Chapter

6

Circuit Fundamentals

6.1 Introduction

Electronic circuits are composed of elements such as resistors, capacitors, inductors, and voltage and current sources, all of which may be interconnected to permit the flow of electric currents. An *element* is the smallest component into which circuits can be subdivided. The points on a circuit element where they are connected in a circuit are called *terminals*.

Elements can have two or more terminals, as shown in Figure 6.1. The resistor, capacitor, inductor, and diode shown in the Figure 6.1*a* are two-terminal elements; the transistor in Figure 6.1*b* is a three-terminal element; and the transformer in Figure 6.1*c* is a four-terminal element.

Circuit elements and components also are classified as to their function in a circuit. An element is considered *passive* if it absorbs energy and *active* if it increases the level of energy in a signal. An element that receives energy from either a passive or active element is called a *load*. In addition, either passive or active elements, or components, can serve as loads.

The basic relationship of current and voltage in a two-terminal circuit where the voltage is constant and there is only one source of voltage is given in Ohm's law. This states that the voltage V between the terminals of a conductor varies in accordance with the current I. The ratio of voltage, current, and resistance R is expressed in Ohm's law as follows:

$$E = I \times R \tag{6.1}$$

Using Ohm's law, the calculation for power in watts can be developed from $P = E \times I$ as follows:

$$P = \frac{E^2}{R} \quad and \quad P = I^2 \times R \tag{6.2}$$

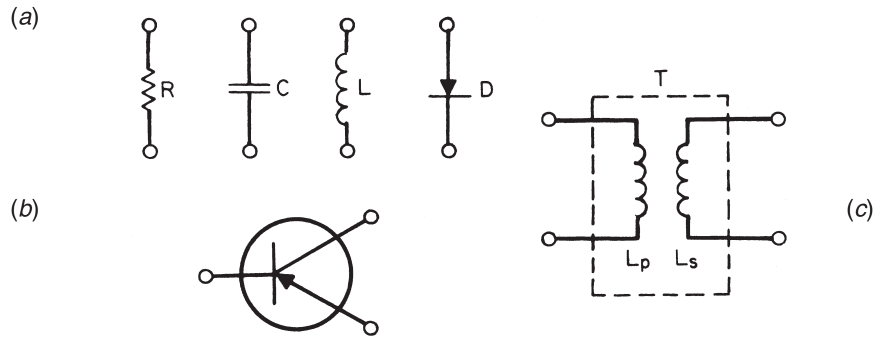


Figure 6.1 Schematic examples of circuit elements: (*a*) two-terminal element, (*b*) three-terminal element, (*c*) four-terminal element.

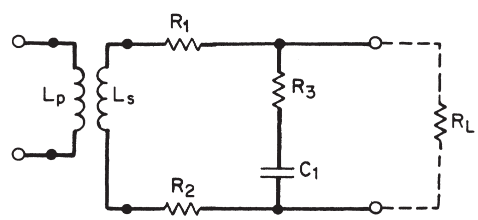


Figure 6.2 Circuit configuration composed of several elements and branches, and a closed loop (R_1, R, C_1, R_2, and L_s).

A circuit, consisting of a number of elements or components, usually amplifies or otherwise modifies a signal before delivering it to a load. The terminal to which a signal is applied is an *input port*, or *driving port*. The pair or group of terminals that delivers a signal to a load is the *output port*. An element or portion of a circuit between two terminals is a *branch*. The circuit shown in Figure 6.2 is made up of several elements and branches. R_1 is a branch, and R_1 and C_1 make up a two-element branch. The secondary of transformer T, a voltage source, and R_2 also constitute a branch. The point at which three or more branches join together is a *node*. A series connection of elements or branches, called a *path*, in which the end is connected back to the start is a *closed loop*.

6.2 Circuit Analysis

Relatively complex configurations of *linear circuit elements*, that is, where the signal gain or loss is constant over the signal amplitude range, can be analyzed by simplification into the equivalent circuits. After the restructuring of a circuit into an equivalent form, the current and voltage characteristics at various nodes can be calculated

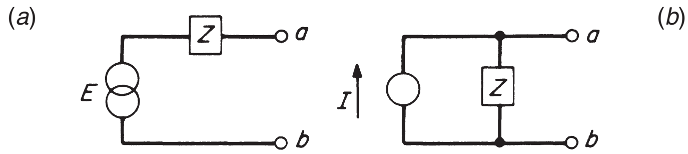


Figure 6.3 Equivalent circuits: (*a*) Thevenin's equivalent voltage source, (*b*) Norton's equivalent current source. (*After* [1].)

using network-analysis theorems, including Kirchoff's current and voltage laws, Thevenin's theorem, and Norton's theorem.

- **Kirchoff's current law (KCL).** The algebraic sum of the instantaneous currents entering a node (a common terminal of three or more branches) is zero. In other words, the currents from two branches entering a node add algebraically to the current leaving the node in a third branch.
- **Kirchoff's voltage law (KVL).** The algebraic sum of instantaneous voltages around a closed loop is zero.
- **Thevenin's theorem.** The behavior of a circuit at its terminals can be simulated by replacement with a voltage E from a dc source in series with an impedance Z (see Figure 6.3*a*).
- **Norton's theorem.** The behavior of a circuit at its terminals can be simulated by replacement with a dc source I in parallel with an impedance Z (see Figure 6.3*b*).

6.2.1 AC Circuits

Vectors are used commonly in ac circuit analysis to represent voltage or current values. Rather than using waveforms to show phase relationships, it is accepted practice to use vector representations (sometimes called *phasor diagrams*). To begin a vector diagram, a horizontal line is drawn, its left end being the *reference point*. Rotation in a counterclockwise direction from the reference point is considered to be positive. Vectors may be used to compare voltage drops across the components of a circuit containing resistance, inductance, and/or capacitance. Figure 6.4 shows the vector relationship in a series RLC circuit, and Figure 6.5 shows a parallel RLC circuit.

Power Relationship in AC Circuits

In a dc circuit, power is equal to the product of voltage and current. This formula also is true for purely resistive ac circuits. However, when a reactance—either inductive or capacitive—is present in an ac circuit, the dc power formula does not apply. The product of voltage and current is, instead, expressed in volt-amperes (VA) or kilovoltamperes (kVA). This product is known as the *apparent power.* When meters

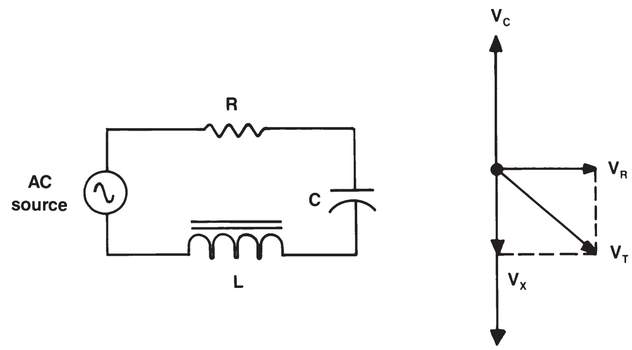


Figure 6.4 Voltage vectors in a series RLC circuit.

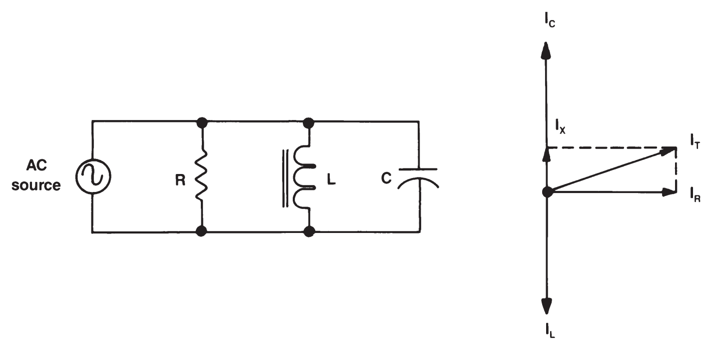


Figure 6.5 Current vectors in a parallel RLC circuit.

are used to measure power in an ac circuit, the apparent power is the voltage reading multiplied by the current reading. The *actual power* that is converted to another form of energy by the circuit is measured with a wattmeter, and is referred to as the *true power*. In ac power-system design and operation, it is desirable to know the ratio of true power converted in a given circuit to the apparent power of the circuit. This ratio is referred to as the *power factor*.

6.2.2 Complex Numbers

A complex number is represented by a *real part* and an *imaginary part*. For example, in $A = a + jb$, A is the complex number; a is the real part, sometimes written as $\mathrm{Re}(A)$; and b is the imaginary part of A, often written as $\mathrm{Im}(A)$. It is a convention to precede the imaginary component by the letter j (or i). This form of writing the real and imaginary components is called the *Cartesian form* and symbolizes the complex (or s) plane, wherein both the real and imaginary components can be indicated graphically

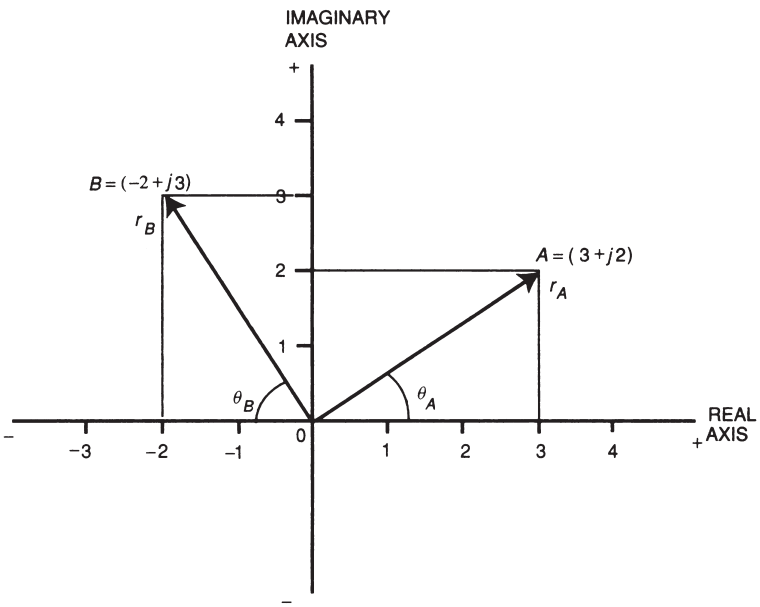


Figure 6.6 The *s* plane representing two complex numbers. (*From* [2]. *Used with permission.*)

[2]. To illustrate this, consider the same complex number A when represented graphically as shown in Figure 6.6. A second complex number B is also shown to illustrate the fact that the real and imaginary components can take on both positive and negative values. Figure 6.6 also shows an alternate form of representing complex numbers. When a complex number is represented by its magnitude and angle, for example, $A = r_A\angle\theta_A$, it is called the *polar representation*.

To see the relationship between the Cartesian and the polar forms, the following equations can be used:

$$r_A = \sqrt{a^2 + b^2} \tag{6.3}$$

$$\theta_A = \tan^{-1}\frac{b}{a} \tag{6.4}$$

Conceptually, a better perspective can be obtained by investigating the triangle shown in Figure 6.7, and considering the trigonometric relationships. From this figure, it can be seen that

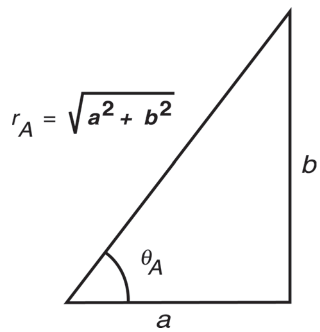


Figure 6.7 The relationship between Cartesian and polar forms. (*From* [2]. *Used with permission.*)

$$a = \mathrm{Re}(A) = r_A \cos(\theta_A) \tag{6.5}$$

$$b = \mathrm{Im}(A) = r_A \sin(\theta_A) \tag{6.6}$$

The well-known *Euler's identity* is a convenient conversion of the polar and Cartesian forms into an *exponential form*, given by

$$\exp(j\theta) = \cos\theta + j\sin\theta \tag{6.7}$$

6.2.3 Phasors

The ac voltages and currents appearing in distribution systems can be represented by *phasors*, a concept useful in obtaining analytical solutions to one-phase and three-phase system design. A phasor is generally defined as a transform of sinusoidal functions from the time domain into the complex-number domain and given by the expression

$$\mathbf{V} = V\exp(j\theta) = P\{V\cos(\omega t + \theta)\} = V\angle\theta \tag{6.8}$$

where $\boldsymbol{V}$ is the phasor, V is the magnitude of the phasor, and θ is the angle of the phasor. The convention used here is to use boldface symbols to symbolize phasor quantities. Graphically, in the time domain, the phasor $\boldsymbol{V}$ would be a simple sinusoidal wave shape as shown in Figure 6.8. The concept of a phasor leading or lagging another phasor becomes very apparent from the figure.

Phasor diagrams are also an effective medium for understanding the relationships between phasors. Figure 6.9 shows a phasor diagram for the phasors represented in Figure 6.8. In this diagram, the convention of positive angles being read counterclockwise is used. The other alternative is certainly possible as well. It is quite apparent that a purely capacitive load could result in the phasors shown in Figures 6.8 and 6.9.

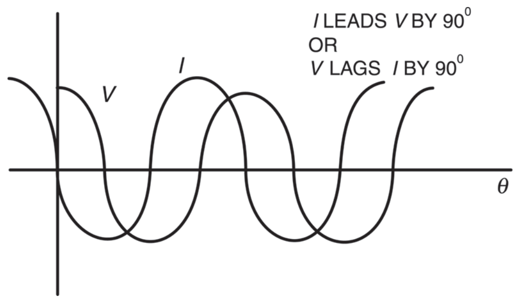


Figure 6.8 Waveforms representing leading and lagging phasors. (*From* [2]. *Used with permission*.)

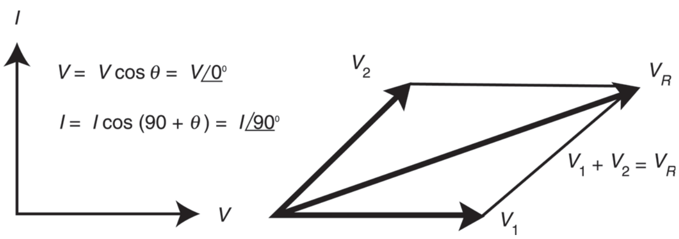


Figure 6.9 Phasor diagram showing phasor representation and phasor operation. (*From* [2]. *Used with permission*.)

6.2.4 Per Unit System

In the *per unit system*, basic quantities such as voltage and current are represented as certain percentages of base quantities. When so expressed, these per unit quantities do not need units, thereby making numerical analysis in power systems somewhat easier to handle. Four quantities encompass all variables required to solve a power system problem. These quantities are

- Voltage
- Current
- Power
- Impedance

Out of these, only two base quantities, corresponding to voltage (V_b) and power (S_b), are required to be defined. The other base quantities can be derived from these two. Consider the following. Let

V_b = voltage base, kV
S_b = power base, MVA
I_b = current base, A
Z_b = impedance base, Q

Then,

$$Z_b = \frac{V_b^2}{S_b} \ \Omega \tag{6.9}$$

$$I_b = \frac{V_b 10^3}{Z_b} \ \text{A} \tag{6.10}$$

6.2.5 Principles of Resonance

All RF systems rely on the principles of resonance for operation. Three basic systems exist:

- Series resonance circuits
- Parallel resonance circuits
- Cavity resonators

Series Resonant Circuits

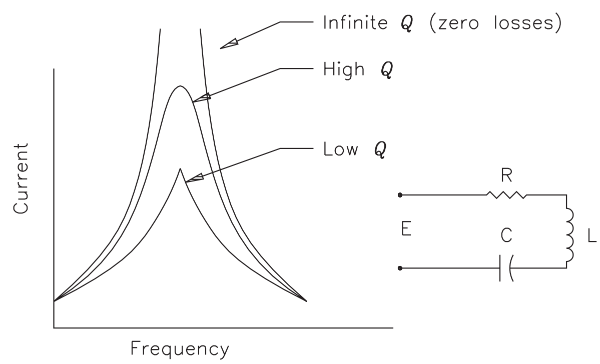
When a constant voltage of varying frequency is applied to a circuit consisting of an inductance, capacitance, and resistance (all in series), the current that flows depends upon frequency in the manner shown in Figure 6.10. At low frequencies, the capacitive reactance of the circuit is large and the inductive reactance is small, so that most of the voltage drop is across the capacitor, while the current is small and leads the applied voltage by nearly 90°. At high frequencies, the inductive reactance is large and the capacitive reactance is low, resulting in a small current that lags nearly 90° behind the applied voltage; most of the voltage drop is across the inductance. Between these two extremes is the *resonant frequency*, at which the capacitive and inductive reactances are equal and, consequently, neutralize each other, leaving only the resistance of the circuit to oppose the flow of current. The current at this resonant frequency is, accordingly, equal to the applied voltage divided by the circuit resistance, and it is very large if the resistance is low.

The characteristics of a series resonant circuit depend primarily upon the ratio of inductive reactance ωL to circuit resistance R, known as the circuit Q:

$$Q = \frac{\omega L}{R} \tag{6.11}$$

The circuit Q also may be defined by:

(*a*)



(*b*)

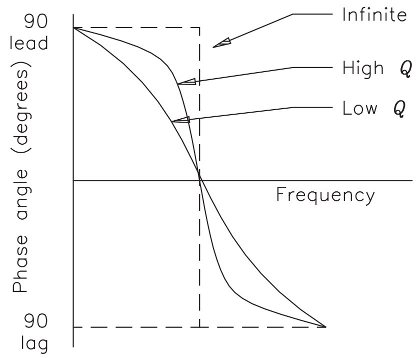


Figure 6.10 Characteristics of a series resonant circuit as a function of frequency for a constant applied voltage and different circuit *Q*s: (*a*) magnitude, (*b*) phase angle.

$$Q = 2\pi \left(\frac{E_s}{E_d} \right) \qquad (6.12)$$

Where:
E_s = energy stored in the circuit
E_d = energy dissipated in the circuit during one cycle

Most of the loss in a resonant circuit is the result of coil resistance; the losses in a properly constructed capacitor are usually small in comparison with those of the coil.

The general effect of different circuit resistances (different values of Q) is shown in Figure 6.10. As illustrated, when the frequency differs appreciably from the resonant frequency, the actual current is practically independent of circuit resistance and is nearly the current that would be obtained with no losses. On the other hand, the current at the resonant frequency is determined solely by the resistance. The effect of increasing the resistance of a series circuit is, accordingly, to flatten the resonance curve by re-

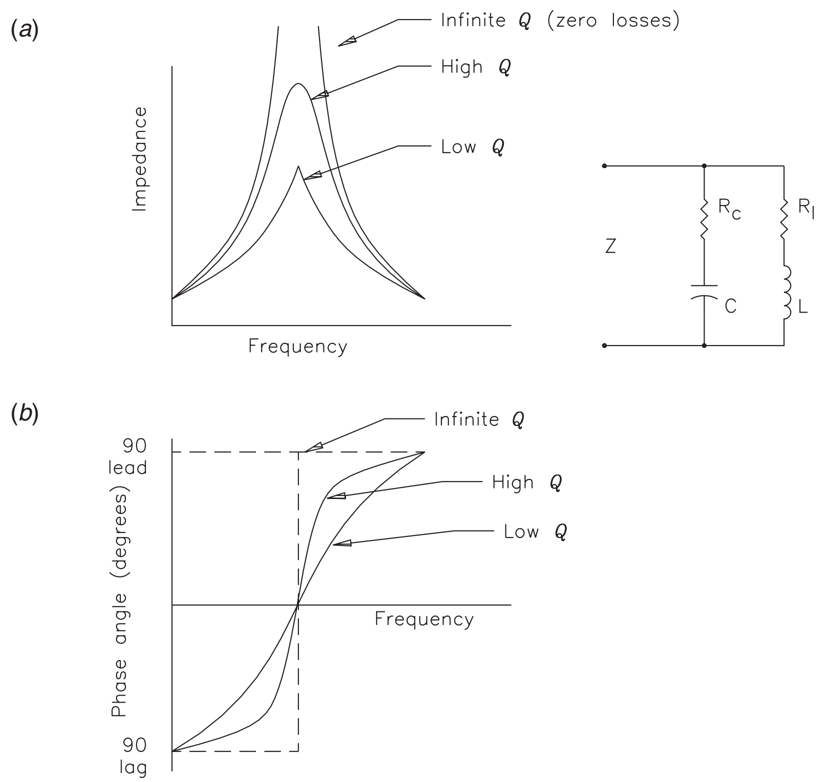


Figure 6.11 Characteristics of a parallel resonant circuit as a function of frequency for different circuit *Q*s: (*a*) magnitude, (*b*) phase angle.

ducing the current at resonance. This broadens the top of the curve, giving a more uniform current over a band of frequencies near the resonant point. This broadening is achieved, however, by reducing the selectivity of the tuned circuit.

Parallel Resonant Circuits

A parallel circuit consisting of an inductance branch in parallel with a capacitance branch offers an impedance of the character shown in Figure 6.11. At low frequencies, the inductive branch draws a large lagging current while the leading current of the capacitive branch is small, resulting in a large lagging line current and a low lagging circuit impedance. At high frequencies, the inductance has a high reactance compared with the capacitance, resulting in a large leading line current and a corresponding low circuit impedance that is leading in phase. Between these two extremes is a frequency at which the lagging current taken by the inductive branch and the leading current entering the capacitive branch are equal. Being 180° out of phase, they neutralize, leaving only a small resultant in-phase current flowing in the line; the impedance of the parallel circuit is, therefore, high.

The effect of circuit resistance on the impedance of the parallel circuit is similar to the influence that resistance has on the current flowing in a series resonant circuit, as is evident when Figures 6.10 and 6.11 are compared. Increasing the resistance of a parallel circuit lowers and flattens the peak of the impedance curve without appreciably altering the sides, which are relatively independent of the circuit resistance.

The resonant frequency F_0 of a parallel circuit can be taken as the same frequency at which the same circuit is in series resonance:

$$F_0 = \frac{1}{2\pi\sqrt{LC}} \tag{6.13}$$

Where:
L = inductance in the circuit
C = capacitance in the circuit

When the circuit Q is large, the frequencies corresponding to the maximum impedance of the circuit and to unity power factor of this impedance coincide, for all practical purposes, with the resonant frequency defined in this way. When the circuit Q is low, however, this rule does not necessarily apply.

6.3 Passive/Active Circuit Components

A voltage applied to a passive component results in the flow of current and the dissipation or storage of energy. Typical passive components are resistors, coils or inductors, and capacitors. For an example, the flow of current in a resistor results in radiation of heat; from a light bulb, the radiation of light as well as heat.

On the other hand, an active component either (1) increases the level of electric energy or (2) provides available electric energy as a voltage. As an example of (1), an amplifier produces an increase in energy as a higher voltage or power level, while for (2), batteries and generators serve as energy sources.

Active components can generate more alternating signal power into an output load resistance than the power absorbed at the input at the same frequency. Active components are the major building blocks in system assemblies such as amplifiers and oscillators.

6.4 References

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