Electrical Tech Note — 217

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Magnetism

There is a relationship between current flow through a conductor and a magnetic field flux that builds up around the conductor. This *Tech Note* explores this relationship and discusses various useful applications. Magnetic flux has a direction which is dependant upon the direction electrical charges flow in a conductor. It is important to define the direction of electrical current flow in order to define the direction of the magnetic flux.

Conventional Current Flow: *Conventional current flow assumes current is flowing from the positive terminal to the negative terminal.* The negative (–) terminal of an electrical supply provides electrons which are available to flow through a conductor. The positive (+) terminal attracts the free electrons. When electricity flows through a conductor electrons are actually flowing from the negative (–) terminal to the positive (+) terminal. *The flow of electrical current through a conductor is actually the rate of flow of electrical charge through the conductor not the actual electrons.* This is illustrated in *Figure 217.1.* A negative charge (–) moves at nearly the speed of light from the negative terminal towards the positive terminal (+) of the source. Negative charges move in the same direction the electrons flow. As a negative charge moves from the negative terminal (–) to the positive terminal (+), a positive charge (+) of equal magnitude moves in the opposite direction at nearly the speed of light from the positive terminal (+) to the negative terminal (–). This phenomenon is discussed in greater detail in *Tech Note 210* and *Tech Note 211*.

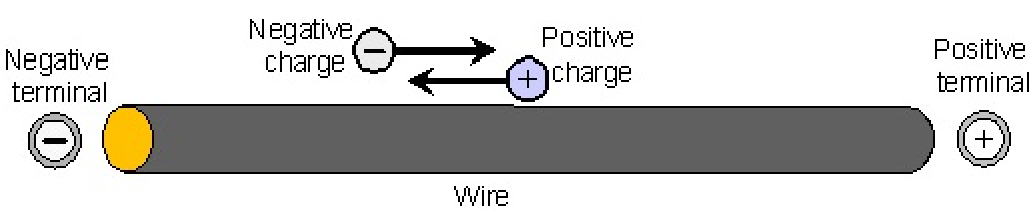

Figure 217.1 *Electrical current flow through a conductor is actually a flow of negative charges in one direction and positive charges flowing in the opposite direction.*

Note in *Figure 217.1* the electrical current flow is actually positive charges flowing in one direction and negative charges flowing in the opposite direction. The flow of electricity through a conductor can, therefore, be defined as flowing from positive (+) to negative (–), or it can be defined as flowing from negative (–) to positive (+).

Some text books define electrical current flow from negative to positive because that is the direction of electron flow through the conductor. Other text books define electrical current flow from positive to negative. This creates confusion for the reader. Engineers and scientists have defined *conventional current* flow based upon a positive charge flowing from the positive terminal (+) to the negative terminal (–) as illustrated in *Figure 217.2.* Electronic equipment makes the positive terminal “hot” and the negative terminal the chassis ground. In direct current circuits the *positive terminal is red* and the *negative terminal is black.* In alternating current circuits polarity changes at regular time intervals and there is no defined positive and negative conductor or terminal. In ac circuits, there are simply grounded and ungrounded conductors.

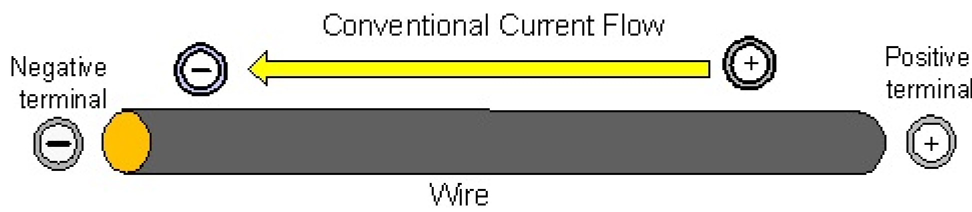

Figure 217.2 *Conventional current flow as defined by engineers and scientists is from positive to negative.*

Magnetic Flux: Natural magnets are materials which have the ability to exert forces on each other and upon some other materials such as iron. A magnet is surrounded by a magnetic field. The forces produced by a magnet are strong next to the magnet, and grow weaker at greater distances from the magnet. This magnetism created by the magnet is called *magnetic flux*. The Weber is the unit of measure of magnetic flux. What is of real significance is the amount of magnetic flux that is concentrated into a given space. This is called *magnetic flux density and a common unit of measure of magnetic flux density is Webers per square meter (Weber/m^2) or Tesla*. One Weber per square meter is equal to one Tesla. Another unit for the measure of magnetic flux density is the Gauss. *The symbol for magnetic flux density is* ***B****.* One Weber per square meter is equal to 10,000 Gauss.

The unit of magnetic flux (Webers) is also defined as torque per Ampere. Torque is in units of Newton-meters, therefore, the Weber is equal to one Newton-meter per Ampere. Since power is torque per unit time, then it can be seen that power is proportional to current flow. These conversions are summarized as follows:

$$1 \text{ Weber/m}^2 = 10{,}000 \text{ Gauss} = 1 \text{ Tesla}$$

$$1 \text{ Weber} = \frac{\text{Newton-meters}}{\text{Ampere}}$$

where Newton-meters is torque

$$\text{therefore,} \quad 1 \text{ Weber} = \frac{\text{torque}}{\text{Ampere}}$$

Magnetic flux has a direction or an orientation in relation to the poles of the magnet. Magnetic poles are defined as North (N) and South (S) as shown in *Figure 217.3.* Within the magnet the magnetic flux is oriented from South (S) to North (N). *On the outside of the magnet the flux is oriented from North (N) to South (S).* This is important to know because these are the forces that operate solenoids and electric motors.

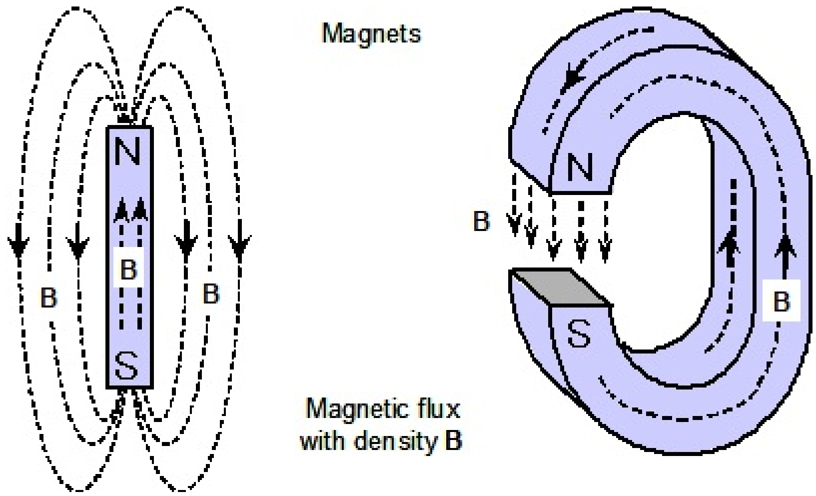

Figure 217.3 *Magnetic flux completes a circuit with the direction from South to North inside the magnet and from North to South outside the magnet.*

H. C. Oersted in 1820 discovered that electrical current flow in a wire produced a magnetic field around the wire. This is illustrated in *Figure 217.4.* Later, A. M. *Ampere developed a mathematical theory which quantitatively described the relationship between the magnetic flux density and the current flow in the conductor.* This is known as **Ampere's law**. The equation involves the use of calculus and will not be discussed in this Tech Note.

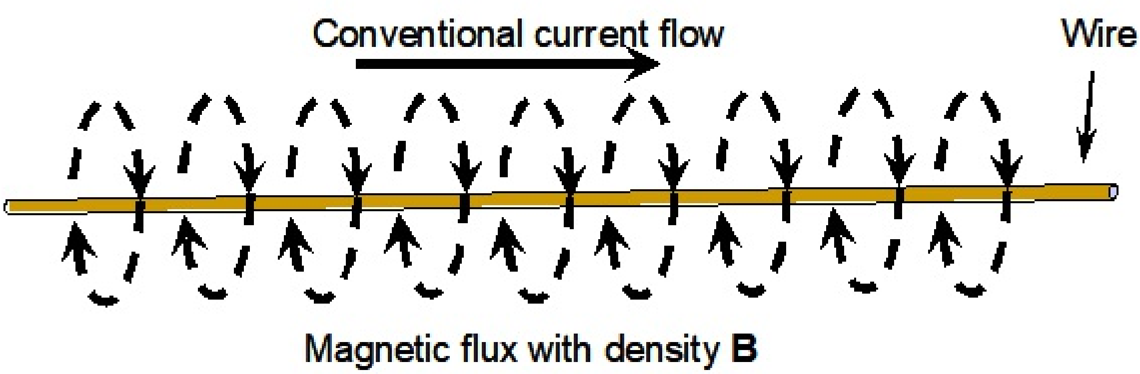

Figure 217.4 *Electrical current flow through a wire produces a magnetic field around the wire.*

The orientation of the magnetic flux around a wire carrying current (conventional current) can be found in Ampere's law. This is known as the ***Right Hand Rule.*** *Grasp the wire with the right hand with the thumb pointing in the direction of the conventional current flow. The fingers of the right hand will curl around the wire with the tips of the fingers pointing in the direction of the magnetic flux.* This is illustrated in *Figure 217.5.* (Text books using electron flow will call this the left hand rule)

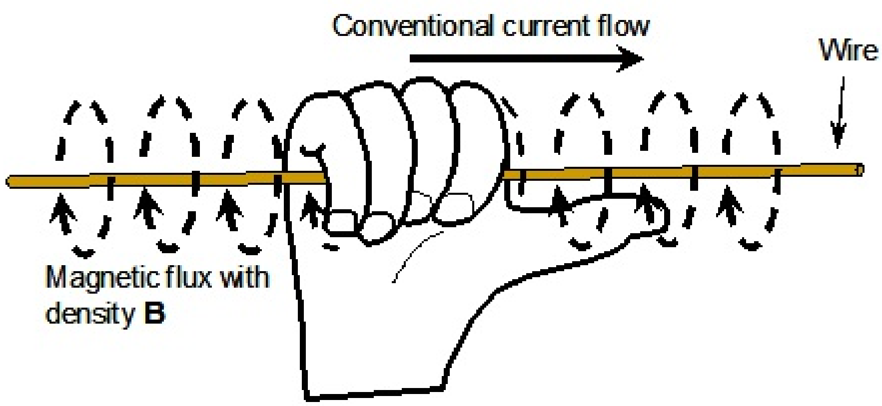

Figure 217.5 *Grasp the wire with the right hand with the thumb pointing in the direction of the current flow and the fingers will curl around the conductor in the direction of the magnetic flux.*

Electromagnets: If there is a magnetic field around a wire carrying electrical current, then it would seem reasonable that an electrical magnet (electromagnet) can be constructed. Imagine a coil of wire such as would be created by wrapping insulated wire around the paper core of a roll of paper towel. Then pass current through the wire. This is illustrated in *Figure 217.6.* By defining current as flowing from positive (+) to negative (−), the rules for determining the orientation of the magnetic flux produced are **Right Hand** rules not left hand rules. Using the right hand rule, the direction of magnetic flux around each wire can be obtained. Note that when this is done for the coil of wire in *Figure 217.6* all of the flux arrows on the inside of the coil are pointing in the same direction. On the outside of the coil, the magnetic flux arrows are also pointing in the same direction. Of course, if the current flow was in the opposite direction, all the magnetic flux lines would point in the opposite direction.

Now remember from the earlier discussion that the magnetic flux points from the South pole (S) to the North pole (N) on the inside of the magnet. Therefore, we can determine the North pole and the South pole of the electromagnet shown in *Figure 217.6.*

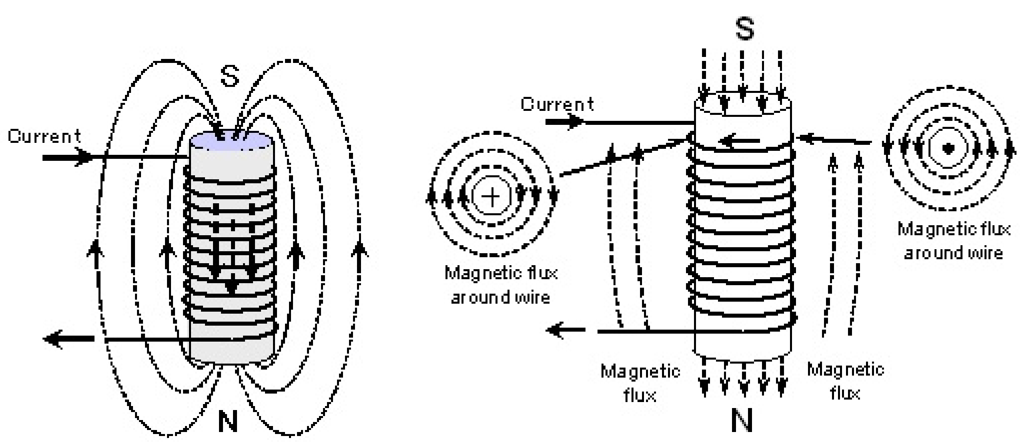

Figure 217.6 *Use the right hand rule to determine the direction of the magnetic flux of each wire in the coil. Flux is oriented South to North inside the magnet. When looking at a cross section of a wire a dot indicated current flowing towards the observer and a cross indicates arrows flowing away from the observer.*

There is another **right hand rule** which can be used to determine the poles of an electromagnet. Grasp the electromagnet with the right hand with the fingers pointing in the direction of current flow around the electromagnet. The thumb is then pointing to the north pole of the electromagnet. This is illustrated in *Figure 217.7.*

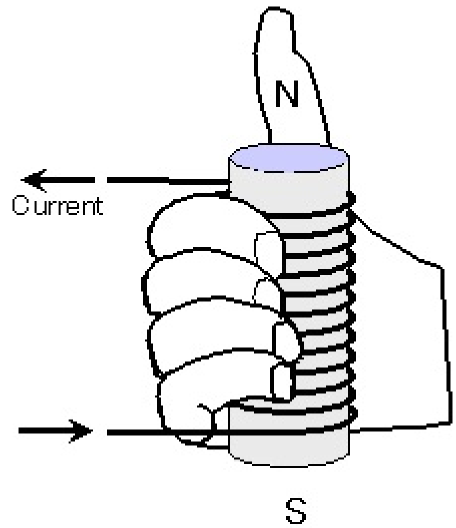

Figure 217.7 *To determine the North pole of an electromagnet, grasp the coil with the fingers coiled in the direction of current flow, and the thumb points to the North pole.*

Current Flows in a Wire Placed in a Moving Magnetic Flux: Michael Faraday in 1831 discovered that when a magnet is moved near a wire completing a circuit, a current flow is induced into the wire. This is illustrated in *Figure 217.8.* **Faraday's law** explains that *when a magnet is moved past a wire completing a circuit, a current is induced into the circuit*. It does not matter whether the wire is moved with the magnet stationary or vice versa. As long as the wire is moving with respect to the magnetic flux, a current is induced to flow in the loop of wire. The motion of the wire must be perpendicular to the orientation of the magnetic flux.

A current induced into a wire by magnetic flux will flow through the wire in such a direction that the magnetic flux produced by the induced current will attempt to repel the original magnetic flux. This means that if a North magnetic pole is moved towards a coil of wire, the induced current flow in the coil of wire will produce a North magnetic pole to *repel* the approaching magnet. This theory was actually deduced from observations with magnets and induced currents in wire circuits by H. F. Lenz in 1834 and became known as Lenz's law. Using ***Lenz's law****, the direction of induced current flow in a wire can be determined*. *Lenz's law also describes the principle upon which an electric induction motor operates*.

Another right hand rule describes the relationship between the magnetic flux, current flow and direction of motion of the wire. *Point the* ***thumb*** *of the right hand in the direction of motion of the wire through the magnetic flux*. *Point the* ***index finger*** *in the direction of magnetic flux from North to South*. Bend the ***second finger*** so it forms a right angle to the index finger. The *second finger* is pointing in the direction of conventional current flow in the loop of wire. This is illustrated in *Figure 217.8.*

Note in *Figure 217.8* that the magnet moving to the right is the same as moving the wire to the left. This can be confusing because when the magnet is moved to the right, even through the wire is stationary, the wire is actually moving to the left with respect to the magnetic flux.

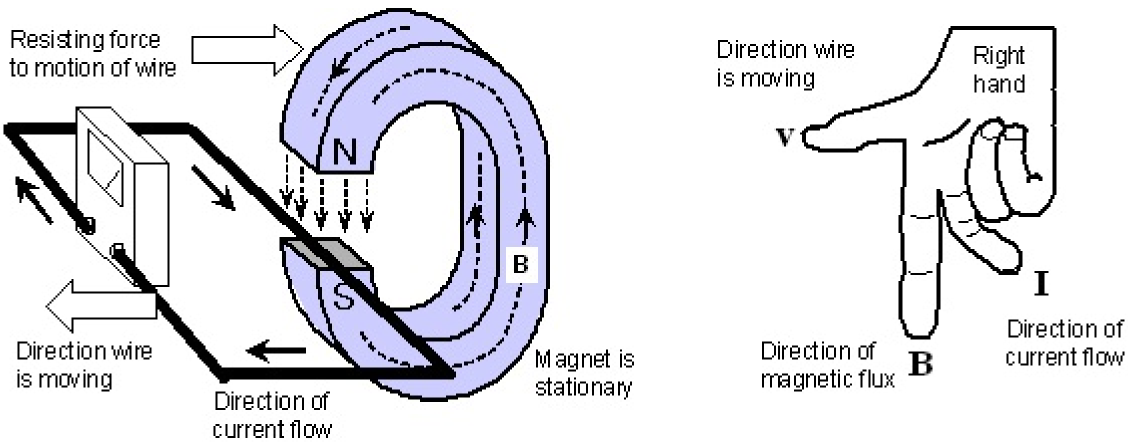

Figure 217.8 *If a wire forming a circuit is moved through a magnetic flux, a current will flow in the wire. The right hand rule can be used to determine the direction of current flow in the wire knowing the direction of magnetic flux and direction the wire is moving with respect to the magnetic flux.*

Mutual Induction: *If an ac current is applied to a coil of wire, the alternating current creates an alternating magnetic field.* The magnetic flux around the coil builds up with the North pole at one end of the coil and the South pole at the other end. Then the current stops, reverses direction, and then flows in the opposite direction. This causes the magnetic poles to reverse as illustrated in *Figure 217.9. With alternating current applied to the coil of wire, the magnetic flux is constantly moving* even though the coil of wire is stationary.

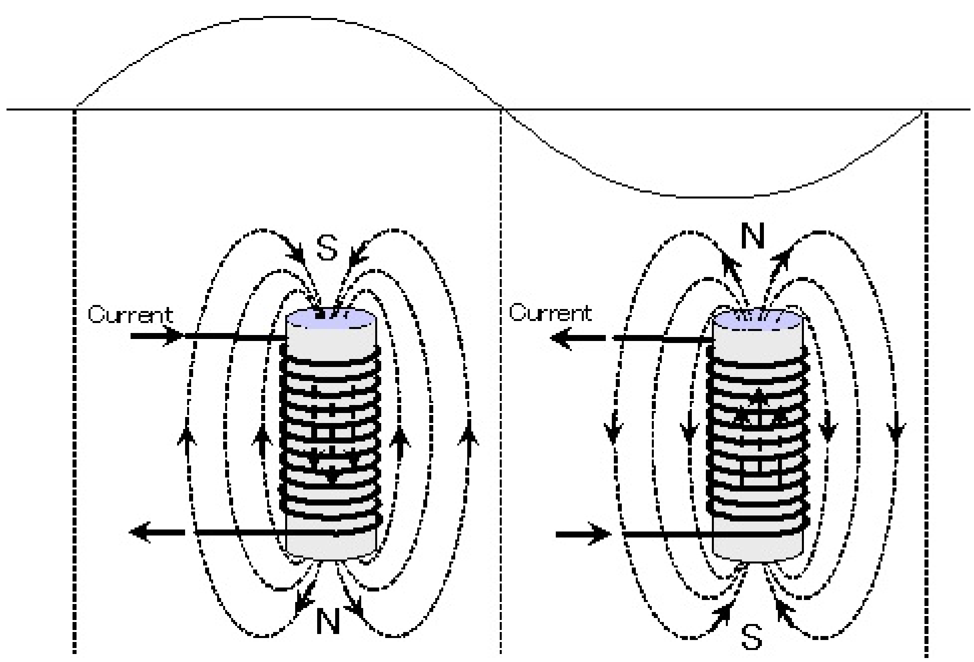

Figure 217.9 *The magnetic flux about a coil of wire is in constant motion when alternating current is applied to the coil with the magnetic poles constantly reversing.*

If a second coil of wire is placed next to the first coil the moving magnetic flux caused by the alternating current flow through the first coil will cut across the wires of the second coil. A current flow will be induced into the second coil if it forms a complete circuit. By ***mutual induction***, *a current is induced into the second coil circuit by the current flow through the first coil.* This is the principle of operation of the transformer. A transformer is illustrated in *Figure 217.10.* The voltage produced in the second coil is equal to the voltage applied to the first coil times the ratio of the number of turns of wire on the second coil divided by the number of turns of wire on the first coil. Note that the two coils are electrically independent of each other, linked only by the magnetic flux. A transformer is useful for isolating one circuit from another. Because the voltage applied to the first coil as compared to the second coil is dependant upon the number of turns of wire on the coils, a transformer can be used to change voltage level in a circuit.

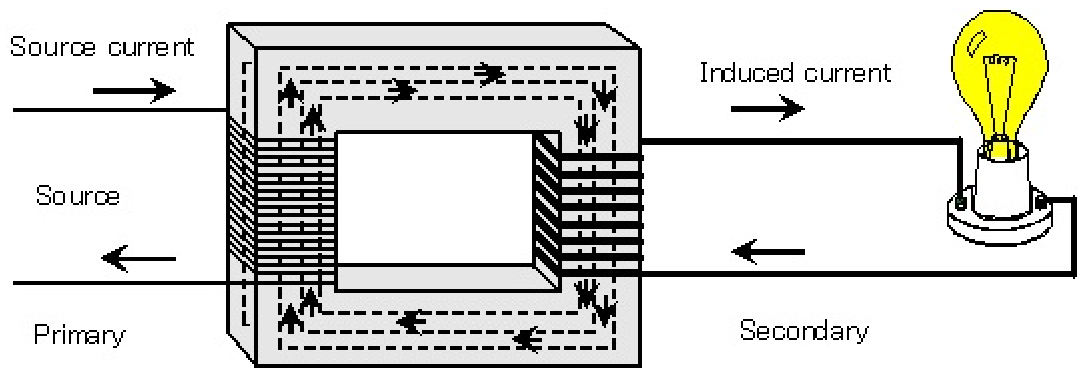

Figure 217.10 *By mutual induction, the current flow in the primary winding of a transformer induces current to flow in the secondary circuit.*

Self Induction: If a voltage can be induced into a wire that is placed in a moving magnetic flux by mutual induction, than the magnetic flux around one wire in a coil will have an effect upon the adjacent wire in the coil. Note in *Figure 217.11* that the magnetic flux on one wire cuts through the adjacent conductors of the coil. *This effect will induce a voltage in the adjacent coils, and that voltage will be in opposition to the applied voltage across the coil.* This is referred to as a reverse voltage or reverse emf. The level of the reverse voltage is dependant upon the current flow through the coil. The process that produces this reverse voltage is called ***self induction***. Self induction is a phenomenon of a coil energized with alternating current and produces an opposition to current flow in addition to the resistance of the wire in the coil. This magnetically produced opposition to current flow in an alternating current circuit is called inductive reactance.

Conclusions: A moving electrical charge or current produces a magnetic flux around the charge. An electromagnet can be constructed by winding wire around an iron or steel core and passing electrical current through the wire. The process is reversible by passing a wire through a magnetic flux at a right angle to the direction of the flux. The more dense the magnetic flux and the greater the velocity of the wire with respect to the flux the more current will flow in the wire. This is the basic principle of the electric generator. By placing a second coil of wire in the magnetic flux of another coil of wire, electrical energy can be transferred from one coil to the other when the first coil is energized with current that produces a moving magnetic flux such as the case with alternating current. This phenomenon is known as mutual induction and is the principle of the transformer which is discussed in *Tech Note 218* and the principle of the induction motor which is discussed in *Tech Note 312.*

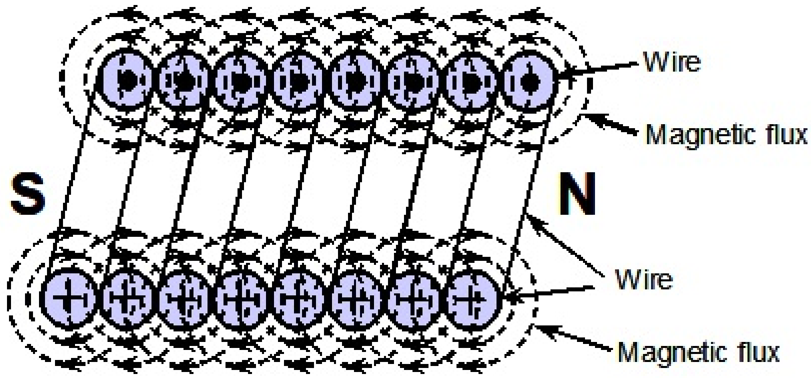

Figure 217.11 *By self induction, the current flow in one wire of a coil will induce a reverse voltage in adjacent wires and this induced voltage will opposes the flow of current in the coil. Along with wire resistance this is what limits current flow in the coil to a maximum level.*

The magnetic field all along an electrical wire encircles the wire in a particular direction depending upon the direction the current is flowing. If a person could view a wire cross section and determine direction of current flow than orientation of the magnetic field can be determined. A "**dot**" in the middle of the wire cross section indicates the current is flowing towards the observer. If a "**plus sign**" is observed then the current is flowing away from the observer. This is illustrated in *Figure 217.12.* This is important to remember because knowing the direction of current flow through a wire is necessary to understand the polarity of the magnetic filed. Understanding magnetic fields is essential to understanding how most electrical equipment operates.

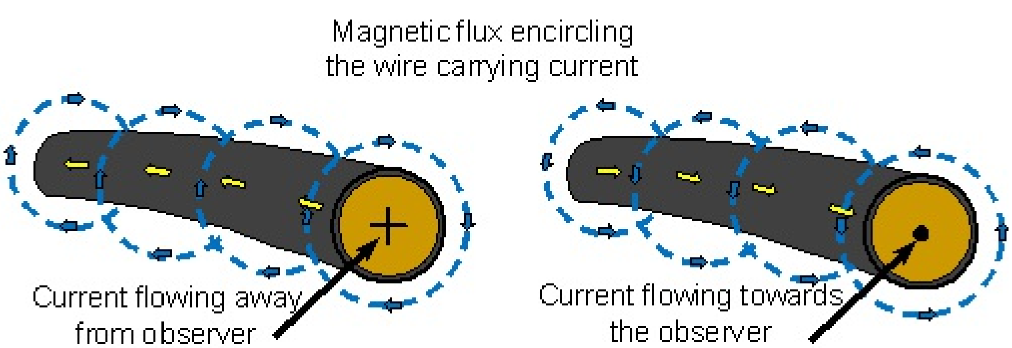

Figure 217.12: *Viewing the wire cross section with current flowing towards the observer (right diagram) the magnetic field encircles the wire in the counter-clockwise direction.*