Fundamentals of electricity and magnetism

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Electricity

Electricity is a form of energy as are heat, light, mechanical, etc. It can be generated from these other forms of energy and converted to other forms of energy. A knowledge of elementary electricity will assist the reader in better understanding of the operating principles of AC generators.

All substances are composed of molecules which are in turn made up of atoms. These atoms consist of electrons, protons and neutrons. Electrons are negatively charged electrical particles, protons are positively charged and neutrons contain no charge. Protons and neutrons are located at the center of the atom (nucleus) with the electrons orbiting in fixed paths around the nucleus. The positive charge at the center equals and attracts the charge of the orbiting electrons to keep the atom intact and stable (Figure 1).

The atoms are in a balanced state and

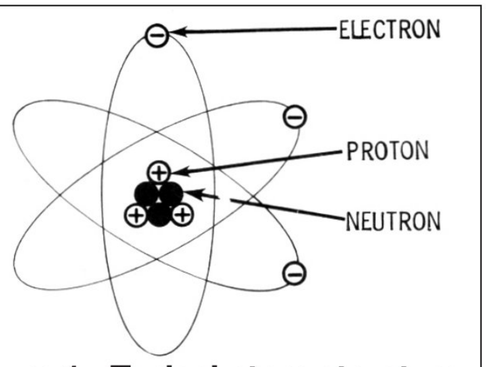


Figure 1—Typical atom structure.

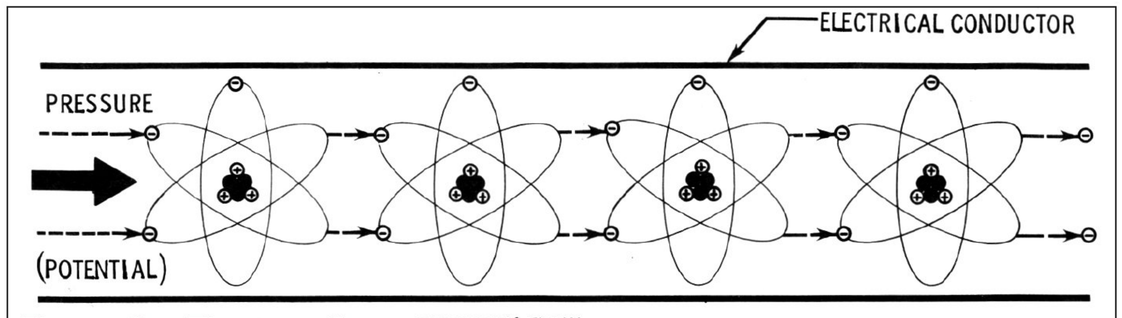


Figure 2 — Electron flow.

no useful electrical current can be made to flow under these conditions. Now, if an atom could be made to momentarily lose an electron, it would attain a net positive electrical charge. If the atom gains an electron, it would assume a negative charge. Hence, positively charged atoms would tend to attract electrons while negatively charged atoms would repel them. In order for balanced atoms to become charged (unbalanced) and initiate current flow, an electrical potential difference (voltage) must be applied to the circuit. This potential difference (or pressure) will then force electrons (negative) to flow from negatively charged atoms (excess electrons) to positively charged atoms (excess protons) in a chain reaction throughout the conductor (Figure 2). This resultant drift of electrons between adjacent atoms constitutes the flow of electrical current through the conductor. The voltage potential necessary to initiate current flow is supplied by the vehicle battery and/or alternator.

Voltage

The volt is the unit used to measure the amount of electrical potential (pressure) and is somewhat analogous to water pressure. The higher the pressure, the faster the water (current) will flow, providing the resistance is constant.

Similarly, higher circuit voltages (greater potential difference between two points in a circuit) will result in an increase in current (electron) flow. Also, whenever current flows to serve some useful purpose in a circuit, some voltage is always lost (consumed). This voltage loss is commonly called "voltage drop" and is dependent on the amount of resistance existing in the circuit.

Ampere

The ampere is the unit used to express the quantity of current flow in a conductor. Since current flow consists of electrons, it takes countless billions of electrons constantly flowing for a given time to equal one ampere. Current flow is affected by the inherent resistance in a circuit such that the current decreases as the resistance increases at a given voltage potential.

Resistance

The difficulty electrons encounter when moving through a conductor is termed resistance. It is the opposition offered to the flow of current in a circuit. The basic unit used for measuring electrical resistance is the ohm. Some materials have lower resistance to current flow than do others. Materials with electrons that are easily displaced from atom to atom under relatively low potential have a low resistance and are commonly called conductors. Silver, copper and aluminum are examples of such materials. Copper is commonly used as a conductor in electrical circuits because of this desirable characteristic. The resistance of a conductor will decrease as its length is shortened or the cross sectional area (diameter) is increased.

Since various materials offer different amounts of resistance to current flow, a basic unit (standard) is needed for comparison purposes. This unit is called "specific resistance" and is the resistance offered by a given material that is one foot in length and one circular mil in diameter. Figure 3 lists several conductor materials in order of specific resistance (K). As can be observed from the table, copper conductors have much lower specific resistance than the other materials. This is the main reason why copper conductors are so widely used in the electrical field. Moreover, the resistance of copper (and most other materials) will rise very slightly (positive temperature coefficient) with an increase in temperature. This resistance change is usually so small that it can be ignored for most practical purposes.

MATERIAL	SPECIFIC RES (K) (Ω/per cir-mil-ft.)
Copper	*10.4*
Aluminum	*17*
Brass	*40*
Lead	*130*
Steel	*275*
Iron	*500*

Figure 3–Specific resistance.

The following formula may be used to determine the resistance offered by con-

ductors of various length, diameter and material.

$R = \frac{KL}{D^2}$ Where, R = resistance, Ω, ohms
K = specific resistance
L = length, ft.
D = diameter, mils (to convert diameter in inches to mils, multiply by 1000)

Figure 4 shows a comparison between two circuits that are essentially the same except for type of conductor material used. Detail A uses steel conductor materal and B uses copper material.

The circuit values for detail A (steel conductors) are computed as follows:

Wire Material = Steel
Wire Length = 100 Ft.
Wire Diameter = 1/6″
Wire Diameter = 1/16″ = 0.0625″

$$R = \frac{KL}{D^2} = \frac{(275)(100)}{(62.5)^2} = \frac{27\ 500}{3906} = 7\,\Omega$$

In detail A,

$$I = \frac{E}{R} = \frac{12}{12+7\ 19} = 0.63 \text{ Amp}$$

E = IR = (0.63) (7) = 4.4 volts

Similarly, the values for detail B (Copper conductors) are:

Wire Material = copper
Wire Length = 100 Ft.
Wire Diameter = 1/16″

Wire Diameter = 1/16″ = 0.0625″

$$R = \frac{KL}{D^2} = \frac{(10.4)(100)}{(62.5)^2} = \frac{1040}{3906} = 0.27\,\Omega$$

$$I = \frac{E}{R} = \frac{12}{12+0.27} = \frac{12}{12.27} = 0.97 \text{ Amp}$$

E = IR = (0.97)(0.27) = 0.26 Volts

A comparison of the two details shows that conductors having low specific resistance should be used in electrical circuits to minimize power loss and maximize efficiency.

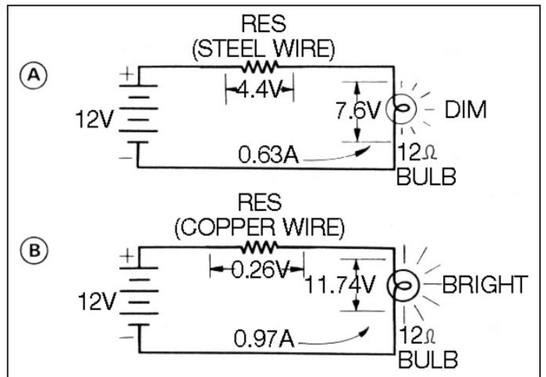


Figure 4–Cicuit conditions with iron and copper conductors.

Other materials, known as insulators, offer a very high resistance to current flow. In these materials, it is very difficult for electrons to travel between atoms even under the influence of very high voltages. Insulators are nonetheless very useful since they can be used to prevent current flow between conductors which are not intended to be interconnected. Some good electrical insulators are glass, mica, Bakelite, varnish and vinyl. Resistance tends to counteract the effects of applied voltage so as to reduce the amount of current flow in a conductor (Figure 5).

Power

Power is defined as the ability of something to do useful work.

a. Electrical power is measured in watts and in electrical terms is the product of the voltage times amperes for DC (direct current) circuitry. All power sources have a practical limit on the amount of power they can supply; this is usually referred to as capacity.
b. Mechanical power is frequently measured in horsepower which is equivalent to 764 watts.

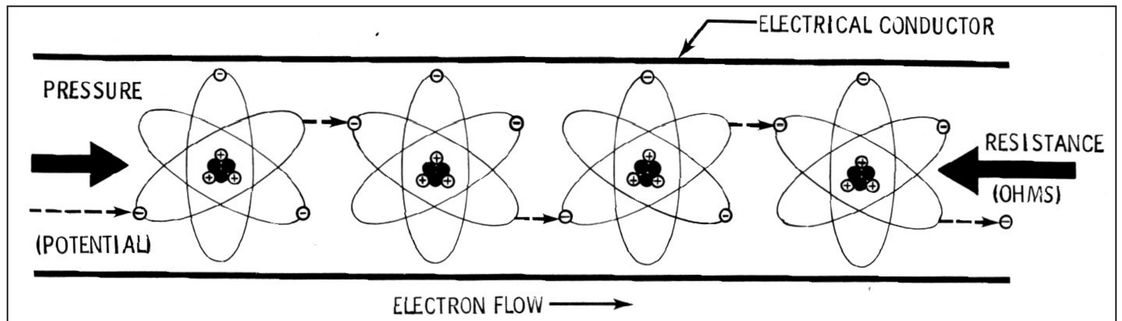


Figure 5–Effect of resistance on electron flow.

Ohm's Law

This law states the relationship between voltage, current and resistance in an electrical circuit. The law states the relationship in the following three ways:

E = IR (Voltage equals current times resistance).

$I = \frac{E}{R}$ (Current equals voltage divided by resistance).

$R = \frac{E}{I}$ (Resistance equals voltage divided by current).

Expressed verbally, one volt will force one ampere of current through one ohm of resistance in an electrical circuit. The voltage (E) is given in volts, current (I) in amperes, and resistance (R) in ohms.

Electrical circuits

A simple circuit consists of a complete path for current (electron) flow. The current flows from the source (battery) through the load (lamps) and returns to the source (Figure 6, page 14).

In the series circuit of Figure 6, the same circuit current flows through both loads (bulbs) on its way back to the source. This current is equal to:

$$I = \frac{E}{R} = \frac{12}{12} = 1 \text{ Amp.}$$

The power taken from the battery is then, P = IE = (1) (12) = 12 Watts.

The parallel circuit has the loads connected in a parallel arrangement. The total current divides between the two loads and recombines again on returning to the battery.

The current in one branch is $I_1 = \frac{E}{R} = \frac{12}{6} = 2$ Amps, and I_2 is the same. The total current drawn from the supply is $I_1 + I_2 = 4$ Amps. The total power is therefore, P = (4) (12) = 48 Watts. Electrical devices such as batteries, motors, starters, radios, etc., can serve as loads in both series and parallel circuits.

Current (electrons) flow in the external circuit from minus (-) source polarity to plus (+) polarity.

NOTE: In the past it was a commonly accepted idea that current flowed from plus to minus in the external circuit (Franklin Theory). However, modern theory (electron theory) has since demonstrated that current consists of electrons and actually flows from minus to plus. In any case, no confusion need result since all polarities, laws and other relationships will remain the same.

Some typical situations that can occur in circuits are termed short and open conditions. In Figure 7A, page 14, the path is broken (open) so that current flow is interrupted; hence, the lamp will not light. Figure 7B shows a "short" condition where the current flows around the load because of lower resistance path. Again, the lamp will be inoperative. In the "open"

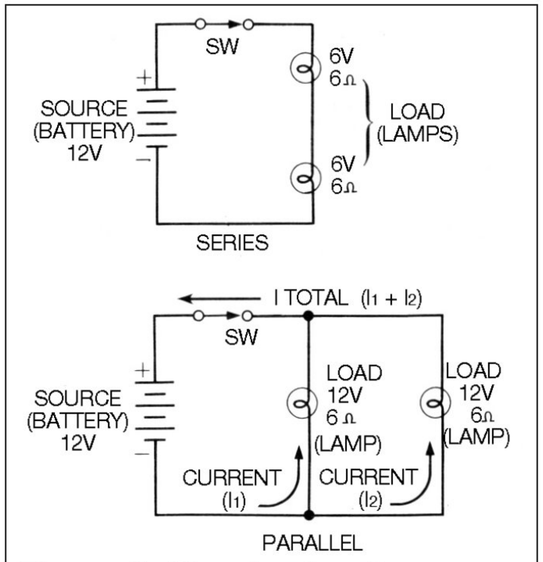


Figure 6–Simple circuits.

condition, no current will be drawn from the battery due to the extremely high circuit resistance; whereas, high current will be drawn in the "shorted" condition.

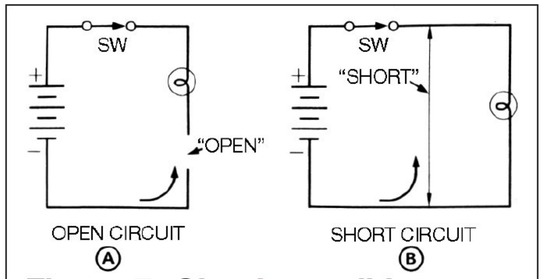


Figure 7–Circuit conditions.

Types of electrical current & voltage

The two basic types of current and/or voltage are:

Direct current (DC)—this current always flows through the circuit in the same direction. The current flowing in Figure 6 is DC since it flows continuously in one direction. Direct current is produced directly by the vehicle storage battery only (which is a chemical reaction). Other sources of DC power are the generator and the alternator. However, both the generator and alternator produce AC which must then be converted into DC by some means. The generator uses a commutator (a form of mechanical rectification) to convert AC to DC, and the alternator uses an electronic rectifier system (diodes).

Alternating current (AC)—this type of current flows back and forth in the circuit. It is commonly used in home and industrial electrical systems. The current flows in one direction and then reverses because the applied voltage changes polarity. The plot (graph) of this wave form starts at zero, increases to a maximum in one direction (positive), reverses, falls to zero and continues to a maximum in the opposite (negative) direction, again reverses and returns to zero. Figure 8 is a plot (graph) of this wave form (called a sine wave) and shows one cycle of the wave form. The frequency of this wave form is defined as the number of cycles per second and the unit of measure is "hertz." As an example, the normal electrical system available to your home or business is 60 hertz or 60 cycles of a sine wave each second.

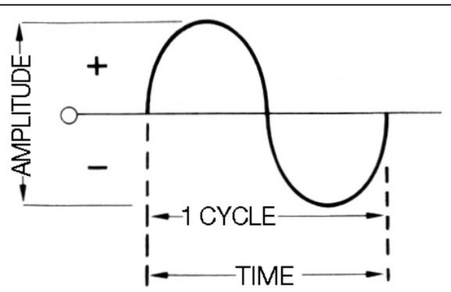


Figure 8–AC voltage waveform.

The positive or negative half of the sine wave is called an alternation.

The simple AC circuit of Figure 9 shows the current direction for the instantaneous polarities indicated. Circuit B shows that the current has reversed due to the momentary change in applied voltage polarity.

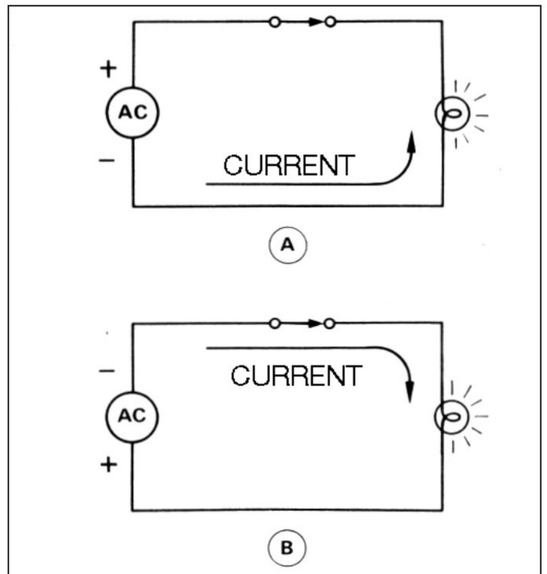


Figure 9–Current flow in an AC circuit.

Both AC and DC power are more or less equivalent and can be used for similar circuit applications. However, DC power must be used for battery charging applications such as in vehicle electrical systems.

Magnetism

Magnetism is very closely related to electricity. Like electricity, magnetism cannot be seen. However, its effects are quite evident in the operation of motors, generators, and other types of electrical equipment.

Permanent magnets

Commercially available magnets consist of special magnetic materials which retain their magnetism for long periods of time; these are termed permanent magnets (Figure 10).

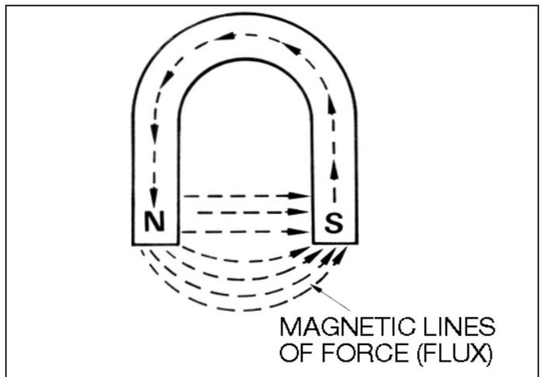


Figure 10–Permanent magnets.

All magnets consist of a north and a south pole. Invisible lines of force (called flux) exist between the poles which attract materials containing iron. The stronger the magnet, the more lines of force it will have between its poles. Similar to electricity, like poles (like charges) will repel each other and unlike poles (unlike charges) will attract each other.

Electromagnets

When passing current through a conductor, an associated circular magnetic field will be produced around the conductor (Figure 11).

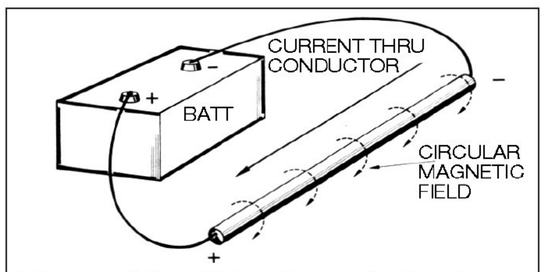


Figure 11— Principle of electromagnetism.

By forming the conductor into a coil, the separate fields all combine in one larger and much stronger magnetic field (Figure 12).

If a good magnetic material such as soft iron is inserted into the coil, the flux will be concentrated in the core and the magnetic field will again be greatly

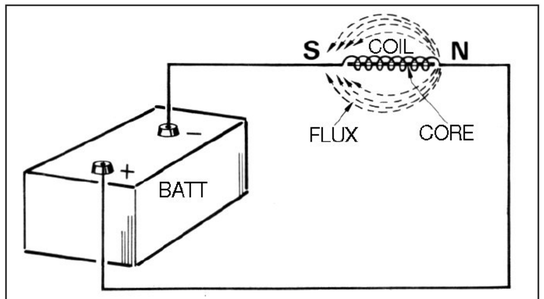


Figure 12— Coil electromagnet.

enhanced. Increasing the coil current and/or number of turns will also result in an increase of magnetic field strength. Electromagnetic principles are used in the design of motors, generators, relays, solenoids and other applications where the magnetic field depends on the coil current. An electromagnet retains little or none of its magnetic properties when there is no current in the coil.

Magnetic induction

If an electrical conductor is moved across or through a magnetic field, a voltage will be induced in the conductor

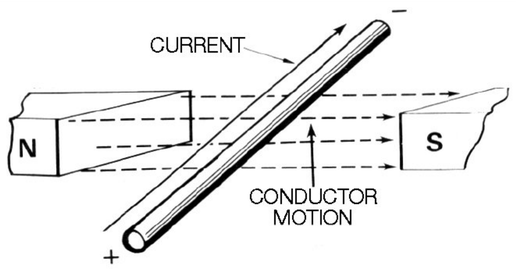


Figure 13— Principle of induced voltage.

(Figure 13).

If the conductor is applied to a closed circuit, current flow will be established. The magnitude of the induced current depends on the speed of the moving conductor, the strength of the magnetic field, and the angle traced through the field by the conductor. The principle of magnetic induction is the basis of operation of all electrical generators.

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