#5a-2. *Electro-Magnetic Induction -- 2.*

(Files in red–history)

- **Index**
- 2. Magnetic Field
  - 2H. Oersted, 1820
- 3. Aurora
  - 3H. Birkeland 1895
  - 3a. Loomis & Aurora
  - 3b. Fritz & Aurora
  - 3c. The Terrella
- 4. Electrons
  - 4H. Thomson, 1896
- 4a. Electric Fluid
- 5. Field Lines
  - 5H. Faraday 1846
- 5a-1. EM Induction--1
- **5a-2. EM Induction--2**
- 6. EM Waves
- 7. Plasma
- 7a. Fluorescent lamp
  - 7H. Langmuir, 1927
- 8. Positive Ions

In the preceding section it was asserted--as experiments confirm--that a "**secondary**" electric current is "**induced**" in a closed conductor loop when the "**magnetic flux**" through it **changes** with time (all terms in quotes are defined and explained there). The change may come from a variation in the strength of the magnetic source--e.g. an electromagnet switched on and off, or one fed by AC. Or else, the change may come because the circuit moves relative to the source--for instance, a conducting circular loop or narrow coil **rotating around a diameter**, thus presenting the magnetic source with a constantly changing frontal area.

What seems strange is that the current itself depends on the **shape and size** of the "secondary" circuit. Many observed effects depend on size and shape--e.g. the center of gravity of a brick, its weight, its kinetic energy when turned around some axis--but these always depend on some **more fundamental laws**, independent of shape and size. One would suspect that some fundamental law stands behind all induction phenomena, and such a law indeed exists--"**Faraday's law of induction**."

The bad news is that it involves calculus, and in three dimensions, too. However, its **intuitive** meaning may perhaps be expressed in plain language, using electric and magnetic **fields**.

The Induced Electric *Field*

As earlier defined, a **magnetic field** is a region where at any point a magnetic force can be observed, in the direction of the field vector **B** and with intensity proportional to the magnitude of **B**. The field may be viewed as modified space, and it exists at a point whether an observaion is made there or not.

Similarly, an **electric field** is a region of electric forces, and the direction of the force--say, on a loose electron--is that of the field vector **E**, with an intensity proportional to the magnitude of **E**.

In particular, if an **electric conductor** is placed in an electric field, an electric current with density **j** (yet another vector!) will usually flow. If the conductor is a metal and obeys Ohm's rule--as in insulated copper wires used in electric machinery--the current will flow along the wire, its shape depending on that of the wire, and its magnitude on the **electric resistance** of the material, which depends on thickness, length and material. In addition, various rules need to be obeyed:

1. The circuit must be **closed**, otherwise electric charges carried by

the current accumulate at its ends and those accumulations create their own electric field, stopping the flow of any additional current.
2. If a current **does** flow, it contributes its own magnetic field, modifying the one creating it and generally weakening it.
3. If some more complicated relation takes the place of **Ohm's Law** (as happens, for instance, in plasmas), that relation rules the current flow, often making it more complex.
4. --And... if there is **NO electric conductor** in the region of changing magnetic field, NO electric current flows. However, there **still exists** an **"induced" electric field E**, a modification of the properties of space, though without any material on which it acts, it would be hard to detect it.

In any case, it is **the induced electric field E** which drives all induced electric currents, and all features related to electromagnetic (EM) induction. The formula for **E**, also known as **Faraday's Law**, allows **E** to be calculated (assuming enough is known about conductivities, etc.)

The Electro-Motive Force

Unfortunately, expressing and applying Faraday's law in general space conditions requires more math than is included here. One reason is that the **induced electric field E** has a **strange form**. Think again about the **two main types** of water flow in a swimming pool, mentioned earlier. There exists the "**source-and-sink" flow** --water entering from "source" pipes, its flow distributing itself around the pool, then converging on the drains or "sinks" where it leaves again ("sloshing" is the special case of no source and no sink). Electric fields (and currents) in circuits powered by batteries flow this way, whether confined by wires (which act as pipes) or spreading out in a conducting volume (as they would around an electric eel). One pole of the battery is the "souce," the other the "sink."

But in addition there also exist swirling "**vortex flows**" whose sources are distributed in space rather than having specific locations (compare book of Ecclesiastes, ch.1, verses 6-7!). The **induced electric field** is of this kind. In the **first** kind of field, **E** has a definite direction, from **high voltage to low**, just as the analogous water flow proceeds from high pressure to low pressure. In a **fluid vortex flow**, the impelling force is **distributed**, and in an electric vortex field ("solenoidal field") the voltage is similarly distributed in space.

Say you have a closed wire loop in a varying magnetic field, with a certain electric conductivity, and you **want to calculate the induced current** at some instant. You choose a starting point on the wire (turns out that any choice gives the same result) and trace **E** around the wire, assigning to it voltages as you go. By the time you have returned to the starting point, you have derived the **effective voltage** driving the induced current, and applying Ohm's law then gives **the induced current itself**.

Obviously, the mathematics of deriving such a distributed electric field is different, but you are helped by Faraday's law, by which the "effective voltage" driving current around any given circuit is proportional to the **rate at which the magnetic flux through it changes**. Faraday named this strange distributed voltage the "**electro motive force**", or e.m.f. for short; a clumsy name, but after nearly two centuries, it has yet to be replaced. The **direction** of the e.m.f. (for there is a choice of two opposing directions around any closed loop) is always such, that if it drives an induced electric current, the resulting magnetic field will **oppose** its source. That is, if the induced current is caused by a **growing** magnetic flux, the field of the current will tend to **reduce** that flux, while if the cause is a **decaying** magnetic flux, the field of he current will try to prop it up and slow down its decay.

If all this seems too qualitative, while you seek some solid numbers to work with, you might browse around the "**hyperphysics**" web site--for instance, http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html and if need be, in the index on the right click on "Faraday's law".

Alternating Current or AC

Faraday's law turns out to be one of the fundamental laws of the electromagnetic field--laws expressed by **James Clerk Maxwell** in his famous equations (involving calculus) and used by him to derive the existence of electromagnetic waves, which include visible light, radio waves, X-rays and many other varieties.

Induced electric currents also made possible a wide variety of technologies, and are the reason why our homes and factories rely on **alternating current** or **AC**, whose voltage rises and falls like a periodic wave, reversing direction 100 or 120 times each second (you need two reversals in each cycle before you return to the starting value, so we speak of AC with 50 or 60 cycles per second).

It is easy enough to generate AC. Suppose that in a wide gap between two opposing magnetic poles you place a circular wire, or better a **narrow circular coil**, and **spin it** around a diameter **perpendicular** to the line connecting the poles. The magnetic flux through the coil then **changes all the time,** completely reversing each half turn. If you then lead the ends of the wire to **twin copper disks** on the shaft on which the disk turns, insulated from the shaft and from each other, and continue the circuit outside through sliding contacts ("brushes") which touch those disks, those contacts will extract AC.

Commercial AC generators are more complicated, but the principle is the same. To get a current of constant polarity from such a "dynamo", each disk must be split into halves insulated from each other by some non-metal layer. The sliding contacts then switch from one half to the other whenever the flux through the coil reverses. This allows the current to maintain the same "+ to –" direction throughout the entire cycle, though its voltage still goes up and down. Old cars used such "DC dynamos" for charging their storage batteries.

Electrical Transformers

AC is widely used to **transform the voltage** of electric currents. The energy transmitted by an electric current depends on the product of **current times voltage**, modified for AC (because of the constant change) to something like 1/2 the peak voltage *times* the peak current (for the simplest case). However, by Ohm's law, energy loss due to electric resistance of the wire depends on the **current intensity alone**. For that reason, it is most economical to transmit electric energy using the **smallest current possible**, which requires (for the same energy) the **highest voltage possible**, say 400,000 volt. The high voltage requires the transmission lines to be extremely well insulated from their surroundings, which is why they are strung high in the air (air is an excellent electric insulator), hanging from elaborate ceramic supports (ceramic insulates too). However, the machinery which generates the AC, and the home appliances which use it, better operate at low voltages (say, we may generate AC at 500 volts and reduce it at the end to 110 volts), because high voltages require too much electric insulation, and also pose dangers of electric shock and fire.

The solution is provided by electrical transformers. The generated AC current powers an electromagnet by passing a "primary coil" C1 wrapped around it, then a "secondary coil" C2 around the same magnetic core creates a secondary electric current which is the one transmitted. Because the same magnetic flux passes both coils, if C1 has 50 windings and C2 has 5000, the varying magnetic flux in C2 is **100 times large**r, creating 100-fold voltages in the secondary circuit.

When the current reaches the consumer, other transformers **step down the voltage**, generally in several steps--say, primary coil of 5000 winding, secondary with 500, lowering the voltage 10 times. This produces intermediate voltages to supply towns or neighborhoods, then a few more steps to the transformers atop power poles, which bring the current down to 110 volts for home use. The lower-voltage power lines carry much less electric power than the high-voltage ones, but the currents are comparable. Power transformers are remarkably efficient, and rather little of the energy is lost when the voltage is stepped up or down. Just a very small part of the electric energy is lost as heat, which power transformers sometimes dissipate by cooling fins, or by loops of pipe sticking out to circulate the oil in which the coils are usually immersed.

Auroral Electrojets

Induction fields are important in shaping magnetic fields in space--especially, the "freezing" of magnetic field lines to the plasma (section #18a, also here) depends on them. One interesting consequence are occasional "power blackouts" in the auroral zone, especially in Canada. In the high layers of the atmosphere--**the ionosphere**--sunlight separates free electrons from some of the atoms and molecules, allowing those layers to conduct electric currents. In the **"E layer"** of the ionosphere, around 125 kilometer or 80 miles, collisions of ions and electrons with neutral molecules are still frequent enough to allow electrons to jump from one field line to its neighbor and carry horizontal currents. Higher up collisions are fewer, electrons and ions tend to be confined around guiding magnetic field lines, and horizontal current flow is inhibited.

Because of the interaction of he magnetosphere and the solar wind, the auroral zone (magnetic latitude 60-70 degrees) carries large horizontal current systems, known as the **auroral electrojets**, whose intensity is concentrated along the **auroral oval**. Usually the electrojets modify the magnetic field beneath them by a fraction of 1%, but during big magnetic storms they briefly intensify and shift to greater distance from the pole--as does the polar aurora, which can then be observed (for a short while) well beyond its usual location.

With this shift, the magnetic field due to the electrojects also changes, enough to **induce an appreciable extra voltage** in the high-voltage long-distance lines of the electric grid. Since the field of the electrojet is weak, those changes are small too--but since they stretch over great distances, the magnetic flux through the grid can change substantially. The transformers of the grid are designed for AC of 60 cycles, but the electrojet varies on the scale of minutes, so the induced voltage acts more like a DC voltage, for which the grid is **not** designed. As a result, circuit breakers may trip and open, and on rare occasions, transformers have overheated and burned out. Luckily such events are quite rare, and engineers now know when to look out for them.

Questions from Users:

*** How can steady magnetic fields induce electric currents?
*** What are "frozen" magnetic field lines?
*** Eddy Currents
*** Can Polar Aurora be seen in Atlanta, Georgia?
*** "Why does this happen?" (electromagnetic induction)
*** How does magnetism spin aluminum disks in power meters?
*** Rapidly reversing magnet

Next Stop: #6 Electro-Magnetic Waves
Back to the Index Page

Timeline **Expanded timeline** **Glossary**

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