OHM'S LAW, ELECTRICAL MATH and VOLTAGE DROP CALCULATIONS

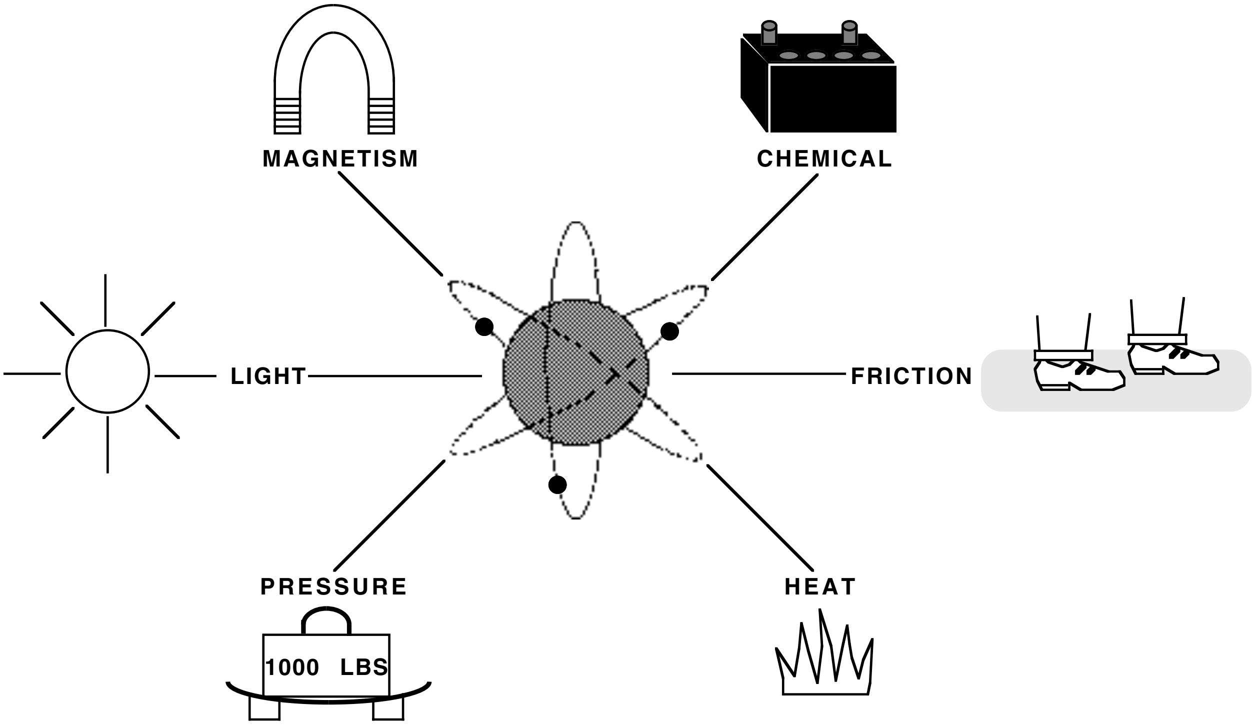
By Tom Henry

HENRY PUBLICATIONS™ SINCE 1985

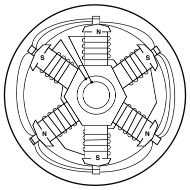
Based on the 2023 NEC®

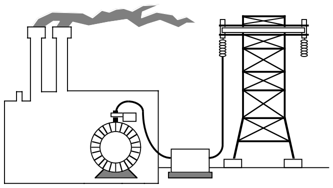
ISBN 978-0-945495-26-0

TABLE OF CONTENTS



The number one producer of electrical energy is the generator which employs the principle of **electromagnetic** induction.





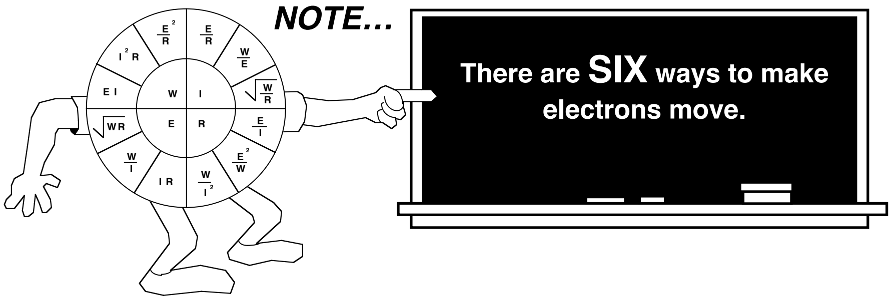
When atoms are added or taken away from the molecules of a substance, the chemical change will cause the substance to take on an electric charge. The process of producing electron flow by **chemical** action is used in **batteries.**

Voltage produced by **pressure** is referred to a **piezoelectricity**. Voltage is produced by compressing or decompressing crystals of certain substances. The power capacity of a crystal is very small. When a crystal of quartz is compressed into a different shape electrons tend to move through the crystal. The crystal is able to convert mechanical force, either pressure or tension, to electrical force. The fundamental reasons for this action are not known. However, the action is predictable, and therefore useful. Crystals are mainly used in communication equipment.

When a length of copper is **heated** at one end, electrons tend to move away from the hot end toward the cooler end. However in some metals, such as iron, the opposite action takes place and electrons tend to move toward the hot end. The heating of two dissimilar metals at a junction causes thermoelectric voltage. This is called a **thermocouple**. Thermocouples have somewhat greater power capacities than crystals, but their capacity is still very small compared with some other sources. Thermocouples are mainly used as heat measuring devices.

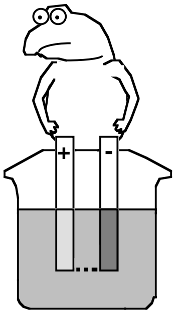
When **light** strikes the surface of a substance, it may dislodge electrons from their orbits around the surface atoms of the substance. This occurs because light has energy, the same as any moving force. Metallic substances are more sensitive to light than other substances. Voltage produced in this manner is referred to as a **photoelectric** voltage. A photocell's capacity is also very small. However, it reacts to light-intensity variations very quickly. This characteristic makes the photocell very useful in television cameras, burglar alarms, etc.

Friction is the last of the six ways to produce electron movement and is the **least** used. Only **5** of the ways can be used to cause a **current to flow** through a wire; friction cannot be used. Friction is an unavoidable method of producing electron movement. Under certain conditions a **static charge** is generated by two objects being rubbed together. Example, walking across carpet on a dry day and touching a grounded object releases the static charge that was built up. Static charges are often a problem causing radio interference. Explosions can be caused by ignition from a static spark.



THE BATTERY

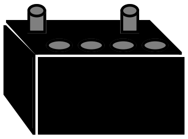
In 1780 Luigi Galvani thought he had discovered an electrical source in animals. Galvani was conducting a class in anatomy at a University in Italy when he removed dissected frog legs from a salt solution and suspended them with a copper wire. Whenever he touched the frog legs with an iron scalpel, the muscles of the frog leg twitched. Galvani realized that electricity was being produced, he thought it came from the muscles of the frog leg.



CURRENT FLOW

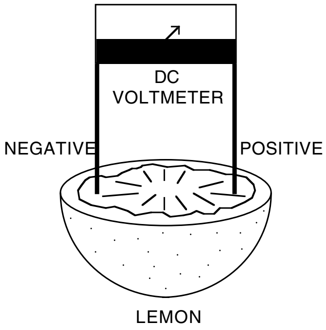
Alessandro Volta found that the muscles of the frog did not produce electricity. Volta discovered that the electricity was a result of a **chemical action** between the copper wire, iron scalpel, and the salt solution.

Volta went on to make the first **wet cell battery** as he found that by putting two **different metals** in certain chemical solutions, electricity could still be produced.

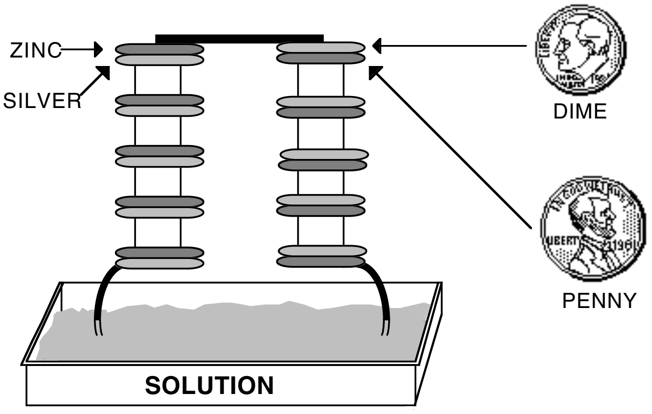


The simplest cell is known today as either a **galvanic** or **voltaic** cell in honor of these two men, Galvani and Volta.

Without having to dissect a frog, you can duplicate Galvani's experiment by substituting a lemon. Roll the lemon on a table to make it juicy. Then cut the top off the lemon. Insert a copper wire and a steel wire opposite each other in the top of the lemon. Just like a battery, one is positive and the other will be negative. Electricity will flow from one terminal to the other because of the **chemical action**.



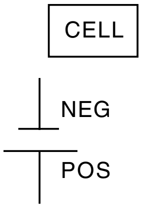
You can duplicate Volta's experiment using a stack of dimes and pennies. Separate the dimes and pennies with a piece of paper towel soaked in vinegar and water. Have **equal** number of dimes and pennies. If you start the stack with a dime, you should end with a penny. Add a tablespoon of vinegar to a glass of water for the solution. A DC meter connected to one end of the penny and dime on the other stack should show a brief deflection of the meter. The larger the stack, the greater the force.



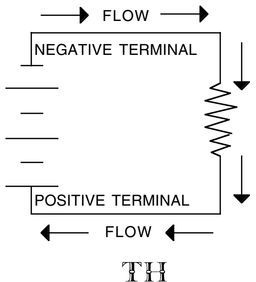
BATTERY TYPES

WET and DRY types
PRIMARY and SECONDARY types

A **cell** is a device that transforms chemical energy into electrical energy. The cell is the fundamental unit of the battery. A simple cell consists of two **electrodes** placed in a container that holds the **electrolyte**. Usually strips of **zinc and copper** metal are used for electrodes with **sulfuric acid** and water for the electrolyte.



The **electrolyte** causes one electrode to lose electrons and develope a **positive charge**, and it causes the other electrode to build up a surplus of electrons and develope a **negative charge**. The difference between the two electrode charges is called the **cell voltage**. The cell is like a chemical furnace in which energy released by the zinc is transformed into electrical energy rather than heat energy.

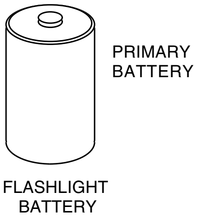


The electrolyte may be salt, an acid, or an alkaline solution. An example would be the automobile storage battery, the electrolyte is in the **liquid form**; while in a **dry cell** battery, the electrolyte is a **paste**.

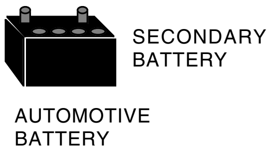
The dry cell is so called because its electrolyte is not in a liquid form. Actually, the electrolyte is a **moist** paste. If it should become dry, it would no longer be able to transform chemical energy to electrical energy. The name **dry** cell, therefore, is not strictly correct in a technical sense.

A cell that is not being used (sitting on the shelf) will gradually deteriorate because of slow internal chemical actions and changes in moisture content. This deterioration is generally very slow if the cells are stored properly in a cool area.

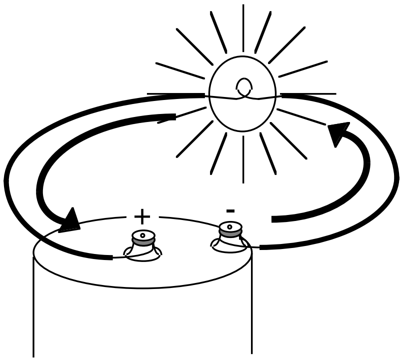
The **primary type** battery converts chemical energy to electrical energy directly, using the chemicals within the cell to start the action. An example would be a flashlight battery. Primary batteries are mostly used where a **limited current** is required.



The **secondary type** battery must first be **charged** before it can convert chemical energy into electrical energy. An automotive battery is an example of a secondary battery as it **stores** the energy supplied to it. The secondary battery is generally used where a **heavy current** is required; secondary batteries are usually **wet** cells. The secondary type battery is referred to as the **storage battery**.

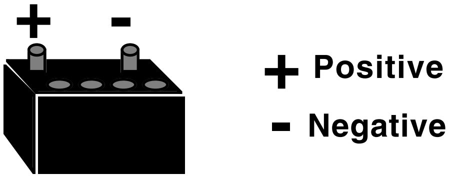


The **electron theory** is that current flows from **negative to positive**. Before the electron theory had been worked out it was believed that an electric fluid moved in a wire from positive to negative. This concept of current flow is called the **conventional current flow**. It doesn't matter which direction you choose as long as you are consistent when solving any circuit problem.



A lead-acid battery is constructed of a number of cells connected together, the number of cells needed depends upon the voltage desired.

A cell consists of a plastic or hard rubber compartment in which contains the cell element, consisting of two types of lead plates, known as positive and negative. These plates are insulated from each other by separators such as plastic, rubber or glass. The plates are submerged in a sulfuric acid solution, referred to as the electrolyte.



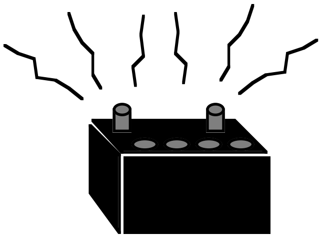
The positive terminal marked (+) is slightly larger than the negative terminal marked (-).

The larger the area that the plates have, the more **current** the battery can supply. This rating is given in **ampere-hours**. If a battery is rated 100 ampere-hours, it means it will supply 5 amperes for 20 hours before the voltage will drop to a discharge level.

When the battery is in its charged condition, the active materials in the lead-acid battery are lead peroxide (used as the positive plate) and sponge lead (used as the negative plate). The electrolyte is a mixture of sulfuric acid and water. The strength (acidity) of the electrolyte is measured in terms of specific gravity.

Concentrated sulfuric acid has a specific gravity of about **1.830**; pure water has a specific gravity of 1.000. The acid and water are mixed in a proportion to give the desired specific gravity.
Specific gravity is the ratio of the weight of a given volume of electrolyte to an equal volume of pure water.

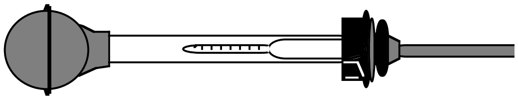
In a fully charged battery, all acid is in the electrolyte so that the specific gravity is at its maximum value. Overcharging does not change the water to more sulfuric acid. Instead, the water is lost as hydrogen and oxygen **gases**. These gases that escape through the vent holes are dangerous and explosive. When these gases are formed during overcharging, the electrolyte appears to be boiling.



As a storage battery discharges, the sulfuric acid is depleted and the electrolyte is gradually converted into water.

The electrolyte that is placed in a lead-acid battery is usually 1.350 or less.

Not all liquids or materials have the same density. Sulfuric acid has a higher density than water. The density can be checked by seeing how a **hydrometer** floated in the electrolyte.



The hydrometer float consists of a hollow glass tube weighted at one end and sealed at both ends. A scale calibrated in specific gravity is laid axially along the body of the tube. The hydrometer float is placed inside the glass syringe and the electrolyte to be tested is drawn up into the syringe. When the syringe is held in a vertical position, the hydrometer float will sink to a certain level in the electrolyte. The reading on the stem at the surface of the liquid is the specific gravity of the electrolyte.

Most storage batteries use 80° F as a normal temperature to which specific gravity readings are corrected. To correct the specific gravity reading, add 4 points to the reading for each 10° F above 80° F and subtract 4 points for each 10° F below 80° F.

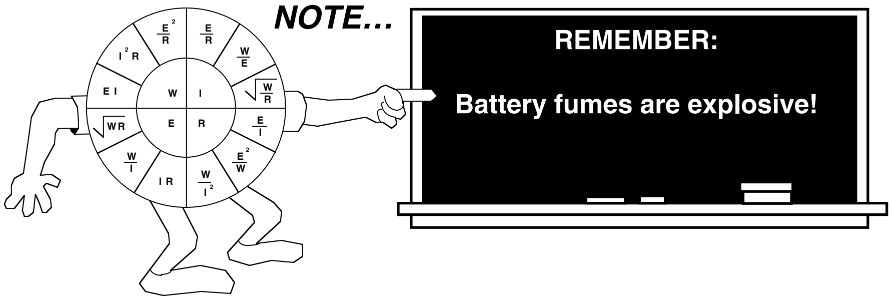
When water is added to a storage battery, the battery should be charged for at least **one hour** before a hydrometer reading is taken. This allows time for the electrolyte to mix.

Hydrometers should be flushed with clean water daily to prevent inaccurate readings.

SPECIFIC GRAVITY READINGS

FROM	TO	CHARGE
1.260	1.280	FULLY CHARGED
1.230	1.250	75% charged
1.200	1.220	50% charged
1.170	1.190	25% charged
1.140	1.160	very little capacity
1.110	1.130	discharged

Persons working near batteries should always wear rubber gloves, a rubber apron, and protective goggles. If the electrolyte is spilled on the skin or clothing, the exposed area should be rinsed immediately with water.

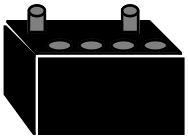


REMEMBER:

Battery fumes are explosive!

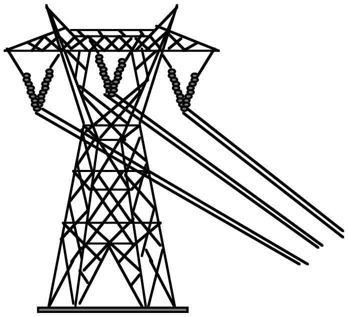
THE MAGNETIC FIELD

In the early days of electricity the only convenient source of electrical energy was the **voltaic cell.** Since cells and batteries were the only sources of power available, some of the early electrical devices were designed to operate from DC.



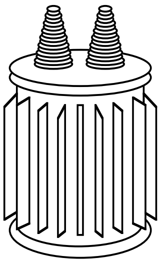
As the use of electricity became more wide spread, certain disadvantages in the use of DC became apparent. Example, to operate a 240 volt lamp, the DC generator must supply 240 volts. A 120 volt lamp could not be operated from this generator by any **convenient** means. A **resistor** would have to be placed in the circuit to reduce the 240 volts to 120 volts. A resistor would consume an amount of power equal to that consumed by the lamp. This is wasting electricity through the heat of the resistor.

Another disadvantage of DC is the large amount of power lost due to the **resistance** of the transmission wires on the towers from the generating plant. This loss can be greatly reduced by operating the transmission lines at a very **high voltage**. This is not practical with a DC generator because of the **commutator** which cannot handle high voltages.



AC generators can be built with much larger power and voltage ratings than DC generators.

AC voltage can be stepped up and down with a device called a **transformer**. Transformers cannot be used with DC.



A magnetic circuit is a complete path through which magnetic lines of force may be established under the influence of a magnetizing force. Most magnetic circuits are composed largely of magnetic materials in order to contain the magnetic flux. These circuits are similar to the **electric circuit**, which is a complete path through which current is caused to flow under the influence of an electromotive force.

Planet earth is a huge magnet and surrounding the earth is the magnetic field produced by earth's magnetism.

There are only two types of magnets: permanent magnets and electromagnets. A magnet is normally made of iron.

Think of magnetic materials as either hard or soft. Soft materials are used in devices where a change in the magnetic field is necessary in the operation of the device, sometimes a very rapid change is required. These are called electromagnets. An electromagnet can be activated by a switch; the magnetic field can be turned on and off by a switching action.

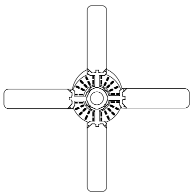
Hard materials are used for permanent magnets such as the magnet that holds a note on a refrigerator.

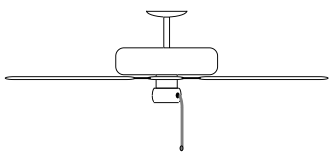
There are three fundamental conditions which must exist before a voltage can be produced by magnetism.

1. There must be a **conductor** in which the voltage will be produced.
2. There must be a **magnetic field** in the conductor's vicinity.
3. There must be a relative **motion** between the field and the conductor. The conductor must be moved so as to cut across the magnetic lines of force, or the field must be moved so that the lines of force are cut by the conductor.

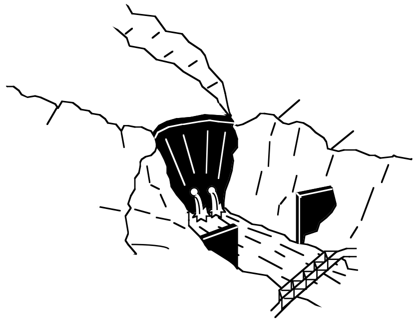
When a conductor or conductors **move across** a magnetic field so as to cut the lines of force, electrons **within the conductor** are impelled in one direction or another. Thus, a voltage (force) is created. This is called a **generator**.

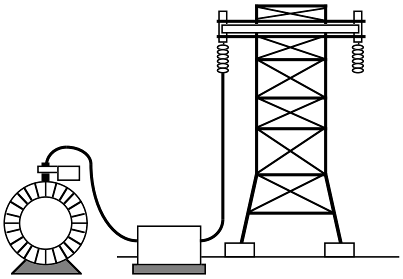
A generator converts **mechanical** energy into **electrical** energy. Whereas an electric motor is just the opposite, it uses electrical energy to perform a mechanical function. An example would be a fan.

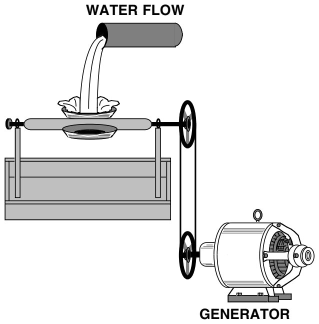




The water falling from a dam is the mechanical energy used to drive a generator to produce electrical energy.

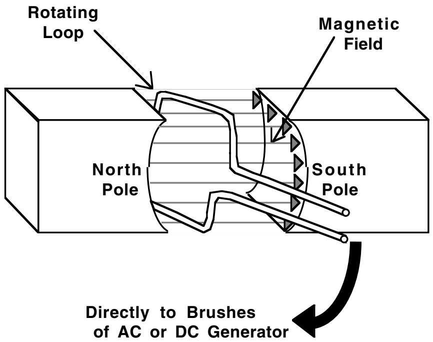






Whatever the orginal source of energy - water, coal, oil, gas, steam, the sun, the wind - the final step is always the conversion of **mechanical energy** from rotation of a generator to produce **electrical energy**.

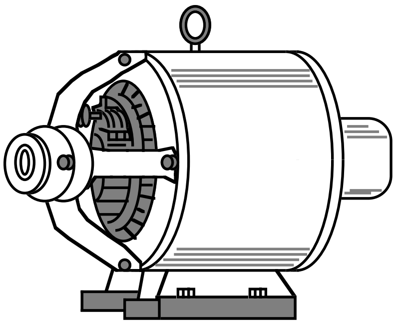
When a conductor is **moved** through a magnetic field in such a way that it cuts the lines of magnetic flux a force is applied to make **electrons move**. This is the basic principle of how an AC generator works.

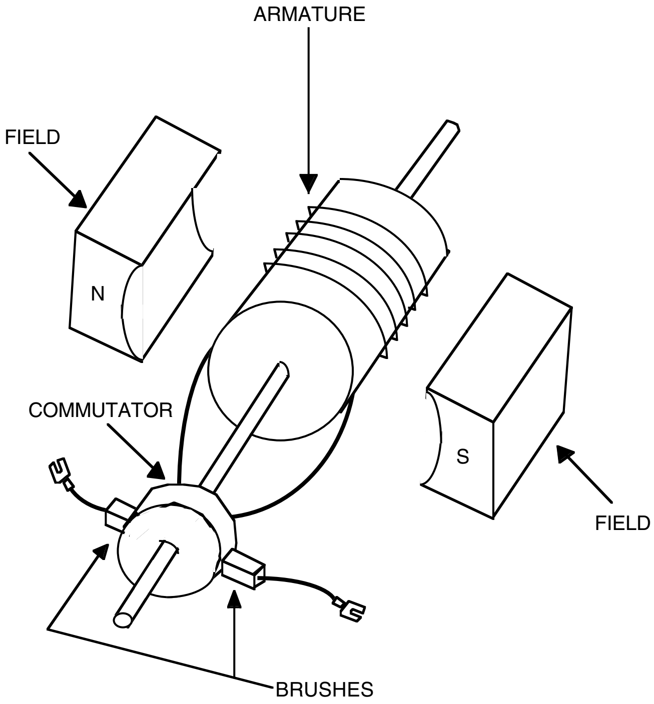


Shown to the right is the simplest form of an AC generator. It consists of a single loop of wire, which is placed between the poles of a permanent magnet and made to **rotate**. As the loop of wire rotates, it cuts through the magnetic lines of force and a **voltage is developed**.

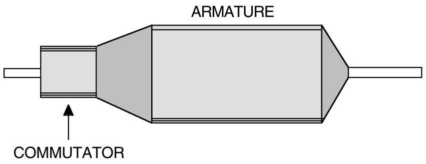
All generators, whether AC or DC consist of a rotating part and a stationary part. The rotating part of a DC generator is referred to as the **armature** . The coils that generate the magnetic field are mounted on the stationary part which is referred to as the **field**. In most AC generators the opposite is true, the field is mounted on the rotating part referred to as the **rotor**, and the armature is wound on the stationary part referred to as the **stator**.

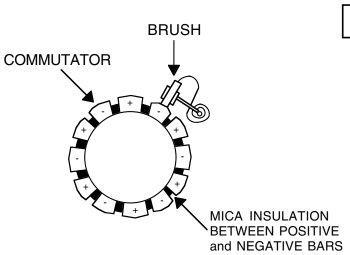
DC GENERATOR



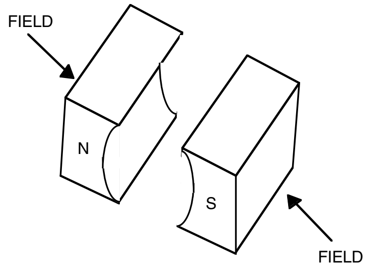


The complete armature, the iron core, winding, commutator and shaft, is positioned inside an iron frame or housing. The field poles are made of iron, either solid or laminations and support coils of wire called field windings. The field winding is an electromagnet.

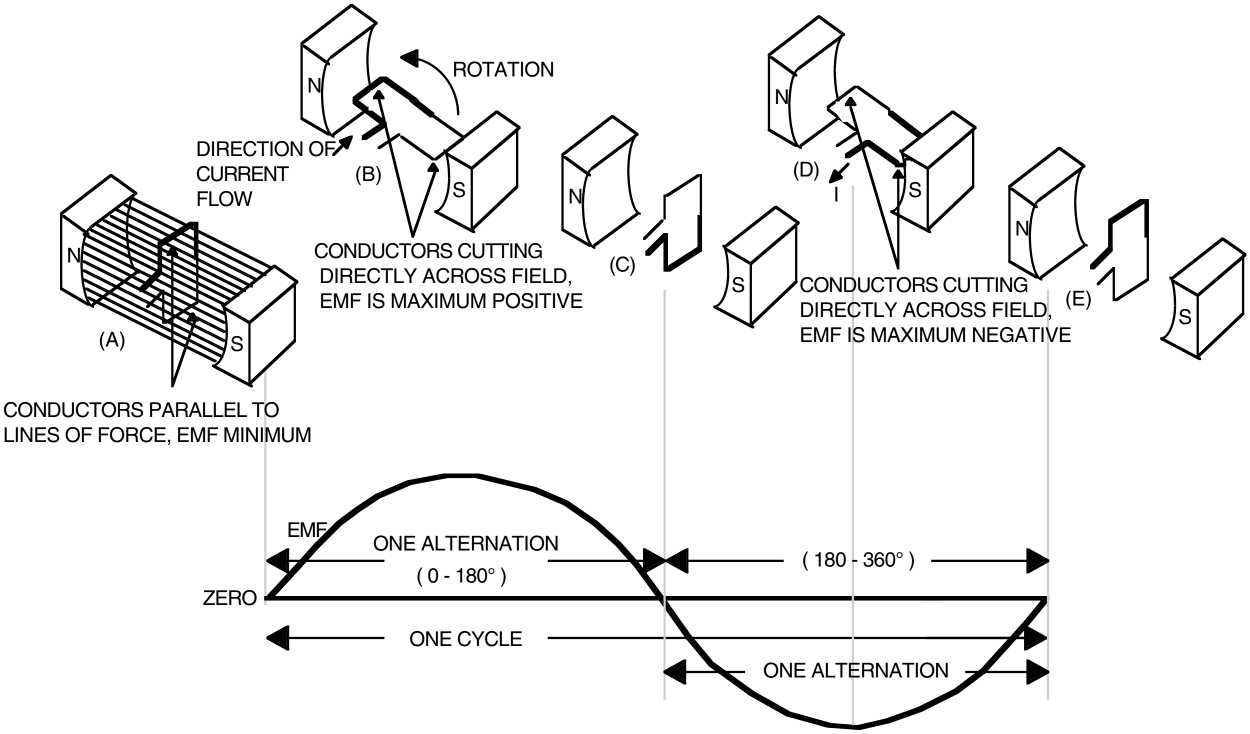




NORTH and SOUTH POLE MAGNETS



When the armature revolves through the lines of flux, the magnetic energy forces current to flow in the wire. When the wire in the armature goes **down** the field current flows in **one direction**; but when the wire goes **up** the field, the current flows in the **other** direction.

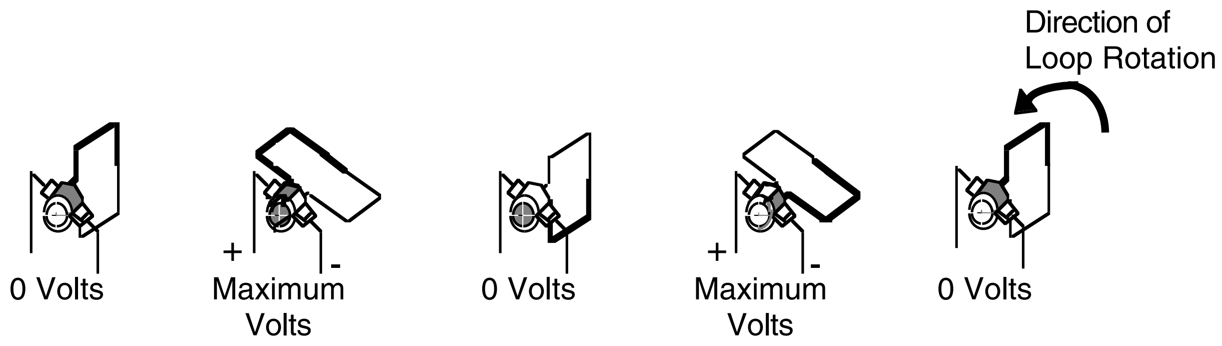


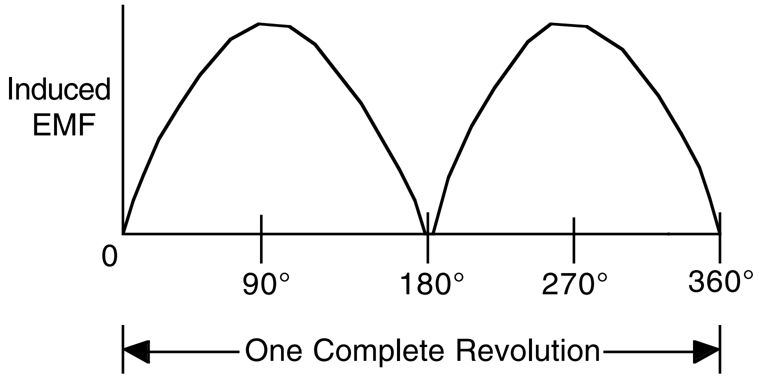
For a single loop rotating in a two-pole field (one-north pole and one-south pole) you can see that each time the loop makes one complete revolution the current **reverses direction twice**. A single hertz (cycle) will result if the loop makes one revolution each **second**. A complete cycle is 360°. There are **two alternations** in one complete cycle. One positive alternation and one negative alternation. This is called a **sine wave**. By reversing the direction twice in one cycle this is called **alternating current** (AC).

To convert AC to DC a switch must be operated twice for every cycle. If the generator output is alternating at 60 Hz (cycles), the switch must be operated 120 times per second to convert AC to DC. Obviously, it would be impossible to operate a switch manually at this high rate of speed.

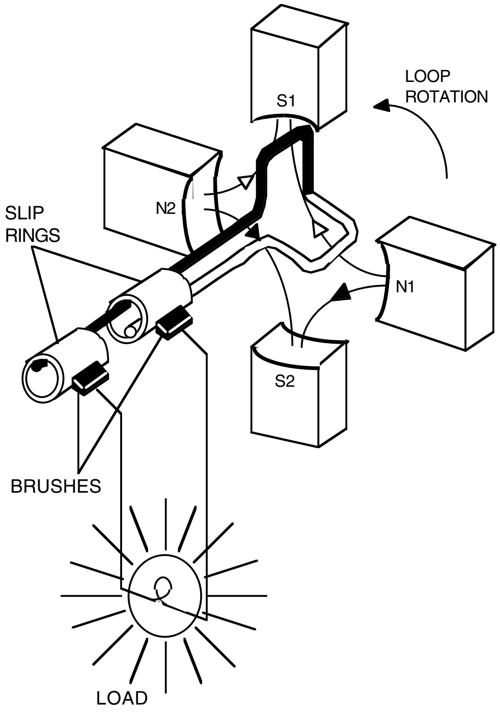
A direct current generator (DC) uses a **commutator** to change the alternating current to direct current.

The carbon brush as it slides on the revolving commutator reverses the connections of the connection in the armature to the external circuit at the instant when the voltage of the conductors is zero and changing in direction. The commutator switches the wires outside the generator while the armature turns, thus keeping the current flow in the **same direction** at all times. If a commutator is not used, the current coming out of the generator will **change direction** as the armature turns.





The brushes are positioned on **opposite** sides of the commutator so that they pass from one commutation half to the other at the instant the loop reaches the point in its rotation where the induced voltage reverses polarity. The brushes are effectively shorting the ends of the loop directly together. So instead of the output voltage reversing polarity after one-half revolution, the voltage output for the second half revolution is identical to that of the first half.



In a practical generator, the revolving loop of wire in the armature will contain several loops of wire cutting the magnetic flux of the fields.

When a coil or armature makes one complete revolution, it passes through 360 **mechanical degrees**, when an emf current passes through one cycle, it passes through 360 **electrical time degrees**.

If the generator makes two complete revolutions per second, the output frequency will be **two Hz** (cycles). In other words, the frequency of a two-pole generator happens to be the same as the number of revolutions (cycles) per second. As the speed is increased, the frequency is increased.

There are only **two types** of generators, AC and DC. Over 90% of all electric power is AC. AC generators do not have commutators and this makes them far superior to a DC generator. AC generators are also called **alternators**, since they produce an **alternating current**.

AC generators can be built with much larger power and voltage ratings than DC generators. The reason is with the AC generator output connections are bolted directly to the stationary windings.

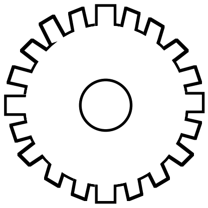
All generators operate on the same basic principle, a magnetic field cutting through conductors or conductors passing through a magnetic field.

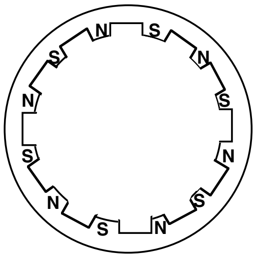
There are two groups of conductors:

I. A group of conductors in which the output voltage is generated
II. A group of conductors through which direct current (DC) is passed to obtain an electromagnetic field of fixed polarity (excitation).

The conductors in which output voltage is generated are referred to as **armature windings**. The conductors in which the electromagnetic field originates are referred to as the **field windings**.

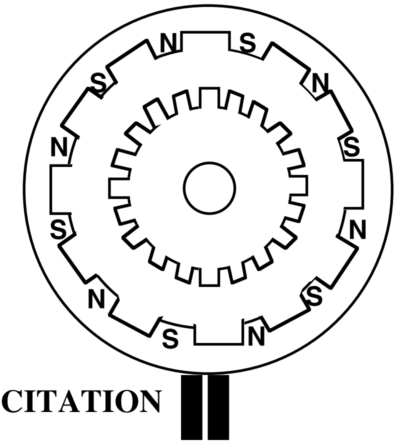
There must be a **motion** between the armature windings and the field windings. AC generators are built in two major assemblies, the **stator** and the **rotor**.

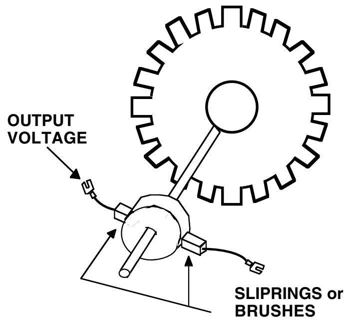




There are two types of motion, either the revolving armature (rotor) or the revolving field (stator).

In the **revolving armature** AC generator, the stator provides a stationary electromagnetic field. The rotor acting as the armature, revolves in the field, cutting the lines of force, producing the desired voltage. In this generator, the armature output is taken through slip rings and thus retains its AC characteristic.

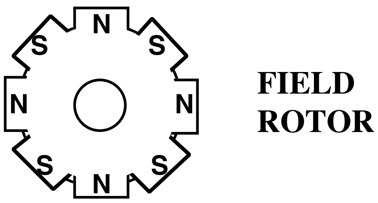


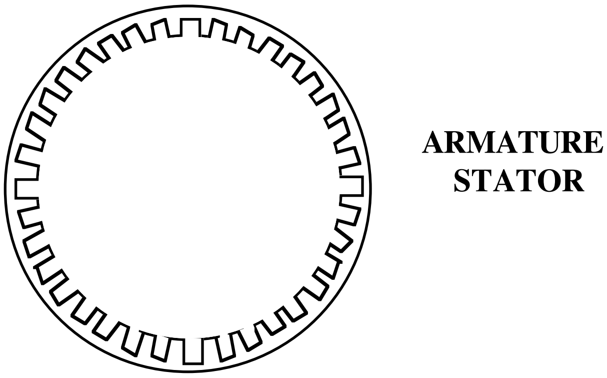


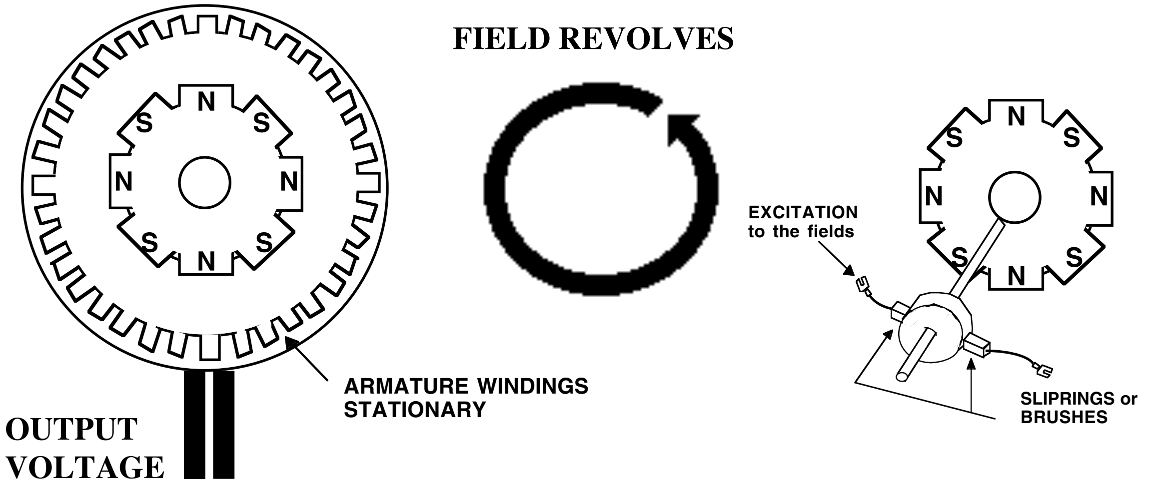
The revolving armature AC generator is **seldom** used. Its primary limitation is the fact that its **output** power is conducted through sliding contacts, sliprings and brushes. The sliprings and brushes **limit the amount of voltage** that can be carried through them due to arcing and flashovers. Consequently, revolving armature AC generators are limited to low-power, low-voltage applications. An example would be an automobile alternator.

Remember you can just as easily rotate the **magnet assembly** (the fields). This is what the Yugoslavian Nikola Tesla developed and received patents on in 1888.

The **revolving field** AC generator is by far the most widely used today. In this type of generator, direct current from a separate source (excitation) is passed through windings on the rotor by means of sliprings and brushes. This maintains a rotating electromagnetic field of fixed polarity. The rotating magnetic field cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, AC voltages are induced in the windings since magnetic fields of first one polarity and then another cut through them. Now here is the important part, since the output power is taken from **stationary windings**, the output may be connected through **fixed** terminals and not revolving sliprings or brushes that would limit high voltages. Sliprings and brushes are adequate for the DC field (excitation) supply because the power level in the field is much smaller than in the armature circuit.







Fixed terminals on stationary winding allows higher voltages.

Excitation through the rotating fields is provided at lower voltages.

AC - DC SUMMARY

DC voltage changes are obtained by using series resistors which causes **low efficiency** due to heat loss.

DC generator rating are limited to relatively low voltage and power values as compared to AC generators.

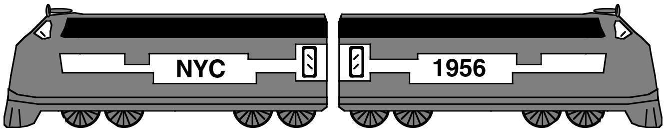
AC armature stator voltages of 13,800 are common compared to 750 volts for a large DC generator.

The initial cost and the maintenance and repair costs for AC is considerably less than the costs for DC.

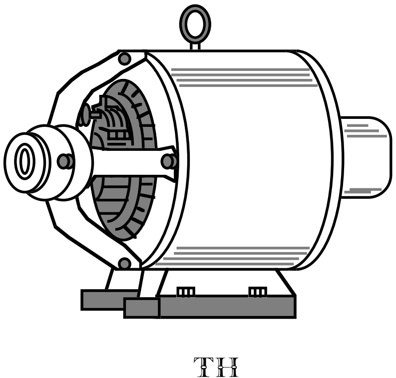
Although, there are a number of applications where **DC** either must be used or will do the job better than AC, such as:

- Charging of storage batteries
- Electronics
- Electroplating process
- Excitation of the field windings of generators
- Varible speed motors

There are special jobs that require **heavy starting torque** and **high rate of acceleration** such as locomotives and monorail trains which are driven by traction motors which require DC. Using DC motors in these applications eliminates the need for clutches, gear shifting transmissions, differential gearing, drive shafts and universal joints.

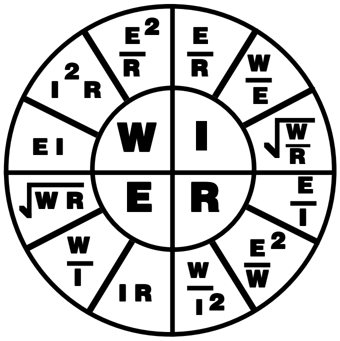


AC is changed to DC by **rectifiers** or **motor-generator** sets. Thus, the costly conversion to DC is needed only for certain applications.



OHM'S LAW

In 1827 George Simon Ohm discovered some laws relating to the strength of a current in a wire. Ohm found that electricity acts like **water** in a pipe. The law was so simple that it was not believed. Ohm was forced to resign his professorship and live in obscurity until he was recognized 14 years after his discovery.



Ohm's Law is one of the most important things that you will use throughout your electrical career. It is a mathematical tool which is of the greatest use in determining an **unknown** factor of voltage, current or resistance in an electrical circuit in which the other two factors are known.

It is a simple law that states the relationship between voltage, current and resistance in a mathematical equation.

In electrical terms, voltage is represented by the letter "E" (electromotive force), current by the letter "I" (intensity), and resistance by the letter "R".

The Ohm's Law formula cannot work properly unless all values are expressed in the **correct units** of measurement:

VOLTAGE is always expressed in VOLTS
CURRENT is always expressed in AMPERES
RESISTANCE is always expressed in OHMS

We measure electromotive force in volts, we measure electric current in amps, and we measure resistance in ohms.

Electricity has many more terms that have to do with measurement: **"VOLTS, "AMPS", "OHMS", "WATTS"** and more.

We must first understand how the electrical system functions and then mathematical analysis can follow.

Since you cannot visually **see** the flow of electrons, current, etc. and you need to **see** the relationship between voltage, current, and resistance, let's do it with some **terms** which you are more familiar with, using **water**.

WATER	**ELECTRICITY**
PUMP	GENERATOR
PIPE	CONDUCTOR
PRESSURE	VOLTAGE
FLOW OF GALLONS	AMPERES
RESTRICTION	RESISTANCE

The **generator** is like a **water pump**, the prime mover.

The **conductor** is like the **water pipe**, the larger the conductor, the less the resistance and the more flow.

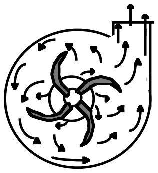
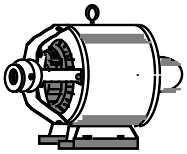
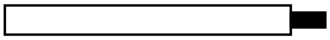
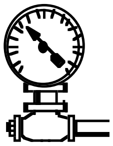
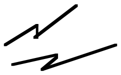
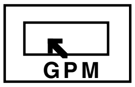
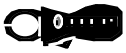
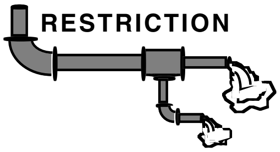
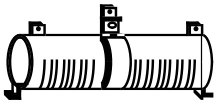
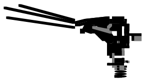
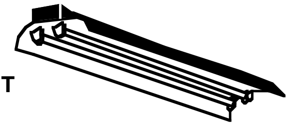
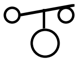
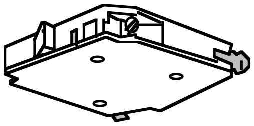
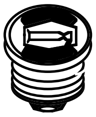
The **voltage** is like the **water pressure**, the force pushing.

The **amperes** are like the **flow of water**, an amount of current flowing is like the gallons per minute in water.

The **resistance** is like the **restriction** in the water pipe. A reduction in the water pipe size would cause opposition to the amount of gallons per minute, as would the resistor in an electrical circuit. It limits the flow of current.

Watts (power) is expressing the **rate of work** involved; the power required. With water it requires more work to pump water up to a water tower than it would to pump water at ground level. Wattage is the rate at which the electrical energy is changed into another form of energy, such as light or heat. The faster a lamp changes electrical energy, the brighter it will be.

Horsepower (hp) is the unit of measurement for mechanical power which is equal to 33,000 foot-pounds per minute. One horsepower is developed when the product of the distance and pounds equals 33,000 and this is done in one minute. In electrical terms, one horsepower = **746 watts**. One horsepower is developed if 33,000 pounds are lifted one foot in one minute. This represents the **work** done by the **output** of a motor.

WATER ⟵		⟶ ELECTRICAL
PUMP 	SOURCE OF SUPPLY	GENERATOR 
PIPE 	PATH	CONDUCTOR 
POUNDS PER SQUARE INCH 	PRESSURE	VOLTAGE 
GALLONS PER MINUTE 	FLOW	AMPERES 
RESTRICTION 	OPPOSITION TO FLOW	RESISTANCE 
USE OF WATER  SANITATION - IRRIGATION	LOAD	USE OF ELECTRICITY  LIGHTING - HEAT
HIGH-PRESSURE CUTOUT SWITCH 	PROTECTION	CIRCUIT BREAKER - FUSE  

OHM'S LAW DEFINITIONS

(E) VOLT: The practical unit of voltage; the pressure required to force one ampere through a resistance of one ohm. To make electrons flow in a conductor, an electrical pressure must be applied and this is called electromotive force (EMF) or voltage.

(I) AMPERE: The practical unit of electric current flow; the electric current that will flow through one ohm under a pressure of one volt.

(Ω) OHM: The practical unit of electrical resistance; the resistance through which one volt will force one ampere.

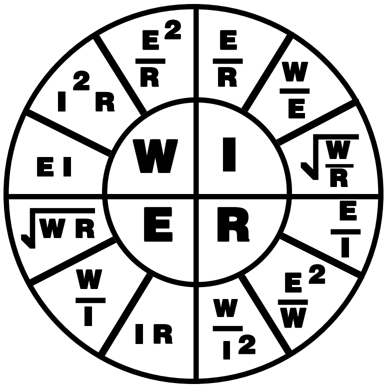
(R) RESISTANCE: The opposition which a device or material offers to the flow of current; the opposition which results in the production of heat in the material carrying the current. Resistance is measured in ohms. All resistances have two dimensions: cross-sectional area and length.

(W) POWER: The rate at which electrical energy is delivered and consumed. Power is measured in watts. A motor produces mechanical power measured in horsepower. A heater produces heat (thermal) power. A light bulb produces both heat and light power (usually measured in candlepower).

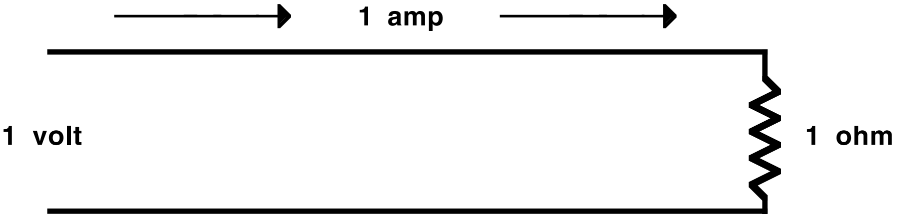
Electrical power is equal to voltage times the amperage. **W = E x I**

Ohm's Law states: In a DC circuit, the current is directly proportional to the voltage and inversely proportional to the resistance. In other words, the water flowing in a pipe (amperage) will be increased if the water pressure (voltage) is increased. And, if the restriction (resistance) in the pipe is **less**, the water flow (amperage) will be **more**.

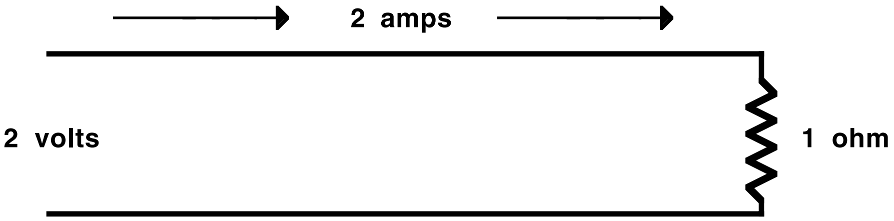
Get into the habit of always sketching out an Ohm's Law circuit **before** you begin trying to solve it.



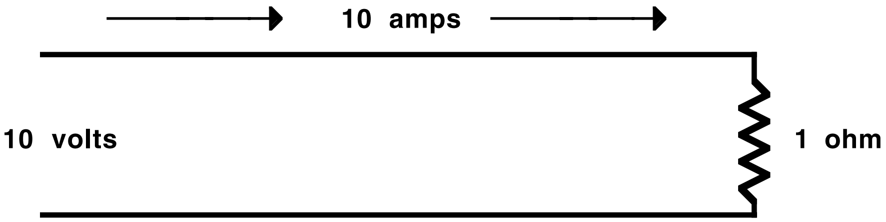
$\boxed{I = E/R}$ One volt will force one amp through a conductor having a resistance of one ohm.



$\boxed{I = E/R}$ If the voltage is increased to 2 volts, the current will be 2 amps through one ohm of resistance.



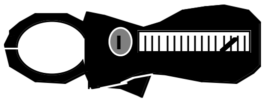
$\boxed{I = E/R}$ If the voltage is increased to 10 volts, the current will be 10 amps through one ohm of resistance.

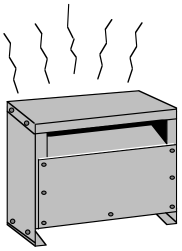


The transformer must be "K-Factor" rated for harmonic loading or they must be derated in kva to assure that the rated-temperature rise is not exceeded.

K-Factor rated transformers do **not** get rid of the harmonic currents, they are designed to handle the extra heat generated by these currents. Nobody even proposes that it is advisable to try to get rid of the harmonic currents.

In many cases harmonic currents are an invisable problem for the electrician. A non-rms amp clamp meter shows the transformer is only **half loaded**, but the transformer feels **really hot**. You should trust the heat and not the meter.

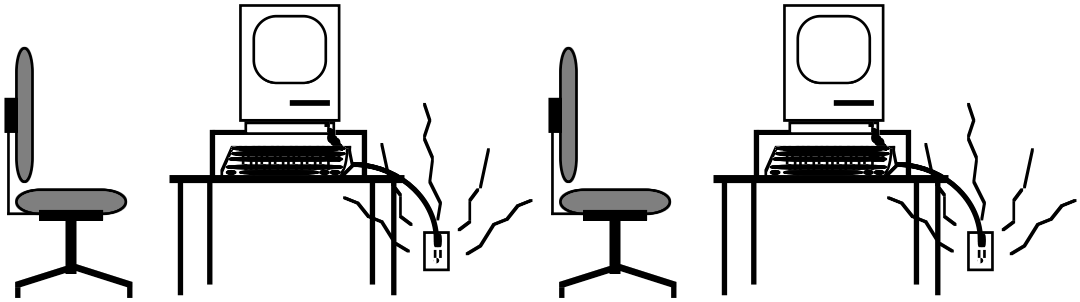




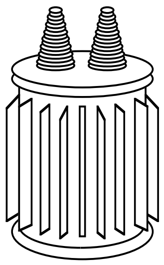
Average-rms ammeters are **not** reliable instruments for evaluating an electrical system's harmonic content. For accurate indication of an electrical system's content, use only a **true-rms meter**.

Phase conductors have been measured showing a balanced load 125 amps per phase and the **neutral** showing **155 amps**. Now you can see how the neutral becomes **a current-carrying conductor** with the added harmonic current heat.

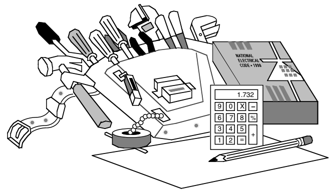
It is quite apparent that feeders and branch circuits serving the **average office space** can have **greater** currents in the neutral than the phase conductors as a result of these **additive** harmonics.



The estimate is that the 1990 load on the utility is 15% harmonic and by the year 2000 harmonic currents will constitute 50% of the loading on the utility transformer.



This message on harmonic currents needs to reach the electrician so the electrician fully understands this problem in our industry. It has been estimated that 70% of the electrical designing is done by the electrician and electrical contractor.



Remember, conductor sizing from the Code is based on **60 Hz**. The system must be designed for the extra heat produced by these non-linear loads.

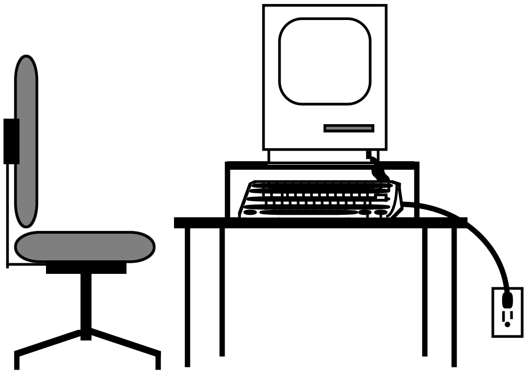
One might consider the use of nonferrous raceways such as aluminum or PVC. This is a standard practice in 400 Hz applications such as aircraft and large computer rooms to reduce heating (eddy currents - skin effect) from the adjacent steel raceways. Remember, 400 Hz is very nearly the 7th harmonic of a 60 Hz system.

Higher harmonics are worse, percentage wise, than the lower 3rd harmonic.

An electrician can not calculate the amount or order of harmonics contained in a piece of equipment. A ballast generally contains 3rd harmonics, but another type of ballast may contain even a higher order of harmonic. A computer may have some 5th, 7th, 9th or even higher harmonics with different percentages of each order of harmonics.

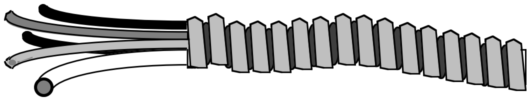
There is no perfect way, at this writing, to solve this **cancer** that is eating away at our conductors and transformers.

When computers, data processing equipment and solid state devices are involved in the circuitry, the electrician should consider the K-Factor transformer, derating the kva of an existing transformer, upsizing the conductors, installing separate or oversized neutrals on multiwire circuits.



On a 20 amp receptacle multiwire branch circuit supplying computers, it is recommended to use #12 ungrounded (hot) circuit conductors with a **#8** (white) grounded or neutral conductor.

Cable manufacturers are now making a cable containing #12 circuit conductors with a **#8 "super neutral"** conductor. Cables with a individual neutral per phase conductor are also available.

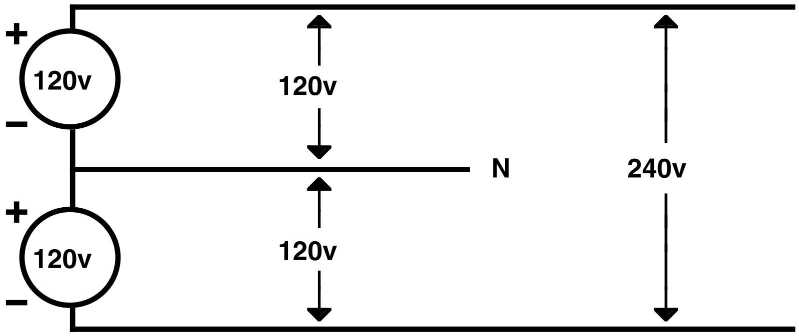


An oversized neutral is not necessary to accommodate the harmonics generated by the 3rd harmonic in ballasts.

THE NEUTRAL CONDUCTOR

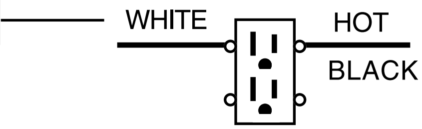
Definition: A neutral conductor carries only the **unbalanced** current of a circuit, as the neutral conductor of a 3-wire single-phase circuit or a 4-wire three-phase circuit.

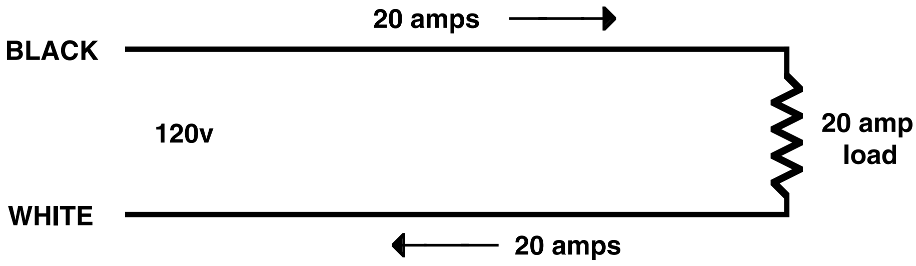
The Edison 3-wire system involves connecting two 120 volt supplies in **series** in a way that their polarities cause the voltages to be added. The common point is called the **neutral**.



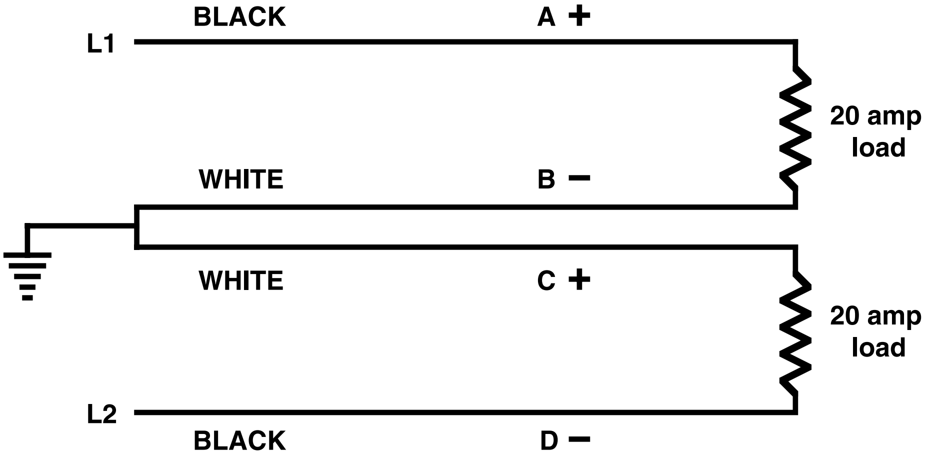
In a 2-wire, 120v circuit, the grounded conductor (identified white in color) is **NOT** a neutral conductor. In a 2-wire circuit the grounded conductor carries the same amount of current as the ungrounded (hot) conductor carries. •Remember the definition of a neutral, it carries the **unbalanced current**. You must have a 3-wire circuit to have a **neutral** conductor.

The "white" wire is NOT a neutral

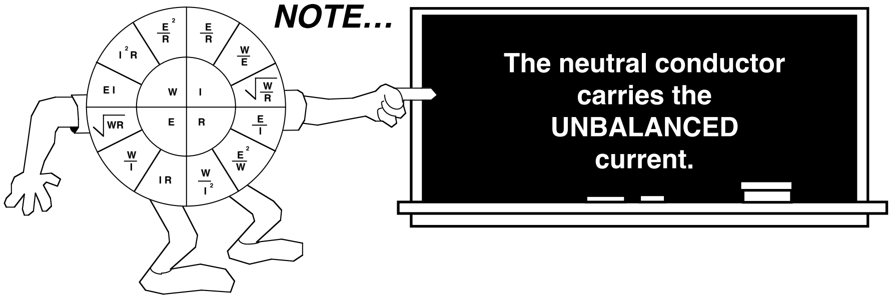




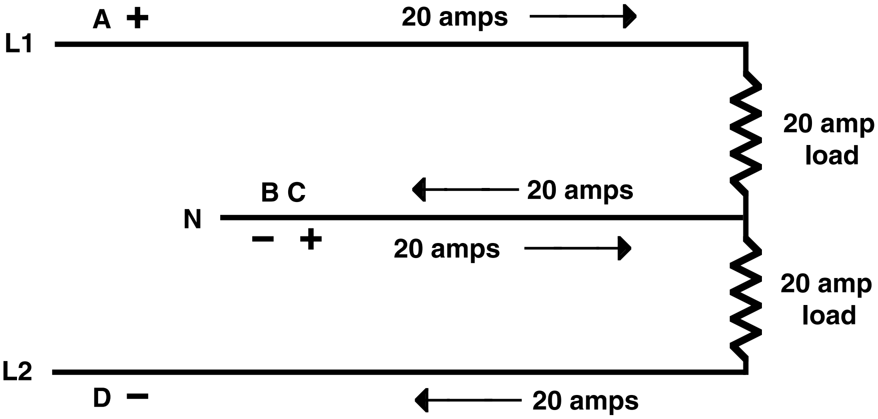
The next sketch shows two 20 amp, 120 volt loads connected, using four conductors. The grounded (white) conductors connect together at the neutral bar in the load center.



Why use two grounded (white) conductors? Why not use just one? You may think that by using **one** white conductor to serve two 20 amp loads, the **one** white conductor would have to be sized **twice** as large to carry 40 amps. This is an incorrect conclusion.



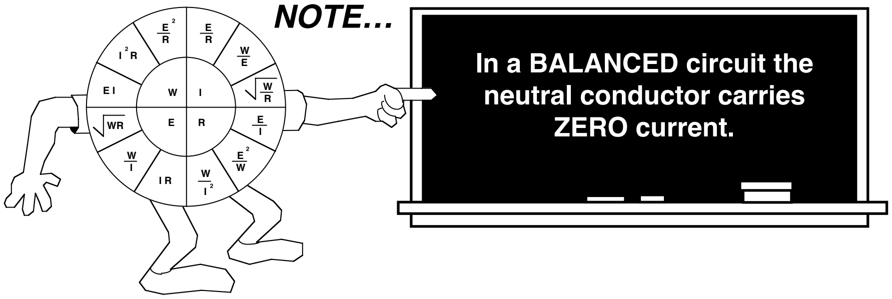
The next sketch shows the same 20 amp loads using only 3 wires, utilizing the neutral conductor.



Each of the conductors B and C carries 20 amps, but note the direction of the arrows. The flow of current in conductor B at any **instant** is in an **opposite** direction of conductor C. So at any given instant, the single neutral conductor is said to be carrying 20 amps in one direction and 20 amps in the **opposite direction**, the two cancel each other and the flow of current in the neutral conductor is zero.

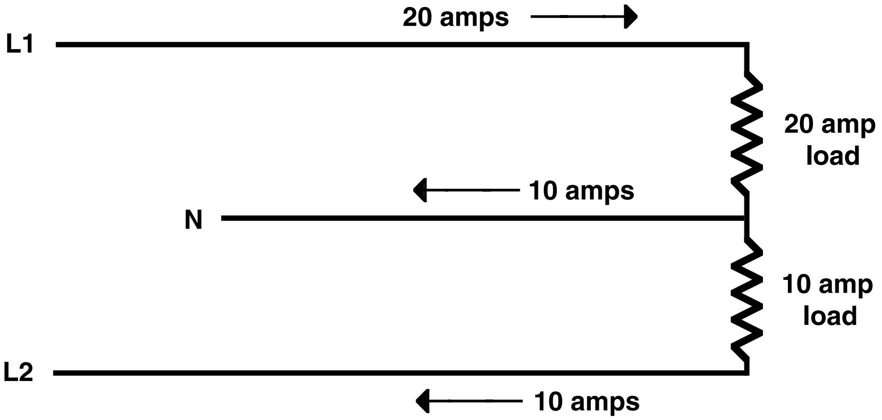
The system is actually 240 volts with the two 20 amp 120 volt loads in **series**.

Since the loads have equal resistance, the voltage of 240 would divide, 120 volts to each load. This is a **balanced** system. In a balanced system the neutral conductor carries zero current.

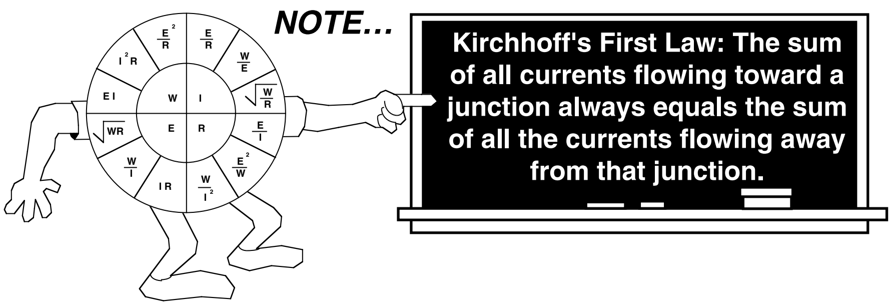

NOTE...

In a BALANCED circuit the neutral conductor carries ZERO current.

The next sketch shows an **unbalanced** system and the effect it has on the neutral conductor.



The neutral conductor carries the **unbalanced** current, 10 amps. The **maximum** current the neutral conductor would ever carry in this sketch would be 20 amps. If the 10 amp load on line 2 was shut off, the neutral conductor would have to carry the 20 amp load from line 1. The maximum neutral current would be 20.



NOTE...

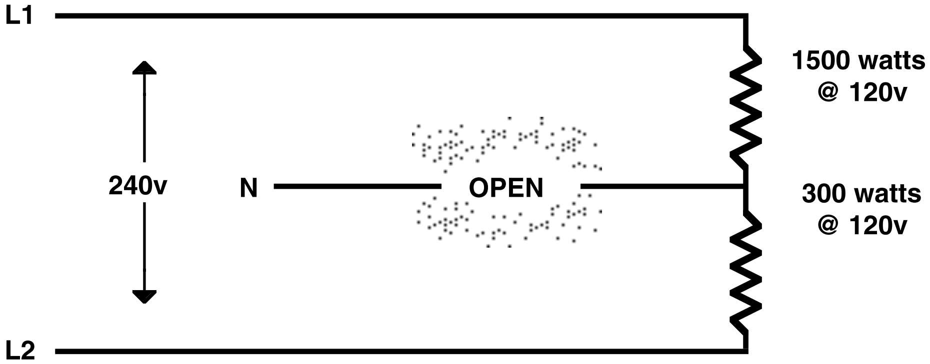
Kirchhoff's First Law: The sum of all currents flowing toward a junction always equals the sum of all the currents flowing away from that junction.

OPEN NEUTRAL CONDUCTOR

A loose neutral connection will cause unusual things to happen in a circuit, fan motors change speed, lights flicker, etc.

A loose neutral connection is a good place for a serviceman to start looking when experiencing unusual happenings in a circuit.

The next sketch shows an open neutral conductor in the system.



With an open neutral conductor this becomes a 240 volt **series** circuit.

Example: Find the total resistance in this series circuit.

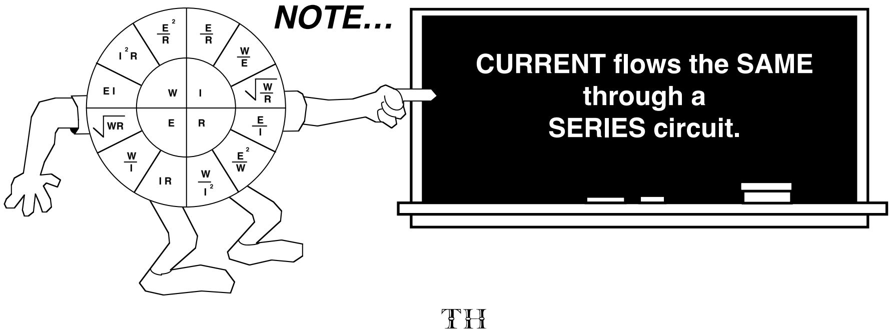
Solution: The 1500 watt load is rated @ 120v, its resistance is fixed and cannot change. Use Ohm's Law formula $R = E^2/W$ = 120v x 120v/1500w = 9.6 ohms.

The 300 watt load is rated @ 120v, its resistance is fixed and cannot change. $R = E^2/W$ = 120v x 120v/300w = 48 ohms.

R total = R1 + R2 9.6 ohms + 48 ohms = **57.6 ohms total series resistance.**

Example: Find the current flowing in this series circuit.

Solution: Use Ohm's Law formula I = E/R = 240v/57.6Ω = 4.1666 or **4.17 amps flowing**.



NOTE...

CURRENT flows the SAME through a SERIES circuit.

Example: Find the voltage across the 1500 watt load.

Solution: Use Ohm's Law formula $E = I \times R = 4.17$ amps x 9.6 ohms = **40 volts** (across the 1500 watt load).

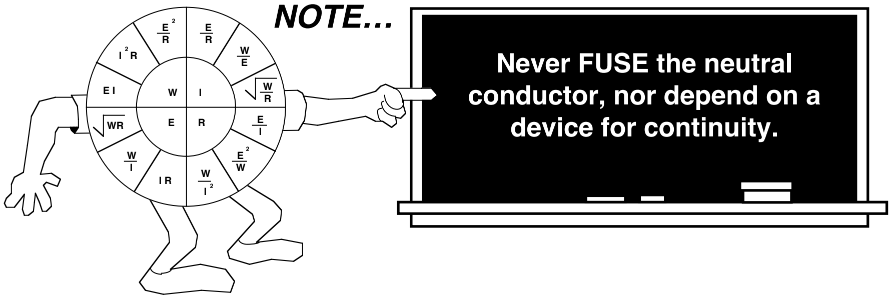
Example: Find the voltage across the 300 watt load.

Solution: Use Ohm's Law formula $E = I \times R = 4.17$ amps x 48 ohms = **200 volts** (across the 300 watt load).

•Checkpoint: 40 volts + 200 volts = 240 volts (the applied voltage).

You can see the danger involved with an **open neutral** conductor. The 1500 watt load rated at 120 volts would receive only **40 volts** which would not damage any lighting or heating equipment, but a motor would not operate properly.

The 300 watt load rated at 120 volts would receive **200 volts**. This higher voltage will damage 120 volt rated equipment.

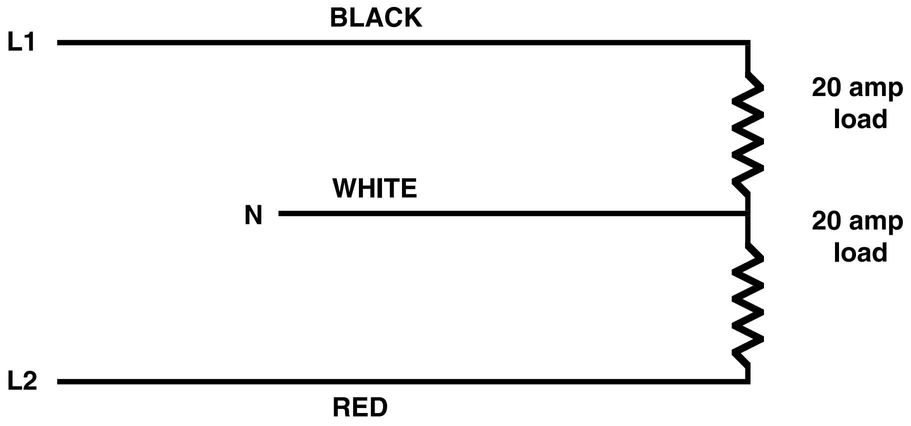


NOTE...

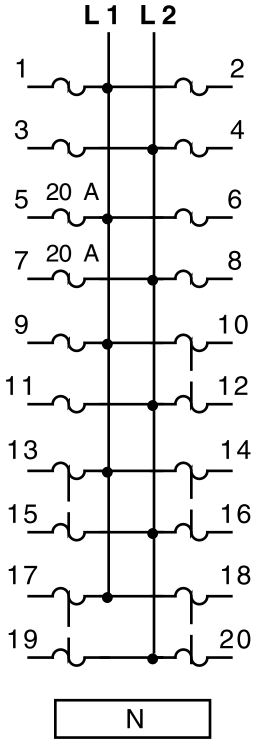
Never FUSE the neutral conductor, nor depend on a device for continuity.

THE MULTI-WIRE BRANCH CIRCUIT

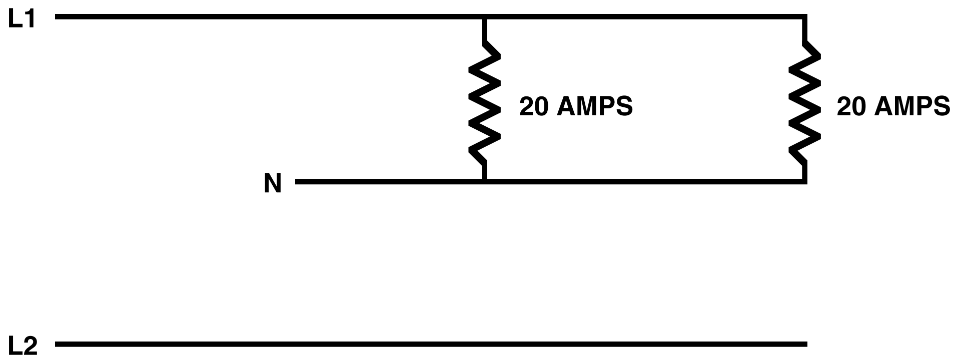
The neutral conductor is common to both circuits. Extreme caution must be used when connecting a three-wire branch circuit to the load panel. The **black** and **red** conductors of the three-wire cable must be connected to **OPPOSITE** lines in the panel to prevent heavy overloading of the neutral conductor.



Connect the black conductor to circuit #5 in the panel which is line 1. Connect the red conductor to circuit #7 which is line 2. Properly connected and with both loads "on", the neutral conductor would carry zero current. The maximum current the neutral would carry is 20 amps if either load was shut off.



The three-wire branch circuit connected **incorrectly**.



If both the black and red wires were connected to the **same** line in the panel with both 20 amp loads "on", the white wire would carry 40 amps which is an overload on a #12 conductor.

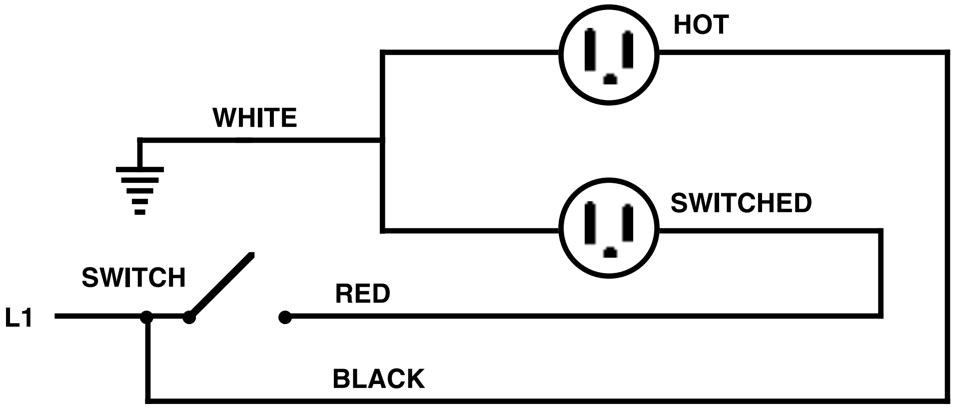
This is referred to as the "white" wire rather than the neutral. By connecting both loads to the same line in a three-wire circuit you no longer have a neutral. Remember the definition of a neutral; it carries only the unbalanced current.

A multiwire branch circuit has two ungrounded conductors with a potential difference between them.

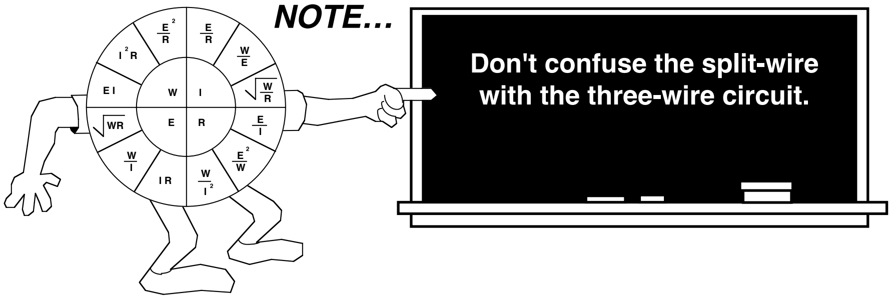
•Checkpoint: The neutral conductor in a three-wire branch circuit shall not be dependent on device connections, such as receptacles, where the removal of the device would interrupt the continuity of the neutral conductor. A pigtail is required.

THE SPLIT-WIRE BRANCH CIRCUIT

This is a circuit where the top portion of the duplex receptacle is hot all the time, while the bottom portion of the duplex receptacle is controlled by a wall switch.



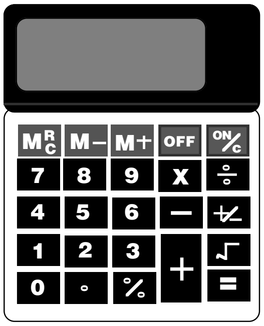
When connecting the split-wire or two-wire branch circuit, **both** the red and black wires are connected to the **same** line either L1 or L2. The white wire is **not** a neutral conductor.



Don't confuse the split-wire with the three-wire circuit.

MATH REVIEW FOR THE EXAM

This section will help you **relearn** mathematical fundamentals. The basic math is not covered in the following pages, only the math as applied to the electrical exam.



Your **calculator** is a very important item that you need to practice and become familiar with. A calculator can reduce the time involved in solving a calculation question and can also provide accuracy. But remember, the **right** numbers have to be pressed to get the **right** answer. It would be a good idea the day of the exam to take along a **spare** calculator as a back up, just in case you would experience problems with your other calculator.

During the exam as you apply Ohm's Law formulas and math you need to **understand what you read**.

When two or more numbers or letters, each in parentheses, follow each other, they are to be **multiplied**.

Example: (2) (4) (6) This means 2 x 4 x 6 = 48

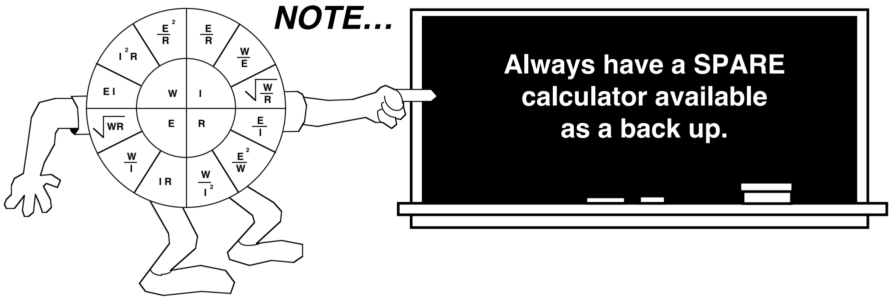
Example: 2KDI means (2) (K) (D) (I) This means 2 x K x D x I

Example: va means (v) (a) This means v x a

Example: (2) (4) -2 This means 2 x 4 = 8 - 2 = 6

Example: (2) (4-2) This means, work subtraction first and then multiply 4 - 2 = 2 x 2 = 4

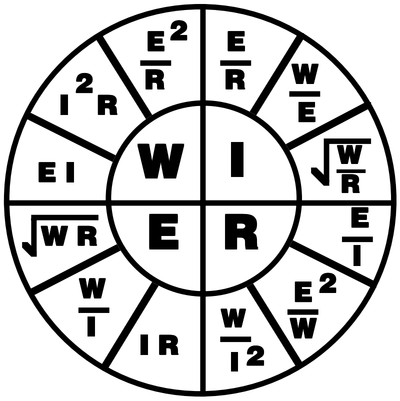
Example: (2) (4 + 2) This means, work addition first and then multiply 4 + 2 = 6 x 2 = 12



NOTE...

Always have a SPARE calculator available as a back up.

When **square root** is to be extracted, as indicated by the sign $\sqrt{\quad}$, everything under the sign must be done first, then the square root extracted.



Example: Ohm's Law circle shows: $E = \sqrt{WR}$

W = 100 watts R = 144 ohms

First multiply 100 watts by 144 ohms = 14,400. Now press the $\sqrt{\quad}$ button on your calculator, answer = **120 volts**. 120 is the square root of 14,400. 120 x 120 = 14,400.

Example: The Ohm's Law circle shows: $I = \sqrt{W/R}$ W = 100 watts R = 144 ohms

First divide 100 watts by 144 ohms = .6944444. Now press the $\sqrt{\quad}$ button on your calculator, answer = **0.8333333** or **0.83 amps**.

Example: Formula for impedance: $Z = \sqrt{R^2 + X^2}$ R = 10 ohms X = 15 ohms

First multiply 10 x 10 = 100. Then multiply 15 x 15 = 225. Now add 100 + 225 = 325. Now press the $\sqrt{\quad}$ button, answer = **18**.

Where a number is followed by a second number that is placed just above and to the right of the first number (10^2), the second number (^{2}) is called an **exponent**. It means the first number is to be used as a factor in **multiplication**, as often as indicated by the exponent.

VOLTAGE DROP FORMULAS

The Code suggests in sections 210.19 Informational Note, and 215.2(A2) Informational Note 2, keeping voltage drop at **3% for branch circuits** and **5% total** will provide reasonable efficiency of operation.

Voltage drop is **wasted electricity** due to heating the conductors. $\boxed{\text{Power Loss} = VD \times I}$

To find:

VOLTAGE DROP ...... $VD = \dfrac{2 \times K \times D \times I}{CM}$ **(or)** $VD = I \times R$

WIRE SIZE .... $CM = \dfrac{2 \times \textcircled{K} \times D \times I}{VD\ \text{permitted}}$

DISTANCE .... $D = \dfrac{CM \times VD\ \text{permitted}}{2 \times K \times I}$

LOAD .... $I = \dfrac{CM \times VD\ \text{permitted}}{2 \times K \times D}$

* The "2" in the formulas is for single-phase circuits, this is the conductor to and from the load

* For 3 phase voltage drop calculations, change the "2" in the formula to **1.732**

* "K" is the resistance of a circular mil-foot. Exact $K = \dfrac{R \times CM}{1000'}$

* When using the formula to find "WIRE SIZE" use the **approximate Ⓚ factor** of 12.9 for copper and 21.2 for aluminum

* "D" is the distance **one way** in a circuit

* "I" is the load in amperes. For motors use the Full Load Current from the motor tables

* "CM" is the size of conductor in circular mils, found only in Table 8

* "VD permitted" is the **percentage of the applied source voltage,** 3% of the source for a branch circuit and 5% of the total applied to the system. Example: On a branch circuit that has a source voltage of 120 the voltage drop permitted would be 120v x 3% = 3.6 volts. Example: On a branch circuit that has a source voltage of 208 the voltage drop permitted would be 208v x 3% = 6.24v. Example: A system with an applied voltage of 240 the **total** voltage drop permitted on the entire service would be 240v x 5% = 12 volts.

I teach in my Code classes to calculate the exact K. It takes only a few seconds with a calculator and using Table 8, and it could be the difference of choosing the right answer on the exam.

Sometimes an **approximate K** factor is used, but only when determining the conductor **size**.

K represents the resistance of a circular mil foot of conductor. Referred to as the resistivity factor of conductor metal. A circular mil foot is .001", 12 inches in length.

We know for a fact that resistance changes with the **size** of the conductor, so "K" will also be a **different** resistance value for **each** conductor size.

$$\textbf{TO FIND EXACT K} = \frac{\overset{\text{Per k/Ft from Table 8}}{R} \times CM \longrightarrow \text{Area Circular Mils from Table 8}}{\underbrace{1000\ \text{Feet}}_{\text{Table 8 Ohms Values are based on 1000 feet}}}$$

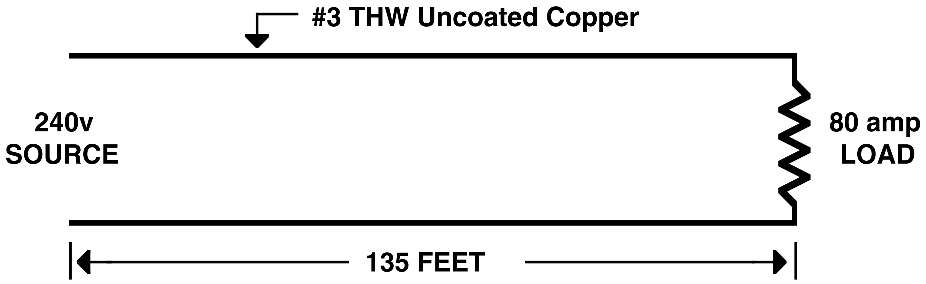
Using the formula above we can find the exact K factor for a #12 solid uncoated copper conductor:

$$\frac{1.93 \text{ ohms} \times 6530 \text{ cm}}{1000 \text{ feet}} = \mathbf{12.6029}$$

The exact K factor for a #12 solid aluminum conductor would be:

$$\frac{3.18 \text{ ohms} \times 6530 \text{ cm}}{1000 \text{ feet}} = \mathbf{20.7654}$$

Example: What is the voltage drop in the following branch circuit? Use **both** formulas for voltage drop and compare for **exact** same answer.



Let's start by using the formula VD = I x R.

I = 80 amps
R = (Table 8) 0.245 ohms per k/ft x .270 feet (2 x 135') = 0.06615 ohm
VD = I x R 80 amps x 0.06615 ohm = **5.292 volts dropped**.

Now use the formula $VD = \dfrac{2 \times K \times D \times I}{CM}$

The first step is to find the exact K factor:

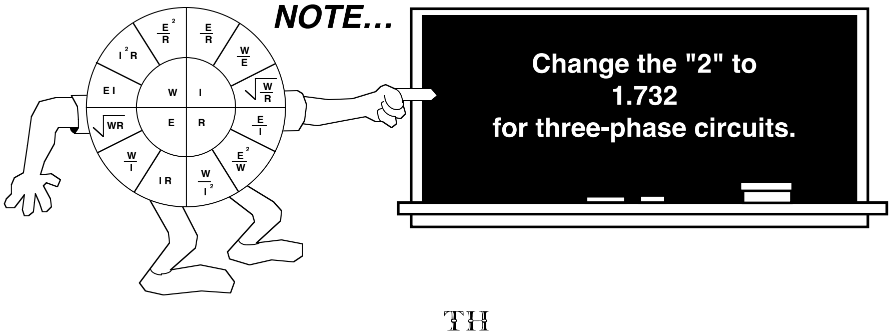
$$\frac{.245 \text{ ohm} \times 52{,}620 \text{ cm}}{1000 \text{ feet}} = 12.8919$$

$VD = \dfrac{2 \times 12.8919 \times 135' \times 80 \text{ amps}}{52{,}620 \text{ cm}}$ = **5.292 volts dropped**.

By using the **exact K** factor you have the **exact** same answer of 5.292 volts dropped by using either formula.

•Note: When using the VD = I x R formula remember you are using the **total length of the conductor** in the branch circuit which is the distance of 135 feet times 2 = 270 feet of conductor. Formula $VD = \dfrac{2 \times K \times D \times I}{CM}$ the "2" in this formula takes care of the total length of conductor as it is multiplied by the "D" in this formula. "D" is the distance one way. In this branch circuit the "D" is 135 feet and by using "2" in the formula = 270 feet.

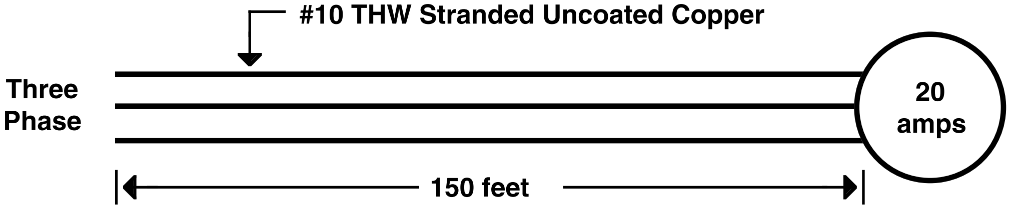
So far we have been calculating voltage drop in a single-phase branch circuit. Now let's switch to a **three-phase branch circuit**. In the formulas change the "2" to **1.732** for three-phase calculations. The advantage is the 1.732 which is the square root of 3. We don't have to calculate the total resistance of three conductors. We are calculating the length of **one conductor** times 1.732.



3 ø VOLTAGE DROP FORMULAS

$$VD = I \times \underbrace{R}_{\text{Length of one conductor}} \times 1.732 \qquad VD = \frac{1.732 \times K \times D \times I}{CM}$$

Let's calculate the voltage drop in the following **three-phase** branch circuit supplying a 20 amp load.



Using the formula VD = I x R x 1.732; I = 20 amps; R = Table 8 shows a resistance of 1.24 ohms per 1000 feet for a #10 stranded uncoated copper conductor. Next step is to find the resistance of **one** conductor, 150 feet in length. 1.24 ohms x .150 feet = .186 ohms.

VD = I x R x 1.732 20 amps x .186 ohms x 1.732 = **6.44 volts dropped**.

Now let's use the formula $VD = \frac{1.732 \times K \times D \times I}{CM}$

First step is to find exact K:

$$\text{Exact } K = \frac{R \times CM}{1000'} = \frac{1.24\Omega \times 10380 \text{ cm}}{1000'} = 12.8712$$

$$VD = \frac{1.732 \times 12.8712 \times 150' \times 20 \text{ amps}}{10380 \text{ cm}} = \textbf{6.44 volts dropped}.$$

•Note: We have been calculating the voltage drop in single-phase and three-phase branch circuits using the formulas for VD. On the following pages we will use formulas to find WIRE SIZE, DISTANCE, and MAXIMUM LOAD.

WIRE SIZE ------ $$\text{CM} = \frac{2 \times \overset{\text{USE APPROXIMATE}}{K} \times D \times I}{\text{VD permitted}}$$

DISTANCE -------- $$D = \frac{\text{CM} \times \text{VD permitted}}{2 \times K \times I}$$

LOAD ------------ $$I = \frac{\text{CM} \times \text{VD permitted}}{2 \times K \times D}$$

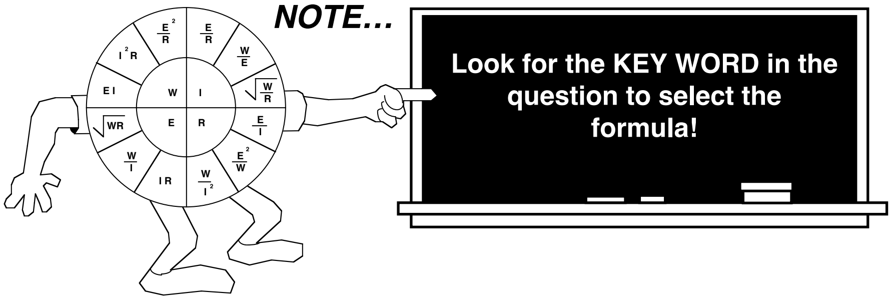
* For the Three-Phase:
change the “2” in the
formulas to 1.732

** For the CM Formula:
use an approximate K factor of
12.9 for Copper and
21.2 for Aluminum

The key to solving exam questions is to recognize the **key** word in the question. The key word will tell you which formula to use.

Example: What size THW conductor is required for a 208 volt single-phase branch circuit that has a 20 amp load, located 175 feet from the source? The **key** word is **size**. Use the formula to find wire **SIZE** ...cm.

The question did not mention copper or aluminum conductors, NEC Article 110.5 states you shall use **copper** unless aluminum is specified.



NOTE...

Look for the KEY WORD in the question to select the formula!