Basic Electricity #6

Ron C. Johnson

I said last month we were going to talk about magnetics this time. And possibly you are all wondering why would we want to know about it for basic electricity. As my students often tell me, they wonder even more after they have wallowed around in this stuff for a while. It's true: magnetism and electromagnetism is a "cat's breakfast" of new terms, formulae and relationships (most of them non-linear) which can be confusing. On the other hand, an understanding of this area is not only useful, but necessary to make sense out of stuff like: inductors, relays, motors, tape recorders... The list goes on.

So we are going to take a run at it on a non-mathematical basis. And if the new terms start to come at you too fast and furious just kick back and imagine yourself listening to one of those foreign language instructional tapes with surf in the background. If it puts you to sleep I want to know.

Maybe I'll market it...

THE MAGNETIC FIELD

To start with we are not going to try to explain what magnetism is in its most fundamental form. Call it one of those mysteries of the universe that only Phd's and people confined to institutions truly understand. For our purposes we want to know the *how* more than the *why*.

All of us are familiar with those strange new life-forms which appear out of nowhere and then multiply on the doors of our refrigerators. Yes, the fridge magnet beings have insinuated themselves into the very fabric of our homes, attaching themselves to our appliances under the guise of grocery list holders, real estate advertisements and kindergarten crafts...What? Ah, yes... the magnetic field. Back to business.

As I said, we are all familiar with magnetism from its various household uses and no doubt we have all played with magnets enough to have a first-hand knowledge of how they are attracted to objects with iron in them. We have also seen how bringing two magnets together will cause either attraction or repulsion depending on how they are oriented with respect of each other. Figure 1 shows a bar magnet with a set of lines (with arrows) extending out of one end and re-entering the other end. These lines are called lines of flux. You will notice that the lines of flux exit the end labelled N (for North) and re-enter the end labelled S (for South). The reason the ends, or poles, of the magnet are labelled North and South is that if the magnet were suspended freely the end labelled N would orient itself toward the magnetic North Pole of the earth (like a compass). The same force that causes this is the force that causes the attraction or repulsion between two magnets. When a North and a South pole are brought together they attract; when two North's or two South's are brought together they repel.

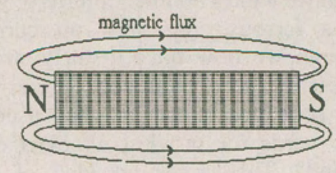

Figure 1. A permanent magnet

Yes, I know that this is nothing new to most of you but the basics bear repeating before we launch into the other good stuff. And there really is an application here: The magnets we are used to seeing are natural or synthetic magnets which are relatively weak. Also, we don't have much control over them other than moving them physically closer or farther away from an object. But if we could control those lines of flux (and the magnetic force that they produce) with electricity, we would be able to build a number of useful things such as: meter movements, relays, breakers, solenoids, motors, etc. (Love that word, "etc." It covers a whole range of things I can't remember.)

Okay, let's look at Electromagnetism. First a history lesson: In 1820, the Danish physicist Hans Christian Oersted discovered (history always starts out the same way, doesn't it?) that the needle of a compass would deflect if brought near a current-carrying conductor. This proved that electricity and magnetism are related. Actually, what

Hans proved was that a magnetic field always occurs in conjunction with current flow. The magnetic flux (same as the lines around a magnet) form concentric rings around the conductor and we can predict the direction of the lines (remember the arrows on the bar magnet lines of flux) by using the "good ol' basic" Right Hand Rule.

The Right Hand Rule is simple. If you were to imagine yourself holding a current carrying conductor in your right hand with your thumb pointing in the direction of conventional current flow (opposite of electron flow, remember), the rest of your fingers point in the direction of the lines of flux as they

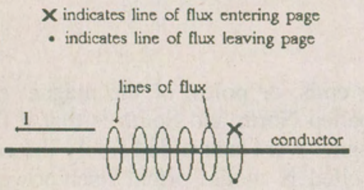

Figure 2a. Right Hand Rule

curve around the conductor. (See Figure 2a)

So that means that any conductor with current flowing through it will produce a magnetic field.

Is that important?

Actually, the strength of the field is small in most cases but there is a way of putting that field to use and making it more powerful. Take a look at Figure 2b. At this point we have to start imagining what is happening in three dimensions. Let's use the convention that an 'x' indicates a line of flux entering the page from above. A dot, '.' indicates a line of flux exiting the page.

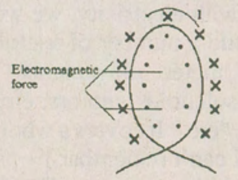

Figure 2b. Right Hand Rule applied to a current carrying loop.

Figure 2b shows a loop of wire with current flowing through it. If we use the Right Hand Rule to determine the direction of the lines of flux and try to visualize it in three dimensions we will find that the lines from one side of the loop point in the same direction as the lines from the other side of the loop. This causes the lines of flux to be concentrated in the middle of the loop. If we were to add several more loops all the lines would reinforce each other increasing the strength of the magnetic field.

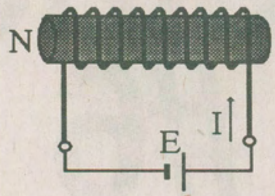

Figure 3. An electromagnet

That's what we have done in Figure 3. Not only have we used several turns of current carrying wire (supplied by the battery), but we have added a "core". The core is a ferrous material which concentrates the lines of flux. This increases what we call the "flux density" because there are more lines of flux in a smaller space. Up to a certain point increasing the flux density increases the "field strength" of the electromagnet, in other words making it a stronger magnet.

Some Applications

Before we get into the nitty-gritty of all this let's look at what it means in practical terms. As I said before, a single conductor with current flowing which creates a magnetic field around it doesn't accomplish much for us. But when we wind a number of turns of wire on a ferrous core and run current through we now have a fairly strong magnetic force produced. Have you ever seen those electromagnets used in junk yards for moving wrecked cars around? That gives an idea of the amount of force that can be produced with an electromagnet. But we have lots of good examples closer to home.

Electric door latches used for security locks in apartment buildings are electromagnets. Normally a spring latching mechanism keeps the latch locked but when the button is pushed in the apartment current flows through the coil of an electromagnet in the latch pulling back a metal bolt which allows the door to be opened. For those of you who have experimented with relays the application is similar: The electromagnet, when energized, pulls in a metal linkage that forces the contacts together (or apart in some cases) positioning the relay contacts in the energized condition. (When you hear the term "normal" as in "normally open contacts" or "normally closed contacts" this means that the relay coil is not energized and the contacts are either open or closed when the relay is at rest.)

Another application for electromagnets is solenoid valves. They are used in common household appliances like your dishwasher to control the water. A valve is controlled by an electromagnet moving a ferrous plunger in or out. Reluctance is symbolized by R and is usually expressed in "per Henrys". (In other words the reciprocal of Henrys)

Keep in mind that I warned you! And it gets worse. Take a deep breath...

So permeance and reluctance are reciprocals. Believe it or not, so are permeability and reluctivity, but don't worry, we don't use these much. If you are interested, reluctivity is the magnetic equivalent to resistivity (in electricity) that we talked about way back when in the first article of this series. Resistivity, we said, was the characteristic of a material that determined how well it conducted electricity, and hence, determined the resistance of a particular shape and size of the material. Well, reluctivity is the characteristic of a material which determines how well it sets up lines of flux and hence, the reluctance or a given piece of that material. In this case we most often use permeability, the reciprocal of reluctivity, which is symbolized, %, and has the units, Henry/metre.

Now that we have looked at flux and reluctance we can backtrack and look at how they relate to magnetomotive force. We know about Ohm's Law from electricity; here is its equivalent in magnetics: Ampere's Circuital Law.

Ampere's Circuital Law says that magnetomotive force equals the magnetic flux, (-), times the reluctance of the material, (R) or:

F = - x R

This operates in the same way as Ohm's Law. For various materials in a magnetic field reluctance is symbolized by R and is usually expressed in "per Henrys". (In other words the reciprocal of Henrys)

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This operates in the same way as Ohm's Law. For various materials in a magnetic circuit (which have different reluctances), the amount of flux present in that section times the reluctance will give the magnetomotive force developed across that section. The same relationships we talked about with respect to Kirchhoff's Voltage Law around a loop apply around a magnetic loop and series and parallel principles apply in the same way. (Figure 4)

Not that it matters...

Actually, you won't find hobbyists, technicians, technologists or even very many engineers use this stuff quantitatively in practical applications. Designing transformers or other special magnetic equipment would require it, but usually we just buy that kind of thing with ready-made specifications available. Even so, the concepts are interesting and help to understand what is going on. In fact, as we continue, we'll see how they help us understand some very practical applications.

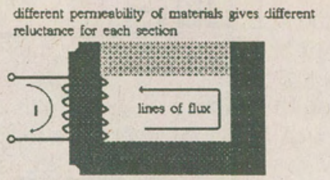


Figure 4. A Magnetic circuit

Coffee's over. Back to work.

Magnetic Field Strength

We all know that when we move a magnet closer to a ferrous object the pull is greater than when it is farther away. How strong the force of that "pull" is can be expressed as magnetic field strength (or intensity) and is symbolized, H, with units, Oersteds. (Well, they had to name *something* after the guy.) It is determined by the magnetomotive force, (F) divided by the distance, (l).

H = F/l

Another important variable in magnetics is called magnetic field density or flux density, (B), given in Teslas. (Some other guy who, incidently, also liked to play with high voltage.) Basically, flux density is the number of magnetic lines of force per unit area, (A). (If you go back and sort through some of the previous stuff, you would find that the number of lines of flux is determined by the magnetomotive force and the reluctance of the material.) So the formula is:

B = -/A

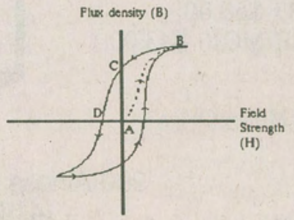


Figure 5. A hysteresis loop

Okay! Believe it or not, we're going to tie this all together now.

Figure 5 shows a graph called a Hysteresis Loop where the vertical axis is labelled B for flux density and the horizontal axis is labelled H for field strength. An interesting thing happens when you use an electromagnet to magnetize a ferromagnetic material: To begin with, before any current flows through the coil, there is no magnetic field strength present and so no flux density (Point A). As current is applied field strength is created by the electromagnetic field set up and this causes a certain flux density to be present in the ferromagnetic material (this material could be the core of the electromagnet or adjacent but within the field). As the field strength (H) is increased eventually the flux density levels off and even though H is increased B will stay the same. (Point B) This is called flux saturation.

Now let's start to reduce the current through the coil (and hence the field intensity). The arrows in Figure 5 show that the flux density does not follow the same path back to zero. In fact, when the field strength is zero B is still quite high. (Point C). Why would this be?

Of course, you have magnetized the material and even though there is no electromagnetic force acting on it, it still retains some flux at the density shown. If we were to reverse the polarity of the current through the coil and force the field intensity to be set up in the opposite direction eventually we could bring the flux density down to zero. (Point D). Continuing on, we could eventually reach a saturated point in the other direction.

What's it all about?

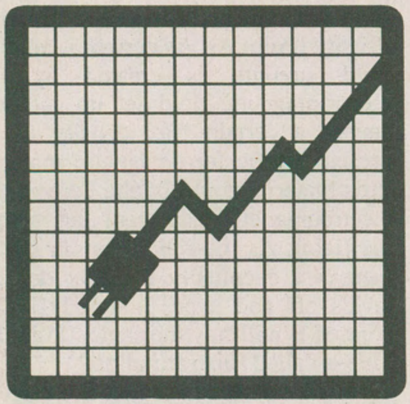
We've just invented core memory! We'll be rich! All we have to do is...

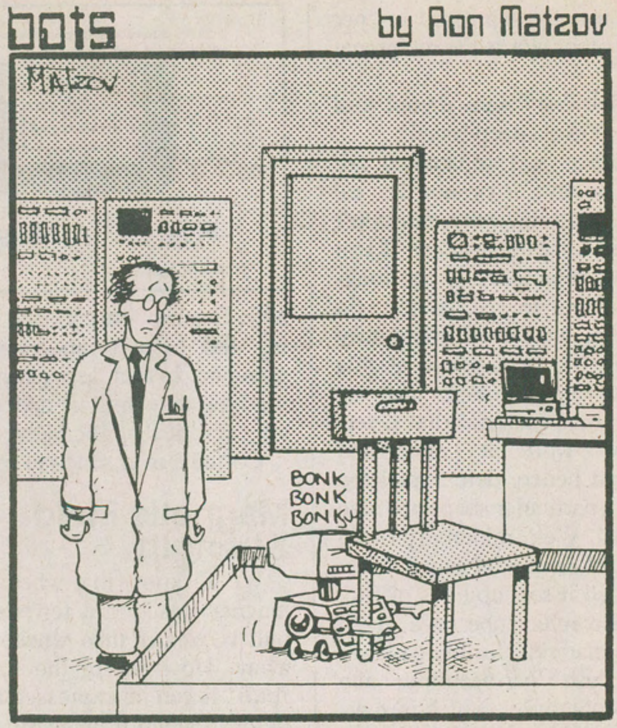
That's what core memory was about: thousands of tiny ferrous toroids with coils through them which would magnetize them in one direction when a pulse of current was supplied. After the power was removed they retained their magnetism. Non-volatile memory. (As long as nobody got silly with a magnet in the vicinity.)

And that's magnetism. Sort of. It actually gets pretty complex when we look at how electromagnetism is used to create electric motors because not only do we have to consider three dimensional vectors but alternating voltages, currents and phase angles come into it as well.

Maybe we'll look at it in another article.

Meanwhile, hopefully this will help you understand the basic concepts without losing you in the jungle of terms. Next time we look at inductors... ❒





Although equipped with the X-700 microprocessor unit and 500 megabytes RAM, the robot still could not understand the concept of going around furniture.

Basic Electricity #7

Ron C. Johnson

Hello, again, and welcome to that game show that has something for everyone! Yes, you guessed it folks, Basic Electricity: Name that Theory. Please welcome my lovely assistant and technician extraordinaire.... Here she comes, folks, Suzy Psi... Thank you very much! My name is Newton Force and I'll be your host today... Thank you, thank you. And now for our first two contestants... Let's hear it for Michael Faraday and Heinrich Lenz.....

Remember the last segment and the good ol' Right Hand Rule? Well, we haven't heard the last of it. This time we'll be continuing with some of the principles we learned in electromagnetics and go on to RLC circuits. We talked about some of the physics and math concerned with producing a magnetic field from an electric current and how the magnetic field behaves in a magnetic circuit. To start, we'll check out the inductor, its principle of operation, physical construction and applications.

The inductor is one of the three main passive electronic components. Way back when, we learned about resistance, how it is based on the conductive properties and geometry of a material. Later, we talked about capacitors, which are based on the principle of electrostatics: charges and their electric fields. The third, as mentioned, is inductors which operate using the principles of electromagnetism and its application.

Faraday's Law of Electromagnetic Induction

The Right Hand Rule we talked about last time stated that if conventional current flow in a conductor flowed the direction of your right thumb the rest of your fingers would point in the direction of the magnetic lines of flux present around the wire. We used that to show how winding the conductor around a core produced a higher level of magnetic flux, because all the lines pointed the same way through the core. Now we'll consider the Right Hand Rule again in a slightly different perspective.

If you have a permanent magnetic field with a conductor which is physically moving through it, you will produce a current in that conductor. (That's not a new development. Michael Faraday proved that way back when, even before the first MASH rerun. 1831 to be exact). The Right Hand Rule says that, with your hand oriented with the palm up and index finger extended, if your thumb points in the direction of motion of the conductor, your index finger indicates the direction of conventional current flow and the other fingers (curved around) indicate the direction of lines of flux present.

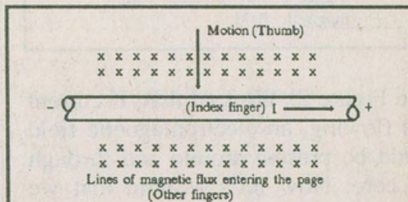


Figure 1. The Right Hand Rule and Faraday's Law

Sounds weird, but try it while looking at Figure 1 and it works. (As in the last article the X's indicate lines of magnetic flux which are entering the page. This convention allows us to visualize in three dimensions.)

But what does it mean?

One application, to start with, is generator action. If we build a mechanism with a strong fixed magnet and then spin a coil of wire in the electric field we will produce current. That's what happens, in its most fundamental sense, in the generator or alternator in your car. And there are other applications, like in inductors, but we have to check out Lenz's Law to see how they operate.

Lenz' Law

If moving the conductor through the lines of flux of a magnetic field creates current, how about keeping the conductor fixed and moving the magnetic field? Okay, would we actually have to move the field physically, or could we just change its intensity? You got it. The induced current is directly proportional to the rate of change of the magnetic field so all we have to do is change its intensity.

Now let's look again at the coil we talked about last time w here we wrapped the conductor around some kind of core (usually ferrous material).

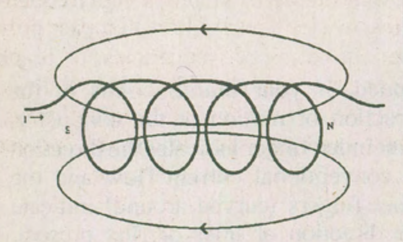


Figure 2. An Inductor with magnetic field

(See Figure 2) We said that, if current was flowing, an electromagnetic field would be present around and through the core. Now let's assume that we reduce the current flowing through the coil. Reducing the current should reduce the level of the magnetic field. According to Faraday's Law, that change in the magnetic field should induce a current into the coil. Sometimes we think of this in terms of a voltage, and actually, because it opposes the change, we call it counter emf (electromotive force). So it happens that, because the magnetic field is collapsing, the direction of the change in the magnetic field produces a counter emf which induces a current in the same direction as the original current flow. This tends to keep the current flowing at the original rate even though we have attempted to reduce it. Of course, we aren't getting something for nothing; the energy which had been stored in the form of the electromagnetic field is just being converted back to electrical energy (generator action). The current changes with time towards the new level and the field eventually stabilizes as the current settles out at the lower rate.

The important thing is that this takes time. Thinking back to capacitors, you might remember that the *voltage* across a capacitor cannot change instantaneously; it takes time for it to charge up to the final voltage. Inductors are the same, only different; the *current* through an inductor cannot change instantaneously. It takes time for the magnetic field to stabilize as it either stores or releases energy to or from the magnetic field. Take a look at Figure 3 and you'll see a graph that is similar to the charge curve of a capacitor. In the case of an inductor, the exponential curve

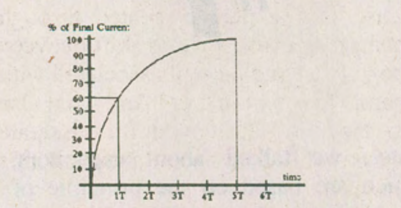


Figure 3A. An RL time constant curve

represents the current changing with time. Figure 3A shows the curve for

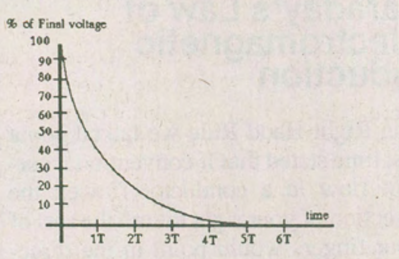


Figure 3B. An RL time constant curve for voltage

increasing current while Figure 3B shows the curve for decreasing current.

The Component

So this ability of a component to oppose a change in current is called self-inductance, or more commonly, just inductance and the component which achieves this is an inductor. Inductors are coils of wire wound on ferrous cores and come in a wide range of sizes, both physical and in terms of their specifications. The formula symbol for inductance is L, and the unit symbol is H, for Henry. Inductors usually come in values ranging from a few microHenrys to several Henrys.

The value of the inductor is determined by the number of turns on the core, the cross-sectional area of the core, the permeability of the core material and the length of the core.

Well, there you have it: a quick look at inductance from the point of view of DC and its transient characteristics. We're going to backtrack a little, now, and try to pull together several topics we've talked about in this series. So I hope all you contestants at home are ready on your buzzers 'cause for 20,000 points and a chance at the bonus round....

How do capacitors and inductors operate with respect of alternating voltages and currents?

I hope you have been following this series since the beginning because back in segment four we introduced the area of alternating voltage and current, what it looks like, its characteristics and the concept of phase differences. This is very important when we talk about inductance and capacitance. In addition, there are a few new terms and concepts we'll talk about here.

Let me start by asking a question: From what we know so far do inductors and capacitors dissipate power (I X V) in the same way that resistors do? The answer is no. We have learned that capacitors and inductors only store energy " in an electrostatic field and electromagnetic field respectively. When required, that energy can be sourced back out of the component and used. (It is true that both these devices have some resistive component to them and as such do have some power loss, but it is insignificant for this consideration.)

Eli The Ice Man

Next, let's consider the action of these devices in an AC circuit. We know that the voltage across a capacitor will not change instantaneously. What about the current through it? With DC when you try to change the voltage across a capacitor, current flows immediately into the cap charging it up at the rate of the current. So we can say the in a capacitor the current leads (changes before) the voltage, or, I leads E in a capacitor.

We also know that the current through an inductor cannot change instantaneously. This means that the voltage may change before the current, or, E leads I in an inductor. We remember these by the simple mnemonic: ELI the

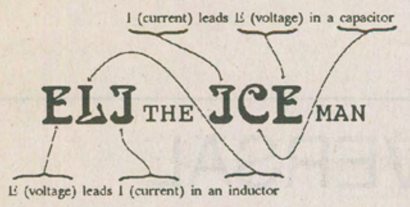


Figure 4. ELI the ICE man

ICE man. (See Figure 4.)

Figures 5 and 6 show the phase relationships between the voltage and

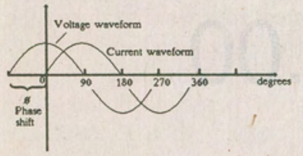


Figure 5. Voltage leads Current by 90 degrees in an inductor

current in inductors and capacitors respectively. The amount of phase shift through the device is always 90° but, using the current waveform as the reference (starting at zero), the inductor's voltage crosses at 90° before the reference whereas the capacitor voltage crosses at 90° after the reference. When the phase shift is to the left of the reference (leading) we give it a positive value, (+90°). When the phase shift is to the right, (lagging), we give it a negative value, (-90°).

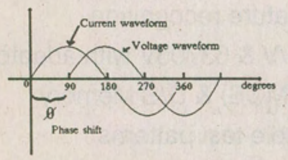


Figure 6. Current leads Voltage by 90 degrees in a capacitor

We can also show these relationships on a phasor diagram, (Figure 8), and we'll be looking at this a little more, shortly. For now, just note that the zero axis for the diagram is the one marked sine. This is the reference. Ninety degrees counter-clockwise we have the cosine or inductive axis, where we can

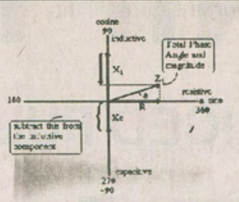


Figure 8. A phasor diagram showing the resultant total impedance

display the inductive component. Ninety degrees clockwise from the reference is the capacitive axis. This is also labelled -90°.

So now we know that inductors and capacitors store energy and that, because of the delays created through them, they cause a phase shift between the voltage and current associated with them. Does that matter? And what else do they do? If they don't dissipate power, why do we care about all this phase shift stuff?

Reactance

Okay. Even though they do not dissipate power, both inductors and capacitors do affect the current flow of the circuit they are in. Moreover, in AC circuits, they affect the current flow differently depending on the frequency of the AC supply voltage or current. We said that these components were mainly used for timing applications in DC. In AC we make use of the fact that capacitors and inductors are frequency dependant components.

We know that resistors have the same value of resistance regardless of the frequency of the current through them. In the case of capacitors and inductors we use the term reactance. Reactance is the property which opposes the flow of AC current through capacitors or inductors. It is similar to resistance in that it is measured in ohms but it is dependant

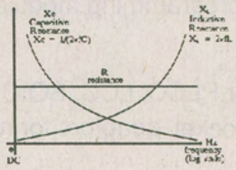


Figure 9. Frequency Vs R, X_L, and X_C

on frequency. Figure 9 shows a graph of resistance, capacitive reactance and inductive reactance versus frequency. It also gives the formulae used to determine the values of X_C and X_L. It is important to note that while the relationship between frequency and reactance is a linear one, it appears nonlinear on the graph because we normally use logarithmic scales to show frequency in order to condense the range. (There are other reasons, as well, but I'll have mercy.) So capacitive reactance starts at a very high value at low frequencies and decreases as frequency increases. Inductive reactance is the opposite: low at DC and high at high frequencies.

What is the application? By the judicious use of combinations of caps and inductors we can build circuits that are frequency dependant: filters that pass low frequencies but block high frequencies, or vice versa; filters that pass only certain bands of frequencies, or block only certain bands... This list is endless. We use them in TV and radio circuits, tone controls and equalizers, power supply filters, noise filters, etc.

The RLC Circuit

We've talked about phase shifts through individual components and the reactances and resistances of individual devices. Now, we'll try to pull some of this together to finish things off.

If the phase shift across an inductor is +90° and it has some value of reactance, and you put this in series with a capacitor, with a -90° phase shift and some reactance, what is the result? And what happens if we add a resistor in series as well? And what if we change the frequency of the AC power supply?

Figure 7 shows a circuit like that: a

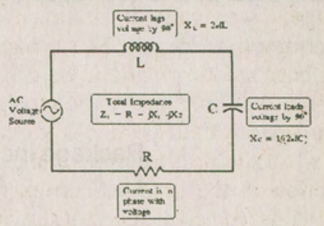


Figure 7. A Series RLC circuit

series RLC circuit. We would like to be able to determine the AC current in this circuit (given an AC supply voltage), but how? If all the components were resistors we would just add them up and use Ohm's Law. In this case it becomes quite a bit more complicated. Instead of total resistance, we have to use total

See **Basic**, *Cont'd. on page 34*

Basic, *Cont'd. from page 19*

impedance. Impedance is the total of all resistances and reactances in the circuit. Unfortunately we can't just add them together algebraically because the reactances have those pesky phase shifts attached to them. If we were going to get into the math of all this, (which we won't), we would have to use vector algebra to find the impedance. (It's a lot of fun if you have a good scientific calculator and know your trigonometry... Hmm...Idea! All of you who really want to know the 'low-down' on vector algebra using polar and rectangular form, write letters to our editor pleading with him to have me write a tutorial on it. He's gonna love me for it.)

Where were we?

Ah, yes. Take a look at Figure 8 again. We can get an idea qualitatively, of how impedance is determined by seeing the vectors displayed and graphically combined. The phasor diagram shows the values of the reactances and resistance in the circuit in Figure 7. Because the capacitive and inductive components have opposing phase shifts we can vectorially add them to get a resultant, which in this case, is a net inductive or +90$ value. This, in turn, is combined with the resistive component to obtain a resultant vector which has a magnitude and angle (). This impedance, Z_T, then, can be used with Ohm's Law to determine the current in the circuit, but the phase angle must be taken into account. The quantity of the impedance divided into the AC supply voltage will give the magnitude of the current, and the phase angle, (when properly manipulated in polar form) will give the phase shift between the current and voltage.

Keep in mind that these calculations would be done at a given supply frequency and that for any other frequency the overall circuit impedance, and thus phase angle, would be different.

I've said all of that just to say that: being able to quantitatively predict what is happening in an AC circuit with reactive components is possible, using the required math, and necessary in certain circumstances. I have tried to stay away from the math and still touch on the basics of what goes on in RLC circuits. Of course, there is lots more we could cover but hopefully this will be useful from the broad perspective.

Next month we'll wrap up this series with a look at how resonant circuits work, as well as a general 'clean up' of miscellaneous loose ends on basic electricity. ❐