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Experiment 118

The Laws at Work

Last month's column ended in the year 1831 as Michael Faraday discovered *electromagnetic induction*. In fact, the day on which I finished this column was the 181st anniversary of that discovery — August 29th.

As a review, Faraday showed how changing currents in one circuit could induce similarly changing currents in another circuit without any direct connection between them. This occurs by first converting the first circuit's electrical energy into magnetic energy in the surrounding field and then back into electrical energy in the second circuit. Electromagnetic induction is described by Faraday's Law as explained in last month's column.[1] The faster the magnetic flux changes because of motion or changes in current, the larger the voltage that is induced in the other circuit.

The minus sign in Faraday's law gives rise to Lenz's law: The *electromotive force* (EMF) induced by the changing magnetic field causes current to flow in the direction that creates a magnetic field *opposing* the original change in magnetic flux. Lenz's law describes the *back EMF* we observe in motors and the *kickback voltage* in a relay coil when it is deenergized. Last month's Figure 3 shows the relative direction of the currents in both circuits.

There are several ways to cause the magnetic field linking the two coils to change. The most obvious way is to simply turn the current generating the field on and off with a switch. Another way is to move one of the coils so it encounters more or less of the magnetic field. This is the principal behind an electrical ac generator. An *armature* coil is rotated inside a current-carrying stationary coil (or *stator*) causing the armature voltage to vary as a sine wave. Similarly, changing the current in the stator causes the armature to turn, creating a motor.

In this month's column we will follow in the steps of pioneers André-Marie Ampère, Hans Christian Ørsted and Faraday by performing some simple experiments demonstrating the various effects they described. Is this purely a historical exercise? Not at all! These phenomena are at the heart of radio — without them we would be wireless-less.

Experiment #1 — Ørsted's Observation

During a lecture, with experimental apparatus scattered across a table, Ørsted noticed that a compass needle deflected away from north when he switched current on and off in a nearby circuit. This was the first observation linking electricity and magnetism and it was the proverbial *Big Deal* in 1820. So let's repeat it.

Head for the kitchen and "borrow" a strong refrigerator magnet capable of holding up a calendar. You'll also need a source of dc power such as a power supply — 12 V is fine — and a coil of several mH with a dc resistance of 10 to 30 Ω. You can either buy or scrounge a suitable inductor but the coil of a 12 V relay will do fine and you may have one in your junk box. (The relay used in experiments #107 through #110 is a good choice. Alternately, a RadioShack 275-001 will work — remove the plastic case to see the coil.)

Working on a nonferrous table (plastic or wood), suspend the magnet a few inches above the table using thread or dental floss. Mark one face with pencil or tape. Connect the inductor to the 12 V supply through a voltmeter configured to measure current — start with the scale for measuring several amps and use a more sensitive scale after confirming the current is low enough not to

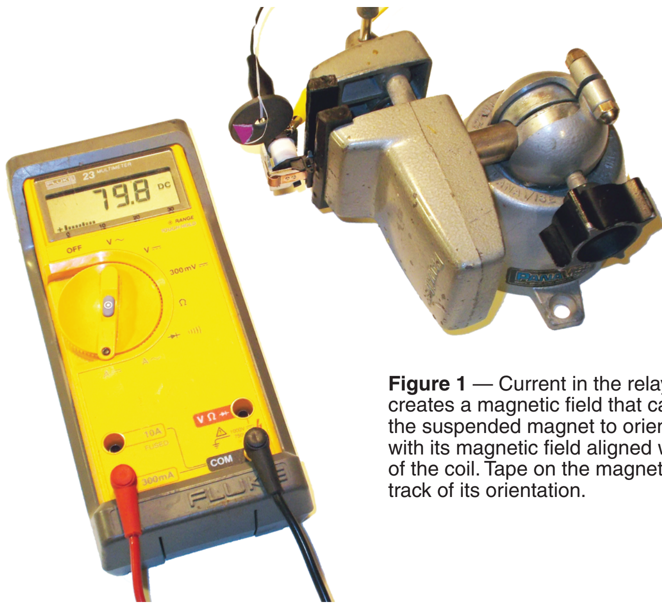

Figure 1 — Current in the relay coil creates a magnetic field that causes the suspended magnet to orient itself with its magnetic field aligned with that of the coil. Tape on the magnet keeps track of its orientation.

When Is E a V and V an E?

Beginners in electronics are often confused about the interchange of V and E in equations and formulas. The term "electromotive force" further muddies the water. When should each be used? Unfortunately, there is no standard definition or convention as described at **en.wikipedia.org/wiki/Electromotive_force**. Nevertheless, in ham radio E is usually used if referring to an electric field (such as the E field of an antenna) or if an electric field causes some effect or action (such as back EMF of an inductor). V is used to describe the difference in voltage between two points in a circuit, or the terminal voltage of a power supply or battery. V is also used as an abbreviation for volts, the unit of voltage.

[1]All previous Hands-On Radio experiments are available to ARRL members at **www.arrl.org/**

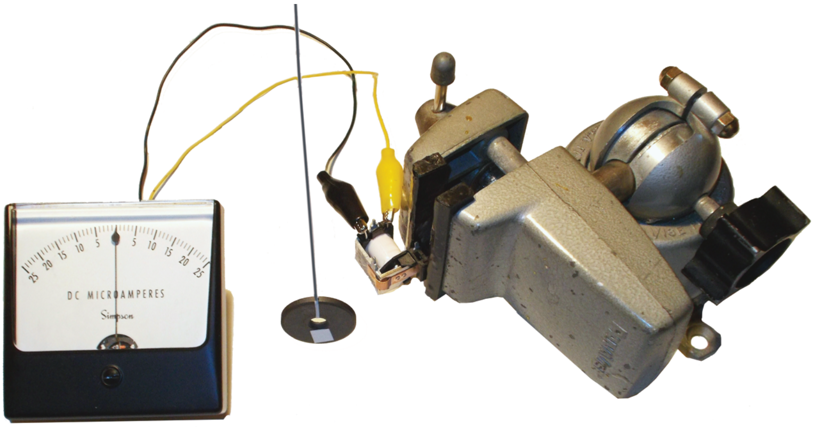

Figure 2 — Moving the magnet toward the coil changes the magnetic field in the coil and induces a current of one polarity in the circuit, causing the meter to deflect. Moving the magnet away from the coil causes an opposite change in the field and reverses the deflection of the meter.

Figure 3 — Current applied from a battery demonstrates the Ampère force separating the two parallel conductors. The conductors are made from a strip of aluminum foil. Wear protective eyewear and gloves when performing this experiment.

overload the meter. Place the coil near the magnet but in a position where it cannot contact the coil or the connecting wires. Wait for the magnet to reach complete rest.

Switch on the current while watching the magnet — the magnet will pivot and move, eventually stabilizing in a fixed position as in Figure 1. (My relay coil is drawing about 80 mA.) When you switch off the current, the magnet will return to its original position. The magnet is moving so that its magnetic field is aligned with the magnetic field of the energized coil.

Cycle the current on and off several times. The magnet will always stabilize with one face of the magnet in the same position. Slowly rotate the coil and verify that the magnet rotates to follow the orientation of the coil. Reverse the power supply leads and verify that the magnet stabilizes with the marked face reversed as well.

Experiment #2 — Faraday's Law

Technically, we're not going to demonstrate Faraday's law exactly so as to keep the setup simple. However, you will be able to see the effect of the orientation of the field on the direction of the induced current in a circuit. You will need a sensitive microammeter or millivoltmeter (also known as a *galvanometer*) capable of showing current or voltage of both polarities. Digital meters work okay, but if you have or can borrow a sensitive analog meter, the effect is easier to see. I found a mint condition 25-0-25 µA meter for $5 at a hamfest so keep your eyes open.

Figure 2 shows the basic setup. Disconnect your coil from the power supply and connect it directly between the meter terminals. Polarity is not important. (If you have a digital meter, use the most sensitive voltage scale, usually 200 or 300 mV.) Hold the magnet in your fingers and move it toward the coil and then away from the coil while watching the meter. You should see the meter deflect or indicate in one direction as the magnet moves toward the coil and then in the other direction as the magnet moves away. Experiment with different orientations of the magnet as you move it past the coil.

There are a number of great YouTube videos that demonstrate Lenz's law in which the induced current creates an opposing magnetic field.[2] You may have seen someone drop a magnet into a copper pipe through which it then falls very slowly. The induced currents are called *eddy currents* and they set up a magnetic field that is almost, but not quite, strong enough to stop the magnet. If the magnet did stop, there would be no eddy current and opposing field so, as a result, the magnet moves just fast enough to overcome the resistive losses in the pipe.

Experiment #3 — Ampère's Force Law

The final experiment is at the heart of what makes an electromagnetic rail gun work — the magnetic force between two current-carrying conductors. Figure 2 in the previous experiment shows how the magnetic fields of two parallel conductors carrying current in the same direction align to force the conductors towards each other. In this experiment, we'll show opposite currents forcing the conductors apart.

Head back to the kitchen and find the aluminum foil. Use a measuring stick to tear or cut off a strip about 18 to 24 inches long and about ¾ inches wide. Back in the lab, suspend the aluminum foil so that it forms a long, narrow ∪ above the table as in Figure 3. Attach heavy clip leads to the open ends of the foil strip.

Get four fresh D cell batteries and use a battery holder or plastic tube to connect them in series — *do not* use a larger battery as the resulting higher currents may be unsafe. Wear eye protection and work gloves for the following step although it is unlikely that any significant heating will occur. Attach one clip lead to the battery's positive terminal cap. Tape or secure both clip leads so that moving the free ends does not cause the foil to move. When the foil is completely still, brush the remaining clip lead's free end against the battery's negative terminal momentarily — you'll see the foil loop expand slightly as several amperes of current flow through it, creating a force separating the parallel conductors. Experiment with different orientations of the foil or create two parallel strips that carry current in the same direction and are forced closer together.

Applying the Law

Do these experiments have any practical application in ham radio today? Most certainly! The effect observed by Ørsted is replicated in every analog meter movement. Faraday's and Lenz's laws are the foundation of transformers and shielded wires. If you've ever seen the inside of a high-voltage power supply after a short circuit, you've also seen the effects of Ampère's force law at work.

[2]YouTube videos **www.youtube.com/watch?v=kU6NSh7hr7Q** and **www.youtube.com/watch?v=G7ysnXH53Wo** are particularly good.