Bob's TechTalk #42
by Bob, AF6C

Inductors (Coils)

In previous TechTalk articles resistance and capacitance were discussed. This month we will begin discussion of the third common passive element, the inductor or coil. This component is at the heart of RF circuitry and is the complement to the capacitor.

While the capacitor stores energy in an electric field, the inductor stores energy in a magnetic field. The amount of energy a capacitor can store per volt is related to its capacitance which is measured in Farads. The amount of energy an inductor can store per ampere is related to its inductance which is measured in Henrys.

For the curious the two energy equations are shown in table 1.

Energy in a Capacitor:	Energy in an Inductor:
$U = \frac{1}{2} C V^2$	$U = \frac{1}{2} L I^2$
Eq. 1	Eq.2

Where:
U = Energy in Joules (Watt Seconds)
C = Capacitance in Farads
V = Voltage in Volts
L = Inductance in Henrys
I = Current in Amperes

Table 1

Inductance:

When an electric current is passed through a length of wire a magnetic field is created around the wire. The strength of the field is dependent on the current and can be detected by bringing a small compass near the wire. The creation of this magnetic field draws energy from the circuit. Should the current in the circuit increase, the magnetic field will become stronger as more energy is drawn from the circuit; likewise should the current decrease, the magnetic field will become weaker and energy will be given back to the circuit. In an ideal inductor the total energy taken and returned will be equal when the current returns to its initial point. This property of storing energy in a magnetic field is called inductance and can affect circuit behavior. At DC and low frequencies the inductance of a length of wire is minimal and has little effect on a circuit; however in mid-VHF and higher frequencies, the designer must take into consideration the inductance of straight wire. The creation of a magnetic field by passing current through a conductor is called **“self inductance”**

There are ways to increase the inductance of a piece of wire. Winding the wire in a coil shape is the most common way to substantially increase the inductance, and winding the coil around material with magnetic properties can strongly further increase the inductance. The inductance of a coil wound in air depends upon the number of turns, the diameter of the turns and the turns per inch. The wire size itself plays a lesser role. If a material other than air is used the inductance also depends upon the a magnetic property of the material called its **“permeability”**. The actual design of a coil is a topic in itself, which won’t be pursued in this article. Instead let’s see if we can get a grasp on how the magnetic field in a coil affects a circuit.

The voltage across an inductor is given by the equation:

$$V = L \frac{d(i)}{dt} \qquad \text{Eq. 3}$$

Don’t let the “d/dt” scare you; The d(i)/dt is just the rate at which the current “i” is changing. This equations says: ***The voltage across an inductor is equal to the coil’s inductance (in Henrys) times the rate at which the current through the coil is changing (in Amperes per second).*** Assuming a perfect inductor, the voltage across an inductor is zero if the current passing through it is constant. A perfect inductor is one that has no DC resistance and has no external leakage of the magnetic field. If the current is changing then a voltage appears across the inductor, and vise versa. The voltage created is higher when the current is changing rapidly and lower when changing slowly. Also the voltage polarity across an inductor depends upon whether the current is increasing or decreasing.

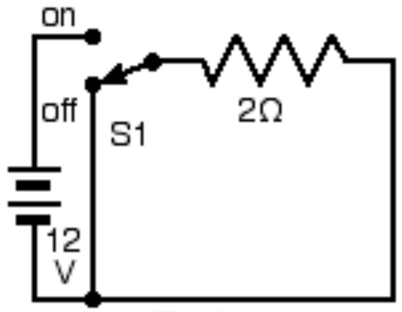

Fig. 1a

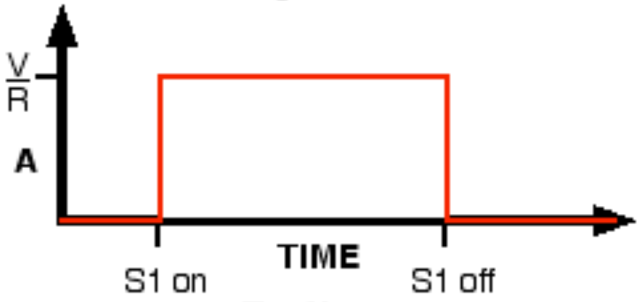

Fig. 1b

Inertia is a mechanical property that most are familiar with. If you push a car (on level ground) it's hard to get it moving, but once moving it tends to move easily and is hard to get it to stop. Inductance has a similar effect on current. ***The voltage created across an inductor is always in the direction that tends to resist the change in current.***

Look at Figure 1a. It is a simple circuit with a 12 volt battery, a switch and a 2 ohm resistor. When the switch is thrown to ON a current of 6 amperes immediately flows through the resistor. This current is equal to the voltage divided by the resistance or V/R as per Ohm's law. When the switch is thrown to off the current stops immediately. The current in relationship to the switch timing is shown in Figure 1b.

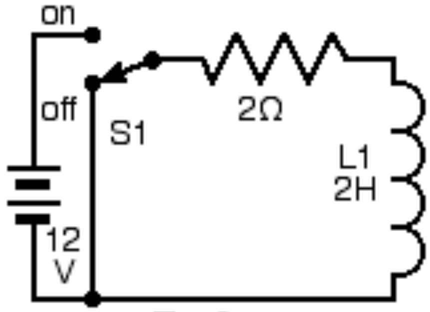

Fig. 2a

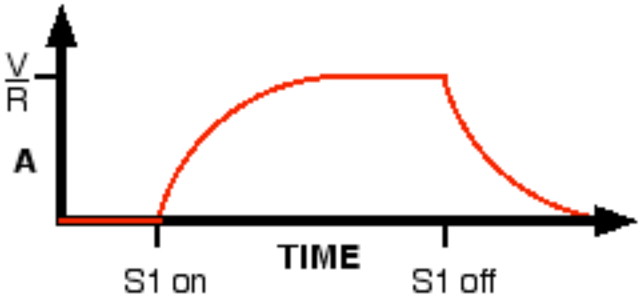

Fig. 2b

Figure 2a adds an inductor L1 in series with the resistor. At the moment the switch is thrown to ON there is no current flowing in the circuit and the full 12 volts appears across the inductor L1. If the inductor is 2 Henrys then the current starts changing from zero at an initial rate of 6 amps per second (from eq. 3). At the same time the inductor is storing energy in its magnetic field. As the current increases the voltage across the resistor increases per Ohm's law, and thus the voltage across the inductor is reduced causing the rate of change of the current to decrease, causing the magnetic field to grow more slowly and the voltage across the resistor to build up more slowly. After a period of time, all the voltage is across the resistor and the current has reached V/R, or in this example 6 amperes (just like in the Figure 1 case). The voltage across the inductor has now dropped to zero since the current is not longer changing; but there is 32 Joules energy stored in the magnetic field of L1 (From table 1).

When the switch is thrown to OFF The external source of energy is removed from the circuit. and the only energy in the circuit is that stored in the magnetic field of the L1. The current wants to drop to zero, but the coil's inertia keeps the current flowing. To do that the coil's polarity becomes reversed form when the magnetic field was building up. Initially -12 volts is across the which drops off as the energy is dissipated in the resistor. Both the increase in current when the switch is turned on, and the decrease in current when the switch is turned to off change exponentially. It is very similar to a capacitor being charged and discharged through a resistor; except now the discussion is current instead of voltage. this theme appears regularly when comparing properties of inductors and capacitors. Look again at Table 1.

You may wonder about the reason for the wire between the OFF contact of the switch and ground. It does nothing in Figure 1a, but is needed in figure 2. If it is not there an interesting thing happens: When the switch is thrown back to OFF the coil has energy stored in it, but there is no place for the current to go. The circuit is open! Actually, there is a place for the current to go. Remember the voltage across a coil depends on the rate of change of the current, which just changed almost instantaneously. The voltage gets really high - high enough to jump the gap pf the opening switch. If the inductance is large, and hence the energy is large this spark across the switch contact can damage the switch over time. There are ways to prevent this by providing an additional path for the energy - a topic worth a future discussion.

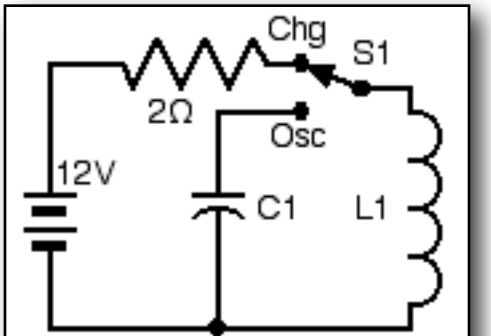

Fig. 3a

Finally we'll discuss the operation of the figure shown in Figure 3a. Here an inductor is brought to a steady-state current of 6 amperes with the switch in the "Chg" position and then switched in series with a discharged capacitor in the Osc position. Since the two components are also in parallel, ***they always share the same current through them and the same voltage across them***. The graph of Figure 3b shows how the voltage (the orange line) and the current (the blue line) change with time. Initially, when the switch is first thrown (Point 'a' in Figure 3b), the voltage is zero. There is no energy in the circuit except the energy stored in the magnetic field of the inductor. However, the coil is passing 6 amperes at the moment the switch is thrown. The inductor tries to keep this current flowing using the energy in its magnetic field. That continued current starts charging the capacitor which begins building up the voltage. From equation 3, as the voltage builds it is increasing the rate at which the current is changing (decreasing in this case) causing it to decrease more rapidly. Finally the point is reached where the current is zero and the voltage is at a maximum. (point 'b') At this point the current is changing at its fastest rate, and the energy is now mostly in the electric field of the capacitor and not the magnetic field of the inductor. However the continued high rate of change of the current due to the large voltage, causes the current to continue right past zero and go negative. This starts to take energy from the capacitor and build back up the magnetic field in the inductor - but in the opposite magnetic polarity. As energy is removed from the capacitor the voltage drops causing the inductor to reduce the rate at which the current is changing. This continues until the rate of current change reaches zero because the voltage has reached zero (point 'c'). Here the current is at a maximum.

At this point the circuit is in the same state as it was except the current and the magnetic field are reversed. The circuit continues as described above (except for the reversed polarity) through point 'd' and to point 'e'. At which point conditions are the same as they were at point 'a', where we started.

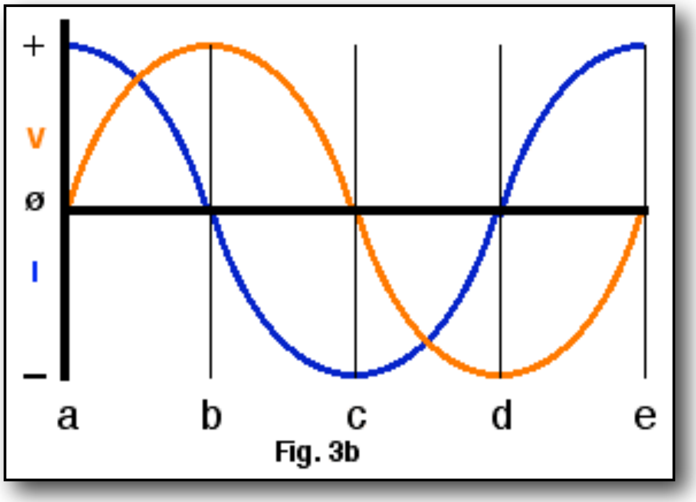

Fig. 3b

If the capacitor and inductor are perfect, so there is no energy loss, this oscillation will continue indefinitely as the energy moves between the coil and capacitor, swapping polarity each time.

In the real world of course the oscillations will dampen out over time. But, if external energy is applied briefly at the correct moments (Say the switch is momentarily thrown back to 'Chg' at every point 'a' the oscillation will continue and energy can be removed for other use. The fact that such an LC oscillator tends to produce low harmonic sine waves at a single frequency makes the LC circuit ideal for oscillators and filters.

In the next Bob's Tech Talk we'll delve a little further into the wonders of the inductor. I hope this explanation of how a coil works will be easy to understand. All the representations I've seen were mathematical and took a good understanding of calculus to fathom.

The trick to understanding the coil is to remember that ***when the value of the current through a coil is changing, a voltage is produced across the coil proportional to how fast the current is changing. And conversely, if a voltage is placed across a coil the current is being forced to change at a rate proportional to that voltage.***

73, from AF6C

This article is based on the TechTalk article that originally appeared in the September 2010 issue of RF, the newsletter of the Orange County Amateur Radio Club - W6ZE.