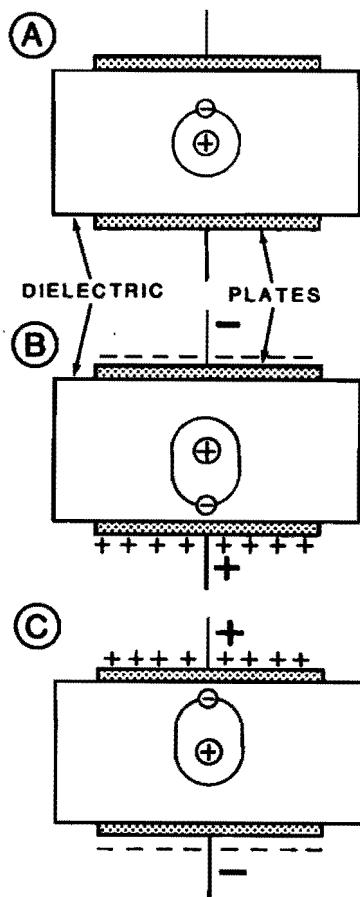


Figure 3-13 Electron distortion in the dielectric of a charged capacitor.

Current-Voltage Relationships in Capacitive AC Circuits

The relationship between current and applied voltage in a capacitive circuit differs from purely resistive AC circuits. Because of the way that a capacitor functions, current and voltage in a capacitive AC circuit are not in phase.

In a purely resistive circuit, when an AC voltage is applied, current through the resistors occurs at the same time and has the same polarity as the applied voltage. In this case, current and voltage are in phase. In other words, the positive and negative half cycles of voltage and current, in a resistive AC circuit are in step with one another.

In a capacitive AC circuit, the capacitor constantly charges and discharges at the rate of change of the applied voltage. Once the capacitor is charged, the voltage across it acts as a voltage source. Its effect is to oppose changes in the external supply voltage. Since the capacitor must charge or discharge to follow the changes in the applied voltage, the resulting current flow is out of step with the changes in

the applied voltage. We say that there is a phase shift between the voltage and current in the circuit. In a purely capacitive circuit the phase shift is 90 degrees. Current leads voltage by 90 degrees.

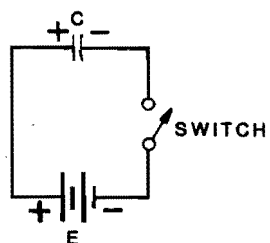


Figure 3-14 A capacitor being charged by a DC source.

To understand the relationship between current and voltage in a capacitive AC circuit, let's review the basic principles of capacitor operation when a DC voltage is applied. Figure 3-14 shows a DC voltage source connected to a capacitor. The capacitor is initially discharged and the switch is open. When the switch is closed, the instantaneous voltage across the capacitor is zero. It might appear that the voltage across the capacitor is initially equal to the applied voltage, the instant the switch is closed. However, it is zero, electrons have not had time to flow to and from the plates of the capacitor. In other words, on the initial closure of the switch, the capacitor is still uncharged.

Immediately thereafter, electrons begin to flow. Electrons flow from the negative terminal of the battery to the right hand plate of the capacitor. The right hand plate obtains an excess of electrons and is negatively charged. At the same time, electrons are drawn from the left hand plate of the capacitor to the positive terminal of the battery. The absence of electrons causes the left hand plate to be positively charged. The polarity of voltage across the capacitor at this time is indicated in Figure 3-14. Note that this voltage is in direct opposition to the applied voltage.

When the capacitor is fully charged to the applied voltage, the two voltages are equal in amplitude and opposite in polarity. The voltages therefore cancel each other, and the effective voltage in the circuit is zero. When the voltages are equal, there is no difference of potential, and current ceases to flow.

Remember Kirchhoff's Voltage Law, the sum of the voltages around a closed loop must equal zero.

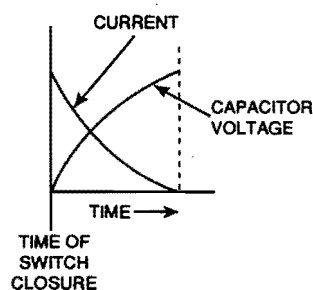


Figure 3-15 Voltage and current relationship in a charging capacitor.

Figure 3-15 illustrates the relationship between the capacitor's current and voltage in the circuit shown in Figure 3-14. When the switch is initially closed, the capacitor voltage is zero and current flow in the circuit is maximum. As the capacitor charges, capacitor voltage begins to increase. The increasing capacitor voltage opposes the applied voltage. This reduces the difference of potential which results in reduced current flowing in the circuit. This action and reaction is why the capacitor changes its charge by 63.2% of the available voltage (difference of potential) in 1 time constant. When the capacitor becomes fully charged, the current in the circuit is reduced to zero.

Using the relationship shown in Figure 3-15, we can show the actual current and voltage relationships in a capacitive circuit when an AC signal is applied. Once the capacitor becomes charged, the voltage across the capacitor is the same as the applied voltage. The current flowing in the circuit is out of phase with the voltage. Current leads voltage by 90 degrees in a purely capacitive circuit, as indicated in Figure 3-15.

The exact relationship between the current and voltage in a capacitive circuit, when a sine wave is applied, is shown in Figure 3-16. Note that when the current is maximum, the voltage across the capacitor is zero. As you can see, there is a phase shift between the current

and voltage in the circuit. This phase shift is expressed in terms of degrees. Remember that one complete cycle of a sine wave contains 360 degrees. The amount of phase shift in the capacitive circuit is one fourth or 90 degrees. We say that the current and voltage in a purely capacitive circuit are 90 degrees out of phase with one another. Another important fact to note is that the change in current **leads** the change in voltage. This is shown by current being at maximum at zero time, 90 degrees later voltage is maximum and current is minimum.

A memory aid that is used to help keep the current voltage relationships straight in capacitive and inductive circuits is:

ELI the ICE man.

The inductor symbol is L. In an inductive circuit E (voltage) leads I (current).

The capacitor symbol is C. In a capacitive circuit I (current) leads E (voltage).

Looking at Figure 3-16 you can see that the capacitor voltage change follows the current change in time. We say that current leads the voltage in a capacitive circuit. In other words, there is a 90 degree leading phase shift in a purely capacitive circuit.

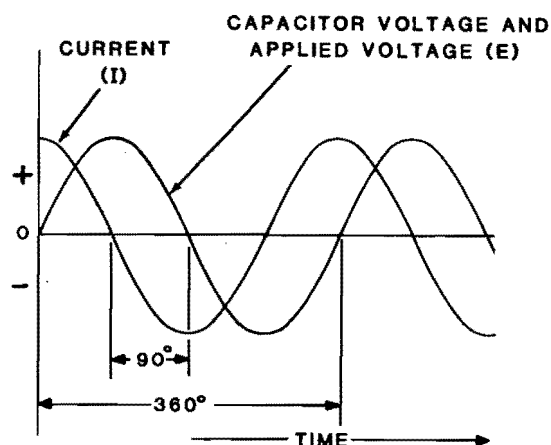


Figure 3-16 Current and voltage relationship in a purely capacitive AC circuit.

Capacitive Reactance

It is the basic nature of a capacitor to oppose changes in voltage. In a DC circuit, a capacitor will charge to the applied voltage. If the applied voltage is increased, the capacitor will then charge to the new higher voltage. If the applied voltage is decreased, the capacitor will discharge until the voltage across it equals the new lower applied voltage. Keep in mind that it takes a finite period of time for a capacitor to charge or discharge to a new voltage level. Charge and discharge time is a function of the capacitor's size and the value of any series resistance in the circuit.

In an AC circuit, the capacitor is constantly charging and discharging because the applied voltage is constantly changing. The voltage across the capacitor is in constant opposition to the applied voltage. This constant opposition to changes in the applied voltage creates an opposition to current flow in the circuit. This opposition to the flow of AC current by a capacitor is called capacitive reactance. Capacitive reactance is represented by the symbol X_C and, like resistance, it is measured in ohms.

The capacitive reactance of a capacitor is determined by its capacitance value and the frequency of the applied voltage. The amount of opposition to current flow in an AC circuit is a function of capacitance and the frequency of the AC voltage. Capacitive reactance is inversely proportional to capacitance and frequency. Therefore, increasing capacitance or frequency will cause capacitive reactance to decrease.

Capacitive reactance is calculated by using the equation:

$$X_C = \frac{1}{2\pi FC}$$

In this expression, X_C is the capacitive reactance in ohms, F is the frequency in Hz, C is the capacitance in farads and pi (π) is a constant that is equal to approximately 3.14. Since $1/(2\pi) = 1/6.28$ which is approximately .1592, you can simplify the expression as shown below:

$$X_C = \frac{.159}{FC}$$

Since farads is an unrealistically high unit of capacitance, this formula is difficult to use. If we assume that the capacitance in the formula is expressed in microfarads, the expression for capacitive reactance becomes:

$$X_c = \frac{.159(10^3)}{FC}$$

The following examples show how to compute capacitive reactance when the frequency of operation and the capacitance are known. These examples illustrate the effect of frequency and capacitance on the reactance.

1. What is the reactance of a 1 microfarad capacitor at 60 Hz?

$$X_c = \frac{159,000}{60(1)} \text{ or } 2,650 \text{ ohms}$$

2. If the frequency is increased to 120 Hz, what is the new value of reactance of the 1 microfarad capacitor?

$$X_c = \frac{159,000}{120(1)} \text{ or } 1,325 \text{ ohms}$$

Doubling frequency decreases reactance by one half.

3. What is the reactance of a 1,000 pF capacitor at 2 kHz?

$$1,000 \text{ pF} = .001 \mu\text{F}$$

$$2 \text{ kHz} = 2,000 \text{ Hz}$$

$$X_c = \frac{159,000}{2,000(.001)} = 79,500 \text{ ohms}$$

79,500 ohms is equal to 79.5 k ohms.

4. If the capacitance is decreased from 1,000 pF to 500 pF, what is the reactance at 2 kHz?

$$500 \text{ pF} = .0005 \mu\text{F}$$

$$X_c = \frac{159,000}{2,000(.0005)} = 159,000 \text{ ohms}$$

159,000 ohms is equal to 159 k ohms.

Halving capacitance doubles reactance.

These examples show how the reactance is computed when the frequency and the capacitance are known. There are often occasions when it is necessary to compute the frequency when the reactance and capacitance are known or to compute the capacitance when the reactance and frequency are known. The formulas for making these calculations are given below:

$$F = \frac{1}{2\pi X_c C}$$

$$C = \frac{1}{2\pi F X_c}$$

Where:

F (frequency) is in Hz.

C (capacitance) is in farads.

X_c (capacitive reactance) is in ohms.

These two equations can be simplified to:

$$F = \frac{159,000}{X_c C}$$

$$C = \frac{159,000}{F X_c}$$

Where:

F (frequency) is in Hz.

C (capacitance) is in microfarads.

X_c (capacitive reactance) is in ohms.

Examples:

1. At what frequency will a .039 microfarad capacitor have a reactance of 7,000 ohms?

$$F = \frac{159,000}{7,000(.039)} = 582 \text{ Hz}$$

2. What value of capacitance has a reactance of 23 k ohms at a frequency of 2 MHz.

Where:

$$23 \text{ k}\Omega = 23,000 \text{ ohms}$$

$$2 \text{ MHz} = 2,000,000 \text{ Hz}$$

$$C = \frac{159,000}{23,000(2,000,000)} \text{ or } .00000346 \mu\text{F}$$

$$C = .00000346 \times 10^{-6} \text{ or } 3.46 \text{ pF}$$

Ohm's Law in Capacitive Circuits

Ohm's Law describes the basic relationship between the current, voltage, and resistance (opposition) to current flow in an electrical cir-

cuit. Because of its capacitive reactance in an AC circuit, a capacitor is just as effective as a resistor in controlling current flow.

In a purely capacitive circuit, one that has capacitance but no resistance, the current is directly proportional to the applied voltage, and inversely proportional to the capacitive reactance. This relationship is shown in the formula below:

$$I = \frac{E}{X_C}$$

For example, assume that an AC voltage of 6.3 volts is applied to a capacitor with a reactance of 210 ohms. The current in the circuit is:

$$I = \frac{6.3 \text{ volts}}{210 \text{ ohms}} \text{ or } .03 \text{ amperes}$$

0.03 amperes is equal to 30 milliamperes.

Rearranging the basic Ohm's Law formula, we can compute voltage and reactance.

$$E = IX_C$$

$$X_C = \frac{E}{I}$$

The following examples illustrate this use of Ohm's Law.

1. A .05 microfarad capacitor has a current of .1 ampere at 400 Hz. What is the voltage dropped across the capacitor?

$$X_c = \frac{159,000}{400(.05)} \text{ or } 7,950 \text{ ohms}$$

$$E = .1(7,950) \text{ or } 795 \text{ volts}$$

2. A capacitor drops 200 volts at 60 Hz with a current of .02 amperes. What is the value of capacitance?

$$X_c = \frac{200}{.02} \text{ or } 10,000 \text{ ohms}$$

$$C = \frac{159,000}{60(10,000)} \text{ or } .265 \mu\text{F}$$

Self-Test Review

41. When an AC voltage is applied to a capacitor, electrons do not flow between the:

_____.

42. When an AC voltage is applied and electrons are attracted to one plate and drawn from the other, the capacitor is said to be:

_____.

43. In a capacitive circuit, the relationship of current to voltage is identified by:

_____.

44. In an AC circuit containing only resistance, the current and the applied voltage are:

_____.

45. Upon initial turn on, in an RC series circuit the voltage across the resistor is:

_____.

46. In a purely capacitive circuit, current and voltage are out of phase by:

_____ degrees.

47. A charged capacitor can act as a:

short/open/source

48. The polarity relationship between a capacitor's charge and its source voltage is always.

_____.

49. The opposition to AC current flow by a capacitor is called:

_____.

50. AC opposition to current flow is measured in:

_____.

51. The amount of capacitive reactance in a circuit is determined by both:

_____ and _____.

52. X_C is _____ proportional to frequency.

53. Increasing the space between a capacitor's plates causes capacitive reactance to:

_____.

54. The formula for calculating capacitive reactance is:

$X_C =$ _____.

55. The reactance of a .0047 microfarad capacitor at 1,500 Hz is:

_____ ohms.

-
56. Current (I) in a capacitive circuit is directly proportional to the applied voltage (E) and inversely proportional to the capacitive reactance. This can be expressed by the Ohm's Law formula:

_____.

57. An AC circuit is operating with an input signal of 5 volts that has a period of 1.25 ms. The circuit contains a .068 microfarad capacitor.

frequency = _____.

X_C = _____.

I = _____.

58. To increase the current in a circuit the reactance must be:

_____.

59. To decrease the current in a circuit frequency or capacitance can be:

_____.

60. A capacitor has a voltage drop of 70 volts at 60 Hz and the current is .08 amperes. The value of the capacitor is:

_____ μF .

RC Circuits

While almost purely capacitive circuits are sometimes used in electronics, more often capacitors are combined with other components to form electronic circuits. The most commonly used circuits contain a resistor and capacitor connected in series. Despite its simplicity, this simple series RC circuit has many applications. Another commonly used capacitor circuit is the paralleled resistor-capacitor combination. While not as common as the series RC circuit, the parallel RC circuit is frequently found in electronic equipment. In this section you are going to investigate the operation and characteristics of both series and parallel RC circuits.

Series RC Circuits

The simplest form of RC circuit is a single capacitor connected in series with a resistor. Figure 3-17 shows such a circuit connected to an AC voltage source. The source voltage is a sine wave (designated E), which causes current to flow in the circuit. The capacitor will charge and discharge as the input voltage varies. The charging and discharging action of the capacitor causes a movement of electrons in the circuit. The charge on the capacitor causes a voltage to be developed across it. This voltage is designated E_C as shown in Figure 3-17. The voltage developed across the capacitor is a sine wave that lags the current flowing in the circuit.

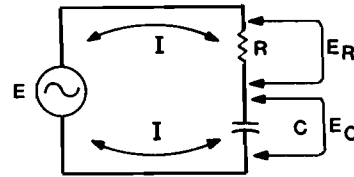


Figure 3-17 Series RC circuit.

The current in the circuit passes through resistor R and develops a voltage drop across it. The voltage across the resistor, designated E_R , is in phase with the current in the circuit. The voltage dropped across the resistor is a function of the resistor's value and the circuit's current ($E_R = IR$). The capacitor's voltage drop is a function of the current flowing in the circuit and the capacitive reactance ($E_C = IX_C$).

Figure 3-18 shows the phase relationships of the various voltages and currents in this series RC circuit. In this illustration, the current sine wave (I), is used as the reference. One of the fundamental characteristics of a series circuit is that the current is common to all components. Note the voltage drop across the resistor (E_R). This voltage drop is in phase with the current. You can see this by noting that the maximum, minimum, and zero crossing points for the voltage waveform (E_R) coincide with those of the current waveform (I).

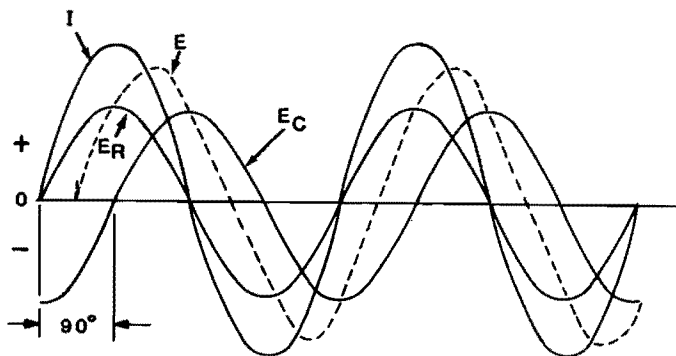


Figure 3-18 Phase relationships between current and voltage in a series RC circuit.

Now refer to the capacitive voltage drop (E_C). The current through a capacitor leads the voltage across it by 90 degrees. Another way of saying this is that the voltage across the capacitor lags (occurs later in time) the current.

Another important characteristic of capacitive AC circuits is that Kirchhoff's Law also applies. Kirchhoff's Voltage Law tells us that the sum of the voltage drops across the components in a series circuit must equal the applied voltage. This law is valid for the circuit in Figure 3-17. Now refer to Figure 3-18. If we add E_R and E_C by summing the amplitudes of the two sine waves at multiple points and plotting the resulting curve, we will obtain the sine wave represented by the dashed line in Figure 3-18.

This waveform represents the applied voltage (E). Note that its amplitude is higher than either the resistor voltage or the capacitor voltage. Another important point is that the applied voltage is not in phase with the current or with either the capacitor or resistor voltages. The current in the circuit leads the applied voltage as it will in any capacitive circuit. But since the circuit is not purely capacitive, the current leads the applied voltage by some angle less than 90 degrees.

In this example, the current leads the applied voltage by approximately 45 degrees. This difference in phase is called the phase shift or, more commonly, the phase angle. Shortly, you will see how the word angle comes into play.

When a circuit has no resistance, it is purely capacitive, and the current through the circuit leads the applied voltage by 90 degrees. When the circuit is purely resistive, the current and voltage are in phase.

When both resistors and capacitance are contained in a circuit, the phase difference between the current and the applied voltage is some value between 0 degree and 90 degrees.

The exact amount of the phase shift is determined by the amount of resistance and capacitive reactance in the circuit. Before we get into phase angle calculations, let's take a closer look at the voltage relationships in a series RC circuit.

To an AC circuit, it is not possible to add the voltage drops across the resistive and capacitive components to obtain the applied voltage. The voltage drops across the resistance and the capacitive reactance are not in phase with one another. In order to obtain the correct applied voltage, you must correct for the phase difference between the two voltages. You do this by vector addition.

Vector Diagrams

In the physical world, there are quantities that are expressed in specific units. Ohms, inches, and pounds are all examples of these quantities. These quantities are measured in scalar values and, in order to find the sum of a number of like quantities, you simply add them together. For example:

$$5 \text{ ohms} + 10 \text{ ohms} = 15 \text{ ohms}$$

Problem solving using scalar quantities is easy because it involves simple addition.

Other physical quantities have two properties; magnitude and direction. Any quantity having both magnitude and direction is called a vector. Miles traveled in a northeast direction, altitude gained in feet while traveling west, and volts at 90 degrees are all examples of vector quantities.

It is possible to add vectors but, you must take into consideration both the magnitude and the direction of the vector. In order to make this easier, you should draw a vector diagram when analyzing AC circuits. The basic format for vector diagramming is shown in Figure 3-19.

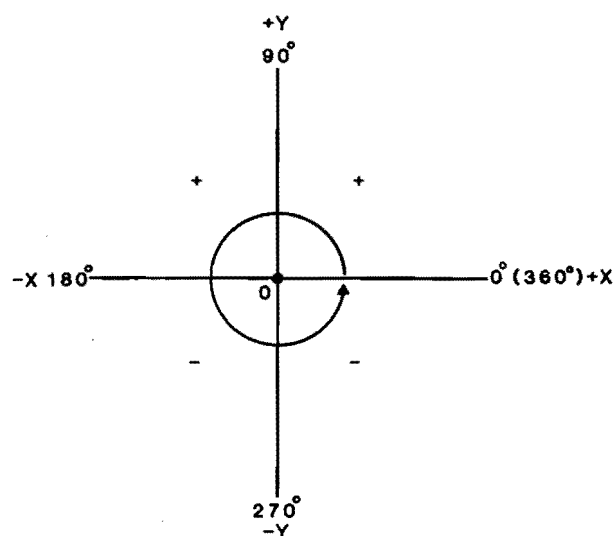


Figure 3-19 Typical AC vector diagram.

This illustration consists of two lines (axis), perpendicular to each other. The horizontal line is the X axis and the vertical line is the Y axis. The point at which these two lines cross is the origin and it is labeled zero. The magnitude, or value, of any vector is measured outward from the origin. The direction of a vector corresponds to its phase differences in degrees.

In Figure 3-19, the ends of the axis are labeled 0 (360), 90, 180, and 270. When the vector is rotated, it starts at 0 and travels in a counter-clockwise direction until it reaches 360. This would be one complete revolution and ends at the origin. Now that we've set the basic groundwork for the vector diagram, let's look at an example.

Figure 3-20 shows the vector diagram for a series RC circuit. A current vector, I , is shown on the X axis pointing to the right. This vector represents the value of the current flowing in the series RC circuit. It is used as a reference vector for the diagram because the current value is the same at all points in a series circuit. Coincidence with this vector is another vector labeled E_R . The length of this vector, from the origin to the point of the vector, represents the voltage dropped across the resistive portion of the circuit. This is the actual voltage as it would be measured with a voltmeter. It is an effective, or rms, voltage and is equal to .707 times the peak voltage across the resistor. The voltage vector overlaps the current vector because they are in phase.

The voltage across the capacitor is labeled E_C . This is the actual voltage measured across the capacitor and it is an effective value. Notice that the direction of the capacitor voltage is shifted 90 degrees from the direction of the resistor voltage. This is because there is a phase shift between the resistive and capacitive components in the circuit.

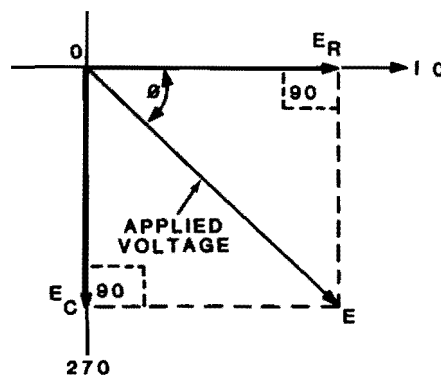


Figure 3-20 Vector diagram of a series RC circuit.

The applied voltage, the voltage supplied to the circuit, is the vector sum of the capacitor and resistor voltages. To graphically accomplish the vector addition, a rectangle is first formed using the resistor and capacitor voltages. This is shown by the dashed lines in Figure 3-20.

The magnitude, or value, of the applied voltage is the distance from the origin to the far corner of the completed rectangle. Stated another way, the value of the applied voltage is represented by the diagonal line drawn from the origin across the rectangle.

The angle formed by the applied voltage vector and the resistive voltage vector represents the amount of phase shift that exists between circuit current and circuit voltage. This angle is always between 0 and 90 degrees. Later you

will learn how to calculate this value but, for now, let's get back to vector addition.

You can now use the illustration created by the graphic solution of vector addition to determine the actual applied voltage. The diagonal line that represents the applied voltage, splits the rectangle into two triangles. These triangles are right triangles because they each have a 90 degree angle as shown in Figure 3-20. In addition, the length of two sides of the triangles, represented by the capacitor and resistor voltages, are also known.

When you know the value, or length, of any two sides of a right triangle, it is possible to determine the value of the third side by using a mathematical formula called the Pythagorean Theorem. Appendix A of this unit describes this theorem in detail. If you are not familiar with the Pythagorean Theorem, refer to Appendix A at this time. Once you understand this theorem, return to this point and continue your study.

In Figure 3-21, the side of the triangle representing the applied voltage is the side directly opposite the 90 degree angle. This side is called the hypotenuse and you can compute its length using the Pythagorean Theorem.

$$E^2 = (E_R)^2 + (E_C)^2$$

This expression says, the resistor voltage squared plus the capacitor voltage squared is equal to the applied voltage squared.

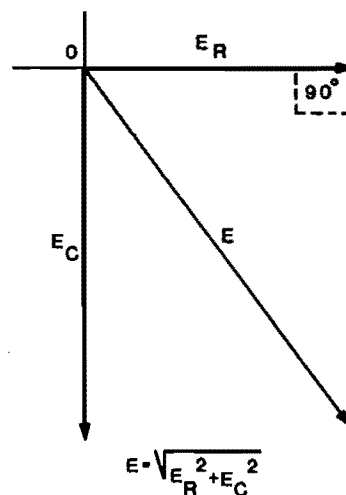


Figure 3-21 Voltage vector triangle for a series RC circuit.

When you take the square root of the sum, the result will be the applied voltage. That is, the equation becomes:

$$E = \sqrt{(E_R)^2 + (E_C)^2}$$

That is the equation for finding the applied voltage, when the resistor and capacitor voltages are known. This equation can be rearranged. The resistor voltage can be computed if the applied voltage and capacitor voltage are known, or the capacitor voltage can be computed if the applied voltage and resistor voltage are known. These two formulas are given below:

$$E_R = \sqrt{(E)^2 - (E_C)^2}$$

$$E_C = \sqrt{(E)^2 - (E_R)^2}$$

The examples below show the use of the formulas.

1. What is the applied voltage in a series RC circuit where the resistor voltage is 12 volts and the capacitor voltage is 18 volts?

$$E = \sqrt{(E_R)^2 + (E_C)^2}$$

$$E = \sqrt{12^2 + 18^2}$$

$$E = \sqrt{144 + 324}$$

$$E = \sqrt{468}$$

$$E = 21.63 \text{ volts}$$

2. The voltage applied to a series RC circuit is 115 volts. The current in the circuit is .0075 amperes. The resistor value is 5 kilohms. What is the capacitor voltage?

$$5k = 5,000$$

First, calculate the resistor voltage:

$$E_R = IR$$

$$E_R = .0075 (5,000)$$

$$E_R = 37.5 \text{ volts}$$

Next, calculate the capacitor voltage:

$$E_C = \sqrt{(E)^2 - (E_R)^2}$$

$$E_C = \sqrt{115^2 - 37.5^2}$$

$$E_C = \sqrt{13,225 - 1,406.25}$$

$$E_C = \sqrt{11,818.75}$$

$$E_C = 108.7 \text{ volts}$$

Note that when any 2 sides of a right triangle are known, the third side can be calculated using the Pythagorean Theorem.

Impedance

Impedance is the total opposition to current flow in an AC circuit. In a circuit consisting of a resistor and a capacitor, the total opposition is the sum of the capacitive reactance and the resistance. Both the reactance and the resistance impede current flow. Because of the phase shift created by the capacitor, the capacitive reactance and resistance cannot be summed directly, just as the voltage drops across the capacitor and resistor in a series RC circuit cannot be summed directly. The impedance is the vector sum of the capacitive reactance and resistance.

The impedance of an AC circuit is expressed in ohms and is designated by the letter Z . We can define the impedance in terms of Ohm's Law just as we defined the total resistance of a DC circuit. The impedance of an AC circuit is equal to the applied voltage divided by total circuit current.

$$Z = \frac{E}{I}$$

This expression can be rearranged to obtain the expressions for voltage and current:

$$E = IZ$$

$$I = \frac{E}{Z}$$

In the previous section, you saw that because of the phase shift caused by the capacitor in a series RC circuit, the voltage drops across the capacitor and resistor could not be added directly to obtain the applied voltage. Instead, a vector sum had to be calculated to obtain the correct value. The voltage drops across the resistor and capacitor in a series RC circuit are directly proportional to the current. Since the current through a series circuit is the same in all components, we can say, that the voltage drops across the circuit components are directly proportional to their resistance or reactance.

For that reason, we can draw a diagram exactly like the voltage vector diagram, to obtain the total impedance of the circuit.

This vector diagram is shown in Figure 3-22. Again, the current vector is used as the reference. The resistance vector coincides with the current vector because the resistive voltage drop is in phase with current. In this case, the length of the vector is proportional to the resistance.

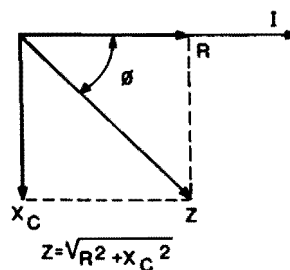


Figure 3-22 Impedance vector diagram of a series RC circuit.

Another vector representing the magnitude of the capacitive reactance, X_C , is drawn 90 degrees out of phase with the resistance vector. This takes into account the 90 degree phase shift produced by the capacitor. Completing the rectangle formed by the resistance and reactance vectors and drawing the diagonal line gives us the magnitude of the impedance. The length of the diagonal line represents the total opposition to current flow in the circuit.

Using the Pythagorean Theorem, we can write an expression for the impedance of the circuit in terms of the resistance and reactance:

$$Z = \sqrt{R^2 + X_C^2}$$

This expression says that the impedance is equal to the square root of the sum of the resistance squared and the capacitive reactance squared. Using basic algebra, this formula can be rearranged to compute the circuit resistance in terms of the impedance and reactance or the capacitive reactance in terms of the impedance and resistance:

$$R = \sqrt{Z^2 - X_C^2}$$

$$X_C = \sqrt{Z^2 - R^2}$$

The examples below illustrate the use of these formulas.

1. What is the impedance of a series RC circuit with a resistance of 50 ohms and a reactance of 75 ohms?

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{(50)^2 + (75)^2}$$

$$Z = \sqrt{2,500 + 5,625}$$

$$Z = \sqrt{8,125}$$

$$Z = 90.14 \text{ ohms}$$

2. A series RC circuit has an applied voltage of 120 volts. The current is .02 amperes. The circuit resistance is 4,000 ohms. What is the capacitive reactance?

First, the impedance:

$$Z = \frac{E}{I}$$

$$Z = \frac{120}{.02} \text{ or } 6000 \Omega$$

Then, using the impedance and the resistance, find the capacitive reactance:

$$X_C = \sqrt{Z^2 - R^2}$$

$$X_C = \sqrt{6,000^2 - 4,000^2}$$

$$X_C = \sqrt{36,000,000 - 16,000,000}$$

$$X_C = \sqrt{20,000,000}$$

$$X_C = 4,472 \Omega$$

Power in AC Circuits

Whenever an AC voltage is applied to a resistance, current flows and electrical energy is converted into heat energy. The heat energy, or power, is dissipated in the resistance. All of the basic formulas for computing power dissipation in resistive DC circuits are applicable to power computation in a resistive AC circuit:

$$P = IE$$

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

When you are using these formulas to compute AC power dissipation, voltage and current should be the effective, or rms, values.

Figure 3-23 is a diagram of the voltage, current, and power in an AC resistive circuit. Note that the applied voltage and the current are in phase. To obtain power, multiply the instantaneous values of current and voltage, and plot the resulting products as a power curve. The instantaneous values are the values of current and voltage at any given instant in time during each current and voltage cycle.

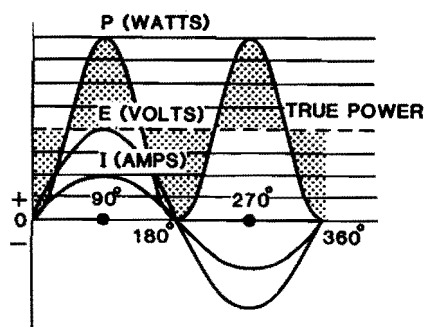


Figure 3-23 Power in a resistive AC circuit.

The product of a positive voltage and a positive current is shown as the first positive power peak. When you multiply the negative current and voltage, you get another positive peak. The power curve is positive and sinusoidal in shape.

Since the entire power curve is positive, it is possible to determine the actual power dissipated if you draw a line halfway between the maximum and zero points on the power curve. The value represented by this line is the product of the rms values of current and voltage in the circuit. For this reason, it is called **true power**. Since power is dissipated only in resistance, the true power is the only power dissipated in an AC circuit.

When you are analyzing an AC circuit, power will appear to be dissipated by both inductive and capacitive components. However, because of the phase shift between the current and voltage through reactive components, they do not actually dissipate power. Figure 3-24 shows why.

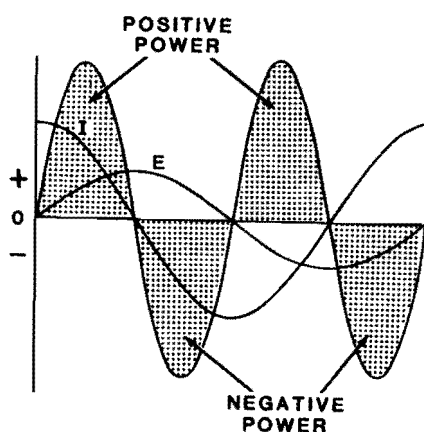


Figure 3-24 Power in a purely capacitive circuit.

In a purely capacitive circuit, current leads the applied voltage by 90 degrees. To compute the power in this circuit, multiply the instantaneous values of current and voltage and plot the resulting power curve. Unlike the resistive power curve in Figure 3-23, the power curve in a purely capacitive circuit is both positive and negative. What this power curve tells us is that during one half cycle of the applied

voltage, the capacitor appears to consume power. This is indicated by the positive part of the power curve. During the other half cycle, the power is negative. It is during this time that the capacitor actually acts as the supply and furnishes power to the source. When the capacitor charges, it consumes power. When it discharges, it gives power back to the circuit. Since the positive and negative power curves are equal and opposite, the total average effect is zero. This means that no power is dissipated in a purely capacitive circuit.

Figure 3-25A illustrates the power in an AC circuit containing both capacitance and resistance. Note that the current leads the voltage by some angle less than 90 degrees. With this condition, the positive power is greater than the negative power. The negative power is still the result of the ability of a capacitor to store a charge and then return it to the circuit. The curve indicates that the resistor is dissipating power in the form of heat. Since a purely capacitive circuit dissipates no power, a purely resistive circuit dissipates all of the power in the form of heat. In a circuit containing both resistance and reactance, power is dissipated only in the resistance.

It is possible to construct a vector diagram for the power that is used, or appears to be used in an RC circuit. Such a diagram is shown in Figure 3-25B. In this diagram, the true power measured in watts (W), is shown on the X axis.

The power that appears to be dissipated by the capacitive portion of the circuit measured in volt/amps reactive (VARs), is shown on the Y axis. The vector sum of the watts and volt/amps reactive is called apparent power. The unit of measure for apparent power is the volt/amp (VA).

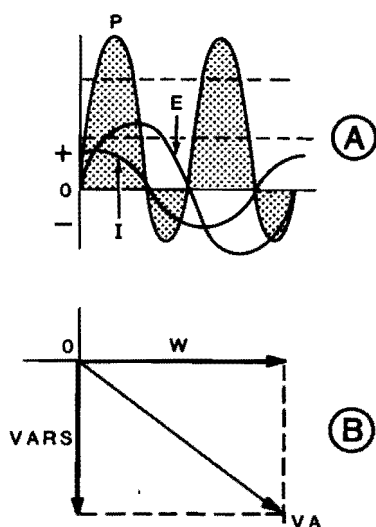


Figure 3-25 Power dissipated in a series RC circuit.

You can calculate all of the values used in the power triangle using the appropriate Ohm's Law power formulas. For example, the power dissipated by the resistive portion of the circuit is the product of the voltage dropped across the resistor and the current through the resistor. The apparent power is the product of

the applied voltage and circuit, or total, current. The volt/amps reactive is the product of the voltage dropped across the capacitive component and the circuit current.

Power Factor

When you use the formula $P = EI$ to compute the power in a circuit containing both resistance and capacitance, you obtain a value called apparent power. It is called apparent power because some of the power only **appears** to be dissipated. In a purely capacitive circuit, current does flow when an AC voltage is applied. However no real power is dissipated. In a purely reactive circuit, one containing only a capacitor, this apparent power is sometimes referred to as reactive power. In a circuit containing both resistance and capacitance, the apparent power includes both the true power dissipated in the circuit resistance, and the power that appears to be dissipated in the capacitor.

The ratio of the true power to the apparent power in an AC circuit is referred to as power factor (PF). This is expressed in the formula below:

$$PF = \frac{\text{true power}}{\text{apparent power}} \text{ or } \frac{\text{watts}}{\text{volt/amps}}$$

The power factor is an indication of the relative amounts of resistance and reactance in a circuit. In a purely resistive circuit, the true power and the apparent power are equal.

Therefore the power factor is equal to one. In a purely reactive circuit, such as one containing only a capacitor, the true power is zero. For circuits containing both resistance and reactance, the power factor is always some value between zero and one. The greater the power factor, the more resistive the circuit. The lower the power factor, the greater the circuit reactance.

More importantly, the power factor is an indication of the efficiency of a circuit. In any circuit, work is performed only by the current that flows through the resistive portion of the circuit. The reactive current performs no work.

Later in the course, during the discussion of tuned circuits, you will learn how the power factor of a circuit can be changed and the circuit made to operate more efficiently.

In a series RC circuit, you can also determine the power factor using the values of the resistance and the reactance in the circuit. In fact, the power factor is equal to the ratio of the resistance to the total impedance of the series RC circuit:

$$PF = \frac{R}{Z}$$

Power factor can also be determined when you know the applied voltage and the voltage dropped across the resistance in the circuit. In this case:

$$PF = \frac{E_R}{E_A}$$

Phase Shift

To compute the phase shift for an RC circuit, you have to use trigonometry. If you do not understand the fundamentals of trigonometry, refer to Appendix B at the end of this unit. Once you have reviewed this appendix, return to this point and continue your study.

In a capacitive AC circuit, the current leads the applied voltage. In a purely capacitive circuit, the current leads the voltage by 90 degrees. When a resistance is introduced into the circuit, the phase shift will be something less than 90 degrees. You can determine the exact amount of the phase shift in a circuit with basic trigonometry. Here's how.

As you know, for any AC circuit, it is possible to construct a voltage, impedance, and power vector diagram. Figure 3-26A is a series RC circuit. The impedance vector diagram is shown in Figure 3-26B, the voltage diagram in 3-26C, and the power diagram in 3-26D. As you can see, in each instance, the vectors are used to construct a triangle. Using the sine and cosine functions, it is possible to determine the phase shift in this circuit.

The sine of an angle is equal to the value of the opposite side divided by the hypotenuse. The sine of the impedance triangle equals:

$$\sin \theta = \frac{O}{H} = \frac{30 \text{ ohms}}{42.4 \text{ ohms}} = .707$$

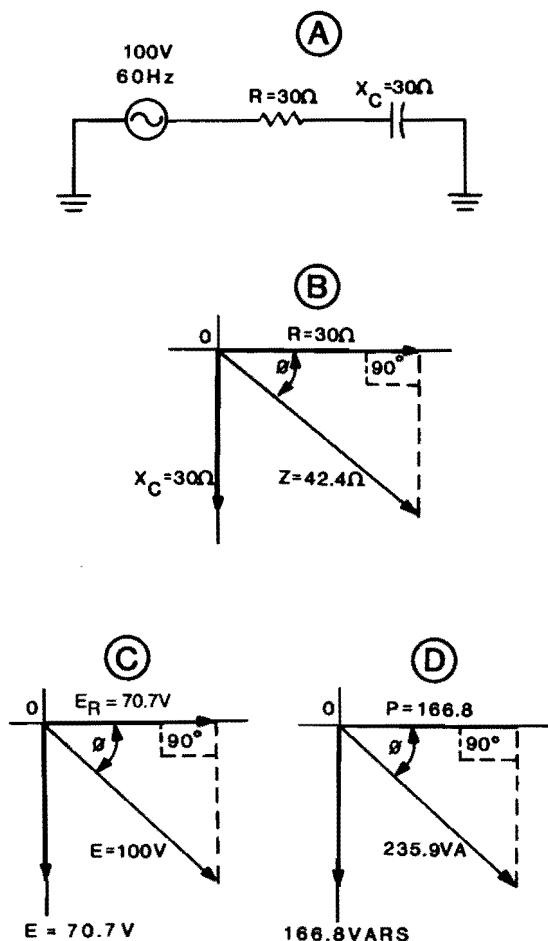


Figure 3-26 A typical parallel RC circuit.

Once you know the sine of the angle, use the table located in Appendix C of this unit. In the table .707 is equal to the sine of 45 degrees. Therefore, the phase shift is equal to 45 degrees.

You can also determine the phase shift by finding the cosine of the angle. This time, however, use the values from the power triangle. The cosine of the angle equals:

$$\cos \theta = \frac{A}{H} = \frac{166.8 \text{ W}}{235.9 \text{ VA}} = .707$$

Again, if you refer to the table in Appendix C, you find that the phase shift is 45 degrees.

Remember that .707 is the rms or effective value of a sine wave. It is also the point where the voltage and current waveforms intersect when the resistance and capacitive reactances are equal. The angle of 45 degrees and the numerical value of .707 are extremely important in electronics.

You may have noticed that, when you calculated the cosine of the angle, you divided the true power by the apparent power. Recall that true power divided by the apparent power is equal to the power factor of the circuit. Therefore:

$$\text{PF} = \frac{\text{True Power}}{\text{Apparent Power}} = \cos \theta$$

Another relationship that you should be aware of is that the sine starts at zero degrees and increases to maximum at 90 degrees. The cosine function is maximum at zero degrees and decreases to minimum at 90 degrees.

Trigonometry, Triangles, and Vector Diagrams

By using the various trigonometric relationships, it is possible to determine not only the phase shift of a circuit but also the length of any vector. This is true when the lengths of two of the vectors are known.

Look at Figure 3-26C. Let's assume that you know the applied voltage, 100 volts, and the voltage dropped across the resistance in the circuit, 70.7 volts. In order to determine the voltage drop across the circuit capacitor, you must first determine the phase shift. Since you know the resistive voltage and the applied voltage, use the cosine:

$$\cos \theta = \frac{A}{H} = \frac{E_R}{E} = \frac{70.7 \text{ V}}{100 \text{ V}} = .707$$

Now refer to Appendix C and find that the angle that has a cosine of .7075 is approximately 45 degrees. Once you know the angle, look up the sine of the angle. This, again, is .707. Now use the formula:

$$\sin \theta = \frac{O}{H}$$

or

$$.707 = \frac{E_C}{100 \text{ V}}$$

now transpose:

$$E_C = .707 \times 100 \text{ volts} = 70.7 \text{ volts}$$

At an angle of 45 degrees the voltage drop across the capacitive portion of the circuit is also approximately equal to 70.7 volts.

Parallel RC Circuits

Thus far, your study of RC circuits has been limited to series RC circuits. It is also possible to connect RC circuits in parallel configurations. An elementary parallel RC circuit is shown in Figure 3-27.

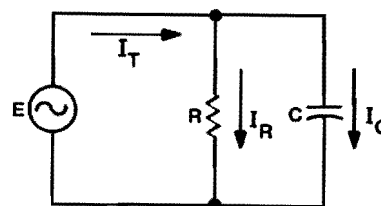


Figure 3-27 A typical parallel RC circuit.

Since voltage is constant across the branches of a parallel circuit it is necessary to vector the changing value (current).

As with the series RC circuit, Ohm's Law applies to all of the components within the circuit. Also, as with the series RC circuit, when you determine circuit unknowns, it is necessary to use vector addition. However, when you are drawing vector diagrams for parallel circuits, there is one major difference.

As you know, in a series circuit, current is used as a reference because it is the same at all points in the circuit. In a parallel RC circuit vector diagram you must use voltage as a reference. Remember, the voltage across all branches of a parallel circuit are equal. Let's look at a basic circuit and some vector diagrams to see exactly what differences there are.

Figure 3-28A shows an elementary RC parallel circuit. In this circuit, the voltage drop across both the resistor and the capacitor is 100 volts. Since the voltage drop, the capacitive reactance, the and resistance are known, it is possible to use Ohm's Law to determine the current through the components.

$$I_R = \frac{100 \text{ V}}{100 \text{ ohms}} = 1 \text{ A}$$

and:

$$I_C = \frac{100 \text{ V}}{50 \text{ ohms}} = 2 \text{ A}$$

$$I = \frac{100 \text{ V}}{50 \Omega} = 2 \text{ A}$$

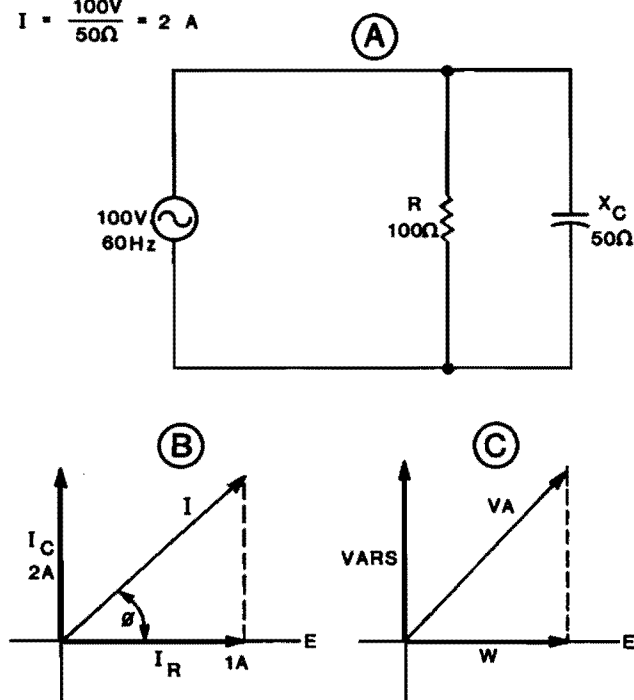


Figure 3-28 A parallel circuit with current and power vector plots.

The vector diagram, using these two values, is shown in Figure 3-28B. You can now find the circuit current by using either the Pythagorean Theorem or trigonometric functions. The Pythagorean Theorem method is shown here:

$$I = \sqrt{I_R^2 + I_C^2}$$

$$I = \sqrt{1^2 + 2^2}$$

$$I = \sqrt{5}$$

$$I = 2.23 \text{ A}$$

The trigonometric method is somewhat more roundabout, but it can also be used.

First, use the available information to form one of the basic trigonometric functions. For the

The next step is to find either the sine or the cosine of the 64 degree angle. Let's use the sine value, .899. Now put the known values into the proper trigonometric equation:

$$\sin \theta = (.899) = \frac{O}{H} = \frac{I_C}{I_T} = \frac{2 \text{ A}}{I_T}$$

now transpose:

$$I_T = \frac{2}{.899} \text{ or } 2.23 \text{ A}$$

You can also solve the triangle for the power vector diagram (Figure 3-28C) by using Ohm's Law, the Pythagorean Theorem, and the various trigonometric functions.

One more thing about parallel RC circuits. You may have noticed that an impedance vector diagram is not shown in Figure 3-28. This is because the impedance triangle for a parallel circuit is somewhat unique. You may recall

from your study of DC electronics that the resistance of a parallel circuit is always less than the smallest resistive branch in the circuit. The same general principle holds true for impedance in a parallel RC circuit. The impedance

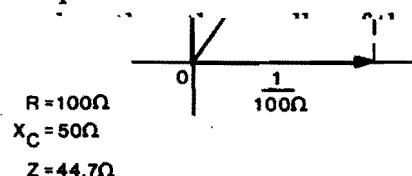


Figure 3-29 An impedance plot.

For this reason, when the impedance vector diagram is constructed, you must use the reciprocal of the resistance and capacitive reactance, and the resulting vector will be the reciprocal of the actual impedance.

Figure 3-29 illustrates this point. Notice, the total impedance is less than either the capacitive reactance or the resistance. If you wish to use either the Pythagorean Theorem or any of the trigonometric functions to solve for impedance, you must always use reciprocal values.

3-50 AC ELECTRONICS

Since reciprocal values are harder to work with than standard numerical values, it is best, when possible, to obtain impedance, resistance, or capacitive reactance by using Ohm's Law.

However, if only the capacitive reactance and resistance are available, you can use this derivation of the parallel resistance formula to calculate impedance:

$$Z = \frac{RX_c}{\sqrt{R^2 + X_c^2}}$$

As you have probably noticed, there are any number of ways to obtain the correct results when analyzing AC circuits. The key is to be extremely familiar with the trigonometric relationships as well as the Pythagorean Theorem. Be sure that you have mastered these formulas before proceeding with the remainder of this text.

Self-Test Review

61. In an AC circuit containing only capacitance, the current and applied voltage are out of phase by:

_____.

62. In a capacitive circuit current:

_____ voltage.

63. The phase angle in a purely capacitive circuit is:

_____ degrees.

64. To use the Pythagorean Theorem, the triangle must have a:

_____.

65. For current and voltage to be in phase the phase angle must be zero or:

_____ degrees.

66. The actual value of phase shift in a series RC circuit is a function of the:

_____ and _____.

67. Capacitive reactance is a function of capacitance and:

_____.

68. To find the value of the sine function you must know which sides?

_____ and _____.

69. The tangent of 45 degrees is equal to:

_____.

70. The sine and cosine functions equal the same value at an angle of:

_____ degrees.

71. The cosine is maximum when the sine is:

_____.

72. Calculate the phase shift of a circuit in which $R = 1,280$ ohms and $X_C = 1,000$ ohms.

_____ degrees

73. The sine of 30 degrees is equal to:

_____.

74. The cosine of 60 degrees is equal to:

_____.

75. The longest leg of a right triangle is its:

_____.

76. Impedance in a series circuit is plotted as which leg of a right triangle?

_____.

77. Resistance in a series circuit is plotted as which leg of a right triangle?

_____ side.

78. Reactance in a series circuit is plotted as which leg of a right triangle?

_____ side.

79. When plotting vector diagrams for parallel circuits:

_____ is vectored.

80. When reactance is divided by resistance, the resultant is the value of the:

_____ function.

81. In a parallel circuit, the length of the hypotenuse is equal to:

_____.

82. Apparent power is calculated using the formula:

$P =$ _____.

83. True power is calculated using the formula:

$P =$ _____.

84. True power divided by apparent power is equal to the:

_____.

85. PF is a measure of a circuits:

_____.

86. The power factor of a circuit has the same value as the:

_____ angle.

Applications of Capacitive Circuits

In this section you will learn some of the more important applications of capacitors in AC circuits. While capacitors are often used alone, usually they are combined with resistors or other components to form RC networks. Such networks have many practical applications. Some of the applications are as AC voltage dividers, filters, decouplers, phase shifters, and coupling networks. Each of these applications will be discussed in this text.

Capacitive Voltage Dividers

A capacitive voltage divider is a series capacitive circuit whose output voltage is a fraction of its input. Figure 3-30 shows a simple capacitive voltage divider made by connecting two capacitors, C_1 and C_2 in series. The input voltage is connected across both capacitors. The output voltage is taken only across capacitor C_2 . The current flowing in the series circuit produces a voltage drop across each capacitive reactance. The sum of the capacitive voltage drops is equal to the input voltage. This is shown in the expression below.

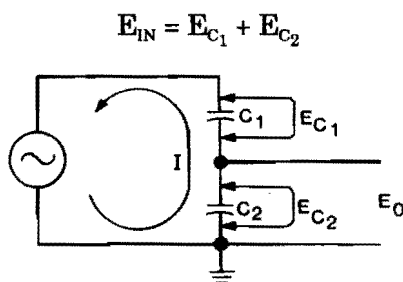


Figure 3-30 A capacitive voltage divider.

In this application, the output voltage is equal to the voltage across capacitor C_2 .

$$E_O = E_{C_2}$$

The amount of voltage developed across each capacitor depends on the current in the circuit and the capacitive reactance. According to Ohm's Law, the output voltage will be:

$$E_O = E_{C_2} \text{ or } IX_{C_2}$$

The voltage dropped across the capacitors in the circuit are in proportion to their capacitive reactances. The greater the capacitive reactance, the greater the voltage drop across that capacitor. Keep in mind that the reactance is a function of the size of the capacitor and the frequency of the applied voltage. Capacitive reactance is inversely proportional to both frequency and capacitance.

$$X_C = \frac{.159}{FC}$$

The output voltage can be expressed in terms of the input voltage and the capacitive reactances, as shown below:

$$E_O = \frac{X_{C_2}}{X_{C_1} + X_{C_2}} (E_{IN})$$

As you can see from this expression, the output voltage is equal to the input voltage multiplied by the ratio of the reactance of C_2 to the sum of the individual reactances. This ratio is referred to as the voltage divider ratio. It is the same ratio used to calculate voltage

division in series resistive circuits. The only difference is that capacitive reactance replaces resistance in the equation.

We can also express the output voltage in terms of the capacitor values rather than the reactances. The formula below gives this relationship:

$$E_o = \frac{C_1}{C_1 + C_2} (E_{in})$$

Note that the output voltage is directly proportional to the voltage division ratio which is the ratio of C_1 to the sum of C_1 and C_2 . When the ratio of capacitance is used it is important to remember that a capacitor's charge is inversely proportional to the capacitive value. This is illustrated by the equation:

$$Q = CE$$

where:

Q is the charge in coulombs.

C is the capacitance in farads.

E is the EMF in volts.

An interesting characteristic of a capacitive voltage divider is that the voltage division ratio is not affected by frequency. Even though the frequency causes the reactances to change, the reactances change together and the voltage division ratio remains constant. For example, as capacitive reactance decreases, the circuit current so that the product (IX_C) remains the same.

Another interesting characteristic of the purely capacitive voltage divider is that no phase shift occurs between the input and the output. The current in this circuit leads the applied voltage, but the voltage across the output capacitor is in phase with the input voltage. Changing the frequency has no effect on this characteristic.

Capacitive voltage dividers are often found in high frequency amplifier circuits. Certain types of oscillators use capacitive voltage dividers. The output voltage from a capacitive voltage divider can be made variable by making either C_1 , or C_2 a variable capacitor. By changing the ratio of capacitance, the output voltage can be adjusted.

RC Filters

A filter is a frequency discriminating circuit. Filters greatly attenuate some frequencies while allowing others to pass with virtually no opposition. Filters are frequency selective in that they pass some frequencies and attempt to block other frequencies.

Two of the most common types of filters used in electronic circuits are the low-pass filter and the hi-pass filter. A low-pass filter allows low frequency signals to pass from the input to the output with little or no opposition (attenuation). In low-pass filter circuits, high frequencies are greatly attenuated by shunting them to ground. A frequency known as the cut-off frequency, F_{co} is the general dividing line between those frequencies that are passed and those that are attenuated.

A high-pass filter is the opposite of a low pass filter. The high-pass filter permits frequencies above the cut-off frequency to pass. Frequencies below the cut-off point are greatly attenuated.

Simple RC networks can be used as low and high-pass filters. Such circuits are able to perform a frequency selective function because of the change in reactance with frequency.

Low-Pass Filter

The simplest form of a low-pass filter is shown in Figure 3-31A. It consists of a resistor and capacitor connected in series across an input voltage. The output voltage is taken across the capacitor. Assume that the input voltage has a fixed rms value, but that its frequency can be varied.

The best way to understand the operation of the low-pass filter is to look at the circuit as a voltage divider. The input voltage is applied across the resistor and capacitor in series. The output voltage is taken across the capacitor. The voltage division ratio depends upon the sizes of the resistance and the capacitive reactance. The value of the resistance remains constant, of course, but the value of the capacitive reactance changes as the input frequency changes.

At very low input frequencies, the capacitive reactance will be very high. If the reactance is

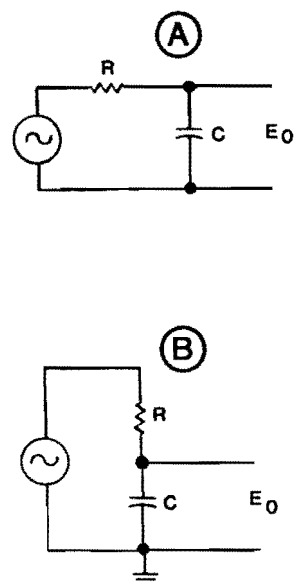


Figure 3-31 RC low-pass filter.

high compared to the resistance, most of the input voltage is dropped across the capacitor. As the input frequency increases, the capacitive reactance decreases. This means that less voltage will be dropped across the capacitor and more across the resistor as the frequency is increased.

For this reason, the output voltage begins to drop off as frequency increases. At very high frequencies, capacitive reactance is very low. When capacitive reactance is significantly lower than the resistor's value, very little voltage will appear at the output terminals (across the capacitor).

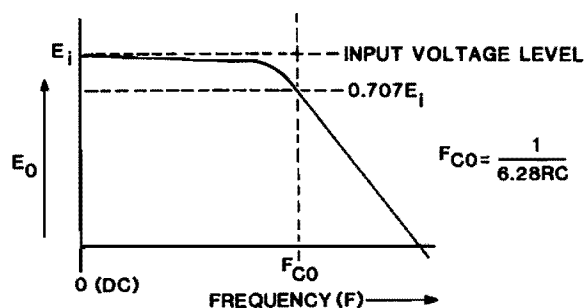


Figure 3-32 Frequency response of an RC low-pass filter.

The frequency response curve shown in Figure 3-32 illustrates this effect. This curve shows the amount of output voltage with respect to frequency. On the left-hand side of the curve, at very low frequencies, the output voltage is nearly equal to the input voltage. In fact, with a frequency of 0 Hz or DC, the capacitor offers maximum opposition, and the output voltage is equal to the input voltage. As the frequency increases, the capacitive reactance begins to decrease. The output voltage then begins to drop off. After the cut-off frequency is reached, the output voltage drops off at a constant rate. At the cut-off frequency, the output voltage is equal to approximately 70.7% of the input voltage or $E_o = .707 E_{in}$. The cut-off frequency is a function of the resistor and the capacitor values. This is expressed by the equation:

$$F_{co} = \frac{1}{2\pi RC} = \frac{1}{6.28 RC}$$

Or, solving for $1/6.28 =$

$$F_{co} = \frac{.159}{RC}$$

Where R is in ohms and C is in farads.

The formula can be modified by expressing C in microfarads:

$$F_{co} = \frac{159,000}{RC}$$

For example, the cut-off frequency of a circuit with a 10 k ohm resistor and .01 microfarad capacitor is:

$$F_{co} = \frac{159,000}{10,000(.01)} \text{ or } 1,590 \text{ Hz}$$

An important thing to note about an RC low-pass filter is that while the circuit is frequency selective, the selectivity is very gradual. The output is not sharply defined at the cut-off frequency. Higher frequencies are only attenuated, not cut out completely. In other words, the low-pass filter does pass frequencies higher than the cut-off frequency but they are more greatly attenuated than those frequencies below the cut off point. Despite this imperfection in RC low-pass filters, these circuits are still very useful. The cut-off point is defined as those frequencies that cause less than the effective voltage to be developed (coupled) to the output.

High-Pass Filter

A simple RC high-pass filter is shown in Figure 3-33A. Like the low-pass filter, it consists of a resistor and a capacitor connected in series to the input voltage. In the high-pass fil-

ter, however, the output voltage is taken across the resistor. In Figure 3-33B, the circuit is drawn as a voltage divider.

At very high input frequencies, the capacitive reactance is very low. When capacitive reactance is low compared to the resistance, little voltage is dropped across the capacitor. At high frequencies most of the input voltage is dropped across the resistor. As frequency decreases, capacitive reactance increases. More voltage is dropped across the capacitive reactance and less across the resistor. When frequency decreases, the output voltage also decreases. The decrease is gradual at first, but at the cut-off frequency, the attenuation becomes more pronounced and the output voltage drops at a constant rate with decreasing frequency.

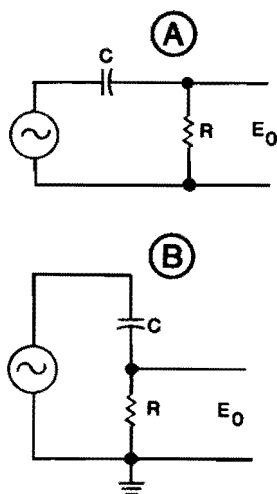


Figure 3-33 RC high-pass filter.

Figure 3-34 shows the frequency response curve of an RC high-pass filter. Note that at high frequencies the output voltage is nearly equal to the input voltage. As the frequency decreases, the output voltage begins to decrease. At the cut-off frequency, the output voltage is approximately 70.7% of the input voltage. Below the cut-off frequency, attenuation increases and the output voltage drops accordingly.

As in the low-pass filter, the cut-off frequency is a function of the resistor and capacitor values. The same expression used for computing the cut-off frequency of a low-pass filter applies to the high-pass filter.

$$F_{CO} = \frac{159,000}{RC}$$

Where:

R is in ohms.

C is in microfarads.

F_{CO} is in Hz.

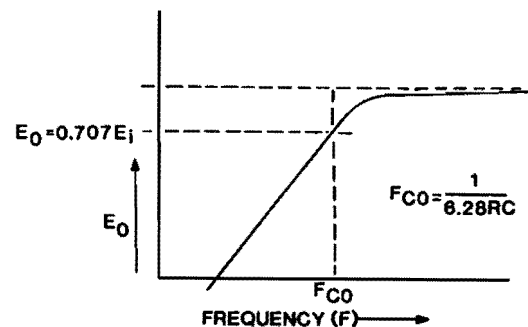


Figure 3-34 Frequency response of an RC high-pass filter.

Circuits Combining AC and DC

Many electronic circuits operate with a combination of both AC and DC voltages. To these circuits, the applied voltage appears to be a DC voltage connected in series with an AC voltage. The result is a DC level (reference) on which an AC signal is superimposed. In this case we say that the AC rides on the DC. The zero line of the sine wave signal coincides with the DC voltage level. RC networks are commonly used with such AC/DC source voltages.

Decoupling Network

Figure 3-35A shows one application of an RC circuit with an AC/DC source. The RC circuit is connected as a low-pass filter. The capacitor will charge to the value of the DC voltage as indicated by the polarity shown. The sine wave voltage will cause the charge on the capacitor to vary above and below the DC value by an amount equal to the peak value of the AC. Figure 3-35B shows the voltage across the capacitor. The combination voltage is often called pulsating DC. The composite voltage is still DC because it never goes negative. In this example, the frequency of the AC voltage is assumed to be lower than the cut-off frequency of the RC low-pass network. When the frequency of the AC input is higher than the cut-off frequency of the RC network, the output amplitude is greatly attenuated.

One of the more common applications for the low-pass RC network shown in Figure 3-35A is decoupling. Decoupling refers to the process of allowing a desired DC voltage to appear between given points, while at the same time eliminating or minimizing the AC at that point. In many electronic circuits, the DC voltage is used to operate the equipment. AC signals in the form of oscillations, noise, and transient spikes sometimes appear as though they are connected in series with the DC supply voltage. The RC low-pass filter is used to eliminate this unwanted AC. By making the cut-off frequency of the RC network low enough, most or all of the undesired AC signals are filtered out leaving, only the desired DC to develop across the capacitor.

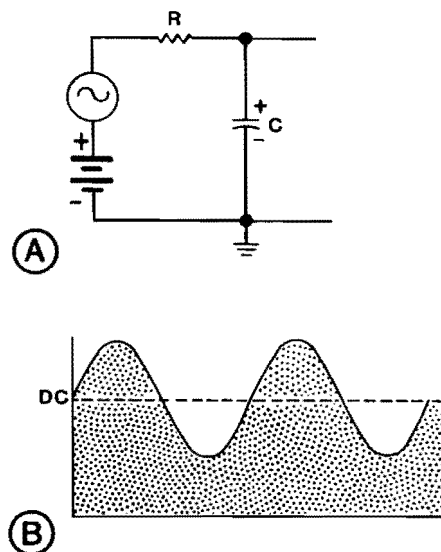


Figure 3-35 RC decoupling network and its output waveform.

Coupling Network

Another application of an RC circuit using AC/DC is shown in Figure 3-36. The source voltage is a combination of both AC and DC signals. This source is applied across a series RC network. However, in this application, the output is taken across the resistor. In other words, the RC network is used as a high-pass filter. The capacitor charges to the applied DC voltage. Once it charges, no further DC current flows in the circuit. Therefore, no DC appears across the output resistance. Instead, only the AC voltage appears as an output.

The sine wave source causes the capacitor to charge and discharge at the AC rate. This creates current flow in the resistor which appears at the output in the form of an AC voltage. In this application, only the AC signal appears at the output. The cut-off frequency of the RC network is adjusted so that it is low enough to permit the AC input to pass without noticeable attenuation.

This circuit is known as a coupling network. It is widely used to couple AC signals from one point to another while blocking DC voltages. The capacitor prevents DC currents from flowing to the output. Care should be taken in the selection of the resistor and capacitor values. Because of the high-pass filter effect, their values should be chosen so that the cut-off frequency permits passage of the desired AC signal with little or no attenuation.

For a circuit to be an effective coupling circuit, the RC time constant should be a minimum of 10 times the period of the waveform being coupled. Under this condition the capacitor will not charge and discharge at the rate that the AC signal is varying. Instead it will charge and couple the AC signal with a minimum of distortion. The longer the RC time constant, the closer the reproduction of the input AC signal in the output.

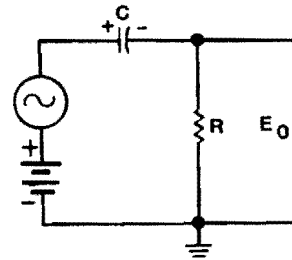


Figure 3-36 RC coupling network.

Phase Shift Networks

RC networks are also used for phase shifting. This is where the phase of an output sine wave signal from a circuit is changed with respect to its input sine wave.

Phase shifting may be used for a number of reasons. Sometimes it is used to correct an unwanted phase shift that has been introduced by another component. In other applications,

the phase shifting is done so that succeeding signals can be compared for magnitude and frequency. Since a capacitor causes the current in the circuit to lead the applied voltage, RC networks can be used to shift the phase of a signal.

Figure 3-37 shows the two most commonly used phase shifting configurations. In Figure 3-37A, the input signal is applied across the RC combination and the output is taken across the resistor. The current in the circuit leads the applied voltage by some phase angle between 0 and 90 degrees, depending upon resistor and capacitor values and the frequency of the applied signal.

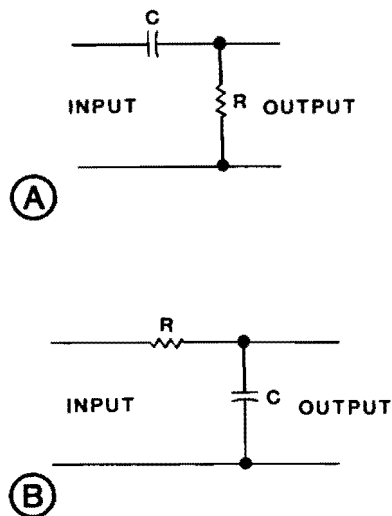


Figure 3-37 RC phase shifting networks.
A. Leading output.
B. Lagging output.

The voltage across the resistor is in phase with the current causing it. Because the current leads the applied voltage in the circuit, the voltage developed across the resistor, by the leading current, also leads the applied voltage. Therefore, the output voltage leads the input voltage. This relationship between input and output voltage is shown in Figure 3-38A.

In the phase shift circuit shown in Figure 3-37B, the output voltage is taken across the capacitor. Again, current leads the applied voltage in the circuit. In this case, however, because the output is taken across the capacitor, the phase shift is different. Now, the voltage at the output lags the input voltage by some phase angle between 0 and 90 degrees. This is shown in Figure 3-38B.

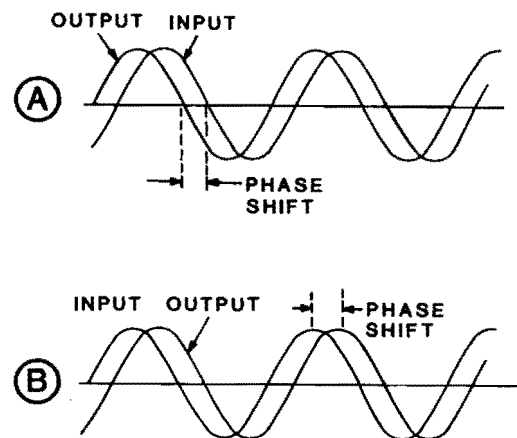


Figure 3-38 Phase shift in a series RC circuit.
A. Leading output.
B. Lagging output.

Notice, in both circuits shown in Figure 3-37, that the comparison is made between the input and output voltages. Circuit A produces a voltage lead and circuit B produces a voltage lag. However, in both circuits, because they are capacitive in nature, the current through the circuit leads the applied voltage.

These elementary RC networks are used when only small amounts of phase shift are required. When a phase shift of greater than 60 degrees is needed, other phase shifting techniques are usually used. The reason for this is that phase shifting networks also act as voltage dividers. As the phase shift across these networks approaches 90 degrees, the capacitor drops a progressively larger percentage of the applied voltage. In addition, the impedance of the circuit itself becomes a problem.

One way to get a greater phase shift is to cascade the simple RC network shown in Figure 3-37. The output of one network can be connected to the input of another network. This creates a total phase shift that is equal to the sum of the individual phase shifts. For example, if three 45 degree phase shift networks are cascaded as shown in Figure 3-39, the total phase shift would be 3×45 degrees or 135 degrees. In this case, the output voltage would lead the input voltage by 135 degrees.

To achieve a lagging phase shift, greater than is obtainable with a single RC network, the circuit of Figure 3-39B can be used. Here two networks are cascaded. For example, if each

network provided a phase shift of 45 degrees, the output would lag the input by a total of 90 degrees.

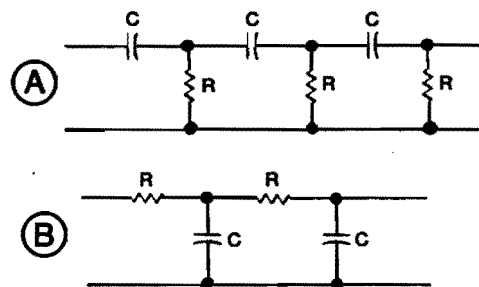


Figure 3-39 Cascaded RC phase shift networks.

Cascaded RC networks can provide any degree of phase shift that you desire. Keep in mind, that each RC section acts as a voltage divider. This means that the output voltage will be much lower than the input voltage. Where such networks are used, amplifiers are generally required to offset the attenuation and bring the output voltage back to a usable level.

Finally, it is important to note that the phase shift produced by an RC network is a function of the resistor and capacitor values. This phase shift is valid for only a single frequency. If an RC network is designed to produce a desired phase shift for one frequency, the amount of phase shift produced by that network at another frequency will be different. The reason for this is simple. If the frequency changes, the capacitive reactance also changes. Changing the reactance changes the phase angle.

Self-Test Review

87. A capacitive voltage divider uses two or more capacitors in:

_____.

88. The output voltage is proportional to the capacitor's:

_____.

89. A 10 volt source is connected across two capacitors that have values of 2 microfarads and 3 microfarads. The 3 microfarad capacitor will develop:

_____ volts.

90. A series RC circuit that passes low frequencies but attenuates high frequencies is called a:

_____ - _____ filter.

91. The input signal is applied across the resistor and capacitor and the output is taken across the capacitor. This is an example of a:

_____ - _____ filter.

92. As the input frequency increases, X_C :

_____ increases/decreases

93. The frequency below which all signals pass with little or no attenuation is called the:

_____.

94. The cut-off frequency (F_{co}) is defined as the frequency at which the output amplitude is equal to what percentage of the input?

_____ % .

95. The formula for cut-off frequency is:

_____.

96. When $R = 15 \text{ k ohms}$ and $C = .05 \text{ microfarad}$, F_{co} is equal to:

_____ Hz.

97. A high-pass filter is an RC circuit where the output voltage is taken across the:

_____.

98. A circuit that passes the AC signal but blocks DC is defined as a:

_____ circuit.

99. When both AC and DC signal sources are fed to an RC series circuit, the AC signal:

_____ on the DC signal.

100. A single RC network is capable of a phase shift up to approximately:

_____ degrees.

101. When a phase shift of more than 90 degrees is required, RC networks can be:

_____.

Desk-Top Experiment 3

Analyzing RC Circuits

Introduction

This experiment provides practice in analyzing RC circuits. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

It is again recommended, that your calculations be done on scratch paper. Once you are satisfied with your calculations, they can be recorded in the spaces provided in this experiment.

Objectives

1. To calculate the parameters of RC circuits.
2. To plot the relationship between voltage, current, and impedance in RC circuits.
3. To plot DC charge curves for an RC circuit.

Procedure

On a separate sheet of paper, draw the circuit shown below. The circuit shown is a series RC circuit. The input sine wave has a measured

value of 100 volts, at a frequency of 1 kHz. Round off your calculations to two decimal places. There are several procedures for solving this problem.

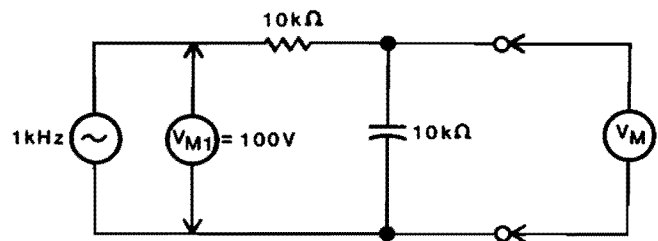


Figure 3-40 Desk-Top Experiment 3.

1. Determine the circuit's RC time constant.
time constant = _____.
2. Calculate the total impedance of the circuit.

$$Z_T = \underline{\hspace{2cm}}$$

3. Calculate the total current flowing in the circuit.

$$I_T = \underline{\hspace{2cm}}$$

In a capacitive circuit, current leads voltage. The voltage drops in a circuit are proportional to the individual component's impedance.

Power dissipated is true power. The power dissipated in the circuit is the power dissipated by the circuit's resistive component.

8. Determine the circuit's RC time constant for the parallel circuit shown.

time constant = _____.

9. Calculate the total impedance of the circuit.

$Z_T =$ _____.

10. Calculate the total current flowing in the circuit.

$I_T =$ _____.

11. Draw a vector diagram, illustrating the relationship of current in the components.

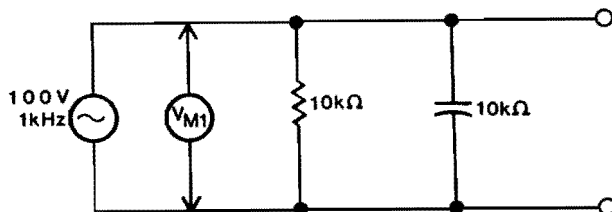


Figure 3-41 Desk-Top Experiment 3.

12. Draw the output vector, in the space provided, to show the relationship of voltage and current.

13. Calculate apparent power dissipated in the circuit.

$$P_A = \underline{\hspace{2cm}}.$$

14. Determine the power dissipated by the resistor in the circuit.

$$P_{R_1} = \underline{\hspace{2cm}}.$$

15. What is the minimum power required from the supply?

$$P_{\text{SOURCE}} = \underline{\hspace{2cm}}.$$

Discussion

You must calculate the value of the capacitor before you can find the RC time constant of this circuit.

Since voltage is constant in a parallel circuit, you should have vectored current, to find I_T . Then, I_T is divided into the source voltage to determine Z_T .

In a capacitive circuit, current leads voltage by an angle between zero and 90 degrees.

Discussion

Apparent power is $I \times E$. Power dissipated is I^2R .

Since reactive components don't dissipate power, the source must supply only the power dissipated by the resistive component.

16. What is the period of the waveform?

_____.

17. Time of the positive alternation is:

_____.

18. Draw the vector that illustrates the phase angle between the voltage and current associated with this parallel circuit.

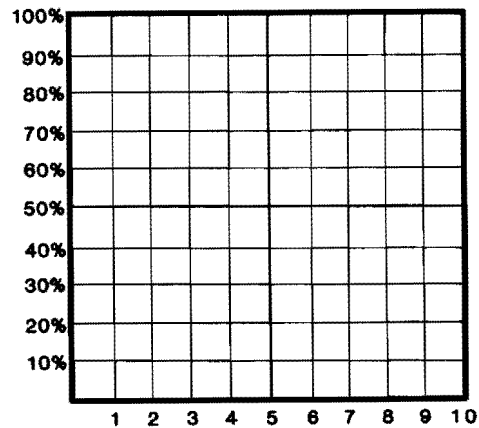


Figure 3-42 Plot the charging of the capacitor.

20. Again, assume the source voltage is changed to 100 volts DC. Plot the capacitor's charge current in Figure 3-43 against the capacitor's charge time for the parallel circuit referred to in Step 8.

Discussion

$T = 1/F$. Current always leads voltage in a capacitive circuit.

A sine wave is symmetrical, thus, the time of each alternation is equal to $T/2$.

19. Assume that the source voltage is changed to 100 volts DC. Plot the capacitor's voltage charge in Figure 3-42 against the capacitor's charge time, for the series circuit referred to in Step 1.

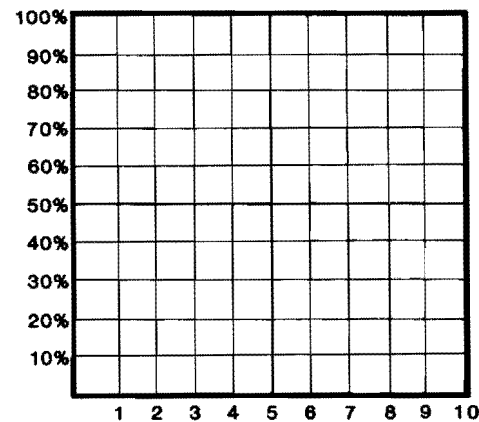


Figure 3-43 Plot the charging of the capacitor.

Discussion

At $t = 0$ (initial turn on) the charge on the capacitor is zero.

In one RC time constant, the capacitor charges to 63.2% of the 100 volt DC source.

During each succeeding RC time constant, the capacitor will charge to 63.2% of the difference in potential between the source voltage and the capacitor's charge.

In 5 RC time constants, the charge on the capacitor is approximately equal to the source voltage. The series circuit current is continually decreasing as the capacitor's charge increases. When the capacitor is fully charged (after 5 RC time constants), the circuit current is effectively zero. When the current decreases to zero, no voltage is dropped across the resistor. At time zero, current is maximum and all the voltage is dropped across the resistor.

In Step 20, current in the capacitive branch is maximum at $t = 0$, and decreases by 63.2% each RC time constant. After 5 RC time constants, the current flowing in the capacitive branch is effectively zero. The current is zero because the capacitor is fully charged. Since this is a parallel circuit, the source voltage is still developed across the resistor.

Summary

When analyzing a series circuit, you should vector voltage or impedance. Voltage is proportional to impedance because current is constant.

When analyzing a parallel circuit, you should vector current because voltage is constant.

You should have realized, that the source voltage is a measured quantity. Therefore, the 100 volt source is an effective or rms value.

In a capacitive circuit (either series or parallel), current leads voltage. In an RC circuit, the phase angle will be between 0 and 90 degrees.

The time constant is equal to $R \times C$, in both series and parallel circuits.

You should have noted that Z_T in a series circuit, is greater than either R or X_C , but less than $R + X_C$. In a parallel circuit, Z_T is always less than either R or X_C .

The power dissipated in a circuit is the power dissipated by the resistive components.

$$P_{\text{DISP.}} = I^2 R$$

Unit Summary

The capacitor is considered an AC component. It effectively passes AC signals and blocks DC signals.

The unit of measure for the capacitor is the farad. However, microfarads (10^{-6} farad) and picofarads (10^{-12}) are the more common values found in electrical circuits. The capacitor has a reactance (X_C) that is rated in ohms. The capacitive reactance is considered an impedance value.

Capacitors connected in series have a combined value that is less than the smallest capacitor in the series combination. Capacitors connected in parallel have a combined value that is the sum of all the capacitors combined.

The capacitive value is directly proportional to the area of its plates, and inversely proportional to the spacing between its plates.

Capacitive reactance and resistance are combined by vector addition to calculate total impedance in an RC series circuit.

Capacitive reactances and inductive reactances are 180 degrees out of phase.

Capacitors are classified by their type of dielectric. The dielectric is the material between the plates. Some of the more common types of dielectrics are air, paper, mica, glass and ceramic.

Capacitors can be either polarized or nonpolarized. When using polarized capacitors, proper polarity must be observed. Electrolytic and tantalum capacitors are examples of polarized capacitors and they have the polarity (either + or -) stamped on the capacitor's body. When proper polarity is not observed the polarized capacitor can explode and cause severe damage to your circuit, equipment, or even cause bodily harm.

In one RC time constant, the capacitor charges to approximately 63.2% of the applied voltage.

The capacitor is considered to be fully charged after 5 time constants.

The charge (Q) on a capacitor is equal to the voltage applied times the capacitive value.

The capacitor also has a DC working voltage. This is the maximum safe voltage that the capacitor can be charged to.

Capacitive circuit values can be calculated using trigonometric functions (sin, cos, and tan) or by using the Pythagorean Theorem ($Z^2 = R^2 + X_C^2$). Z is the hypotenuse of the right

triangle, R is the adjacent side of the right triangle, and the reactive component (X_C) is the opposite side of the triangle.

Capacitors are used as voltage dividers, to block DC voltages, and for coupling and decoupling (filtering). They are also used to shift the phase of an AC signal.

Appendices

APPENDIX A: SOLVING RIGHT TRIANGLES

The following is a lesson describing a method of solving right triangles. Right triangles are widely used in electronics to represent electrical quantities and solve problems involving them. This lesson explains right triangles and gives you a simple method of dealing with them.

The material in this lesson is presented to you a step at a time. The information to be learned is divided into small pieces called frames. In each frame we present a key fact or idea. You are then immediately tested on this fact. You respond by filling in a blank to complete a statement. The correct answer is given in parentheses at the beginning of the next frame. As you read each frame, keep the frames below covered with a piece of paper. Begin now with frame 1.

1. A triangle is a three-sided geometric figure. See Figure A1. The three sides are labeled A, B and C and form three angles which we call a, b and c. The sum of the angles in any triangle is 180° or $a + b + c = 180^\circ$.

All triangles have _____ sides and _____ angles.

2. (three, three) The sum of the three angles is always _____ degrees.

3. (180) One of the most commonly encountered triangles is the right triangle. A right triangle is one that contains one 90° angle. Figure A2 shows a typical right triangle.

A triangle with one 90° angle is called a _____ triangle.

4. (right) In Figure A2, the right angle is identified by the letter _____.

5. (c) If the right angle c has 90° , the sum of the other two angles (a + b) must be _____ degrees.

6. (90) In order for the sum of angles a and b to be equal to 90° , each must be less than 90° . Any angle less than 90° is called an acute angle.

An angle of 57° is an _____ angle.

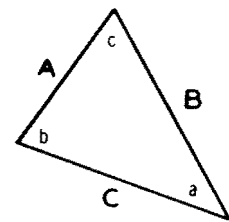


Figure A1

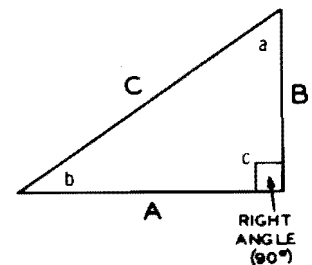


Figure A2

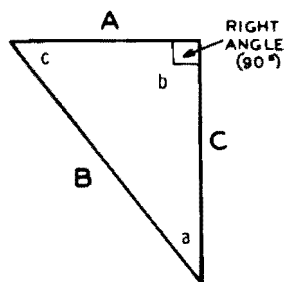


Figure A3

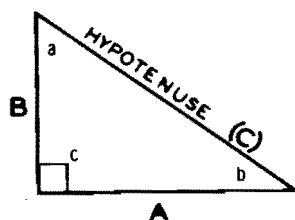


Figure A4

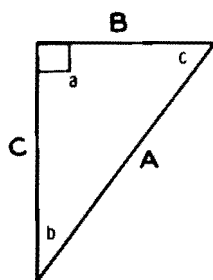


Figure A5

7. (acute) In a right triangle there are _____ (how many) acute angles?
8. (two) Angle c in Figure A2 is a right angle while angles a and b are acute angles.

In Figure A2, angle a = 35° . Angle b = _____ degrees.
9. (55) If c = 90° then a + b must equal 90° . Therefore, b = $(90 - a)$ or $90^\circ - 35^\circ = 55^\circ$. Remember that all triangles have a total of 180° or a + b + c = 180° .

The sides forming the right angle in Figure A2 are _____ and _____.
10. (A, B) Sides A and B meet at a right angle. We say that side A is perpendicular to side B.

In the right triangle of Figure A3, which two sides are perpendicular? _____.
11. (A and C) Sides A and C form a 90° angle so they are perpendicular. Note that the right angle is always identified by the small square in the corner formed by the perpendicular sides.

The right angle in Figure A3 is designated by the letter _____.
12. (b) The side of the triangle directly opposite the right angle is called the hypotenuse. See Figure A4. The hypotenuse is side C.

Study Figure A5. Which side is the hypotenuse? _____.
13. (A) The hypotenuse is always the side opposite the right angle. The lengths of the sides of a right triangle are related by a unique relationship. This relationship is expressed by the formula below:
$$C = \sqrt{A^2 + B^2}$$

This formula says that the length of the hypotenuse (side C) is equal to the square root of the sum of the squares of the other two sides.

Sketch a right triangle that illustrates this relationship. Identify all sides and angles. Label the hypotenuse.

14. (see Figure A6) With this formula, you can calculate the length of the hypotenuse if you know the lengths of the other two sides. For example, if side A = 3 inches and side B = 4 inches, what is the length of the hypotenuse? The solution is given below:

$$C = \sqrt{A^2 + B^2}$$

$$C = \sqrt{3^2 + 4^2}$$

$$C = \sqrt{9 + 16}$$

$$C = \sqrt{25}$$

$$C = 5$$

NOTE: The expression A^2 means to square A, or multiply A by itself. $A^2 = A \times A$. If $A = 3$ then $A^2 = 3 \times 3 = 9$. The square root of a number is another number that when multiplied by itself gives the original number. It is the opposite of finding the square of a number. For example, the square root of 9 is $\sqrt{9} = 3$ since $3 \times 3 = 9$. You can find the square root of a number by the long-hand process you learned in school. But the easiest way to find the square root is to use an electronic calculator with the square root function ($\sqrt{X}$).

What is the length of the hypotenuse of a right triangle with sides of A = 6 and B = 9? $C = \underline{\hspace{2cm}}$.

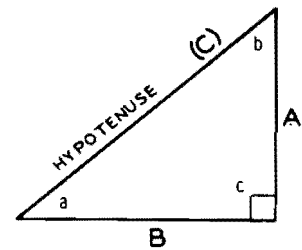


Figure A6

15. (10.8) The solution to the problem is as given below:

$$C = \sqrt{A^2 + B^2}$$

$$C = \sqrt{6^2 + 9^2}$$

$$C = \sqrt{36 + 81}$$

$$C = \sqrt{117}$$

$$C = 10.8$$

By using algebra, the formula can be rearranged so that the length of a side can be found if the length of the hypotenuse and the length of the other side are known. The formulas given below are used for this purpose.

$$A = \sqrt{C^2 - B^2}$$

$$B = \sqrt{C^2 - A^2}$$

The hypotenuse is designated by the letter $\underline{\hspace{2cm}}$.

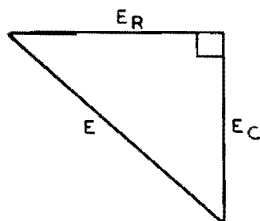
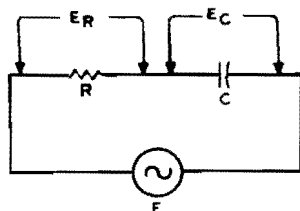


Figure A7

16. (C) The hypotenuse is usually called C although there are no set rules about this. For all of the examples given here, Figure A6 applies. The hypotenuse is called C.

If the hypotenuse is 14 and side A = 6, what is side B?

B = _____.

17. (12 .65) See the solution below:

$$B = \sqrt{C^2 - A^2}$$

$$B = \sqrt{14^2 - 6^2}$$

$$B = \sqrt{196 - 36}$$

$$B = \sqrt{160}$$

$$B = 12.65$$

Right triangles are often used to solve electronic problems. They are particularly useful in solving problems involving circuits containing inductance or capacitance. Inductors or capacitors introduce a 90° phase shift into the circuit. This 90° shift is represented by the right angle. The lengths of the sides of a right angle can represent the voltages in a simple series RC circuit.

In Figure A7, which voltage is represented by the hypotenuse?

_____.

18. (E, applied voltage) Instead of using A, B and C for the sides, we use E_R , E_C and E .

Write the formula for finding the applied voltage if the resistor and capacitor voltages are known. _____.

19. ($E = \sqrt{E_R^2 + E_C^2}$) The formula for the applied voltage is the same as the formula for finding the hypotenuse. The length of the side of a right triangle can also be used to show the relationship between the resistance, capacitive reactance and the impedance of a series RC circuit. In this circuit, the lengths of the sides are expressed in _____.

20. (ohms) Remember that the unit of measurement for resistance, reactance and impedance is ohms.

Figure A8 shows a right triangle relating these quantities.

Write the formula for computing the impedance. _____.

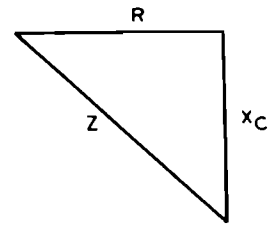


Figure A8

21. ($Z = \sqrt{R^2 + X_c^2}$) In this expression, the hypotenuse of the right triangle is _____.

22. (Z or impedance) If the resistance is 40 ohms and the capacitive reactance is 60 ohms, the impedance is _____ ohms.

23. (72.1) The solution is as shown below:

$$Z = \sqrt{R^2 + X_c^2}$$

$$Z = \sqrt{40^2 + 60^2}$$

$$Z = \sqrt{1,600 + 3,600}$$

$$Z = \sqrt{5,200}$$

$$Z = 72.1 \text{ ohms}$$

What is the formula for finding the reactance if the resistance and impedance are known? $X_c =$ _____.

24. ($X_c = \sqrt{Z^2 - R^2}$) The impedance Z (the hypotenuse) and the resistance R (one side) are known. To find the reactance X_c (the other side) the formula above is used.

As you can see, the basic right triangle formula can be adapted to any application involving the electrical quantities in an RC circuit. Just remember that the formulas apply only to right triangles.

APPENDIX B: INTRODUCTION TO TRIGONOMETRY

The purpose of this lesson is to give you the basic concepts and skills that will permit you to use trigonometry in the solution of electronic circuit problems.

Read each of the numbered frames below in sequence. Answer the question in each frame by filling in the blank before going on to the next frame. Keep the frames below the one you are reading covered with a piece of paper to avoid the temptation to look at the answer. Start now with frame 1.

NOTE: If you have not read Appendix A, please do so before beginning this lesson.

1. Trigonometry (often shortened to trig) is the study of triangles. It provides a system of dealing with triangles on a mathematical basis. More specifically, trigonometry gives us methods and procedures for calculating the lengths of the sides and the angles of a triangle. The sizes of the angles and the sides are related in a very unique way. The study of triangles is called _____.

2. (trigonometry) While trig provides techniques for solving any type of triangle, our discussion here will be limited to the use of trig as it applies to right triangles.

A right triangle is a three-sided geometric figure that has one _____ angle.

3. (right) A right angle, as you recall, has _____ degrees.

4. (90) With trigonometry you can quickly calculate the sides and angles of a right triangle. If you know the length of one side and the size of one angle (other than the right angle), you can readily determine the sizes of all other sides and angles.

There are six basic trigonometry functions. These are ratios that express the relationship between one of the two acute angles in a right triangle and two of the sides. The size of the angle is a direct function of the lengths of the related sides.

In the same way, the lengths of any two sides are a direct function of the size of the related _____.

5. (angle) Refer to Figure A9. We will use this right triangle to show the basic trig functions. Note that we have selected one of the acute angles to use in expressing the functions. We call this angle θ (the Greek letter theta). The sides are labeled with reference to this angle. The side directly across from θ is called the opposite side (O). The side next to θ is called the adjacent side (A).

Of course, the side opposite the right angle is always called the _____.

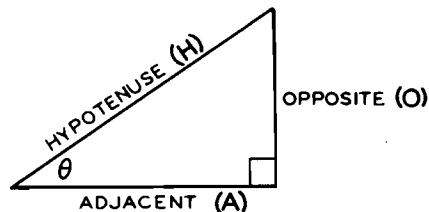


Figure A9

6. (hypotenuse) The six basic trig functions of the angle θ in Figure A9 are given below:

$$\text{sine } \theta = \frac{\text{opposite}}{\text{hypotenuse}} \text{ or } \frac{O}{H}$$

$$\text{cosine } \theta = \frac{\text{adjacent}}{\text{hypotenuse}} \text{ or } \frac{A}{H}$$

$$\text{tangent } \theta = \frac{\text{opposite}}{\text{adjacent}} \text{ or } \frac{O}{A}$$

$$\text{secant } \theta = \frac{\text{hypotenuse}}{\text{opposite}} \text{ or } \frac{H}{O}$$

$$\text{cosecant } \theta = \frac{\text{hypotenuse}}{\text{adjacent}} \text{ or } \frac{H}{A}$$

$$\text{cotangent } \theta = \frac{\text{adjacent}}{\text{opposite}} \text{ or } \frac{A}{O}$$

Of these six, only the first three are widely used. We will discuss only these three functions in this lesson.

Consider the sine function above. This expression tells us that the numerical value of $\sin \theta$ is the ratio of the _____ side and the _____.

7. (opposite, hypotenuse) The ratio of the length of the opposite side to the length of the hypotenuse is the numerical value that indicates the size of θ . For example, if the opposite is 3 and the hypotenuse is 6, then:

$$\sin \theta = \frac{3}{6} = .5$$

A value of .5 corresponds to an angle of 30° or:

$$\sin 30^\circ = .5$$

Regardless of the actual lengths of the sides of the triangle, if the ratio of the opposite to hypotenuse is .5, the angle is 30° .

If $H = 20$ and $O = 10$, the sine is _____.

8. (.5) $\sin \theta = \frac{O}{H} = \frac{10}{20} = .5$

Mathematicians have computed all of the ratios of the various sides and determined the corresponding angles. All of this information has been put into a table for convenient reference. See Appendix C. If you want to find the sine of 30° you would find 30° in the Degrees column. Then you would locate the number to the right of 30° in the Sine column.

What is the sine of 42° ? (Use Appendix C.) Sine $42^\circ =$ _____.

9. (.669) This means that the ratio of the opposite side to the hypotenuse is .669

$$\sin 42^\circ = \frac{O}{H} = .669$$

The tables in Appendix C can also be used to find the cosine or tangent of an angle. To do this, you first locate the angle in the Degrees column. Then you locate the desired numerical ratio in either the Cosine or Tangent columns.

The cosine of 30° is _____.

10. (.866) What is the tangent of 9° ? Tan $9^\circ =$ _____.

11. (.158) Trig tables are easy to use. First find the angle in the Degrees column. Then find the sine, cosine or tangent of that angle to the right in the appropriate column.

The tangent is the ratio of the _____ to _____ sides.

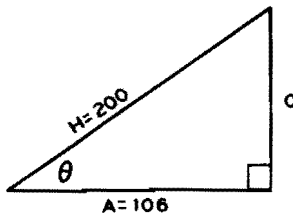


Figure A10

12. (opposite, adjacent) $\tan \theta = \frac{O}{A}$

The cosine of the angle θ is the ratio of the adjacent side to the hypotenuse.

Refer to Figure A10. The cosine of θ is _____.

13. (.53) The cosine is the ratio of the adjacent to the hypotenuse or:

$$\cos \theta = \frac{A}{H} = \frac{106}{200} = .53$$

The angle corresponding to a Cosine of .53 (from Appendix C) is _____.

14. (58°) If $O = 77$ and $A = 77$, then $\tan \theta =$ _____.

15. (1) $\tan \theta = \frac{O}{A} = \frac{77}{77} = 1$

What angle does this correspond to? $\theta =$ _____.

16. (45°) In Appendix C you look up 1 in the Tangent column. Then you locate the corresponding angle in the Degrees column.

When the opposite and adjacent sides are equal, the tangent is always 1 and this corresponds to an angle of 45°.

In a right triangle, angle $\theta = 45^\circ$. The adjacent side is 14. The opposite side is _____.

17. (14) By using algebra to rearrange the trig formulas, you can compute the length of any side if you know the angle and one other side. This is illustrated below with the sine:

$$\begin{aligned}\sin \theta &= \frac{O}{H} \\ O &= H \sin \theta \\ H &= \frac{O}{\sin \theta}\end{aligned}$$

For example, if the hypotenuse is 150 and $\theta = 30^\circ$, the opposite side is:

$$\begin{aligned}O &= H \sin \theta = 150 \sin 30^\circ \\ O &= 150 (.5) = 75\end{aligned}$$

If $H = 90$ and $\theta = 60^\circ$, $O =$ _____.

18. (78) $O = H \sin \theta = 90 \sin 60^\circ = 90 (.866) = 77.94$ or approximately 78. To solve this problem, you look up the sine of 60° in the tables, then multiply it by the length of the hypotenuse.

Knowing the opposite side and the angle you can compute the hypotenuse:

$$H = \frac{O}{\sin \theta}$$

The opposite side is 15 and the angle is 55° . The hypotenuse is _____.

19. (18.3) You look up the sine of 55° in the table then divide it into the length of the opposite side.

$$H = \frac{O}{\sin \theta} = \frac{15}{\sin 55^\circ} = \frac{15}{.819} = 18.3$$

The cosine function can also be rearranged to solve for any side.

$$\begin{aligned}\cos \theta &= \frac{A}{H} \\ A &= H \cos \theta \\ H &= \frac{A}{\cos \theta}\end{aligned}$$

If you know the angle and the length of the hypotenuse, you would use which formula to compute the adjacent side? _____.

20. ($A = H \cos \theta$) If $H = 70$ and $\theta = 20^\circ$, $A =$ _____.

21. (65.8) $A = H \cos \theta = 70 \cos 20^\circ = 70 (.94) = 65.8$. Knowing the adjacent side and the angle, you can find the hypotenuse.

$$H = \frac{A}{\cos \theta}$$

If $A = 25$ and $\theta = 68^\circ$, $H =$ _____.

22. (66.7) $H = \frac{A}{\cos \theta} = \frac{25}{\cos 68^\circ} = \frac{25}{.375} = 66.7$

Here are the formulas for computing the opposite and adjacent sides if the tangent of the angle is known:

$$\begin{aligned}\tan \theta &= \frac{O}{A} \\ O &= A \tan \theta \\ A &= \frac{O}{\tan \theta}\end{aligned}$$

If the opposite side and angle are known, you would use which formula to compute the length of the adjacent side? _____.

23. $\left(a = \frac{O}{\tan(\theta)}\right)$ If $O = 17$ and $\theta = 36^\circ$ $A =$ _____.

24. (23.4) $A = \frac{O}{\tan \theta} = \frac{17}{\tan 36^\circ} = \frac{17}{.727} = 23.4$

To compute the opposite side you use the expression $O = A \tan \theta$ if the _____ side and _____ are known.

25. (adjacent, angle) $O = A \tan \theta$. If $A = 40$ and $\theta = 45^\circ$, $O =$ _____.

26. (40) If $\theta = 45^\circ$ then $A = O$. What is the opposite side if the adjacent side is 115 and $\theta = 80^\circ$? $O =$ _____.

27. (652) $O = A \tan \theta = 115 \tan 80^\circ = 115 (5.671) = 652$.

Right triangles are widely used in electronics to solve circuit problems. The lengths of the sides of the triangle represent voltages, currents or impedances. The angle represents the circuit phase shift.

Refer to Figure A11. This triangle represents an RC circuit. The sides of the triangle represent circuit _____.

28. (voltages) The hypotenuse represents the applied voltage E . The adjacent side represents the voltage across the resistor E_R . The voltage across the capacitor is represented by the _____ side.

29. (opposite) The phase angle of the circuit represented by the triangle in Figure A11 is _____.

30. (39°) The adjacent side and the hypotenuse are given in Figure A11. Therefore you use the $\cos$.

$$\begin{aligned}\cos \theta &= \frac{A}{H} = \frac{7}{9} \\ \cos \theta &= .777 \\ \theta &= 39^\circ\end{aligned}$$

Compute the capacitor voltage in Figure A11.

$E_C =$ _____ volts.

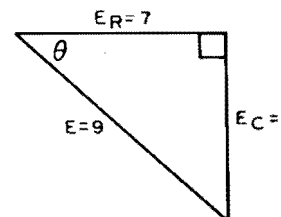


Figure A11

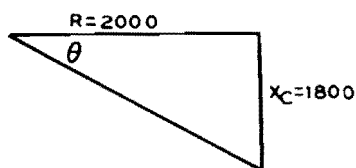


Figure A12

31. (5.66) You could use the sine function since you want to compute the opposite side. The adjacent side and hypotenuse are given in Figure A11 and θ was computed in the previous frame.

$$O = H \sin \theta$$

$$O = 9 \sin 39^\circ$$

$$O = 9(.629) = 5.66 \text{ volts}$$

What other trig function could you use to compute the opposite side? _____.

32. (tangent) $\tan \theta = \frac{O}{A}$

You know the angle and the adjacent side, therefore:

$$O = A \tan \theta$$

$$O = 7 \tan 39^\circ$$

$$O = 7(.81) = 5.67 \text{ volts}$$

Refer to Figure A12. The hypotenuse represents what quantity? _____.

33. (impedance or Z) What is the phase angle of the circuit represented by this triangle? $\theta =$ _____.

34. (42°)

$$\tan \theta = \frac{O}{A} = \frac{1,800}{2,000} = .9$$

The opposite side (capacitive reactance) and the adjacent side (resistance) are known. Their ratio is the tangent. And the corresponding angle, from Appendix C, is 42° . The impedance of this circuit is _____ ohms.

35. (2,691) Since the phase angle and both the opposite and adjacent sides are known you can use either sine or cosine.

$$H = \frac{O}{\sin \theta} = \frac{X_c}{\sin \theta} = \frac{1,800}{\sin 42^\circ} = \frac{1,800}{.669} = 2,691 \text{ ohms}$$

$$H = \frac{A}{\cos \theta} = \frac{R}{\cos \theta} = \frac{2,000}{\cos 42^\circ} = \frac{2,000}{.743} = 2,691 \text{ ohms}$$

As you can see, to solve AC circuit problems with trig, you first identify all of the data you have available. Then you determine the quantities to be computed. Finally, you select the appropriate trig function and compute your answer.

APPENDIX C:

TABLE OF TRIGONOMETRIC FUNCTIONS

Degrees	Sine	Cosine	Tangent	Degrees	Sine	Cosine	Tangent
0	0.000	1.000	0.000	46	0.719	0.695	1.036
1	0.017	1.000	0.017	47	0.731	0.682	1.072
2	0.035	0.999	0.035	48	0.743	0.669	1.111
3	0.052	0.999	0.052	49	0.755	0.656	1.150
4	0.070	0.998	0.070	50	0.766	0.643	1.192
5	0.087	0.996	0.087	51	0.777	0.629	1.235
6	0.105	0.995	0.105	52	0.788	0.616	1.280
7	0.122	0.993	0.123	53	0.799	0.602	1.327
8	0.139	0.990	0.141	54	0.809	0.588	1.376
9	0.156	0.988	0.158	55	0.819	0.574	1.428
10	0.174	0.985	0.176	56	0.829	0.559	1.483
11	0.191	0.982	0.194	57	0.839	0.545	1.540
12	0.208	0.978	0.213	58	0.848	0.530	1.600
13	0.225	0.974	0.231	59	0.857	0.515	1.664
14	0.242	0.970	0.249	60	0.866	0.500	1.732
15	0.259	0.966	0.268	61	0.875	0.485	1.804
16	0.276	0.961	0.287	62	0.883	0.469	1.881
17	0.292	0.956	0.306	63	0.891	0.454	1.963
18	0.309	0.951	0.325	64	0.899	0.438	2.050
19	0.326	0.946	0.344	65	0.906	0.423	2.145
20	0.342	0.940	0.364	66	0.914	0.407	2.246
21	0.358	0.934	0.384	67	0.921	0.391	2.356
22	0.375	0.927	0.404	68	0.927	0.375	2.475
23	0.391	0.921	0.424	69	0.934	0.358	2.605
24	0.407	0.914	0.445	70	0.940	0.342	2.748
25	0.423	0.906	0.466	71	0.946	0.326	2.904
26	0.438	0.899	0.488	72	0.951	0.309	3.078
27	0.454	0.891	0.510	73	0.956	0.292	3.271
28	0.469	0.883	0.532	74	0.961	0.276	3.487
29	0.485	0.875	0.554	75	0.966	0.259	3.732
30	0.500	0.866	0.577	76	0.970	0.242	4.011
31	0.515	0.857	0.601	77	0.974	0.225	4.332
32	0.530	0.848	0.625	78	0.978	0.208	4.705
33	0.545	0.839	0.649	79	0.982	0.191	5.145
34	0.559	0.829	0.675	80	0.985	0.174	5.671
35	0.574	0.819	0.700	81	0.988	0.156	6.314
36	0.588	0.809	0.727	82	0.990	0.139	7.115
37	0.602	0.799	0.754	83	0.993	0.122	8.144
38	0.616	0.788	0.781	84	0.995	0.105	9.514
39	0.629	0.777	0.810	85	0.996	0.087	11.43
40	0.643	0.766	0.839	86	0.998	0.070	14.30
41	0.656	0.755	0.869	87	0.999	0.052	19.08
42	0.669	0.743	0.900	88	0.999	0.035	28.64
43	0.682	0.731	0.933	89	1.000	0.017	57.29
44	0.695	0.719	0.966	90	1.000	0.000	∞
45	0.707	0.707	1.000				

Unit 4

Inductive Circuits

Contents

Introduction	4-3	Applications of Inductive Circuits	4-44
Unit Objectives	4-4	Desk-Top Experiment 4	
Review of Inductors and Inductance	4-5	Analyzing LR Circuits	4-48
Inductors in AC Circuits.....	4-22	Unit Summary	4-54
RL Circuits	4-32		

Introduction

In this unit you are going to study inductors and how they are used in AC circuits. An inductor is an electronic component that opposes changes in the current flow through it. Like a capacitor, it offers opposition to the flow of alternating current. When used in sinusoidal circuits, an inductor introduces a phase shift. Inductors can be combined with resistors and/or capacitors to form a variety of electronic circuits.

Your previous studies in DC electronics should have included inductors and inductive circuits. You should know what an inductor is, how it works, and what effect it has in DC circuits.

The first part of this unit is devoted to a review of inductors and inductance.

In the remaining sections, you will study the effects of inductance in an AC circuit. The characteristics and applications of simple resistor-inductor, RL, networks will also be considered.

Inductance is a characteristic found in virtually all electronic circuits. You must understand its effect in order to analyze, design or troubleshoot electronic circuits. In addition, your understanding of inductance is vital to your successful completion of the units on transformers and tuned circuits.

Unit Objectives

When you have completed this unit, you should be able to:

1. Define: Inductance, inductive reactance, self inductance, mutual inductance, coefficient of coupling, and RL filter.
2. Draw a vector diagram illustrating the phase relationship between voltage and current in an RL circuit.
3. Determine the impedance of an RL circuit.
4. Calculate the phase angle for a series or a parallel RL circuit.
5. Given the inductance and frequency, determine the inductive reactance of an inductor.
6. Given the inductive reactance and frequency, determine the inductance of an inductor.
7. Determine the Q of an inductor.
8. Name three applications for RL circuits.
9. Name four factors that affect the inductance of a coil.
10. Explain the relationship of the L/R time constant.

Review of Inductors and Inductance

When current flows through an electrical conductor such as a wire, a magnetic field is generated around it. Each electron in the conductor has a minute magnetic field associated with it. The electrons in the conductor are aligned in a random manner, when no current is flowing through it. For that reason, the tiny magnetic fields associated with each electron tend to cancel one another. With no current flowing through the conductor, no external magnetic field exists. When a voltage is applied to the conductor, electrons begin to flow. This tends to align the electrons so that their magnetic fields add. The total strength of the magnetic field is the sum of the individual electron fields. The higher the applied voltage or the lower the resistance of the conductor, the greater the number of electrons flowing. The magnitude of the magnetic field surrounding the conductor increases as the amount of current flow increases. This effect is known as electromagnetism. See Figure 4-1.

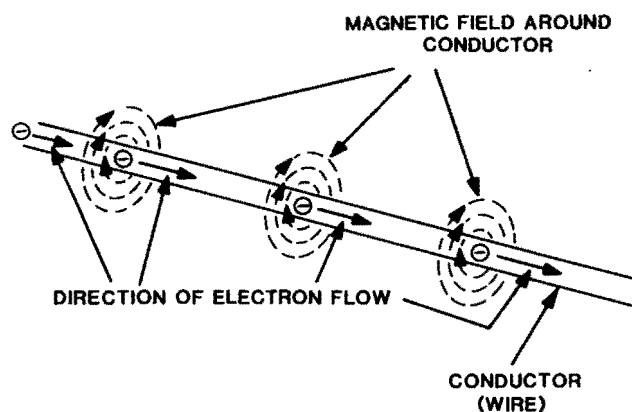


Figure 4-1 Magnetic field around a current carrying conductor.

Current flowing in a conductor produces a magnetic field. In addition, a magnetic field can cause a current to flow in a conductor. This current flows when there is relative motion between the magnetic field and the conductor. When a conductor or wire is passed through a stationary magnetic field, a voltage or electromotive force (emf) is induced into that conductor. Alternately, when a magnetic field is passed across a fixed conductor, a voltage is induced into the conductor. As long as there is relative motion between the magnetic field and the conductor, an induced voltage is generated in the conductor. As the conductor is moved, the magnetic fields of the electrons in the conductor are affected by the external magnetic field. The motion between the conductor and the magnetic field forces the electrons to move in one direction or the other. This effect creates a small voltage across the conductor. There is a difference of potential from one end of the conductor to its opposite end.

When the conductor forms a complete electrical circuit, current will flow in the circuit. See Figure 4-2.

The amount of voltage induced into a conductor, by its motion in a magnetic field, depends upon the strength of the magnetic field. The stronger the field, the more influence it has on the electrons inside the conductor, and the greater the induced voltage. The length of the conductor also determines the amount of induced voltage. For a given magnetic field, the longer the conductor, the greater the induced

voltage. The speed with which the conductor cuts the magnetic field also influences the magnitude of the induced voltage. Moving the conductor through the field slowly causes only a small voltage to be induced. When the conductor is moved quickly through the magnetic field, a larger voltage is induced.

The direction of motion between the conductor and the magnetic field also determines the amount of induced voltage. When the conductor moves in the same direction and at the same speed as the magnetic field, no voltage is induced. The conductor must cut across the

magnetic lines of force in order for a voltage to be generated. When the conductor moves perpendicular (90 degrees) to the magnetic lines of force, maximum voltage is induced.

The amount of induced voltage is directly proportional to the strength of the magnetic field, the length of the conductor, the speed of the conductor and the direction of movement of the conductor relative to the magnetic field. This effect is known as electromagnetic induction. Electromagnetism and electromagnetic induction are both responsible for the property of inductance and the effect it has on electrical circuits.

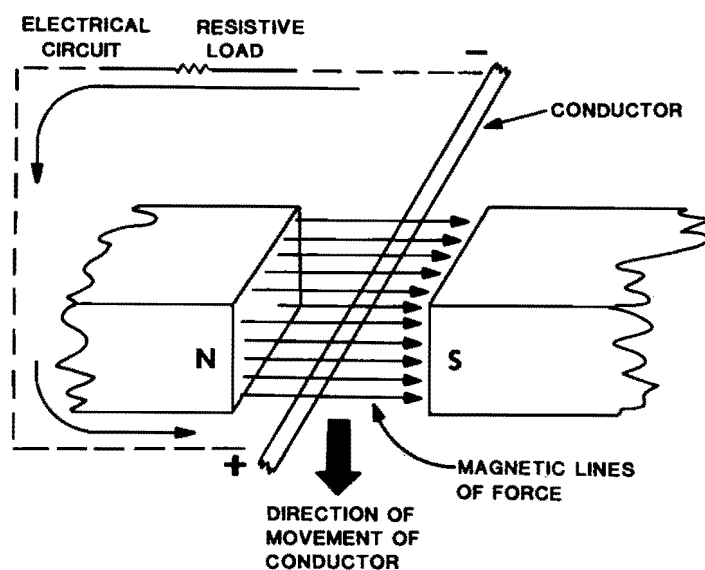


Figure 4-2 Electromagnetic induction.

Self-Induction

When voltage is applied to a conductor, current flows. This current flow results in a magnetic field being generated around the conductor. This field is not created immediately when voltage is applied to the conductor. Rather, the field builds gradually as current flow through the conductor increases. When current flow reaches its maximum value, the magnetic field around the conductor is at its maximum strength.

As the magnetic lines of force expand outward from the center of the conductor, the magnetic field induces a voltage into the conductor itself. In other words, the magnetic field generated by the conductor induces a voltage in the conductor. The expansion of the magnetic lines of force with respect to the conductor represents the relative motion between the conductor and the magnetic field, required to induce a voltage. The polarity of the induced voltage opposes the polarity of the voltage that causes the magnetic field.

As long as the magnetic field is moving with respect to the conductor, an induced voltage is generated. As the magnetic lines of force continue to expand outward from the conductor during the rise of the current in the circuit, induced voltage is present. When the current in the circuit reaches its maximum, as determined by the applied voltage and the resis-

tance of the conductor, the magnetic field becomes stationary. Since there is no further relative motion between the conductor and the magnetic field, there is no induced voltage. At this time, the current in the circuit is strictly a function of Ohm's Law.

When the voltage applied to the conductor is removed, current flow decreases. With less movement of electrons in the conductor, the magnetic field starts to collapse. As it collapses, the lines of force cut across the conductor and induce a voltage. Again, the collapsing lines of force cause relative motion between the conductor and the magnetic field. Therefore, a voltage is induced into the conductor. The polarity of the induced voltage is such that it tends to keep current flowing in the same direction.

The application or removal of the voltage source causes a self-induced voltage. This self induction takes place for any current changes that occur. Increasing or decreasing the current in a circuit causes the magnetic lines of force to expand or collapse and thereby cut the conductor. The conductor cutting induces a voltage that opposes the applied voltage. The induced voltage is referred to as counter emf or back emf since it always opposes the applied voltage. The ability of a conductor to generate a voltage, with a change in current, is called self-induction. It is this characteristic that produces the property called inductance.

Inductors and Inductance

Inductance is the property of an electrical circuit that tends to oppose any change of current in the circuit. The conductor or wire we have been discussing exhibits the property of inductance because it opposes changes in the current flow. When the current through a conductor suddenly increases, a voltage is induced within the conductor that opposes the applied voltage. The induced voltage attempts to cancel the applied voltage. This action/reaction tends to hold the current to its previous level. The induced voltage opposes the applied voltage and therefore opposes the increase in current. The current still rises, however, because the induced voltage appears only during the time that the current is increasing. Once there is no longer a relative motion between the conductor and the magnetic field, no further induced voltage or additional opposition takes place.

When the current in a circuit is suddenly decreased, the magnetic lines of force collapse and induce a voltage into the conductor that opposes the applied voltage. When the applied voltage is suddenly decreased, the induced voltage maintains the current at the same level. The current will eventually decrease, however, as the magnetic field stops its collapse and no further induced voltage is generated.

As you can see, changing the current in a circuit causes a voltage to be induced into the conductor that opposes the change of current. The induced voltage tends to cause current in the circuit to remain constant, at least this is true for a short period of time. This ability to oppose the change in an electrical current is defined as inductance.

The electronic component that most exhibits the property of inductance is called an inductor. The conductor or wire that we have been considering up to this point can be referred to as an inductor. While any wire or electrical conductor exhibits the property of inductance, it is normally not referred to as an inductor. Instead, an inductor is considered to be a separate and distinct type of passive electronic component. The most common inductor is a coil of wire. The term coil is often used interchangeable with the name inductor.

Whenever a wire is wound into a coil, the inductor formed becomes more manageable. Winding the wire into a coil makes the inductor smaller and more compact. At the same time, inductance is greatly increased. By keeping the turns of wire close together, the magnetic field surrounding the wire will become more concentrated. The greater the magnetic field, the greater the induced voltage and therefore the higher the inductance.

Unit of Inductance

The unit of inductance is the henry. One henry is defined as the amount of inductance that a coil has when the current, changing at the rate of one ampere per second, produces one volt of induced voltage. Inductance is a measure of how much counter emf is generated in an inductor, for a specific amount of change in the current through that inductor.

The henry, abbreviated H, is a fairly large unit of inductance. While there are inductors available with an inductance of one henry or more, most inductors used in electronic circuits have a much lower inductance value. These inductance values are expressed in smaller units known as the millihenry, and microhenry. One millihenry is one thousandth of a henry. One microhenry is one millionth of a henry. One microhenry is also one thousandth of a millihenry. In formulas, inductance is usually indicated by the letter L.

Table 4-1 shows the relationship between the henry, the millihenry, and the microhenry. Table 4-2 gives the rules for converting from one unit of inductance to another.

1 henry = 1000 or 10^3 millihenry
1 henry = 1,000,000 or 10^6 microhenry
1 millihenry = $1/1000$ or 10^{-3} henry
1 millihenry = 1000 or 10^3 microhenry
1 microhenry = $1/1000000$ or 10^{-6} henry
1 microhenry = $1/1000$ or 10^{-3} millihenry

Henry = H
Millihenry = mH
Microhenry = μ H

Table 4-1 Units of inductance.

The examples below show how the information in Tables 4-1 and 4-2 can be used to convert from one unit to another.

1. Convert 100 mH to H. $100 \text{ mH} = 100 / 1,000 = .1 \text{ H}$.
2. Convert 78.6 μ H to H. $78.6 \mu\text{H} = 78.6 / 1,000,000 = .0000786 \text{ H}$ or $78.6 \times 10^{-6} \text{ H}$.
3. Convert 22 mH to μ H. $22 \text{ mH} = 22 \times 1,000 = 22,000 \mu\text{H}$.

To Convert	To	Action
Henry	Millihenry	Multiply by 1000 or (10^3); or move the decimal point three places to the right.
Henry	Microhenry	Multiply by 1,000,000 or (10^6); or move the decimal point six places to the right.
Millihenry	Henry	Divide by 1000 or (10^3); or move the decimal point three places to the left.
Millihenry	Microhenry	Multiply by 1000 or (10^3); or move the decimal point three places to the right.
Microhenry	Henry	Divide by 1,000,000 or (10^6); or move the decimal point six places to the left.
Microhenry	Millihenry	Divide by 1000 or (10^3); or move the decimal point three places to the left.

Table 4-2 Converting units of inductance.

Factors Affecting Inductance

It is the physical characteristics of a coil that determines its inductance. The amount of inductance that a coil has depends upon the number of turns in the coil, the spacing between the turns, the wire size, the shape of the coil, the number of layers of windings, the type of windings, the diameter of the coil, the length of the coil and the type of core material. Refer to Figure 4-3.

The inductance of a coil is directly proportional to the number of turns of wire and the diameter of the coil. The greater the number of turns, the greater the magnetic field produced by the coil. In addition, for a given number of turns, the greater the diameter of the coil, the more magnetic lines of force produced. Anything done to increase the magnetic field produced by the coil will increase its inductance.

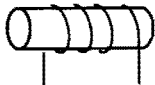
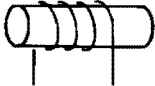
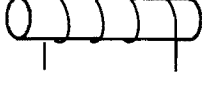
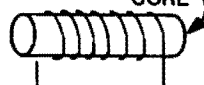
FACTOR	LOW INDUCTANCE	HIGH INDUCTANCE
NUMBER OF TURNS		
DIAMETER		
LENGTH AND TURNS SPACING		
CORE MATERIAL		

Figure 4-3 Factors influencing inductance.

The spacing between the turns also affects the inductance. Keeping the turns very close together causes the magnetic lines of force produced by each turn to add together and produce a stronger magnetic field. More space between the turns of the coil reduces the addition of the lines of force produced by each turn. This additive effect is called mutual inductance and it can be increased or decreased by adjusting the spacing between turns. The spacing of the turns also affects the coil's length. Inductance is inversely proportional to the length of the coil. That is, increasing the length decreases the inductance. When the length is increased the resistance is also increased, this reduces current flow. Current flow is the movement that results in the property called inductance.

Do not confuse length of the wire to make the coil with the length of the conductor in a magnetic field.

The wire size used in the coil does not directly affect the inductance of the coil, however, it will influence the spacing between the turns when the turns are directly adjacent to one another. The smaller the wire, the closer the turns and the greater the inductance. The diameter of the conductor wire used to form the coil is a factor, but reduced diameter allows a greater number of turns to be formed which is a much more important factor.

The number of layers of winding used will also affect the inductance. The greater the number of windings, the greater the inductance will be. The shape of the coil and the method of winding the wire also affects the inductance.

The type of core material used in the coil also affects the inductance. Core material refers to the type of form on which the wire is wound. Many coils are self-supporting and have no form or core. Such coils are referred to as air-core inductors. The inductance of an air-core coil is strictly a function of the factors we have just discussed. When a core is used, however, the inductance will be affected.

Most inductors are made with a core that has magnetic properties. Cores made of iron, steel, nickel, or some related alloy concentrate the magnetic lines of force, produced by the coil. When the lines of force are concentrated the field density increases, which increases the intensity of the magnetic field, the amount of induced voltage and therefore the inductance.

It is the permeability of the core material that determines its effect on the inductance of the coil. Permeability is the ability of a material to support the magnetic lines of force. The greater the ease with which magnetic lines of force can be set up within the core materials, the higher the permeability will be. Air has a permeability of 1 while a magnetic material like iron has a permeability of 7,000.

All of these factors can be related in a formula that is used to compute the inductance of a single-layer inductor. This is shown in Figure 4-4.

$$L = \frac{.04\mu N^2 r^2}{l}$$

L is the inductance in microhenrys, N is the number of turns, r is the radius of the coil in

centimeters (1 inch = 2.54 centimeters), l is the coil length in centimeters and μ is the permeability. For example, an air-core coil with a radius of 2 CM, a length of 7 CM and 100 turns has an inductance of:

$$L = \frac{.04(1)(100)^2(2)^2}{7} = \frac{1,600}{7} = 228.57 \mu\text{H}$$

Air core has a permeability of 1.

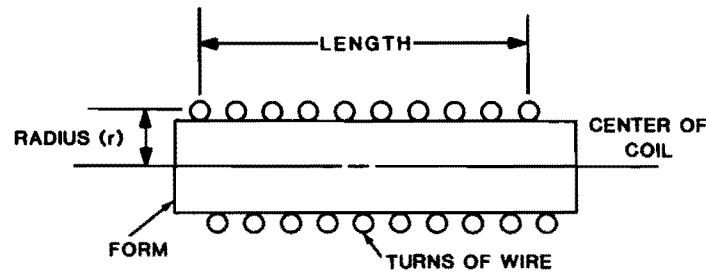


Figure 4-4 Cross-sectional view of a single layer inductor.

Types of Inductors

There are two basic types of inductors used in electronic circuits, fixed inductors and variable inductors. Fixed inductors are further classified by the type of core material used. The two major kinds of fixed inductors are air-core and iron-core. Variable inductors are inductors whose inductance value can be varied. Most variable inductors use an iron-core.

Fixed Inductors

Inductors are made by winding a length of wire around a core. Solid copper wire with an enamel insulation is the most commonly used conductor. The core can be a non-conducting non-magnetic material such as bakelite, plastic, or ceramic. When these cores are used, their primary purpose is to support the coil of wire. These insulator-material cores have no magnetic properties and, therefore, do not affect the inductance of the coil.

When heavy wire is used to make the coil, a form may not be needed for support. The wire may be rigid enough to support itself. Coils with non-magnetic forms or no form at all are referred to as air-core inductors. Their coils generally have very low values of inductance. Air cores are usually used in high frequency applications. Figure 4-5A is the schematic symbol used to represent an air-core inductor.

Figure 4-5B shows a special type of fixed inductor. The inductor is a spiral of copper foil on a printed circuit board. The advantage of such a coil is that it can be formed when the printed circuit board is being made. Because of the physical configuration dictated by this type of construction, only very small values of inductance are obtained. This type of inductor is widely used in high frequency circuits.

Another common type of fixed inductor is the iron-core choke. The term **choke** is used interchangeably with inductor. In this type of inductor, a multi-layered coil is wound on a laminated iron-core. The iron-core has magnetic properties that concentrate the magnetic field, which increases its inductance. Values of inductance approaching 100 henrys are possible with such iron-core chokes. Iron-core inductors such as this are used primarily in DC and low frequency AC applications. Figure 4-5C shows a typical iron-core choke and its schematic symbol.

Another specially shaped iron-core choke is the toroidal inductor shown in Figure 4-5D. The donut-shaped core is either a powdered iron called ferrite or a spiral wound tape of magnetic metal. Toroids are used in both low and high frequency applications. At one time toroidal coils were extensively used in digital computer memories. Today, the memory that is most common is the solid state integrated circuit.

A special iron-core fixed inductor is the ferrite bead inductor shown in Figure 4-5E. Here, a tiny cylindrical-shaped ferrite bead is simply slipped around a wire conductor. The short wire has inductance, but the ferrite bead concentrates and intensifies the magnetic field around the wire. The small ferrite bead in-

creases inductance without adding critical spacing, size, or much additional weight to the circuit. Only small values of inductance can be obtained with a bead, but such small inductors are very useful in high frequency applications.

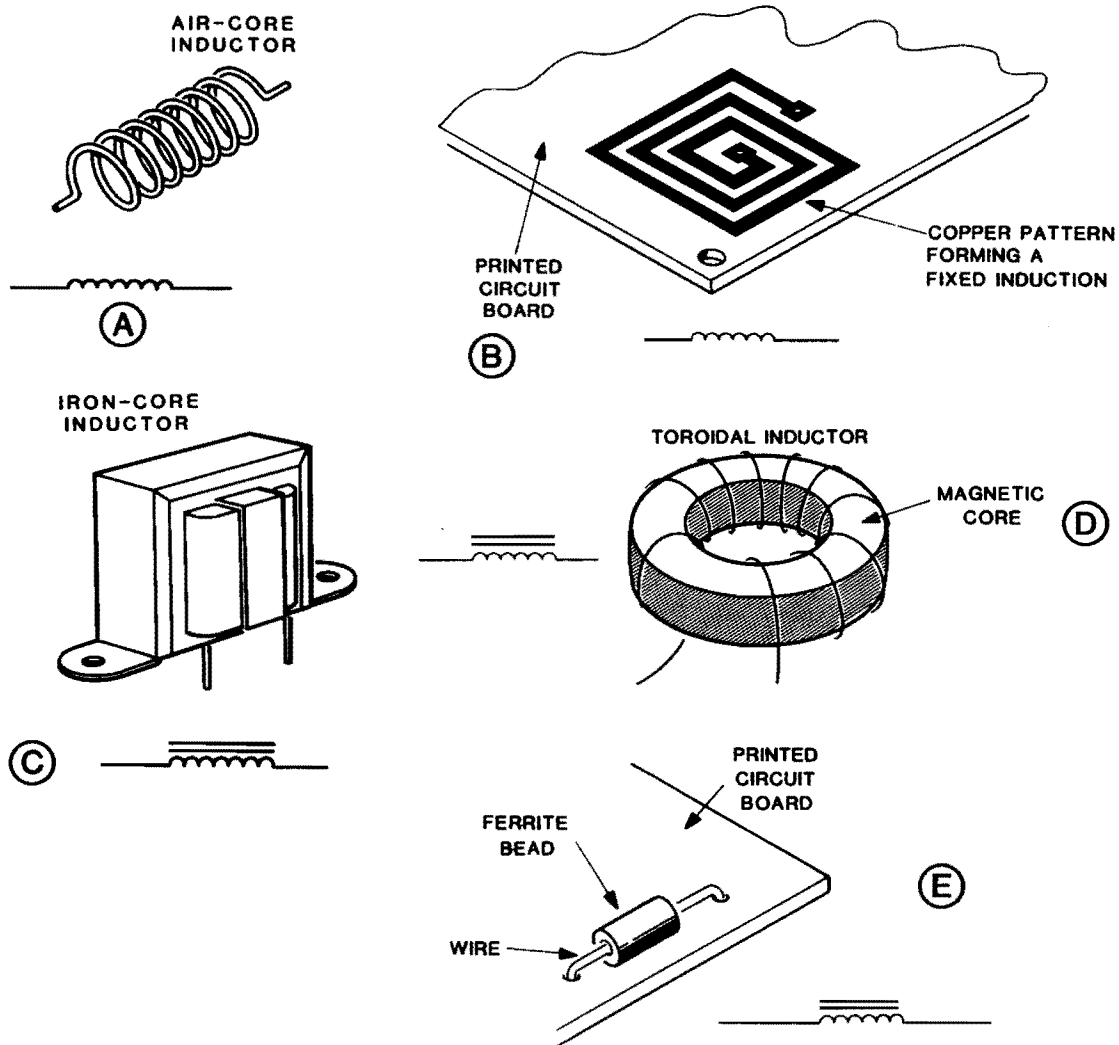


Figure 4-5 Typical fixed inductors and their schematic symbols.

Variable Inductors

A variable inductor is one whose inductance can be changed. Most variable inductors consist of a coil of wire wound on a non-magnetic form. A core is placed inside the form. The core, usually made of powdered iron known as ferrite, is movable. The position of the core with respect to the coil can be changed so that the inductance value varies as the core is moved into or out of the coil form. Variable inductors such as this are widely used in tuned circuits in radio applications. Figure 4-6 shows a typical variable inductor and its schematic symbol.

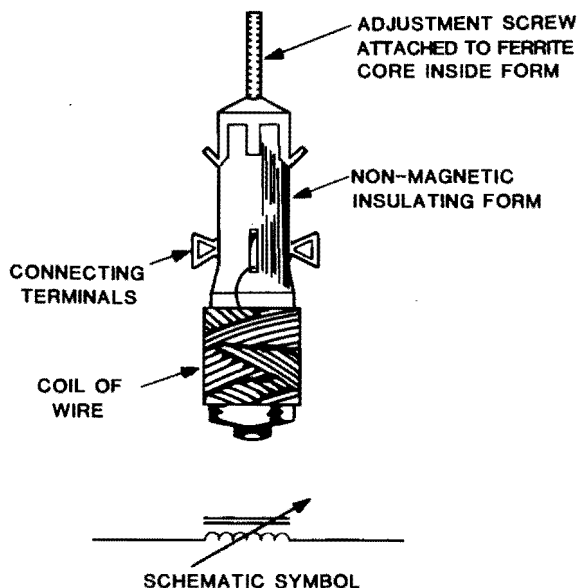


Figure 4-6 Typical variable inductor and its schematic symbol.

Inductors in DC Circuits

Inductance has no effect upon direct current unless the DC is changing (turned on, turned off, or pulsating). In most DC circuits, the current flowing in the circuit is constant. When an inductor is used in a DC circuit, only the resistance of the wire affects the current. The property of inductance depends upon a changing current which produces a self-induced voltage. When the current in a DC circuit changes, the inductance affects it. The current in a DC circuit usually changes only when voltage is applied or removed. The inductor is used in DC circuits to reduce AC ripple from the supply voltage and noise that might be riding on the DC.

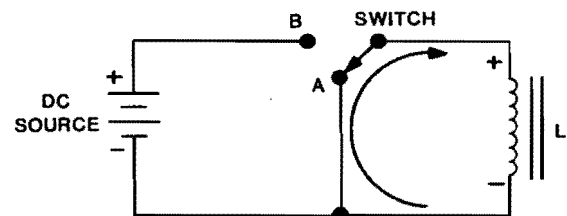


Figure 4-7 Inductance in a DC circuit.

Figure 4-7 shows inductor L connected to a DC source through a switch. When the switch is in position A, the inductor is not connected to the DC supply. When the switch is moved to position B, the battery is connected to the inductor. When the switch is moved from position A to position B, the DC source voltage will cause current to flow. The instant electrons

begin to flow, a magnetic field is generated. As the magnetic field expands outward, it cuts the turns of the inductor and induces a counter emf. The polarity of the induced voltage opposes the applied voltage, and the amount of current flowing in the circuit is initially limited. Because of the opposition of the induced voltage, the current cannot rise instantaneously. Instead, it takes a finite time to reach its maximum value.

Figure 4-8A shows how the current varies with time when a DC voltage is first applied to the inductor. Once the magnetic field stops expanding, no further counter emf is induced and the current is maximum. Maximum current is determined by the amplitude of the applied voltage and the resistance of the inductor.

The resistance of the inductor is its DC resistance, not its inductive reactance. Inductive reactance is an AC resistance and is defined as X_L . To DC the inductor's resistance is usually very low. The DC resistance varies from a few ohms to a few hundred ohms. The actual DC resistance is determined by the type of conductor used, its diameter, and its length. The AC resistance (inductive reactance) is a function of the inductor's value in henrys and the frequency of operation. Inductive reactance

(X_L) will be discussed in the next section of this unit.

When the switch is moved from position B to position A, the connection to the DC source is broken. This causes the magnetic field around the inductor to collapse. As it collapses, it induces a voltage when the magnetic field cuts the turns of the coil. When the DC source voltage is removed, current does not drop to zero instantaneously. Instead the collapsing magnetic field induces a voltage which causes the current flow to continue in the same direction. When the magnetic field is completely collapsed, no further voltage is induced, and the current drops to zero. Figure 4-8B shows the decay in current when the power is removed from the inductor.

As you can see from the graphs in Figure 4-8, the inductor opposes changes in current in DC circuits. When a voltage is applied to the inductor, the inductor opposes (slows) the rise of current in the circuit. When the voltage is removed from the circuit, the inductor again opposes the change in current flow by keeping the current flowing in the same direction for a short time.

Inductive Time Constant

Whenever a DC voltage is applied to or removed from an inductor, it takes a definite period of time for the current to reach its maximum or minimum values. The effect is simi-

lar to the time that it takes for a capacitor to charge or discharge. The time that it takes the inductive circuit's current to rise or fall is referred to as the time constant of the inductor.

The time constant of an inductor is defined as the time required for the current to rise to 63.2% of its maximum value or to decrease to 36.8% of its maximum value. The time constant is illustrated in Figure 4-8.

The value of the inductive time constant is a function of the inductance and resistance in the circuit. The time constant is directly proportional to the inductance and inversely proportional to the resistance. The equation below expresses this relationship.

$$T = \frac{L}{R}$$

As you can see, the greater the inductance, the greater is the time constant. The reason for this is that a larger inductance produces a larger counter emf. Therefore, the opposition to the applied voltage is greater. This means that the current in the circuit will take longer to rise to its final or maximum value.

Just the opposite happens when the resistance increases. The larger the resistance, the smaller the current is. Since current is reduced, the strength of the magnetic field and the induced voltage is also reduced.

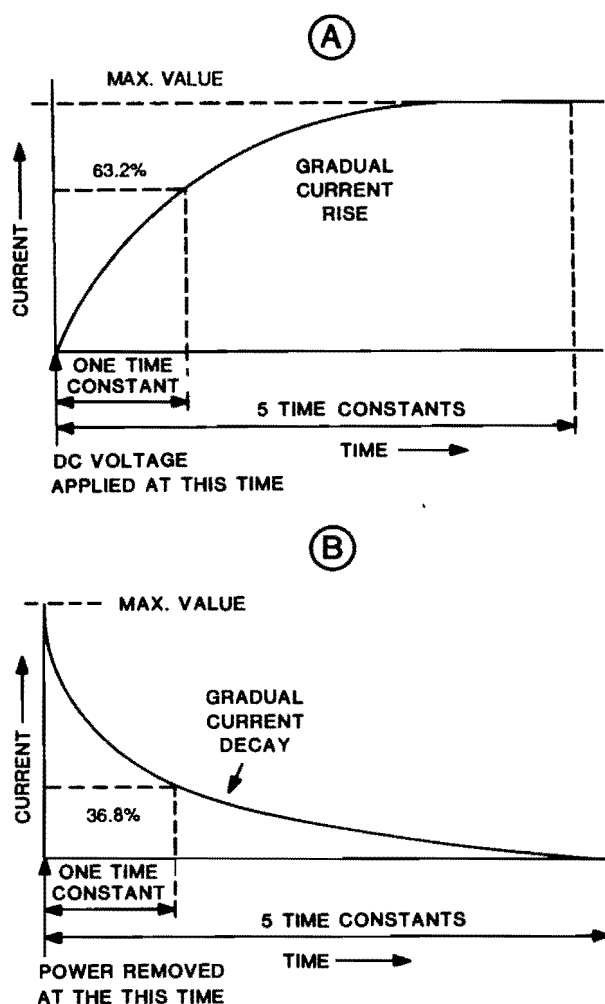


Figure 4-8 Charging and discharging curves.

In this expression, T is in seconds, L is in henrys, and R is in ohms. For example, a 1.5 henry inductor has a resistance of 100 ohms, the time constant is:

$$T = \frac{1.5}{100} \text{ or } .015 \text{ S or } 15 \text{ ms}$$

This means that it takes 15 milliseconds for the current to rise to 63.2% of its maximum value or to fall to a value of 36.8% of the maximum circuit current. It takes approximately 5 time constants for the current to rise to its maximum value from zero or to drop from its maximum value to zero.

Note that the 5 time constants it takes the inductor to completely change between maximum and minimum is the same as the capacitor took to completely charge and discharge.

Remember that in a capacitive circuit, initially, current was maximum and voltage reached its maximum across the capacitor after 5 time constants. In this case, we said that current

led voltage. In a purely capacitive circuit, current leads voltage by 90 degrees.

In an inductive circuit, initially, current is zero and voltage is maximum. In this case, voltage leads current. In a purely inductive circuit, voltage leads current by 90 degrees.

The voltage and current relationship become very important later in your studies when we combine capacitors and inductors in a variety of circuit configurations.

One time constant in an RC circuit is $R \times C$. In an LR circuit one time constant is L/R .

When the maximum current in the example above is 600 milliamperes, it will take 15 milliseconds for the current to rise to 63.2% of 600 or $.632 \times 600 = 379.2 \text{ mA}$. It will take $5 \times 15 = 75$ milliseconds for the current to rise to the full 600 mA.

Self-Test Review

1. To increase the strength of the magnetic field, the current must be:
_____.
2. A magnetic field that is produced by current flow is called a/an:
_____ field.
3. To induce current into a conductor from a magnetic field there must be relative:
_____.
4. The process known as induction is actually:
_____ induction.
5. Current through a conductor and the magnetic field around the conductor are:
_____ proportional.
6. The conductor generating the varying magnetic field induces a voltage into itself. This process is called:
_____.
7. The polarities are such that an induced voltage and the applied voltage:
_____ aid/oppose.
8. The property of an electrical circuit that opposes a change in current is called:
_____.
9. The electronic component that exhibits this characteristic is called a/an
_____.
10. The unit of measure for the inductor is the:
_____.
11. Inductors are made by winding a conductor into a/an:
_____.
12. Another common name for an inductor besides coil is:
_____.
13. Inductance is designated by the letter:
_____.

14. The inductance of a coil is determined by its physical characteristics. List four of the important factors:

1. _____.
2. _____.
3. _____.
4. _____.

15. Increasing the number of turns, decreasing the spacing between turns, or inserting an iron core:

_____.

16. The two basic types of inductors are:

_____ and _____.

17. The two types of cores most often used in inductors are:

_____ and _____.

18. Most variable inductors usually contain a/an:

_____ core.

19. The core is moved with respect to the coil of wire to vary inductance. Moving the core out of the coil:

_____ inductance.

20. When DC is applied to or removed from a circuit, the inductor:

_____ the change.

21. In an LR series circuit, the time constant is calculated using the formula:

$T =$ _____.

22. The time that it takes the current to rise to 63.2% of its maximum value in an LR circuit is:

_____.

_____.

23. Upon initial turn on, an LR circuit's current is:

minimum/maximum

24. An inductor with an inductance of 4.5 henrys and a resistance of 200 ohms is connected to a 9 volt DC source. The maximum circuit current is approximately:

_____ amperes.

25. In the circuit described in question 24, maximum current occurs after:

_____ seconds.

Inductors In AC Circuits

When an inductor is used in an AC circuit, it offers continuous opposition to any change in current flow. Because the applied AC voltage is constantly varying, it causes a counter emf to be continuously induced into the coil. The counter emf opposes the applied voltage, limiting the amount of current flowing in the circuit. Like a capacitor or resistor, the inductor opposes the flow of alternating current.

Because of the unique relationship between the applied voltage, induced voltage, and current in an inductive circuit, an inductor introduces a phase shift. The applied voltage and current will be out of phase with one another because of the inductance.

Current-Voltage Relationship

Assume that a sine wave AC voltage is applied to an inductor as shown in Figure 4-9. Since the applied voltage is sinusoidal, the current flowing in the inductor will also be sinusoidal. The current through the coil periodically (every 180 degrees) reverses direction. This reversal of current is because the applied voltage reverses polarity.

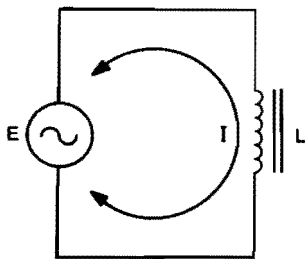


Figure 4-9 Sine wave applied to an inductor.

The current in this inductive circuit is illustrated by the current waveform in Figure 4-10. The changing current causes the magnetic field around the inductor to rise and fall, repeatedly cutting the turns of the coil and inducing a voltage. The induced voltage, called the counter emf, opposes the applied voltage. The counter emf waveform is also illustrated in Figure 4-10. Note that the counter emf is 90° out of phase with the current sine wave.

Recall that the voltage induced into a conductor is proportional to the rate of change of the magnetic field. The faster the magnetic field expands or collapses, the higher the induced voltage. As you can see in Figure 4-10, the most rapid change in current occurs at points A and B. Here, the current is changing from positive to negative or from negative to positive. The rate of change of current is highest at these points, and it is also at these points that the induced voltage is highest.

The positive and negative peaks of the counter emf occur at the zero crossing points of the current waveform. The rate of change of current is zero at the positive and negative peaks of the current waveform. As a result, the induced voltage at these points is also zero. Note that, the counter emf is 90 degrees out of phase with the current.

Counter emf opposes the applied voltage. Since the induced voltage is in direct opposition, it is exactly opposite in phase to the applied voltage. We say that the applied voltage and the

counter emf are 180 degrees out of phase with one another. Keep in mind that one cycle of a sine wave represents 360 degrees. One half cycle represents 180 degrees, and one quarter of a cycle is 90 degrees. As you can see from Figure 4-10, current increases 90 degrees later in time. When the applied voltage decreases, the current decreases 90 degrees later. In a purely inductive circuit, current lags the applied voltage by 90 degrees. This is sometimes stated as the voltage leads the current by 90 degrees. This is opposite the voltage-current relationship in capacitive circuits.

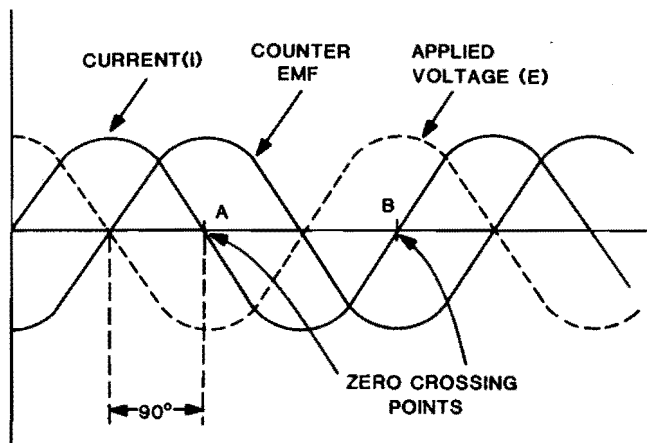


Figure 4-10 Current-voltage relationship in an inductive circuit.

Inductive Reactance

The counter emf induced into an inductor by a varying current opposes the applied voltage. As a result, the total effective voltage in the AC circuit is called inductive reactance. Like resistance (R) and capacitive reactance (X_C), inductive reactance (X_L) is measured in ohms.

The amount of inductive reactance offered by a coil is directly proportional to its inductance and the frequency of the applied voltage. The greater the inductance the greater is the magnetic field. The greater the magnetic field the higher is the induced voltage, for a given current. The higher the induced voltage, the greater is the inductive reactance.

As the frequency of the applied AC voltage increases, the rate of change of current also increases. As the rate of change of current increases, the magnitude of the induced voltage becomes greater. This increased induced voltage causes greater opposition to the applied voltage.

Inductive reactance is represented by the symbol X_L . The inductive reactance in ohms is expressed by the formula given below:

$$X_L = 2\pi FL$$

or:

$$X_L = 6.28 FL$$

In this formula, X_L is in ohms, F is the frequency in Hz, and L is the inductance in henrys. For example, to compute the inductive reactance of a .25 henry coil at 400 Hz you would make the following calculations:

$$X_L = 6.28 FL$$

$$X_L = 6.28 (400) (.25)$$

$$X_L = 628 \text{ ohms}$$

By simple algebra, the basic inductive reactance formula can be rearranged to solve for frequency or inductance.

$$F = \frac{X_L}{6.28L}$$

$$L = \frac{X_L}{6.28F}$$

Ohm's Law For Inductive Circuits

Ohm's Law applies equally to inductive AC circuits as it does to resistive or capacitive AC

circuits. The current flowing in an inductive AC circuit is directly proportional to the applied voltage and inversely proportional to the inductive reactance. This relationship is represented mathematically by the expression:

$$I = \frac{E}{X_L}$$

In this expression the current is in amperes, the voltage in volts, and the reactance in ohms. Increasing the voltage or decreasing the reactance causes an increase in current. Decreasing the applied voltage or increasing the reactance causes a decrease in current.

This relationship between the current, voltage, and reactance is illustrated in the following example.

What is the current flowing in a 2.5-millihenry choke when a 10 volt, 100 kHz sine wave is applied? To solve this problem, the inductive reactance must first be computed.

$$X_L = 6.28 FL$$

$$X_L = 6.28 (100,000) (.0025)$$

$$X_L = 1,570 \text{ ohms}$$

Now that the inductive reactance and the applied voltage are known, Ohm's Law can be used to compute the circuit current.

$$I = \frac{10 \text{ V}}{1,570 \Omega} = .00637 \text{ A}$$

Mutual Inductance

The term inductance is more accurately described as self-inductance. This is the ability of a coil to induce a voltage into itself. The varying current in the coil produces a changing magnetic field. The magnetic lines of force cut the turns of the coil. Thus, the coil induces a voltage into itself that opposes the applied voltage. This is known as self-induction.

The varying magnetic field surrounding an inductor can also influence other nearby conductors. As the magnetic field varies, the lines of force can cut the turns of an adjacent coil and induce a voltage into it as well as into the inductor producing the field. The process by

which one inductor causes a voltage to be induced into another is called mutual induction.

Figure 4-11 shows an inductor, with the primary coil (the coil closest to the voltage source), connected to an AC voltage source. When current flows in the primary coil, a varying magnetic field is produced. This causes a voltage to be induced into the primary coil itself as well as into the secondary coil. Note that the secondary coil is not directly connected to the source voltage. The magnetic lines of force cut the turns of an adjacent (secondary) inductor, and induce a voltage into it. The induced voltage causes current to flow through the load resistor.

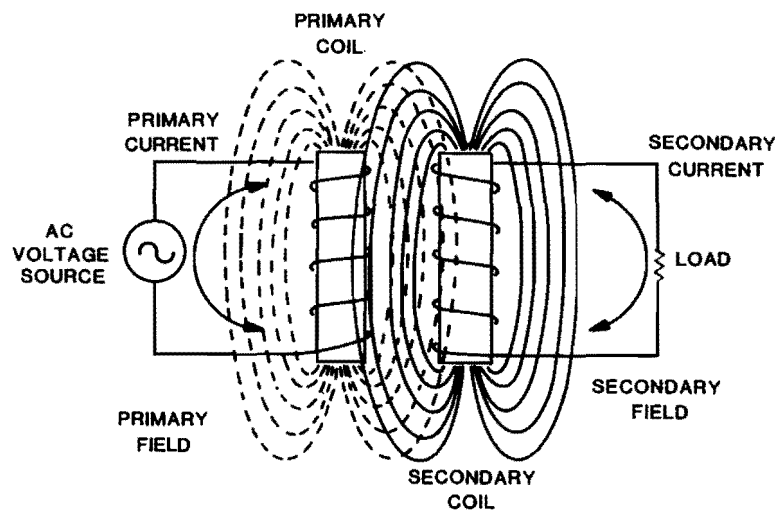


Figure 4-11 Mutual inductance between adjacent coils.

When current begins to flow in the secondary coil, a varying magnetic field is produced around it. This magnetic field induces a voltage into the secondary coil. The varying magnetic field from the secondary coil also induces a voltage back into the primary winding. As you can see, there are four induced voltages that affect the operation of the circuit. These are the two self-induced voltages and the two mutually induced voltages. The overall effect is complex because of the interrelationship between the magnetic fields.

The two coils in Figure 4-11 have mutual inductance because one coil induces a voltage into the other. Mutual inductance is designated by the symbol L_m . The unit of mutual inductance is the henry. A mutual inductance of one henry exists if a current change of one ampere per second in one coil, induces one volt into another coil.

The amount of mutual inductance that exists between two adjacent coils depends upon the degree of coupling between them. In other words, mutual inductance is determined by how many lines of force from one coil cut the turns of an adjacent coil. The degree of coupling between the coils is expressed by a factor called the coefficient of coupling, K . A coefficient of coupling of one, $K = 1$, represents 100 percent coupling of the magnetic lines of force.

When all of the magnetic lines of force produced by one coil do not cut all of the turns of the other coil, the coefficient of coupling is less

than 1. The worst case situation is where none of the magnetic lines of force produced by one coil cut the turns of the other coil. In this case, the coefficient of coupling is zero. This happens when the distance between coils is too great or when the coils are mounted perpendicular to each other.

For other combinations of spacing and relative positions of the coils, a coefficient of coupling between 0 and 1 is obtained.

The mutual inductance that exists between two coils is a function of the coefficient of coupling and the values of inductance of the two coils. Mutual inductance is expressed by the equation given below:

$$L_m = K\sqrt{L_1L_2}$$

Mutual inductance occurs where the magnetic lines of force produced by one coil affect another adjacent coil. In some situations no mutual inductance is possible. For example, when the two iron-core chokes are used the coefficient of coupling between them is zero or very close to it. The iron-core in an inductor concentrates the lines of force and prevents them from extending outward beyond the coil. This is particularly true in iron-core chokes that have a completely closed loop core. None of the magnetic lines of force leave the core. The property of mutual inductance is generally associated with coils mounted on a common core or closely spaced air-core coils.

Inductors in Series and in Parallel

Often inductors are connected in series or parallel combinations to produce different values of inductance. In these cases, the rules for determining the total inductance are the same as the rules for computing total resistance of resistors connected in combinations.

Series Inductance

When inductors are connected in series, the total inductance is the sum of the individual inductances. Figure 4-12 shows three inductors in series. The total inductance is:

$$L_T = L_1 + L_2 + L_3$$

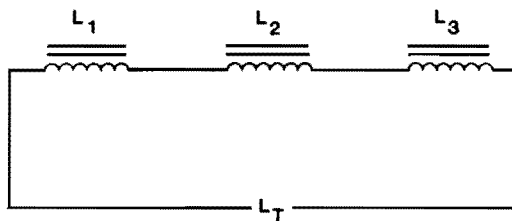


Figure 4-12 Inductors in series.

The calculation assumes that no mutual inductance exists between the inductors. When mutual inductance is involved, total inductance is determined by the sum of the individual inductance values plus the value of mutual inductance.

When two inductors are connected in series so that their magnetic fields aid one another, the total inductance is:

$$L_T = L_1 + L_2 + 2 L_m$$

When two coils are connected in series where their magnetic fields oppose one another, the total inductance is computed using the formula:

$$L_T = L_1 + L_2 - 2 L_m$$

When mutual inductance is present, the magnetic lines of force of one coil affect those of the other. The magnetic fields can aid or oppose. The directions of the magnetic fields are determined by how the coils are wound. When the series connected coils are wound so that their turns are all in the same direction, the magnetic fields add. In this case, the magnetic fields are series-aiding. When the turns are wound in opposite directions, the magnetic fields oppose one another. In this case, there is some cancellation of the magnetic effect be-

tween the two coils. When it is desirable to minimize the mutual inductance, the two coils should be positioned at right angles (perpendicular) to one another.

Parallel Inductance

When two inductors are connected in parallel as shown in Figure 4-13, the formula for total inductance is:

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

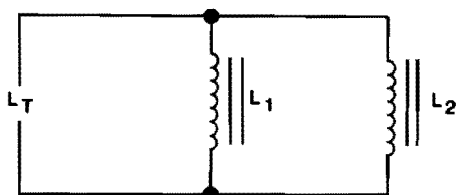


Figure 4-13 Inductors in parallel.

This expression is similar to the formula for parallel resistors. When more than two inductors are connected in parallel, the total inductance of the combination can be determined with the expression above by combining the inductors two at a time until the total is obtained. This expression assumes that no mutual inductance exists.

The reciprocal method used to find R_T can also be used to solve for L_T , for a circuit that con-

tains any number of inductors in parallel. That is:

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \dots}$$

Up to this point in our discussion, we have assumed that an inductor is perfect. A perfect inductor or a purely inductive circuit is one that has no resistance. In a purely inductive AC circuit, the only opposition to current flow is the inductive reactance. However, from a practical standpoint, perfect components do not exist. Since the inductor is a coil of wire, it has resistance. The resistance of an inductor is the specific resistance of the wire used to manufacture the coil. It is not unusual for a choke (coil or inductor) to have a resistance of several hundred ohms.

In many circuits, the resistance of the inductor is so low that it is considered negligible. In these cases, it has little or no effect on the operation of the circuit. In other applications, the resistance of the inductor is higher and can greatly affect the operation of the circuit.

Low resistance is a desirable characteristic of an inductor. The primary reason for this is that power is dissipated by a resistance. Therefore, power is dissipated by an inductor because of its resistance. The quality of an inductor is determined by its resistance. The inductors resistance is primarily determined by:

1. The type of conductor material used to make the coil. The material used most often is copper.

2. The wire's diameter (cross sectional area or gauge). The larger the diameter is, the lower the resistance. The smaller the gauge is, the larger the diameter, and the lower the resistance. For example a #18 wire has a larger diameter than a #22 wire. Resistance is inversely proportional to the conductor's diameter.
3. Length of the wire used. The longer the wire is, the higher its resistance. Resistance is directly proportional to the conductor's length.

Since most inductors are made from copper, the inductor's power dissipation is sometimes called copper loss. The terms copper loss and DC resistance of an inductor are commonly used to discuss the power loss in inductive circuits.

The quality or figure of merit of an inductor is called its Q . The Q of a coil is the ratio of the energy stored in the coil, in the form of a magnetic field, to the energy dissipated in its resistance. This is expressed as:

$$Q = \frac{\text{energy stored}}{\text{energy dissipated}}$$

Since the inductive reactance is a measure of the energy stored in a coil and since the resistance is a measure of the energy dissipated, the Q of a coil can also be expressed as the

ratio of the inductive reactance to the resistance.

$$Q = \frac{X_L}{R}$$

For example, at 10 kHz, the Q of a 88 mH coil with a resistance of 50 ohms is:

$$X_L = 6.28 FL$$

$$X_L = 6.28 (10,000) (.088)$$

$$X_L = 5,526.4 \text{ ohms}$$

$$Q = \frac{X_L}{R} = \frac{5,526.4}{50} = 110.528$$

Q is a figure of merit and is expressed as a numerical value without a unit of measure. It is simply a ratio.

This relationship is widely used to indicate the quality of an inductor. Generally, the higher the Q is the better the coil. A high Q coil is one that has a Q of 20 or greater.

Since Q is directly proportional to the inductive reactance, Q increases as frequency increases. The resistance is essentially a constant at low frequencies. Due to certain electrical characteristics, the resistance of an inductor increases as frequency increases. However, the resistance does not increase as rapidly as inductive reactance. Therefore, Q increases with frequency.

Self-Test Review

26. When an AC voltage is applied to an inductor:
_____ flows.
27. If the current is sinusoidal, the induced voltage will be:
_____.
28. The induced voltage and the applied voltage are 180 degrees:
_____.
29. At the peaks of the current waveform, the rate of change of current is:
_____.
30. The greatest rate of change occurs when the current waveform:
_____.
31. When the voltage and current waveforms do not coincide, the waveforms are said to be:
_____.
32. In a purely inductive circuit, the current and voltage relationship is:
_____.
33. The opposition offered to the flow of AC current by an inductor is called:
_____.
34. The unit of measure for inductive reactance is the:
_____.
35. Inductive reactance is a function of two factors, they are:
_____ and _____.
36. To increase inductive reactance, frequency is:

increased/decreased
37. Inductive reactance is computed using the formula:
_____.
38. The frequency of the applied voltage is 2 kHz and the inductor in the circuit has a value of 90 mH. The inductor's reactance is equal to:
_____.
39. Increasing inductance in an AC circuit causes the current to:
_____.

40. Current in an AC inductive circuit is calculated using the formula:

_____.

41. The effect of one inductor inducing a voltage into another is referred to as:

_____.

42. When all the lines of force of one coil cut all the turns of the other, the coefficient of coupling is equal to:

_____.

43. The coefficient of coupling is equal to zero when the inductors are spaced too far apart or when the inductors are mounted:

_____ to each other.

44. When two inductors are connected series aiding, total inductance is expressed by the equation:

_____.

45. Disregarding mutual inductance, when three inductors are connected in series, total inductance can be expressed by the equation:

_____.

46. The total inductance (L_T) of a 750 mH choke (L_1) and a 1.2 H choke (L_2) in series is:

_____.

47. When mutual inductance is involved, total series inductance will be:

_____ increased/decreased/increased or decreased

48. When two inductors are connected in parallel, total inductance:

_____.

49. The figure of merit for an inductor is expressed by the symbol:

_____.

50. The figure of merit for a 50 mH inductor at 75 kHz with a resistance of 80 ohms is:

_____.

RL Circuits

The most commonly used inductive circuit is a series connected resistor and inductor. This combination is called an RL circuit. Even a circuit containing only an inductor is a series RL circuit because of the resistance of the inductor. In this section, you are going to analyze the operation and characteristics of a series RL circuit.

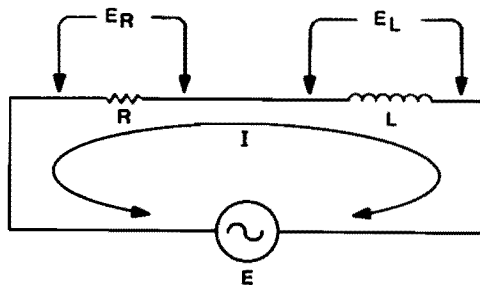


Figure 4-14 Series RL circuit.

Series RL Circuits

Figure 4-14 shows a resistor and inductor connected in series with an AC voltage source. The current in the circuit causes voltage drops across the inductor and the resistor. These voltages are proportional to the current and the resistance and inductive reactance values. The resistor voltage E_R , and the inductor volt-

age, E_L , expressed in terms of Ohm's Law are:

$$E_R = IR$$

$$E_L = IX_L$$

For this discussion, we will assume the inductor to be a perfect inductance. That is, the inductor has no resistance. In this example all of the resistance in the circuit is represented by the resistor R .

Because this is an inductive circuit, the current flowing in the circuit will lag the applied voltage. In a purely resistive circuit the current and voltage are in phase. In a purely inductive circuit, the current lags the applied voltage by 90 degrees. In a series RL circuit, the current will lag the applied voltage by some phase angle between 0 degrees and 90 degrees. The amount of phase shift is a function of the values of the resistor and the inductive reactance.

As in any series electrical circuit, the sum of the voltage drops across the various elements in the circuit, equals the applied voltage. In a circuit containing a reactive component, such as an inductor, because of the phase shift in the circuit, the sum of the voltages must be a vector sum.

Vector Diagrams

As in a series RC circuit, a vector diagram can be used to show the relationship between the current and voltages in a series RL circuit. The length of the vectors represent voltage and current amplitudes. The directions of the vectors indicate the phase relationships.

Figure 4-15 shows a vector diagram of a series RL circuit. The reference vector is labeled I and represents the currents in the circuit. Current is common to all circuit elements in a series circuit. The voltage across the resistor is in phase with the current flowing through it. Therefore, the resistor voltage vector, E_R coincides with the current vector as shown.

The voltage across the inductor leads the current by 90 degrees. In other words, the circuit current lags the voltage across the inductor by 90 degrees. Therefore, the inductive voltage vector, E_L , is shown 90 degrees out of phase (leading) with the current vector.

Recall that we assume that each of the vectors in the diagram is rotating in the counterclockwise direction around the origin. The rotation of the vectors represents the variations of voltages and currents, in a sinusoidal manner, for a given period of time. One complete rotation represents one AC cycle. With the counterclockwise direction of rotation, you can see that the inductor voltage is ahead of (leading) the current vector.

Another way of looking at this is that the current vector is lagging the inductive voltage vector by 90 degrees.

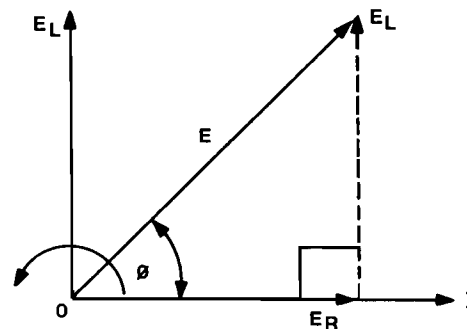


Figure 4-15 Vector diagram of a series RL circuit.

The applied voltage is the vector sum of the resistor and inductor voltages. To find this vector sum, we form a right triangle using the resistor voltages as one side and the inductor voltages as the other side. The applied voltage, E , is the hypotenuse. Note that the applied voltage leads the current by an angle that is between 0 and 90 degrees. Knowing the resistor and inductor voltages, the applied voltage can be found by solving for the hypotenuse of the right triangle. You can do this by using the Pythagorean Theorem: $(E^2 = E_L^2 + E_R^2)$.

In RC circuits we used the Pythagorean Theorem to solve these type of vector additions. However, in RC series circuits the current led the voltage. In RL series circuits, the voltage

leads the current. This is indicated by the sign (either positive or negative) of the phase angle.

The formula for the applied voltage is:

$$E_A = \sqrt{E_R^2 + E_L^2}$$

By rearranging the above formula, either the resistor or inductor voltages can be computed if the applied voltage and the remaining voltage are known. These formulas are:

$$E_R = \sqrt{E^2 - E_L^2}$$

$$E_L = \sqrt{E^2 - E_R^2}$$

Several examples illustrate the use of these formulas.

1. In a series RL circuit the resistor voltage is 15 volts and the inductor voltage is 18 volts. What is the applied voltage?

$$E = \sqrt{E_R^2 + E_L^2}$$

$$E = \sqrt{15^2 + 18^2}$$

$$E = \sqrt{225 + 324}$$

$$E = \sqrt{549}$$

$$E = 23.43 \text{ volts}$$

2. The AC voltage applied to a series RL circuit is 80 volts. The resistor's voltage drop is 32 volts. What is the inductor's voltage?

$$E_L = \sqrt{E^2 - E_R^2}$$

$$E_L = \sqrt{80^2 - 32^2}$$

$$E_L = \sqrt{6,400 - 1,024}$$

$$E_L = \sqrt{5,376}$$

$$E_L = 73.32 \text{ volts}$$

Impedance

The impedance of an RL circuit is the total opposition to current flow offered by both the resistor and the inductor. The applied voltage and total circuit current is used to determine the circuit's impedance. According to Ohm's Law:

$$Z = \frac{E}{I}$$

Impedance is a function of the resistance and the inductive reactance and is calculated using the formula:

$$Z = \sqrt{R^2 + X_L^2}$$

The impedance of a series RL circuit is the square root of the sum of the squares of the resistance and the inductive reactance. Impedance, like resistance and inductive reactance, is expressed in ohms. The basic formula can be rearranged to solve for the resistance or the reactance in terms of the other two factors.

$$R = \sqrt{Z^2 - X_L^2}$$

$$X_L = \sqrt{Z^2 - R^2}$$

You should recognize that the basic impedance formula is the Pythagorean Theorem. Therefore the resistance, inductive reactance, and total impedance can be represented by the sides of a right triangle. This is illustrated in Figure 4-16. This vector diagram is similar to the voltage vector diagram given earlier. The resistor and inductor voltages are directly proportional to the resistance and the inductive reactance, respectively. Therefore, the impedance and voltage vector diagrams are proportional. The angle between the impedance and the resistance is the phase angle of the circuit. It indicates the amount the circuit current lags the applied voltage. The examples below demonstrate the use of the impedance formulas.

1. What is the impedance of a 1.5-henry choke with 200 ohms of resistance at 60 Hz?

First find X_L :

$$X_L = 6.28 \text{ FL}$$

$$X_L = 6.28 (60)(1.5) = 565.2 \Omega$$

Then find the impedance:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{200^2 + 565.2^2}$$

$$Z = \sqrt{40,000 + 319,451}$$

$$Z = \sqrt{359,451} = 599.5 \Omega$$

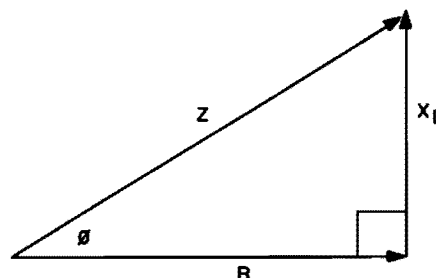


Figure 4-16 Impedance triangle of a series RL circuit.

2. In a series RL circuit, the resistor voltage is 20 volts and the applied voltage is 32 volts at 400 Hz. The resistance is 1,000 ohms. What is the inductance of the coil?

First, find the current in the circuit:

$$I = \frac{E_R}{R} = \frac{20}{1,000} = .02 \text{ amperes}$$

Next, determine the impedance:

$$Z = \frac{E}{I} = \frac{32}{.02} = 1,600 \text{ ohms}$$

Then, solve for L :

$$X_L = \sqrt{Z^2 - R^2}$$

$$X_L = \sqrt{1,600^2 + 1,000^2}$$

$$X_L = \sqrt{2,560,000 + 1,000,000}$$

$$X_L = \sqrt{1,560,000} = 1,249 \text{ ohms}$$

$X_L = 6.28 \text{ FL}$ therefore:

$$L = \frac{X_L}{6.28 F}$$

$$L = \frac{1,249}{6.28(400)} = \frac{1,249}{2,512} = 0.497 \text{ H}$$

Phase Shift

The phase shift in a series RL circuit will be some value between 0 and 90 degrees. The actual value is a function of the resistance and inductive reactance. The phase angle is illustrated in Figure 4-15 and 4-16. It is a function of the tangent in the voltage and impedance triangles. The tangent is the ratio of the opposite side divided by the adjacent side. In Figure 4-16, the tangent is the ratio of the inductive reactance (opposite side), to the resistance (adjacent side). Expressed mathematically this is:

$$\text{tangent of the angle} = \frac{X_L}{R}$$

Since current is the same in both the resistor and the inductor, the voltages dropped across them are directly proportional to the resistance and reactance values. Therefore, you can determine the tangent of the phase angle, by using the inductor and resistor voltages. This is expressed mathematically

$$\text{tangent of the angle} = \frac{E_L}{E_R}$$

To find the phase shift in a series RL circuit, determine the resistance and reactance values, or the resistor and inductor voltage drops. Plug these values into the appropriate equation above and divide. Look that value up in a table of trigonometric functions. The function tables are located in Appendix C at the end of Unit 3. Look up the numerical value in the

Tangent column. Locate the closest angle corresponding to that value in the Degrees column.

An important point to remember is that the tangent of 45 degrees is equal to one. Many times in electronics it is desirable to make the resistive and reactive values equal. The value of both the sine and cosine at an angle of 45 degrees is equal to .707.

The next example demonstrates how to compute phase angle. What is the phase shift produced by a 1.5 henry choke with a resistance of 200 ohms, at a frequency of 60 Hz?

First, find X_L :

$$\begin{aligned} X_L &= 6.28FL \\ &= 6.28 (60) (1.5) \\ &= 565.2 \text{ ohms} \end{aligned}$$

Then find the tangent of the angle:

$$\begin{aligned} \tan \text{ of the angle} &= \frac{X_L}{R} \\ &= \frac{565.2}{200} \\ &= 2.826 \end{aligned}$$

From Appendix C, tangent of 70 degrees = 2.748 and the tan of 71 degrees = 2.904. Therefore the angle corresponding to a tangent of 2.826 is between 70 degrees and 71 degrees or about 70.5 degrees.

Power in an Inductive Circuit

In a series RL circuit, power is dissipated only by the resistance. To compute true power dissipation, any of the three standard power formulas can be used.

$$P = EI$$

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

The inductor, like the capacitor, is a reactive component that does not dissipate power in its pure form. The inductor alternately stores energy in the form of a magnetic field and then releases it. During one half cycle of AC operation, storage of electrical energy occurs in the magnetic field built around the inductor. When the magnetic field collapses, it induces a voltage into the inductor. This self induced voltage then acts as a source that provides energy to the circuit. The consumption and release of energy cancel one another. Therefore, the total average power dissipated by the inductive reactance is zero. Figure 4-17 shows the current, voltage, and power relationships in a purely inductive circuit.

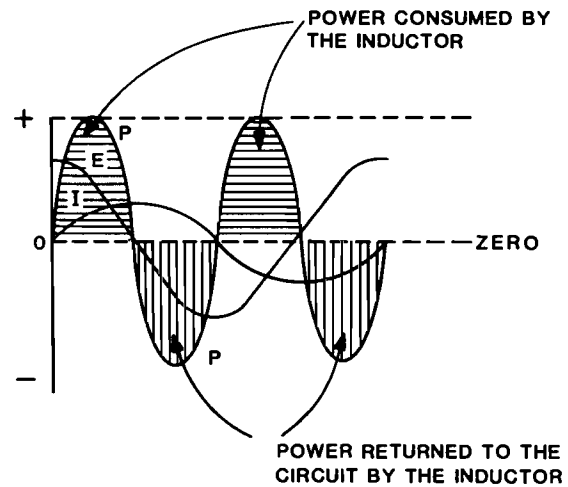


Figure 4-17 Power dissipation in a purely inductive circuit.

Unlike a capacitor, however, an inductor has resistance. For that reason, an inductor actually dissipates some power. It is the resistive portion of the inductor that causes the power to be dissipated. This is called true power. Figure 4-18 shows the current, voltage, and power curves of a series RL circuit where the phase angle is 45 degrees. The power curve, above the zero line, represents the power dissipated in the resistance (true power) and the power consumed by the inductance. The power curve below the zero line is the power returned to the circuit by the inductance.

Figure 4-18B shows a power vector diagram for a series RL circuit. True power, the power actually dissipated by the resistive portion of the circuit is given in watts and is shown as the adjacent side of angle theta.

The volt/amps reactive is the power in the inductive portion of the circuit that is both produced and used by the inductor. This power is shown in Figure 4-18A as the power below the zero line. In Figure 4-18B, this value is shown as the side opposite angle theta.

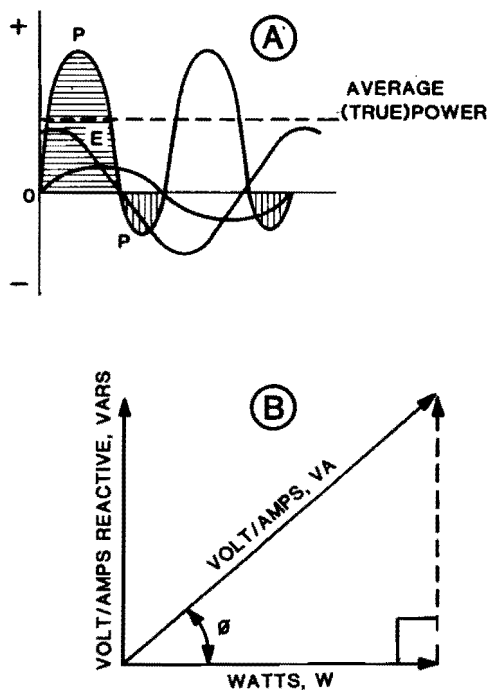


Figure 4-18 Power dissipated in a series RL circuit with a 45° phase shift.

The vector sum of true power in watts and the volt/amps reactive is the apparent power measured in volts/amps. The apparent power is indicated as the hypotenuse of the power triangle.

Voltage, Impedance, and Power Relationships in RL Circuits

When you studied RC parallel circuits, you learned that there is a relationship between the voltage, impedance, and power vector diagrams. The same relationship holds true for vector diagrams of RL circuits. This is illustrated in Figure 4-19.

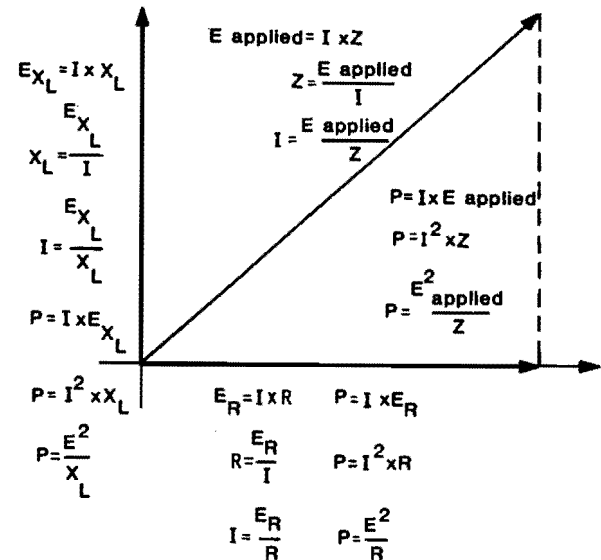


Figure 4-19 Impedance vector of a series RL circuit.

and its variations, apply to the sides of the triangles. For example, if you know the circuit current and the resistance of the circuit, you can determine the voltage drop across the resistance using the formula:

$$E_R = I \times R$$

You can find the applied voltage in the same way by using this variation of Ohm's Law:

$$E_A = I \times Z$$

Ohm's Law can be used to find any quantity on any side of this triangle.

In addition, the phase shift that you determined using quantities from any of the triangles, applies to all of the triangles. All three triangles relate to the same circuit. Therefore, the phase shift indicated by all three triangles must be the same. Here's a problem to demonstrate these concepts.

Draw a vector diagram for a circuit with a resistance of 40 ohms, an inductive reactance of 30 ohms, and a circuit current of .1 amperes. The phase angle of the circuit is about 37 degrees.

$$E_{x_L} = .1A \times 30 \text{ ohms or } 3 \text{ volts}$$

Once you have calculated these two voltages, use the Pythagorean Theorem to determine the applied voltage:

$$E_A = \sqrt{4 \text{ V}^2 + 3 \text{ V}^2}$$

$$E_A = \sqrt{16 + 9} = \sqrt{25} \text{ or } 5 \text{ V}$$

You can now find the circuit impedance using the Ohm's Law derivation:

$$Z = \frac{E_A}{I} = \frac{5 \text{ V}}{.1 \text{ A}} = 50 \text{ ohms}$$

Now, the power formulas can be applied and you can determine the three sides of the power vector diagram.

$$P = I \times E_R$$

$$P = .1A \times 4V$$

$$P = .4 \text{ W}$$

and:

$$P = I \times E_{x_L}$$

$$P = .1A \times 3V$$

$$P = .3 \text{ VARS}$$

and:

$$\begin{aligned}P &= I \times E_A \\P &= .1\text{A} \times 5\text{V} \\P &= .5\text{ VA}\end{aligned}$$

As you can see, once you have solved the vector diagram for any one triangle, it is a simple matter to apply Ohm's Law and determine all of the other quantities necessary to analyze the circuit.

Parallel RL Circuits

Another type of inductive circuit is the parallel RL circuit. A basic RL circuit is shown in Figure 4-20. Notice that this circuit is no more than a coil and a resistor connected in parallel. Although the coil itself has some internal resistance, this resistance will not be considered in the following discussion.

As you will recall from your study of DC electronics, in a parallel circuit, the source or applied voltage is dropped across each of the branches of the circuit. In addition, in a parallel circuit, the resistance of the entire circuit is always less than the resistance of the smallest branch in the circuit. These are important points, when analyzing a parallel RL circuit. Let's see why.

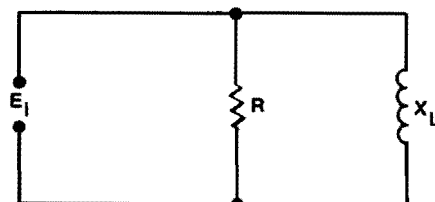


Figure 4-20 Parallel RL circuit.

First, since the voltage across each of the branches is equal to the source voltage, voltage is used as the reference when constructing a vector diagram for parallel RL circuits. Although the voltage across each branch is the same, the current through each branch varies according to the amount of opposition to current flow in that branch. Also, current through the inductive branch lags the current through the resistive branch. The inductive current will lag by an angle of less than 90 degrees. Figure 4-21 shows a typical vector diagram for a parallel RL circuit.

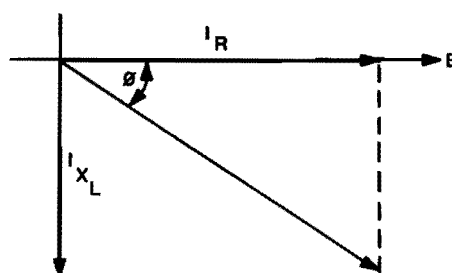


Figure 4-21 Current vector of a parallel RL circuit.

The impedance of a parallel circuit is always less than either the resistance or the inductive reactance of the circuit. Therefore, it is not possible to construct an impedance triangle, unless you use the reciprocal values for resistance, inductive reactance, and impedance. Here's an example.

Assume that you have an RL circuit where the resistance is 50 ohms and the inductive reactance is 50 ohms. To determine the impedance of the circuit, you can use the Pythagorean Theorem. Remember to use reciprocal values.

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}$$

$$\frac{1}{Z} = \sqrt{.02^2 + .02^2}$$

$$Z = 35.35 \text{ ohms}$$

The impedance vector diagram is shown in Figure 4-22.

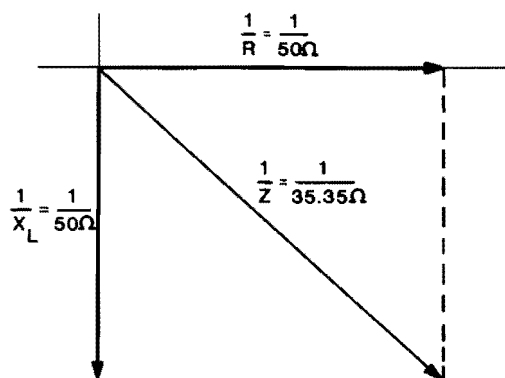


Figure 4-22 Impedance vector of a parallel RL circuit.

You can also find impedance in a parallel RL circuit by using a variation of the product over the sum formula. The impedance equation is:

$$Z = \frac{R \times X_L}{\sqrt{R^2 + X_L^2}}$$

You may recognize this formula from the preceding unit. In fact, everything discussed thus far for the RL parallel circuit is a repetition of the formulas presented for the RC parallel circuits. This is because the mathematical theory is identical. The difference between parallel RC and parallel RL circuits is that, in an RC circuit, the current leads the voltage while in an RL circuit the current lags the voltage. All Ohm's Law and vector diagram relationships that apply to RC circuits also apply to RL circuits. With this in mind, if you have any further questions regarding RL parallel circuits, simply refer to the section on RC parallel circuits in Unit 3.

You may find it easier to solve for individual branch currents and plot the vector relationships in the form of current vectors. The important thing to remember is that current is used as the reference in series circuits. Voltage is used as the reference in parallel circuits. The values that are constant are always used as the reference.

Self-Test Review

51. Voltage drops are computed by using:

_____.

52. When current, resistance, and inductive reactance in a series circuit are known, the voltage drops can be expressed by the equations:

_____ and _____.

53. In any series circuit, the sum of the voltage drops is equal to the applied voltage (E). In an RL series circuit this is referred to as a:

_____.

54. Across the resistor, the phase relationship between current and voltage is:

_____.

55. Across the inductor, the phase relationship between current and voltage is:

_____.

56. In a series RL circuit the resistor voltage is 9 volts and the inductor voltage is 12 volts. The applied voltage is:

_____ volts.

57. The total opposition to current flow in an RL circuit is called:

_____.

58. What is the impedance of a 250 mH choke at 2 kHz?

_____ ohms.

59. The phase shift in a series RL circuit is a function of:

_____ and _____.

60. In a purely resistive circuit the phase angle between the current and applied voltage is:

_____.

61. In a purely inductive circuit, the current and applied voltage are:

_____ out of phase.

62. In an RL circuit the phase angle is always between:

_____ and _____.

63. When resistance is increased relative to the inductive reactance, the phase angle:

_____.

64. The phase angle in an RL circuit can be computed using the tangent formula when you know the:

_____ and _____ sides.

65. What is the phase angle of a series circuit that has a resistance of 10 k ohms and an inductive reactance of 10 k ohms?

_____ degrees.

66. What is the impedance of the circuit described in question 65?

_____.

67. In the circuit described in question 65, the current and voltage are out of phase by:

_____ degrees.

68. Power is dissipated in an inductive circuit across the:

_____ component.

69. The power dissipated across both the resistive and inductive components is called:

_____ power.

70. What is the power dissipated by the choke in the circuit described in question 65. when the applied voltage is 10 volts .

_____ W.

Applications of Inductive Circuits

Inductive circuits, like capacitive circuits, are widely used in electronics. The reactive effect of an inductor makes the inductor valuable in filtering and phase shift applications. However, the inductor is less widely used than the capacitor in such applications. The reasons for this is that inductors are larger, heavier, and more expensive. They also come in a narrower range of standard values and they dissipate power. This makes the inductor far less valuable as a reactive component than the capacitor.

The greatest advantage of the inductor is that it can produce a reactive effect, while completing the DC circuit path. The capacitor produces a reactive effect but blocks DC current. Often a complete DC current path is required, as well as the reactive effect.

Inductive Filters

Series RL networks are used as simple low and high-pass filters in the same way that series RC circuits are used. Figure 4-23 shows the two basic types of RL filter circuits. These circuits are resistor-inductor voltage dividers.

The circuit in Figure 4-23A is a low-pass filter. The input signal is applied across the coil and resistor in series and the output voltage is taken from across the resistor. At low frequencies the reactance of the coil is low, and

very little voltage is dropped across it. Most of the voltage is dropped across the output resistor. As the input frequency increases, inductive reactance increases. The inductive reactance becomes larger with respect to the resistance and more of the input voltage is dropped across the coil. Therefore less voltage appears across the output resistor. As you can see, increasing the frequency causes an increase in the inductive reactance and a corresponding decrease in the output voltage. Low frequencies are passed with little or no attenuation while high frequencies are greatly reduced in amplitude by the inductor's reactance.

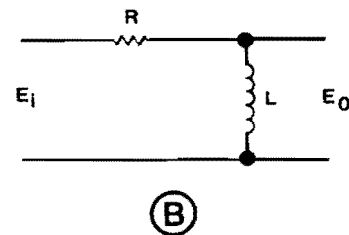
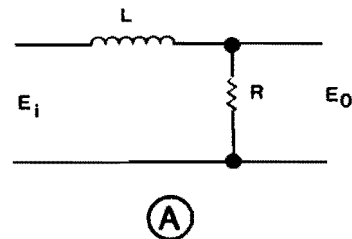


Figure 4-23 Single section RL filters.

- A. Low-pass with lagging phase shift.
- B. High-pass with leading phase shift.

The circuit in Figure 4-23B is a high-pass filter. Again the circuit is a voltage divider with the input AC voltage applied across the coil and resistor in series. The output voltage is taken across the inductor. At very high frequencies, the inductive reactance is very high compared to the resistance. Most of the input voltage is developed across the coil for the output terminals. As the input frequency decreases, the inductive reactance decreases. Less voltage is dropped across the coil and more across the resistor. The lower the frequency the lower the inductive reactance and the lower the output voltage. High frequencies are passed with little or no attenuation. Low frequencies are greatly attenuated due to the voltage divider effect.

These simple low-pass and high-pass RL filter circuits produce the same result as equivalent RC circuits. However, they are less desirable because the inductors are larger and more expensive than capacitors. RC circuits are preferred for filter networks when DC current paths are not required.

The cut-off frequency, F_{co} of the RL filter network shown in Figure 4-23 is:

$$F_{co} = \frac{R}{2\pi L} = \frac{R}{6.28L}$$

The cut-off frequency is that frequency above or below which frequencies are passed or attenuated. In the expression above, R is in ohms, L is in henrys and F is in Hz. At the cut-off frequency, X_L equals R and the phase shift is 45 degrees. At the cut-off frequency, the out-

put voltage E_o , is approximately 70 percent (.707) of the input voltage, E_{in} , or $E_o = .707 E_{in}$. For example, when the input voltage is 8 volts, the output voltage, at the cut-off frequency, will be $8 \text{ V} \times .707 = 5.656$ volts.

Inductive Phase Shifters

Because an inductor causes the current in a circuit to lag the applied voltage, inductive circuits can be used for phase shifting. The simple series RL circuits shown in Figure 4-23 can also serve as phase shifters. With these circuits, a phase shift between 0 degrees and 90 degrees can be obtained. In the circuit shown in Figure 4-23A, the output voltage lags the input voltage. The phase angle is determined by the inductive reactance and the resistance values.

The circuit of Figure 4-23B produces a leading phase shift. The output leads the input by a phase angle between 0 degrees and 90 degrees. As the amount of phase shift produced by the circuit approaches 90 degrees, the output voltage becomes greatly attenuated. Theoretically, with a 90 degree phase shift the output is zero. For that reason, simple RL phase shift circuits are used to provide phase shifts of approximately 60 degrees or less. The greater the phase shift, the greater the need for amplification in the circuit, to restore the amplitude of the output signal.

The amount of phase shift produced by these circuits is a function of the inductance, the resistance, and the input frequency. The tangent of the phase shift is given in the formula below.

$$\tan \text{ of the angle} = \frac{X_L}{R} \text{ (Figure 4-23A)}$$

$$\tan \text{ of the angle} = \frac{R}{X_L} \text{ (Figure 4-23B)}$$

These formulas assume that the resistance of the inductor is negligible when compared to the resistor's value.

To obtain phase shifts greater than 90 degrees, the simple RL networks in Figure 4-23 are cascaded. While large values of phase shift can be obtained, the attenuation of the cascaded circuit is considerable. Some type of amplification is generally required to offset the loss in the circuit. Later in your studies, you will study the transistor amplifier combined with the RL network.

As with RL filters, RL phase shifters are less desirable than RC phase shifters. Inductors are larger, more expensive and have greater losses than capacitors. RC networks are preferred when DC current paths are not required.

Self-Test Review

71. RL circuits are used for:

_____ and _____

72. When frequency increases inductive reactance:

_____.

73. When an RL circuit is used in frequency selective applications, the circuit is called a:

_____.

74. When the output of a series RL circuit is taken across the resistor, the circuit is a:

_____ filter.

75. To use the series RL circuit as a high-pass filter, the output is taken across the:

_____.

76. The frequency that designates the dividing line between frequencies that are passed or attenuated is called the:

_____.

77. The formula for computing the cut-off frequency is:

_____.

78. When $R = 140$ ohms and $L = 107$ mH, the cut-off frequency is:

_____ Hz.

79. To achieve an output that leads the input, the voltage is taken across the:

_____.

80. The maximum possible phase shift of a series RL circuit is:

_____.

81. The practical phase shift limit of a single RL network is usually considered to be:

_____ degrees.

82. When phase shifts of 90 degrees or more are required, RL networks are usually:

_____.

83. List 3 disadvantages of RL networks, compared to RC networks.

1. _____.

2. _____.

3. _____.

84. Name the primary condition when an RL network can not be replaced by an RC network.

_____.

Desk-Top Experiment 4

Analyzing RL Circuits

Introduction

This experiment provides practice in analyzing RL circuits. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

It is recommended that you do your calculations on scratch paper. Once you are satisfied with your calculations, they can be recorded in the spaces provided.

Objectives

1. To calculate the parameters of RL circuits.
2. To plot the phase relationship between voltage and current in an inductive circuit.
3. To plot the DC charge curves for an RL circuit.

Procedure

On a separate sheet of paper, draw the circuit shown in Figure 4-24. The circuit is a series RL circuit. The input sine wave has a value of

100 volts, at a frequency of 1 kHz. Round off your calculations to two decimal places.

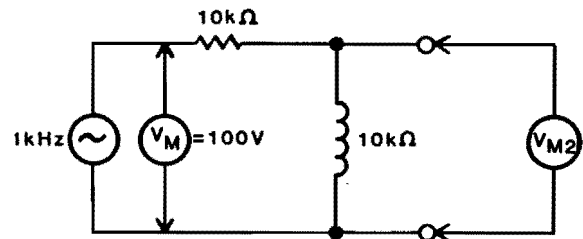


Figure 4-24 Desk-Top Experiment 3.

1. Determine the circuit's RL time constant.

time constant = _____.

2. Calculate the total impedance of the circuit.

$Z_T =$ _____.

3. Calculate the total current flowing in the circuit.

$I_T =$ _____.

4. Draw the vector diagrams, in the space provided, illustrating the voltage and impedance relationships between the components.

What minimum size resistor is required in this circuit?

_____ watt.

7. Explain how it is possible to develop voltages across the components that total more than the supply voltage.

_____.

5. Draw the output vectors, in the space provided, to show the relationship of voltage and current.

6. Calculate the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}.$$

Discussion

The voltage developed across the inductor is not dropped. It is stored in an opposing electromagnetic field around the inductor.

Reactive components don't actually dissipate power. Only resistive components dissipate power.

Before you can find the L/R time constant for this circuit, you must calculate the value of L.

Total impedance is a vector sum in a series RL circuit. Total impedance is greater than either R or X_L , but less than $R + X_L$.

In an inductive circuit, voltage leads current, and as always, voltage is proportional to impedance.

Power dissipated in an RL circuit is the power dissipated by the resistive components.

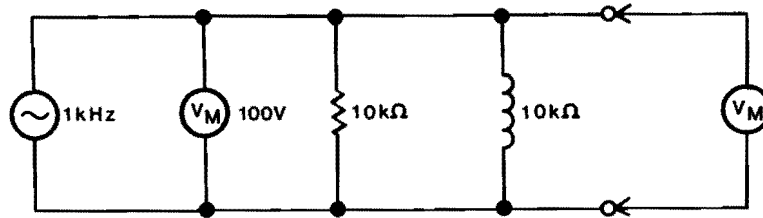


Figure 4-25 Parallel RL circuit.

8. Determine the circuit's RL time constant for the parallel circuit shown.
11. Draw the vector diagram, in the space provided, illustrating the current relationship between the components.

time constant = _____.

9. Calculate the total impedance of the circuit.

$Z_T =$ _____.

10. Calculate the total current flowing in the circuit.

$I_T =$ _____.

12. Draw the vector diagram, in the space provided to show the actual relationship of voltage and current in the inductor.

13. Calculate the apparent power dissipated in the circuit.

$$P_A = \underline{\hspace{2cm}}$$

14. Determine the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}$$

15. What is the minimum power required from the supply.

$$P_{\text{SOURCE}} = \underline{\hspace{2cm}}$$

Discussion

You should have first calculated the value of inductance. Next, you should have calculated the RL time constant.

Since voltage is constant in a parallel circuit, you should have vectored current to find I_T . Then you can use the value of I_T to calculate Z_T .

Since the circuit is inductive, voltage leads current.

Discussion

Apparent power is $I \times E$. The power dissipated is I^2R . Reactive components don't dissipate power, only the resistive components dissipate power. In this example, we neglected the small resistance in the inductor.

16. What is the period of the waveform?

_____.

17. Time of positive alternation is:

_____.

18. Assume the source voltage in the circuit referred to in Step 1 is changed to 100 volts DC. Plot the voltage buildup against charge time, in the space provided.

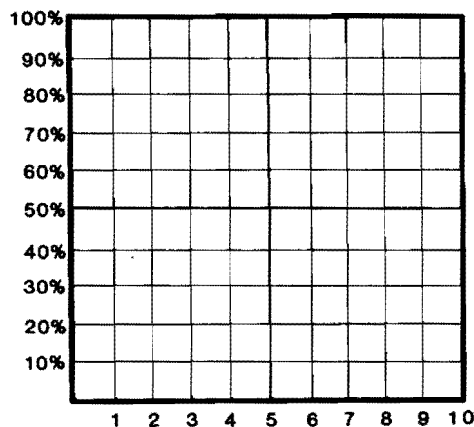


Figure 4-26 Grid square.

19. Assume the source voltage in the circuit referred to in Step 8 is changed to 100 volts DC. Plot the current curve for the electromagnetic field buildup.

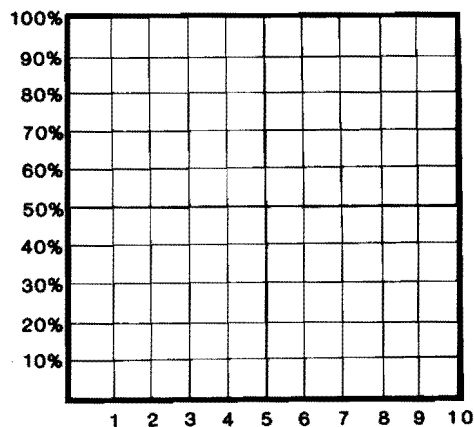


Figure 4-22 Grid square.

Discussion

Time is the reciprocal of frequency. Voltage always leads current in an inductive circuit.

A sine wave is equally divided into positive and negative alternations.

At $t = 0$ (initial turn on), all of the voltage is developed across the inductor, in a series RL circuit. In one RL time constant, the inductor's voltage decreases by 63.2%, while the current increases by 63.2%. After 5 RL time constants, all of the voltage will be dropped across the resistor. Except for initial turn on, and again at turn off, the inductor is almost a short circuit to DC current.

In Step 19, initially, current in the inductive branch is zero. It then increases to 63.2% in one RL time constant. After 5 time constants, the current is maximum, and the voltage is minimum.

Summary

When analyzing a series RL circuit, you can vector either voltage or impedance.

When analyzing a parallel RL circuit, you should vector current.

In an inductive circuit, voltage leads current by an angle between 0 and 90 degrees.

The time constant in an RL circuit, is equal to L/R in both series and parallel circuits.

Z_T , in a series circuit, is always greater than either R or X_L , but less than $R + X_L$.

In a parallel circuit, Z_T is always less than either R or X_L .

The power dissipated in an RL circuit is dissipated by only the resistive components in the circuit.

Sine waves are balanced. This means that the time of the positive alternation is equal to the time of the negative alternation.

In Step 18, E_L is initially maximum and current is minimum. After 5 RL time constants, voltage is minimum and current is maximum.

In Step 19, the initial current through the inductive branch is minimum. It increases, after 5 RL time constants, to a maximum value. In a DC circuit, initially, X_L has an almost infinite impedance. After 5 RL time constants its impedance decreases to almost zero.

Unit Summary

The inductor opposes a change in current. The unit of inductance is the henry. However, millihenry (10^{-3}) and microhenry (10^{-6}) values are more common in electrical circuits. Inductive values are combined the same as resistors. In a series RL circuit they are additive. In a parallel circuit, total inductance is the sum of the reciprocal inductor values.

Inductance (L) is a function of the coil's type material, type of core, diameter, length, number of turns, and spacing between the turns. Inductance is indirectly proportional to its length and directly proportional to the other factors listed.

The inductor has an impedance (X_L) that is measured in ohms. The inductor's impedance is called inductive reactance. Total impedance in an RL circuit is a calculated value and is the vector sum of X_L and R.

Inductors have a small resistance to DC currents, and their AC impedance is directly proportional to frequency. $X_L = 2\pi FL$.

In an inductive circuit, voltage leads current by an angle between zero and 90 degrees.

Two inductors can be series aiding, series opposing, or unaffected by each other. When a current flows through a conductor it builds a magnetic field around the conductor. When current ceases to flow, the field collapses and causes current to continue in the same direction, for a short time. This is called induction and is defined as the transfer of energy from a magnetic field to a conductor.

The magnetic field around the coil has a polarity that is opposite the potential that caused it. Induced voltage always opposes the current causing it. This is usually called counter EMF or electromotive force and is measured in volts.

The L/R time constant of a circuit is L divided by R. Initially, all the voltage is developed across the inductor in an RL series circuit. Five L/R time constants later all the voltage will be dropped across the resistor. In one L/R time constant, the inductor (coil) changes its charge by 63.2%.

The Q (figure of merit) of an inductor is equal to its inductive reactance divided by its resistance.

Inductors are used for coupling, decoupling, filtering, and phase shifting in an RL circuit.

Unit 5

Tuned Circuits

Contents

Introduction	5-3	Q and Bandwidth in Series Resonant Circuits	5-31
Unit Objectives	5-4	Parallel Resonance	5-38
RLC Circuits	5-5	LC Filters	5-53
Resonance.....	5-12	Desk-Top Experiment 6 Analyzing RLC Series-Parallel Circuits .	5-60
Series Resonance	5-17	Unit Summary	5-64
Desk-Top Experiment 5 Analyzing RLC Circuits	5-22	Appendix A: Resonance Nomograph	5-67

Introduction

Tuned circuits are used extensively in electronics. They are used to determine the frequency at which oscillators and amplifiers operate, to separate wanted signals from unwanted signals, and to eliminate interference and noise. Without tuned circuits many phases of electronics would not exist.

Much of the math used in this unit is derived from equations used in Units 3 and 4. In addition, a great deal of the background theory necessary for understanding Unit 5 is from earlier units. Be sure that you thoroughly understand the concepts presented in Unit 3 and 4 before continuing Unit 5.

Unit Objectives

When you have completed this unit, you should be able to:

1. Define: Resonance, resonant frequency, half-power point, flywheel effect, tank circuit, self-resonant, band-pass filter, and band-stop filter.
2. Calculate the impedance, current, voltage, power factor, and phase angle for series and parallel RLC circuits.
3. Determine the capacitor rating, in kilovars, necessary to correct an inductive circuit for a unity power factor.
4. State the characteristics of a series resonant RLC circuit.
5. State the characteristics of a parallel resonant RLC circuit.
6. Determine the Q of a series or parallel circuit at its resonant frequency.
7. Calculate the power savings, in kilowatt hours, of a circuit that has been corrected to a unity power factor.
8. From a given schematic diagram, identify the six basic types of filters.
9. Name the type of filter that would produce a given response curve.
10. Calculate the resonant frequency of an RLC circuit.
11. Determine the bandwidth of a series or parallel resonant circuit.

RLC Circuits

RLC circuits have resistors, inductors, and capacitors connected together in series, parallel, or series-parallel combinations. The simplest RLC circuit consists of a resistor, an inductor, and a capacitor connected in series. This is called a series RLC circuit.

Series RLC Circuits

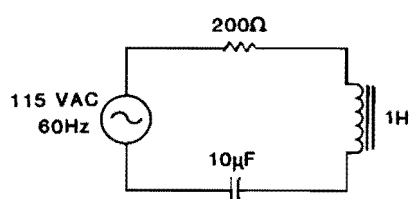


Figure 5-1 Series RLC circuit.

Figure 5-1 shows a resistor, coil, and capacitor connected in series with an AC generator. Because the values of capacitance, inductance, and frequency are given, the reactances in the circuit can be computed using the formulas:

$$X_L = 2\pi FL \text{ and } X_C = \frac{1}{2\pi FC}$$

The inductive reactance is:

$$X_L = 2\pi FL$$

$$X_L = 6.28 \times 60 \text{ Hz} \times 1 \text{ H}$$

$$X_L = 377 \text{ ohms}$$

The capacitive reactance is:

$$X_C = \frac{1}{2\pi FC}$$

$$X_C = \frac{1}{6.28 \times 60 \text{ Hz} \times 0.00001 \text{ F}}$$

$$X_C = \frac{1}{0.00377}$$

$$X_C = 265 \text{ ohms}$$

The reactance values combine with the resistance value to form an impedance to current flow. Recall that there is a general formula for impedance:

$$Z = \sqrt{R^2 + X^2}$$

When the reactance is caused by capacitance, the formula becomes:

$$Z = \sqrt{R^2 + X_C^2}$$

When inductive reactance is involved, the formula becomes:

$$Z = \sqrt{R^2 + X_L^2}$$

The circuit shown in Figure 5-1 contains both capacitive and inductive reactance. Thus, a formula is needed which contains both X_C and X_L . A vector diagram of the reactances and resistance in the circuit will help us to develop such an equation. Figure 5-2 shows the vector diagram for this circuit. Following the conventions established earlier, R is plotted at zero degrees. X_L is plotted at + 90 degrees, and X_C is plotted at - 90 degrees.

Notice that this places X_L 180 degrees out of phase with X_C . For this reason, X_L and X_C tend to cancel. However, because X_L is greater than X_C , the resultant reactance is inductive.

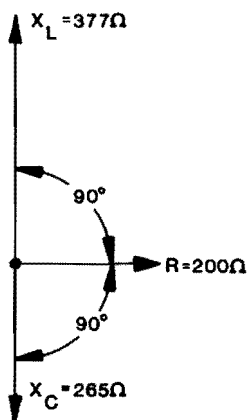


Figure 5-2 Vector diagram for series RLC circuit.

Figure 5-3 shows the resultant vector. Because X_L is 377 ohms and X_C is 265 ohms, X_L completely cancels X_C , and still has a value of 112 ohms. That is:

$$377 \text{ ohms} - 265 \text{ ohms} = 112 \text{ ohms.}$$

Thus, when a circuit has both capacitive reactance and inductive reactance, the net reactance is the difference between the two. Because of this, the complete formula for the impedance in a series AC circuit is:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{200^2 + (377 - 265)^2}$$

$$Z = \sqrt{200^2 + 112^2}$$

$$Z = \sqrt{40,000 + 12,544}$$

$$Z = \sqrt{52,544}$$

$$Z = 229 \text{ ohms}$$

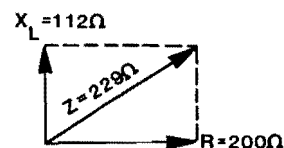


Figure 5-3 Resultant vector after X_L cancels X_C .

The net result is the same as when a coil having an X_L of 112 ohms is connected in series with a resistance of 200 ohms. Figure 5-3 shows the final vector diagram.

The above formula for impedance is used when X_L is greater than X_C . Obviously, there will be cases where X_C is larger than X_L as shown in Figure 5-4A. Here, X_L is 10 ohms, X_C is 40 ohms, and R is 40 ohms.

Figure 5-4B shows the vector diagram for this circuit. Notice that in this case X_C more than

cancels X_L . Thus, the net reactance is found by subtracting X_L from X_C . This is shown in Figure 5-4C and results in a capacitive reactance of 30 ohms. When X_C is larger than X_L , the formula for impedance becomes:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

Using this formula, we find that the total impedance of this circuit is:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

$$Z = \sqrt{40^2 + (40 - 10)^2}$$

$$Z = \sqrt{40^2 + 30^2}$$

$$Z = \sqrt{1,600 + 900}$$

$$Z = \sqrt{2,500}$$

$$Z = 50 \text{ ohms}$$

Once the impedance of the circuit is known we can determine other circuit values. Using formulas developed in earlier units, we can compute values such as current, the voltage dropped by each component, and the power factor. For example, the current in Figure 5-4A must be:

$$I = \frac{E}{Z} = \frac{10 \text{ V}}{50 \text{ ohms}} = 0.2 \text{ amps}$$

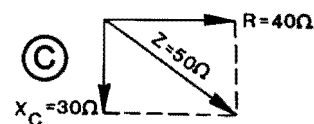
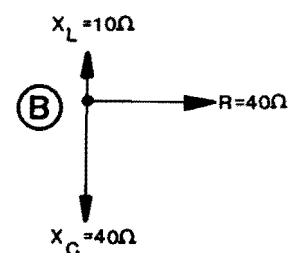
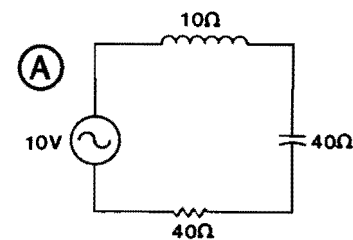


Figure 5-4 Circuit and vectors in which X_C is greater than X_L .

This allows us to find the voltage drop across each component:

$$E_R = I(R) = 0.2 \text{ A} \times 40 \text{ ohms} = 8 \text{ V}$$

$$E_L = I(X_L) = 0.2 \text{ A} \times 10 \text{ ohms} = 2 \text{ V}$$

$$E_C = I(X_C) = 0.2 \text{ A} \times 40 \text{ ohms} = 8 \text{ V}$$

The power factor can be determined using the formula:

$$PF = \frac{R}{Z} = \frac{40 \text{ ohms}}{50 \text{ ohms}} = 0.8$$

Since the power factor is also equal to the cosine of the angle, we can find the angle using the chart at the end of Unit 3. We find that the angle is about 36.5 degrees. The vector shown in Figure 5-4C shows that this is a negative angle. This means that the circuit reactance is capacitive.

We can compute apparent power in volt/amps by multiplying the applied voltage times the current:

$$VA = E \times I$$

$$VA = 10 \text{ V} \times 0.2 \text{ A}$$

$$VA = 2 \text{ VA}$$

The true power is less, since only the resistor dissipates power:

$$P = I^2 R$$

$$P = (0.2 \text{ A})^2 \times 40 \text{ ohms}$$

$$P = 0.04 \text{ A} \times 40 \text{ ohms}$$

$$P = 1.6 \text{ W}$$

The above procedure is a step-by-step way of analyzing a series RLC circuit. Using this procedure, we can compute some of the more important circuit values.

Parallel RLC Circuits

Figure 5-5 shows a parallel RLC circuit. Because the three components are in parallel, the same voltage is applied across each. It is easier to work with currents in parallel circuits. Recall that when a reactance is in parallel with a resistance, the total current is the vector sum of the two branch currents.

$$I_T = \sqrt{I_R^2 + I_X^2}$$

In this formula, I_X may be the current through either a capacitor or an inductor.

This formula can be expanded to handle situations like that shown in Figure 5-5A. Figure 5-5A is a parallel RLC circuit. The first step is to find the current through each branch. This is easy to do since enough of the values are given. The branch currents are:

$$I_R = \frac{E}{R} = \frac{10 \text{ V}}{20 \Omega} = 0.5 \text{ ampere}$$

$$I_L = \frac{E}{X_L} = \frac{10 \text{ V}}{10 \Omega} = 1 \text{ ampere}$$

$$I_C = \frac{E}{X_C} = \frac{10 \text{ V}}{25 \Omega} = 0.4 \text{ ampere}$$

Figure 5-5B shows the branch currents plotted as vectors. I_R is in phase with the applied voltage and is plotted at zero degrees. I_L lags the applied voltage by 90 degrees. I_C leads the applied voltage by 90 degrees. Notice that I_C is 180 degrees out of phase with I_L . As far as the source current is concerned, these two currents tend to cancel.

I_L is larger than I_C . Thus, the total current through the two reactive components is I_L minus I_C or 1 ampere minus 0.4 ampere equals 0.6 ampere. Because the reactive currents subtract, the formula for total current is written:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{0.25 + 0.36}$$

$$I_T = \sqrt{0.61}$$

$$I_T = 0.78 \text{ A}$$

This is further illustrated by the vector shown in Figure 5-5C. The total current is shown as the vector sum of I_R and I_L . The value of I_L is the resultant current after the value of I_C is subtracted from the original value of I_L .

Once we know the total current in the circuit, we can compute other values. For example, the impedance of the circuit is:

$$Z = \frac{E}{I_T} = \frac{10 \text{ V}}{0.78 \text{ A}} = 12.8 \Omega$$

This is the impedance of the three components in parallel.

Also, the phase angle can be found using the formula:

$$\tan \text{ of the angle} = \frac{I_X}{I_R} = \frac{0.6}{0.5} = 1.2$$

Using Appendix C at the end of Unit 3, you will find that a tangent of 1.2 corresponds to an angle of approximately 50 degrees. However, as shown in Figure 5-5C, the angle is negative because the circuit is inductive (ELI) and the plot is for current. Consequently, the total current lags the applied voltage by about 50 degrees.

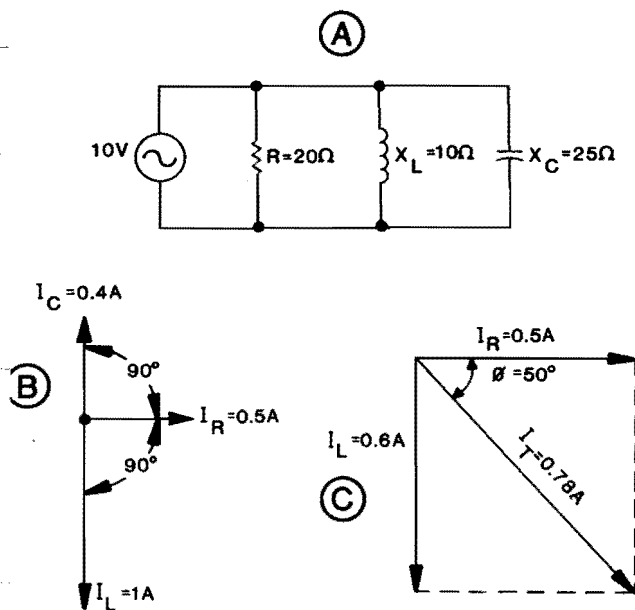


Figure 5-5 Parallel RLC circuit.

Let's use this formula and solve for the total current in Figure 5-5A.

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{0.5^2 + (1 - 0.4)^2}$$

$$I_T = \sqrt{0.5^2 + 0.6^2}$$

Self-Test Review

1. The formula for finding the total impedance in a series RLC circuit is:
_____.
2. A series circuit has an X_L , X_C , and R that are all equal to 10 k ohms at a frequency of 1 kHz. In this circuit at 1 kHz, total impedance is equal to:
_____ ohms.
3. In the circuit described in question 2, when the frequency is doubled, the circuit becomes:
_____.
inductive/capacitive/resistive
4. A series RLC circuit has an inductor with an X_L of 25 ohms, a capacitor with an X_C of 10 ohms, and a resistance of 15 ohms. The total impedance is:
_____ ohms.
5. The applied voltage in the circuit described in question 4 is 18 volts. The current in the circuit is:
_____ A.
6. The voltage drop across the resistor in question 4 is:
_____ V.
7. The voltage drop across the inductor in question 4 is:
_____ V.
8. The voltage drop across the capacitor in question 4 is:
_____ V.
9. The apparent power in the circuit in question 4 is:
_____ VA.
10. The true power in question 4 is:
_____ W.
11. The power factor of the circuit in question 4 is:
_____.
12. In the circuit described in question 4 current and applied voltage are out of phase by:
_____ degrees.
13. The phase relationship between voltage and current in the circuit described in question 4 is:
_____.

14. In a parallel RLC circuit, currents should be:

_____.

15. A parallel circuit has an AC source voltage of 20 volts and an X_L , X_C and R that are all equal to 10 k ohms at a frequency of 1 kHz. In this circuit at 1 kHz, total impedance is equal to:

_____ ohms.

16. In the circuit described in question 15, when the frequency is halved, the circuit appears:

inductive/capacitive/resistive

17. In the circuit described in question 15 the total impedance is now:

_____ ohms.

18. In the circuit described in question 15 the total current in the circuit is:

_____ A.

19. The voltage drop across the resistor in question 15 is:

_____ V.

20. The current through the inductor in question 15 is:

_____ A.

21. The current through the capacitor in question 15 is:

_____ A.

22. The apparent power in the circuit in question 15 is:

_____ VA.

23. The true power in question 15 is:

_____ W.

24. The power factor of the circuit in question 16 is:

_____.

25. In the circuit described in question 15, current and applied voltage are out of phase by:

_____ degrees.

26. The phase angle for the circuit described in question 15 is:

negative/positive

Resonance

In earlier units you studied the inductive reactance of coils and the capacitive reactance of capacitors. Figure 5-6A shows a coil and a capacitor connected in parallel. When a voltage is applied between terminals A and B, the operation of this circuit depends on the frequency of the applied voltage. When the voltage is DC, the capacitor acts like an open, and the inductor acts like a short. Effectively X_C is infinite and X_L is zero.

Now let's assume that the applied voltage is not DC but is a very low frequency AC. In this case, X_L has a very low value and X_C is quite high. The exact values will depend on the values of C, L, and the applied frequency.

When the frequency is gradually increased, X_L gradually increases and X_C gradually decreases. As the frequency is increased, a point is reached where the value of X_L is the same as the value of X_C . That is, for every combination of L and C, there is some frequency at which X_L equals X_C . This is true whether the two components are connected in parallel as shown in Figure 5-6A or connected in series as shown in Figure 5-6B. The condition where X_L is equal to X_C is called **resonance**. Also, the frequency at which X_L is equal to X_C is called the **resonant frequency** and is abbreviated F_o .

The formula for X_L is:

$$X_L = 2\pi FL$$

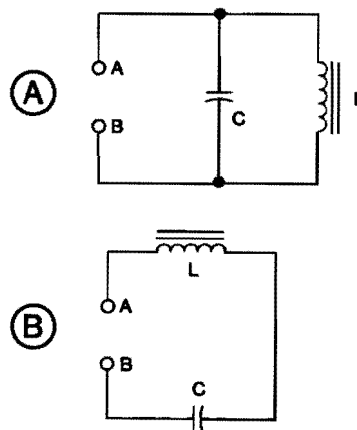


Figure 5-6 LC circuits.

The formula for X_C is:

$$X_C = \frac{1}{2\pi FC}$$

Using these two formulas, we can derive an equation for the resonant frequency, F_o . By definition, at resonance, $X_L = X_C$.

Therefore:

$$2\pi FL = \frac{1}{2\pi FC}$$

To solve for the frequency at which L and C are resonant, we can rearrange this formula. First we multiply both sides of the equation by $2\pi FC$. This gives us:

$$2\pi FL (2\pi FC) = \frac{1 (2\pi FC)}{2\pi FC}$$

$$2\pi FL (2\pi FC) = 1$$

Simplifying we find that:

$$4\pi^2 F^2 LC = 1$$

Dividing both sides by $4\pi^2 LC$ we get:

$$F^2 = \frac{1}{4\pi^2 LC}$$

Now, we take the square root of both sides:

$$\sqrt{F^2} = \frac{\sqrt{1}}{\sqrt{4\pi^2 LC}}$$

Where:

$$\sqrt{F^2} = F$$

Thus our equation becomes:

$$F = \frac{\sqrt{1}}{\sqrt{4\pi^2 LC}}$$

The square root of 1 is 1 and the square root of $4\pi^2$ is 2π . Thus, our final equation is:

$$F_o = \frac{1}{2\pi\sqrt{LC}}$$

Dividing 2π into 1:

$$F_o = \frac{0.159}{\sqrt{LC}}$$

We can apply this formula to any LC circuit to find its resonant frequency. For example, let's assume that a 100 mH coil is connected in series with a .022 microfarad capacitor. What is the resonant frequency?

$$L = 0.1 \text{ H}$$

$$C = .000\,000\,022 \text{ F}$$

$$F_o = \frac{0.159}{\sqrt{LC}}$$

$$F_o = \frac{0.159}{\sqrt{0.1 \text{ H} \times 0.000\,000\,022 \text{ F}}}$$

$$F_o = \frac{0.159}{\sqrt{0.000\,000\,0022}}$$

$$F_o = \frac{0.159}{0.000\,047}$$

$$F_o = 3,383 \text{ Hz or } 3.383 \text{ kHz}$$

Let's try another example. A 5 microfarad capacitor is paralleled with a 50 microhenry coil. What is the resonant frequency?

$$L = 0.000\,05 \text{ H}$$

$$C = 0.000\,005 \text{ F}$$

$$F_o = \frac{0.159}{\sqrt{0.000\,05 \text{ H} \times 0.000\,005 \text{ F}}}$$

$$F_o = \frac{0.159}{\sqrt{0.000\,000\,000\,25}}$$

$$F_o = \frac{0.159}{0.000\,0159}$$

$$F_o = 10,000 \text{ Hz or } 10 \text{ kHz}$$

By rearranging the resonance formula in a different way, we can derive two more important equations. First, we can derive an equa-

tion for finding the value of capacitance needed to resonate with a given value of inductance at a given frequency.

$$X_L = X_C$$

$$2\pi FL = \frac{1}{2\pi FC}$$

$$4\pi^2 F^2 LC = 1$$

$$C = \frac{1}{4\pi^2 F^2 L}$$

We can rearrange the equation differently to give:

$$L = \frac{1}{4\pi^2 F^2 C}$$

This equation can be used for finding the value of inductance needed to resonate with a given value of capacitance at a given frequency. Let's try using these two formulas.

What value of capacitor must be connected across a 5 henry coil to make the circuit resonate at 60 Hz?

$$L = 5 \text{ H}$$

$$F = 60 \text{ Hz}$$

$$C = \frac{1}{4\pi^2 F^2 L}$$

$$C = \frac{1}{4(3.14)^2 (60)^2 (5)}$$

$$C = \frac{1}{39.4 (3,600) (5)}$$

$$C = \frac{1}{709,200}$$

$$C = 0.000\,0014 \text{ F}$$

$$C = 1.4 \mu\text{F}$$

What value of coil must be connected in series with a 1 microfarad capacitor to cause the circuit to resonate at 5 kHz?

$$C = 0.000\,001 \text{ F}$$

$$F_o = 5,000 \text{ Hz}$$

$$L = \frac{1}{4\pi^2 F^2 C}$$

$$L = \frac{1}{4(3.14)^2 (5,000)^2 (.000\,001)}$$

$$L = \frac{1}{39.4 (25,000,000) (.000\,001)}$$

$$L = \frac{1}{985}$$

$$L = .00102 \text{ H}$$

$$L = 1.02 \text{ mH}$$

These examples show how to find the resonant frequency, the value of L, or the value of C. Using these formulas, we can find any one of these variables, when the other two are known. These formulas work equally well for both series and parallel LC circuits. That is, for given values of L and C, the resonant frequency is the same regardless of how L and C are connected.

However, as you will see later, a series resonant circuit behaves very differently than a parallel resonant circuit

Some values of L and C are shown in Appendix A at the end of this unit. The values are arranged in accordance with the frequency at which X_L and X_C are equal. This is the resonant frequency for particular values of L and C .

Self-Test Review

27. When X_L equals X_C the circuit is operating at its:

_____ frequency.

28. The formula for resonant frequency is:

_____.

29. A 1 henry coil and a 1 microfarad capacitor have a resonant frequency of:

_____ Hz.

30. What value inductor must be connected across a 5 microfarad capacitor in order for the circuit to resonate at 100 Hz?

$L =$ _____ H.

31. What value of C is required to cause an LC circuit to resonate at 1 kHz when the inductance is 1 henry?

$C =$ _____ microfarad.

Series Resonance

The previous section defined resonance and gave a formula for determining the resonant frequency of any LC circuit. In this section, you will see that an LC circuit has characteristics at resonance that are not present at any other frequency. These unusual characteristics make the resonant circuit extremely useful.

Figure 5-7 shows a series circuit consisting of a capacitor, an inductor, and a resistor. The values of L and C are not given, nor is the frequency of the applied signal. Nevertheless, we know that the circuit is at the resonant condition because X_L is equal to X_C .

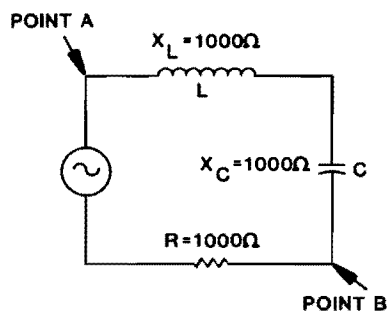


Figure 5-7 At resonance $X_L = X_C$.

The applied AC signal forces current to flow through the series circuit. Because the components are in series, the same current flows through all of the components.

As current flows through the circuit, a voltage is developed across each component. Because $R = X_L = X_C$, the voltages developed across each

component are equal. That is, $E_R = E_L = E_C$. However, this is true only of the **magnitude** of the voltage. The phase of the voltage is different across each component. The voltage across R is in phase with circuit current. The voltage across the coil leads the current by 90 degrees. The voltage across the capacitor lags behind the current by 90 degrees.

Remember the memory phrase for current and voltage relationships in inductive and capacitive circuits. **ELI** the **ICE** man.

The best way to visualize these phase relationships is with vector diagrams.

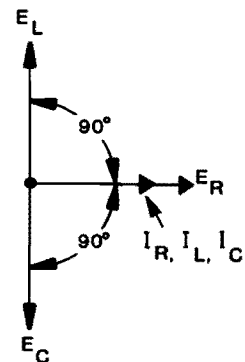


Figure 5-8 Vector diagram of series resonant circuit.

Figure 5-8 shows the vector diagram of the voltage drops and current. I_R, I_L, I_C , and E_R are all in phase with the applied current. Consequently, they are shown with a phase angle of zero and are used as the reference for the re-

lationship plots. E_L is drawn at + 90 degrees and E_C is drawn at -90 degrees. Thus, E_L is 180 degrees out of phase with E_C .

This illustrates one of the most important characteristics of the series resonant circuit. At resonance, the voltages across the capacitor and coil are of equal magnitude but they are 180 degrees out of phase. Consequently, E_L exactly cancels E_C . Thus, as far as the source is concerned, the sum of these two voltages is zero. Therefore, a voltmeter connected between points A and B in Figure 5-7 measures zero volts.

When the combined voltage drops across X_L and X_C equals zero, then all of the applied voltage must be dropped across R. For example, when the source voltage is 10 volts, the voltage dropped across R is 10 volts. A voltmeter placed across R measures 10 volts. However, since the same current must flow through C, a voltmeter placed across C also measures 10 volts. Moreover, a voltmeter placed across L measures 10 volts. At first this seems to violate Kirchhoff's Voltage Law (the sum of the voltage drops around a closed loop must equal zero). Because the 10 volts across C is canceled by the 10 volts across L, the sum of the voltage drops around the closed loop is equal to zero. As Figure 5-8 shows, the vector sum of E_L and E_C is zero volts.

Since the combination of L and C produces no voltage drop, their total reactance or impedance must be zero. That is, the source sees the

LC combination as a perfect conductor having 0 ohms of impedance. Thus, the only opposition to current flow in the circuit is the resistance of R. At resonance the source sees no capacitance and no inductance, only resistance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

This is proven by applying the impedance formula:

When $X_L = X_C$, $X_L - X_C = 0$. Therefore:

$$Z = \sqrt{R^2 + 0}$$

$$Z = \sqrt{R^2}$$

$$Z = R$$

In a series resonance circuit, total impedance is equal to R. This means that current and voltage, as seen by the source, are in phase. Therefore the power factor is 1.

It is important to emphasize again that these conditions occur only at resonance. When the applied frequency is above or below resonance, X_L does not exactly equal X_C . Consequently, the voltage drops across L and C do not completely cancel. In this case, there is some resultant value of reactance.

The third unusual thing which happens in series resonant circuits is the most mysterious of all. It is not evident in Figure 5-7 because the value of R is equal to the value of X_L and X_C . However, look at the circuit shown in Fig-

ure 5-9. Here the value of R is much less than that of X_L or X_C . Nevertheless, the circuit is still at resonance because X_L equals X_C .

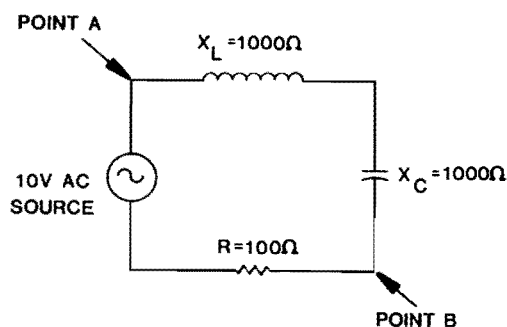


Figure 5-9 R is less than X_L or X_C .

We have seen that the current in a resonant circuit is determined solely by the applied voltage and the value of the series resistance. In Figure 5-9 circuit current is:

$$I = \frac{E}{R}$$

$$I = \frac{10 \text{ V}}{100 \text{ ohms}}$$

$$I = 0.1 \text{ ampere}$$

This same current flows through C and L . Therefore, the voltage drop across C must be $E_C = I(X_C) = 0.1 \text{ A} \times 1,000 \text{ ohms} = 100 \text{ V}$. Also, the voltage drop across L must be $E_L = I(X_L) = 0.1 \text{ A} \times 1,000 \text{ ohms} = 100 \text{ V}$. Notice that the voltage across L or C is actually ten times higher than the voltage being applied to the circuit.

Once again, this may seem to violate Kirchhoff's Voltage Law. However, it does not since the 100 volts across L is exactly cancelled by the 100 volts across C . A voltmeter connected from point A to point B measures zero volts. But, if the meter is connected across L or C separately, it measures the 100 volts.

The ability to produce a voltage higher than the applied voltage is one of the most remarkable characteristics of the series resonant circuit. This is possible because of the ability of the coil and the capacitor to store energy.

The inductor (coil) stores energy in its magnetic field. The capacitor stores energy in its dielectric in the form of an electrostatic field.

This storage occurs at resonance any time that the value of R is lower than the value of X_L or X_C . The lower the value of resistance, when compared to reactance, the higher the voltage developed across the reactance. If all series resistance could be eliminated entirely, the current in the circuit would theoretically rise to an infinitely high value. The voltage across the coil and the capacitor would also become infinitely high.

In practice, of course, some series resistance always exists. The AC source and the connecting wires always have some value of series resistance. However, in LC circuits the largest source of series resistance is usually the coil. Most coils are wound from lengths of very

small wire. Thus, they have a relatively large value of series resistance (when compared to source resistance or conductor wire). This resistance reduces the resonant current even when physical resistors are not used.

To summarize, the series resonant circuit has several important characteristics. These are listed below:

1. The impedance across the circuit is low and is equal to the series resistance.
2. The current flow is high and is limited only by the series resistance.
3. The applied voltage is dropped by the series resistance.
4. The voltage across the coil or capacitor is equal to the current times the reactance. This voltage may be higher than the applied voltage.
5. The circuit acts resistive. The source current and voltage are in phase and the power factor is 1.

Self-Test Review

32. A series RLC circuit is resonant at the frequency at which X_L is equal to:

_____.

33. When X_L is equal to X_C , the voltage developed across the inductor is the same as that developed across the:

_____.

34. The relationship between the voltage drops across the capacitor and the inductor, in a series RLC circuit, at resonance is:

_____ degrees.

35. In a series resonant circuit, total impedance is equal to:

R/L/C

36. A series RLC circuit, with a supply voltage of 100 volts, is operating at its resonant frequency. A voltmeter connected in parallel with the inductor and capacitor measures:

_____ volts.

37. The combined total impedance of the coil and capacitor at resonance is:

_____ ohms.

38. In a series resonant circuit with 30 volts AC applied, the resistance, inductive reactance, and capacitive reactance is 10 ohms. What is the current in the circuit?

_____ A.

39. In the circuit in question 38, what is the voltage drop across X_L ?

_____ volts.

40. When a reactive voltage drop is compared to the applied voltage in a series RLC resonant circuit, the combined voltage drop is usually:

_____ than/as the applied voltage.
larger/smaller/the same

41. In a series RLC resonant circuit, current is always:

_____.
maximum/minimum/constant

Desk-Top Experiment 5

Analyzing RLC Circuits

Introduction

This experiment provides practice in analyzing RLC circuits. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

It is recommended that you do all of your calculations on scratch paper. Once you are satisfied with your calculations, they can be recorded in the spaces provided in this experiment.

Objectives

1. To calculate the parameters of RLC circuits.
2. To evaluate the effects of increasing and decreasing frequency in series RLC circuits.
3. To evaluate the effects of increasing or decreasing frequency in parallel RLC circuits.

Procedure

On a separate sheet of paper, draw the circuit shown below. The circuit is a series RLC circuit. The input sine wave has an effective value of 100 volts at 1 kHz. Round off your calculations to two decimal places.

Calculate the circuit parameters listed below. Record your answers in the spaces provided in this experiment.

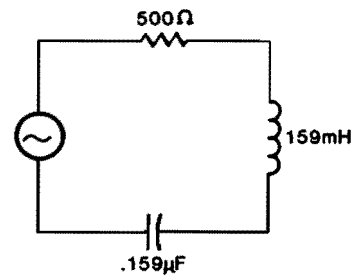


Figure 5-10 Desk-Top Experiment 5.

F kHz	R k Ω	X _L k Ω	X _C k Ω	Z _T k Ω	I _T mA	$\angle\theta$	P _A W	P _T W	E _R V	E _L V	E _C V

Figure 5-11 At resonance.

1. Calculate the total impedance of the circuit.
4. Draw the voltage vector diagram, in the space provided, that illustrates the relationship between the components.

$$Z_T = \underline{\hspace{2cm}}.$$

2. Calculate the total current flowing in the circuit.

$$I_T = \underline{\hspace{2cm}}.$$

3. Calculate the voltage drop across each component.

$$E_R = \underline{\hspace{2cm}}.$$

$$E_C = \underline{\hspace{2cm}}.$$

$$E_L = \underline{\hspace{2cm}}.$$

5. Draw three vector diagrams, in the space provided, to show the relationship of voltage and current in each of the components.

Discussion

You should have found that X_L and X_C are approximately equal. This indicates that the circuit is resonant at 1 kHz. At resonance, in a series circuit, impedance is minimum and line current (current supplied by the source) is maximum.

At resonance Z_T is equal to R , true power and apparent power are equal, and the circuit appears to be purely resistive. In a resistive circuit, voltage and current are in phase.

6. Calculate the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}$$

7. In the series RLC circuit described in Step 1, the frequency is increased from 1 kHz to 10 kHz. Plot the effects of the increased frequency, in the spaces provided. Use directional arrows to indicate the effects of increasing frequency. The flight of the arrows are as follows; arrow up means increase, arrow down means decrease, and horizontal arrow means remains the same.

ARROW												
	F	R	X_L	X_C	Z_T	I_T	$\angle\theta$	P_A	P_T	E_R	E_L	E_C
VALUE												

Figure 5-12 Above resonance.

ARROW												
	F kHz	R k Ω	X_L k Ω	X_C k Ω	Z_T k Ω	I_T mA	$\angle\theta$	P_A W	P_T W	E_R V	E_L V	E_C V
VALUE												

Figure 5-13 Below resonance.

8. In the series RLC circuit described in Step 1, the frequency is decreased from 1 kHz to 100 Hz. Using directional arrows, indicate the effects of decreasing frequency in the spaces provided.

Discussion

Above resonance, total impedance increases and becomes a vector sum, X_L increases, X_C decreases, and the circuit changes from a resistive circuit to an inductive circuit. In an inductive circuit, voltage leads current. When impedance increases, line current decreases. Both apparent power and true power decrease, but they are no longer equal.

Below resonance, total impedance increases and becomes a vector sum, X_C increases, X_L decreases, and the circuit changes from a resistive circuit to a capacitive circuit. In a ca-

pacitive circuit, current leads voltage. When impedance increases, line current decreases. Both apparent power and true power decrease, but they are no longer equal.

9. Calculate the reactive impedances for the parallel RLC circuit shown.

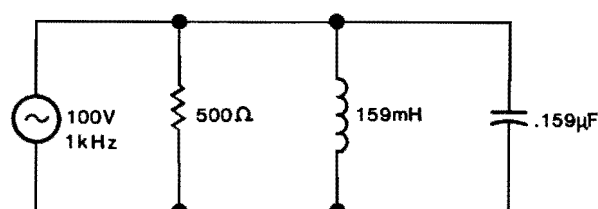


Figure 5-14 Parallel circuit.

$$X_L = \underline{\hspace{2cm}}$$

$$X_C = \underline{\hspace{2cm}}$$

-
10. Calculate the total impedance of the circuit.

$$Z_T = \underline{\hspace{2cm}}.$$

11. Calculate the branch currents flowing in the circuit.

$$I_R = \underline{\hspace{2cm}}.$$

$$I_L = \underline{\hspace{2cm}}.$$

$$I_C = \underline{\hspace{2cm}}.$$

12. Calculate the total (line) current flowing in the circuit.

$$I_T = \underline{\hspace{2cm}}.$$

13. Draw the vector diagram, in the space provided, illustrating the current relationship between the components.

14. Draw the three vector diagrams, in the space provided, to show the relationship of voltage and current, in each of the components.

15. Calculate the apparent power delivered by the source.

$$P_A = \underline{\hspace{2cm}}.$$

16. Calculate the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}.$$

17. Fill in the calculated parameters, in the spaces provided.

F kHz	R k Ω	X _L k Ω	X _C k Ω	Z _T k Ω	I _T mA	$L\theta$	P _A W	P _T W	I _R mA	I _L mA	I _C mA

Figure 5-15 At resonance.

Discussion

You should have found that X_L and X_C are again equal. You should know that this is an indication that the circuit is at resonance. For these component values, 1 kHz is the approximate resonant frequency.

At resonance in a parallel circuit, impedance is maximum and line current is minimum. Apparent power and true power are equal. I_L and I_C are equal and opposite, and therefore, cancel each other. The only effective impedance, in the circuit, is the resistive branch.

Since the only impedance in the circuit is the resistor, the circuit is purely resistive, and current and voltage are in phase.

ARROW												
	F	R	X_L	X_C	Z_T	I_T	$\angle\theta$	P_A	P_T	I_R	I_L	I_C
VALUE												

Figure 5-16 Above resonance.

18. In this parallel RLC circuit, increasing the frequency from 1 kHz to 10 kHz changes some of the circuit's parameters. Record the effects of increasing frequency in the spaces provided. Use directional arrows to indicate direction of change.

19. In this parallel RLC circuit, decreasing the frequency from 1 kHz to 100 Hz, changes some of the circuit's parameters. Record the effects of decreasing frequency in the spaces provided. Use directional arrows to indicate direction of change.

ARROW												
	F	R	X_L	X_C	Z_T	I_T	$\angle\theta$	P_A	P_T	I_R	I_L	I_C
VALUE												

Figure 5-17 Below resonance.

Discussion

Above resonance in a parallel RLC circuit, X_L is greater than X_C and they no longer cancel. Therefore, line current (I_L) is a vector sum and it increases. This is because any impedance added in parallel decreases total impedance. Apparent power ($I \times E$) increases but true power (I^2R), remains the same. Since X_L is larger than X_C , I_C is larger than I_L and the circuit appears to be capacitive.

Note that when X_L is greater than X_C in a series RLC circuit, the circuit is inductive. In parallel RLC circuits, the circuit is current controlled, and capacitive.

Below resonance, in a parallel RLC circuit, X_C is larger than X_L and they no longer cancel. Line current is a vector sum and it increases, because total impedance decreases. Again, apparent power increases and true power remains the same. Since I_L is now larger than I_C , the circuit is inductive and voltage leads current.

This is opposite what happens in a series RLC circuit. Below resonance, a series RLC circuit is capacitive and the parallel RLC circuit is inductive.

Summary

First you calculated the values of X_L and X_C .

$$X_L = 2\pi FL$$

$$X_C = \frac{1}{2\pi FC}$$

When $X_L = X_C$, the circuit is at resonance and the total impedance is equal to R . Apparent power and true power are equal.

In a series resonant circuit impedance is minimum, current is maximum, and voltage and current are in phase.

In a parallel resonant circuit impedance is maximum, line current is minimum, and voltage and current are in phase.

Above resonance in a series RLC circuit X_L is greater than X_C and impedance is a vector sum. Impedance increases and current decreases. The circuit appears to be inductive and voltage leads current.

Above resonance, in a parallel RLC circuit X_L is still larger than X_C . However, current is vectored in parallel circuits. Since I_C is larger than I_L the circuit appears to be capacitive and current leads voltage.

Below resonance in a series RLC circuit X_C is larger than X_L and impedance is a vector sum. Impedance increases and current decreases. The circuit appears to be capacitive and current leads voltage.

Below resonance in a parallel RLC circuit X_C is still larger than X_L . However, current is vectored in parallel circuits. Since I_L is larger than I_C , the circuit appears to be inductive and voltage leads current.

Q and Bandwidth in Series Resonant Circuits

The series resonant circuit has two characteristics which we have not yet discussed. These are called **Q** and **bandwidth**. **Q** was introduced earlier as a figure of quality for coils. However, the term **Q** as used with resonant circuits has additional aspects which must be understood. Bandwidth was also mentioned earlier in connection with filters. Here, we will discuss bandwidth in more detail.

Q in Series Resonant Circuits

One of the most important characteristics of a resonant circuit is its **Q**. Other names for **Q** are quality figure, figure of merit, and magnification factor. The **Q** factor is defined as the ratio of the reactance at resonance, to the series AC resistance. That is:

$$Q = \frac{X_L}{R}$$

Since at resonance $X_L = X_C$.

$$Q = \frac{X_C}{R}$$

Normally, the reactance of a circuit in terms of **Q** is expressed as an inductive property which is X_L .

In a resonant circuit in which $X_L = X_C = 1,000$ ohms, and the series AC resistance is 100 ohms, the **Q** factor is 10.

$$Q = \frac{X_L}{R} = \frac{1,000 \text{ ohms}}{100 \text{ ohms}} = 10$$

Since **Q** is the ratio of reactance to resistance, the ohms in each term cancel. **Q** is a number without associated units.

In a series resonant circuit, **Q** is the magnification factor that determines how much the voltage across **L** or **C** is increased above the applied voltage. For example, a 1 V peak-to-peak AC signal is applied to a series resonant circuit with a **Q** of 10. The voltage across **L** or **C**, at resonance, is 10 V peak-to-peak. Thus, the applied voltage, E_{IN} , is magnified by the **Q** factor. Expressed as an equation:

$$E_L = Q \times E_{IN}$$

And:

$$E_C = Q \times E_{IN}$$

When the applied voltage, E_{IN} , and the voltage across **L** or **C** (E_L or E_C), are known, the **Q** factor is calculated using the formula:

$$Q = \frac{E_L}{E_{IN}} \text{ or } Q = \frac{E_C}{E_{IN}}$$

Q can be determined by measuring E_{IN} and E_L or E_C and using the above formula. For ex-

ample, E_{IN} is measured with an AC voltmeter and found to be 0.1 volt. E_L is measured and found to be 15 volts. The Q of the circuit must be:

$$Q = \frac{E_L}{E_{IN}} = \frac{15 \text{ V}}{0.1 \text{ V}} = 150$$

This method of determining Q generally gives more accurate results than the X_L/R method. The reason for this is that the AC resistance of the circuit is difficult to voltmeter. The oscilloscope is also used to measure voltage when peak-to-peak values are required.

Generally, the largest single factor that makes up the series resistance is the AC resistance of the coil. A circuit's AC resistance can be much higher than its DC resistance. The DC resistance can be measured with an ohmmeter. The AC resistance of a component is difficult to measure. AC resistance (impedance) is usually determined by measuring the AC voltage across and the current through a component. Then using Ohm's Law the AC resistance is calculated.

A coil has a Q factor of its own. When the only series resistance in a series resonant circuit is the coil, the Q of the circuit is the same as the coil. This is the highest Q that a resonant circuit can have. When additional series resistance is added, the Q of the circuit is lower than the Q of the coil.

While it is difficult to directly measure the AC resistance of a series resonant circuit, the value can be computed from known or measured circuit quantities. For example, a series resonant circuit develops 10 volts across a 1 henry coil, at 100 Hz, with a 0.1 volt AC input. The circuit Q and AC resistance are:

$$Q = \frac{E_L}{E_{IN}} = \frac{10 \text{ V}}{0.1 \text{ V}} = 100$$

$$Q = \frac{X_L}{R}$$

$$R = \frac{X_L}{Q}$$

You have seen that Q is 100. Thus, if we find X_L , you can determine R .

$$X_L = 2\pi FL$$

$$X_L = 8.28 (100 \text{ Hz}) (1 \text{ H})$$

$$X_L = 628 \text{ ohms}$$

Therefore:

$$R = \frac{X_L}{Q}$$

$$R = \frac{628 \text{ ohms}}{100}$$

$$R = 6.28 \text{ ohms}$$

This shows some of the reasons that Q is important. However, Q is also important in determining the bandwidth of a resonant circuit.

Bandwidth and Q

Resonant circuits are selective circuits. They respond more favorably to their resonant frequency, F_0 , than to other frequencies. While the resonance effects are greatest at F_0 , these same effects exist to a smaller extent at frequencies slightly above and below F_0 . Thus, a resonant circuit actually responds to a band of frequencies. The width of this band of frequencies is called the **bandwidth** of the resonant circuit. The bandwidth is the frequencies that have amplitudes from .707 of the peak value to the peak value. Remember, the sine wave increases from zero to a peak and back to zero. The bandwidth is the frequencies between the .707 increasing and .707 decreasing points of the output waveform.

Measuring Bandwidth

Figure 5-18 illustrates how bandwidth is measured. This graph shows the current passed by a series resonant circuit at various frequencies below, at, and above the resonant frequency. Naturally, maximum current flows at the resonant frequency. In this example, F_0 is 1,000 Hz and the maximum current is 10 mA.

The bandwidth of the series resonant circuit is generally considered to include that group of frequencies with a response 70.7% of maximum. In our example, frequencies which pro-

duce a current of 7.07 mA or higher are considered within the bandwidth. This band of frequencies extends from f_1 (900 Hz) to f_2 (1,100 Hz).

The **bandwidth** is defined as the width of this band of frequencies. Consequently the bandwidth (BW) is $f_2 - f_1$, or 1,100 Hz – 900 Hz = 200 Hz. The bandwidth is that band of frequencies which produce a response of 70.7% of maximum current.

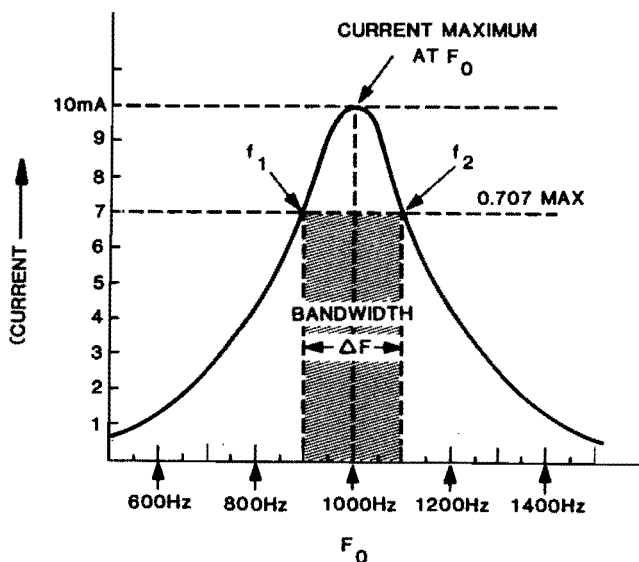


Figure 5-18 Bandwidth is measured between half-power points.

Half-Power Points

You may wonder why the 70.7% points were chosen to indicate the bandwidth. Actually this is a very convenient point to use because it represents the point at which the power in the circuit is exactly one-half the maximum value. Thus, the points marked f_1 and f_2 in Figure 5-18 are referred to as **half-power points**.

An example demonstrates that the power in a circuit drops to one-half when the current drops to 70.7%. Consider a circuit in which the resistance is 2,000 ohms and the current is 10 mA. The power is:

$$P = I^2 R$$

$$P = (0.01 \text{ A})^2 \times 2,000 \text{ ohms}$$

$$P = 0.0001 \text{ A} \times 2,000 \text{ ohms} = 0.2 \text{ watt}$$

Now let's assume that the current drops to 70.7% of maximum or to 7.07 mA. The power drops to:

$$P = I^2 R$$

$$P = (0.00707 \text{ A})^2 \times 2,000 \text{ ohms}$$

$$P = 0.00005 \text{ A} \times 2,000 \text{ ohms} = 0.1 \text{ watt}$$

This is one-half the previous power. Thus, reducing the current to 70.7% reduces the power to 50%.

Bandwidth Equals F_o/Q

With the bandwidth measured between the half-power points, an interesting relationship exists between the bandwidth, the resonant frequency, and the value of Q . This relationship is expressed by the equation:

$$BW = \frac{F_o}{Q}$$

This states that the bandwidth is equal to the resonant frequency divided by Q .

For the example shown in Figure 5-18, the Q is 5 because:

$$BW = \frac{F_o}{Q}$$

$$BW = \frac{1,000 \text{ Hz}}{5}$$

$$BW = 200 \text{ Hz}$$

The equation states that the bandwidth is directly proportional to the resonant frequency, but inversely proportional to Q .

The f_2 point is defined as the upper frequency limit of the bandwidth. The f_1 point is defined as the lower frequency limit of the bandwidth.

Therefore, the bandwidth is all of the frequencies from the f_1 point to the f_2 point.

The curves shown in Figure 5-19 illustrate that the bandwidth increases as the value of Q decreases. When the value of Q is high, the current in the circuit is relatively high. The resonant circuit responds to a very narrow band of frequencies. The resonant frequency is 100 kHz. Thus, if the Q is 50, the bandwidth is:

$$BW = \frac{F_o}{Q} = \frac{100 \text{ kHz}}{50} = 2 \text{ kHz}$$

Notice what happens to the curve when the Q is reduced to 25. The current is lower and the curve is wider. The bandwidth increases to:

$$BW = \frac{F_o}{Q} = \frac{100 \text{ kHz}}{25} = 4 \text{ kHz}$$

When the Q is reduced to 10, an even wider response curve results. The current is relatively low and the bandwidth is:

$$BW = \frac{F_o}{Q} = \frac{100 \text{ kHz}}{10} = 10 \text{ kHz}$$

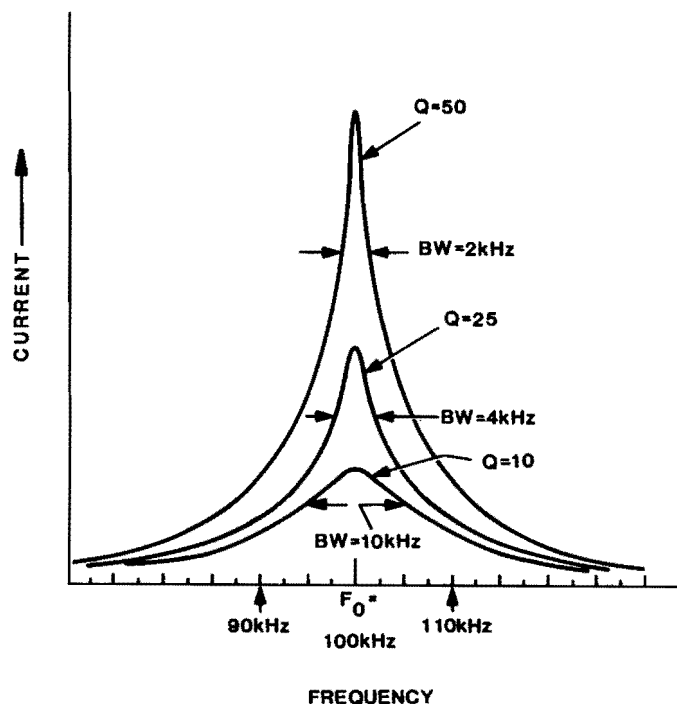


Figure 5-19 Bandwidth increases as Q decreases.

Figure 5-20 shows three circuits which produce curves like those shown in Figure 5-19. The three circuits are identical except for the value of resistance. The value of R determines the Q of the circuit. Q determines bandwidth.

Notice that the value of R does not affect the resonant frequency, only Q and bandwidth. As the value of R increases, Q decreases, and bandwidth increases.

Self-Test Review

42. The Q of a series resonant circuit is generally defined as the ratio of the reactance to the series:

_____.

43. In a series resonant circuit the resistance formula for Q is:

_____.

44. The reactance normally associated with a circuit's Q is:

_____.

45. When E_{IN} is 5 volts and Q is 10, the voltage across the capacitor is:

_____ volts.

46. The relationship between a circuit's Q and bandwidth is expressed by the formula:

_____.

47. The bandwidth of a series resonant circuit is measured between the:

_____ - _____ points.

48. The f_1 and f_2 points are the points where the current has a value of:

_____ of maximum.

49. The exact frequency at which power is maximum is defined as the circuit's:

_____.

50. When resistance is increased, Q :

_____.
increases/decreases

51. When Q is decreased, bandwidth:

_____.
increases/decreases

Parallel Resonance

Up to now we have considered only those resonant circuits in which the capacitor is in series with the inductor. In this section, we will consider another type of resonant circuit called a parallel resonant circuit. When the capacitor is placed in parallel with the inductor, the characteristics of the resonant circuit change completely.

Ideal Circuit

A parallel resonant circuit is shown in Figure 5-21. We know that the circuit is in the resonant condition because X_L is equal to X_C . Thus, the applied AC signal is at the proper frequency to cause the circuit to resonate.

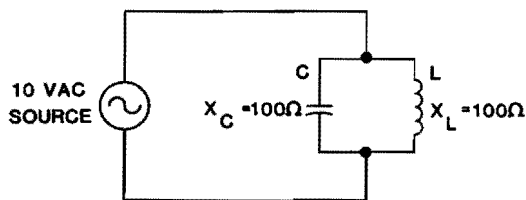


Figure 5-21 Parallel resonant circuit.

To simplify the explanation of this circuit, let's initially assume that L and C are ideal components so that there is no resistance in the circuit. Of course, in practical circuits there is always some resistance and we will consider its effects later. But for now, let's see what would happen in an ideal parallel resonant circuit.

When the capacitor is temporarily disconnected from the circuit as shown in Figure 5-22A, the current through the coil can be determined using Ohm's Law:

$$I_L = \frac{E}{X_L} = \frac{10 \text{ V}}{100 \text{ ohms}} = 0.1 \text{ A}$$

The current must be supplied by an AC source. Since L is a pure inductor, I_L must lag the applied voltage by 90 degrees (ELI).

When the capacitor is reconnected and the inductor is disconnected as shown in Figure 5-22B, the current through the capacitor can be determined using Ohm's Law:

$$I_C = \frac{E}{X_C} = \frac{10 \text{ V}}{100 \text{ ohms}} = 0.1 \text{ A}$$

In a capacitor the current leads the voltage by 90 degrees (ICE). Thus, I_C must lead the applied voltage by 90 degrees. Now, we will consider the operation of the complete circuit. When I_C leads the applied voltage by 90 degrees, and I_L lags the applied voltage by 90 degrees, then I_C must be 180 degrees out of phase with I_L . This means that when the current is flowing in one direction through L, an equal current must be flowing in the opposite direction through C.

For example, at the instant when 0.1 A is flowing up through L, exactly 0.1 A must be flowing down through C. By applying Kirchhoff's Current Law to point A in Figure 5-22C, we discover that there is no current flowing into or out of the source. That is, the same current

that flows up through L also flows down through C and no current flows to or from the source. On the next alternation, the current flows up through C and down through L but still no current flows in the external circuit. The current oscillates back and forth between the capacitor and the inductor.

In the ideal parallel resonant circuit, the source voltage is required only to start the oscillation. Once started, the source can be dis-

connected and the oscillations will continue indefinitely. As mentioned earlier, this is true only if there are no losses in the circuit.

Now let's consider how the parallel resonant circuit appears to the AC source. The AC voltage is applied across the LC combination and yet no current flows to or from the source. Consequently, as far as the source is concerned, the circuit appears to be open. That is, it appears to have infinite impedance.

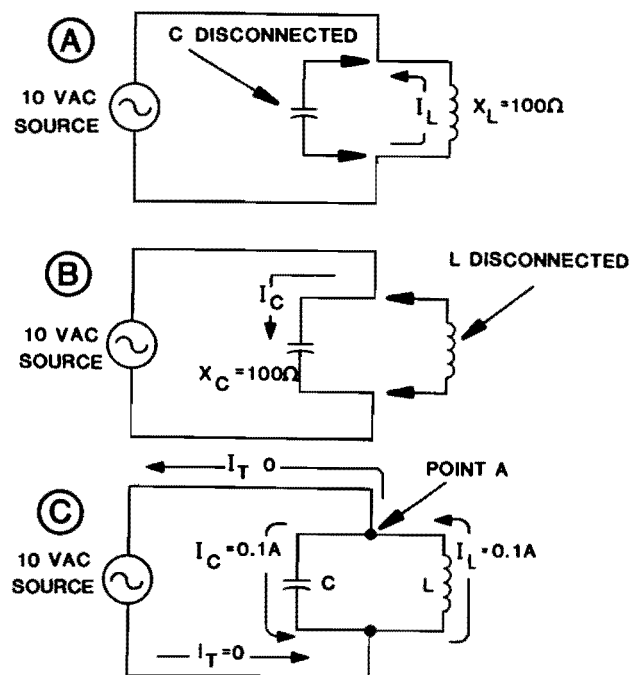


Figure 5-22 Current in the parallel resonant circuit.

Flywheel Effect

The ability of a parallel resonant circuit to sustain oscillation after the source voltage is removed is called the flywheel effect. It gets this name because the action is similar to that of a mechanical flywheel. Once the mechanical flywheel is started, it tends to keep going until stopped by friction or some outside force. The flywheel effect of the parallel resonant circuit is illustrated in Figure 5-23.

Initially, energy is supplied to the circuit by an AC source. Once started, the energy is alternately stored by the capacitor and then by the coil. Let's pick up the action at the point where C is fully charged as shown in Figure 5-23A.

The applied voltage can be removed since it has supplied the necessary starting energy. As shown in Figure 5-23B, the capacitor begins to discharge through L. As current flows through L, a magnetic field builds up around the inductor.

When C is completely discharged, the current through L momentarily stops. Consequently, the magnetic field around L starts to collapse, this induces an EMF with the polarity shown in Figure 5-23C. This keeps the current flowing in the same direction and charges C to the polarity shown.

When the magnetic field has collapsed, the condition shown in Figure 5-23D exists and the capacitor is again fully charged. At the next instant, the capacitor begins to discharge. This time, the current flows in the opposite direction through the coil as shown in Figure 5-23E. This causes a magnetic field of the opposite polarity to build up around L.

When C is again completely discharged, the current through L stops and the magnetic field collapses. As shown in Figure 5-23F, an EMF is induced which keeps current flowing in the same direction. Thus, C is again charged to its initial polarity.

At this point the cycle repeats itself. As you can see, the energy is interchanged between the capacitor and the coil. Initially, the energy is stored as an electrostatic field in the capacitor's dielectric. Then, it is stored as a magnetic field around the inductor. Theoretically, neither the capacitor nor the coil dissipates energy. Therefore, the oscillations would continue indefinitely. Remember, we assumed a pure inductor, a pure capacitor, and no resistive losses in the circuit.

A circuit of this type stores energy, and is commonly called a **tank circuit**.

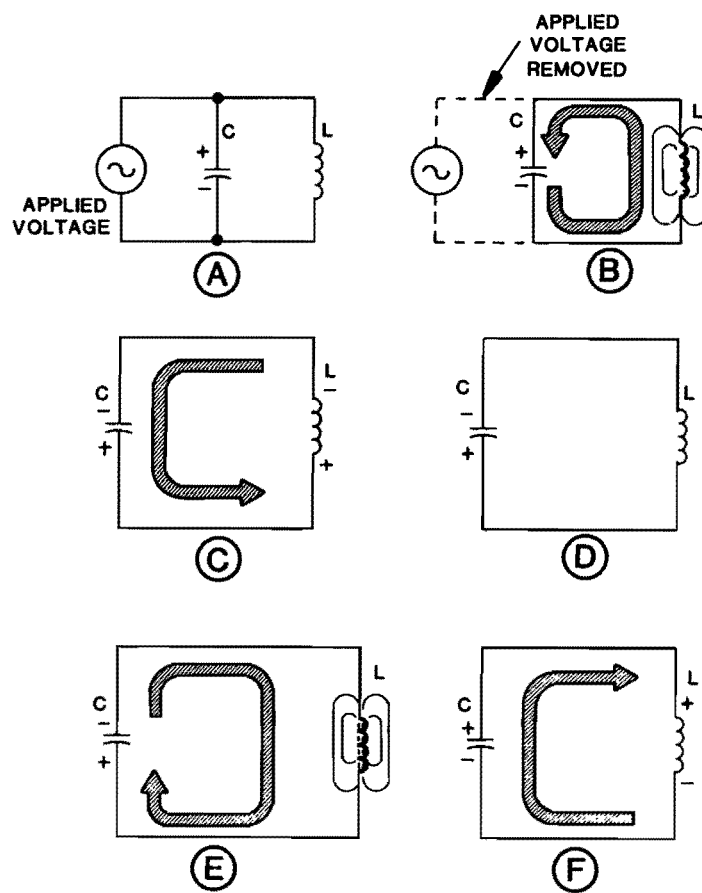


Figure 5-23 The flywheel effect.

Practical Tank Circuits

The ideal tank circuit is one which has no resistance or losses of any kind. Unfortunately, such a tank circuit does not exist. The capacitor, the coil, and the interconnecting wires all have resistance. Normally, only the resistance of the coil is high enough to be of importance. In reality, practical tank circuits must be analyzed as if there is a resistor in series with the inductor as shown in Figure 5-24. R represents the resistance of the coil.

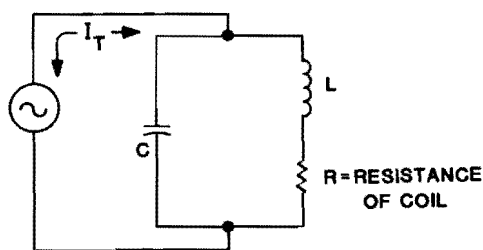


Figure 5-24 Practical tank circuit.

Unlike reactance, resistance dissipates power. As the current oscillates between the coil and the capacitor, the resistor dissipates some of the power in the form of heat. Consequently, energy is removed from the tank circuit during each cycle of operation. For this reason, in a practical tank circuit, the oscillations will die out (cease) when the AC source is disconnected. Figure 5-25 shows how the voltage waveform across the tank circuit would look if

the source was disconnected. Each cycle gets progressively weaker (lower amplitude) as the resistance dissipates the energy stored in the circuit. The waveform produced is called a damped sine wave.

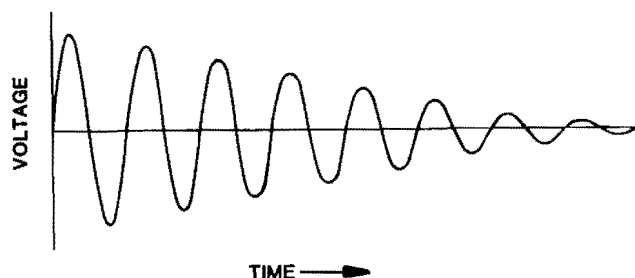


Figure 5-25 Damped sine wave.

Because energy is lost in the circuit, energy must be supplied from the source to make up for the loss. The AC source provides just enough energy to make up for the loss caused by resistance. The result is that some current flows from the AC source to the tank circuit. If the resistance value in the tank is high, more power will be dissipated, and the current drawn by the tank from the source will be higher.

This may seem to contradict Ohm's Law since current is inversely proportional to resistance. The resistance limits the circulating current within the tank. However, in doing so, it consumes power. This power must be supplied by the AC source. Therefore, the current from the source must increase.

Remember that a source must be able to supply the power to drive the load. The load demands the current needed to drop the voltage around a closed loop. In a circuit without resistance there is no load. Effectively the cir-

In the series resonant circuit we found Q by dividing the applied voltage, E_{IN} into either E_C or E_L . This will not work in parallel resonant circuits since E_{IN} is applied directly across both C and L . In the parallel resonant circuit, we are concerned with current rather than with voltage. Thus, in the parallel resonant circuit, Q can be determined by dividing the source current into the tank current. Recall that in a good quality tank circuit (one with a high Q), the source current is very low while the circulating current can be very high. Therefore:

$$Q = \frac{I_{TANK}}{I_{SOURCE}}$$

When source current is 1 mA and tank current is 100 mA, Q is:

$$Q = \frac{100 \text{ mA}}{1 \text{ mA}} \text{ or } 100$$

As with the series resonant circuit, Q can also be expressed as the ratio of X_L or X_C , to R . Where R is the total AC resistance within the tank. It is usually higher than the value of R that can be measured with an ohmmeter.

hance. The impedance of the tank is equal to the reactance of L or C times Q . That is:

$$Z_{TANK} = X_L (Q)$$

$$Z_{TANK} = X_C (Q)$$

For example, when the value of X_L , and X_C , at resonance, are 1,000 ohms, and Q is 100, the impedance of the tank will be:

$$Z_{TANK} = X_L (Q)$$

$$Z_{TANK} = 1,000 \text{ ohms} \times 100$$

$$Z_{TANK} = 100,000 \text{ ohms}$$

$$Z_{TANK} = 100 \text{ k ohms}$$

By transposing the equation, we can develop another useful equation. That is:

$$Q = \frac{Z_{TANK}}{X_L}$$

Thus we have three equations for Q . They are:

$$Q = \frac{I_{TANK}}{I_{SOURCE}}$$

$$Q = \frac{X_L}{R}$$

$$Q = \frac{Z_{TANK}}{X_L}$$

The last equation is the most useful for determining Q . It is difficult to use the first equation because it is hard to measure AC current. The second equation also presents problems because it is hard to determine the total AC resistance.

To use the last equation, all we need are the values of X_L and Z_{TANK} . X_L can be computed when the values of L and the resonant frequency are known. The impedance of the tank can be easily determined by the method shown in Figure 5-26.

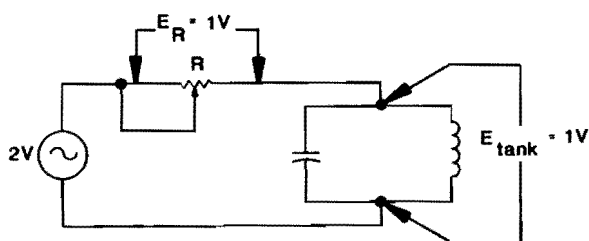


Figure 5-26 When $E_R = E_{TANK}$, $Z_{TANK} = R$.

Here, a variable resistor is placed in series with the tank circuit. At the resonant frequency, the resistor is adjusted until the voltage across the resistor is equal to the voltage across the tank. That is:

$$E_R = E_{TANK}$$

$$E_R = 1/2 E_{IN}$$

At this point, R drops the same amount of voltage as the tank. Thus, R must be equal to the impedance of the tank. The circuit is then disassembled and the value of R can be measured with an ohmmeter. This method provides the value of Z_{TANK} . This value is then used in the equation to determine the Q of the circuit.

Bandwidth in Parallel Resonant Circuits

Like the series resonant circuit, the parallel tank circuit responds to a band of frequencies rather than a single frequency. Figure 5-27 shows a typical response curve. Notice that this curve has the same shape as the response curve shown earlier for the series resonant circuit. However, if you examine Figure 5-27 more closely you will see that it shows the **impedance** of the circuit rather than the current through the circuit.

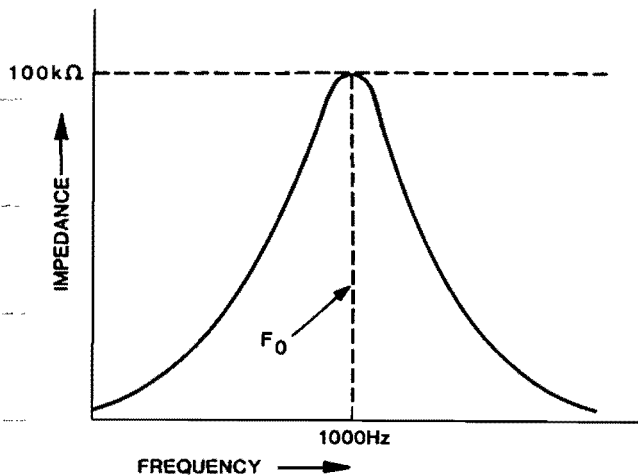


Figure 5-27 Response curve of a parallel resonant circuit (impedance vs. frequency).

At the resonant frequency in a parallel resonant circuit, impedance is maximum. Below resonance, the coil offers a low reactance and the circuit impedance decreases. Above resonance, the capacitor offers a low reactance and the circuit impedance again decreases.

Remember that any time resistance (reactance) are combined in parallel, total impedance is decreased. At resonance X_L and X_C are exactly equal and have opposite polarities. Effectively, they appear as an open (infinite impedance).

Impedance in a parallel resonant circuit is maximum and current is minimum.

Impedance in a series resonant circuit is minimum and current is maximum.

Because the source or line current is inversely proportional to the impedance, the current response curve has the shape shown in Figure 5-28. Notice that the line current decreases as the resonant frequency is approached.

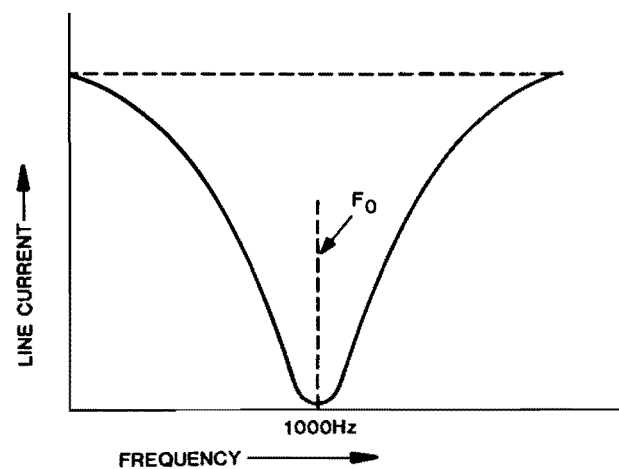


Figure 5-28 Response curve of a parallel resonant circuit (line current vs. frequency).

As with the series resonant circuit, the width of the band of frequencies to which the circuit responds is determined by the Q of the circuit. The bandwidth is determined by the formula:

$$BW = \frac{F_0}{Q}$$

For example, when a parallel resonant circuit has a resonant frequency of 1,000 Hz and a Q of 20, the bandwidth will be:

$$BW = \frac{F_o}{Q}$$

$$BW = \frac{1,000 \text{ Hz}}{20}$$

$$BW = 50 \text{ Hz}$$

This circuit responds to the band of frequencies between 975 Hz and 1,025 Hz.

Often a parallel resonant circuit will be more selective than we want. That is, it responds only to a very narrow band of frequencies. In these cases, we can increase bandwidth by connecting a relatively small valued resistor across the tank circuit as shown in Figure 5-29A. The resistor provides an alternate path for line current which increases line current.

Recall that:

$$Q = \frac{I_{TANK}}{I_{LINE}}$$

For this reason, Q is inversely proportional to line current. When the line current increases, Q decreases.

The next formula shows that bandwidth is inversely proportional to Q.

$$BW = \frac{F_o}{Q}$$

When Q decreases, bandwidth increases. Therefore, connecting a resistor across the tank circuit always increases bandwidth. This is often called loading the tank circuit. When the tank circuit is paralleled by a resistor, the resistor is sometimes called a shunt resistor or swamping resistor.

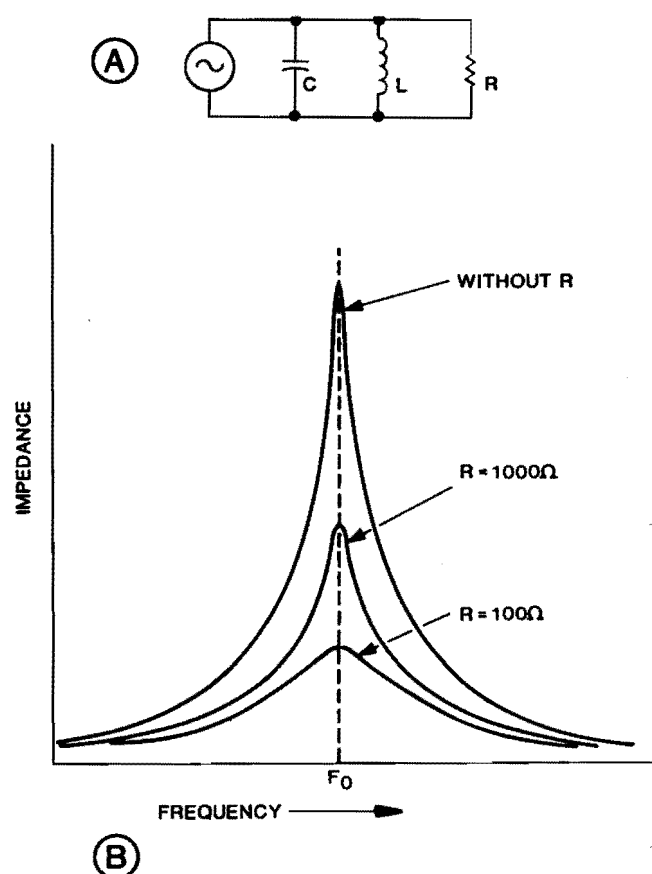


Figure 5-29 Bandwidth may be increased by loading the tank circuit.

Figure 5-29B shows the effect that a loading resistor has. Without the resistor, the impedance is extremely high and the circuit responds to a very narrow band of frequencies around the resonant frequency. When a 1,000 ohm resistor is used, the additional parallel path for current reduces circuit impedance and broadens bandwidth. A 100 ohm resistor reduces the impedance still further and widens the bandwidth even more.

Distributed Capacitance and Self Resonance of Coils

As mentioned earlier, every coil has a certain value of distributed capacitance. That is, the coil acts as if a small value capacitor is connected in parallel. At some frequency, the coil and this value of distributed capacitance form a parallel resonant circuit. At this frequency, the coil is said to be self-resonant. Thus, a single coil can have the characteristics of a parallel resonant circuit at its self-resonant frequency.

In this case the inductor acts as a tank circuit and could self oscillate. In most cases this is undesired and therefore a capacitor is used to ensure that the inductor does not cause self oscillation. This will be explained later in your study of electronic circuits in the specific applications where it usually causes problems.

Power Factor and the Parallel Resonant Circuit

In industrial applications of AC electronics, especially where large motors are used, power factor is an important consideration. Let's look at a typical industrial situation.

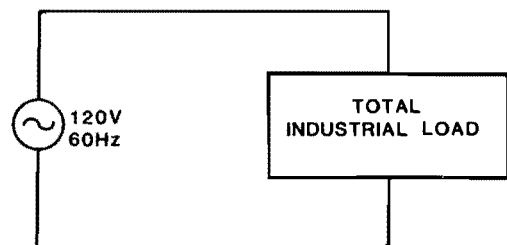


Figure 5-30 Inductively loaded circuit.

Figure 5-30 represents the entire circuit load for a small factory. This load may be any number of motors, lighting fixtures, and other components connected in parallel. This load is connected to a 120 volt, 60 Hz source. The line current is 50 amperes and the power factor for the entire circuit is .707. Remember, power factor is equal to the true power divided by the apparent power and is the same as the cosine of the phase angle.

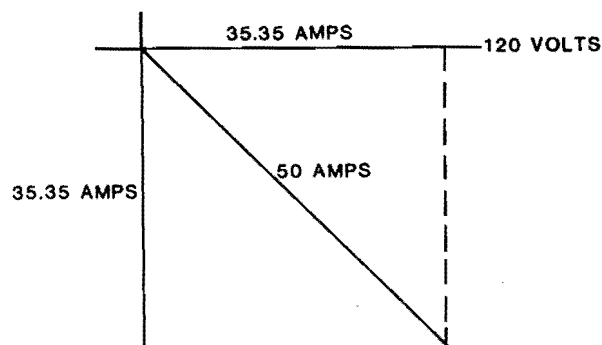


Figure 5-31 Current plot of an inductive load.

Since the motors are inductive, the load appears to be inductive. In Figure 5-31, the current vector diagram for the circuit is shown. Notice that the line current, 50 amps, is the current through the impedance of the entire circuit. The line current is shown as the hypotenuse of the current triangle. The current through the resistive portion of the circuit (35.35 amps), and the current through the reactive portion of the circuit (35.35 amps), are calculated using the trigonometric relationships:

Tangent is the opposite side divided by the adjacent side.

Recall also that when two sides of a right triangle are equal the angle must be 45 degrees

and the sine and cosine of 45 degrees is 0.707. The tangent of 45 degrees is equal to 1.

At any rate, the industrial customer must pay the utility company for the power that appears to be used in the circuit. The amount of power consumed is calculated using the line current and the voltage applied. This "power" is:

$$120 \text{ volts} \times 50 \text{ amps} = 6,000 \text{ volt/amps.}$$

Notice that the power company considers the power used in the factory to be the same as the number of volt/amps or apparent power for the circuit. As you know, the inductive portion of the circuit does not actually consume power. It merely stores energy and then releases it. This, however, is not taken into consideration when the power consumption is calculated.

There is a way to correct this obvious problem. Remember, the current through a reso-

In order to bring apparent power into line with the amount of power actually being used, it is necessary to add a capacitor in parallel with the inductive circuit. Since X_L and X_C are equal at resonance, you must first determine the

inductive reactance of the circuit. Then you can determine what size capacitor is required to cause resonance.

This is done by applying Ohm's Law to the inductive portion of the circuit. The inductive reactance is:

$$X_L = \frac{120 \text{ volts}}{35.35 \text{ amps}} \text{ or } 3.39 \text{ ohms}$$

Since X_L and X_C are equal, then:

$$3.39 = \frac{1}{2\pi FC}$$
$$3.39 = \frac{1}{6.28 \times 60 \times C}$$

This transposes to:

$$C = \frac{1}{6.28 \times 60 \times 3.39} \text{ or } .000783 \text{ F}$$

783 microrarads is equal to .000783 F

By adding a 783 microfarad capacitor in parallel with the industrial circuit (factory load), the circuit becomes a parallel resonant circuit. Now, when power consumption is calculated, only the true power is indicated. The power consumed by the parallel resonant circuit is:

$$P = 120 \text{ V} \times 35.35 \text{ A} = 4,242 \text{ W}$$

The factory in this case saved the difference between 6,000 VA and 4,242 watts.

A factory's current requirements are much higher than the assumed value of 50 amperes, that we used as an example. Many homes have 200 ampere service drops. Many factory service drops are rated in the kiloampere range.

A service drop is the line that routes power from the main power line to the point of entry (usually the power company's meter).

Capacitor Ratings

Capacitors that are actually used to correct the power factor in industrial applications are rated in kilovars. To determine the size of the capacitor necessary to correct a particular circuit, you must know the inductive power used in the circuit. For the example, this is:

$$\begin{aligned} \text{reactive power} &= 120 \text{ V} \times 35.35 \text{ A} \\ &= 4,242 \text{ VARS} \end{aligned}$$

In order to calculate the rating of the capacitor, divide the number of VARS by 1,000 like this:

$$\frac{4,242}{1,000} = 4.242 \text{ kilovars}$$

A 4.424 kilovar capacitor is needed to correct the circuit used in our example.

Calculated Power Savings

Utility companies usually bill customers for the number of kilowatt hours used during a given period. In order to convert the power used into kilowatt hours use the formula:

$$\text{kilowatt hours} = \frac{\text{watts}}{1,000} \times \text{time}$$

Let's calculate the power saving for our typical industrial customer for an 8 hour day. Without a corrected power factor, the industry uses:

$$\text{kW hours} = \frac{6,000 \text{ W}}{1,000} \times 8 \text{ hours} = 48 \text{ kW hrs}$$

Now, with a corrected power factor, the power company supplies the industry with:

$$\text{kW hours} = \frac{4,242 \text{ W}}{1,000} \times 8 \text{ hours} = 33.94 \text{ kW hrs}$$

The savings for a single day amounts to more than 10 kW hrs, or almost a 23% reduction in power used.

Most factories monitor their power factor and make adjustments to compensate for heavy load variations such as peak and slack production periods. Since heat has an effect on components and electronic equipment, the power factor is also monitored and adjusted seasonably.

Many industrial sites can adjust their power factor. This is accomplished with an assortment of capacitors, that can be added or removed by switches, to compensate for changes in inductive loads.

Self-Test Review

52. In a parallel LC resonant circuit, impedance is:

_____.

53. In a parallel LC resonant circuit, current is :

_____.

54. The current that flows between the capacitor and inductor in a tank circuit is called:

_____ current.

55. The oscillations of a tank circuit is referred to as the:

_____ effect.

56. In practical tank circuits, energy is dissipated by:

_____.

57. Generally, the largest source of AC resistance is the resistance of the:

_____.

58. For a tank circuit to continue to oscillate some current must be supplied by the:

_____.

59. At resonance, the line current when compared to the tank current is:

_____.
more/less/the same

60. A tank circuit that consumes power is characterized by an output that tapers off. In oscillators (tank circuits) these waveforms are said to be:

_____ waveforms.

61. The current formula for finding Q is:

$Q =$ _____.

62. When the line current is 2 mA and the tank current is 100 mA, the Q of the circuit is:

_____.

63. The formula for finding resonant frequency, when both Q and bandwidth are known is:

_____.

64. A circuit with an F_o of 64 kHz and a Q of 16 has a bandwidth of:

_____.

65. The f_2 point for the circuit in question 64 is:

_____.

66. Adding a swamping or shunt resistor to a tank circuit:

_____ bandwidth.

67. Adding a swamping resistor in parallel to a resonant tank circuit:

_____ tank impedance.

68. Adding a swamping resistor to a tank circuit:

_____ circuit Q.

69. Power factor is equal to the:

_____ of an angle.

70. The power factor correction component is usually:

_____.
resistive/inductive/capacitive

71. When the power factor is equal to 1, apparent power is:

_____ true power .
lower than/higher than/the same as

LC Filters

In an earlier unit you saw that RC and RL circuits pass some frequencies more easily than others. When an RC or RL circuit is designed to be frequency selective, the resulting circuit is called a filter.

In this unit we have seen that LC circuits are frequency selective. Therefore LC circuits can make good filters.

Types of Filters

There are several types of filters used in electronics. Generally, a basic filter circuit can be placed in one of four categories.

A **band-pass** filter is designed to pass a narrow band of frequencies, while rejecting both higher and lower frequencies. Such filters are used in radios and TV receivers to pass the frequencies of the selected station while blocking the frequencies of all other stations.

A **band-stop** filter is designed to pass all frequencies except a narrow band. This type of filter can be used to clip out an annoying frequency without interfering with wanted frequencies.

A **low-pass** filter is used to attenuate all frequencies above a certain **cutoff** frequency. Thus, it passes low frequencies but blocks high frequencies.

A **high-pass** filter has the opposite characteristic. It passes signals above the **cutoff** frequency but blocks those below.

All four types of filters are commonly used. The frequencies which are blocked or passed depend on the component values used and how the components are arrayed. Let's look at some typical filters starting with the band-pass filter.

Band-Pass Filter

A very simple band-pass filter is shown in Figure 5-32A. The filter is the series resonant circuit composed of L and C. R_L is the load to which the voltage is applied. At the resonant frequency, the series resonant circuit has a very low impedance. Thus, it drops very little of the applied voltage, E_{IN} . Most of the voltage is developed across R_L . Consequently, E_{OUT} is high at the resonant frequency.

Below the resonant frequency, the X_C of the capacitor is higher than the resistance of R_L . Consequently, most of E_{IN} is dropped across C. This leaves only a small voltage across R_L . Thus, E_{OUT} is a low voltage.

Above the resonant frequency, the X_L of the coil is higher than R_L . Therefore, most of the voltage is dropped across the coil and E_{OUT} is again a low voltage.

Figure 5-32B shows how the circuit responds to a band of frequencies. At the resonant frequency of L and C , E_{OUT} is high. Above and below resonance E_{OUT} drops off quickly to a low voltage.

Figure 5-32C shows that the parallel resonant circuit can also be used as a band-pass filter. Whereas the series resonant circuit is placed in series with the output, the parallel resonant circuit is placed across the output. The reason for this becomes evident when we remember the characteristics of a parallel resonant circuit.

At resonance the impedance of the tank circuit is maximum. Consequently, very little current flows through the tank circuit. Most of the current flows through R_L . The current through R_L is maximum at resonance.

Below resonance, X_L of the coil is small when compared to the value of R_L . Thus, most of the current flows through L and very little current flows through R_L . Above resonance, most of the current flows through the capacitor again leaving little current for R_L . That is, above and below resonance, R_L is partially shorted (bypassed) by the low impedance of the tank. Thus, most of the applied voltage is

dropped across R_S . However, at resonance, the impedance of the tank is high and R_L provides the path of least resistance.

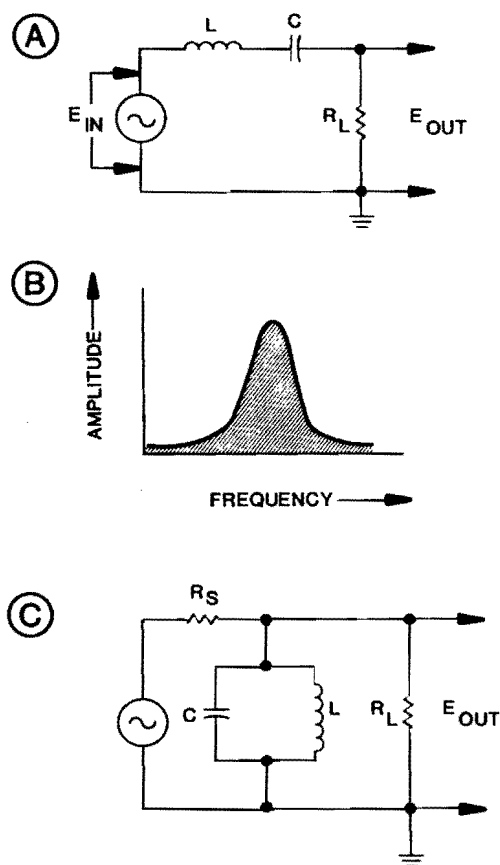


Figure 5-32 Band-pass filter.

Figure 5-33A shows another type of band-pass filter. This one uses a transformer. Recall that the windings of a transformer have an inductance value like any other coil. Therefore, a capacitor can be connected across one of the windings to form a parallel resonant circuit.

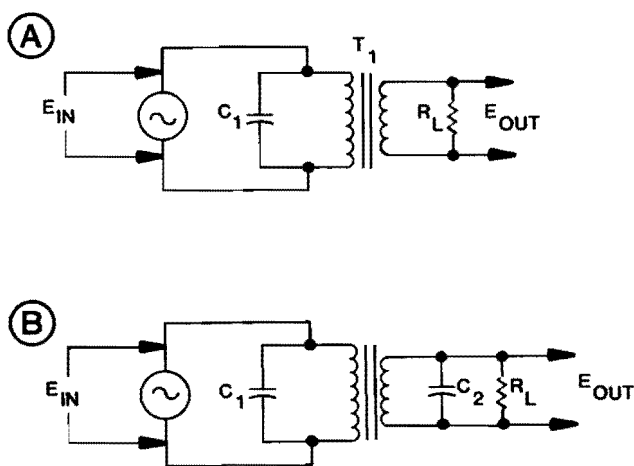


Figure 5-33 A tuned transformer can act as a band-pass filter.

In Figure 5-33A, C_1 is connected across the primary of the transformer. This causes the transformer to respond much more readily to the resonant frequency than to other frequencies. Recall that at resonance the circulating current within the tank is at its maximum value. This heavy current flows in the primary of the transformer and develops a strong magnetic field. Consequently, maximum voltage is coupled (induced) into the secondary, at the resonant frequency. Often, both the primary

and the secondary are tuned as shown in Figure 5-33B. The bandwidth of this circuit depends mainly on three factors:

1. The Q of the tuned primary circuit.
2. The Q of the tuned secondary circuit.
3. The coefficient of coupling.

When the coefficient of coupling is close to 1, the bandwidth is extremely wide. However, when the coefficient of coupling is very low, the bandwidth is very narrow.

Band-Stop Filter

The response of the band-stop filter is opposite that of the band-pass filter. That is, the band-stop filter stops, attenuates, or rejects the frequency to which it is tuned.

Figure 5-34A shows a simple band-stop filter. Here L and C form a parallel resonant circuit. The resonant circuit is in series with the load, R_L . At resonance, the impedance of the tank circuit is much higher than R_L . Consequently, most of E_{IN} is dropped across the tank, and very little voltage is available at the load. Above and below resonance, the resistance of R_L is higher than the impedance of the tank. Therefore, most of E_{IN} is developed across R_L . Figure 5-34B shows the response of the circuit. The sharpness of the curve is determined by the Q of the resonant circuit.

Another circuit that produces about the same response is shown in Figure 5-34C. Here a series resonant circuit is connected across the load. At resonance, the series resonant circuit offers a very low impedance to current flow. This shorts (bypasses) most of the current around the load. Most of the applied voltage is dropped across R_s . Above and below resonance, the impedance of the filter is much higher, and R_L is no longer bypassed.

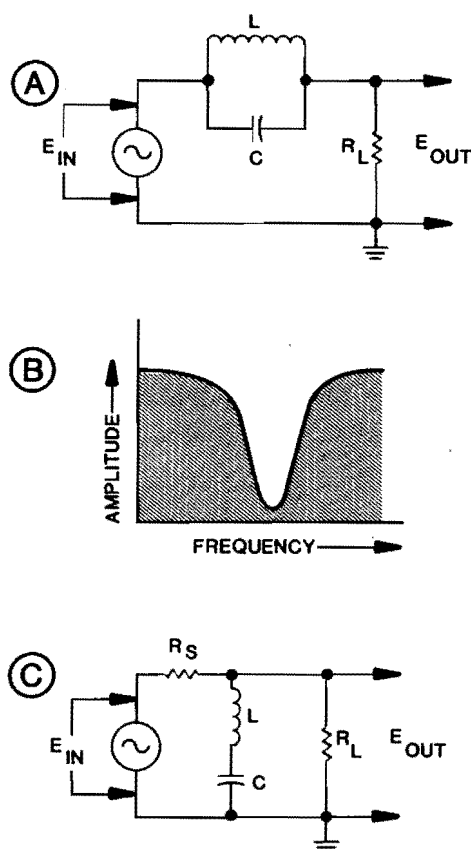


Figure 5-34 The band-stop filter.

Low-Pass Filter

A low-pass filter passes all frequencies below a certain cutoff frequency. A simple low-pass filter is shown in Figure 5-35A. At low frequencies X_L is much lower than the resistance of R_L . Thus, most of E_{IN} is developed across R_L . Furthermore, the X_C of the capacitor is high at low frequencies. Thus, most of the current flows through R_L and E_{OUT} is high at low frequencies.

At high frequencies the situation reverses, X_L of the coil increases, dropping most of the applied voltage. Only a small voltage is developed across R_L . Furthermore, X_C of the capacitor decreases, so that most of the current is shunted around R_L . Hence, the filter effectively blocks high frequency signals. The response curve for this filter is shown in Figure 5-35B.

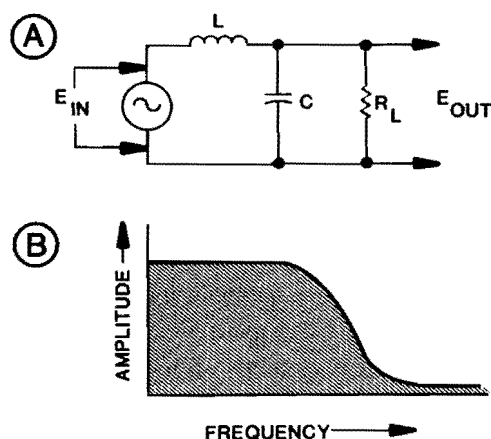


Figure 5-35 Low-pass filter.

High-Pass Filter

The high-pass filter passes all frequencies above a certain cutoff frequency. Figure 5-36 shows the high-pass filter and its response curve. At high frequencies, X_C is low and X_L is high. Thus, the capacitor and coil have little effect. Most of E_{IN} is developed across R_L . At low frequencies, X_C is high and X_L is low. Thus, the high value of X_C drops most of the applied voltage. The low value of X_L tends to bypass R_L . Thus, the circuit passes high frequencies but blocks low frequencies.

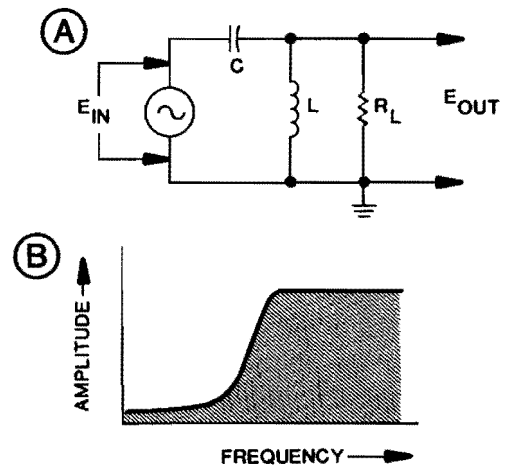


Figure 5-36 High-pass filter.

Self-Test Review

72. A circuit designed to pass some frequencies and block others is called a:

_____ filter.

73. A series resonant LC circuit is used as:

_____ filter.

74. When a series resonant circuit is placed across the load, at the resonant frequency it:

_____ the load.

75. When a parallel resonant circuit is placed in series with a load, it is called a:

_____ filter.

76. When a parallel resonant circuit is connected across the load it acts as a:

_____ filter.

77. A low-pass filter blocks all frequencies above the:

_____ point.

78. A high-pass filter passes all frequencies above the:

_____ point.

79. In a low-pass LC filter, the component connected in series with the load is the:

_____.

80. In a low-pass filter, the component connected across the load is the:

_____.

81. Filter circuits are best described as circuits that are frequency:

_____.

82. Match the type filters to their output waveform.

- A. _____.
B. _____.
C. _____.
D. _____.

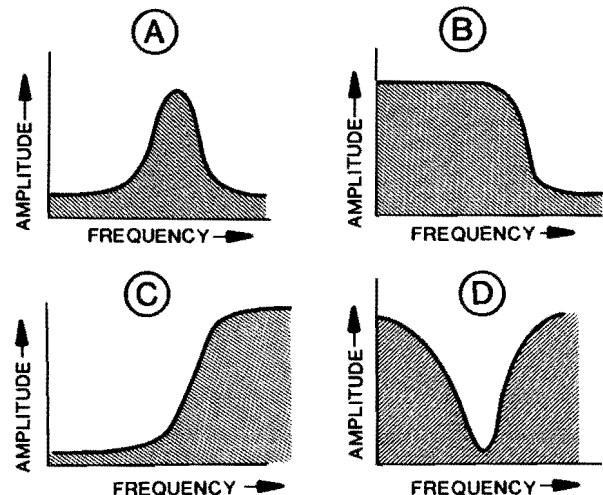


Figure 5-37

83. Figure 5-38 shows six types of filters.
Match the following circuits to their application .

Figure 5-38A _____.
 Figure 5-38B _____.
 Figure 5-38C _____.
 Figure 5-38D _____.
 Figure 5-38E _____.
 Figure 5-38F _____.

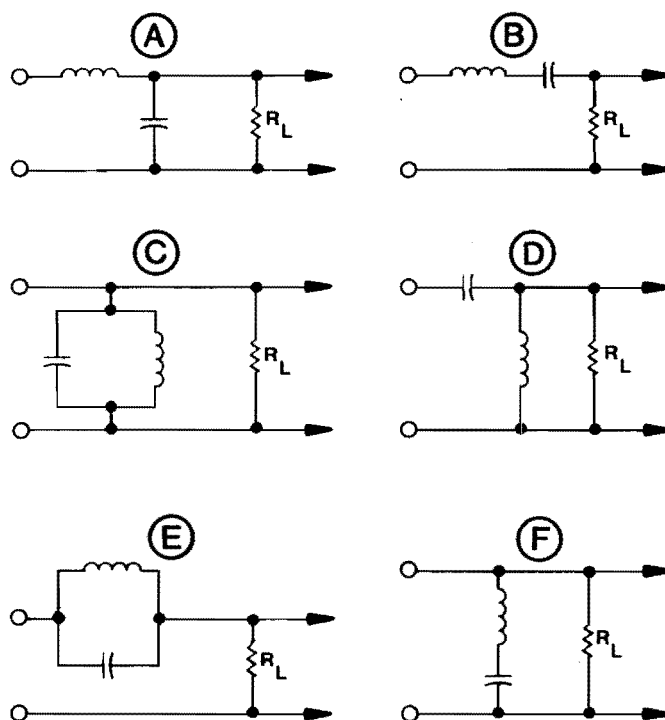


Figure 5-38

Desk-Top Experiment 6

Analyzing RLC Series-Parallel Circuits

Introduction

This experiment provides practice in analyzing RLC series-parallel combination circuits. Ohm's Law and Kirchhoff's closed loop equations are used to evaluate points of interest in the circuit.

The world of electronics is generally considered to have a tolerance of 10%. This is because many of the components have tolerance factors of 10%. A number of components are usually required to form a useful circuit. You will notice, in your calculations of the circuit's parameters that, although mathematics is an exact science, the components used are not perfect. Therefore, for this experiment, and electronic circuits in general, when the values are within 10%, they may be considered as equal.

For example, when X_C is 90 ohms and X_L is 100 ohms, at a particular frequency, they could be considered equal. This is especially true, when R is equal to 100 ohms or more. When vectored, 100 ohms and 90 ohms are effectively equal to 100 ohms. The phase angle would be so small that it has little effect on the circuit.

Objectives

1. To calculate the parameters of RLC series-parallel circuits.
2. To evaluate the effects of increasing and decreasing frequency in series parallel combination RLC circuits.

Procedure

On a separate sheet of paper, draw the circuit shown below. The circuit is a series parallel RLC combination circuit. It has an input AC sine wave with a value of 20 volts, at a frequency of 5 kHz. Round off your calculations to two decimal places.

Calculate the parameters listed below and fill in your calculated answers, in the spaces provided in steps 1 through 6.

1. Calculate the impedance in the circuit.

$$X_{L_1} = \underline{\hspace{2cm}}$$

$$X_{C_1} = \underline{\hspace{2cm}}$$

$$X_{L_2} = \underline{\hspace{2cm}}$$

$$X_{C_2} = \underline{\hspace{2cm}}$$

$$Z_T = \underline{\hspace{2cm}}$$

2. Calculate the currents flowing in the circuit.

$$I_T = \underline{\hspace{2cm}}$$

$$I_{L_2} = \underline{\hspace{2cm}}$$

$$I_{C_2} = \underline{\hspace{2cm}}$$

3. Calculate the voltage drop across each component.

$$E_R = \underline{\hspace{2cm}}$$

$$E_{C_1} = \underline{\hspace{2cm}}$$

$$E_{L_1} = \underline{\hspace{2cm}}$$

$$E_{C_2} = \underline{\hspace{2cm}}$$

$$E_{L_2} = \underline{\hspace{2cm}}$$

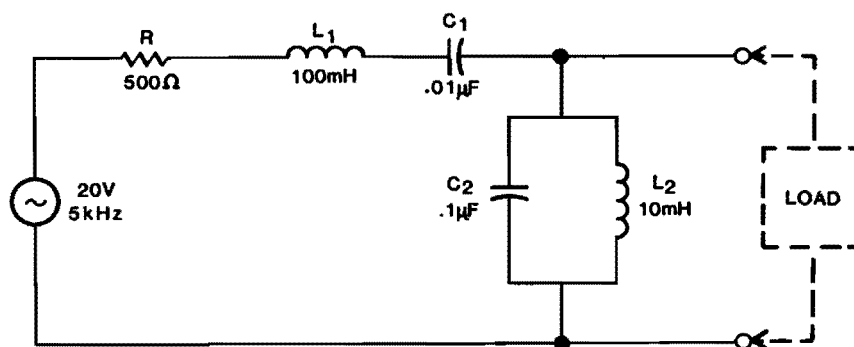


Figure 5-39 Desk-Top Experiment 6.

4. Draw the vector diagram that illustrates the relationship between voltage and current in the circuit.

5. Calculate the apparent power delivered by the source.

$$P_A = \underline{\hspace{2cm}}$$

6. Calculate the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}$$

Discussion

The circuit is resonant at 5 kHz. The only effective resistance in the circuit is R.

$$X_{L_1} = X_{C_1}$$

$$X_{L_2} = X_{C_2}$$

When a load is connected across the parallel tank, a current of 40 mA at a frequency of 5 kHz is available to the load.

When the frequency is increased, most of the current flows through the low reactance of ca-

pacitor C_2 . This current is not available to the load.

When the frequency is decreased, most of the current flows through the low reactance of inductor L_2 . This current is not available to the load.

The series LC circuit (L_1 and C_1) at resonance is a band-pass filter. The band-pass filter provides maximum current and minimum impedance to the input signal, at the resonant frequency.

The parallel tank circuit (L_2 and C_2) at resonance is a blocking circuit. The blocking circuit is sometimes called a band-reject filter. The band-reject filter provides maximum impedance and minimum current flow at the resonant frequency.

7. Change the frequency to 100 kHz. Calculate the new circuit parameters. Record your calculations in the spaces provided in steps 8 through 12.
8. Calculate the component impedance in the circuit when the frequency is 100 kHz.

$$X_{L_1} = \underline{\hspace{2cm}}$$

$$X_{C_1} = \underline{\hspace{2cm}}$$

$$X_{L_2} = \underline{\hspace{2cm}}$$

$$X_{C_2} = \underline{\hspace{2cm}}$$

9. Select the approximate total impedance of the circuit, at 100 kHz.

$$Z_T = \underline{\hspace{2cm}}.$$

10. Calculate the total current flowing in the circuit at 100 kHz.

$$I_T = \underline{\hspace{2cm}}.$$

11. Calculate the apparent power delivered by the source.

$$P_A = \underline{\hspace{2cm}}.$$

12. Calculate the true power dissipated in the circuit.

$$P_{\text{TRUE}} = \underline{\hspace{2cm}}.$$

Discussion

As you can see from your calculations, when frequency is changed the circuit's parameters change drastically. The circuit is usable as a coupling circuit at 5 kHz, but not at 100 kHz.

Summary

First you calculated the values of X_L and X_C .

$$X_L = 2\pi FL$$

$$X_C = \frac{1}{2\pi FC}$$

When $X_L = X_C$ the circuit is at resonance, and the total impedance is equal to R . Apparent power and true power are equal.

When the frequency varies by more than 10%, the circuit changes from resistive to reactive, impedance increases and current decreases.

When the frequency changes by more than 50%, the circuit is not an efficient coupling circuit.

A half-power point is defined as, the point at which both the current and voltage are equal to .707 of their peak values. The frequency at which power is equal to $E_p \times I_p$, is defined as the circuit's half-power point. This is the frequency at which the circuit power is reduced by 50%. The frequencies between the f_1 and f_2 points are defined as the circuit's bandwidth. It is this bandwidth that is either passed or rejected.

Unit Summary

With series RLC circuits, it is easier to vector voltage or impedance. In a series RLC circuit, total impedance is calculated using the formula:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

When X_C is larger than X_L , the formula becomes:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

With parallel RLC circuits, it is easier to vector currents. The formula for finding total current is:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

When I_C is larger than I_L , the formula is:

$$I_T = \sqrt{I_R^2 + (I_C - I_L)^2}$$

When a capacitor and an inductor are paralleled, they form a tank circuit. The tank resonates at a specific frequency.

At the resonant frequency, X_L is equal and opposite X_C . When the reactances are equal and opposite they cancel each other, and the only impedance in the circuit is the effective resistive component of the inductor.

Once power is applied to a tank circuit it starts to oscillate, at its resonant frequency, and power can be disconnected. Even when power is disconnected, a circulating current continues to flow, between the capacitor and the inductor.

The output of the LC tank circuit is referred to as the flywheel effect. The self sustained output waveform loses some of its amplitude each cycle. This loss is caused by the resistive component of the circuit and the waveform is considered to be damped.

The output waveform reaches its peak value at the resonant frequency (F_o). The tank is said to be frequency selective. The frequency of the tank output is the band of frequencies from the f_1 to the f_2 point. This band of frequencies is considered to be the circuit's bandwidth. It is also called the half-power points of a circuit and occurs at .707 of E_{peak} .

A tank circuit has a figure of merit called Q . The higher the Q , the more selective the circuit. This means that the output amplitude is higher and the bandwidth is narrower.

$$Q = \frac{F_o}{BW}$$

A tank circuit's Q is reduced and the bandwidth widened by paralleling the LC tank with a small resistor. This is referred to as swamp-

ing the tank and the resistor is called a shunt or swamping resistor.

For any LC circuit, there is a frequency at which X_L is equal to X_C . This frequency is called the resonant frequency, F_o . The resonant frequency can be determined using the formula:

$$F_o = \frac{.159}{\sqrt{LC}}$$

Some of the characteristics of a series resonant circuit are different from those of a parallel resonant circuit. The table in Figure 5-40 summarizes the differences and the similarities. The conditions described are generally true for high Q resonant circuits.

SERIES RESONANT CIRCUIT	PARALLEL RESONANT CIRCUIT
Current maximum at resonance.	Line current minimum at resonance.
Impedance minimum at resonance.	Impedance maximum at resonance.
$Q = \frac{X_L}{R}$, $Q = \frac{E_C}{E_{in}}$, $Q = \frac{E_L}{E_{in}}$	$Q = \frac{X_L}{R}$, $Q = \frac{Z_{tank}}{X_L}$, $Q = \frac{I_{tank}}{I_{source}}$
Acts purely resistive at F_o .	Acts purely resistive at F_o .
At resonance, the source current and voltage are in phase.	At resonance, the source current and voltage are in phase.
Below resonance, the circuit acts capacitively.	Below resonance, the circuit acts inductively.
Above resonance, the circuit acts inductively.	Above resonance, the circuit acts capacitively.

Figure 5-40 Comparing series and parallel resonant circuits.

Tuned circuits are used as filters. Figure 5-41 summarizes the six basic types of filters discussed in this unit.

The power factor is equal to the cosine of the phase angle. It is the result of the inductive

properties of the load. Power factor can be compensated for by varying capacitance to obtain resonance. At resonance the power factor is equal to 1 and the circuit is said to be 100% efficient. The cosine of 1 is zero degrees, which means the source and load are in phase.

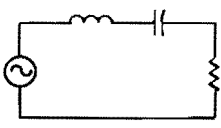
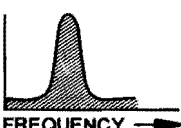
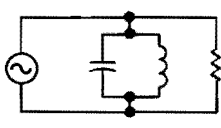
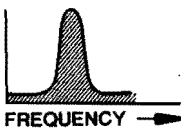
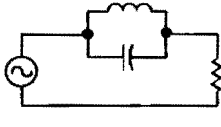
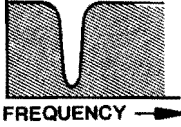
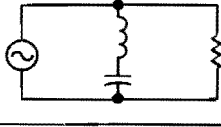
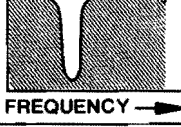
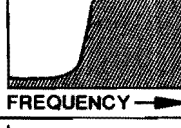
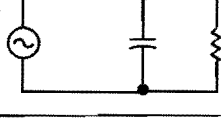
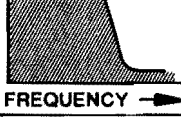
TYPE	TYPICAL CIRCUIT	RESPONSE CURVE	COMMENTS
BAND-PASS			PASSES A BAND OF FREQUENCIES AROUND F_0 .
BAND-PASS			PASSES A BAND OF FREQUENCIES AROUND F_0 .
BAND-STOP			BLOCKS OR ATTENUATES A BAND OF FREQUENCIES AROUND F_0 .
BAND-STOP			BLOCKS OR ATTENUATES A BAND OF FREQUENCIES AROUND F_0 .
HIGH-PASS			BLOCKS OR ATTENUATES FREQUENCIES BELOW A CERTAIN CUTOFF FREQUENCY.
LOW-PASS			BLOCKS OR ATTENUATES FREQUENCIES ABOVE A CERTAIN CUTOFF FREQUENCY.

Figure 5-41 Comparing types of filters.

Appendix A

Resonance Nomograph

Figure A-1 is a nomograph which can be used for solving resonance problems. The accuracy of this graph is about 5% for most problems. It can be used for solving three types of resonance problems.

1. It can be used to determine the resonant frequency of a series or parallel resonant circuit when the inductance and capacitance values are known. For example, if a 100 mH coil is connected in series with a .022 microfarad capacitor, what is the resonant frequency? A straight line is drawn from 0.022 microfarad capacitor in the left column to 100 mH inductor in the right column. The resonant frequency is read from the center column. Figure A-1 shows a resonant frequency of about 3.4 kHz. The exact value should be 3.383 kHz. So as you can see the graph is fairly accurate.
2. The graph can also be used to determine the inductance when the capacitance and resonant frequency are known. For example, what value of inductance will resonate at 3.4 kHz when connected in parallel with a .022 microfarad capacitor? A straight line is drawn from .022 microfarad capacitor on the left column through 3.4 kHz in the center column. The inductance is read from the point at which this line crosses the right column.
3. The graph can be used to find the capacitance when the resonant frequency and the inductance are known. A straight line is drawn from the two known quantities. The capacitance is read from the point at which this line crosses the left column.

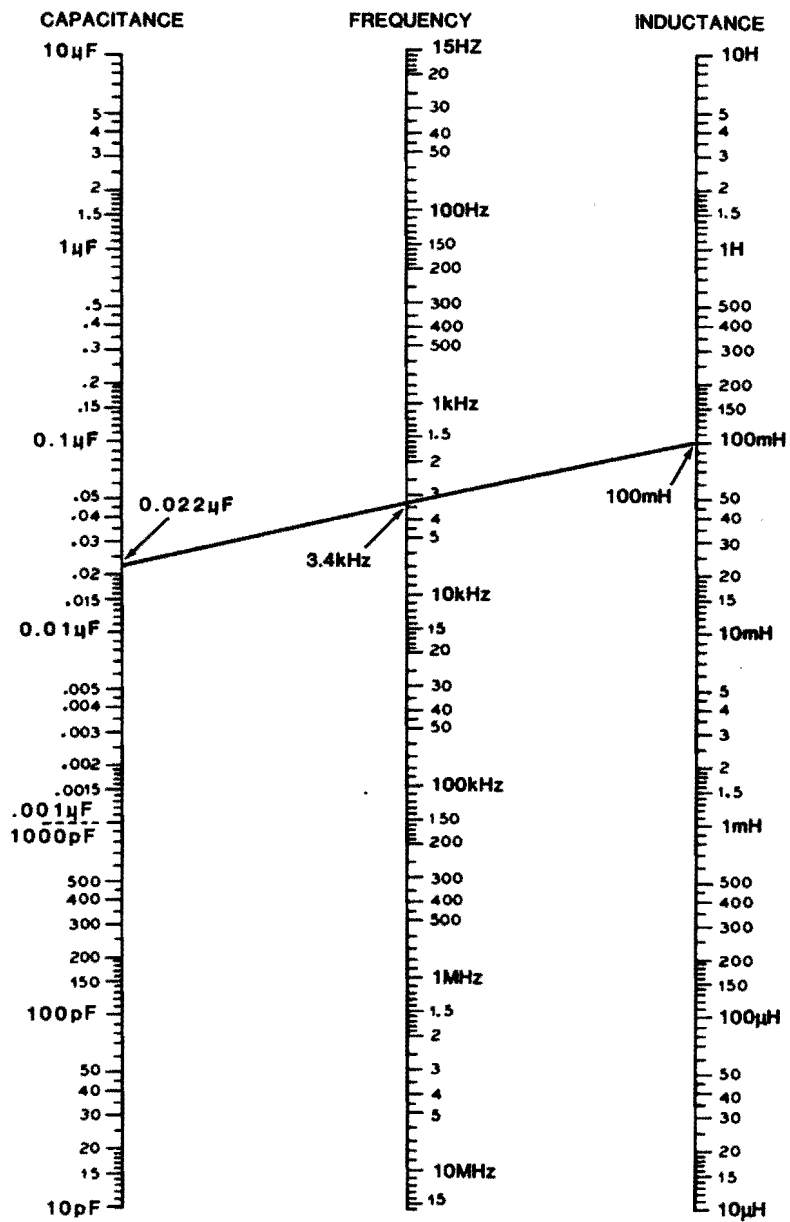


Figure A-1 Resonance Nomograph.

Unit 6

Transformers

Contents

Introduction	6-3	Transformer Ratios	6-17
Unit Objectives	6-4	Transformer Losses	6-26
Transformer Action	6-5	Transformer Application	6-32
Transformer Theory	6-12	Unit Summary	6-41

Introduction

A transformer is a device that transfers AC electrical energy from one circuit to another. It does this by means of electromagnetic mutual inductance. Generally, the transformer consists of two coils placed close together so that the magnetic field around one coil cuts the other coil. In this way energy is transferred from one coil to the other.

The transformer is an important component that is used in AC electrical distribution systems. The transformer is widely used in electronics. It can step-up or step-down voltage or current, isolate one circuit from another, match

impedances, and provide safety protection to the equipment user.

The transformer does not amplify power. When it steps-up voltage, it steps-down current. The power in its primary is always equal to the power in its secondary (ideal transformer). Actually the power in the secondary is always less than the power in the primary because of the resistance present in the coils and the slight separation between the coils. In other words, two equal coils will not result in a ratio of 1:1. However, efficiencies as high as 90% are obtained, as you will see in this unit.

Unit Objectives

When you have completed this unit you should be able to:

1. Define: Transformer primary, transformer secondary, eddy current loss, and hysteresis.
2. Calculate turns ratio, voltage ratio, power ratio, current ratio, and impedance ratio.
3. List four types of losses that effect transformer efficiency.
4. Calculate transformer efficiency.
5. State five uses for the transformer.
6. Determine the relationship between voltage, current, and impedance ratios.
7. Name the parts of an elementary transformer.
8. State the difference between a transformer and an autotransformer.
9. Explain why the transformer is **not used** in DC circuits.
10. Explain why the transformer is considered a safety device.

Transformer Action

The transformer is used to transfer alternating current from one circuit to another. Normally, some characteristic of the AC signal is changed in the transformation process. For example, a low voltage AC may be **stepped-up** to a higher value, or a higher voltage may be **stepped-down** to a lower value. Often it is the current which must be changed. The transformer is also used to step-up or step-down current. However, the transformer can not step-up or step-down both current and voltage at the same time. In this section, we will take a look at the action which allows the transformer to change voltage and current levels.

Mutual Inductance

The principle on which transformer action is based is called electromagnetic mutual inductance. This phenomenon was discussed earlier when you studied inductors. Let's briefly review the principles of mutual inductance.

Recall that when current flows through a conductor, a magnetic field builds up around the conductor. When alternating current is used, the magnetic field builds, collapses, builds again in the opposite direction, and collapses again for each cycle of the applied current. Another conductor placed in this moving magnetic field will have an EMF induced into it.

The transformer is a device that takes advantage of this principle. The two conductors are

wound into coils and placed close together so that one coil is cut by the magnetic flux lines of the other. Often the coils are wound one on top of the other. When this is the case, each inductor is coated with a thin insulator material to prevent shorts.

Figure 6-1 illustrates transformer action. Coil L_1 is connected to an AC voltage source. As alternating current flows through the coil, a varying magnetic field is set up. During one half cycle, current will flow through L_1 in the direction shown. This establishes a north magnetic pole at the top of L_1 . As the current increases, the field expands outward cutting the turns of wire in L_2 . This induces an EMF into L_2 and in turn, causes current to flow up through the load resistor. Thus, the current in L_1 causes current to flow through L_2 .

Notice that the coils are wound in opposite directions. The current flows into the top of L_1 . This induces a voltage that is negative at the top and positive at the bottom of L_1 . This field induces a current into the secondary (L_2) that develops a voltage that is positive at the top and negative at the bottom. The polarity of the secondary voltage causes electrons to flow up through the load resistor. In this type transformer, the secondary voltage is polarity inverted (180 degrees out of phase) from input to output.

If you are having problems following the description of transformer operation, a review of the left hand rules for conductors is recommended.

At the end of the first half cycle, the current through L_1 drops to 0 for an instant as the sine wave input passes through 180 degrees. As the current decreases, the field collapses back into L_1 . When the current in L_1 decreases, the current through L_2 also decrease .

On the next half cycle, the direction of current through L_1 reverses. This causes a magnetic field of the opposite polarity to expand outward from L_1 . Once again, the field cuts the turns of L_2 inducing an EMF. However, because the polarity of the magnetic field is reversed, the polarity of the voltage induced into L_2 is also reversed. Thus, the induced EMF causes current to flow down through the load resistance.

Notice that the current in L_2 follows the current in L_1 . Each time the current in L_1 reverses direction, the current in L_2 also reverses. Therefore, the alternating current in L_2 has the same frequency as the alternating current in L_1 . Energy is transferred from one circuit to another even though the two circuits are electrically insulated (physically separated) from each other.

The circuit shown in Figure 6-1 is a simple transformer. The coil to which the AC voltage is applied is called the **primary winding**. Current in this winding is caused by the AC voltage source and is called the **primary current**. The coil into which current is induced is called the **secondary winding**. The induced current is called the **secondary current**.

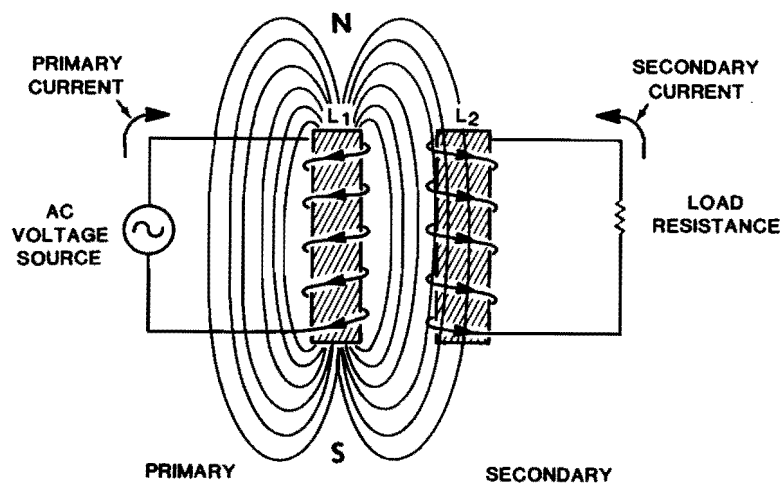


Figure 6-1 Transformer action.

The amount of EMF induced into the secondary winding depends on the amount of mutual induction between the two coils. In turn, the amount of mutual induction is determined by the degree of **flux linkage** between the two coils. The flux linkage can be thought of as the percentage of primary flux lines which cut the secondary winding. Another expression which means approximately the same thing is the **coefficient of coupling**. The coefficient of coupling is a number between 0 and 1. When all the primary flux lines cut the secondary coil, the coefficient of coupling is 1. If the two coils are positioned so that some of the primary flux lines do not cut the secondary, then the coefficient of coupling is less than one.

The coefficient of coupling and the resistive properties of the coils account for the statement that "input (primary) power is always more than the output (secondary) power."

Figure 6-2 illustrates that the amount of mutual inductance depends on the flux linkage or the coefficient of coupling. In Figure 6-2A, the secondary coil, L_2 , is wound directly on the primary coil, L_1 . Using this arrangement, nearly all of the flux lines produced by the primary cut the secondary windings. Therefore, the coefficient of coupling is close to one.

In Figure 6-2B the transformer consists of two coils. Here only a few lines of flux from the primary cut the secondary. Therefore, the coefficient of coupling is low.

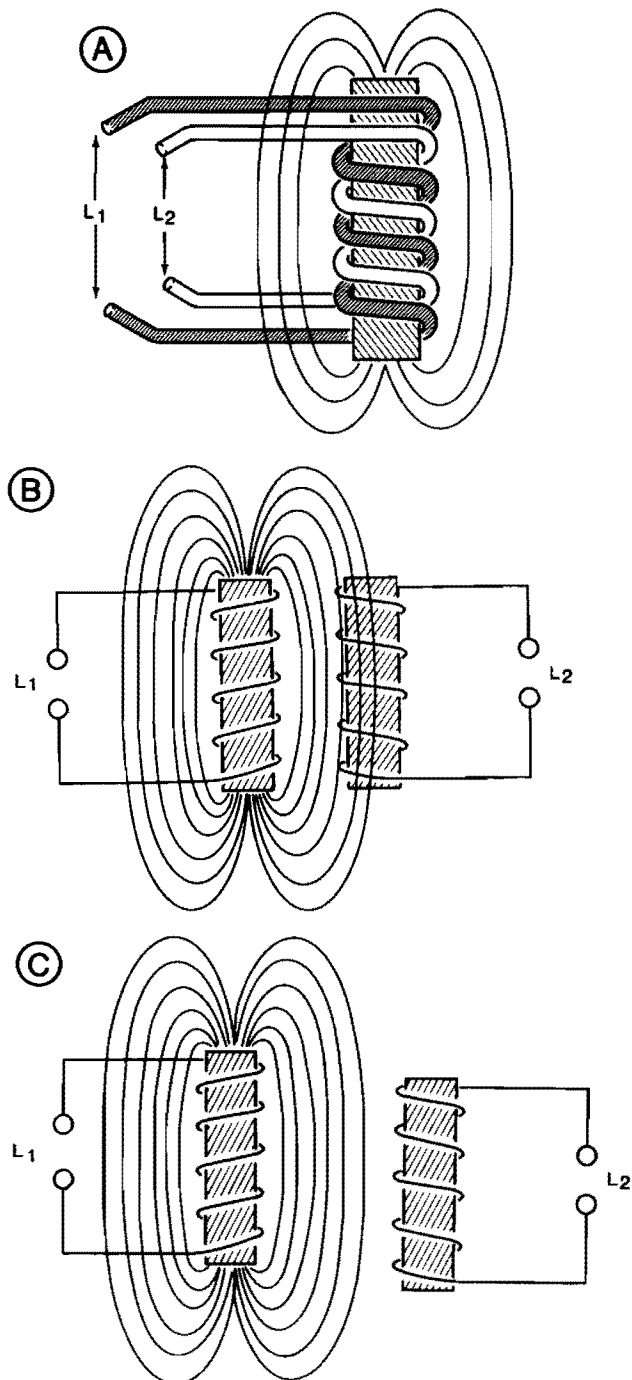


Figure 6-2 Mutual induction depends on the coefficient of coupling.

Figure 6-2C illustrates that when the two windings are placed far enough apart, there is no flux linkage between them. In this case, there is no mutual inductance and the coefficient of coupling is zero. While this arrangement has no practical purpose, it illustrates the importance of the coefficient of coupling. Remember also that when coils are mounted perpendicular to each other the coefficient of coupling is zero.

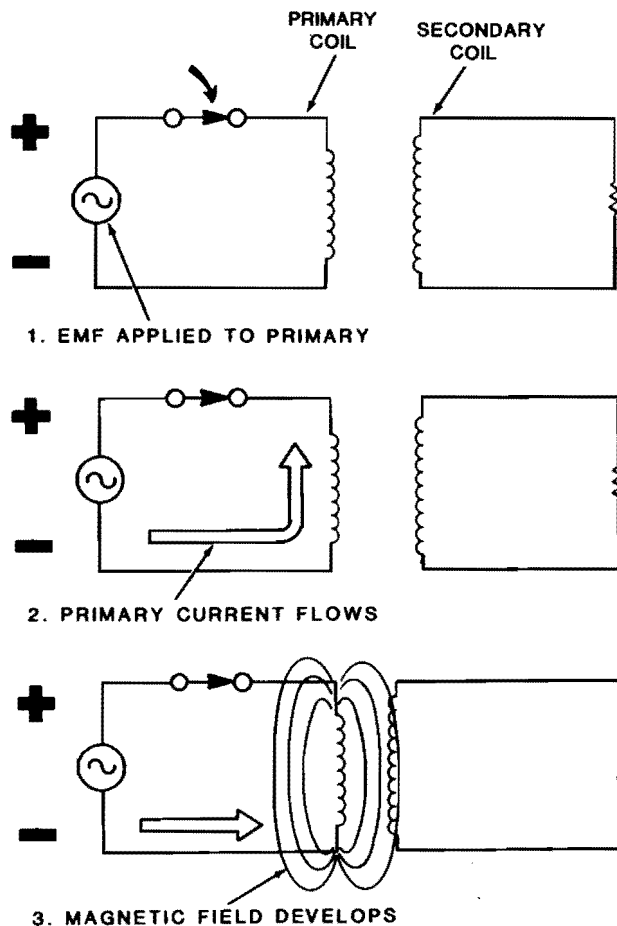


Figure 6-3 Sequence of events in transformer action.

Transformer Action

Figure 6-3 illustrates the step-by-step sequence of events in transformer action. When the switch is closed the EMF of the generator is applied across the primary. This causes current to flow through the primary. The current produces magnetic flux lines which expands outward, cutting the secondary. This induces an EMF in the secondary winding. When a path for current flow exists, the EMF causes a secondary current to flow. The load is connected across the secondary. Energy is transferred from the generator to the load even though the two circuits are not physically connected.

The transformer is not used in DC circuits because, except for initial turn on and turn off of the source voltage there is no movement of flux lines. Without relative motion (expanding and collapsing) of the magnetic field there is no induced voltage. Therefore, the transformer is considered to be an AC component.

Transformer Construction

The construction techniques for transformers vary depending on the type of transformer and the particular application. All transformers can not be used for the same application. A substation transformer used in a power distribution system may approach the size of a small house. On the other hand, an IF transformer used in a transistor radio may be no larger than a pencil eraser. In spite of the vast size difference, these two transformers operate on the same basic principle. Both have primary and secondary coils. In both, energy is coupled from the primary to the secondary by mutual inductance.

The design of the transformer is dictated by the frequency that it must pass, the voltage and current involved, and several other factors. A power transformer may be required to handle 115 VAC 60 Hz, at 1 ampere. On the other hand, an IF transformer may work with a frequency of 455 kHz at a few millivolts and a few microamperes.

Transformers are bulky, heavy, and expensive when compared to other electronic components. Therefore, they are used only in limited applications.

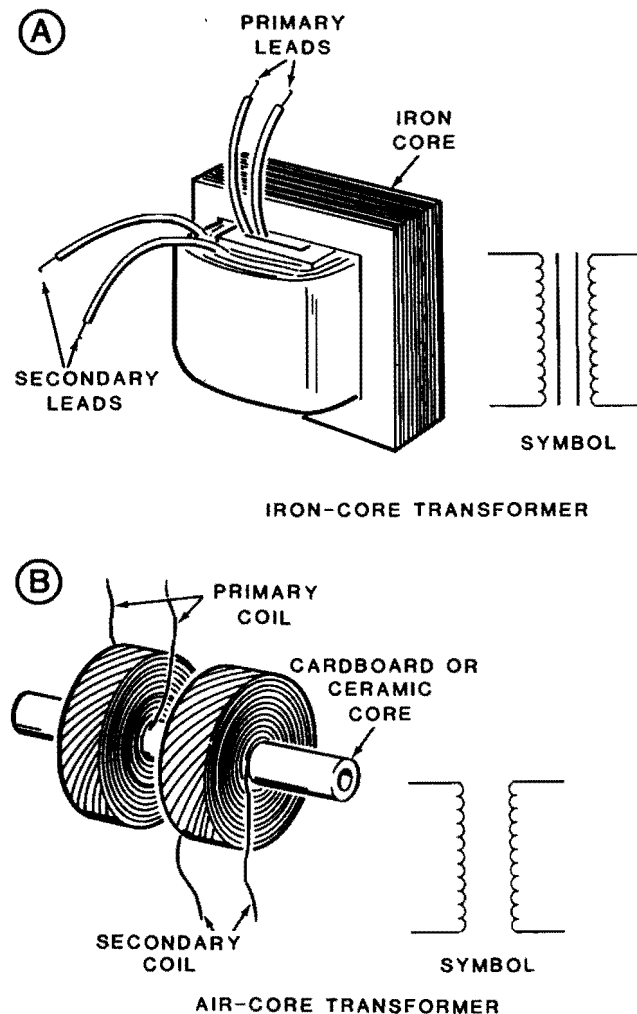


Figure 6-4 Typical transformers and their symbols.

Figure 6-4 compares the construction of an iron-core transformer with that of an air core transformer. The iron-core transformer is much larger and heavier. The primary winding is wound on one arm of the core. The secondary is wound directly on top of the primary. Notice that the symbol for the transformer shows the two coils. The two lines between the coils represent the iron core. The purpose of the iron core is to concentrate the lines of force into a small area. Remember, from the unit on inductance that iron has a high perme-

ability and that permeability means easy to magnetize.

The construction of the air-core transformer is different. It is designed to be used at much higher frequencies. Iron core losses increase as frequency increases. Transformers designed to operate at high frequencies use little or no iron in the core. Instead a nonconductive material that has the same permeability as air is used. High frequency cores are usually either ceramic or simply small cardboard tubes.

Self-Test Review

1. The transformer usually contains:
_____ coils.
2. The winding to which an input alternating current is applied is called the:
_____ winding.
3. The winding into which an EMF is induced and where the output is taken is called the:
_____ winding.
4. In a transformer the frequency of the applied voltage and the frequency of the output voltage is always:
_____.
the same/different
5. Transformers designed to work at low frequencies usually have:
_____ cores.
6. Transformers designed for very high frequency operation usually have:
_____ cores.
7. Draw the schematic symbol for an iron core transformer.
8. The permeability of iron cores is:
_____.
high/low/one
9. Transformers operate on the principle of:
_____ induction.
10. The transformer is considered to be a/an:
_____ component.

Transformer Theory

In the previous section we saw how transformer action can be used to couple an AC signal from one circuit to another. In this section, we will explore this action further.

Transformer With No Load

Figure 6-5A shows a transformer being operated without a load. This means that the secondary of the transformer is open. Therefore there is no secondary current. Even so, there is primary current because the primary is connected across an AC voltage source.

In this case, the amount of primary current is determined by the impedance of the transformer's primary and the applied voltage. Since no power is being used in the secondary, the primary acts like an inductor. The primary of a typical iron-core transformer can have an inductance of several henrys. This tends to keep the primary current very low.

In addition to the inductance, the primary winding has a certain value of AC resistance. This limits the current even further. The small amount of primary current that flows with no load is called the excitation current. Figure 6-5B illustrates two functions that the exciting current must perform. First, it overcomes the AC resistance of the primary. In Figure 6-5B, the resistance of the inductor is shown as a separate resistor. This resistance dissipates power in the form of heat. Secondly, the exciting current supports the magnetic field in the core.

X_L of the primary is normally much larger than its AC resistance. Thus, the exciting current lags behind the applied voltage by almost 90 degrees. Consequently, when no current flows in the secondary, the primary of the transformer acts like an inductor.

When you studied inductors, you learned that the current lagged the applied voltage because of the counter EMF produced by the coil. Let's briefly review this principle.

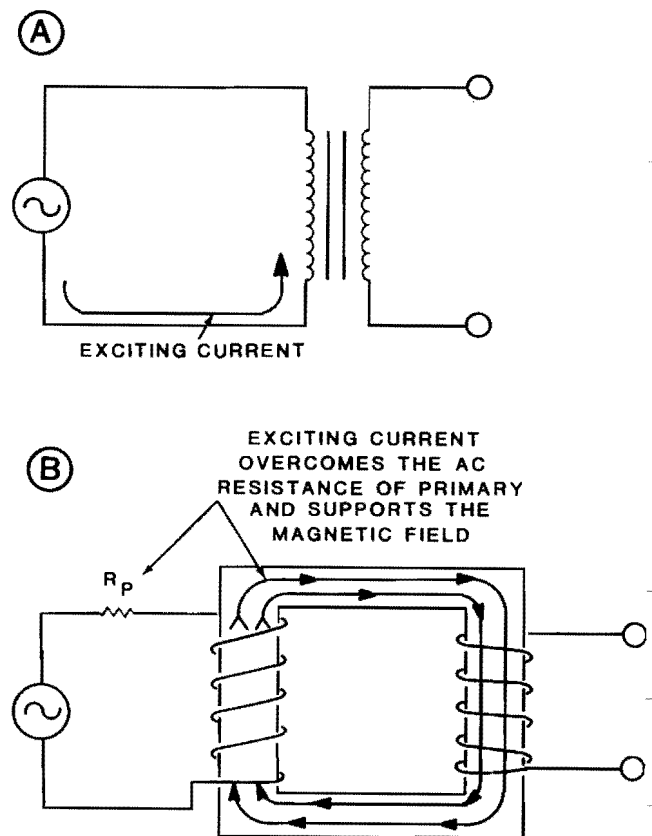


Figure 6-5 Transformer with no load.

In Figure 6-5B, the applied EMF causes current to flow in the primary winding. In turn, this current establishes the magnetic field. However, as the magnetic field expands outward, it cuts the primary winding inducing a counter EMF. This counter EMF opposes the applied EMF. Thus, the primary current lags behind the applied voltage.

This is the situation which occurs when there is no secondary current. However, when secondary current flows, these conditions are changed and the transformer operates differently. Since the transformer is normally operated with a secondary load, we must understand why it operates differently when secondary current flows.

Transformer With Load

Figure 6-6 shows a simple transformer with a load resistor connected across the secondary winding. When AC current flows in the primary, it induces a current into the secondary. Let's see how the current in the secondary affects the operation of the transformer.

In Figure 6-6A, the polarity of the applied voltage is negative at the top of the primary and positive at the bottom. This forces current to flow down through the primary winding. Using the left-hand rule developed earlier, we find that the current develops a magnetic field in the direction shown.

As this magnetic field expands outward, it induces a counter EMF in the primary winding. This counter EMF opposes the applied EMF. The applied EMF forces current to flow down through the primary, the counter EMF tries to force current up through the primary. The net result is a small current which flows down through the primary.

Notice that the secondary is wound directly on top of the primary. Therefore, the expanding magnetic field caused by the primary current also cuts the secondary winding. Since the secondary is wound in the same direction as the primary, the EMF induced into secondary has the same polarity as the **counter** EMF in the primary. Thus, the induced current in the secondary flows in the direction shown.

Notice that in this configuration there is no polarity inversion between the primary and secondary windings.

The current flow in the secondary establishes a magnetic field of its own as shown in Figure 6-6B. Using the left-hand rule, you can verify that the magnetic field has the polarity shown. As the magnetic field expands, it cuts the secondary winding inducing a counter EMF. This counter EMF tries to force current to flow down through the secondary in opposition to the induced current.

The expanding flux in the secondary also cuts the primary turns. This induces yet another EMF back into the primary winding. This induced EMF is in the same direction as the counter EMF of the secondary. Thus, this EMF tends to force current to flow down through the primary. If you have been keeping track of the various EMFs, you will see that the EMF induced into the primary from the secondary opposes the counter EMF originally developed in the primary. Or stated another way, the current induced into the primary, from the secondary, aids the original primary current. This causes the primary current to increase.

This increase in primary current is caused by the expanding magnetic field of the secondary. The more current that flows in the secondary, the stronger the secondary magnetic field. This, in turn, increases the primary current. Consequently, an increase in secondary current causes an increase in primary current. Later, you will see that the exact amount of increase in each depends upon the turns ratio.

The sum of the effects just described is called mutual inductance. The inductance is said to be mutual because the primary induces a volt-

age into the secondary and, simultaneously, the secondary induces a voltage back into the primary.

To be certain you have the idea, let's review this process once more.

- Step 1. AC in the primary establishes a fluctuating magnetic field.
- Step 2. The varying flux induces a counter EMF into the primary and an EMF into the secondary.
- Step 3. The induced EMF causes current to flow in the secondary.
- Step 4. The current in the secondary establishes a magnetic field which is opposite the field caused by the primary current.
- Step 5. The secondary flux induces an EMF back into the primary which opposes the counter EMF of step 2. This decreases the primary counter EMF.
- Step 6. Primary current increases because the counter EMF decreases.

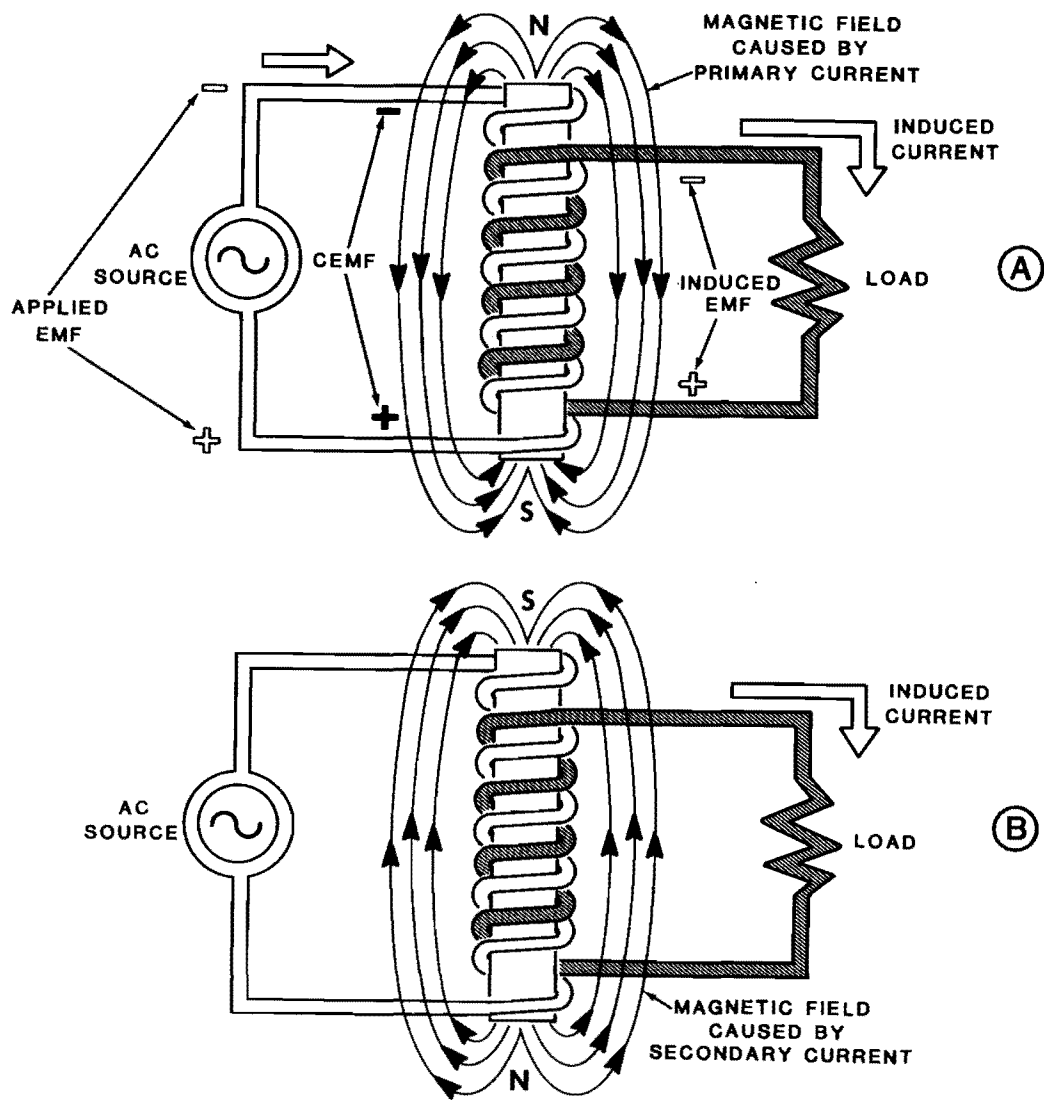


Figure 6-6 Transformer with load.

Self-Test Review

11. When a transformer is operated without a load the primary winding acts like a/an:
_____.
12. In the unloaded condition the current flowing in the primary winding is called:
_____ current.
13. The main purpose of the current in question 12 is to overcome the:
_____ of the primary.
14. When a load is connected to the secondary, the primary current:
_____.
increases/decreases
15. The secondary magnetic field induces an EMF into the primary which opposes the primary's:
_____ EMF.
16. The interaction of the two magnetic fields is called:
_____ induction.
17. When the current in the secondary increases, the current in the primary:
_____.
increases/decreases

Transformer Ratios

Transformers have many applications. They are used to step-up or step-down voltage. Also, they are used to step-up or step-down current. They are also used as coupling or isolation devices. In each case, we are concerned with a ratio.

In the first case, the ratio is that of an input voltage to an output voltage. In the second case, the ratio is that of a primary current to a secondary current. In the third case, the ratio is that of an input impedance to an output impedance. Each of these ratios is determined by the number of turns in the primary winding compared to the number of turn in the secondary.

Voltage Ratio

Transformers are frequently used to step-up or step-down voltages. Most electronic devices are powered by 115 VAC at 60 Hz. Some applications require higher voltages while others can get by with much lower voltages. The transformer is used to transform the 115 VAC to whatever value is required.

Recall that when AC is changed to DC the process is called rectification. When AC values are increased by transformer action the process is simply called transformed.

When the output (secondary) voltage is higher than the input (primary) voltage, the transformer is a **step-up** transformer. The amount of step-up is determined by the **turns ratio** of the transformer.

Figure 6-7A illustrates the turns ratio of a typical transformer. Notice that the primary consists of 1,000 turns of wire while the secondary has 2,000 turns. The turns ratio can be defined as the ratio of the number of turns in the secondary, N_s , to the number of turns in the primary, N_p ; that is:

$$\text{Turns ratio} = \frac{N_s}{N_p}$$

In Figure 6-7A, the turns ratio is:

$$\begin{aligned}\text{Turns ratio} &= \frac{N_s}{N_p} \\ &= \frac{2,000}{1,000} \\ &= 2\end{aligned}$$

This is expressed as a turns ratio of “2 to 1” or 2:1. When the secondary has more turns than the primary, the voltage is “stepped-up.” For example, When the turns ratio is 2:1, then the secondary voltage will be twice as high as the primary voltage. Thus, the voltage ratio is equal to the turns ratio. The voltage ratio is directly proportional to the turns ratio. This is expressed by the equation:

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

In some cases, it is more convenient to think of the turns ratio as:

$$\frac{N_p}{N_s}$$

When we do this, the voltage ratio equation is:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

We can use either of these equations to find the secondary voltage when the turns ratio and the primary voltage are known. Figure 6-7B shows 115 VAC applied to the primary. We find the secondary voltage by rearranging the formula:

$$\begin{aligned}\frac{E_s}{E_p} &= \frac{N_s}{N_p} \\ E_s &= \frac{N_s}{N_p} \times E_p \\ E_s &= \frac{2,000}{1,000} \times 115 \text{ V} \\ E_s &= 2 \times 115 \text{ V} \\ E_s &= 230 \text{ V}\end{aligned}$$

By choosing the proper turns ratio, the input voltage can be stepped-up to any value required.

Remember that when an AC voltage is listed it is understood to be an rms or effective value unless otherwise specified. You should also recognize the 115 voltage value as being the effective voltage that is available in most homes and industry.

On many pieces of equipment you may have noticed a power function switch that is labeled 115/230. This switch selects the desired turns ratio (either 1:1 or 2:1).

The transformer can also be used to step down a voltage. To accomplish this, the secondary should have fewer turns than the primary. For example, in Figure 6-7C, the primary has 1,000 turns while the secondary has 250 turns. The primary voltage is given as 100 VAC. Let's find the secondary voltage.

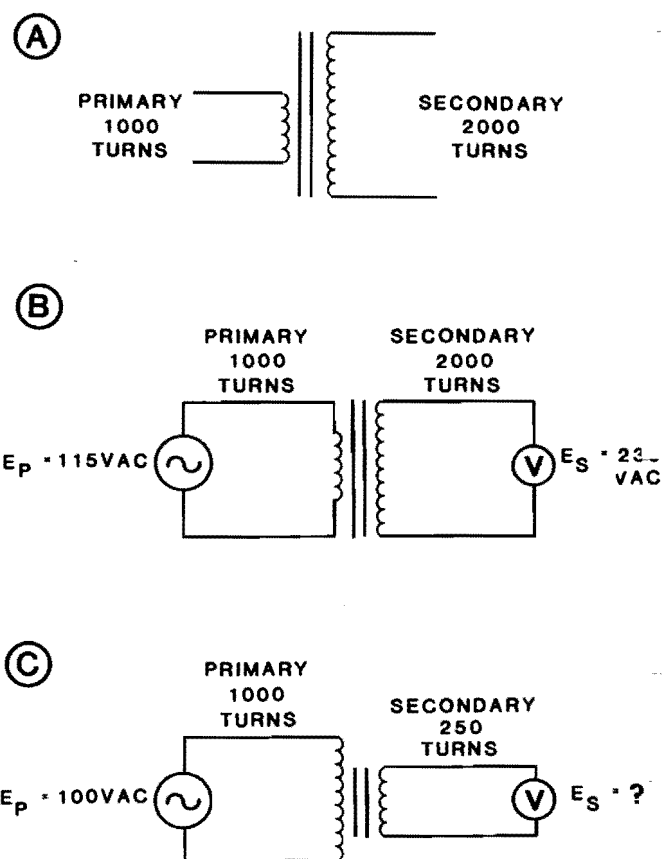


Figure 6-7 The voltage is determined by the turns ratio.

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

$$E_s = \frac{N_s}{N_p} \times E_p$$

$$E_s = \frac{250}{1,000} \times 100 \text{ V}$$

$$E_s = \frac{1}{4} \times 100 \text{ V}$$

$$E_s = 25 \text{ V}$$

These equations hold true as long as the coefficient of coupling is high and the transformer losses are low. To be completely accurate, the transformer must have a coupling coefficient of 1 and an efficiency of 100%. While these conditions are impossible to achieve in practice, some transformers come very close. In this section, we will assume that an ideal transformer is used. Later, we will see that general purpose transformers fall far short of the ideal transformer. General purpose transformers have efficiency ratings between 60 and 80%.

Power Ratio

When we ignore the losses in the transformer, the power in the secondary is the same as the power in the primary. Thus, in the ideal transformer the power ratio is 1. Although the transformer can step-up voltage, it cannot step-up power. We can never take more power from the secondary than we put in at the primary.

Thus, when a transformer steps-up a voltage, it steps-down the current. Thus, the output power is assumed to be the same as the input power. This is expressed by the equation:

$$P_p = P_s$$

Current Ratio

A transformer which **steps-up** voltage must at the same time **step-down** current. Otherwise, it would deliver more power in the secondary than is supplied by the primary.

We can prove this by deriving an equation for the current ratio. Remember that, ignoring losses:

$$P_p = P_s$$

Recall that the formula for power is:

$$P = EI$$

Thus the power in the primary is equal to $E_p \times I_p$ while the power in the secondary is equal to $E_s \times I_s$.

Therefore, if $P_p = P_s$ then:

$$E_p \times I_p = E_s \times I_s$$

The voltage ratio equation is:

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

Transposing:

$$E_s = \frac{N_s}{N_p} \times E_p$$

Substituting this expression for E_s in the previous equation provides:

$$E_p \times I_p = \frac{N_s}{N_p} E_p \times I_s$$

Dividing both sides by E_p , provides:

$$I_p = \frac{N_s}{N_p} \times I_s$$

Dividing by I_s , provides:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

This states that the current ratio is inversely proportional to the turns ratio. Voltage is directly proportional to turns ratio. This makes sense since more turns means more wire and more wire means more resistance. Anytime resistance increases current decreases.

Figure 6-8A shows a transformer with a turns ratio of 4:1. This means that the secondary has 4 times as many turns as the primary. Thus, the voltage is stepped-up by a factor of four, from 10 V to 40 V. However, the current is stepped-down from 1 ampere in the primary

to only 0.25 amperes in the secondary. We can prove this, by rearranging the current ratio formula:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Cross multiplying provides:

$$I_s(N_s) = I_p(N_p)$$

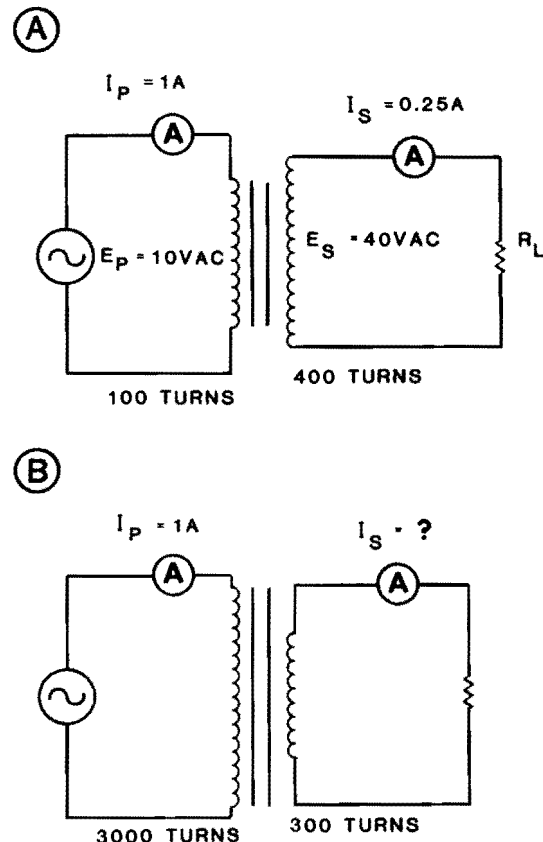


Figure 6-8 The turns ratio determines the current ratio.

Dividing by N_s provides:

$$I_s = \frac{I_p(N_p)}{N_s}$$

$$I_s = \frac{N_p}{N_s} \times I_p$$

$$I_s = \frac{100}{400} \times 1 \text{ A}$$

$$I_s = \frac{1}{4} \times 1 \text{ A or } .25 \text{ A}$$

A transformer can also be used to step-up current. However in doing this, it must step-down voltage. To step-up current, the primary must have more turns than the secondary as shown in Figure 6-8B. The secondary current is:

$$I_s = \frac{N_p}{N_s} \times I_p$$

$$I_s = \frac{3,000}{300} \times 1 \text{ A}$$

$$I_s = 10 \times 1 \text{ A or } 10 \text{ A}$$

Solving Transformer Problems

Once you understand how to use the voltage and current ratio formulas, you can solve a wide variety of transformer problems. For example, consider the circuit shown in Figure 6-9A. The number of turns, I_s , and the value of R are given. We wish to find E_p and I_p . We

can determine I_p immediately since I_s and the turns ratio are given:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

$$I_p = \frac{N_s}{N_p} \times I_s$$

$$I_p = \frac{500}{100} \times 10 \text{ mA}$$

$$I_p = 5 \times 10 \text{ mA or } 50 \text{ mA}$$

Since you know the turns ratio, you can find E_p if you know E_s .

$$E_s = I_s (R_1)$$

$$E_s = 10 \text{ mA} \times 1 \text{ kilohm}$$

$$E_s = 10 \text{ V}$$

Now you can find E_p :

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

Cross multiplying:

$$E_s (N_p) = E_p (N_s)$$

Dividing by N_s provides:

$$E_p = \frac{E_s(N_p)}{N_s}$$

Rearranging the equation provides:

$$E_p = \frac{N_p}{N_s} \times E_s$$

$$E_p = \frac{100}{500} \times 10 \text{ V}$$

$$E_p = \frac{1}{5} \times 10 \text{ V}$$

$$E_p = 2 \text{ V}$$

secondary current, and primary current, and the value of R_1 .

Because the turns ratio and E_p are given, we can compute the value of E_s :

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

$$E_s = \frac{N_s}{N_p} \times E_p$$

$$E_s = \frac{100}{500} \times 10 \text{ V}$$

$$E_s = \frac{1}{5} \times 10 \text{ V or } 2 \text{ V}$$

Figure 6-9B shows another problem. Here, the turns ratio, the primary voltage, and the power dissipated in the secondary circuit are given. We want to find the secondary voltage, the

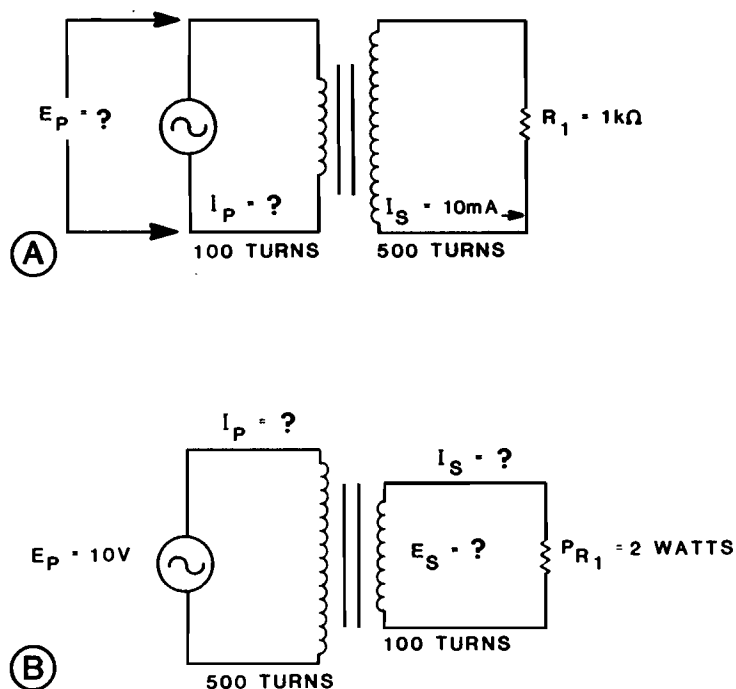


Figure 6-9 Solving transformer problems.

Once you know E_s , you can compute I_s :

$$P_s = E_s \times I_s$$

$$I_s = \frac{P_s}{E_s}$$

$$I_s = \frac{2 \text{ W}}{2 \text{ V}}$$

$$I_s = 1 \text{ A}$$

You can find the same value by rearranging the power formula:

$$P = I^2 R$$

$$R = \frac{P}{I^2}$$

$$R = \frac{2 \text{ W}}{1}$$

$$R = 2 \text{ ohms}$$

When you know I_s and the turns ratio, you can compute I_p ;

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

$$I_p = \frac{N_s}{N_p} \times I_s$$

$$I_p = \frac{100}{500} \times 1 \text{ A}$$

$$I_p = \frac{1}{5} \times 1 \text{ A}$$

$$I_p = 0.2 \text{ A}$$

The value of R_l can now be computed using Ohm's Law:

$$R_l = \frac{E_s}{I_s}$$

$$R_l = \frac{2 \text{ V}}{1 \text{ A}}$$

$$R_l = 2 \text{ ohms}$$

Impedance Ratio

In electronics, one of the most important applications of a transformer is impedance matching. Maximum power is transferred from a generator to a load, when the impedance of the generator matches the impedance of the load. When impedances do not match, power is wasted.

There are many cases in electronics in which the impedance of the signal source or generator, does not match the load which it must drive. For example, a transistor amplifier stage might be most efficient when driving a 100 ohm load. Nevertheless, the amplifier may be required to drive a 4-ohm speaker. This is a mismatch that results in wasted power and inefficient operation.

The transformer is used to correct for this mismatched impedance. The transformer can make one value of impedance appear to be another value. In the above example, a trans-

former is placed between the transistor amplifier and the speaker. By choosing the proper turns ratio, the transformer can make the 4 ohm speaker appear to be a 100 ohm load, to the transistor amplifier.

You have seen that the voltage or current step-up of a transformer depends on the turns ratio. The impedance matching capability of a transformer also depends on the turns ratio. However, the impedance ratio is equal to the turns ratio **squared**. That is:

$$\frac{Z_p}{Z_s} = \left(\frac{N_p}{N_s}\right)^2$$

Z_p is the impedance of the primary circuit. Z_s is the impedance of the secondary circuit.

The formula can be rearranged to provide:

$$\frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}}$$

You can use this equation to solve impedance matching problems.

The problem is to find a turns ratio that matches a 100 ohm generator (such as the transistor amplifier) to a 4 ohm load (such as a speaker). This type problem is solved using the formula:

$$\begin{aligned}\frac{N_p}{N_s} &= \sqrt{\frac{Z_p}{Z_s}} \\ \frac{N_p}{N_s} &= \sqrt{\frac{100 \text{ ohms}}{4 \text{ ohms}}}\end{aligned}$$

$$\begin{aligned}\frac{N_p}{N_s} &= \sqrt{25} \\ \frac{N_p}{N_s} &= 5\end{aligned}$$

This is a primary to secondary turns ratio of 5:1. Thus, when the number of primary turns is 5,000, the number of secondary turns must be 1,000. As you can see, any transformer with a turns ratio of 5:1 has an impedance ratio of $(5)^2:1$ or 25:1.

Let's consider another example. Suppose you need to match a generator that has an impedance of 6,000 ohms to a 60 ohm load. The needed turns ratio is:

$$\begin{aligned}\frac{N_p}{N_s} &= \sqrt{\frac{Z_p}{Z_s}} \\ \frac{N_p}{N_s} &= \sqrt{\frac{6,000}{60}} \\ \frac{N_p}{N_s} &= \sqrt{100} \\ \frac{N_p}{N_s} &= 10\end{aligned}$$

The turns ratio must be 10:1. The primary must have 10 times as many turns as the secondary.

Impedance matching is one of the most important applications of a transformer. By choosing the proper turns ratio, transformers can match a wide range of impedances.

Self-Test Review

18. List 4 common applications for transformers.

_____.

_____.

_____.

_____.

19. Ignoring losses, the voltage ratio between the primary and secondary is directly proportional to the:

_____ ratio.

20. An AC source of 10 volts is connected to a transformer that has 100 turns in the primary and 1,000 turns in the secondary. The secondary voltage is:

_____ volts.

21. Ignoring losses, when the circuit described in question 20 has a load of 1 k ohm connected across the secondary, the power in the secondary will be:

_____ W.

22. What is the current flowing in the secondary of the circuit described in question 21?

_____ A.

23. What is the power supplied to the primary winding?

_____ W.

24. Explain the relationship between the turns ratio and:

Voltage _____ proportional.

Current _____ proportional.

Impedance _____ proportional.

25. The turns ratio that causes a 600 ohm source to appear to be 8 ohms is approximately:

_____.

26. Maximum transfer of power occurs when the impedances of the source and load are:

_____.

27. The impedance ratio of a transformer is equal to the:

_____ squared.

Transformer Losses

Transformers used in electronic circuits are very efficient devices. An efficiency of ninety percent or better is normal. All transformers have some losses. In many cases, these losses dictate the design of the transformer. Power transformers in particular are designed so that losses are minimized. The losses are separated into several categories.

Core Losses

In power transformers the largest loss occurs in the transformer's core. Even so, a much larger core loss would occur if it were not for special construction techniques. Core losses can be divided into two separate parts. Let's examine each of these losses.

Eddy Current Losses

The cores of power transformers are generally made of soft iron or steel. Because iron and steel are good conductors, and are ferromagnetic, a current can be induced into the core. This occurs when the core is subjected to a moving magnetic field. As we have seen, a moving magnetic field is a requirement in all transformers. Unless special precautions are taken, large circulating currents are induced into the core of the transformer. These induced circulating currents are called eddy currents.

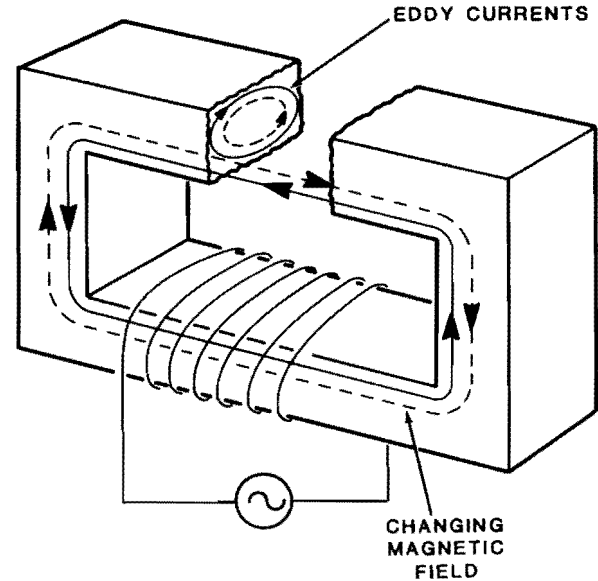


Figure 6-10 Eddy currents are induced in the core by the changing magnetic field.

Figure 6-10 shows how eddy currents are induced into the core. When alternating current flows through the winding, a changing magnetic field is developed around the core. As this field expands and contracts it induces a voltage into the core. The induced EMF causes eddy currents to flow as shown in Figure 6-10. These eddy currents are sometimes referred to as skin effect because they flow along the conductor's surface.

Eddy currents are reduced by changing the construction of the core. In Figure 6-10 a solid block of metal is used as the core. Because the cross sectional area of the core is large, it has very little resistance and large eddy currents flow.

The eddy currents produce a power loss that is proportional to the current squared ($P = I^2R$). When the eddy currents are reduced, the power loss is reduced.

Eddy currents are reduced by using many thin sheets of metal for the core rather than a solid block of metal. Figure 6-11 illustrates how this reduces the eddy currents. Figure 6-11A shows large eddy currents flowing through the low-resistance solid core. However, a core having the same magnetic characteristics can be formed using several thin sheets as shown in Figure 6-11B.

The individual sheets are coated with an insulating varnish so that no current can flow between the sheets. Thus, any eddy currents produced are restricted to a single sheet of metal. Because the cross sectional area of a sheet is quite small, the resistance of each sheet is relatively high. This high resistance keeps the magnitude of the eddy currents low. Consequently, the power loss is much lower when the core is made of thin laminated (insulated) sheets.

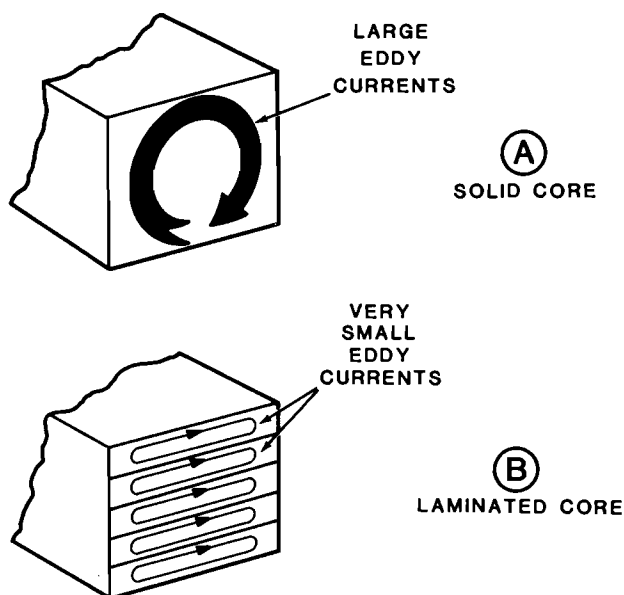


Figure 6-11 Eddy currents can be reduced by laminating the core.

The thin sheets that make up the core are called **laminations**. A laminated iron core is shown in Figure 6-12. The lamination is named according to its shape. Frequently, an iron core is constructed by combining “E” and “I” laminations as shown. Remember, the purpose of laminating a core is to reduce the power loss caused by eddy currents.

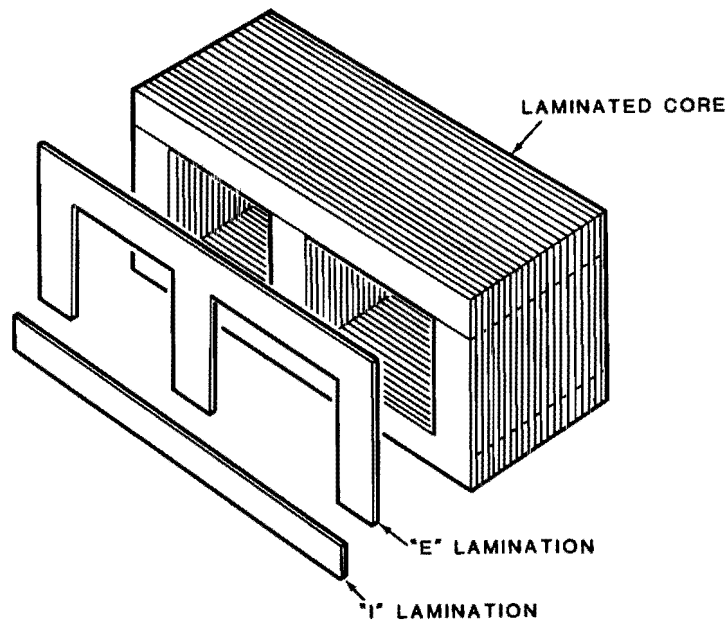


Figure 6-12 Laminated core construction.

Hysteresis

Another type of loss that occurs in the core of a transformer is called **hysteresis**. When iron is not magnetized, its magnetic domains are arranged in a random pattern. However, when a magnetizing force is applied, the domains are lined up by the magnetic field. When the magnetic field reverses, the domains must also reverse their alignment.

In a transformer, the magnetic field reverses direction many times each second. The number of reversals per second is determined by the frequency of the applied AC source. For example, with a 60 hertz source the magnetic field reverses 120 times per second. Remember the magnetic field reverses twice each cycle. When reversing direction, the domains must overcome friction and inertia. In doing this a certain amount of power is dissipated in the form of heat. This power loss is referred to as the **hysteresis loss**.

The terms friction and inertia refer to the basic laws of physics that state “a body at rest tends to remain at rest” and “a body in motion tends to remain in motion”. Therefore, anytime you have relative motion there is friction and inertia. They are a form of resistance to motion and they do cause power to be dissipated.

Some materials such as soft iron normally have high hysteresis losses. The hysteresis loss in steel is lower than soft iron. Some large power transformers use a special type of metal called silicon steel because it has a low hysteresis loss.

The amount of loss caused by hysteresis increases as frequency increases. An iron-core transformer that has a small hysteresis loss at low frequencies, may have a large hysteresis loss at higher frequencies. Hysteresis loss is directly proportional to frequency.

Copper Loss

Another type of loss present in all transformers is called **copper loss**. This loss is caused by the resistance of the copper wire in the primary and secondary windings. A transformer winding can consist of hundreds of turns of fine copper wire. Because of the length of the wire and its small cross sectional area, its resistance can be quite high. As current flows through this resistance, some power is dissipated in the

form of heat. The amount of power dissipated in the form of heat is determined by the formula:

$$P = I^2R$$

Thus, another name for copper loss is the I^2R loss.

The amount of copper loss is proportional to the current squared. When the current through a transformer doubles, the copper loss increases by a factor of 4.

The copper loss is reduced by increasing the size (reducing the wire gauge number) of the copper wire used for the windings. The larger the diameter of the wire, the smaller its resistance. As you can see by the formula, power dissipated and resistance are directly proportional. Decreasing resistance decreases the I^2R loss. Another method of reducing copper or I^2R loss, is to keep the current in the transformer as low as possible.

External Induction Loss

As the magnetic field expands and contracts around the transformer it often cuts an external conductor of some kind. When a current is induced into an external conductor, some power is taken from the transformer circuit. In most cases, the power lost by external induction is so small that it can be ignored. However, the voltage induced into outside circuits

sometimes causes problems. For example, in a sensitive amplifier circuit, the unwanted induced voltage from a transformer may interfere with the signal being amplified.

Interference caused by magnetic induction can be reduced by shielding. Often, sensitive circuits are placed inside a metal shield which will prevent stray magnetic fields from reaching the circuits. Also, transformers themselves are often placed in thin metal housings to prevent magnetic fields from escaping.

Before we used a high permeability material (soft iron) to form a core to concentrate the magnetic force lines into a magnetic field close to our inductor. In this case the flux lines are prevented from cutting the external conductor. These shields are called permeability shields. Remember, magnetic flux lines can not be blocked. However, they can be rerouted.

Transformer Efficiency

Because of transformer losses, more power is applied to the primary of the transformer than

is available for use in the secondary. All transformers have power losses. Hence the **efficiency** of a transformer is always less than 100%.

The efficiency of a transformer is the ratio of output power to input power. For example, when a transformer has an input power of 100 watts and an output power of 90 watts, its efficiency is:

$$\begin{aligned}\text{efficiency} &= \frac{\text{output power}}{\text{input power}} \\ &= \frac{90 \text{ W}}{100 \text{ W}} \text{ or } .9\end{aligned}$$

0.9 is equal to 90%

Efficiency is normally stated in terms of a percentage (%). Thus, the decimal fraction must be multiplied by 100 to convert it to a percentage. The input power is the primary power. The output power is the secondary power. The formula for a transformer's percent of efficiency is:

$$\% \text{ efficiency} = \frac{P_s}{P_p} \times 100$$

Self-Test Review

28. List the 4 common losses associated with transformers and explain the main cause of each.

_____.

_____.

_____.

_____.

29. Eddy currents can be reduced by using a:

_____ core.

30. What are the losses caused by the reversing action of the magnetic field called?

_____ losses.

31. Explain the term magnetic domain.

_____.

32. The efficiency of a transformer is always less than:

_____.

33. Magnetic lines of force can be blocked.

- A. True
B. False

34. Sensitive components can be isolated from magnetic fields by the use of:

_____ shields.

35. A transformer has an input of 100 volts and a primary current of 1 ampere. The transformer's secondary has an induced voltage equal to 90 volts. The load resistor is equal to 100 ohms. What is the efficiency of the transformer?

_____.

Transformer Applications

Transformers are versatile devices. They are used to step-up voltage, to step-down voltage, to step-up current, to step-down current and to match impedance. Also, they can produce a 180 degree phase shift, provide two signals which are 180 degrees out of phase, and isolate one circuit from another. They can pass AC while blocking DC. They can also provide several signals at various voltage levels. Let's look at some of these applications in more detail.

Power Distribution

One of the most important applications of transformers is in the transmission of power over long distances. Often the power generating stations are located near coal fields or dams. These are usually far from the electrical power company customer. Thus, the electrical energy must be transported over great distances by way of transmission lines. The transformer plays a major role in transmitting this energy.

Long distance transmission lines are generally made of aluminum. Copper lines have better electrical characteristics but are too expensive, too heavy, and lack structural strength. You will recall that aluminum has a higher resistivity (ρ or specific resistance) than copper. Consequently, power losses in aluminum lines are high, unless special precautions are taken.

Most of the power lost in a transmission line is caused by the resistance of the line. Recall that:

$$P = I^2R$$

Thus, the amount of power loss is proportional to the resistance of the line and to the **square** of the current. Obviously then, the easiest way to reduce the power losses in the line is to keep the current as low as possible.

For example, suppose a generating station produces 12,000 volts at 10 amperes. Let's assume that this 120,000 watts of power is transmitted over a transmission line having a resistance of 100 ohms. When transmitted as 12,000 V at 10 A, the power loss in the line is:

$$P = I^2R$$

$$P = (10 \text{ A})^2 \times 100 \text{ ohms}$$

$$P = 100 \times 100$$

$$P = 10,000 \text{ watts}$$

Using a transformer, the 120,000 watts can be transmitted as 120,000 V at 1 A. In this case, the power loss is:

$$P = I^2R$$

$$P = (1 \text{ A})^2 \times 100 \text{ ohms}$$

$$P = 1 \times 100$$

$$P = 100 \text{ watts.}$$

Notice that by stepping the current down by a factor of 10, the power loss is reduced by a factor of 100. For this reason, power is transmitted over great distances at very high voltage levels and very low current levels. Upon reaching its destination, the electrical power is stepped-down in voltage to the values required in homes and by industry.

Electronic Applications

In electronic devices the transformer is used to step-up or step-down voltage. Many electronic devices require 115 VAC for power. Most of the devices have a power transformer which steps the voltage up or down, as required. In transistorized equipment, the AC line voltage is usually stepped-down and then changed to DC by a process called rectification. In older vacuum-tube equipment, the line voltage is usually stepped-up and then rectified. Vacuum tubes require higher DC voltages than transistors. As you can see, the transformer can be used to make the line voltage compatible with both types of equipment.

Transformers are also used as impedance-matching devices. They can match the impedance of one circuit to that of another. The im-

pedances must be matched for maximum power to be transferred from one circuit to another circuit.

The above applications were discussed in detail earlier. Now let's take a look at some additional applications.

Phase Shifting

Depending on how the transformer is wound, it provides either a 180 degree phase shift or zero degree phase shift. This means that the voltage in the secondary is either in phase, or 180 degrees out of phase with the voltage in the primary.

In some applications the phase shift is unimportant, such as when AC is rectified to DC. In other applications it is extremely important. Figure 6-13A shows a transformer in which the input signal is in phase with the output signal.

The voltage at point A with respect to ground has the same phase as the voltage at pin 1 with respect to ground. When a 180 degrees phase shift between input and output is needed, you can reverse the secondary's leads when connecting them to the load. Figure 6-13B shows the leads reversed. Notice that this places ground at pin 3 of the transformer. The voltage at point A is now 180 degrees out of phase with the input voltage.

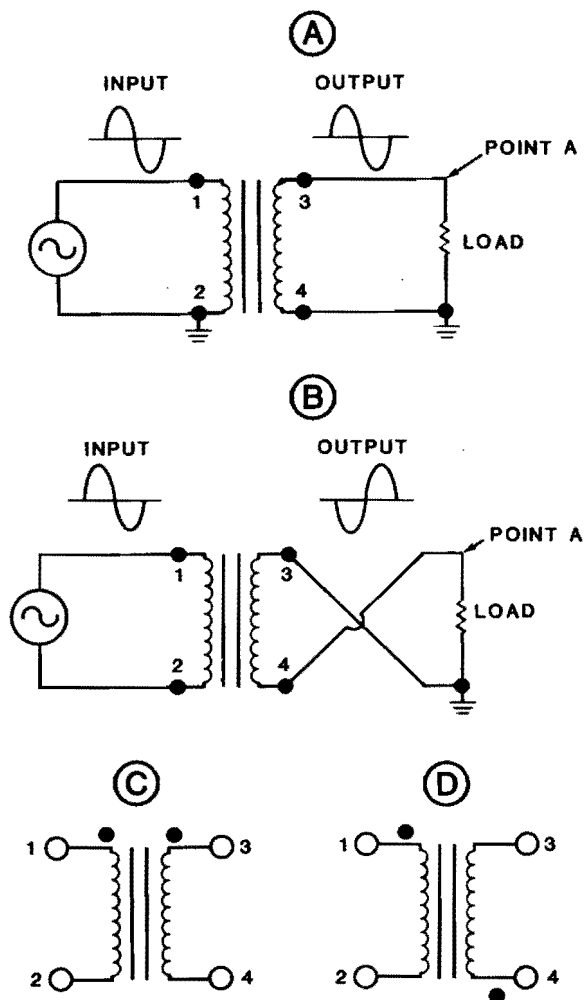


Figure 6-13 Phase relationships in transformers.

The phase relationship between the windings of the transformer is sometimes indicated on schematic diagrams by dots as shown in Figure 6-13C. The ends of the windings marked by dots are in-phase. Thus, the voltage at pin 3 is in phase with the voltage at pin 1. Figure 6-13D shows a transformer that is wound differently. Here the voltage at pin 4 is in phase with the voltage at pin 1. Stated another way, the voltage at pin 3 is 180 degrees out of phase with the voltage at pin 1.

Figure 6-14 shows that an in-phase output or 180 degrees out-of-phase output can be obtained from either type transformer. Notice that the phase can be reversed simply by reversing the leads to the load.

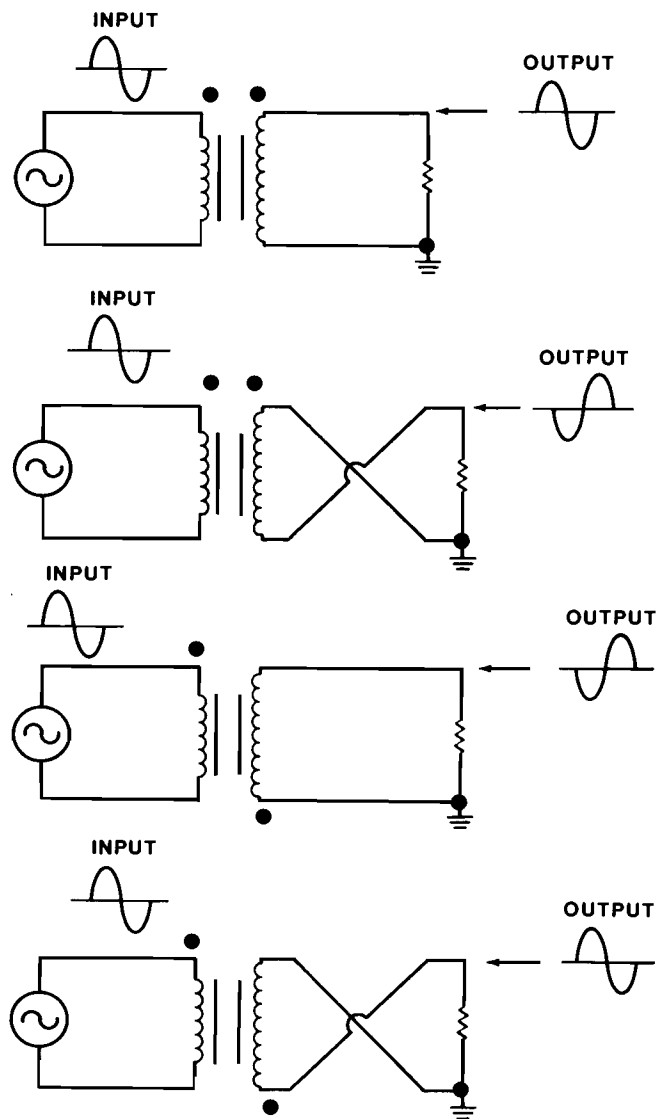


Figure 6-14 The phase can be reversed by reversing the leads to the load.

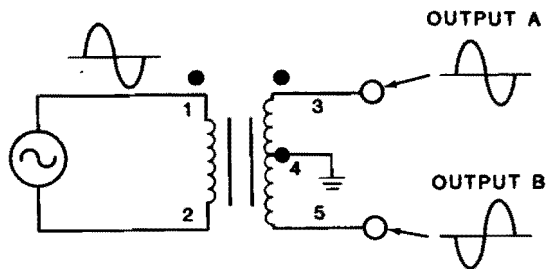


Figure 6-15 A center-tapped secondary produces two signals which are 180° out-of-phase.

Phase Splitting

Some circuits require two AC signals of equal amplitude, but 180 degrees out of phase. A transformer can be used to provide the two out-of-phase signals. Figure 6-15 shows a transformer with a center-tapped secondary. This means that the center of the secondary is connected to a terminal, in this case the terminal is labeled pin 4 and it is grounded. The dots indicate that the voltage at pin 3 is in phase with the voltage at pin 1. Ignoring the center tap, the voltage at pin 5 must be 180 degrees out of phase with the voltage at pins 1 and 3. When the center tap is grounded, two signals which are equal in amplitude and 180 degrees out of phase exist at the opposite ends of the secondary winding. Transformers are often used to produce two equal amplitude signals that are 180 degrees out of phase.

Later in your study of electronic circuits you will see this application used with audio amplifiers as part of a push-pull system.

Isolation

Another purpose of a transformer is to isolate one circuit from another. An AC device that does not use a power transformer often has a metal chassis that connects to one side of the AC power line. Anyone touching this chassis and ground at the same time can receive an electrical shock. When a power transformer is used, the chassis is isolated from the input AC line. Separating the circuit from the input power greatly reduces the possibility of accidental shock.

Frequently, technicians must repair transformerless equipment. When the “hot” chassis is removed from its plastic or wooden cabinet, the possibility of accidental shock increases. To safeguard himself, the technician places an isolation transformer between the AC line and the equipment being repaired. The isolation transformer has a turns ratio of 1 to 1. That is, it takes 115 VAC from the line and delivers 115 VAC to the equipment. This isolates the chassis from the AC line and provides additional protection from shock to the technician.

Autotransformer

The autotransformer is a special type of transformer. In the autotransformer there is no isolation between the primary and the secondary windings. A single continuous coil is wound on a core. Part of this coil is used as the primary, while another part is used as the secondary. Usually, part of the coil is used as both primary and secondary.

Figure 6-16A shows the autotransformer being used to step-down the applied voltage. Here, the entire winding serves as the primary. The lower half of the coil is also used as the secondary winding. Because there are fewer turns in the secondary than in the primary, the voltage is stepped-down and the current is stepped-up.

Figure 6-16B shows that the transformer can be turned around and used to step-up voltage. Here, the lower half of the coil is used as the primary while the entire coil is used as the secondary. Since the secondary has more turns, the transformer steps-up voltage and steps-down current.

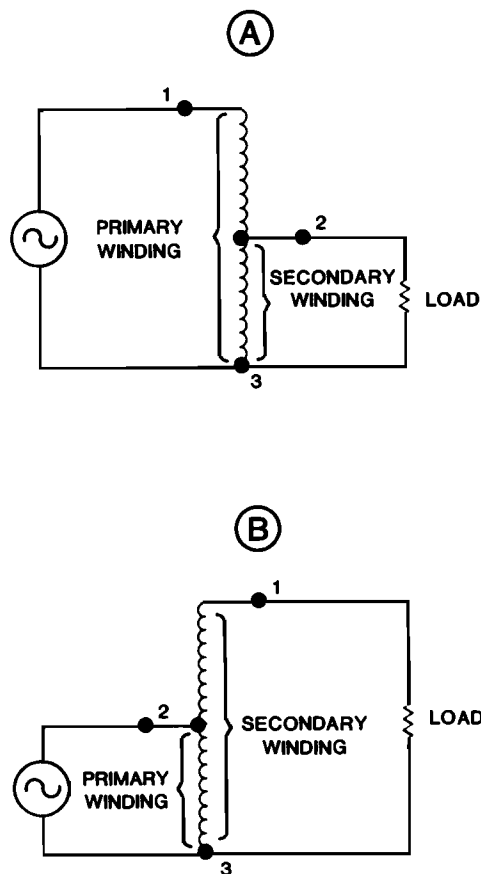


Figure 6-16 The autotransformer.

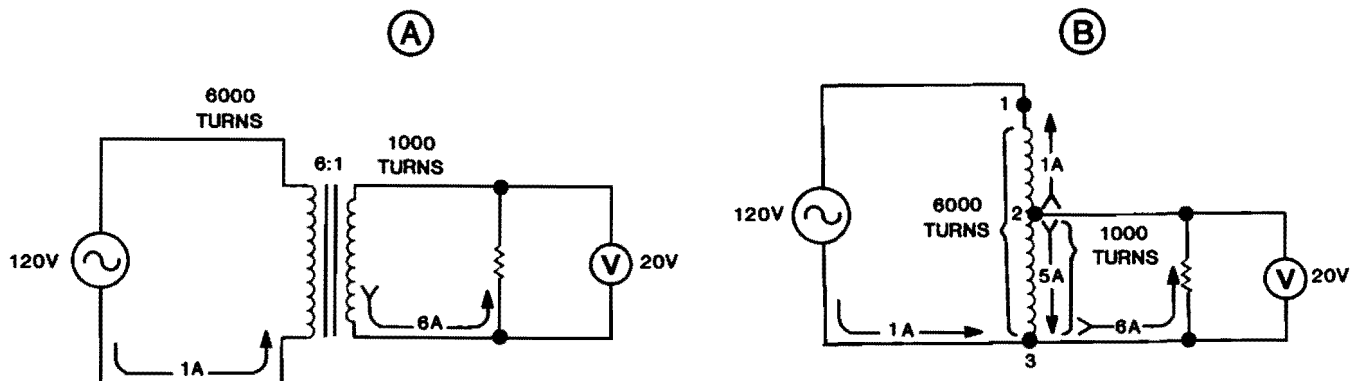


Figure 6-17 Comparing the autotransformer to a conventional transformer.

Figure 6-17 compares the autotransformer with a conventional transformer. The conventional transformer in Figure 6-17A steps the applied voltage down from 120 VAC to 20 VAC. This requires a turns ratio of 6:1. Ignoring losses the current is stepped-up from 1A to 6A.

Figure 6-17B shows how the same job can be accomplished with an autotransformer. The tap at pin 2 is placed at 1,000 turns. Thus, the primary, in this case the entire coil, has 6,000 turns. Only 1,000 of the turns are used for the secondary. Notice that 6 amperes flows in the load, but only 5 amperes flows through the secondary winding. The reason for this is that the current in the secondary winding flows in

the opposite direction to the current flowing in the primary. Thus, the 1 ampere primary current subtracts from the 6 amperes of secondary current.

This illustrates the advantages of the autotransformer. First notice that fewer turns of wire are required in the autotransformer. Also, since the current in the secondary winding is lower, the I^2R loss is lower. In many cases, the autotransformer is also easier to construct and therefore less expensive. Its main disadvantage is that the secondary is not isolated from the primary. It is usually used in electronic circuits that have low current and high frequency requirements.

A special type of autotransformer is shown in Figure 6-18. The load is connected between the movable arm and the bottom of the coil. By moving the arm up or down the turns ratio can be changed. This causes a corresponding change in voltage across the load. The output voltage can be varied from almost zero to over 130 VAC. This device is called a variable autotransformer.

The autotransformer gets its name because it is usually used in the audio frequency range. The audio frequency range is considered to extend from approximately 10 hertz to 25,000 hertz.

Because of their inductive reactance, transformers see limited use in high frequency cir-

cuits. The exception, is the special tuned tanks used in IF and RF applications. These special signal coupling transformers are used in extremely low current applications. This coupling requirement is usually in the microampere range.

Examine the AC source provided on your trainer. If you are using Heath's ET-3100 series trainer you will see three terminals marked 15 AC, ground, and 15 AC. This is the secondary of a center tapped transformer. It steps the 115 VAC input voltage down to 30 VAC. The center tap splits the 30 volts into two 15 volt supplies. The 15 VAC supplies are equal in amplitude and out of phase by 180 degrees.

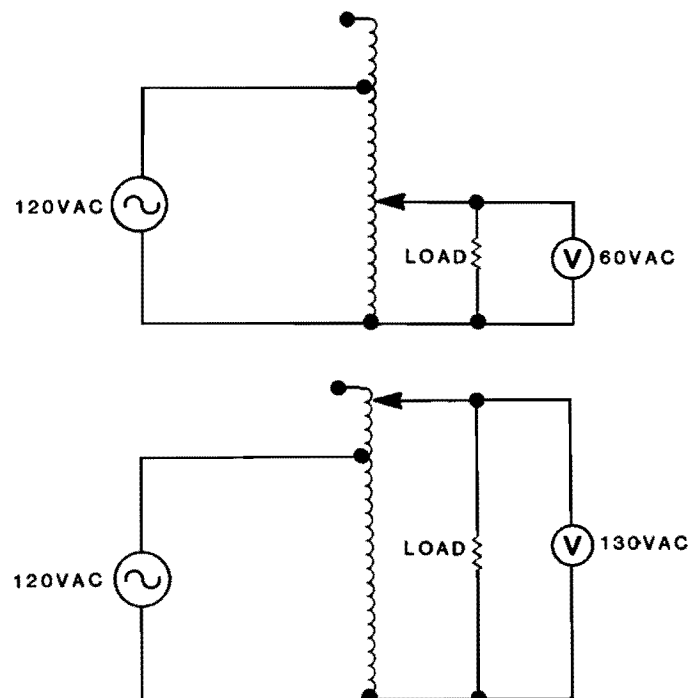


Figure 6-18 The variable transformer.

Self-Test Review

36. When power is transmitted over long distances, the current flowing in the transmission line is:

_____ high/low
37. When a transformer has multiple taps in the secondary it is used to provide voltages of:

_____.
38. What is the major loss associated with transmission lines?

_____ loss.
39. In electronic applications a transformer is used between two circuits to:

_____.
40. Name the application in which polarity inversion between the primary and secondary is not a consideration.

_____.
41. Explain why a transformer is considered a safety device.

_____.
42. When a transformer is used as a safety device the proper name is:

_____ transformer.
43. Transformers can produce phase shifts of:

_____ and _____ degrees.
44. A center-tapped secondary produces two voltages which are:

_____ in amplitude.
45. A center-tapped secondary produces two voltages that are out of phase by:

_____ degrees.
46. A transformer consisting of a single continuous tapped winding is called a/an:

_____.
47. The disadvantage of the autotransformer is that it does not provide:

_____.
48. Compared to conventional transformers the autotransformer's resistance is:

_____ higher/lower.
49. Autotransformers are mainly used at frequencies between:

_____ and _____ hertz.
50. The tap on an autotransformer is moved to adjust the:

_____.

Unit Summary

The transformer is a device that couples AC signals from one circuit to another.

During the transform process, the voltage or the current can be stepped-up or stepped-down. When voltage is stepped-up, current is stepped-down. When current is stepped-up, voltage is stepped down. In an ideal transformer, power in the primary is equal to power in the secondary. However, frequency is never changed.

A transformer consists of two or more windings wound on a core. The winding to which an input signal is applied is called the primary. The winding from which an output signal is taken is called the secondary. The core material is usually air, steel, soft iron, or silicon steel. Metal cores have a high permeability that increases magnetic flux density.

Transformer action is based on electromagnetic mutual inductance. Current in the primary produces a magnetic field which induces an EMF into the secondary. In turn, secondary current produces a magnetic field which induces an EMF into the primary. This EMF opposes the counter EMF of the primary. Consequently, an increase in secondary current causes an increase in primary current. When the secondary is open an excitation current still flows in the primary winding.

The voltage ratio, the current ratio, and the impedance ratio of a transformer is determined by the turns ratio. Turns ratio is the number of turns in the primary compared to the number of turns in the secondary. Voltage and impedance are directly proportional to the turns ratio and current is inversely proportional to the turns ratio.

The formulas using turns ratios assume that the transformer is ideal (has no losses). This is the same as assuming that the transformer is 100% efficient. Since all transformers have losses, their efficiencies are less than a 100%. However, 90% efficient is considered to be the norm.

A transformer can be used to match the impedance of one circuit to that of another. This is important since maximum power is transferred only when the impedance of the source matches that of the load.

Transformer losses consist primarily of core losses and copper losses. Core losses are caused by eddy currents and hysteresis. Many transformer cores are laminated to reduce eddy current losses. Copper losses are caused by the AC resistance of the transformer's windings. Hysteresis losses are kept small by using small values of current.

Transformers are also used to provide a 180 degree phase shift between two signals. To isolate one circuit from another, to isolate an operator from the line voltage, and to block DC while passing AC signals.

An autotransformer is a special type transformer that consists of a continuous winding on a core. It may be used like any other transformer except that it does not provide isola-

tion between the input and output. Autotransformers are usually used in the audio frequency range which is between 10 hertz and 25 kilohertz.

An isolation transformer is a special purpose transformer that is used to isolate one circuit from another. Frequently, a 1:1 isolation transformer is used by technicians to isolate a transformerless chassis from the AC line.

Unit 7

Motors and Motor Controls

Contents

Introduction	7-3	Motor Speeds.....	7-20
Unit Objectives	7-4	Motor Control Circuits	7-24
Review of DC Motors	7-5	Motor Control Systems	7-28
Types of Induction Motors	7-9	Desk-Top Experiment 7	
AC Motors	7-13	Identifying Motor Symbols	7-38
		Unit Summary	7-42

Introduction

In this unit on motors and motor controls you will learn about the basic differences between motors, basic motor control components, and motor control systems. This unit was designed to introduce you to motors, motor terminology, and to motor's principles of operation. The types of motors and controls explained in this unit are the types that you will encounter both in your home and in industrial applications.

This unit combines what you learned about resistors, inductive and capacitive principles, and electromagnetic induction principles in DC and AC electronics into practical circuits.

Let's start this discussion by reviewing electromagnetic induction, generators, and DC motors.

Unit Objectives

When you complete this unit you will be able to:

1. Define the term motor.
2. Demonstrate the right-hand rule for motors.
3. Explain the principle of electromagnetic induction.
4. Explain the operation of the following types of motors:
Series type.
Shunt type.
Compound type.
5. Draw the waveform for a single-phase motor.
6. Name the common use for a two-phase motor.
7. Explain the phase relationships between the windings of a three-phase motor.
8. Calculate the percent of regulation for a motor when the loaded and unloaded operating speed is known.
9. Explain the relationship between the magnetic field strength and RPM.
10. State the type of motor that is called a universal motor.
11. Explain the relationship between a motor's slippage and its torque.
12. Define the motor terms inertia and friction.
13. Draw a DC control circuit that can reverse a motor's direction and change its speed of operation.
14. Differentiate between a servo system and a synchro system using a schematic diagram.
15. Define the terms synchronous and asynchronous as they apply to motors.
16. Explain the relationship between torque and synchronous and asynchronous motors.

Review of DC Motors

In your study of DC Electronics, you saw that a generator converts mechanical energy into electrical energy. A DC motor does just the opposite: it converts electrical energy to mechanical energy. Figure 7-1 illustrates the principle that makes this conversion possible. In the figure, a current carrying conductor is shown in a magnetic field. This current is not induced. Instead the current flows because the conductor is connected to a battery. Because of the current, a magnetic field develops around the conductor, in the direction shown. This can be verified by the left-hand rule for conductors.

Induction Principles

In the figure, the magnetic field around the conductor interacts with the field of the per-

manent magnet. On one side of the conductor, the two magnetic fields are in the same direction and they add. This aiding magnetic field produces a strong magnetic field. On the other side of the conductor, the two magnetic fields are in opposite directions. Opposing magnetic fields tend to cancel each other, resulting in a weak magnetic field.

As you can see in Figure 7-1, the flux lines are more numerous on one side of the conductor than on the other. Thus, on one side, the lines are bent and forced very close together. These lines have a natural tendency to straighten and move farther apart. However, the only way they can do this is to push the conductor out of the way. Thus, a force develops that pushes the conductor in the direction shown.

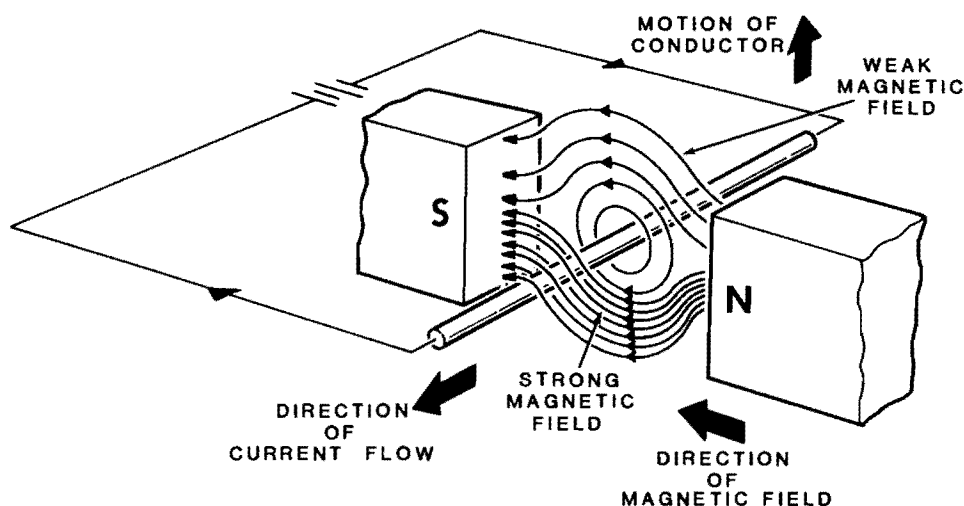


Figure 7-1 DC motor theory.

The rule used to determine the direction that the conductor will move in the magnetic field is called the right-hand motor rule. The right-hand rule is illustrated in Figure 7-2. Using your right hand, point your index finger in the direction of the field of the permanent magnet. Point your middle finger in the direction of current flow through the conductor and at a right angle to the index finger. Point your thumb straight up and at a right angle to both the index and middle fingers. Your thumb now points in the direction that the conductor will move. By applying this rule, you can see how a simple DC motor operates.

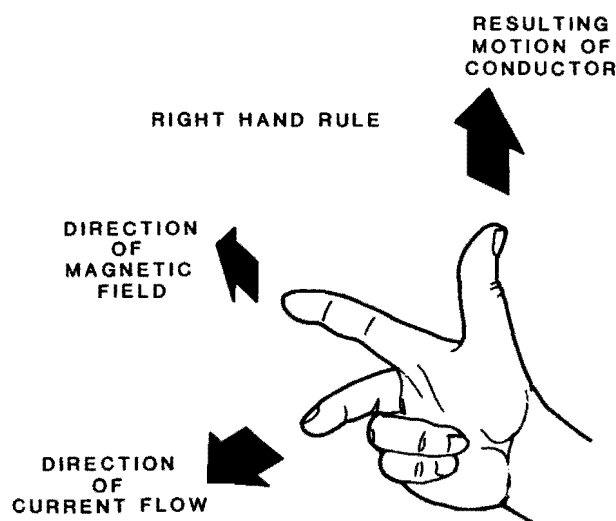


Figure 7-2 Rule for motor action.

A simplified drawing of a DC motor is shown in Figure 7-3. This is similar to the DC generator described earlier. However, there are two important differences between generators and motors. First with the generator, the armature is turned by an outside mechanical force. However, in a motor the armature turns because of the electrical force applied. Second, in the generator, a DC voltage is picked off the armature by the brushes. In a motor, an external DC voltage is applied to the brushes.

Right-Hand Motor Rule

Current flows through the armature as indicated by the arrows in Figure 7-1. By applying the right-hand motor rule to the side of the armature near the south pole of the magnet, you find that the conductor tends to move up. When you apply the same rule to the side near the north pole, you find that this side tends to move down. Thus, the armature rotates in a counterclockwise direction. After one half cycle of revolution, the two sides of the armature reverse positions. Nevertheless, current still flows in the same direction and through the side closest to the south pole. Whichever side of the armature appears at this point, the resulting motion is always up. The upward force at the south pole and the downward force at the north pole causes the armature to rotate.

The motor shown in Figure 7-3 is not practical because a single loop of wire is used as an armature. Motors use hundreds of turns of wire in the armature winding. Using many conductive wires for the armature causes a very strong twisting motion, or **torque**, to be developed. The single loop is used to demonstrate what happens because of motor action. The many loops in the armature all operate on this principle and they are additive (aiding).

Small DC motors are rated in fractional horsepower (HP). Fractional horsepower motors are usually operated using a split phase winding. That is the single winding is divided into a start and a run section. The primary advantage of the DC motor is its simplicity of design and flexibility. Its primary disadvantage is its tendency to run away under no load conditions.

DC Motor Problems

The most common cause of a malfunction in DC motors is brush related. Therefore, a visual inspection of the brushes for wear, spring tension, and arcing should be part of a periodical inspection phase. As the brush wears, it deposits conductive dust inside the motor housing. This dust can accumulate and cause short circuits. Replacing the brushes before they damage the armature will save you money and time. Brushes are relatively inexpensive

and armatures are very expensive. When motors are periodically inspected and serviced they don't cause as many unscheduled shut downs as when serviced only when they malfunction.

Many motors require periodic lubrication. Lubrication prevents excessive surface wear on the motor's bearings and the armature's shaft. Care should be used so that excessive amounts of lubrication are not used. Excessive oil or grease can trap dirt and foreign materials which could increase friction or cause shorts. Some lubrication materials are nonconductive and if allowed to get onto the armature could rub off on the brush face and insulate the brush from the armature's surface.

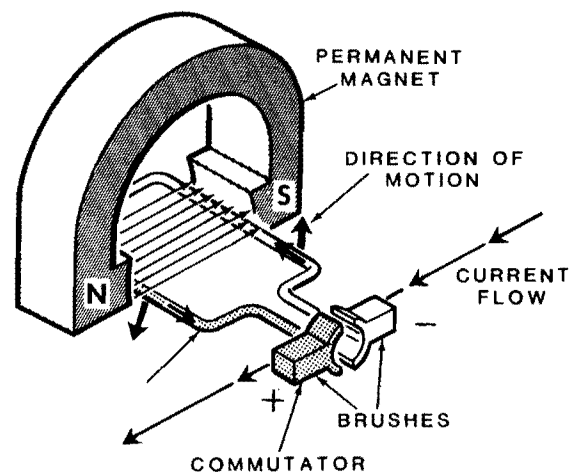


Figure 7-3 The DC motor.

Self-Test Review

1. Using the right-hand motor rule the thumb points in the direction of the:

2. The twisting force applied to a motor is defined as:

3. The advantages of DC motors when compared to AC motors are its simplicity of design and:

4. One serious disadvantage of a DC series motor under no load conditions is its tendency toward:

5. The most common cause of problems in DC motors is:
_____ related.

Types of Induction Motors

As you know from your study of generators, the magnetic induction principle is used along with the left-hand rule to explain generator action. A generator converts mechanical energy into electrical energy and a motor converts electrical energy into mechanical energy (motion). It was explained earlier in your studies that meter movements work on the motor principle. It was also stated, that motors use the right-hand rule to explain induction.

Induction motors are classified according to their internal construction. Internal construction types are the series wound, shunt wound, compound type, and universal type. Let's examine each of these types of motor construction.

Series Motor

In series motors, the field coils are in series with the armature. In other words, the same current that flows through the armature flows in the field windings. This is shown in Figure 7-4A.

The series motor must always use a resistive load. Without a resistive load, as the speed of the armature increases, the counter electromagnetic induction increases. The increasing counter emf causes a decrease in the armature's current. This decreasing current causes the field to start to collapse. As the field collapses, it provides an inductive kick to the armature current. This cycle continues, cur-

rent keeps increasing until the motor reaches a speed at which it self-destructs. This is referred to as motor run-away.

Another disadvantage of the series motor is its tendency to heat up. This is because of its high torque and resistive load requirement. When the motor overheats it wastes power.

Series motors are usually used to move heavy loads. They develop maximum torque (turning power) and are geared down as the speed starts to increase. The speed of the series type motor can be controlled by installing a resistor in series as shown in Figure 7-4B. The variable resistor provides a method of adjusting the current. The current in turn has control of the magnetic field strength, which controls the induced voltage in the armature. Anytime a resistance is added in a series loop, current decreases in that loop.

Series-type motors can be used with DC or AC inputs.

Shunt Motor

The shunt motor is shown in Figure 7-4C. In this type motor, the field windings are connected in shunt (parallel) with the armature. The shunt motor is classified as a constant speed motor. Soon after the motor starts, it reaches a speed at which the field and armature currents are almost equal. This is the

speed that is considered the motor's constant speed. The constant speed characteristic of the shunt motor is considered to be its primary advantage. Low torque is the main disadvantage of shunt type motors.

The shunt motor's constant speed can be changed by installing a resistor in series with either the field or the armature. In Figure 7-4D, the speed control resistor is in series with the armature. Note that the inductor (field winding) parallels both the resistor and the armature.

Adding the resistor in series with the field winding reduces the current flowing in the field. Decreasing the field current reduces the voltage that is induced in the armature. The induced voltage opposes the polarity of the voltage that caused it. This reduces the opposition to the motor's rotation and increases the motor's speed. Unfortunately, adding the resistor also reduces the motor's power efficiency rating. As is usually the case, in most electronic circuits, efficiency is sacrificed to achieve control.

Thus, by installing the resistor in series with the armature, we decrease the armature's current, which decreases the motor's speed of operation.

The shunt type motor is not normally used with AC.

Compound Motors

Compound motors use both series and shunt fields. This is shown in Figure 7-4E. The series winding provides a high starting torque, which overcomes initial friction. Once operating speed is approached, the shunt winding takes control and the constant speed characteristic becomes the most important characteristic. The compound motor combines the advantage of both types (series and parallel) of motors, and at the same time compensates for their disadvantages. The result is a constant speed motor that is capable of developing high torque. The possibility of thermal runaway is also eliminated.

Compound motors come in two varieties. When the series and parallel windings are wound so that they are aiding each other the motor is called a **cumulative** compound motor. When the series and parallel windings are wound so that they oppose each other, the motor is called a **differential** compound motor.

The compound motor is used with DC input voltages.

Universal Motor

The universal motor is a series type motor that uses resistors in series with its brushes to limit high currents. The added resistance also reduces brush arcing. The universal motor is

usually limited to low power applications (fractional horsepower ratings). Universal motors are used in small electric hand drills, small fans, and toys.

A DC motor can be used as a generator. The AC motor cannot be used as a generator.

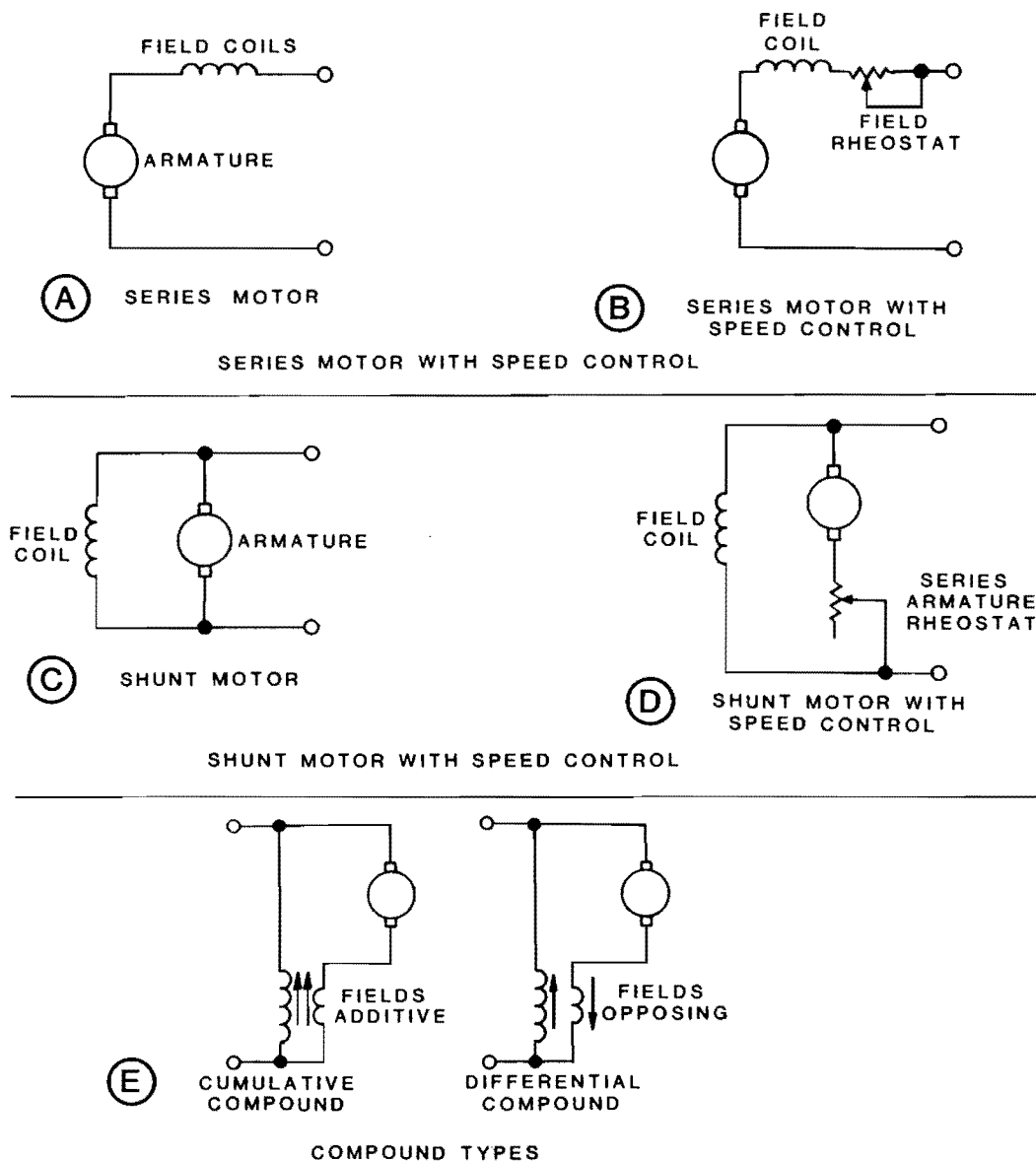


Figure 7-4 Induction type motors.

Self-Test Review

6. The three types of construction used in induction motors are:
1. _____.
 2. _____.
 3. _____.
7. A motor that is used with both AC and DC voltages is called a/an:
_____ motor.
8. Which type motor is **NOT** normally used with AC?
_____.
9. A resistor connected in series with the stator winding causes the motor speed to:
_____.
increase/decrease
10. When a motor has both series and parallel-aiding fields, it is called a:
_____ type.
11. When the series and parallel fields oppose each other, the motor is a:
_____ type.
12. In a compound motor, which winding provides the high starting torque needed to overcome initial friction and inertia?
_____ winding.
13. Maximum torque and friction occur when the motor is at:
_____.

AC Motors

As stated earlier the series type motor can be used as an AC motor, but the induced current must be kept low.

Besides the universal motor, there are several types of AC motors in common use. Most of the motors in your home fall into the following motor classifications: single phase, two-phase, or three-phase. In addition there is a classification called polyphase motors. In general the term polyphase means two or more phases.

In this course, the polyphase motor is the three-phase motor. Three-phase motors are very common in every home. Motors that require more than three phases are specific function motors like those used in heavy industry.

We will limit our discussion to the types of motors that you are most likely to see. Let's begin the discussion with the single phase motor.

Single-phase Motors

The single-phase motor consists of a rotor and two stator windings as shown in Figure 7-5. The rotor is forced to turn by the unequal magnetic fields around the stator windings. The stator fields are unequal because the two fields (start and run) are made of different diameter wires, and there is a different number of turns in the windings. This automatically

causes a lead/lag difference between the stator's fields. The rotor starts to turn toward the stronger stator field. The AC input causes the stator's electromagnetic field to continually change. The rotor reacts to the induced change. However, the rotor can never overtake the stator fields. The effect can never overcome the cause, in a mechanical system.

Induction motors can be started by placing their starter field 90 degrees from the run field. Since the winding has some resistive component, the phase angle will be slightly less than 90 degrees. This physical separation induces a current into the armature that overcomes friction and inertia. When friction and inertia are overcome the motor starts to rotate. Once rotation has started there is relative motion and magnetic fields will continue to be produced. The faster the motor turns, the stronger the attraction to turn. This is true until the speed of operation is reached. Once the speed of operation is reached, the armature and stator winding are separated by a predetermined amount.

Let's combine some of the information presented earlier to explain angular motion and some of the common terms used to describe generator and motor actions.

Notice in Figure 7-5 that the input waveform is an AC sine wave that is marked as $\pi/2$, π , $\pi/4$, and 2π . The sine wave, as you know, rotates for one complete cycle that is equal to

grees. The sine wave is also measured in radians per second. A radian is approximately equal to 57.3 degrees. The term radian is used to represent angular displacement.

The sine wave is a vector that rotates counter clockwise for 360 degrees. A radian is an angle that intercepts an arc (B to C) equal in length to the radius (C to A) of a circle as illustrated in Figure 7-6.

When an armature rotates for one complete cycle, regardless of whether it is generating a sine wave (generators), or being driven by a sine wave (AC motor), the armature rotates through 360 degrees or 2π radians. The circle is divided into 4 (IV) equal quadrants.

In Figure 7-6, the sign of the angle in each of the quadrants is listed (either positive or negative) for the sine, cosine, and tangent function of the angle.

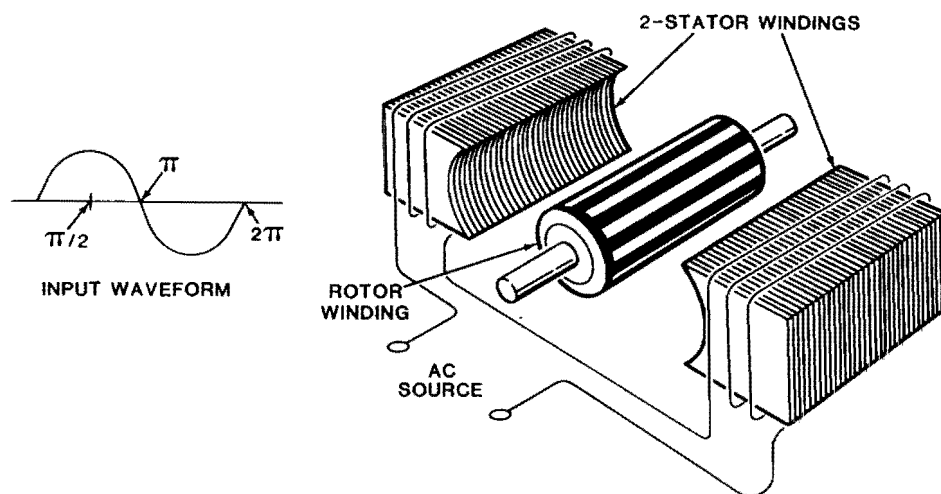
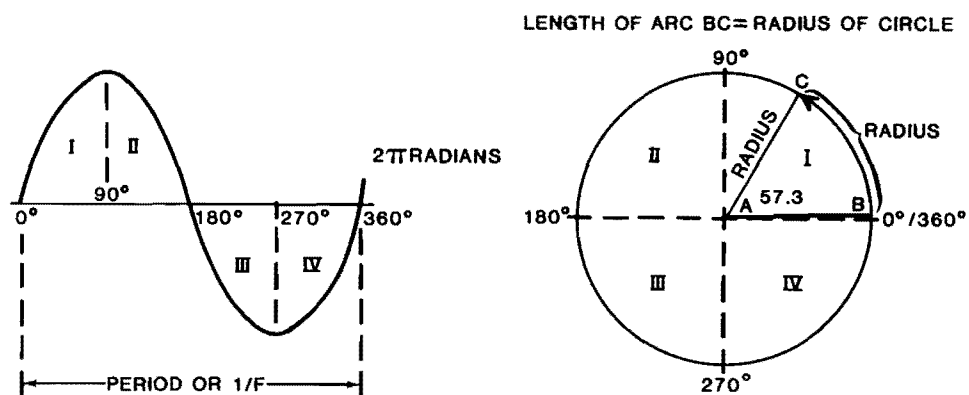


Figure 7-5



Signs of the Functions

Quadrant	$\sin \theta$	$\cos \theta$	$\tan \theta$
I	+	+	+
II	+	-	-
III	-	-	+
IV	-	+	-

$\pi \approx 3.14$
 $6.28 \text{ radians} = 360^\circ$
 $2\pi \text{ radians} = 360^\circ$
 $\pi \text{ radians} = 180^\circ$
 $1 \text{ radians} = 57.2958^\circ$
 $1 \text{ degree} = 0.01745 \text{ radian}$
 $\text{SIN OF } 57.3^\circ = .8415$
 $\text{COS OF } 57.3^\circ = .5402$
 $\text{TAN OF } 57.3^\circ = 1.5577$

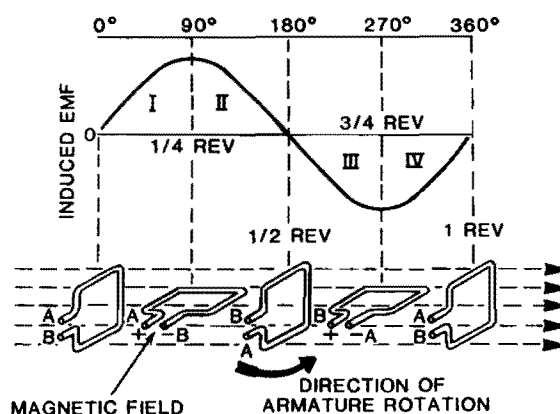


Figure 7-6 Angular rotation relationships.

Remember, motors use windings and windings are essentially inductive components. In inductive components, voltage leads current.

When the single-phase motor comes up to speed, a centrifugal switch disconnects the starter (stator S_1) winding. Until power is removed from the circuit or an increased load slows the motor to the point where the centrifugal switch is reconnected and the motor continues to turn using the run (stator S_2) winding. This is shown in Figure 7-7.

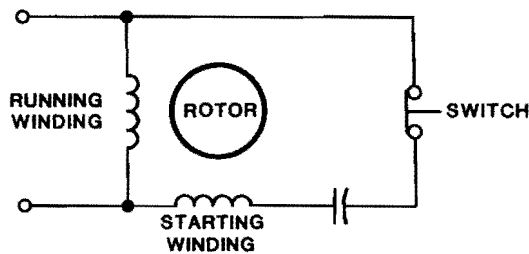


Figure 7-7 A single (split phase) motor with a capacitor and centrifugal switch.

A capacitor can be installed as shown in Figure 7-7. The capacitor is installed between the stator windings to increase the phase difference between stator windings. Increasing the phase difference causes the current to lead (ICE) the voltage and increases the starting torque of the motor.

Shaded motor poles also increase the starting torque of a motor. A shaded pole is when a portion of a pole face has a heavy copper wire wrapped around it. This causes a higher induced current in one side of the pole face. The shading acts as an aid in starting rotation.

Two-phase Motors

The two phase motor is the simplest form of polyphase motors used in industry. The term polyphase is used to describe any motor that has more than one input. (Two phase motors are mainly used as servomotors. The servomotor will be covered in more detail later in this unit). For now, a two-phase motor is a motor that has two inputs that are 180 degrees out of phase. The two-phase motor must be driven from two separate inputs. To reverse the direction of rotation, simply reverse the inputs. A typical two phase motor is shown in Figure 7-8.

Polyphase Motors

Any motor with more than one input is considered a polyphase motor. Industry uses more three-phase motors than any other type. Applications that require power ratings above a fraction of a horsepower nearly always have three or more input windings.

In fact, the three-phase motor is so common that the terms polyphase and three-phase are used interchangeably. Polyphase motors use a squirrel cage rotor like the one shown in Figure 7-8.

As shown in Figure 7-9, a three-phase motor is operated by three inputs that are separated by 120 degrees. This is accomplished using 3 stator windings that are electrically separated by 120 degrees around a squirrel cage rotor. To reverse the direction of rotation in a 3 phase motor, reverse any 2 of the 3 inputs.

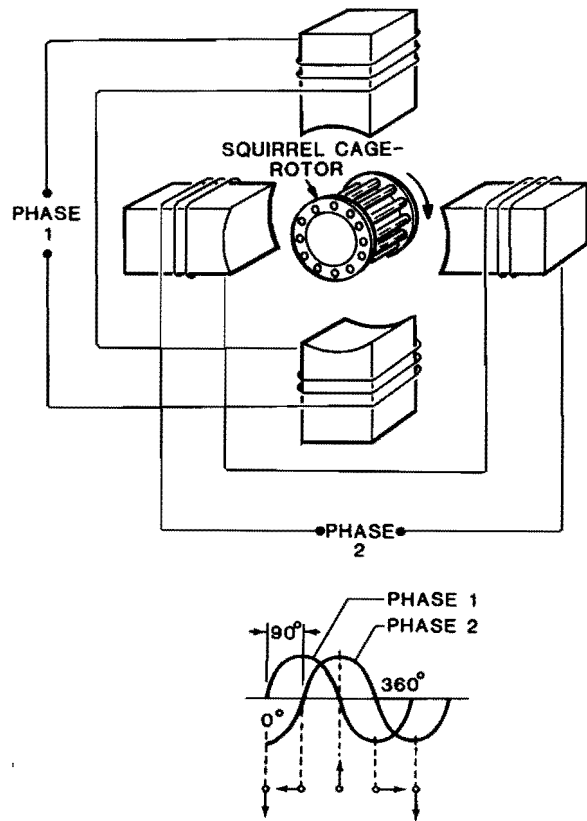


Figure 7-8 Two phase motor.

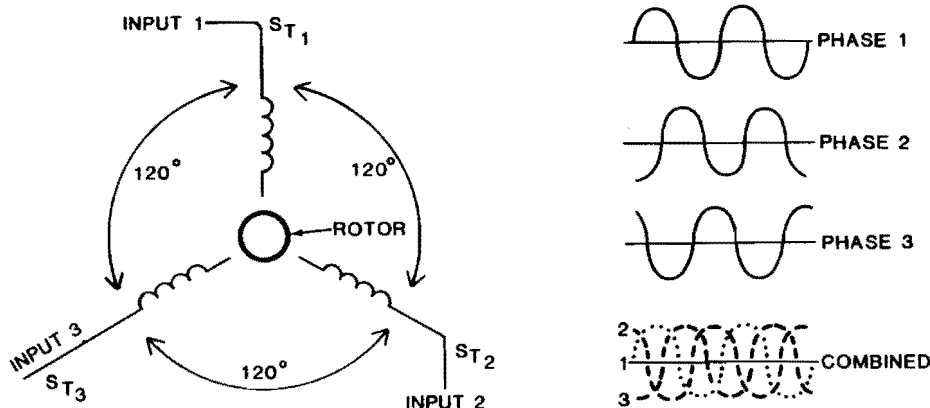


Figure 7-9 Polyphase motor contains a rotor and 3-stator winding that are separated by 120°.

Three-phase motors may use one of two wiring configurations. The stator windings may be wound in the delta or Y (star) configurations as shown in Figure 7-10. In the delta winding an input is applied across a single winding. In this case, the voltage is lower and the current higher than is the case with the Y or star winding. In the Y or star wiring configuration, the input is applied across two windings and the voltage developed is higher, but the current lower than in the delta configuration. The number of turns in the winding or windings is directly proportional to the impedance (resistance). Remember, Ohm's Law states that ($E = IR$) current and resistance are inversely proportional, as long as voltage is held constant.

Three-phase motors should be checked periodically to ensure that they are operating at the proper speed and temperature. When one of the phases of an operating three-phase motor opens, the motor runs slower and heats up. This may not be detected in some applications until the internally generated heat completely destroys the motor.

A simple three-phase motor has a pair of poles for each phase. Therefore a two-pole, three-phase motor has 6 poles. The poles are separated by 60 degrees ($6 \times 60 \text{ degrees} = 360 \text{ degrees}$).

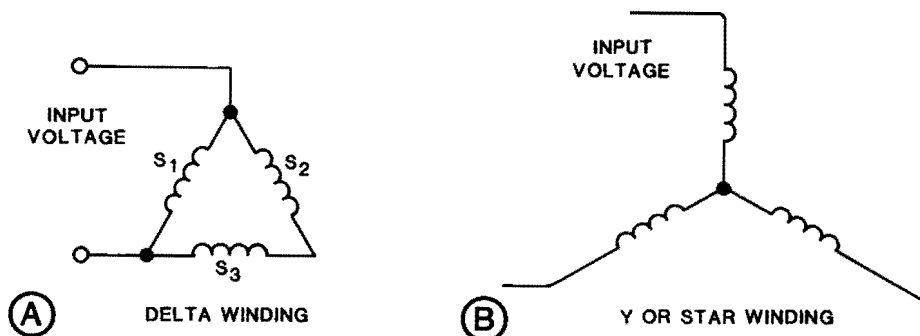


Figure 7-10 Motor winding configurations.
A. Delta wound for high current
B. Y or Star wound for high voltage.

Self-Test Review

14. The AC motor can be used as a generator.
A. True
B. False
15. The automatic speed control that is usually mounted directly on the motor is the:
_____ switch.
16. The single phase motor contains a rotor and:
_____ windings.
17. To develop maximum torque, the stator winding should be:
_____ from the rotor.
18. Define 2π radians.
_____.
19. The sine wave is a vector that rotates:
_____.
clockwise/counterclockwise.
20. The polarity of the cosine function in the third quadrant is.
_____.
positive/negative
21. A starting capacitor is connected in series with the starter winding to:
_____ phase difference.
increase/decrease
22. The stator windings in a three-phase motor are electrically separated by:
_____ degrees.
23. A polyphase motor is defined as a motor having 2 or:
_____ phases.
24. Single-phase motors usually have power rating that are in:

_____.
25. One phase of a three phase motor opens while it is in operation. The motor will:
1. _____.
2. _____.
26. A polyphase motor is converted from Y wound to delta wound. This results in lower:
_____ and higher _____.

Motor Speeds

Speed is motion or distance for a specific period of time. In the car, it is miles per hour or kilometers per hour. In motors, it is RPM (revolutions per minute) or RPS (revolutions per second).

Common terms associated with motor speeds are RPM (revolutions per minute), synchronous, and asynchronous. Synchronous and asynchronous are terms used to compare the rotor's speed to the stator's speed.

RPM

The term RPM for induction motors is calculated using the formula:

$$\text{RPM} = \frac{VF}{P}$$

Where:

RPM is revolutions per minute.

VF is the applied voltage and its frequency.

P is the number of poles produced in the stator's field.

For example: A 3-phase, 4-pole induction motor has an input voltage of 120 volts at 60 hertz. The motor's RPM is:

$$\text{RPM} = \frac{120 \times 60}{4}$$

$$\text{RPM} = \frac{7,200}{4}$$

$$\text{RPM} = 1,800$$

As you can see by the formula, either increasing the input voltage or increasing the frequency of the input, causes the motor to turn at a higher speed.

The 120 volts applied in this example is high for most electronic circuits. However, there are many motors in homes that operate with 120 volts.

Increasing the number of poles in a motor causes the motor to turn at a slower speed, but with increased torque.

The counter emf in a motor is directly proportional to its speed and the strength of the magnetic field.

$$\text{counter emf} = \text{speed} \times \text{field strength}$$

By rearranging the equation, we get

$$\text{speed} = \frac{\text{counter emf}}{\text{field strength}}$$

Therefore, speed is inversely proportional to field strength.

Motor Regulation

Most motors have a calculated regulation factor. In the case of a series motor, it must be regulated so that if the load opens, the motor doesn't continue to increase speed to the point of self destruction. You can regulate the motor by connecting a physical resistor in series with the stator winding.

A motor requires more current to start rotating than it does to continue rotating. This makes sense because once friction is overcome, the start winding can be disconnected. This is usually accomplished by using a centrifugal throw out switch. The switch opens the starter winding when the motor reaches its run speed. The motor's speed is then controlled by the input voltage and the run winding.

Synchronous Speed

When a motor's rotor rotates at the same speed as the stator winding, the motor is called a **synchronous** motor. If this condition ever existed, there would be no relative motion between the stator and rotor fields. Without relative motion there wouldn't be any drive current induced into the rotor.

Synchronous speed is an ideal term, in actual practice when the rotor turns at almost the same speed as the stator it is considered to be operating at its synchronous speed. Actually it oscillates in speed very close to the stator's speed.

A synchronous speed motor turns very fast, but has a very low torque capability. This makes the synchronous motor suitable for turning light loads at high speeds.

Asynchronous Speed

Asynchronous motors have a definite lag behind the stator windings. This lag is called **slippage** and it is the slippage that determines the angle at which the stator field cuts the rotor's conductor material. The closer to 90 degrees separation, between the stator windings and the rotor, the greater the number of lines cut. The higher the number of lines cut, the stronger the induced current. Maximum torque is developed at 90 degrees of separation.

Percent of Regulation

Motor regulation is expressed as a percentage of unloaded speed of operation. The amount (percentage) of regulation depends upon the actual load that the motor is turning. Thus, the more torque that must be generated to turn a load, the slower the motor turns.

The equation for a motor's percent of regulation is equal to:

$$\frac{\text{no load speed} - \text{full load speed}}{\text{full load speed}} \times 100$$

For example, a motor has a no load speed of 1,000 RPMs, but when fully loaded it has a speed of 800 RPMs. The percent of regulation for this example is:

$$\begin{aligned}\% \text{ of regulation} &= \frac{1,000 - 800}{800} \times 100 \\ &= \frac{200}{800} \times 100 \\ &= .25 \times 100 \\ &= 25\end{aligned}$$

The percent of regulation is 25 percent. This should not be confused with a motor's speed

control. Speed control is a term which means external circuitry used to control the speed of a motor. The series resistor used to control a series DC motor and the centrifugal switch could be considered as external components, to the basic motor.

Later in your studies of Semiconductor Devices and Electronic Circuits, you will study special devices and complete circuits that are used to control motor speed and motor direction of rotation.

Self-Test Review

27. Comparing synchronous and asynchronous motors, which type operates at the higher speed:

_____.

28. The amount of lag between a rotor and the stator field is defined as:

_____.

29. A simple three-phase motor has:

_____ poles.

30. Shading the motor's poles has what effect on the motors starting torque?

_____.
increases/decreases

31. When the number of poles in a motor is increased, the motor's speed:

_____.
increases/decreases

32. When the operating frequency of the applied voltage is increased the motor's speed:

_____.
increases/decreases

33. When the magnetic field strength is increased, the motors speed:

_____.
increases/decreases

34. Define synchronous speed.

_____.

35. Torque and motor speed are:

_____ proportional.
directly/inversely

36. The voltage necessary to overcome the effects of friction and inertia is called:

_____ voltage.

37. The formula for % of regulation is:

_____.

Motor Control Circuits

It is possible to operate a DC motor using a switch to turn it on and off. However, there are times when you will want to vary the speed or direction of the motor rotation. When this happens, it is possible to use resistors or variable resistors to control the motor.

DC Control Circuits

Figure 7-11 shows the simplest DC motor control circuit. In the figure the DC motor is shown as a circle with an M inside the symbol. This is the schematic symbol for a DC motor. Switch S_1 controls the power to the circuit. Ultimately, this switch determines whether or not the motor is running. Resistor R_1 is a series limiting resistor. This resistor prevents excessive current from flowing through the circuit when the motor is operating without a load. It is good practice to have a current limiting resistor in the circuit anytime a motor is connected in series with a DC power source. The actual control in the circuit is variable resistor R_2 .

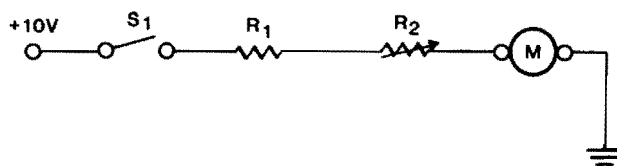


Figure 7-11 Elementary DC motor control.

The variable resistor R_2 actually controls circuit current. When R_2 is adjusted to its maximum resistance, the voltage drop across the motor, and therefore the current through the motor, is severely restricted. This results in the motor turning at a slower speed. As the resistor is adjusted for less resistance, the motor speeds up. In this way, you can use R_2 to control the speed of a DC motor.

You might assume that, even with R_2 adjusted to its maximum value, the motor would begin to rotate the instant switch S_1 is closed. This, however, is not true, because one of the fundamental laws of physics states that **"Bodies in motion tend to remain in motion, and bodies at rest tend to remain at rest"**. In order to start rotating and come up to operating speed, the motor must overcome two quantities: inertia and friction.

Friction can be defined as the resistance to relative motion between two objects in contact. In other words, any time two objects come in contact they tend to hold each other in place. In a DC motor, there are many points of contact. Most of the friction is the contact between the brushes and the commutator.

Inertia is the property of an object, by which it remains in motion or at rest, unless acted upon by some external force. Inertia results from the mass of an object. The greater the mass, the greater the force necessary to over-

come the inertia. Anyone who has tried to push a stalled automobile will readily understand this concept. The weight of the object (automobile or armature) is a direct effect of the gravitational force acting upon it. Weight is proportional to mass, therefore, the analogy between weight and mass is valid. It takes a certain amount of energy to overcome the properties of friction and inertia in a DC motor. For this reason, a given amount of voltage must be applied to the motor before it develops enough torque, or twisting force, to begin turning. This voltage is called the **offset voltage**. In a well designed DC motor control circuit, torque and inertia are compensated for by selecting components to ensure that the voltage applied to the motor always meets or exceeds the value of the offset voltage. This along with the starter winding electrically positioned at 90 degrees, in relationship to the armature, will start motor rotation.

Incidentally, once inertia and friction are overcome and the motor is running, you can decrease the voltage applied to the motor and still maintain its operating speed. This principle also applies to changing loads. When the load is increased, current must also be increased to maintain the same speed. This can be accomplished by either increasing the applied voltage or decreasing the resistance. When the load is decreased, you must decrease the applied voltage or increase the resistance to maintain the same motor speed. More armature current is always required to move a heavier load.

Sometime, you might need to change a motor's direction of rotation. Figure 7-12 shows a motor control circuit consisting of a potentiometer, switch, limiting resistor, and DC motor. In this figure, the wiper (center tap) on the potentiometer is centered. That is, the resistance between points A and B equals the resistance between points B and C. At point B, the voltage is 10 volts positive with respect to one power supply and 10 volts negative with respect to the other. In this configuration, current flows between the + 10 V supply and the - 10 V supply and no current flows through the motor. This is the motor's **null** (no difference of potential) position and the motor is at rest (stationary).

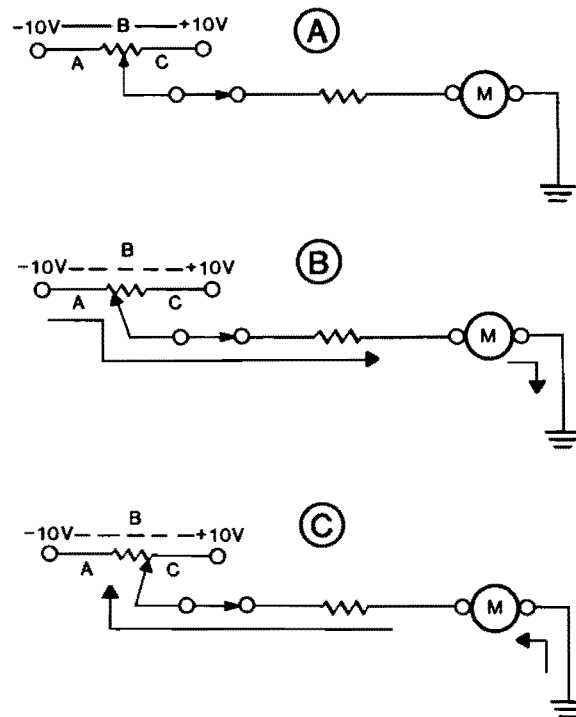


Figure 7-12 DC motor direction and speed control.

As the potentiometer is moved from its centered position, current begins to flow through the motor. This is shown in Figure 7-12B. Notice here that there is much less resistance between the -10 V supply and ground than there is between the $+10\text{ V}$ supply and ground. Therefore, the current flows from left to right in the illustration causing the motor to rotate in one direction.

When the potentiometer is adjusted in the other direction, current begins to flow from right to left as shown in Figure 7-12C. In this instance, the motor direction has changed along with the direction of current flow through the motor. The motor in examples 7-12B and 7-12C turns in opposite directions.

Besides changing direction, the potentiometer can be used to vary the speed of the motor. However, the same problems of inertia and friction occur with this control as did with the variable resistor and single voltage source used in Figure 7-11. The advantage of using both a positive and negative source is that the motor can be nulled and reversed without having to make changes to the circuit wiring.

The squeeze trigger device is another type of control device. The squeeze trigger device is used to regulate the speed of a drill, or to regulate the speed of toy cars on a slot car racing track. Soldering guns also use these devices to control the amount of heat produced. The squeeze trigger device is simply a series variable resistance that is adjusted by finger pressure.

Remote Controls

The term remote control means control at a distance. For example, the garage door opener that you use while still seated in your car is a remote control device.

The most common remote control device is the relay. The garage door opener uses a relay along with an RF transmitter and RF receiver. The transmitter that you carry in your car sends out a radio frequency signal that is picked up by the receiver mounted inside the garage. The receiver triggers a relay that activates the motor which lifts or lowers the garage door. There is usually a switch located in the house or garage that is directly wired to the relay. The switch is an alternate remote control device to open or close the garage door.

The lock-in or lock-out box, which is usually located near industrial machines, is another example of control at a distance. Most assembly lines have this safety feature. This is to ensure that you are ready for the motors to be started or stopped. Most dangerous machines require 2 switches to be closed before operation can begin. These same machines can be turned off by either of the switches.

Another common safety device that provides control at a distance is the micro-switch. Micro-switches can be configured (wired) to either turn on or turn off, and are often used as pressure sensors or limit switches. The micro-switch is the type of control that senses when

the garage door is fully opened and closed. The micro-switch is commonly called a limit switch. When the door reaches its limit (fully open or fully closed) the micro-switch disconnects the relay from the drive motor.

Most heavy duty motors are equipped with a thermo-switch that is set to the maximum safe operating temperature of the motor. When the temperature of the motor exceeds the switch's setting, the switch opens and shuts the motor

off. Many of these thermo-switches will reactivate once they cool below a specific temperature. Others, for example the circuit breaker, must be manually reset. These types of control devices provide thermal protection or heat control. These heat sensing switches operate by using the thermocouple principle.

These motor control circuits are very simple and are meant only as an introduction to motor controls.

Motor Control Systems

Some controls are built into the motor. Other motor controls are components that are mounted directly on the motor. For example, the size and direction in which the fields are wound is a built-in control. A resistor in series with the winding, the centrifugal switch, and the thermal cut off switch are examples of add on features.

The control circuit is often a complete system. For example, the heating system in a house is a complete control system. The furnace (source) supplies the heat. The convection air currents form the loop (conductor path). The thermostat provides a reference and error detection. The thermostat also sends out the correction signal. A system that is controlled by a feedback loop (the air currents) is considered a closed-loop system. When a system must be continually adjusted (such as increasing and decreasing a potentiometer) to maintain a constant speed, the system is considered to be an open-loop system.

A switch control system is sometimes called a go/no go or bang bang system. For example, there are no decisions or comparisons to be made in a go/no go system. The light switch in your home can be used to turn a light off or on. If the light is already on, the switch can only turn the light off.

Remote Control System

The automatic garage door opener is a remote control system that contains a motor. In this case, the system is made up of a transmitter, a receiver, and motor. The transmitter is carried in the car (a remote location) and the receiver is located in the garage. The transmitter sends out RF pulses, the receiver intercepts the pulses, and starts the motor. Limit switches or pressure switches turn the motor off when the work (opening or closing the door) is accomplished. The garage door opener is an example of a radio-controlled system. The RF (radio frequency) pulses are made up of frequencies in the radio frequency band.

There are other common motor control systems in use in industry and other applications. The two most common are called synchro systems and servo systems.

Synchro Systems

The basic synchro system is a device for angular positioning of a shaft to indicate position, or to turn a load. A synchro system does not provide amplification and is considered a 1:1 device. In other words, the mechanical power applied is equal to the mechanical power out.

This is very similar to transformer operation. In fact it is some times referred to as a variable transformer application.

The synchro system is usually made up of 3 elements. The 3 elements are a synchro transmitter (TX), synchro differential transmitter (CDX), and a synchro receiver (RX). A basic synchro system block diagram is shown in Figure 7-13.

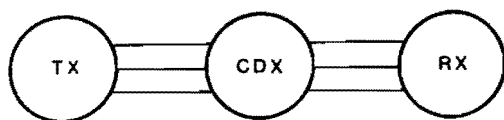


Figure 7-13 Block diagram of a synchro system.

Balanced Systems

The relationship between the synchro's rotor and stator windings is usually a ratio of 2.2:1. For example, when 115 volts AC at 60 hertz is applied to the rotor winding, it induces 52 volts into the stator winding with which it is aligned. Figure 7-14 illustrates the voltages developed across each winding when the rotor is aligned with stator winding S_2 . Note that the voltage induced into S_2 is 52 volts AC. When R_1 is aligned with S_2 , R_2 is aligned with the 180 degree position.

The stator windings are spaced 120 degrees apart. When S_2 is at zero degrees, S_3 will be at 120 degrees, and S_1 will be at 240 degrees. Since the maximum induced voltage into a winding is 52 volts and the rotor is aligned halfway between S_3 and S_1 , the voltage induced into S_3 and S_1 is 26 volts.

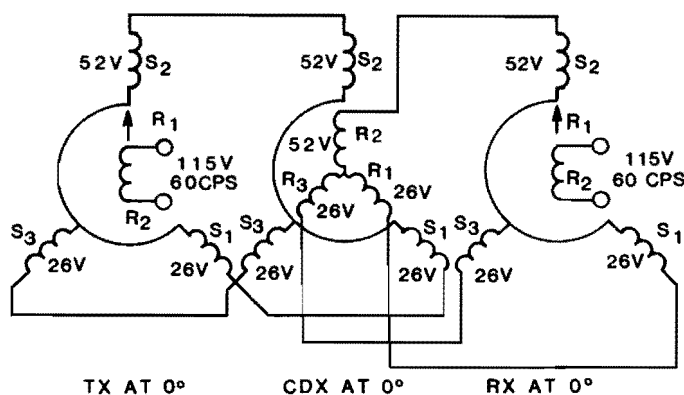


Figure 7-14 Balanced synchro system.

The voltage induced from the reference stator winding to the end of either of the other stator windings is always 78 volts. In most synchro systems stator winding S_2 is defined as the reference stator winding. Notice that in Figure 7-14 the rotors in the synchro transmitter and the synchro receiver are aligned. Note also that the voltages developed across the windings of both the transmitter and receiver are equal.

Direct-Coupled Systems

Notice that in Figure 7-15 the synchro transmitter and receiver appear to be electrically the same. However, they do differ because the transmitter's rotor is not free to turn and the receiver's rotor is free to turn. The transmitter's rotor is normally coupled to an input shaft. The input shaft loads the rotor so

that it does not move by electromagnetic induction. When the input shaft is mechanically rotated, the transmitter's rotor winding rotates and develops a voltage across its three stator windings. The amount of voltage developed is determined by the angular displacement of the input shaft. The voltage developed across the stator's windings determines the amount (degrees of rotation) that the rotor moved.

The stator windings of the synchro transmitter are connected to the stator windings of the synchro receiver. The synchro receiver's rotor is free to turn. The rotor of the synchro receiver is usually connected to a dial pointer (very light load). The receiver rotor's position is controlled by the voltages that are developed in the receiver's stator windings. The receiver's rotor repositions the dial pointer to indicate the new angular position of the input shaft.

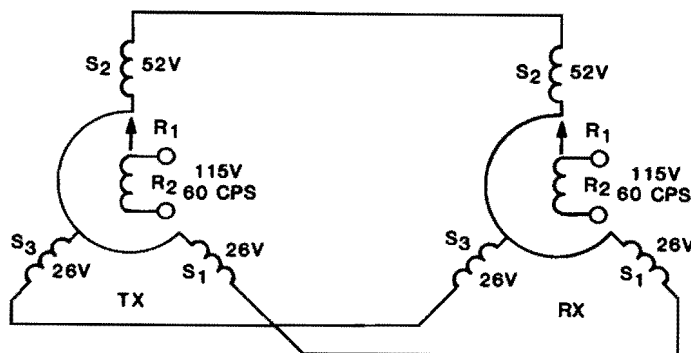


Figure 7-15 Synchro transmitter and receiver.

Unbalanced Systems

For example, when the input shaft is attached to the rotor of the synchro transmitter and it is rotated to the right 30 degrees, the transmitter's rotor develops a voltage across its stator windings. This developed voltage is coupled to the receiver's stator windings. The stator windings in the synchro receiver induce a current into the receiver's rotor that causes it to rotate 30 degrees to the right. The amount of displacement of the transmitter's rotor is indicated by a pointer that is attached to the receiver's rotor.

Electrically, the synchro transmitter is equivalent to a transformer. In this analogy, the rotor is the primary winding and the stator windings are the secondary. In the synchro receiver, the stator winding acts as the primary and the rotor winding acts as the secondary.

The synchro transmitter and receiver combination is used in remote indicator applications. For example, the compass indicator in the cockpit of an aircraft uses this system. The synchro receiver is built into the indicator located in the cockpit. The synchro transmitter is part of the compass located in the aircraft electronic compartment.

Differential Synchro Systems

Another type of synchro system that uses 3 elements is shown in Figure 7-16. In this configuration, the synchro transmitter and receiver are separated, and a synchro control transmitter is added between the transmitter and receiver. Note that the differential transmitter has 3 rotor windings and 3 stator windings. The windings are again separated by 120 degrees and the turns ratio between the rotor windings and stator windings are 1:1.

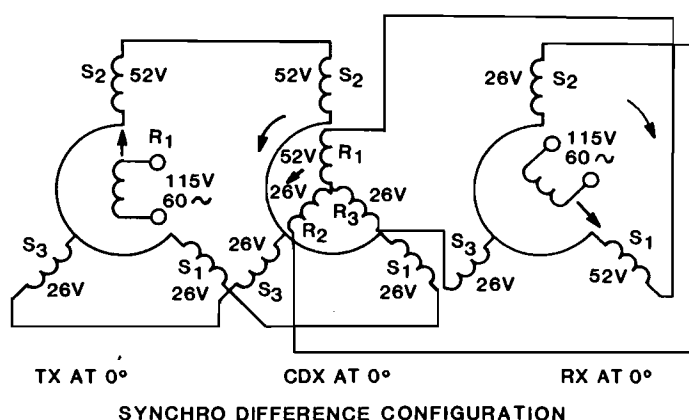


Figure 7-16 Synchro differential system.

The Differential Transmitter (CDX)

The differential transmitter (CDX) is an error detection device. It senses the difference between the synchro transmitter (input device) and the synchro receiver (output device). Note that the differential stator windings are connected to the stator windings of the synchro transmitter. Its rotor windings are connected to the receiver's stator windings.

The rotor of the differential transmitter is not free to turn. It can be mechanically repositioned to program a difference reading. Note that in Figure 7-16, when the differential transmitter is turned to the 120 degree position, and the transmitter is set to the zero position, the receiver rotates to the 240 degree position.

In other words, the receiver rotates 120 degrees in the opposite direction. When used in

this configuration, the receiver setting equals the transmitter setting minus the differential transmitter setting.

$$TX - CDX = RX$$

$$0 \text{ or } 360 - 120 = 240$$

When the differential transmitter is connected as shown in Figure 7-17, the receiver indicates the sum of the transmitter and differential transmitter settings. Compare the synchro configurations shown in Figure 7-16 and 7-17. You should have noticed, the change from a difference detector to a summing detector is accomplished by reversing windings. Windings R_1 and R_3 , and S_1 and S_3 must be reversed in the differential transmitter for the summing operation.

$$TX + CDX = RX$$

$$0 \text{ or } 360 + 120 = 120$$

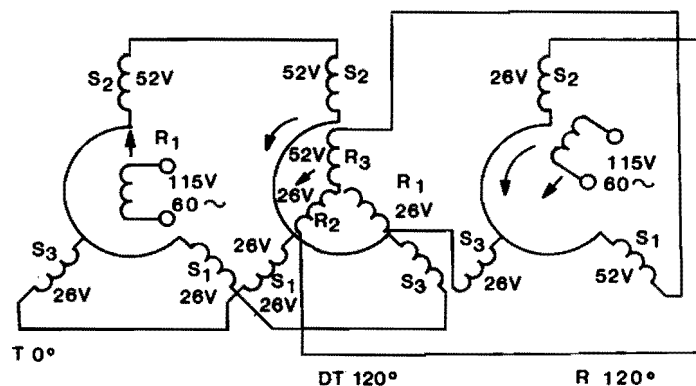


Figure 7-17 Synchro tracking system.

Figure 7-18 is a simplified wiring diagram of a synchro adder. Compare this wiring diagram to the circuit shown in Figure 7-17. Both circuits perform the same function and are therefore considered to be equivalent circuits.

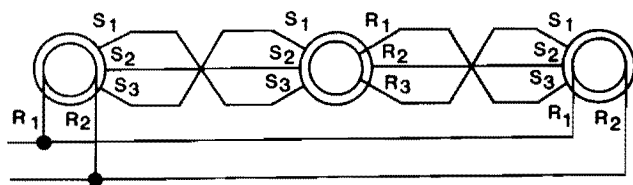


Figure 7-18 Wiring diagram for tracking system.

The Differential Receiver (CDR)

There is also a differential receiver (CDR) that is very similar to the differential transmitter. The primary difference between the differen-

tial transmitter and receiver is in the rotors. The rotor in the differential transmitter is not free to turn. It must be mechanically repositioned. In the differential receiver the rotor is free to turn.

When a differential receiver is used between a synchro transmitter and synchro receiver as shown in Figure 7-19, repositioning the transmitter's rotor sets up a field in the stator windings of the CDR. This field induces a current through the CDR's rotor. The rotor of the CDR develops a field in the stator windings of the synchro receiver. This field causes the synchro receiver's rotor to turn. The synchro receiver's moving rotor induces a current back into the receiver's stator windings. The synchro receiver continues to rotate until the field across the receiver's stator windings cancels the field developed in the differential receiver's rotor windings. At this time, the synchro receiver indicates the angular difference between the synchro transmitter and the differential receiver.

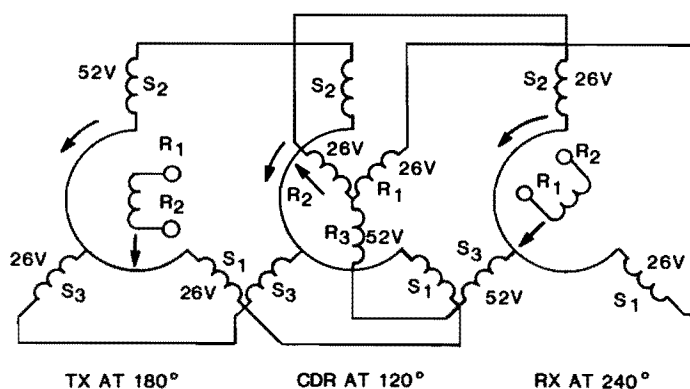


Figure 7-19 Synchro differential receiver between two synchro transmitters.

Servo Systems

A servomechanism is a mechanically coupled device that is driven by a difference between its input and its output. The main parts of a servo system are a prime mover, a feedback loop, error detector, and an amplifying device. The prime mover is the servo motor, the feedback loop compares the output to a reference, or back to the input signal. The error detector is a component that determines the difference between the reference and the output. The amplifying device compensates for losses in the line. The losses could be from friction or line resistance. A typical servo system block diagram is shown in Figure 7-20.

AC Servo System

The conventional AC servo motor is a two phase induction motor. One input is applied to the reference winding and the error input is applied to the control winding. When the input (reference) and the output are the same there is no error voltage to detect. When there is a phase difference, the error voltage is applied to the control winding, and the servomotor turns until the input and output are in phase. As in other induction motors, maximum torque is developed when the input and output are out of phase by 90 degrees.

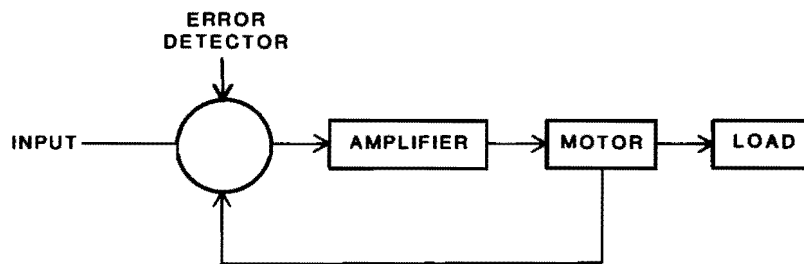


Figure 7-20 A typical servo block diagram.

DC Servo System

DC servomechanisms are high torque devices and are used to move heavy loads. The motors are specially constructed to develop a linear proportional change in output current, for a change in input voltage. The DC servo motor moves much slower and smoother than the AC servo motor. Speed and direction of movement is easily controlled by using DC servos.

AC servomechanisms are used in applications when fast response and low cost are the primary concerns. The constant speed aspect of AC motors makes control circuitry for the AC servomechanisms more complex than control circuits for DC servomechanisms.

Therefore, AC servomechanisms have faster response times and are less expensive than DC servomechanisms. DC servomechanisms are more accurate and require less control circuitry.

A Home Servo System

The servo system shown in Figure 7-21 is the remote antenna adjustment system that is popular in home use. The rotor control usually sits near the television. When you change the television channel, sometimes you align the rotor control to a new direction. The electrical difference between the direction the antenna was pointing and the new direction is determined by the error detection component. Next, the error signal is coupled to the servo motor. The servo motor turns, sending a current to a drive motor. The antenna is physically attached to the drive motor, and it rotates as the motor drives. Once the motor is realigned to the reference, the error signal is reduced to zero, and the motor stops turning.

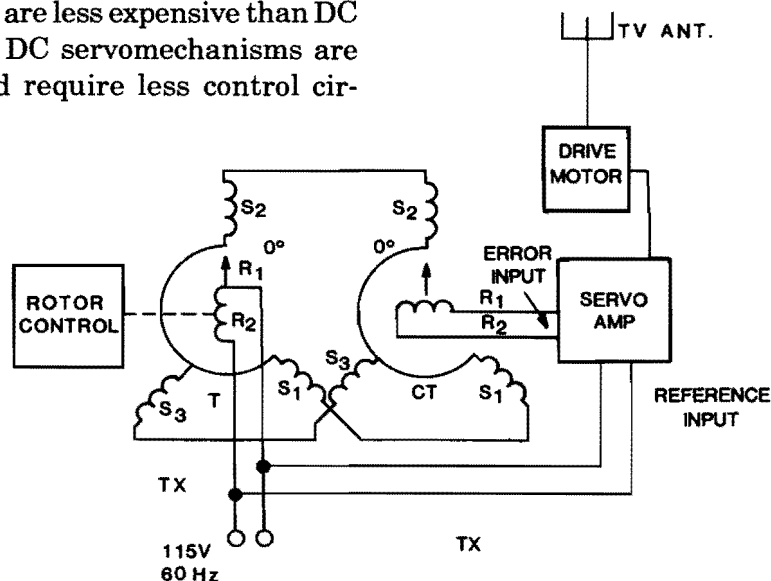


Figure 7-21 Home servo antenna control system.

Frequency Controlled Servo Systems

Model airplane flying is another example of a radio frequency remote control system. In this system, there are 2 sets of controls. One control is used to roll the plane and is called a roll servo. The roll servo controls the horizontal axis. The other control axis is nose up and nose down. It controls the plane's climb and dive, which is the vertical axis. This control is called a pitch servo.

Flying model airplanes requires servo motors to be mounted on the airplane itself. An electronic device that works on the same principle is the **joy stick**. The joy stick is part of many home video games. The joy stick is used to control the vertical and horizontal axis of a television set. This control is accomplished by varying the potential applied to the television's vertical and horizontal deflection plates. The television set operates much like the oscilloscope discussed earlier in this course.

Commercial and military airplanes have 3 servo systems to control their vertical and horizontal axis. They are roll, pitch, and yaw. The yaw servo keeps the nose of the plane from varying from side to side.

When the pilot selects autopilot, the servo systems are actually flying the airplane. That is, a reference is fed to the servos, and the servos receive information about altitude, drift, speed, direction of flight, and the plane's attitude in relationship to the horizon. When any of the

references change, an error signal is automatically fed back to the servo. The servo then acts on the error signal and returns the airplane to the desired flight path.

Many servomechanisms have null and anti-hunt circuits built into the servomechanism's amplifier. These circuits dampen error signals to prevent over correction. Later, in your studies of Electronic Circuits you will study these nulling and anti-hunt circuits.

Comparing Synchro And Servo Systems

The basic servomechanism is a synchro system that is connected to an amplifier. Therefore, the primary difference between a synchro system and a servo system is gain. Synchros are considered to be unity gain systems. Servo systems are high gain systems. Both systems may use a feedback loop. The feedback loop is used to route the difference signal (error), back to the input for automatic correction. Automatic correction servos are examples of closed loop operation. When the error is detected but not routed back to the input, it is an open loop servo system.

The purpose of the amplifier in a servo system is to compensate for losses such as friction and inertia. The amplifier is also capable of supplying large currents to move heavy loads.

Self-Test Review

38. Explain the difference between a motor that is not turning and a motor that is nulled.
_____.
39. The turns ratio of the rotor winding to stator winding in a synchro transmitter is:
_____.
40. The turns ratio of the rotor winding to the stator winding in a CDX is:
_____.
41. The transmitter in the synchro system is free to turn.
A. True
B. False
42. The receiver in a synchro system is usually used to drive a/an:
_____.
43. The synchro system usually contains an amplifier block.
A. True
B. False
44. The synchro transmitter's stator winding are connected to the:
_____ windings.
45. The differential transmitter has three stator windings and:
_____ rotor windings.
46. To convert a differential synchro system from a difference detector to a summation system reverse the:
_____.
47. The primary difference between a synchro and a servo system is:
_____.
48. Electrically, a synchro transmitter is equivalent to a:
_____.
49. The stator windings in a servo system are displaced from each other by:
_____ degrees.
50. The stator winding that is used as the standard in synchro transmitters and receivers is the:
_____ winding.

Desk-Top Experiment 7

Identifying Motor Symbols

Introduction

This experiment provides practice in identifying the motor symbols used in schematic drawings. It also serves as a review of the various motors discussed in this unit.

Objectives

1. To identify schematic drawings used to represent various motors.
2. To match motor applications to the symbol that represents the motor most used for that particular application.
3. To identify, by symbol, which motors are used with AC and DC supplies.

Procedure

1. In the spaces provided, select the symbol or symbols that represent the following types of motors. The motor symbols are located on the last page of this experiment.

Series wound _____.

Shunt wound _____.

Compound wound _____.

Three-phase _____.

Two-phase _____.

Single-phase _____.

Induction type _____.

Synchro _____.

Universal type _____.

2. Which symbol or symbols represent a motor that could have series aiding or series opposing field windings?

_____.

3. Which symbol or symbols represent motors whose rotor winding have a 2.2 : 1 ratio to their stator windings?

_____.

4. Which symbol or symbols represents a control differential transmitter?

_____.

5. Which symbol or symbols have their stator or field winding separated electrically by 120 degrees?

_____.

6. Which symbol or symbols represent either a receiver or transmitter motor?

_____.

7. Which symbol or symbols have their rotor windings separated electrically by 120 degrees?

_____.

8. Which symbol or symbols represent the motor most used to develop power ratings of more than 746 watts?

_____.

9. Which symbol represents the least expensive motor?

_____.

10. Which symbol or symbols are **not** used for AC applications?

_____.

Discussion

The motors in this experiment are all induction type motors. They are generally divided into three categories. The categories are required voltage supply, type construction, and application.

Summary

The series wound motor (I) is the most commonly used motor for small loads. It can be used in both AC and DC applications. When modified by inserting a small resistance in series with its brushes it is called a universal motor (either AC or DC). Series motors also require some type of resistive load to prevent thermal runaway. The series motor uses a split field for its starting and running fields.

Shunt (A) and compound motors (H and J) are never used for AC applications. Shunt motors develop lower torque than series motors, but they have a higher starting speed. The shunt motor is considered a constant speed motor.

Compound motors can have series aiding (cumulative) or opposing (differential) fields. Compound motors usually have a starter field, which is disconnected (opened) by a centrifugal switch, when it approaches its running speed.

Single-phase motors are usually used for loads that require less than 1 horsepower.

Two-phase motors are normally used in synchro/servo systems. These systems are used to detect an error, or in automatic error correction systems.

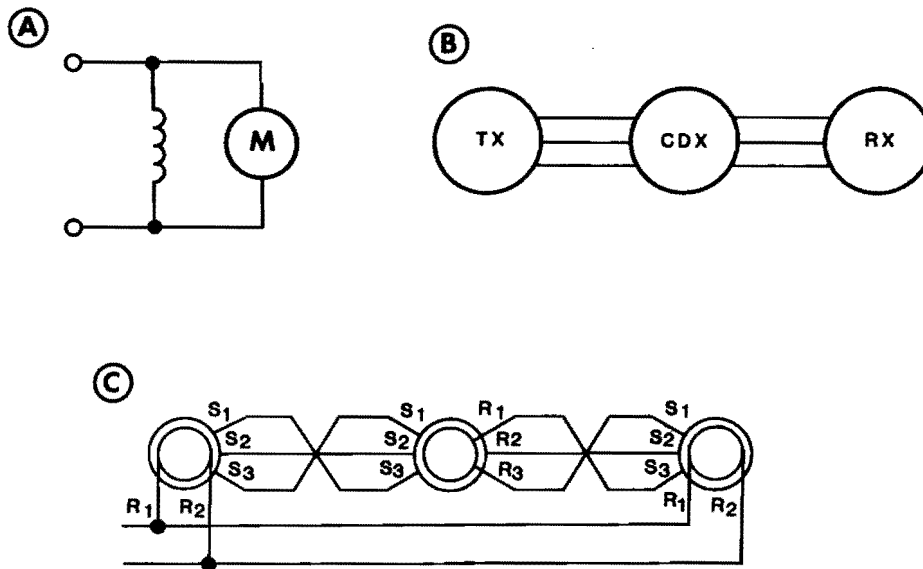
Three-phase motors (K) have their stator windings electrically separated by 120 degrees. They normally have a squirrel cage rotor, and are used for load requirements in excess of 746 watts.

Synchro motors (E) have three rotor and three stator windings, electrically separated by 120 degrees. The turns ratio from their rotor to stator winding is 1:1.

Servo motors (D) have 3 stator windings that are separated electrically by 120 degrees.

Stator S_2 is the reference winding in a servo motor. The turns ratio, from the rotor winding to the stator winding, is 2.2:1. When used in a circuit with amplification, the circuit is called a servomechanism. The servomechanism sometimes uses a synchro transmitter as its error detection component.

Almost all electrical motors are driven using the electromagnetic induction principle. Therefore, most motors are induction motors.



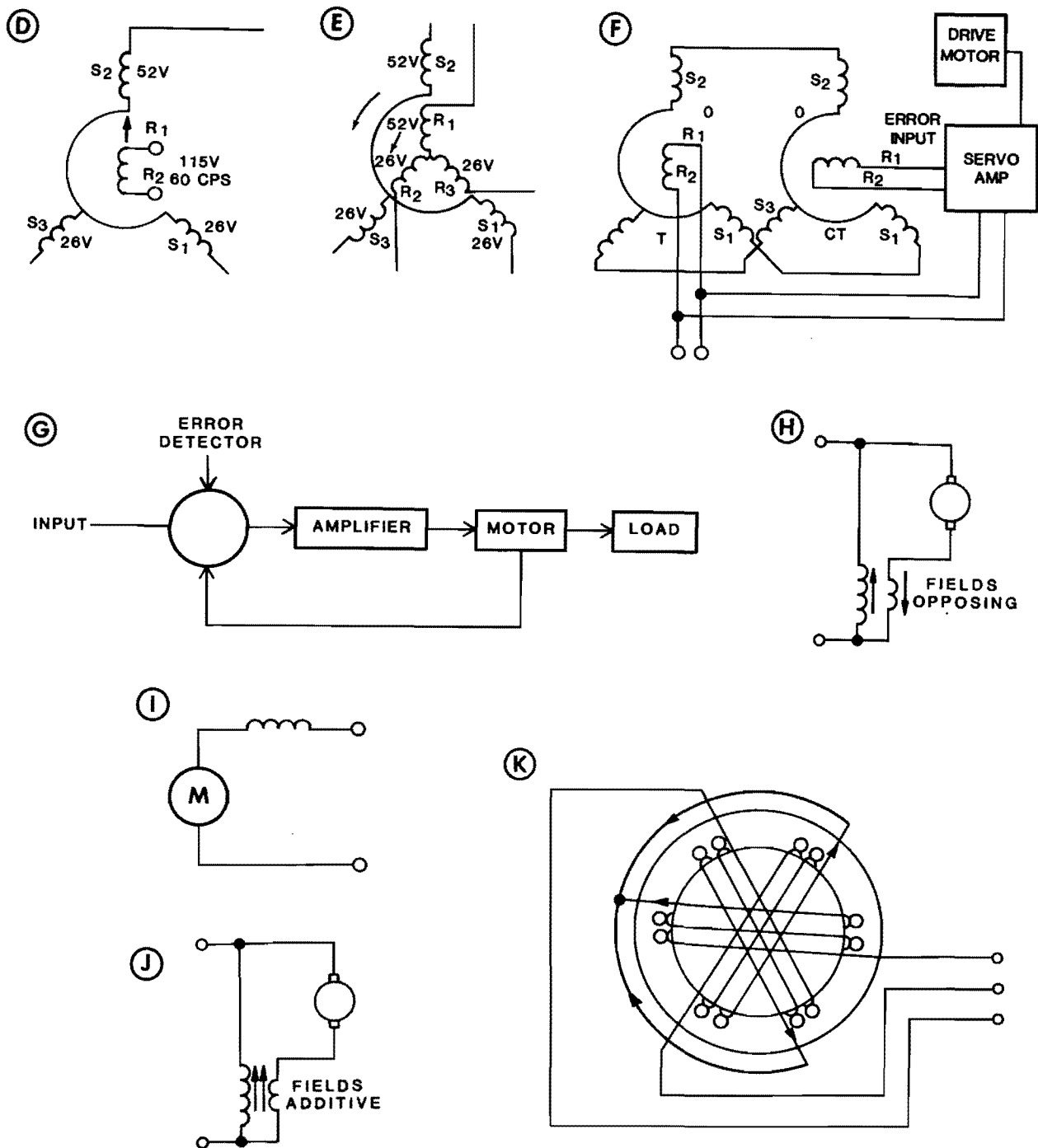


Figure 7-22 Desk-Top Experiment 7.

Unit Summary

The left-hand rule is used for generator operations. The right-hand rule is used for motor operation.

Induced voltages and currents oppose the potentials which caused them.

Inertia and friction are the two primary physical characteristics that must be overcome to cause a mechanical object (armature) to rotate. Inertia and friction are both maximum when the motor is at rest.

Torque and motor speed are inversely proportional. The faster a motor turns the less torque it develops. Motor speed is usually referred to as either synchronous or asynchronous speed. A synchronous motor's armature turns at almost the same speed as the field windings. An asynchronous motor's armature lags the field windings by an angle of up to 90 degrees. This lag angle is called slippage. When an armature lags the field by 90 degrees, maximum torque is developed.

One cycle of armature rotation is equal to 360 degrees. One cycle is also equal to 2π radians. One radian is equal to approximately 57.3 degrees. Two π is usually rounded off to 6.28. A radian is an arc equal to the radius of a circle.

DC motors are more versatile than AC motors.

Motors are usually classified by their construction. They can be series, shunt, or compound motors. A series motor has the field and arma-

ture in series with each other. The shunt motor has the field and armature windings connected in parallel. In a compound motor, one winding is in series and the other winding is in parallel.

The series motor is the most common type of motor. It can be used with AC or DC voltages, and is sometimes referred to as a universal motor. When the series motor is used, a resistive load must be used to prevent motor runaway, if the load opens. When used in an AC application, the brushes should have resistance added in series, to reduce arcing. Arcing can destroy the motor's armature, as well as the brush face.

The main cause of a malfunction in DC motors is usually brush related.

AC motors are usually referred to as either single-phase or three-phase motors. Most fractional horsepower motors are single-phase. Most motors rated at more than one horsepower are polyphase motors. The term polyphase means more than one phase.

Most two-phase motors are used as synchro or servo motors. The three-phase motor is considered the most popular type of polyphase motor for industrial applications.

In a single-phase motor, the start field winding is usually placed at 90 degrees, in reference to the armature. This provides a maximum induced current to cause initial rotation.

When resistance is added in series with the field winding, current is reduced and the induced (opposite polarity) voltage decreases. This decrease in opposing potential causes the motor to increase RPM. When the resistance goes out of phase. The motor is controlled by 2 separate inputs. When you want to reverse its operation, reverse its inputs. This type motor is normally a nulling device.

The three-phase motor has the fields separated by 120 degrees and may use either the delta or Y (star) wiring configuration.

Field windings in a motor are called stator windings. The rotating conductor is called the armature or rotor.

An AC motor's speed (RPM) is directly proportional to applied voltage and frequency and inversely proportional to the number of poles. In a simple, three-phase motor each field has 2 poles.

Motor regulation is expressed as a percentage. The formula for % of regulation is:

$$\frac{\text{no load speed} - \text{full load speed}}{\text{full load speed}} \times 100$$

The simplest motor control device is a series resistor. Any time resistance is added in series, motor speed decreases. A potentiometer can be used to control a DC motor's speed and direction of rotation.

of motor control mechanisms. The main difference between a synchro and a servo system is that the synchro has unity gain and the servo has a very high gain.

The synchro system is made up of a synchro transmitter (TX), differential transmitter (CDX) or receiver (CDR), and a synchro receiver (RX).

The servo system is a synchro system with an added amplifier.

Both synchros and servos may be operated with either closed or open loops. A closed loop system is when a sample of the output is fed back to the input.

In both synchro and servo systems the transmitters are not free to turn. The receivers in both systems are free to turn. The synchro system is usually used to drive a pointer or dial indicator. A servo system is used to control a heavier load.

Unit 8

AC Home Applications

Contents

Introduction	8-3	Desk-Top Experiment 8	
Unit Objectives	8-4	Designing AC Loads	8-21
The Service Drop	8-5	Safety	8-26
Paralleling Loads	8-13	Unit Summary	8-34

Introduction

This unit is designed to provide a better understanding of AC electrical systems that you use in your home everyday. Most of us take AC for granted. We turn on lights, cook meals, watch TV, stay warm, and hundreds of other applications daily without thinking about how the various equipment are powered.

There are various **RULES** about what you can and can't do to house wiring. These rules fall into Electrical Codes and are controlled by government regulations. The government regulations come from the federal government, state government, county government, and even city and town codes. This course is only informational and not designed to supplement or supersede any regulations (codes) that apply in your district. In most areas, unlicensed persons (home owners) are allowed to do little more than change fuses, reset circuit breakers, and plug components into existing power outlets.

The purpose of electrical codes is to safeguard people and property from hazards associated with electricity. The exact codes vary from location to location. You should check with the local power company and the building inspector assigned to your district before making any changes to existing wiring. In most cases, electrical wiring changes must be done by a locally licensed electrician.

Earlier in this course we discussed the power company and their high voltage power line. We will pick up this discussion at the high voltage power line and continue to the individual service drop. Then we will follow the routing of the service drop through a typical house.

Read the unit objectives carefully. They will help you identify and relate the various text material to common knowledge and electronic rules and principles studied earlier.

Unit Objectives

When you have completed this unit you will be able to:

1. Explain the term service drop.
2. Identify the point at which the home owners responsibility begins.
3. Explain the term power distribution box.
4. Calculate the maximum AC load for a given power outlet.
5. Explain the limitation placed on paralleling loads.
6. Name the two common types of safety devices used to disconnect excessive loads from their voltage source.
7. Identify which motors in your home are universal types and which are single-phase, two-phase, and three-phase motors.
8. Calculate the current, voltage, and power required to operate typical appliances from the data supplied on its nameplate.
9. List the common electrical safety equipment that should be in every home.
10. Identify the type circuit used to recharge DC appliances such as cordless electric shavers, smoke detectors, portable mixers, and cordless hand held vacuum cleaners.
11. Identify potential electrical fire hazards in your home.
12. Recognize a blown fuse.
13. Explain the advantage and disadvantage of fuses when compared to circuit breakers.

The Service Drop

As a power company customer, you are primarily concerned with the power that actually enters your home. More specifically, you are concerned with the power that you must pay for. This is the power ($I \times E$) that is used from your service drop.

Earlier in this course we said that the power company transported power at extremely high AC voltages and low current values. They do this because it is easier, safer, and less expensive than transmitting low voltages at high currents.

However, before the electrical power can be used in your house, it must be converted to a lower voltage and a higher current. This is accomplished by the service drop.

Transformer

The power company's main line is fed into a step-down transformer. The transformer lowers the line voltage from an extremely high voltage to the 120 volt, 60 hertz source that is supplied, through the service drop, to the individual customer or household.

The transformer, mounted either on a power pole or underground on the utility company's right-of-way, determines how much power its

secondary can supply. The transformer is usually protected by circuit breakers that are mounted directly on the transformer or in a power company utility service box.

The transformer may supply power to more than one service drop or residence. Therefore, a power failure in your home may be caused by your neighbors. The power line in this example is called a common or shared feeder line. Even when you don't share a transformer with your neighbor, your power loss can be caused by weather or some other disturbance in the line.

Before the service drop enters your house it passes through a droop loop. The droop loop prevents rain and moisture from draining into the wall where it could cause damage by rotting the wall or causing short circuits. The droop loop is designed to route water away from the house.

The service drop is usually 3 wires that provide 120 volts, 60 Hz service to the house. Two of the lines are 180 degrees out of phase with each other. The two lines that are out of phase by 180 degrees may be used to provide a 240 volt source. Each of the two lines may also be used as 120 volt sources. The service drop is routed through the electric company's power meter, and terminated in a power distribution box.

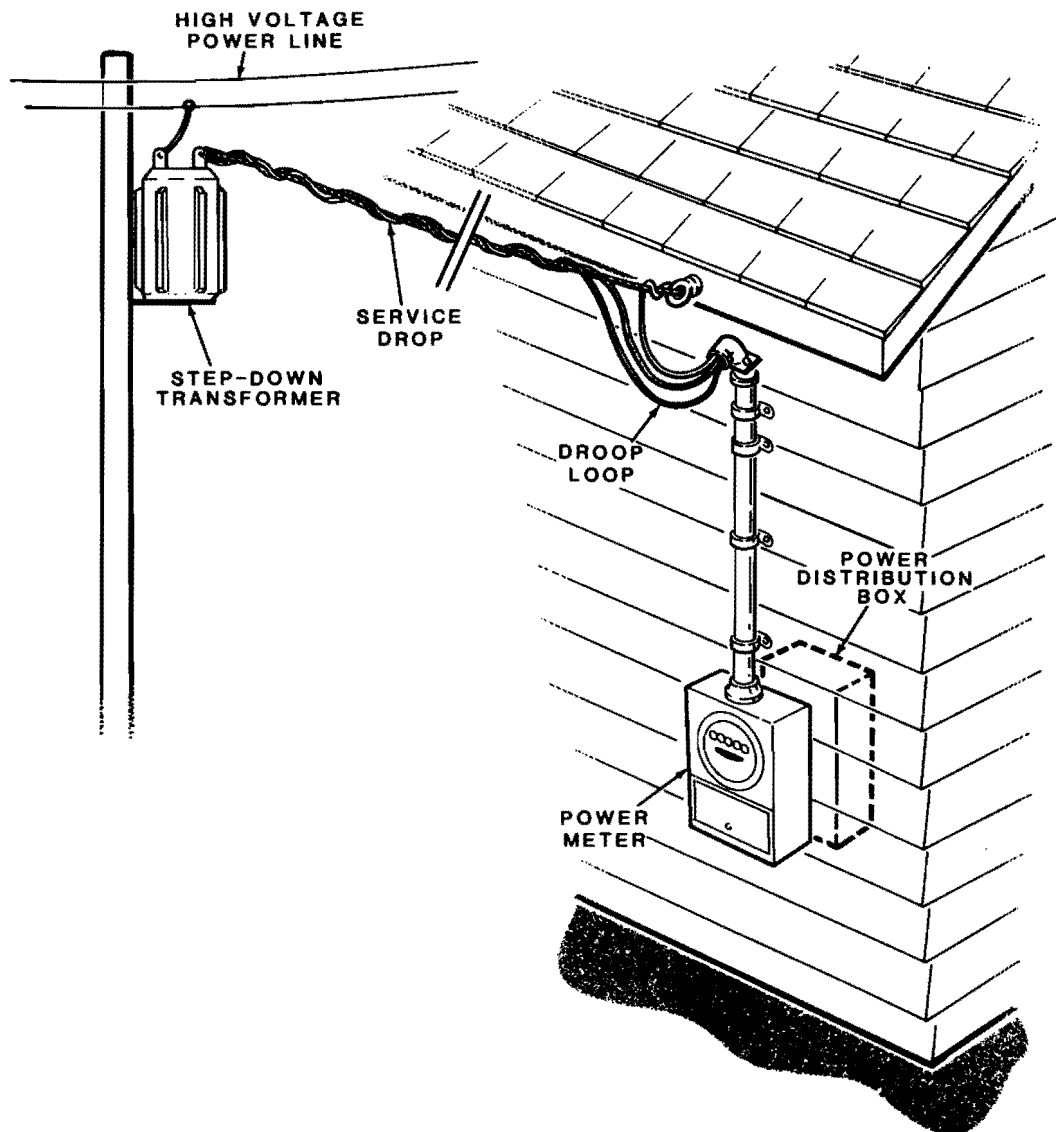


Figure 8-1 The service drop.

Power Meter

The power meter is usually mounted on the outside wall of the house, near the power distribution box. The service drop also has an ampere rating. This is the maximum current that can be supplied by the service drop. Normally, single family houses have either, a 100 ampere service (for older houses), or 200 ampere service (for newer and larger homes).

Service ampere rating is an important consideration when buying a house. For example, some older houses are wired with a 60 ampere service drop. When the house was originally wired it may have been heated with fireplaces or oil space heaters. However, there have been numerous electrical appliances marketed in recent years that were not available when the house was originally wired.

For example, suppose you buy an older home and install an electric furnace, refrigerator, freezer, garbage disposal, electric dishwasher, electric hot water heater, electric range, radio, TV, electric can opener, garage door opener, a well motor, and a variety of plug in appliances. You may then find that the service drop is not equipped to handle the load. When this is the case, you must contact the power company and arrange for an increase in your service drop and hire a licensed electrician to install another power distribution panel.

The electric power company's meter has a tamper proof seal that must not be removed. The power company reads the meter, usually monthly, to determine the power actually used by the residence. They then compute your electric bill. The power that you consume (use) is rated in kilowatt hours and it has a sliding rate scale. Once you surpass their standard fixed rate; the more power you use, the cheaper the rate per kilowatt hour.

The electric company reads the power meter that is attached to your house. The 5 dials at the top of the power meter are read left to right. The left dial is the most significant digit. Note in Figure 8-2 that there is a small 1 located near the left dial. The 1 marks the most significant dial for the meter reader.

The meter in Figure 8-2 reads 25050, in kilowatt hours. Assume that the electric company charges .045 cents per kilowatt hour for the power used. Comparing the meter's present reading (25050) to the reading on file from the last reading (for example 24050). You will see that at the start of the pay period (the last time the meter was read) to this meter reading there is a difference of 1,000 kilowatt hours. This is the power that you actually used during the pay period. The cost of the power used is:

$$1,000 \times 0.045 = \$45.00.$$

The electric company's rate varies from one company to another. The rate also varies because of the amount of power that you use. To find the exact rate for your usage, you can contact your local power company, or you can calculate the rate by dividing the cost of the power, by the amount of power used. This information is included as part of your electric bill that comes from the power company.

Examine the power meter attached to your residence. The rotating dial in the center of the meter is actually keeping pace with the rate at which you are using power. The more power you use the faster the dial turns.

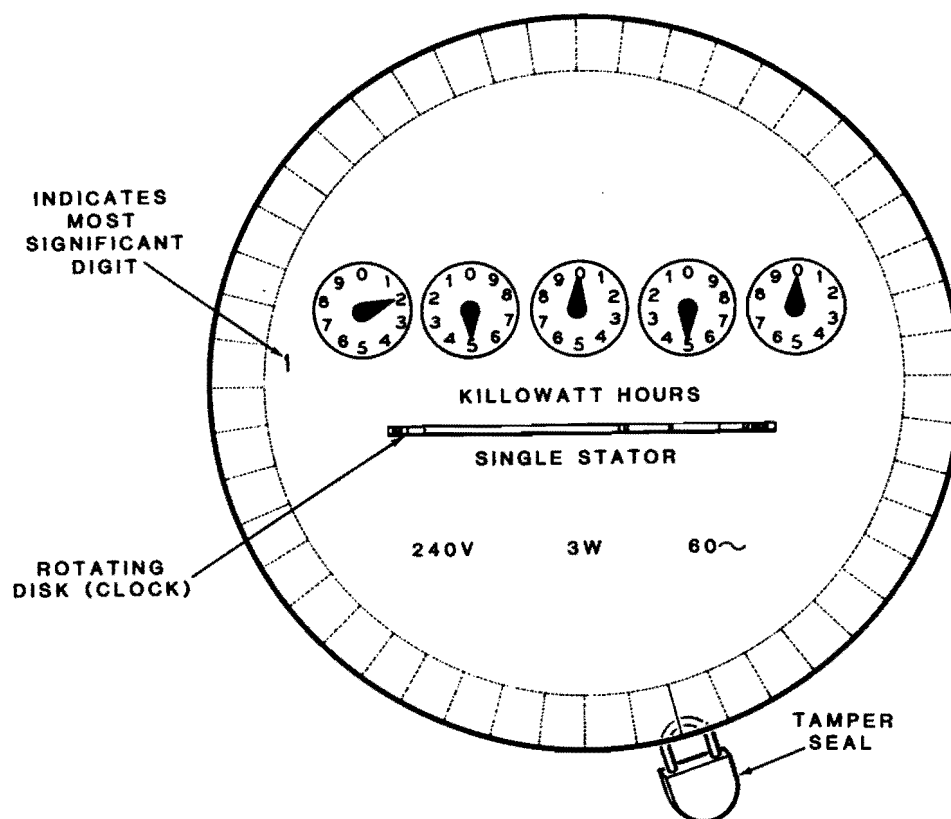


Figure 8-2 The power meter.

There may be additional charges on your electric bill such as cost recovery factor, which varies month to month and power company to power company. A tax is also added to your bill. Another charge that is common on electric bills is for rented equipment. One example of a rented equipment is the security light that the power company installs and maintains at your request. A typical electric bill is shown in Figure 8-3.

By comparing your electric bill month-to-month you can ensure that the power company doesn't make a mistake on your electric bill. You will also know, when your bill has been

estimated and how much you have been over charged or under charged. This eliminates the surprise, when they actually read the meter and make the adjustment, to compensate for the estimated bill.

On the bottom of the electric bill, your cost per day is calculated for you. This is the average cost per day, for that particular pay period. When these numbers change drastically, from one pay period to the next, there should be a valid reason. The reasons that are most common are, additional people using power (house quests), and severe changes in weather.

SERVICE PERIOD FROM TO		METER READINGS PREVIOUS PRESENT		kWH USED
09-30	10-29	24050	25050	1000
BALANCE AS OF LAST BILLING DATE			AMOUNT	
PAYMENT RECEIVED 10-03			50.00	
PREVIOUS BALANCE			00.00	
1000 kwh USED THIS PERIOD			45.00	
POWER SUPPLY COST RECOVER FACTOR AT .005/kWH			5.00	
SECURITY LIGHT RENTAL			4.50	
TAX AT 5%			2.70	
TOTAL			57.20	
DUE DATE			PAY THIS AMOUNT	
11-15			57.20	

Figure 8-3 Typical electric bill.

Power Distribution Box

The power distribution point of the power system is the dividing point between what you own, and what you rent from the power company. Even though the utility pole, transformer, and power meter may be on your property, they belong to, and are maintained by the power company. Power companies as well as other public utilities have a right-of-way under, over, or through private property.

The power distribution box is used to separate the service drop into power busses. The number of busses in a distribution box may vary

house-to-house. A power buss is the voltage source or sources located inside the power distribution box.

Generally, the incoming power is divided into two busses. Each buss is protected by a series in-line fuse. In the case of a house with 200 ampere service, usually four 50 ampere fuses are used. These fuses are placed inside a plastic housing, and are used to disable power to your house. The electrical code book states that complete power must be disconnected by no more than 6 switches. That means that you could have your service drop divided into 6 separate buss boxes, if each buss box can be disabled by a single switch.

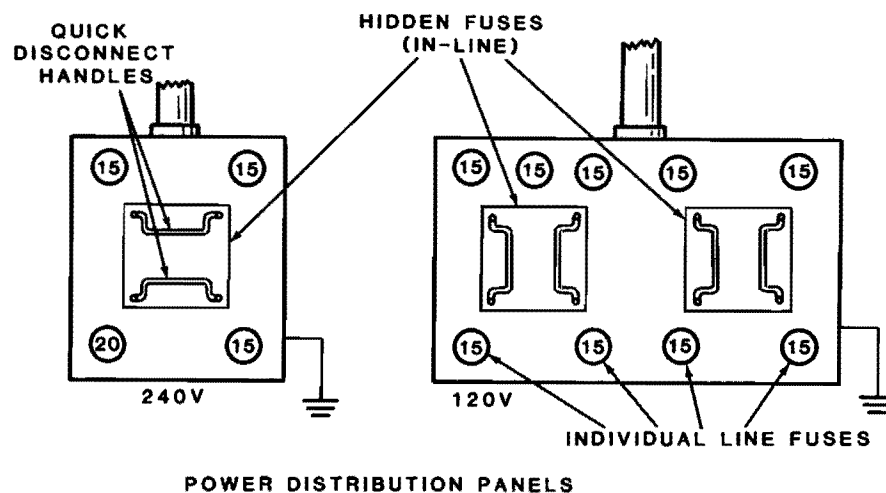


Figure 8-4 Two hundred ampere distribution box.

Grounding The Power Box

The power distribution box must be earth grounded. One very effective earth ground is the cold water input pipe to your house. Another effective earth ground is obtained by driving a solid copper conductor into the ground, to a depth of 4 feet. A heavy conductive wire is then bolted between the grounding rod and the chassis (frame) of the power distribution box.

Do not use your hot water pipe for a ground. It may not provide a good ground. The heat from the pipe causes the wire to oxidize and corrode. This causes the ground to become ineffective after a period of time.

Wire Gauges

Another consideration when wiring a house is the gauge of wire that must be used. Figure 8-5 is a sample of standard wire gauges and their current ratings.

Most of the wiring inside houses is #12 gauge insulated copper wire. The electric range and clothes dryer may require a much heavier (lower number) gauge wire. The service drop into your home is a very large diameter wire. In many cases, you can see the size of the bare conductor that enters the power meter and the power distribution box from the service drop. Comparing these wires to the size of the wires entering your home to supply power to individual loads; you will notice the difference in size.

WIRE GAUGE	CURRENT RATING
# 6	60A
# 8	40A
#10	30A
#12	20A
#14	15A

Figure 8-5 Copper wire gauge chart.

Self-Test Review

1. The service drop is connected to the main power line through a:
_____.
_____.
2. The service drop has a voltage and:
_____ rating.
3. The service drop is maintained by the power company and includes the:
 1. _____.
 2. _____.
4. The power distribution box is the responsibility of the:
_____.
5. How many dials are on the standard power meter to record power used?
_____.
6. The power company charges for power by the:
_____.
7. What part of the power meter measures the rate at which power is used?
_____.
8. Which dial on the power meter designates the most significant digit?
_____.
9. The most common service drop for new houses is:
_____ ampere service.
10. The voltage from the service drop is a/an:
_____ value.
11. Explain the purpose of the power distribution box.
_____.
12. The power distribution box is protected by:
_____ fuses.
13. What is the maximum number of disconnects required to separate household current from the service drop?
_____.

Paralleling Loads

Inside the individual buss box, the circuits may be split into separate lines, and are fuse or circuit breaker protected against circuit overloads. These safety devices disconnect shorted appliances or wiring from the source voltage by opening the current path. Fuses and circuit breakers protect the loads from the source voltage, and in turn, protect the loads from supply surges.

Current Paths

Each current path is limited to a specific current load. In many homes individual lines are protected by 15, 20, and 30 ampere fuses or circuit breakers. However, 15 ampere fuses are the most commonly used. Even the wall receptacles and on/off switches in most houses are safety tested and rated for 120 volts at 15 amperes. This means that a buss line could safely carry a load of $(120\text{ V} \times 15\text{ A})$ 1,800 watts.

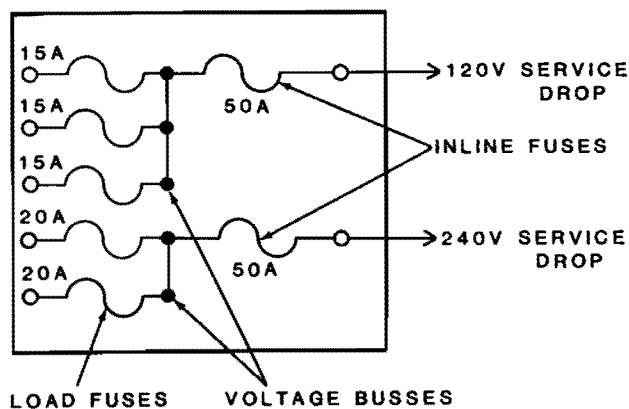


Figure 8-6 Power distribution box.

For your own information examine the power distribution box in your home. Note the current ratings marked on the fuses (and/or circuit breakers) that are used. Also note if it uses all fuses, all circuit breakers, or a combination of fuses and circuit breakers. You should know where the distribution box is located in your own home. You should also ensure that you have a supply of spare fuses for each rating that is used in your particular distribution box.

In Figure 8-6, all of the power used in the house can be disconnected by pulling the quick disconnect fuse blocks. Each of the fuse blocks could be divided and still remain within code. Remember, all power must be disconnected by no more than 6 disconnects. In many power boxes, some or all, of the disconnects are in the form of knife switches.

Each line from the distribution box is capable of supporting 15 A. The 15 A line is divided, by paralleling loads, until the parallel branch currents equal nearly 15 amperes. The wall plugs are usually paralleled in lighter loads to allow additional loads to be plugged in.

Most overhead lighting is connected in parallel to each other, and then connected through a fuse to the 120 volt supply. In this case, the line could support thirty, 60 watt light bulbs.

$$P = 120 \text{ V} \times 15 \text{ A or } 1,800 \text{ W}$$

$$1 \text{ light bult} = 60 \text{ W}$$

$$\frac{1,800 \text{ W}}{60 \text{ W}} = 30$$

By connecting the lights in parallel, all of the lights won't go out when a single bulb fails. A light bulb usually fails because the filament (heating element) melts and opens.

One of the most common light bulbs found in the average home are incandescent, 55 or 60 watt bulbs. The higher the wattage of the light bulb, the more light it puts out. The brighter the bulb the more heat it dissipates. When more light is needed in a specific area; a light fixture that contains more sockets is normally used.

Caution should be used when light bulbs are replaced with bulbs that have a higher wattage rating. Many lamps and light fixtures have warning statements that specify the maximum wattage rating that can be used safely.

Home Appliances

Lighting and wall plugs actually account for very little of the total power used in homes. The majority of the power is used by large ap-

pliances. Cooking, heating, laundry, washing dishes, and taking baths consume well over half of all of the power used in the home.

ELECTRIC STOVE	30.0A
DISHWASHER	* 6.0A
1500 W HEATER	12.5A
ELECTRIC FURNACE	* 20A
HOT WATER HEATER	12A
CLOTHES DRYER	* 20A
GARBAGE DISPOSAL	* 3A
WASHING MACHINE	* 3.0A
FREEZER	*10.0A
REFRIGERATOR	* 3.0A
ICE MAKER	* 1.0A
ELECTRIC IRON	10.0A
ELECTRIC SKILLET	10.4A
TOASTER	8.0A
CAN OPENER	* 1.0A
LIGHTING 10%	
OF SERVICE DROP	20.0A
WALL PLUGS 10%	
OF SERVICE DROP	<u>20.0A</u>
TOTAL	189.9A

*INDICATES MOTOR CONTROLLED DEVICE

Figure 8-7 Typical household loads.

For example, a single 1,500 W, 120 V baseboard heater requires 12.5 A of current. If you had 4 of these heaters in a house they would account for almost half of the 200 A service. When the same wattage heater is operated using a 240 volt source the current is reduced to under 7 A.

A typical 14,000 BTU air conditioner operated with a 120 volt source draws 8 A of current. A 240 volt, 14,000 BTU air conditioner requires approximately 4 A of current.

Therefore, electric stoves, clothes dryers, air conditioners over 12,000 BTU, hot water heaters, and heaters rated over 1,000 watts are usually wired for 240 volts.

Appliances wired for 120 volts and 240 volts are not interchangeable. Special line cords and receptacles are required for 240 volt operation.

Since the power used is I^2R , this is much more efficient than using the higher currents required by the 120 volt examples listed on this page.

Combining Loads

A power distribution box that contains 6 output lines can handle a maximum load of $(6 \times 1,800 \text{ W})$ 10,800 watts or 180 sixty watt light bulbs. This is also referred to as 10.8 kW. Remember it is kilowatt (kW) hours that you pay for. For this to be true, all of the lights must be on for one hour. Even though your service may be rated at 200 amperes, rarely if ever, will you be using maximum current on all lines at the same time.

Suppose that each output line, in each power buss, is capable of supplying exactly 15 amps. Let's also assume that the house is wired for

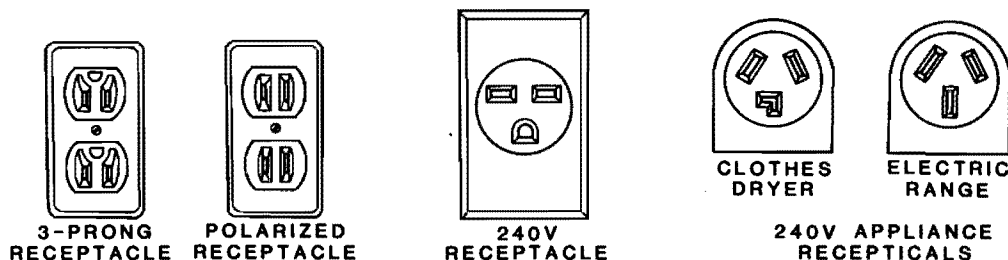


Figure 8-8 Typical home power receptacles.

200 ampere service. In this case, the house could contain a maximum of 13 (200 divided by 15) separate and distinct 15 ampere lines, with 5 amps left over.

Fortunately, the peak or instantaneous power is not what you pay for, and you don't use all of your electrical appliances at the same time. The assumption of 13 balanced lines is also invalid. In every house, there are appliances that are wired directly into the power distribution box. Some of these are electric stoves, electric dryers, electrical hot water heaters, electric furnaces, and central air conditioners.

It is also safe to say that not all of your appliances are rated at 120 volts. Many of the larger load appliances are rated at 220/240 volts. This accounts for the variety in sizes of fuses and circuit breakers found in the average home.

A 15 ampere branch can support 15 appliances that draw 1 ampere of current each. This can become a problem when using extension cords. When you plug an extension cord into a wall outlet, you have no way of knowing how much of the branch current is already being used. That is why it is recommended, you don't connect extender junction boxes to wall plugs. When a branch is overloaded, in most cases it blows (causes to open) a fuse in the distribu-

tion power box. If the overload is severe enough, and the protective device fails to disconnect (open) the circuit, it could cause a fire.

Load Power

Power is dissipated in the form of heat. When light duty (small wire gauge) extension cords are used; they may overheat which softens their insulation. Also, when the insulation is hot, it tends to scrap off causing a potential shock hazard or short circuit. Extension cords, as well as other power cords, tend to fray and become weakened at their ends. This is caused by twisting as you plug and unplug them. This can also result in a short circuit and a potential shock hazard. Care should be taken not to route electrical wiring of any kind where it could receive pressure. Pressure can come from stepping on the cord, dragging objects over the cord, or even bending the cord around corners.

Never unplug extension cords or appliances by pulling on the cord. Always grasp the body of the plug when connecting or disconnecting a cord.

Inspect your extensions cords on a regular basis. Discard or repair any wiring that shows excessive signs of wear or cracked insulation.

A 2 horsepower (HP) circle saw, operated from a 120 volt source, draws 12.5 amperes of current.

$$1 \text{ HP} = 746 \text{ watts}$$

$$2 \text{ HP} = 1,492 \text{ watts}$$

$$\frac{1,492 \text{ W}}{120 \text{ V}} = 12.5 \text{ A}$$

Since most wall plugs are rated at 15 amperes, the circle saw in conjunction with only 3 other amps of load current, is an overload. When a light duty extension cord is used to power the circle saw, the extension cord will heat up. When you are using insulated extension cords, periodically touch the cord to see if it is warm. If it is, lighten the load current or use a heavier (smaller number) gauge conductor.

Remember, the smaller the conductor's diameter the higher its resistance. Also, the longer the extension cord, the higher its resistance. For example, an extension cord has a resistance of only 2 ohms. When connected between the 2 HP circle saw in the earlier example and the 120 volt wall plug, the extension cord drops $(12.5 \text{ A} \times 2 \text{ ohms})$ 25 volts. Thus, the saw has an applied voltage of only 95 volts. The lowered voltage causes the saw to turn at a lower RPM. You may not notice that it is turning slower, but you will notice that it doesn't cut as efficiently as it should. This could lead you to the false assumption that the saw blade is dull and should be replaced.

Extension cords should be kept as short as possible. Power dissipated is I^2R , and using a larger diameter shorter extension cord is less expensive and more efficient. The cord in the example (wastes) dissipates:

$$I^2R = (12.5 \text{ A})^2 (2 \text{ ohms}) = 312.5 \text{ watts}$$

Broken strands within the conductor weakens an extension cord and increases its resistance by decreasing its diameter.

Direct Wired Appliances

Some appliances must be connected to specific receptacles. For example, the electric range and the electric clothes dryer are both 240 volt appliances but they have very different power requirements. The receptacles and power plugs for each of these appliances are matched so that they cannot be interchanged. When you have a wall plug wired for 240 volts, the receptacle is different than the standard 120 volt receptacle. If you don't have a 240 volt wall receptacle in your home, the next time you are in an appliance store, examine the power plug on the heavy duty appliances. Note the difference between the 120 and 240 volt appliance's line cords. This is another code restriction that must be adhered to.

Other appliances that are never used at the same time, can be paralleled by wiring into a single switch. For example, the dishwasher

and garbage disposal should never be used at the same time. They can be wired to a single throw, double pole switch. In this case, either of the appliances can be selected, but not both at the same time. This wiring configuration allows you to combine loads that actually total more than the line can handle. However, since they can't be operated at the same time it does not constitute an overload, and it will not blow the fuse in the distribution box.

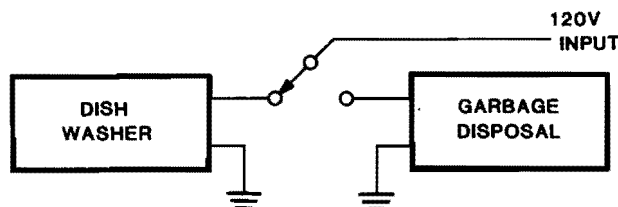


Figure 8-9 Either/Or circuit.

This is sometimes called an either/or circuit. You can select one or the other, but not both. Later, in your study of Digital Techniques, you will see that this is a commonly used circuit. This selective circuit is called an Exclusive OR in digital logic terms.

Another example of an either/or circuit, is the light that can be turned on or off from two different locations. For example, a switch at both exits from a room or the light at the top of a flight of stairs. Figure 8-10 is a very simple wiring diagram that provides either/or control at two remote locations.

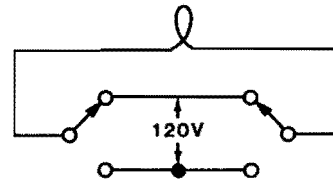


Figure 8-10 Two location light switch.

Typical Household Loads

Motors that are rated in the higher horsepowers are probably three phase induction motors. Some of the small appliances and hand tools that are motor driven use series constructed universal motors. Some of the motors in hand-tools and appliances are DC motors. The DC voltage needed to run these motors is obtained by converting the input AC to DC by a rectifier circuit. The rectifier circuit is inside the appliance or tool.

The television set probably has the highest voltage potential of all of the loads in your home. The high voltages are isolated and insulated from the operator. The voltage inside a television reach levels of approximately 35,000 (35 kV) volts. However, the current draw of a television is very low (on the order of mA). The television's high voltage does not figure into the load current for the house. The high voltage is obtained by transformer step up action. The television uses many DC voltage values which are obtained by rectifying the multi-tapped transformer's secondary windings.

The television system's antenna and rotor control uses a servomotor. The servo motor is a 2 phase motor that detects and corrects a programmed error signal. The servomechanism corrects the offset error that you introduce when you move the rotor controller. The servomotor corrects for the error by repositioning the antenna to the new reference.

In an average household, all of the concepts discussed in DC and AC Electronics are used. The average home also contains many semiconductor devices, electronic circuits, and digital devices.

Self-Test Review

14. The two common protection devices used in the power distribution box are:

1. _____.

2. _____.

15. The most common rated fuse in the power distribution box is usually:

_____ amperes.

16. How much power can a 200 ampere service drop supply to a house?

_____ watts.

17. How many 15 ampere loads can a 200 ampere distribution box support?

_____.

18. The power distribution box is usually grounded to:

1. _____.

2. _____.

19. The power lines leaving the power distribution box and entering your home are in:

series/parallel

Desk-Top Experiment 8

Designing AC Loads

Introduction

This is an exercise in calculating and organizing typical AC loads. The loads used in this experiment are found in nearly all homes. This experiment provides information necessary for you to visualize the procedures followed in wiring a house. A variety of loads are combined, and then, connected to load lines. The load lines are routed individually to a power distribution box fuse.

The loads should first be divided into loads requiring 240 volts, and those requiring 120 volts.

You will then connect the loaded lines into power distribution boxes. Next, you will calculate the service drop required to support the full loads.

Objectives

1. To convert loads into their current draws.
2. To combine similar loads into groups that draw slightly less than 15 amperes.
3. To calculate the service drop required to support specified loads.

Procedure

1. Draw a block diagram of the following loads.

Three 1,500 watt, 240 volt baseboard heaters.

A washing machine with a 120 volt supply that draws 4 amps.

A 3 HP, 240 volt three-phase motor.

Two 2 HP, 120 volt motors.

Four 1/2 HP single-phase motors.

Three 3-way lamps rated at 50, 250, and 350 watts each.

Light bulbs:

1 - 300 watt bulb.

2 - 250 watt bulbs.

3 - 100 watt bulbs.

15 - 60 watt bulbs.

2. Label each block as to its current requirement.

Discussion

First you should have divided the loads into two groups. One group should contain all of the 240 volt loads. The other group should contain all of the 120 volt loads. Each load can then be assigned a block.

Next you should have converted all of the loads (blocks) to their respective current draws.

For example 1 HP is equal to 746 watts. When the source voltage is 240 volts.

$$\frac{746 \text{ W}}{240 \text{ V}} = 3.103 \text{ A}$$

The current should always be rounded high, as an additional safety feature.

3. Now, combine the similar individual loads into groups of less than 15 amperes.
4. Route the combined loads to their respective, fused, supply voltages.
5. Connect service drops to the supply buses and calculate the required service drops to support the loads.

Discussion

The term similar load, in this case, means voltage supply. Therefore, you should have divided the loads into 240 volt sources and 120 volt sources.

Each load or group of loads should have been arranged into slightly less than 15 A loads. Each 15 A load line should have been routed to a fuse in the appropriate 240 V or 120 V distribution box.

The opposite ends of the fuses should have been connected to the properly rated voltage buss. All of the 240 volt fuses are referenced to the same point. All of the 120 volt fuses are referenced to the same voltage.

The voltage busses should have been separated from the service drop by in-line fuses and quick disconnect switches. An example is shown in the figure located after the summary in this Desk-Top Experiment.

Summary

The 1,500 watt, 240 volt heaters each draw approximately 6.3 amps.

The three HP, 240 volt motor, draws approximately 9.4 amps.

Two of the heaters can be combined into a single load of approximately 12.6 amps. Therefore, the 240 power buss will have three load lines.

A two HP, 120 volt motor draws approximately 12.5 amps. Therefore, each 2 HP motor should be wired individually to a load line.

A one half HP, 120 volt motor draws approximately 3.2 amps. All 4 of the 1/2 HP motors could be combined into a load of approximately 12.5 amps.

The current draw of the three 3-way lamps should be calculated using their maximum wattage ratings. The maximum rating of 1,000 watts will draw a current of approximately 7.5 amps. Two 250 watt light bulbs draw approximately 4.2 amps. A 300 watt light bulb draws approximately 2.5 amps. The combined current draw for this group is approximately 14.2 amps.

Three 100 watt bulbs draw approximately 2.5 amps. Fifteen 60 watt bulbs draw approximately 7.5 amps. The washing machine current is listed as 4 amps. This combined total is 14 amps.

The 120 volt buss will have 5 load lines, that go to 5 separate fuses, in the 120 volt distribution box. The other end of all 5 fuses should be tied together, and connected to the 120 volt buss.

The 120 volt buss should be wired through an in-line fuse and quick disconnect switch, to the 120 volt service drop.

The 240 volt service drop must supply at least 34.6 amperes of current. In this example we used three 15 ampere load lines. Therefore, the 240 volt service drop should be capable of supplying 45 amps.

The 120 volt service drop must supply at least 67.5 amperes of current. In the example, we used five 15 ampere load lines. Therefore, the 120 volt service drop should be capable of supplying 75 amps.

All of the loads were rounded high. This provides additional protection for the fuses against surge currents.

There are other combinations that could have been used.

Notice that the 120 volt load line on the right combines the washer with light bulbs. When

the washer's motor first starts, and again when it changes speed, these lights may dim. This is the reason why appliances that draw large currents are not normally connected to the same line as lighting systems. There is also the possibility of surge current blowing fuses.

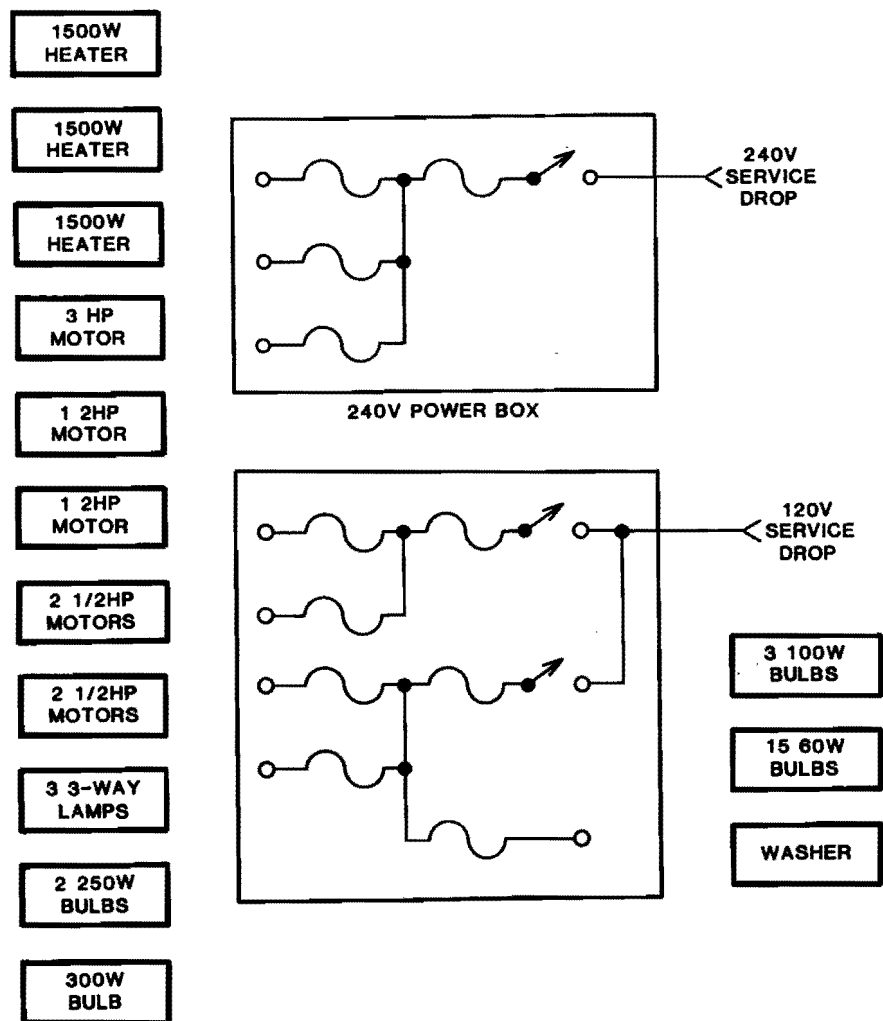


Figure 8-11 Desk-Top Experiment 8.

Self-Test Review

20. The loads for a house power line are wired in:

_____.

21. The percentage of the service drop reserved for the lighting system in the average house is:

_____ %.

22. Wall receptacles are usually paralleled with:

_____ loads.

23. A 1,500 watt baseboard heater is wired to a 120 volt source. The current draw for this heater is:

_____ A.

24. The following light bulbs are connected to the same 120 volt service line. What is their combined current?

15 watt bulb.
40 watt bulb.
55 watt bulb.
60 watt bulb.
75 watt bulb.
100 watt bulb.

_____.

25. A 1 horsepower appliance is connected to a 120 volt source. The current draw for this appliance is:

_____ A.

26. Explain why some appliances are wired directly into the power distribution box instead of being combined with other loads.

_____.

27. List 4 common power receptacles found in the average home.

1. _____.

2. _____.

3. _____.

4. _____.

28. Why is it possible to parallel loads that exceed the fuse rating for their supply?

_____.

29. List one household application that uses a single-phase, a two-phase, and a three-phase motor:

1. Single-phase motor _____.

2. Two-phase motor _____.

3. Three-phase motor _____.

Safety

Most accidents happen in the home. Many of these accidents are a result of misusing electricity. Most of the home accidents are caused by carelessness. Failure to think before you act causes many accidents. Using an appliance for anything other than what it is designed for is an accident looking for a place to happen. For example, drying objects in the oven and lighting cigarettes using the stove's burner.

Safety Grounds

You may notice that some of your appliances have a round terminal on their power plug. This ground terminal provides earth ground to the chassis of the appliance. Earth grounding the chassis of an appliance, prevents the appliance operator from receiving a shock because of an internal short in the appliance. The ground terminal is usually found on appliances that draw substantial currents. Some of which are the washing machine and power tools that are rated in horsepower. For example a 2 horsepower circle saw should have a 3 wire line cord and a 3 prong power plug.

Some 2 wire systems use polarized plugs. These line cords have one terminal that is larger than the other. This prevents the line cord plug from being inserted wrong (reversed by 180 degrees). Many TV sets use polarized plugs. The larger terminal is connected internally to the TV chassis and acts as a safety ground. This type is often used in place of the 3 prong plug used on powered hand tools.

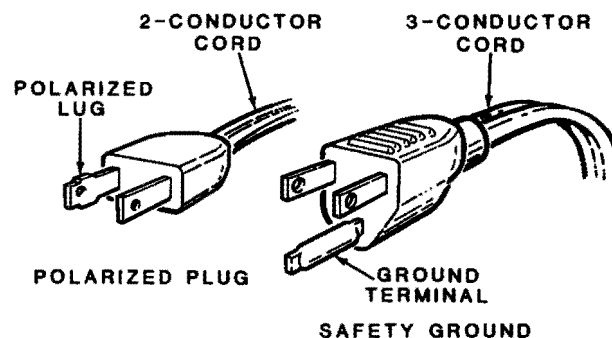


Figure 8-12 Grounded plugs.

The ground terminal should not be removed from any power plug. When a 3 input wall plug is not available, a 3 to 2 terminal converter plug can be used on a limited basis. These are not recommended, but they are available, in many stores, at a very reasonable price, and they are commonly used by individual home owners.

In residential wiring, ground leads are specified as either white or neutral gray, in the electrical code book. This is important because inside electronic equipment, black wire is usually used as the ground (reference) wire.

Extension cords and line power cords cause many problems such as fires and burns. Improper use and improper maintenance are the usual cause of this problem. Removing the earth grounding terminal or prong from a 3 prong plug can result in a shock hazard. Overloading wall receptacles can start fires. Using appliances when either you or the appliances are wet is a shock hazard.

Improper fusing and by-passing fuses can start fires.

Improper cleaning causes fires. This is especially true of the electric cook stove. Excessive lint inside an electric clothes dryer can start a fire or cause a short circuit, by collecting moisture, when the dryer is not in use.

The heating element in a dishwasher, stove burner, and broiler rack gets extremely hot. They can cause a very serious burn even after they are turned off. You should avoid touching any element, until it has time to cool.

Electrical shorts and fires have been caused by bugs that shorted a voltage potential to ground. Fires have been started by rodents chewing the insulated wiring. Red squirrels are prone to chew wiring, when they get into the attic of a house.

Safety Devices

The most common safety devices in a house are the fuses and circuit breakers. They work even while you sleep. Smoke detectors also work while you sleep, but they don't prevent damage. Smoke detectors alert you so that you can prevent the damage from spreading. Automatic sprinkler systems are also automatic protection devices, although they are not normally used in moderately priced houses.

Fire Extinguisher

Other safety equipment that is not automatic or electrical include the fire extinguisher. Every home should have a fire extinguisher that is kept in or near the kitchen.

Many fires in the home are caused by electrical shorts. Even when the fire is not started by electrical current, it is almost impossible to spray an area in a house without spraying an electrical component of some kind. Therefore, a water filled fire extinguisher should not be used.

Instead, CO₂ type extinguishers are recommended for home fires. The carbon dioxide filler is very effective in fighting fires and it doesn't cause the mess associated with water filled extinguishers. Also it doesn't cause shorts, the spray is easily controlled, and is much easier to clean up afterward. However, prolonged breathing of the carbon dioxide fumes should be avoided. Once the fire is out, ventilate the room, and the fumes will rapidly dissipate.

To extinguish a fire, it must be deprived of either fuel or oxygen. Another method of putting out a fire is to lower the temperature of the burning material below its flash point. There are common substances found in virtually every kitchen that are effective on small fires. Salt and baking soda are excellent for

extinguishing fires on electric stoves. Usually if the fire is confined to the inside of a pan, a lid can be used to shut off the oxygen supply.

Fuses

The fuse is a device that has almost zero resistance. It is designed with a center conductor that melts at a specific temperature. The resistance of the fuse and the current through the fuse generate the heat dissipated by the fuse. The fuse is in series with the household load. When the fuse's rating is exceeded, the fuse blows, causing that branch to become open. A blown fuse can usually be located visually. You can see the discoloration or the open section of its element. Fuses used in homes

usually have glass bodies that screw into a fuse holder. The fuse holder is located in the power distribution panel. The fuse's rating is printed on the face of the fuse. Figure 8-13 shows typical household fuses. Figure 8-13A shows a good fuse while Figure 8-13B shows a blown fuse.

The fuse shown in Figure 8-13C was referred to earlier as the hidden fuses that are mounted inside the quick disconnect plastic box. With this type fuse, you can't always determine if it is good or blown, by visual inspection. In this case, a meter is needed to verify the condition of the fuse. House fuses come in different physical sizes as well as current ratings. Every house should have a box of spare fuses.

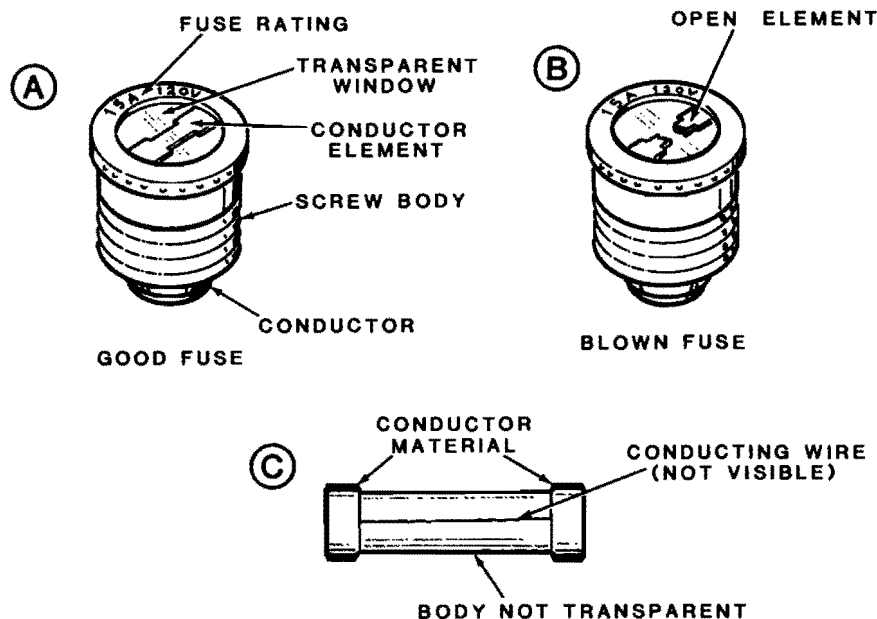


Figure 8-13 Typical fuses found in homes.

Fuses can blow because of a line surge. A line surge can be caused by temporary arcing or shorting in the main power line or from lightning. Just because you blow a fuse doesn't necessarily mean that you have an overload in your home. When you replace the fuse and it blows again, you should assume that the problem (overload) is in your home. Unplug as many of the loads from that particular line as possible. Loads that you can't unplug should be turned off. The fuses used in homes are slow blow type fuses. Slow blow fuses have larger elements to withstand a current surge. If the current surge is within certain limits, and then decreases below the fuse's rating, the element will not get hot enough quick enough to melt. There are also fast blow fuses, which blow the instant the current surge exceeds the fuse's rating.

Replace the fuse again. If the fuse doesn't blow, turn the loads on and then back off, one at a time. If you have a shorted load, the fuse will blow as soon as that load is plugged in or turned on. Once the faulty load is located, remove it (unplug), and replace the fuse. Turn your other loads on, to ensure that your wiring is good. If you can't isolate the problem to a load that is plugged in, you should call a licensed electrician, and turn the problem over to an expert.

Circuit Breakers

Circuit breakers and fuses perform the same function. That function is to disconnect power.

The most common circuit breaker is actually a spring loaded thermocouple. When the two metal contacts heat, they expand at different rates. When they exceed their operating temperature the metal contacts separate. This separation opens the current path. Unlike the fuse, the circuit breaker is reusable. Once the metal contacts cool, the circuit breaker can be reset. (Some circuit breakers are magnetic devices. Magnetic circuit breakers are explained in more detail in Electronic Circuits).

The reset characteristic makes the circuit breaker an ideal substitute for a fuse when trying to isolate the faulty load. There are also circuit breakers that are constructed to screw directly into the fuse holder, located in the power distribution box. The circuit breaker requires more time to react to an overload than an equally rated fuse. In most cases the increase in time is insignificant, and is outweighed by the circuit breaker's ability to be reset (used more than once).

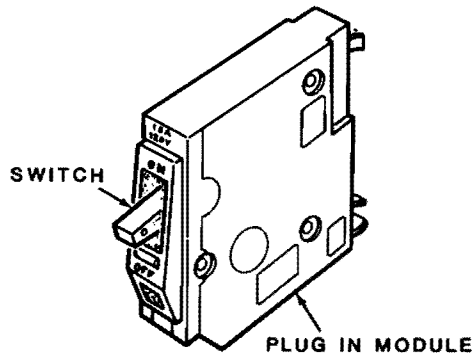


Figure 8-14 Plug-in circuit breaker.

The circuit breakers most often used in homes look like a switch. They are labeled as to which position is off, and which position is on. Figure 8-14 shows a typical circuit breaker that is used in homes.

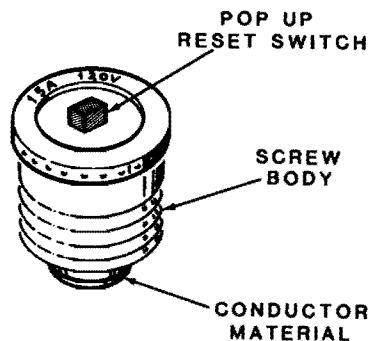


Figure 8-15 Screw-in circuit breaker.

Figure 8-15 is a typical circuit breaker that can be used in the home to replace fuses.

Examine the back of your TV (the back should not be removed). There should be a red button sticking through the back. This is a circuit breaker. This particular circuit breaker is designed to disconnect the television's high voltage circuits. When you enclose the TV in a small place, it can't dissipate enough heat. When the heat builds up, it may cause this circuit breaker to pop (open the circuit). When the circuit breaker pops, it shuts the TV off. In this case, there is nothing wrong with your TV. Once the television is allowed to cool, the circuit breaker can be reset by pushing the red button and holding it for approximately one second. Line surge can also cause the circuit breaker to pop.

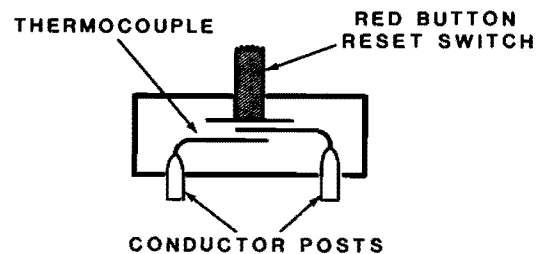


Figure 8-16 Typical TV circuit breaker.

Never hold the circuit breaker in longer than it takes for it to catch (set). If the circuit breaker pops again after the set cools, this is an indication of internal failure. Further attempts to reset the breaker should not be attempted.

Most garbage disposals are protected by a circuit breaker. The circuit breaker is mounted directly on the disposal's motor. When the disposal is jammed by silverware or bones, the circuit breaker disconnects the circuit, before the motor is damaged. In this case, turn the disposal off, free the obstruction, reset the circuit breaker, and turn the disposal on. If the

circuit breaker pops again, your garbage disposal may be the problem.

Never hold a circuit breaker to prevent it from popping. Preventing the circuit breaker from opening the circuit could easily cause a fire. Even if it didn't start a fire, it would destroy your appliance.

Self-Test Review

30. What is the main advantage of the fuse when compared to a circuit breaker?
_____.
31. Explain the term power buss.
_____.
32. The circuit breaker operates on the same principle as a/an:
_____ or _____.
33. The color of the wire specified by the electrical code as ground is:
_____.
34. The rounded center terminal on a 3 wire power plug is designed to be:
_____.
35. Explain the term polarized power plug.
_____.
36. Where are extension cords most likely to be damaged?
_____.
37. The most common cause of a blown fuse that services wall outlets is:
_____ circuit.
38. The greatest danger from an electric stove is:
_____.
shock/burn
39. The most important safety feature in the home is the:
_____.
40. Automatic safety devices that are found in all homes are:
_____ and _____.
_____.
41. The automatic safety device that should be installed on every floor is the:
_____.
_____.
42. What type fire extinguisher is recommended for home use?
_____ type.

43. A blown fuse should always be replaced by a fuse with:

_____.

44. Fuses can be replaced with circuit breakers that have the same rating.

- A. True
- B. False

45. When a circuit breaker pops, can it be immediately reset?

_____.

yes/no

46. Why?

_____.

Unit Summary

AC service drops are routed from the secondary of a step-down transformer. The common voltages available to home owners are 120 volts and 240 volts. This voltage value is its RMS value and the frequency is 60 hertz.

Two of the 120 volt lines that are 180 degrees out of phase can be used to provide 240 volt service. When the 240 volt service is available from wall plugs, the plugs must be specifically rated at 240 volts.

Residential service drops are also rated in amperes. Houses usually have 60, 100, or 200 ampere service drops. With the advent of the wide variety of electrical appliances, the 200 ampere drop is becoming the most popular. Even if you don't need 200 amperes, it's nice to have the capability of adding loads, without having to first call the power company.

The power distribution box in your house must be earth ground referenced. This is usually accomplished by connecting the chassis of the distribution box to either the cold water pipe or to a copper rod driven 4 feet into the ground.

Another code requirement, for the distribution box, is that all household power must be routed through no more than 6 disconnects.

Household power is divided into busses and fused. The busses are then divided into power lines and these lines are protected against overloads by fuses or circuit breakers. The individual power lines are usually protected by

15 ampere fuses or circuit breakers. Load currents are paralleled until the branch currents total a little less than 15 amperes and the paralleled load is wired to the individual power line.

A 200 ampere service drop could be divided into 13 individual, 15 ampere power lines. The individual lines are then fused with the appropriate rated slow blow fuse. The fuses are rated as slow blows, to prevent their being blown by surge currents. One type surge current that could cause problems if slow blow fuses are not used, is when your washing machine shifts into the spin cycle.

The spin cycle starts a motor from stop, under full load conditions (tub full of wet clothes and water). This results in a high surge of starting current.

The largest household loads are used for cooking, drying dishes and clothes, heating the house, and heating water. These heavy loads are usually wired for 240 volt operation.

Approximately 10% of the total service drop is used for lighting. Another 10% is usually reserved for wall plug loads. These applications usually use 120 volt supplies. A single 15 ampere, 120 line is capable of supplying 1,800 watts ($15\text{ A} \times 120\text{ V}$). This would supply power to light thirty 60 watt light bulbs. The lights are paralleled in a house so that all of the lights don't go out when a single bulb opens.

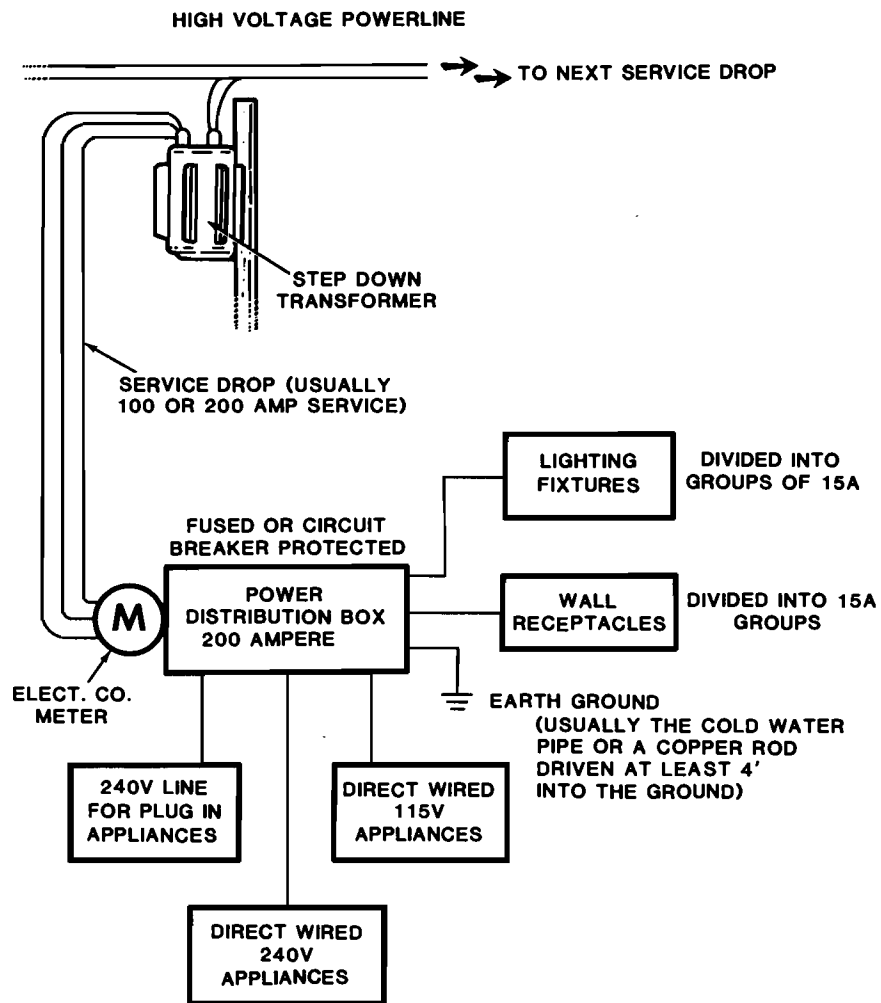


Figure 8-17 AC wiring block diagram for a typical home.

Wall receptacles are usually paralleled with small loads. This ensures that the line will not be overloaded by plugged in appliances. The 240 V and 120 V receptacles are constructed so that appliances can't be plugged into lines that can't handle their load.

The most important safety device is the home owner. There is no substitute for common sense and attention to detail.

Commercial safety devices used in homes are fuses, circuit breakers, smoke detectors (one per floor), and a carbon dioxide (CO₂) fire extinguisher. The fuses and circuit breakers are considered as protection devices for individual loads and the house itself. Smoke detectors

are considered to be people protection devices. A handy fire extinguisher can prevent a minor fire from becoming a major fire.

The fuse operates (opens) faster than the mechanical circuit breaker. The fuse is a one time device, once it blows it must be discarded, and a new fuse of the same rating installed. When a circuit breaker pops (opens), it can be reset after it cools.

Besides the power distribution box, circuit breakers are commonly used in televisions and garbage disposals. Other appliances may also be fused or protected by internal fuses or circuit breakers.

Index

- AC capacitive circuits, applications, 3-54
- AC capacitive circuits, ohms law, 3-31
- AC circuits, capacitors in, 3-25
- AC circuits, inductive, 4-23
- AC circuits, inductors in, 4-22
- AC circuits, parallel RC, 3-48
- AC circuits, power in, 3-43
- AC circuits, resistance, 2-41
- AC circuits, resistive, ohms law, 2-42
- AC home applications, 8-1
- AC generator, 1-16
- AC measurement, summary, 2-56
- AC motors, 7-13
- AC resistance, parallel, 2-45
- AC resistance, series, 2-43
- AC resistive circuits power, 2-41
- AC series RC circuits, 3-35
- AC servo system, 7-34
- AC summary, 1-57
- Air core coil, 4-14
- Alternation, positive and negative, 1-35
- Alternator, 1-13
- Amplifier, horizontal, 2-32
- Amplifier, vertical, 2-31
- Amplitude, maximum, 1-36
- Amplitude, peak, 1-36
- Apparent power, 3-47
- Applications, AC capacitive circuits, 3-54
- Applications, inductive circuits, 4-16
- Applications, transformers, 6-39
- Armature, 1-16
- Asynchronous speed, 7-21
- Attenuator control, vertical, 2-34
- Audio frequency, 1-45
- Autotransformer, 6-37
- Average value, sine wave, 1-27

- Back emf, 4-7
- Balanced Systems, 7-29
- Balanced Syncro systems, 7-29
- Band-pass filter, LC, 5-53
- Band-stop filter, LC, 5-53
- Bandwidth and Q, 5-33
- Bandwidth and Q in series resonant circuits, 5-33
- Bandwidth equals FO/Q, 5-34
- Bandwidth in parallel resonant circuits, 5-44
- Bandwidth measuring in, resonant circuits, 5-31
- Bandwidth, resonant circuits, 5-31
- Base, horizontal time, 2-32
- Basic meter movement, 2-6
- Bead-ferrite, inductor, 4-15
- Bridge rectifier schematic, 2-10
- Broadcasting system, television, 1 -11
- Brushes, 1-19
- BW, 5-33
- BW and Q, 5-33

- C, 3-8
- CDX, 7-32
- CDR, 7-33
- Capacitance, distributed, and self resonance of coils, 5-47
- Capacitance, factors determining, 3-11
- Capacitance, unit conversion table, 3-10
- Capacitance, units of, 3-10
- Capacitive AC circuits, applications, 3-54
- Capacitive AC circuits, current and voltage, 3-26

Capacitive circuits combining AC and DC, 3-59
 Capacitive reactance, 3-29
 Capacitive voltage divider, 3-54
 Capacitive defects, 3-15
 Capacitor leakage, 3-15
 Capacitor ratings, 3-14
 Capacitors, high frequency, 3-13
 Capacitors in AC circuits, 3-25
 Capacitors in DC circuits, 3-18
 Capacitors, parallel, 3-16
 Capacitors, peak voltage rating, 3-15
 Capacitors, review of DC, 3-5
 Capacitors, series, 3-16
 Capacitors, types of, 3-12
 Cascade, 3-62
 Chart, frequency, 1-46
 Choke, iron core, 4-15
 Circuits-AC capacitive, applications, 3-54
 Circuits-AC capacitive, current and voltage, 3-26
 Circuits-AC capacitive, Ohms Law, 3-31
 Circuits-AC, capacitors in, 3-25
 Circuits-AC inductive, current and voltage, 4-22
 Circuits-AC, inductors in, 4-24
 Circuits-AC, parallel RC, 3-48
 Circuits-AC, power in, 3-43
 Circuits-AC, resistance in, 2-41
 Circuit breakers, 8-29
 Circuits-capacitive, combining AC and DC, 3-59
 Circuits-DC capacitors in, 3-18
 Circuits-DC, inductors in, 4-16
 Circuits-inductive, ohms law, 4-24
 Circuits-parallel resonant, bandwidth in, 5-38

Circuits-printed, inductors, 4-14
 Circuits-RC, phase shift (phase angle), 3-60
 Circuits-RC, vector diagrams, 3-38
 Circuits-resonant, bandwidth, 5-31
 Circuits-resonant, measuring bandwidth, 5-33
 Circuits-RL, 4-32
 Circuits-RL, impedance, 4-34
 Circuits-RLC, 5-5
 Circuits-RLC, parallel, 5-8
 Circuits-RLC, series, 5-5
 Circuits-RLC, summary, 5-64
 Circuits-series RC in AC, 3-35
 Circuits-series resonant, Q and bandwidth, 5-31
 Circuits-series RL, 4-32
 Circuits-series RL, vector diagrams, 4-33
 Circuits-sync, 2-33
 Circuits-tanks, 5-42
 Circuits-tank, loading, 5-43
 Circuits-tank, practical, 5-42
 Clamp-on meter, 2-17
 Coils, air core, 4-15
 Coils, distributed capacitance and self resonance, 5-47
 Coils, primary, 4-25
 Coils, secondary, 4-25
 Coils, single layer, inductance, 4-12
 Combining AC and DC, capacitive circuits, 3-59
 Combining loads, 8-15
 Compound motors, 7-10
 Concentric vane meter movement, 2-14
 Conductor, voltage induced into, 1-16
 Constant, dielectric, 3-11
 Constant-dielectric, table of, 3-11
 Construction, transformer, 6-9

-
- Control, vertical attenuator, 2-34
 - Control, vertical, sensitivity, 2-34
 - Conversion table, units of capacitance, 3-10
 - Conversion table, units of inductance, 4-10
 - Copper loss, 6-29
 - Copper oxide rectifier, 2-8
 - Core—air, coil, 4-15
 - Core—iron, choke, 4-14
 - Core losses, 6-26
 - Coupling network, 3-60
 - CRT, 2-31
 - Current and voltage in capacitive AC circuits, 3-26
 - Current Eddy, losses, 6-26
 - Current, exciting, 6-12
 - Current, primary, 6-8
 - Current paths, 8-13
 - Current, secondary, 6-8
 - Current voltage relationships in inductive AC circuits, 4-26
 - Cycle, 1-31
 - Damped sine wave, 5-42
 - DC and AC, combining in capacitive circuits, 3-59
 - DC capacitors, review of, 3-18
 - DC circuits, capacitors in, 3-18
 - DC circuits, inductors in, 4-16
 - DC Motors, review of, 7-5
 - DC Motors, problems of, 7-7
 - DC Servo System, 7-35
 - Decoupling, 3-59
 - Decoupling network, 3-59
 - Defects, capacitor, 3-15
 - Deflection, plate, horizontal, 2-31
 - Deflection plate, vertical, 2-31
 - Determining factors, capacitance, 3-11
 - Dielectric constant, 3-11
 - Dielectric constants, table of, 3-11
 - Differential Receiver, 7-33
 - Differential Synchro systems, 7-31
 - Differential transmitter, the, 7-32
 - Diode—junction rectifier, 2-9
 - Diode, schematic symbol, 2-9
 - Direct-Coupled systems, 7-30
 - Direct wired appliances, 8-17
 - Distortion, electron orbit, 3-26
 - Distributed capacitance and self resonance of coils, 5-47
 - Distribution, power, 6-32
 - Distribution system, power, 1-9
 - Divider—voltage, capacitance, 3-54
 - Division ratio, voltage, 6-17
 - Eddy current losses, 6-26
 - Effect flywheel, 5-40
 - Effective value of sine wave, 1-39
 - Efficiency, transformers, 6-30
 - Electrodynamometer movement, 2-26
 - Electromagnetic induction, 1-13
 - Electron orbit distortion, 3-25
 - Electronic applications, transformers, 6-32
 - EMF, counter, 6-13
 - Exciting current, 6-12
 - Factor, power, 3-45
 - Factor, Q, 5-43
 - Factors affecting inductance, 4-11
 - Factors determining capacitance, 3-5
 - Ferrite bead inductor, 4-15
 - Field magnet, 1-16
 - Filter definition, 5-53

Filter, LC band-pass, 5-53
Filter, LC band-stop, 5-53
Filter, LC high-pass, 5-53
Filter, LC low-pass, 5-53
Filter, RC high-pass, 3-57
Filter, RC low-pass, 3-56
Filter, RL high-pass, 4-44
Filter, RL low-pass, 4-44
Filters, inductive, 4-44
Filters, LC, 5-53
Filters, RC, 3-55
Filters, types of, 5-53
Fire Extinguisher, 8-27
Fixed inductors, 4-14
Flux linkage, 6-7
Flywheel effect, 5-40
 F_o , 5-34
 F_o/Q equals bandwidth, 5-34
Formulas—impedance (Z), RC circuits, 3-40
Formulas—phase shift, RC circuits, 3-46
Formulas, transformers, 6-32
Frequency, 1-42
Frequency, audio, 1-45
Frequency, chart, 1-46
Frequency, controlled servo systems, 7-36
Frequency—high, capacitors, 3-14
Frequency, measuring, 2-36
Frequency, radio, 1-45
Frequency, resonant, 5-45
Friction, 7-24
Full-wave rectification, 2-11
Fuses, 8-28
Generator, AC, 1-16
Generator operation, 1-17
Generator rule, left-hand, 1-14

Giga, 1-44
Graticule, 2-34

Henry, 4-10
Half-power points, 5-34
Half-wave rectification, 2-11
Hertz, 1-42
High frequency capacitors, 3-57
High-pass filter, LC, 5-57
High-pass filter, RC, 3-57
Home appliances, 8-14
Home servo system, 7-35
Hook-on meter, 2-17
Horizontal amplifier, 2-32
Horizontal deflection plate, 2-32
Horizontal time base, 2-32
Household loads, typical, 8-14
Hysteresis, 6-28

Impedance, 3-40
Impedance ratio, 6-23
Impedance, RL circuit, 4-34
Induced voltage, 1-13
Induced voltage in a conductor, 1-20
Inductance, 4-8
Inductance, factors affecting, 4-11
Inductance, mutual, 4-25
Inductance, parallel, 4-28
Inductance, series, 4-27
Inductance, single layer coil inductor, 4-13
Inductance, units of, 4-9
Induction, electromagnetic, 1-13
Induction—external, loss, 6-29

- Induction, mutual, 6-5
- Induction, self, 4-7
- Inductive AC circuits, current-voltage relationships, 4-22
- Inductive circuits, applications, 4-44
- Inductive circuits, Ohms Law, 4-24
- Inductive circuits, power, 4-37
- Inductive filters, 4-44
- Inductive phase shifters, 4-45
- Inductive principles, of DC motors, 7-5
- Inductive reactance, 4-23
- Inductive time constant, 4-18
- Inductive units, conversion table, 4-10
- Inductor, ferrite bead, 4-15
- Inductor, printed circuit, 4-15
- Inductor, toroidal, 4-14
- Inductor, variable, 4-16
- Inductors and inductance, 4-8
- Inductors and inductance, review of, 4-5
- Inductors, fixed, 4-14
- Inductors in AC circuits, 4-22
- Inductors in DC circuits, 4-16
- Inductors in series and parallel, 4-27
- Inductors, schematic symbols, 4-16
- Inductors, types of, 4-16
- Inertia, 7-24
- Instantaneous value, 1-32
- Iron core choke, 4-15
- Iron-moving, meter, 2-13
- Isolation transformer, 6-36
- Junction diode rectifier, 2-9
- K, 4-26
- K, 3-12
- Kilo, 1-44
- L, 4-13
- L, single layer coil inductor, 4-13
- Laminations, 6-27
- LC filter, band-pass, 5-53
- LC filter, band-stop, 5-53
- LC filter, high-pass, 5-53
- LC filter, low-pass, 5-53
- LC filters, 5-53
- Leakage, capacitor, 3-15
- Leakage resistance, 3-15
- Left-hand generator rule, 1-14
- Line, time, 1-38
- Linkage, flux, 6-7
- Lissajous patterns, 2-37
- Lm, 4-26
- Load, transformer with, 6-13
- Load power, 8-16
- Loading a tank circuit, 5-42
- Loss, copper, 6-29
- Loss, external induction, 6-29
- Losses, core, 6-26
- Losses, eddy current, 6-26
- Losses, transformer, 6-26
- Low-pass filter, LC, 5-56
- Low-pass filter, RC, 3-56
- Magnet field, 1-13
- Measurement-AC, summary, 2-56

Measuring bandwidth, resonant circuits, 5-33
Measuring frequency, 2-36
Measuring phase relationships, 2-36
Mega, 1-44
Meter, clamp on, 2-17
Meter, hook-on, 2-17
Meter, movement, basic, 2-6
Meter, movement, concentric vane, 2-14
Meter, movement, electro dynamometer, 2-26
Meter, movement, radial-Vane, 2-13
Meter, moving iron, 2-13
Meter, moving vane, 2-13
Meter, rectifier type moving coil, 2-5
Meter sensitivity, 2-20
Meter, snap around, 2-17
Meter, split-core, 2-17
Meter, thermocouple, 2-16
Meter, watt, 2-26
Metric prefixes (kilo, mega, giga), 1-44
Motor control circuits, 7-24
Motor control circuits, 7-24
Motor regulations, 7-21
Motor speeds, 7-20
Movement, basic meter, 2-25
Movement-meter, electro dynamometer, 2-25
Moving coil rectifier type meter, 2-5
Moving iron meter, 2-13
Moving vane meter, 2-13
Mutual inductance, 4-25
Mutual induction (electromagnetic), 6-5

Negative alternation, 1-32
Network, coupling, 3-60
Network decoupling, 3-59
Network, phase shift, 3-60
No load, transformer, 6-12

Nomograph, resonance, 5-67
Nonsinusoidal wave forms, 1-49

Offset voltage, 7-25
Ohms law, AC capacitive circuits, 3-31
Ohms law, in inductive circuits, 4-24
Ohms law in resistive AC circuits, 2-41
Operation, generator, 1-17
Orbit distortion, electron, 3-26
Oscillator, sweep, 2-32
Oscilloscope, 2-30

Parallel AC resistance, 2-45
Parallel capacitance, 3-16
Parallel inductance, 4-28
Parallel RC in AC circuits, 3-48
Parallel resonance, 5-38
Parallel resonant circuits, bandwidth in, 5-44
Parallel resonant circuits, Q in, 5-43
Parallel RLC circuits, 5-8
Paralleling loads, 8-13
Patterns, Lissajous, 2-37
Peak amplitude, 1-36
Peak-to-peak value, 1-36
Peak value, 1-35
Percent of Regulation, 7-21
Period, 1-41
PF, 3-45
Phase relationships, measuring, 2-36
Phase shift formulas, RC circuits, 3-46
Phase shift network, 3-60
Phase shift (phase angle), RC circuits, 3-46
Phase shift, RL circuits, 4-36
Phase shifter, inductive, 4-36

-
- Phase shifting, transformers, 6-33
 - Plate, horizontal deflection, 2-31
 - Plate, vertical deflection, 2-31
 - Polyphase motors, 7-16
 - Positive alternation, 1-32
 - Power, AC resistive circuits, 2-47
 - Power, apparent, 3-45
 - Power box, grounding, 8-11
 - Power, distribution, 6-32
 - Power distribution box, 8-10
 - Power distribution system, 1-9
 - Power factor, 3-46
 - Power-half points, 5-34
 - Power in AC circuits, 3-45
 - Power meter, 8-7,8-8
 - Power ratio, 6-19
 - Power, true, 3-43
 - Power-true, in inductive circuits, 4-37
 - Practical tank circuits, 5-42
 - Prefixes, metric (kilo, mega, giga), 1-44
 - Primary coil, 6-8
 - Primary current, 6-8
 - Primary winding, 6-6
 - Printed circuit inductors, 4-15

 - Q and bandwidth (BW), 5-33
 - Q and bandwidth in series resonant circuits, 5-31
 - Q factor, 5-31
 - Q in parallel resonant circuits, 5-38

 - Radial-vane meter movement, 2-13
 - Radio frequency, 1-46

 - Rating, capacitor peak voltage, 3-14
 - Ratings, capacitor, 3-14
 - Ratio, current, 6-19
 - Ratio, impedance, 6-23
 - Ratio, power, 6-19
 - Ratio, turns, 6-17
 - Ratio, voltage, 6-17
 - Ratio, voltage division, 3-80
 - Ratios, transformer, 6-17
 - RC circuits in AC, 3-35
 - RC circuits, phase shift (phase angle), 3-47
 - RC circuits-series, in AC, 3-35
 - RC circuits, vector diagrams, 3-37
 - RC filters, 3-55
 - RC high-pass filter, 3-57
 - RC low-pass filter, 3-56
 - RC parallel circuits in AC, 3-48
 - Reactance, capacitive, 3-29
 - Reactance, inductive, 4-23
 - Rectification, full-wave, 2-11
 - Rectification, half-wave, 2-11
 - Rectifier bridge, schematic, 2-10
 - Rectifier, copper oxide, 2-8
 - Rectifier, junction diode, 2-9
 - Rectifier, schematic symbol, 2-9
 - Rectifier type moving coil meter, 2-5
 - Rectifiers, 2-8
 - Remote controls, 7-26
 - Remote control system 7-28
 - Resistance in AC circuits, 2-41
 - Resistance, parallel AC, 2-45
 - Resistance, series AC, 2-43
 - Resistor, shunt, 2-21
 - Resonance, 5-12
 - Resonance nomograph, 5-67

Resonance, parallel, 5-43
Resonance-self and distributed capacitance
of coils, 5-47
Resonance, series, 5-17
Resonance-series, summary, 5-29
Resonant circuits, bandwidth, 5-44
Resonant circuits, measuring bandwidth, 5-33
Resonant circuits-parallel, Q and
bandwidth, 5-33
Resonant frequency, 5-12
Review of capacitors, DC, 3-5
Review of inductors and inductance, 4-5
Right-hand motor rule, 7-6
Ring, slip, 1-17
RL circuits, 4-32
RL circuits, impedance, 4-34
RL circuits, phase shift, 4-36
RL circuits, series, 4-32
RL filters, 4-44
RL high-pass filter, 4-44
RL low-pass filter, 4-33
RL series circuits, vector diagram, 4-33
RLC circuits, 5-5
RLC circuits, parallel, 5-8
RLC circuits, series, 5-5
RLC circuits, summary, 5-29
RMS, 1-39
RPM, 7-20
Root-mean-square (rms), 1-39

Safety, 8-26
Safety devices, 8-27
Safety grounds, 8-26
Sawtooth wave, 1-50
Scale, square law, 2-15
Schematic bridge rectifier, 2-10
Schematic symbol diode, 2-9
Schematic symbol rectifier, 2-10
Schematic symbols inductors, 4-15
Schematic symbols transformers, 6-12
Scope, 2-30
Synchronous speed, 7-21
Synchro systems, 7-28
Synchros and servos systems,
comparisons, 7-36
Secondary coil, 6-8
Secondary current, 6-8
Secondary winding, 6-6
Self-induction 4-7
Self-resonance, 5-47
Sensitivity control, vertical, 2-34
Sensitivity, meter, 2-20
Series capacitance, 3-16
Series inductance, 4-27
Series motor, 7-9
Series RC circuits in AC, 3-35
Series resonance, 5-17
Series resonance summary, 5-29
Series resonant circuits, Q and
bandwidth, 5-31
Series RL circuits, 4-32
Series RL circuits, vector diagrams, 4-33
Series RLC circuits, 5-5
Service drop, the, 8-5
Shunt motor, 7-9
Shunt resistors, 2-21
Shunt-type motor, 7-10
Signs of the Functions, motors, 7-15
Sine, trigonometric function, 1-28
Sine wave, 1-27
Sine wave, average value, 1-27
Sine wave, damped, 5-42
Sine wave, effective value, 1-39

Single layer coil, inductance, 4-13
 Single-phase motors, 7-13
 Sinusoidal waveform, 1-27
 Skin effect, 2-17
 Slip ring, 1-17
 Slippage, 7-21
 Snap-around meter, 2-17
 Solving transformer problems, 6-21
 Split core meters, 2-17
 Split-phase motor, 7-16
 Square law scale, 2-15
 Square wave, 1-49
 Summary, AC, 1-56
 Summary AC home applications, 8-23
 Summary, AC measurement, 2-56
 Summary, Motors and motor controls, 7-42
 Summary, RLC circuits, 5-64
 Summary, transformers, 6-41
 Sweep oscillator, 2-30
 Sweep time, 2-35
 Sync circuit, 2-33
 Synchronous motor, 7-21

 Table, capacitance unit conversion, 3-10
 Table, conversion of inductive units, 4-9
 Table of dielectric constants, 3-11
 Tank circuits, 5-42
 Tank circuits, loading, 5-42
 Tank circuits, practical, 5-42
 Television broadcasting system, 1-9
 Theory, transformer, 6-12
 Thermocouple meter, 2-16
 Time base, horizontal, 2-32
 Time constant, inductive, 4-18
 Time line, 1-41
 Time, sweep, 2-35

 Toroidal inductor, 4-15
 Torque, 7-7
 Transformer, 8-5
 Transformer action, 6-8
 Transformer applications, 6-32
 Transformer-auto, 6-37
 Transformer construction 6-9
 Transformer efficiency, 6-30
 Transformer isolation 6-36
 Transformer losses, 6-26
 Transformer problems, solving 6-21
 Transformer ratios, 6-19
 Transformer schematic symbols, 6-12
 Transformer theory, 6-12
 Transformer, variable, 6-39
 Transformer with load, 6-13
 Transformer with no load, 6-12
 Transformers, electronic application, 6-33
 Transformer, phase shifting, 6-33
 Transformer summary, 6-41
 Triangular wave, 1-50
 Trigonometric function, sine, 1-28
 Trigonometric functions, table of, 1-29
 True power, 3-47
 Turns ratio, 6-17
 Types of capacitors, 3-12
 Types of filters, 5-53
 Types of inductors, 4-14
 Types of inductive motors, 7-9
 Typical electric bill, 8-9
 Two-phase motors, 7-16

 Unbalanced systems, motor, 7-31
 Universal motor, 7-11
 Unit conversion table, capacitance, 3-10

Units of capacitance, 3-8

Units of inductance, 4-9

Value—average, sine wave, 1-39

Value—effective, sine wave, 1-39

Value—peak, 1-38

Value—peak-to-peak, 1-36

Vane—concentric, meter movement, 2-13

Vane—moving meter, 2-13

Vane—radial, meter movement, 2-13

Variable inductor, 4-16

Variable autotransformer, 6-39

Vector diagram, series RL, 4-33

Vector diagrams, RC circuits, 3-41

Vertical amplifier, 2-31

Vertical attenuator control, 2-34

Vertical deflection plate, 2-31

Vertical sensitivity control, 2-34

Voltage and current in capacitive AC
circuits, 3-26

Voltage and current in inductive AC
circuits, 4-22

Voltage divider, capacitive, 3-54

Voltage—peak, capacitance ratings, 3-14

Voltage ratio, 6-17

Wattmeter, 2-26

Wave, damped sine, 5-42

Wave, fluctuating DC, 1-50

Wave—full, rectification, 2-11

Wave—half, rectification, 2-11

Wave, nonsinusoidal, 1-49

Wave, sawtooth, 1-50

Wave, sine, 1-27

Wave—sine, average value, 1-27

Wave—sine, effective value, 1-39

Wave, sinusoidal, 1-27

Wave, square, 1-49

Wave, triangular, 1-50

Winding, primary, 6-6

Winding, secondary, 6-6

Wire gauges, 8-11

Wire gauge chart, 8-11

X_C , 3-29

X_L , 4-29

Z, 3-51

Zero reference line, 1-38