FB-DC6 Electric Circuits: Magnetism and Electromagnetism

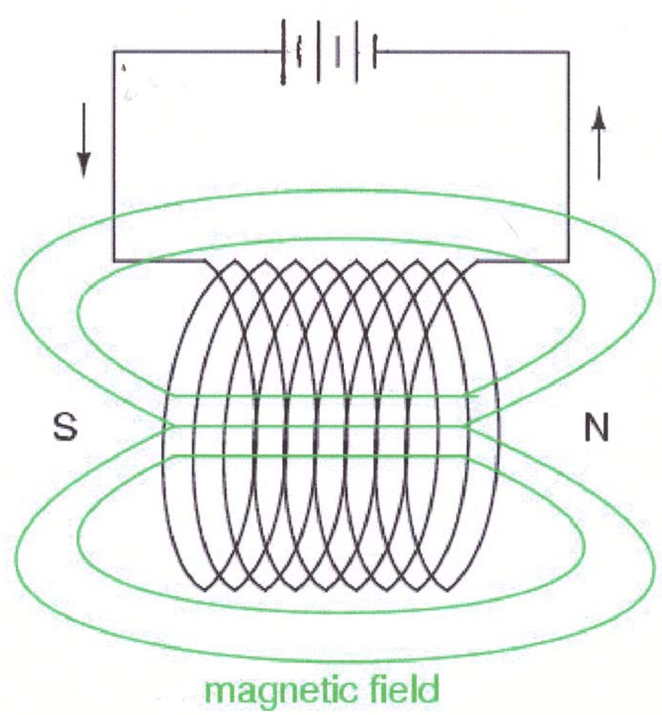
Contents

1. **Electromagnetism**
2. **Magnetic units of measurement**
3. **Permeability and saturation**
4. **Electromagnetic induction**
5. **Mutual inductance**

1. Electromagnetism

The discovery of the relationship between magnetism and electricity was, like so many other scientific discoveries, stumbled upon almost by accident. The Danish physicist Hans Christian Oersted was lecturing one day in 1820 on the *possibility* of electricity and magnetism being related to one another, and in the process demonstrated it conclusively by experiment in front of his whole class! By passing an electric current through a metal wire suspended above a magnetic compass, Oersted was able to produce a definite motion of the compass needle in response to the current. What began as conjecture at the start of the class session was confirmed as fact at the end. Needless to say, Oersted had to revise his lecture notes for future classes! His serendipitous discovery paved the way for a whole new branch of science: electromagnetics.

Detailed experiments showed that the magnetic field produced by an electric current is always oriented perpendicular to the direction of flow. The magnetic field encircles this straight piece of current-carrying wire, the magnetic flux lines having no definite "north" or "south' poles.
While the magnetic field surrounding a current-carrying wire is indeed interesting, it is quite weak for common amounts of current, able to deflect a compass needle and not much more. To create a stronger magnetic field force (and consequently, more field flux) with the same amount of electric current, we can wrap the wire into a coil shape, where the circling magnetic fields around the wire will join to create a larger field with a definite magnetic (north and south) polarity:



The amount of magnetic field force generated by a coiled wire is proportional to the current through the wire multiplied by the number of "turns" or "wraps" of wire in the coil. This field force is called *magnetomotive force* (mmf), and is very much analogous to electromotive force (E) in an electric circuit.

An *electromagnet* is a piece of wire intended to generate a magnetic field with the passage of electric current through it. Though all current-carrying conductors produce magnetic fields, an electromagnet is usually constructed in such a way as to maximize the strength of the magnetic field it produces for a special purpose. Electromagnets find frequent application in research, industry, medical, and consumer products.

As an electrically-controllable magnet, electromagnets find application in a wide variety of "electromechanical" devices: machines that effect mechanical force or motion through electrical power. Perhaps the most obvious example of such a machine is the *electric motor*.

Section Review:

- When current flow through a conductor, a magnetic field will be produced around that conductor.
- The magnetic field force produced by a current-carrying wire can be greatly increased by shaping the wire into a coil instead of a straight line. If wound in a coil shape, the magnetic field will be oriented along the axis of the coil's length.
- The magnetic field force produced by an electromagnet (called the *magnetomotive force*, or mmf) is proportional to the product (multiplication) of the current through the electromagnet and the number of complete coil "turns" formed by the wire.

2. Magnetic units of measurement

First, we need to get acquainted with the various quantities associated with magnetism. There are quite a few more quantities to be dealt with in magnetic systems than for electrical systems. With electricity, the basic quantities are Voltage (E), Current (I), Resistance (R), and Power (P). The first three are related to one another by the first Ohm's Law equation (E=IR), while Power is related to voltage and current by another (P=IE). All other Ohm's Law equations can be derived algebraically from these two. With magnetism, we have the following quantities to deal with:

Magnetomotive Force -- The quantity of magnetic field force, or "push." Analogous to electric voltage (electromotive force).

Field Flux -- The quantity of total field effect, or "substance" of the field. Analogous to electric current.

Field Intensity -- The amount of field force (mmf) distributed over the length of the electromagnet. Sometimes referred to as *Magnetizing Force*.

Flux Density -- The amount of magnetic field flux concentrated in a given area.

Reluctance -- The opposition to magnetic field flux through a given volume of space or material. Analogous to electrical resistance.

Permeability -- The specific measure of a material's acceptance of magnetic flux, analogous to the specific resistance of a conductive material (ρ), except inverse (greater permeability means easier passage of magnetic flux, whereas greater specific resistance means more difficult passage of electric current).

As with common quantities of length, weight, volume, and temperature, we have both English and metric systems. However, there is actually more than one metric system of units, and multiple metric systems are used in magnetic field measurements! One is called the *cgs*, which stands for **C**entimeter-**G**ram-**S**econd, denoting the root measures upon which the whole system is based. The other was originally known as the *rmks*, standing for **R**ationalized **M**eter-**K**ilogram-**S**econd.
This ended up being adopted as an international standard and renamed *SI* (**S**ysteme **I**nternational) and is the only one that should now be considered (the others are included merely for comparison):

Quantity	Symbol	Unit of Measurement and abbreviation		
		CGS	SI	English
Field Force	mmf	Gilbert (Gb)	Amp-turn	Amp-turn
Field Flux	Φ	Maxwell (Mx)	Weber (Wb)	Line
Field Intensity	H	Oersted (Oe)	Amp-turns per meter	Amp-turns per inch
Flux Density	B	Gauss (G)	Tesla (T)	Lines per square inch
Reluctance	ℜ	Gilberts per Maxwell	Amp-turns per Weber	Amp-turns per line
Permeability	μ	Gauss per Oersted	Tesla-meters per Amp-turn	Lines per inch-Amp-turn

As you might have guessed already, the relationship between field force, field flux, and reluctance is much the same as that between the electrical quantities of electromotive force (E), current (I), and resistance (R). This provides something akin to an Ohm's Law for magnetic circuits:

A comparison of "Ohm's Law" for electric and magnetic circuits:

Electrical	Magnetic
$E = IR$	$mmf = \Phi \Re$

And, given that permeability is inversely analogous to specific resistance, the equation for finding the reluctance of a magnetic material is very similar to that for finding the resistance of a conductor:

A comparison of electrical and magnetic opposition:

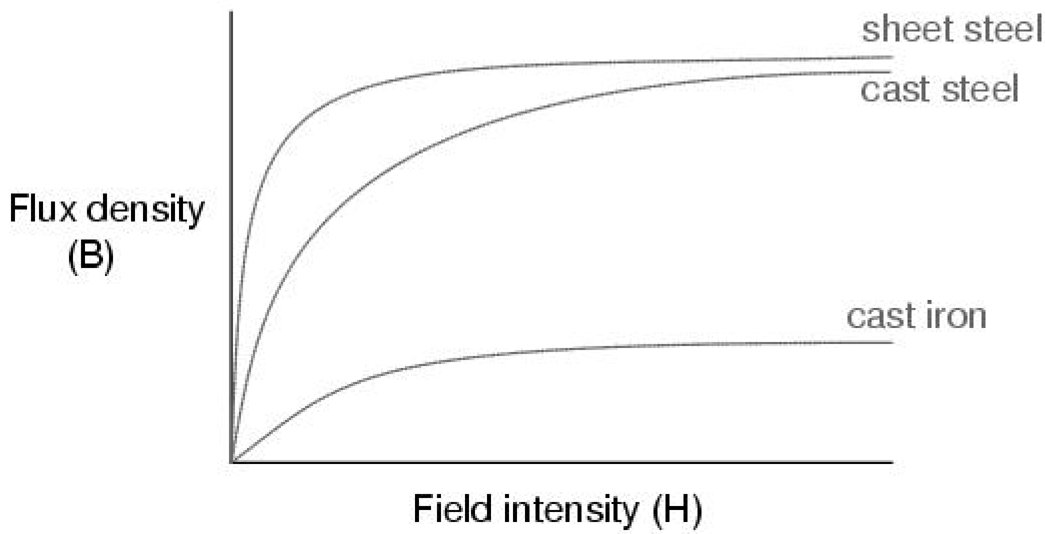
Electrical	Magnetic
$R = \rho \frac{l}{A}$	$\Re = \frac{l}{\mu A}$

In either case, a longer piece of material provides a greater opposition, all other factors being equal. Also, a larger cross-sectional area makes for less opposition, all other factors being equal.

The major caveat here is that the reluctance of a material to magnetic flux actually *changes* with the concentration of flux going through it. This makes the "Ohm's Law" for magnetic circuits nonlinear and far more difficult to work with than the electrical version of Ohm's Law. It would be analogous to having a resistor that changed resistance as the current through it varied.

3. Permeability and saturation

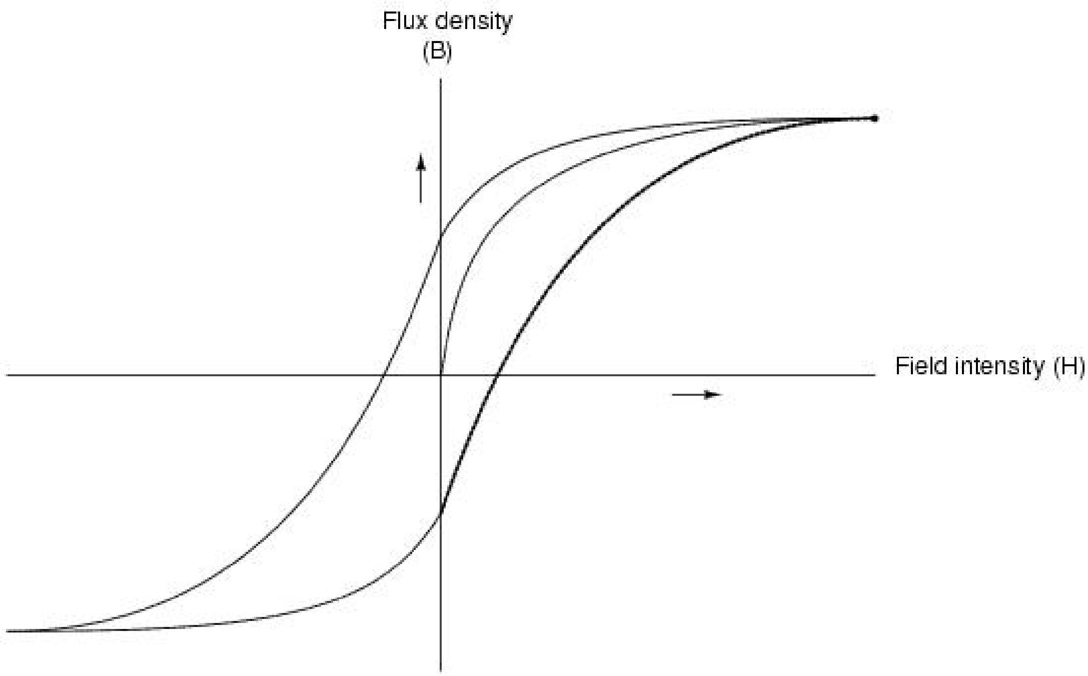
The nonlinearity of material permeability may be graphed for better understanding. We'll place the quantity of field intensity (H), equal to field force (mmf) divided by the length of the material, on the horizontal axis of the graph. On the vertical axis, we'll place the quantity of flux density (B), equal to total flux divided by the cross-sectional area of the material. We will use the quantities of field intensity (H) and flux density (B) instead of field force (mmf) and total flux (Φ) so that the shape of our graph remains independent of the physical dimensions of our test material. What we're trying to do here is show a mathematical relationship between field force and flux for *any* chunk of a particular substance, in the same spirit as describing a material's *specific resistance* in ohm-cmil/ft instead of its actual *resistance* in ohms.



This is called the *normal magnetization curve*, or *B-H curve*, for any particular material. Notice how the flux density for any of the above materials (cast iron, cast steel, and sheet steel) levels off with increasing amounts of field intensity. This effect is known as *saturation*. When there is little applied magnetic force (low H), only a few atoms are in alignment, and the rest are easily aligned with additional force. However, as more flux gets crammed into the same cross-sectional area of a ferromagnetic material, fewer atoms are available within that material to align their electrons with additional force, and so it takes more and more force (H) to get less and less "help" from the material in creating more flux density (B). To put this in economic terms, we're seeing a case of diminishing returns (B) on our investment (H). Saturation is a phenomenon limited to iron-core electromagnets. Air-core electromagnets don't saturate, but on the other hand they don't produce nearly as much magnetic flux as a ferromagnetic core for the same number of wire turns and current.

Another quirk to confound our analysis of magnetic flux versus force is the phenomenon of magnetic *hysteresis*. As a general term, hysteresis means a lag between input and output in a system upon a change in direction. Anyone who's ever driven an old automobile with "loose" steering knows what hysteresis is: to change from turning left to turning right (or visa-versa), you have to rotate the steering wheel an additional amount to overcome the built-in "lag" in the mechanical linkage system between the steering wheel and the front wheels of the car. In a magnetic system, hysteresis is seen in a ferromagnetic material that tends to stay magnetized after an applied field force has been removed (see "retentivity" in the first section of this chapter), if the force is reversed in polarity.
Let's use the same graph again, only extending the axes to indicate both positive and negative quantities. First we'll apply an increasing field force (current through the coils of our electromagnet). We should see the flux density increase (go up and to the right)

according to the normal magnetization curve. Decreasing the field force to zero, reversing it and then bringing it back to zero produces the curve below:



The "S"-shaped curve traced by these steps form what is called the *hysteresis curve* of a ferromagnetic material for a given set of field intensity extremes (-H and +H).

Having to overcome prior magnetization in an electromagnet can be a waste of energy if the current used to energize the coil is alternating back and forth (AC). The area within the hysteresis curve gives a rough estimate of the amount of this wasted energy.

Other times, magnetic hysteresis is a desirable thing. Such is the case when magnetic materials are used as a means of storing information (computer disks, audio and video tapes). In these applications, it is desirable to be able to magnetize a speck of iron oxide (ferrite) and rely on that material's retentivity to "remember" its last magnetized state.

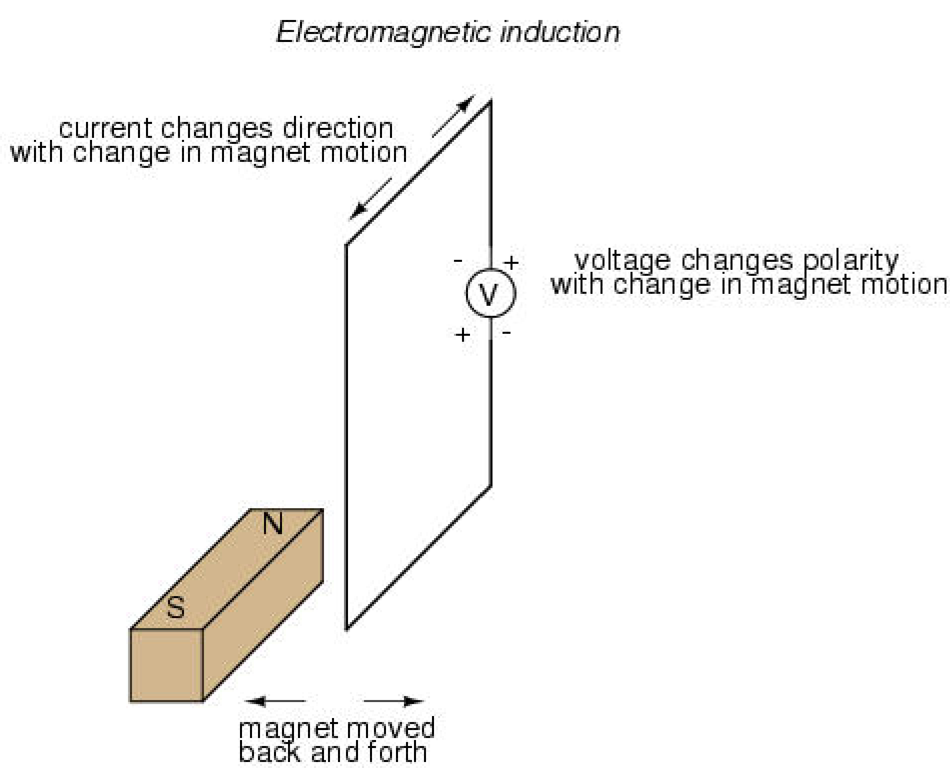
Section Review:

- The permeability of a material changes with the amount of magnetic flux forced through it.
- The specific relationship of force to flux (field intensity H to flux density B) is graphed in a form called the *normal magnetization curve*.

- It is possible to apply so much magnetic field force to a ferromagnetic material that no more flux can be crammed into it. This condition is known as magnetic *saturation*.
- When the *retentivity* of a ferromagnetic substance interferes with its re-magnetization in the opposite direction, a condition known as *hysteresis* occurs.

4. Electromagnetic induction

While Oersted's surprising discovery of electromagnetism paved the way for more practical *applications* of electricity, it was Michael Faraday who gave us the key to the practical *generation* of electricity: electromagnetic induction. Faraday discovered that a voltage would be generated across a length of wire if that wire was exposed to a perpendicular magnetic field flux of changing intensity.
An easy way to create a magnetic field of changing intensity is to move a permanent magnet next to a wire or coil of wire. Remember: the magnetic field must increase or decrease in intensity *perpendicular* to the wire (so that the lines of flux "cut across" the conductor), or else no voltage will be induced:



Faraday was able to mathematically relate the rate of change of the magnetic field flux with induced voltage (note the use of a lower-case letter "e" for voltage. This refers to *instantaneous* voltage, or voltage at a specific point in time, rather than a steady, stable voltage.):

$$e = N \frac{d\Phi}{dt}$$

Where,

e = (Instantaneous) induced voltage in volts

N = Number of turns in wire coil (straight wire = 1)

Φ = Magnetic flux in Webers

t = Time in seconds

This phenomenon is put into obvious practical use in the construction of electrical generators, which use mechanical power to move a magnetic field past coils of wire to generate voltage. However, this is by no means the only practical use for this principle.

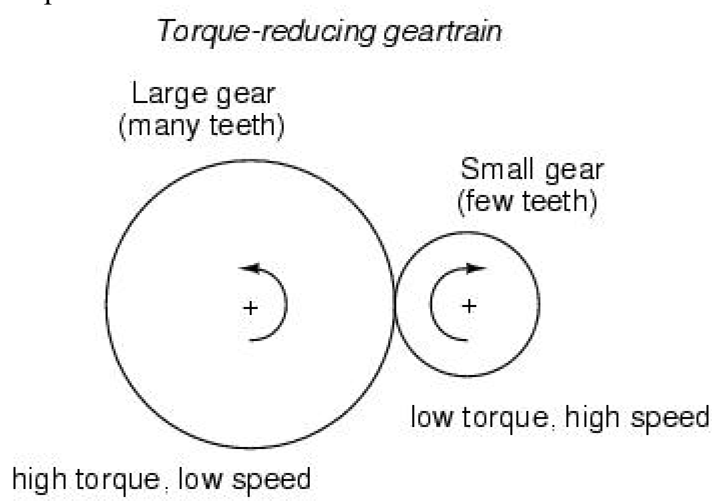
If we recall that the magnetic field produced by a current-carrying wire was always perpendicular to that wire, and that the flux intensity of that magnetic field varied with the amount of current through it, we can see that a wire is capable of inducing a voltage *along its own length* simply due to a change in current through it. This effect is called *self-induction:* a changing magnetic field produced by changes in current through a wire inducing voltage along the length of that same wire. If the magnetic field flux is enhanced by bending the wire into the shape of a coil, and/or wrapping that coil around a material of high permeability, this effect of self-induced voltage will be more intense. A device constructed to take advantage of this effect is called an *inductor*, and will be discussed in greater detail in the next chapter.

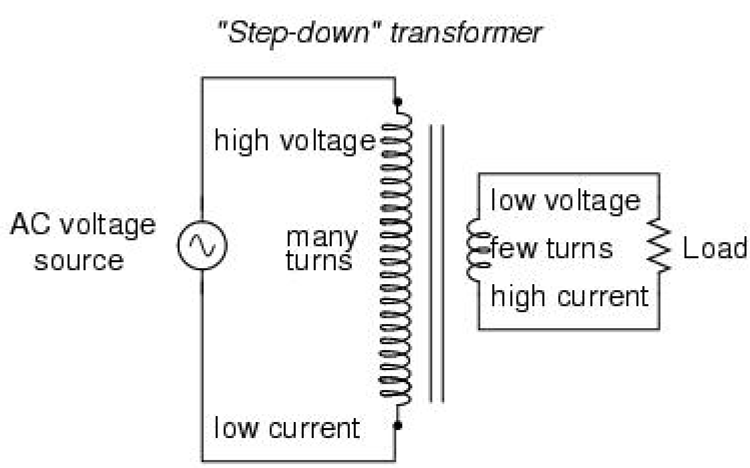
Section Review:

- A magnetic field of changing intensity perpendicular to a wire will induce a voltage along the length of that wire. The amount of voltage induced depends on the rate of change of the magnetic field flux and the number of turns of wire (if coiled) exposed to the change in flux.
- Faraday's equation for induced voltage: $e = N(d\Phi/dt)$
- A current-carrying wire will experience an induced voltage along its length if the current changes (thus changing the magnetic field flux perpendicular to the wire, thus inducing voltage according to Faraday's formula). A device built specifically to take advantage of this effect is called an *inductor*.

5. Mutual inductance

If two coils of wire are brought into close proximity with each other so the magnetic field from one links with the other, a voltage will be generated in the second coil as a result. This is called *mutual inductance:* when voltage impressed upon one coil induces a voltage in another. This is the principle of operation of the transformer.
Because magnetically-induced voltage only happens when the magnetic field flux is *changing* in strength relative to the wire, mutual inductance between two coils can only happen with alternating (changing -- AC) voltage, and not with direct (steady -- DC) voltage.
A very useful property of transformers is the ability to transform voltage and current levels according to a simple ratio, determined by the ratio of input and output coil turns. If the energized coil of a transformer is energized by an AC voltage, the amount of AC voltage induced in the unpowered coil will be equal to the input voltage multiplied by the ratio of output to input wire turns in the coils. Conversely, the current through the windings of the output coil compared to the input coil will follow the opposite ratio: if the voltage is increased from input coil to output coil, the current will be decreased by the same proportion. This action of the transformer is analogous to that of mechanical gear, belt sheave, or chain sprocket ratios:





Section Review:

- Mutual inductance is where the magnetic field generated by a coil of wire induces voltage in an adjacent coil of wire.
- A *transformer* is a device constructed of two or more coils in close proximity to each other, with the express purpose of creating a condition of mutual inductance between the coils.
- Transformers only work with *changing* voltages, not steady voltages. Thus, they may be classified as an AC device and not a DC device.