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Basic Motors & Drives

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Basic Motors

Module - 1

Introduction

Electricity is probably the single most utilized form of energy in today's modern society and is used extensively in its many forms throughout industry. One of the primary industrial uses of electricity is to power electrical motors.

Electric Motors

The primary purpose of an electric motor is to convert electrical energy into mechanical energy in the form of rotary motion. This is accomplished by the creation of magnetic fields within the motor, which cause the motor shaft to turn. To fully understand how AC motor drives work, it is necessary to have a good understanding of how the AC motors they are "driving" work. As motors operate magnetically, it is essential to understand how magnetic fields are created within electric motors and how they interact with each other to create rotary motion of the motor shaft.

Magnetism

Magnetism (like electricity and gravity) is one of the fundamental forces of the universe. Magnetism is generally defined as that property of a material that enables it to attract pieces of iron. Any material possessing this property is considered a *magnet*.

Magnetic Materials

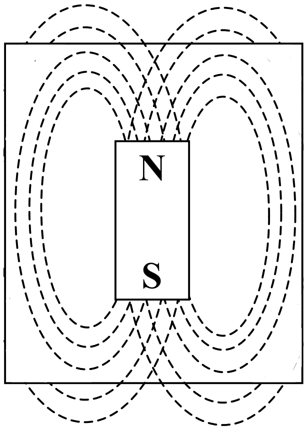
The ancient Greeks found stones having this characteristic and called them *magnetite*. Materials that are attracted by a magnet, such as iron, steel, nickel and cobalt can become magnetized, and so are called *magnetic materials*. Nonmagnetic materials cannot become magnetized.

The most important magnetic materials associated with electricity and electronics are the *ferromagnetic* materials. Ferromagnetic materials are relatively easy to magnetize and generally include iron, steel, cobalt, and the alloys Alnico and Permalloy. (An *alloy* is a combination of two or more elements, one of which must be a metal.)

Magnetic stones, such as those found by the ancient Greeks are naturally occurring magnets. These stones can attract small pieces of iron in a manner similar to the magnets common today. The Chinese are said to have studied the effects of magnetism as early as 2600 B.C. They observed that freely suspended magnetic stones had a tendency to assume a nearly north and south direction. Because of this directional quality of these magnetic stones, they were also called *lodestones* or "leading stones."

Lodestones are commonly found in the United States, Norway and Sweden, but they no longer have any practical use, as it is now possible to easily produce much more powerful magnets artificially.

Magnetic Fields



The space surrounding a magnet where magnetic forces act is called the *magnetic field*. Magnetic forces have a definite pattern of directional force that can be observed by performing an experiment with iron filings. If one were to place a piece of glass over a bar magnet and then sprinkle iron filings on the surface of the glass, the magnetizing force of the magnet will be felt through the glass. Due to their low reluctance and high permeability, each iron filing then becomes a temporary magnet.

If the glass was then tapped gently, the vibration would allow the iron particles to overcome friction against the glass and they will physically move to align themselves with the magnetic field surrounding the magnet. The now magnetically aligned filings will form a definite pattern, which is a visible representation of the forces comprising the magnetic field.

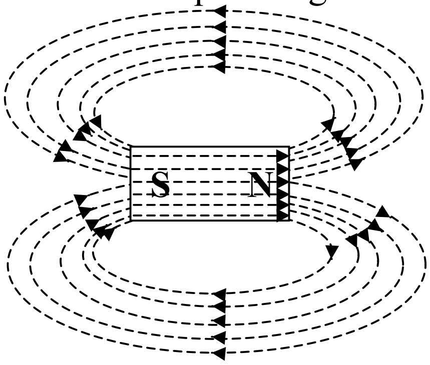
The arrangements of iron filings indicate that the magnetic field is very strong at the poles and weakens as the distance from the poles increases. They also show that the magnetic field extends from one pole to the other in a loop around the magnet.

Magnetic Lines of Force (Magnetic Flux)

To describe and work with magnetic phenomena, <u>imaginary</u> lines are normally used to graphically represent the force existing in the area surrounding a magnet. These imaginary lines are called *magnetic lines of force* and are commonly used to illustrate and describe the pattern of the magnetic field.

Magnetic Poles

The magnetic force surrounding a magnet is <u>not</u> uniform, but has a greater concentration of strength at each end of the magnet and a relatively weaker force at the center. This is illustrated by the fact that most of the iron filings are attracted to the two ends of the magnet, while much fewer remain at the center. The two ends, which are the regions of concentrated lines of force and greatest magnetic strength, are called the *poles* of the magnet. Magnets always have two magnetic poles and both poles have equal magnetic strength.



The *magnetic lines of force* are generally assumed to emanate from the North Pole of a magnet, pass through the surrounding space and enter the South Pole. They then travel <u>inside the magnet</u> from the South Pole to the North Pole, thus forming a closed loop.

Flux Density

The total number of *magnetic lines of force* leaving or entering the poles of a magnet is called *magnetic flux*. The number of flux lines per unit area is called *flux density*. The greater the *flux density,* the greater the *field intensity*, as the intensity of a magnetic field is directly related to the magnetic force exerted by the field.

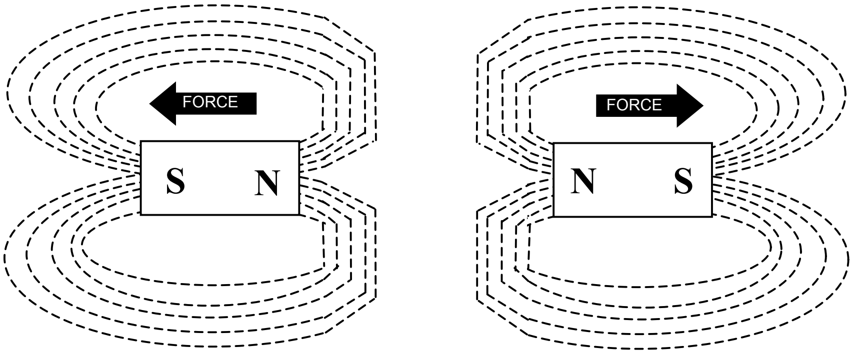
Magnetic Effects

Although *magnetic lines of force* are actually imaginary, by assuming they have certain real properties we can portray a simplified picture of many magnetic phenomena. The lines of force are similar to rubber bands that stretch outward when a force is exerted on them and contract when the force is removed.

The general characteristics of magnetic lines of force are:

- Magnetic lines of force are continuous and will always form closed loops.
- Magnetic lines of force do not cross one another.
- Parallel magnetic lines of force traveling in the same direction repel one another.
- Parallel magnetic lines of force traveling in opposite directions extend to unite with each other and form single lines traveling in a direction determined by the magnetic poles creating the lines of force.
- Magnetic lines of force tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to be pulled together.
- Magnetic lines of force pass through all materials, both magnetic and nonmagnetic.
- Magnetic lines of force always enter or leave a magnetic material at right angles to the surface.

As described previously, when "like" poles are brought together, their fields will be traveling in the same direction and tend to repel one another. The mutual repulsion of their parallel fields will actually distort (flatten out) both fields where they are in closest proximity.

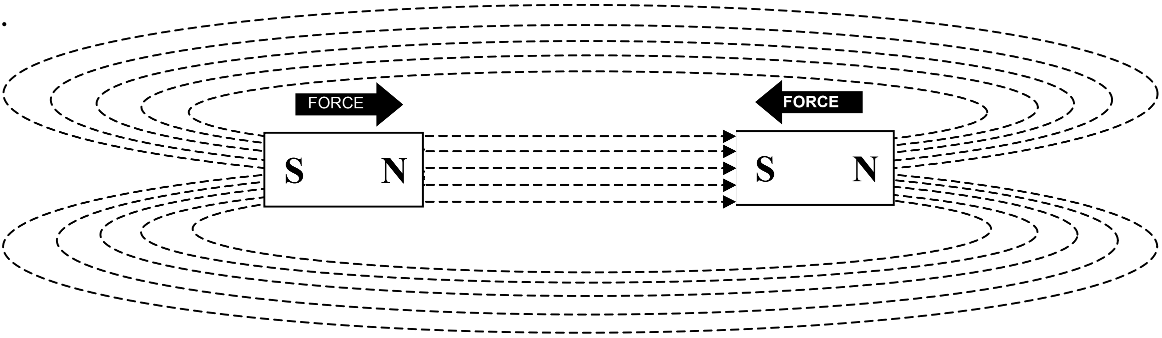


Mutual Repulsion

Due to the elasticity of their nature, the fields will also attempt to return to their normal shape and will exert physical force against one another, which tends to physically drive the two magnets apart.

When "unlike poles are brought together, the fields from the poles in closest proximity travelling in opposite directions will unite with one another, forming a <u>single field</u> traveling from the North Pole of one magnet to the South Pole of the other.

The fields from the poles furthest apart will extend and also unite to form a single field, as illustrated below. As magnetic lines of force always tend to shorten themselves as much as possible, physical force will be exerted that will tend to pull the two magnets toward one another.



Mutual Attraction

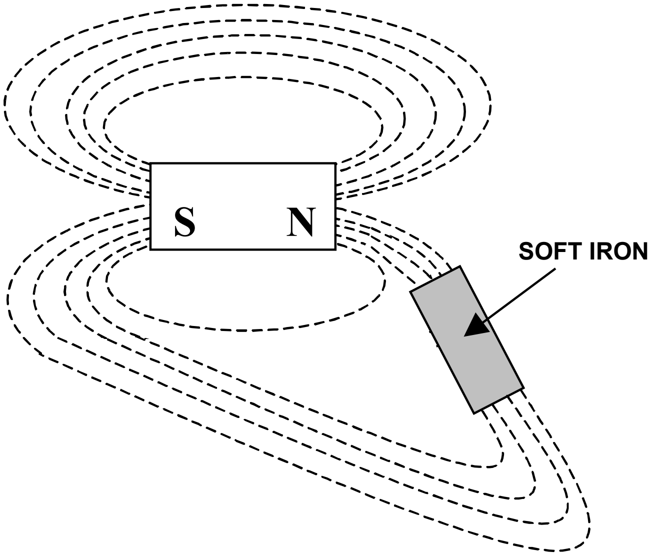
In general, the attraction and repulsion characteristics of magnets behave in a very similar manner as like and unlike electrostatic charges. In 1750, John Michell (1724-1793), a Fellow at Queen's College in Cambridge, England, published observations showing that *the force of attraction or repulsion between magnets is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between the poles.*

In this way, magnetic fields behave according to Newton's *inverse-square law* for gravitational bodies, published in 1687. Later, *Coulomb's Law of Charged Bodies* showed the repulsive and attractive forces produced by electrostatic charges also behave in the same manner.

Magnetic Shielding

There is no known material that has the ability to block the passage of magnetic flux. If a nonmagnetic material is placed within a magnetic field, there is no appreciable change in flux as the flux penetrates the nonmagnetic material. But if a magnetic material with a high permeability (such as soft iron) is placed in a magnetic field, the flux will be redirected to flow within that material because of the greater permeability of the magnetic material.

Stray magnetic fields can influence the sensitive mechanisms of electric and electronic instruments and meters that can cause errors in their readings.



Effects of a High Permeability Magnetic Material on a Magnetic Field

As instrument mechanisms cannot be directly insulated against magnetic flux, to help prevent this type of magnetic interference, the flux is normally directed around the instrument by placing a soft-iron case (called a *magnetic screen* or *magnetic shield*) about the instrument. Because the magnetic flux can travel more readily through the iron (even though the path is larger) than through the air inside the case, the instrument can be effectively shielded in this manner.

Electromagnetics

Modern electric motors do not actually utilize real magnets, but instead utilize *electromagnets*. To understand electromagnetics, it is necessary to discuss how electric current flow and magnetic fields relate to one another.

In the late 18th and early 19th centuries, the attributes of both electricity and magnetism were being investigated simultaneously. In 1819, Danish physicist Hans Christian Oersted made an important discovery when he found that a magnetic needle could be deflected by an electric current flowing through a wire. This discovery was the first that showed a definite connection existed between electricity and magnetism. Oersted's discovery was followed up by French scientist André Marie Ampère, who studied the forces between wires carrying electric currents and also by French physicist Dominique François Jean Arago, who was the first to magnetize a piece of iron by placing it near a current-carrying wire.

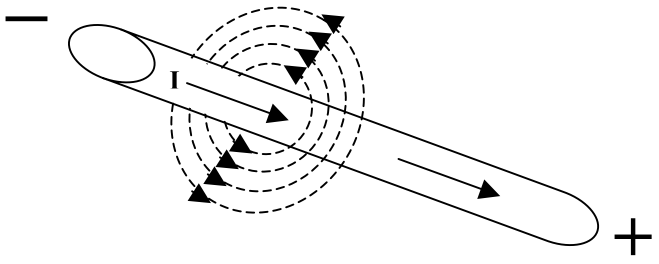
In 1831, English scientist Michael Faraday discovered that moving a magnet near a wire induces an electric current to flow within that wire, the inverse effect to that found by Oersted:

- Oersted showed that an electric current creates a magnetic field
- Faraday showed that a magnetic field could be used to create an electric current.

The full unification of the theories of electricity and magnetism was achieved by the English physicist James Maxwell, who also predicted the existence of electromagnetic waves and identified light as an electromagnetic phenomenon.

So, what does all this really mean in the study of electric motors? When an electric current flows through a conductor, a small magnetic field will build up around the conductor, perpendicular to the direction of current flow.

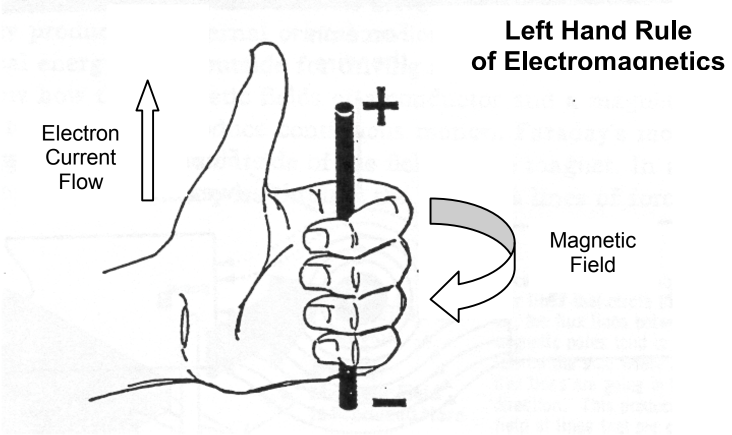
This magnetic field is only generated when charges (electrons) are actually moving (current flowing) through the conductor. (Stationary charges may, or may not, create an *electrostatic field*, but will not generate an *electromagnetic field* until they start to move.)



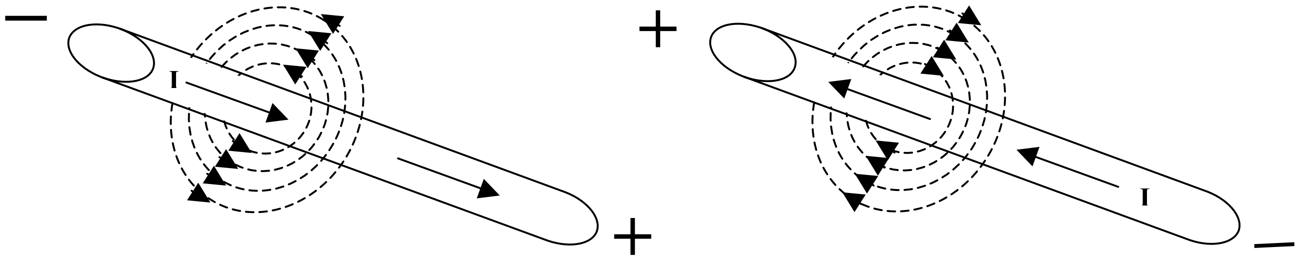
The <u>strength</u> (flux density) of an *electromagnetic field* is directly proportional to the <u>amount</u> of current flowing in the conductor. The *polarity* (direction) of the magnetic field is determined by the direction of the current flow.

Left-Hand Rule of Electromagnetics

The direction of the magnetic field that builds up around conductors having electric current flowing through them can be determined using the *Left-Hand Rule of Electromagnetics*. If you completely open your left hand with your thumb pointing straight up and then curl your fingers back until they are pointing toward your palm, the curled fingers will point to the direction the magnetic flux will assume when current is flowing in the direction that your thumb is pointing (see illustration below):



If the direction of electric current flow reverses, then the direction (and polarity) of the magnetic field around the wire reverses.



Electromagnetic Induction

There are basically three ways that electricity and magnetism are related:

1. An electric current produces a magnetic field.
2. A magnetic field can interact with the negative electrostatic charge of electrons and influence the direction of electron flow in a vacuum.
3. An electric current is generated in a wire by moving it through a magnetic field.

Faraday also discovered that a steady (non-fluctuating) magnetic field does <u>not</u> produce electric current. Only a *changing* (fluctuating) magnetic field produces electric current flow.

Electromotive force (emf)

Electromotive force, or *emf* is actually a difference in voltage potential (measured in volts) that can cause an induced current to flow in a wire. The exact amount of *induced emf* can be calculated using the following formula:

$$emf = BLv \sin \phi$$

Where: <u>*emf*</u> is the difference in potential, measured in volts, <u>*B*</u> is the strength of the magnetic field, (measured in Telsa's or Gauss) <u>*L*</u> is the length of the wire within the magnetic field, <u>*v*</u> is the velocity with which the wire is moved through the magnetic field *B*, and <u>*sine* ϕ</u> is a trigonometric function of the angle at which the wire is moved within the magnetic field.

In actuality, it really doesn't matter whether a moving conductor passes through a stationary magnetic field, or a fluctuating magnetic field is expanding and contracting through a conductor; electrical current flow will be generated within the conductor either way.

Electromagnetic induction is the name of the process whereby electric current is produced when either a wire or a magnetic field moves, relative to one another. As long as the wire cuts across magnetic field lines during the motion, a current will be produced.

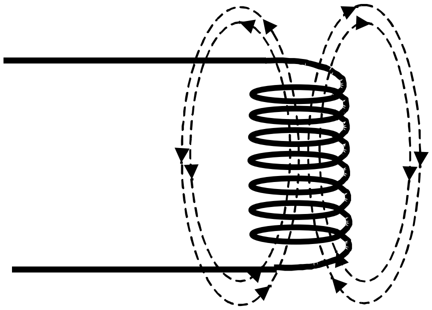
<u>Therefore</u>:

- A voltage (emf) is induced across a conductor if it is moved into or out of a magnetic field.
- A voltage (emf) is induced across a conductor if a magnetic field expands or contracts through a wire.

The greater the magnitude of the change, or the more rapid the change, the greater the amount of *electromotive force* (voltage) that will be developed and hence, the more current that will flow.

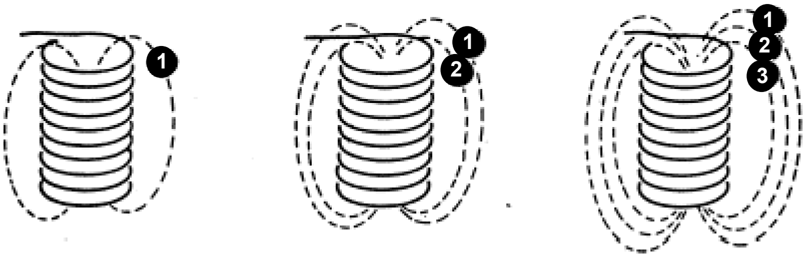
Magnetic Amplification Using Coils

Whenever a current carrying wire is looped back onto itself in the shape of a coil, the magnetic field surrounding the wire will interact with itself. Because the flux lines are all going the same direction, the effect is additive and will produce a significantly stronger field surrounding the coil, as compared to that surrounding the wire where it is not coiled. The higher the number of turns in the coil, the stronger the magnetic field that is developed around it.



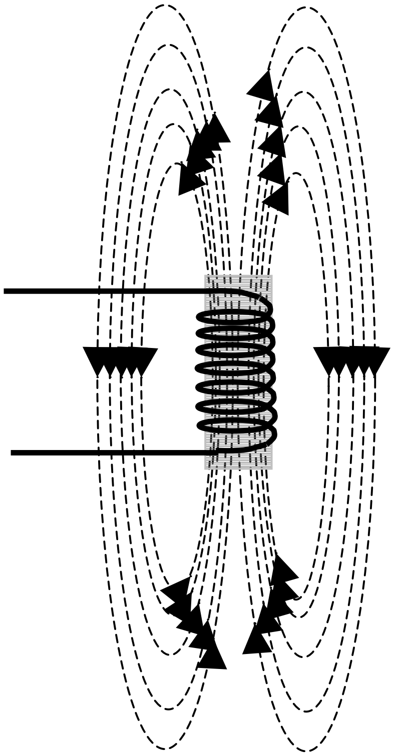
Magnetic Amplification of a Coil

For a fixed number of turns in a coil, the magnetic field strength is directly proportional to the amount of current flowing within the coil, as shown in the illustration on the right:



Magnetic Field Expands as Current Increases

Ferromagnetic Cores



Effect of a Ferromagnetic Core

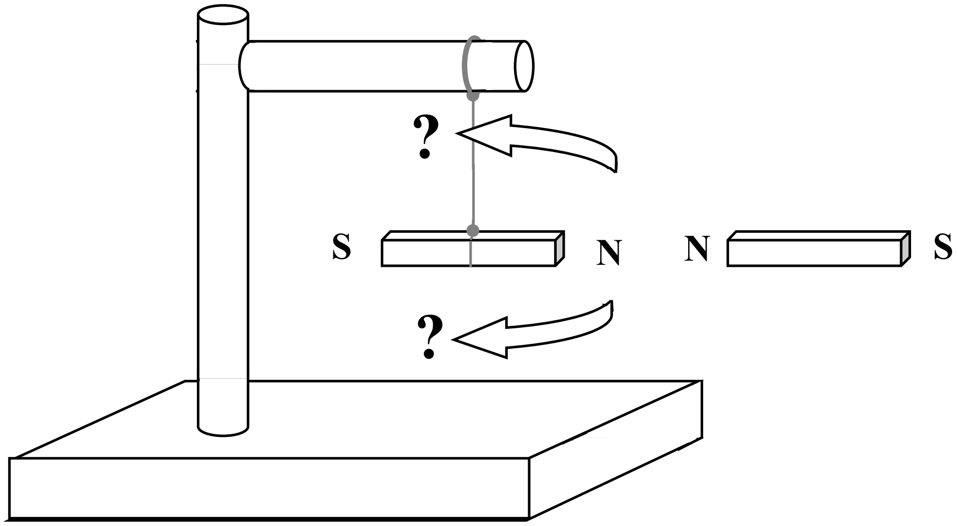
As previously discussed, certain types of *ferromagnetic materials* (such as soft iron) are much more conducive to conveying magnetic lines of flux than is air, due to their high permeability. If a coil were wound around one of these *ferromagnetic materials*, the magnetic field resulting from current flowing through the coil would be much stronger, as compared to that produced by the same coil without the *ferromagnetic core*. In some cases, this increase is on the order of thousands of times.

Not only is the resulting magnetic field larger, it is also much stronger in terms of *flux density*, as a ferromagnetic core can easily contain many more flux lines than can air, or a core made of a dielectric material such as wood, glass or plastic.

Creation of Rotary Motion using Magnetic Fields

A magnet suspended from a string will tend to orient itself towards the earth's magnetic poles. If a second magnet were introduced in close proximity to the magnet suspended from the string, it's effect would be much greater that that of the earth's magnetic field and the suspended magnet will physically move in reaction to the second magnet's magnetic field.

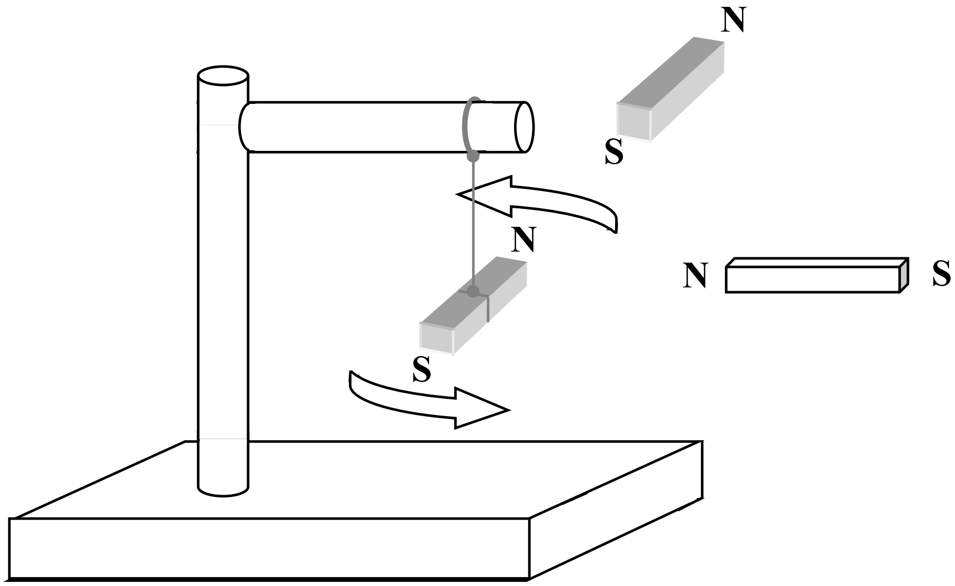
As shown below, if the North Pole of the second magnet is placed in close proximity to the North Pole of the suspended magnet, the suspended magnet will rotate away from the second magnet due to mutual repulsion. But in which direction? With no other influences involved, there is no way to control or predict which direction the suspended magnet will turn.



The direction can be controlled, however, if additional magnetic fields are introduced.

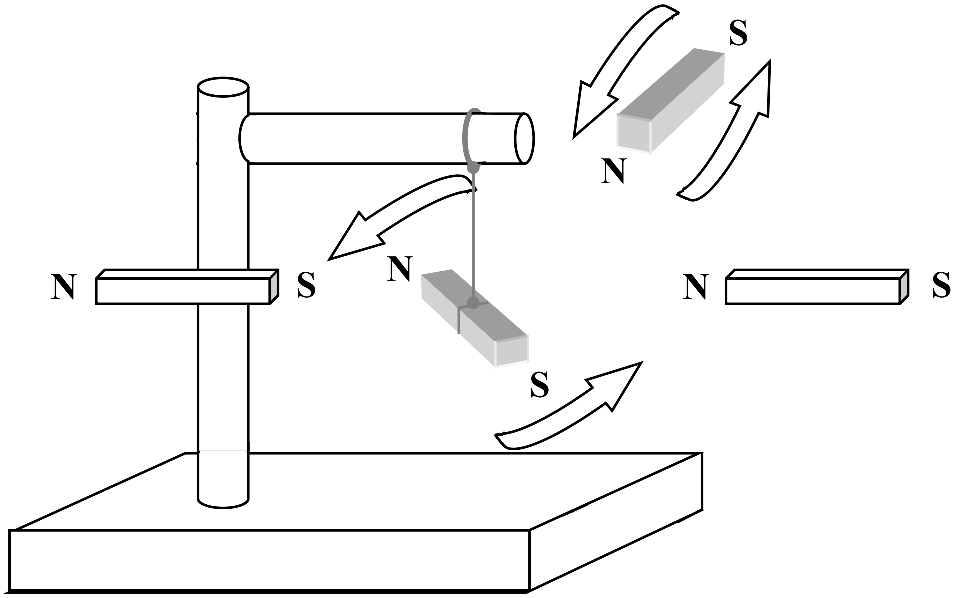
For example:

If the south pole of a third magnet was placed at a 90° angle to the second magnet, the mutual repulsion between the two North Poles, and the attraction of the third magnet will combine, causing the suspended magnet to turn in a definite direction; towards the third magnet, as shown on the right:

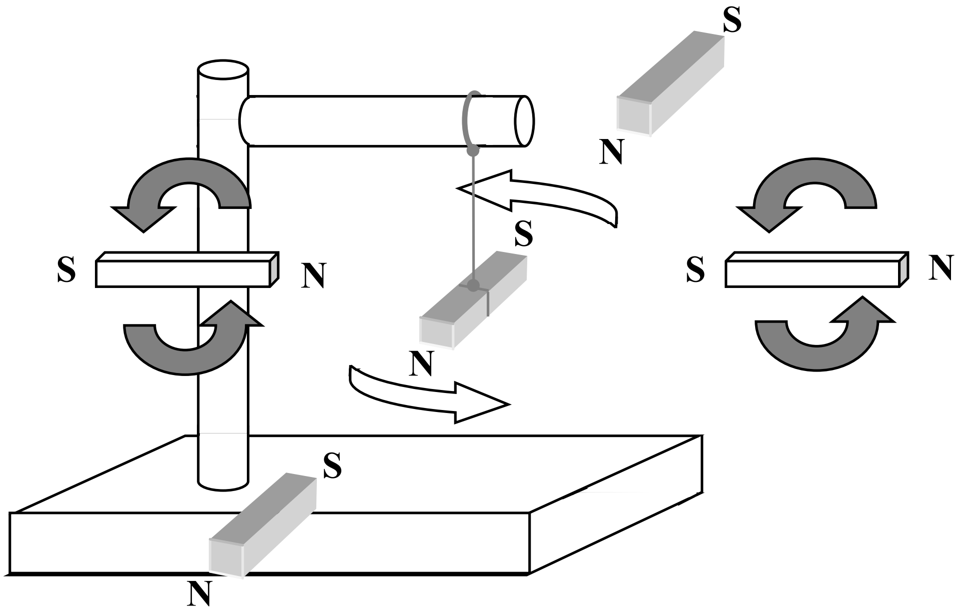


The suspended magnet will turn to line up with the third magnet, due to the mutual attraction between their North and South Poles. If nothing else were to happen, the inertia of the suspended magnet would tend to swing it past alignment with the third magnet, but their mutual attraction would slow it's rotation sufficiently for it to swing back into alignment, where motion of the suspended magnet would then stop.

But, if the third magnet were rotated (reversing the polarity of it's magnetic field) at just the right time, (just as the suspended magnet was swinging past their alignment point) the mutual repulsion between them will push the suspended magnet away, making it's rotation continue in the same direction. Addition of a fourth magnet whose South Sole is at a 90° angle to the third magnet, will add it's attraction properties to further enhance continued rotation in the desired direction.



Again, the suspended magnet will continue to turn away from the North Pole of the third magnet, towards the South Pole of the fourth magnet.



If a fifth magnet (with it's south pole at a 90° angle to the third magnet) were added to the mix, and the fourth and second magnets are both rotated to reverse the polarity of their magnetic fields at just the right time, the rotation of the suspended magnet will continue in the same direction as before.

As the suspended magnet nears alignment with the third and fifth magnets, if the polarity their magnetic fields were both reversed, rotation of the suspended magnet will continue.

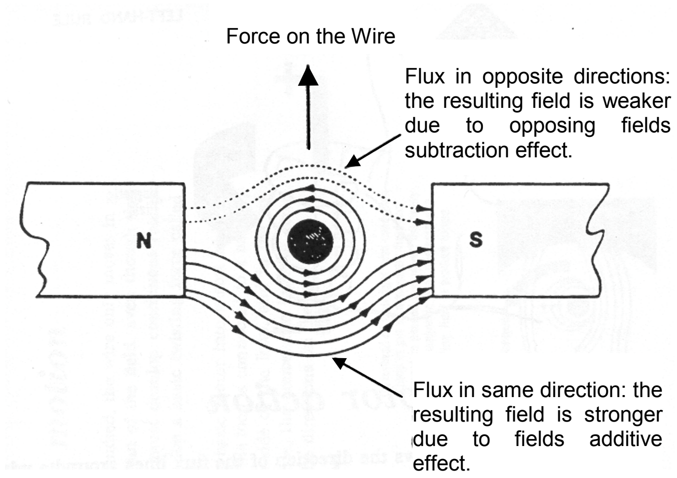
By continually reversing the polarity of the magnetic fields surrounding the suspended magnet, (at just the right times) the suspended magnet can be made to rotate continuously. In effect, this is how DC electric motors work.

Motor Action

In electric motors, *electromagnetic fields* are generally created using electrical current flow. If a piece of wire were suspended within a magnetic field, and an electric current passed through it, as previously noted, a magnetic field will build up around the wire. Polarity of the magnetic field around the wire is dependent upon the direction of current flow within the wire.

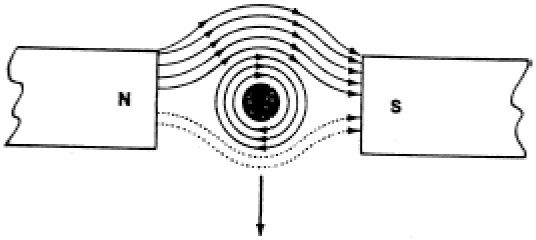
The magnetic field around the wire will interact with the externally applied magnetic field. On one side of the wire, where the magnetic flux of the two fields are going in the same direction, their interaction is additive producing a strong field (high flux density) on that side of the wire.

On the other side of the wire, where the magnetic flux of the two fields are going in opposite directions their interaction is subtractive producing a weak field (low flux density) on that side of the wire.



The field imbalance (strong on one side, weak on the other) will create mechanical force, which will cause the wire to physically move away from the stronger field, towards the weaker field, as illustrated above. This phenomenon is called *motor action*.

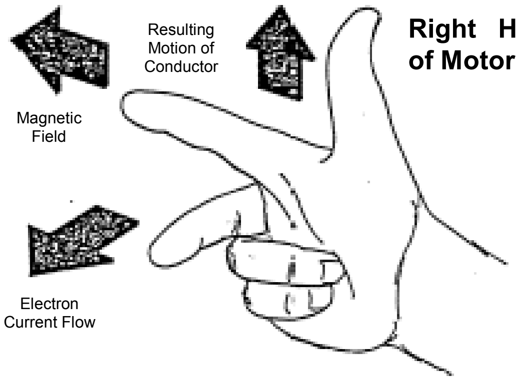
Reversing the direction of current flowing in the wire will reverse the polarity of the field around the wire and cause the wire to move in the opposite direction, as shown below:



Force on the Wire

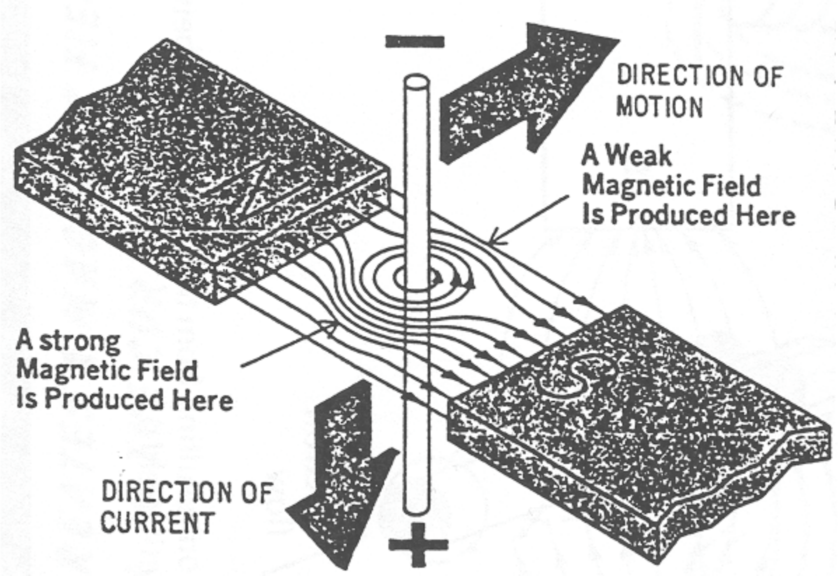
Right-Hand Rule of Motor Action

The direction of the mechanical force (motor action) applied to the wire can be determined using the *Right-Hand Rule of Motor Action.* Completely open your right hand with your thumb pointing straight up and the forefinger pointing straight out, curl all but the forefinger to a 90° angle to the forefinger, as shown on the right:



Right Hand Rule of Motor Action

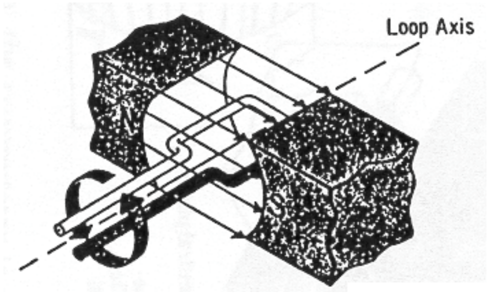
The middle finger is indicative of the direction of current flow. The forefinger indicates the direction of the external magnetic field and the thumb shows the resulting direction of wire motion.



Rotary Motion and Torque

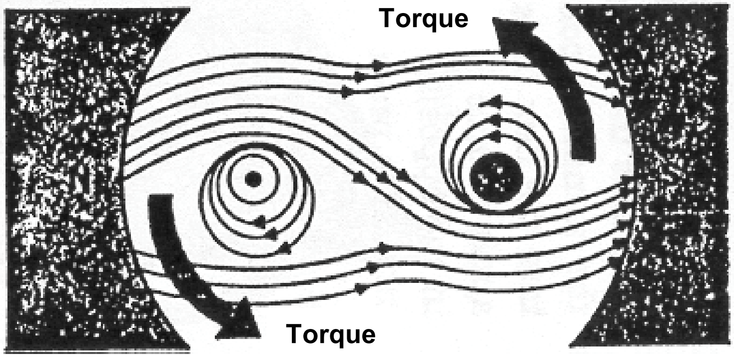
In the examples previously discussed, the wire moves only in a straight line and would stop moving after leaving the external magnetic field. In an electric motor, continuous *rotary motion* must be developed to produce a twisting mechanical force called *torque*, in order to perform practical work.

The first step in producing *torque* is accomplished by bending the wire back into a loop, within the magnetic field, as shown on the right:



If a battery were connected to the wire, current will flow in one direction on one side of the loop and in the opposite direction on the other side of the loop.

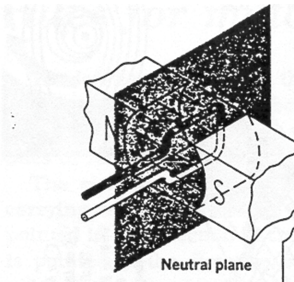
This will create opposite polarity magnetic fields on opposite sides of the loop, within the same magnetic field, as shown below:



In the illustration above, current is flowing into the page on the right side of the wire, and back out of the page on the left. The resulting magnetic fields will interact and push the right side of the wire up, while the left side of the wire is pushed down (rotary motion).

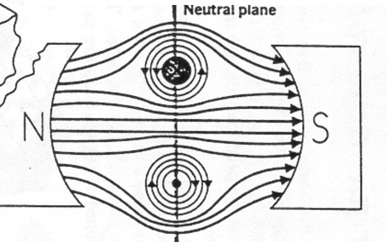
The wire will continue rotating in a counter-clockwise direction until the two sides of the loop are perpendicular to the externally applied magnetic field (called the *neutral plane*), as shown on the right:

When the loop is in the *neutral plane*, magnetic forces are balanced on both sides of the wire and the wire will stop moving because of magnetic equilibrium between the fields.



When the plane of the loop becomes perpendicular to the field, the armature is in the neutral plane.

When the armature is in the neutral plane, magnetic interaction is in equilibrium and no torque is developed.



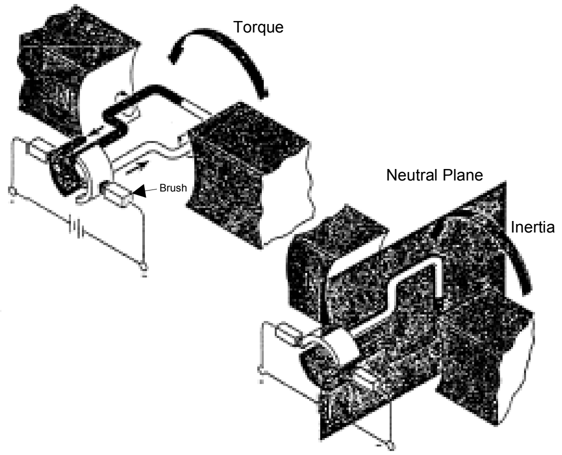
Just as the suspended magnet could be made to rotate in a complete circle by timed reversal of the polarity of magnetic fields around it, the same effect can be accomplished by reversing the direction of current flow within the wire just as it reaches the *neutral plane*.

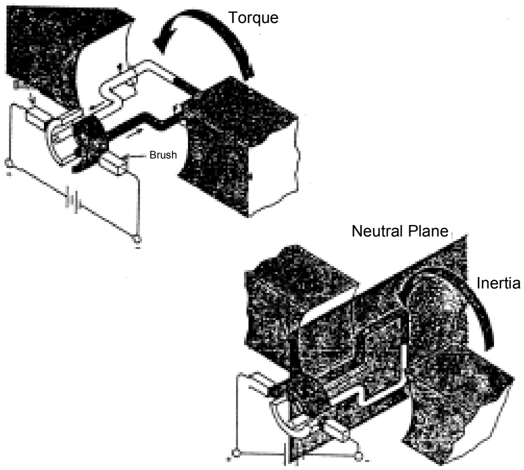
DC Motors

In any electric motor, the part creating the external magnetic field that does not rotate is called the *stator* and the part of the motor that rotates is called the *rotor*. In DC motors, the rotor is often called the *armature* because of electrical DC power being externally applied to the rotating windings of wire through via carbon brushes and a copper commutator.

Commutator

Electric DC motors utilize a commutator to accomplish the desired reversal of current direction within the armature. A commutator is basically a split copper ring that connects to each end of the armature winding (wire loop).





DC power is transferred to the commutator rings by carbon brushes and current flow through the armature is as illustrated on the top-left. This causes the armature to rotate as previously discussed. As the armature approaches the neutral plane, the splits in the commutator ring disconnect the DC power source from the armature. Inertia (momentum) of the rotating armature will carry the now unpowered armature past the *neutral plane* where the carbon brushes will again come into contact with the commutator ring. But now, each of the brushes are connected to the opposite side of the armature, reversing the direction of current flow through the armature, causing it to continue rotating in the same direction as previously discussed. In this way, a DC motor can create continuous rotary motion and can transfer that motion via the rotor shaft to create the torque required to drive a mechanical load.

Ohm's Law

The single most useful tool in the study of electricity is known as "*Ohm's Law*," as it provides us with the mathematical relationship between voltage, current and resistance in electrical circuits. In mathematical expressions, voltage is represented by the letter "E," current is represented by the letter "I" and resistance is represented by the letter "R." Simply stated, Ohm's law tells us that in an electrical circuit, the current (I) will be equal to the voltage (E) divided by the resistance (R).

In mathematical form, ohm's law looks like this:

$$I_{\textit{(current in amps)}} = \frac{E\ \textit{(voltage in volts)}}{R\ \textit{(resistance in ohms)}} \qquad \text{OR} \qquad I = \frac{E}{R}$$

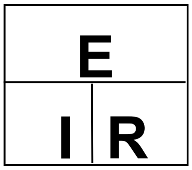
By mathematically transposing the equation, we can also determine that:

$$E = I \times R \qquad \text{AND} \qquad R = \frac{E}{I}$$

Ohm's law, in all its simplicity, states that 1 volt of electromotive force will cause 1 amp of current to flow through a circuit path having 1Ω of resistance.

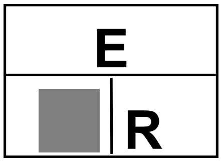
$$\frac{1V\ (E)}{1\Omega\ (R)} = 1A\ (I)$$

If by taking measurements with instruments designed for that purpose, we know the values of any two of the three, we can utilize Ohm's law to calculate the third.



Pictured on the left is a graphic we can use as a handy memory jogger in the use of ohm's law in practical application. If any two values are known, simply cover the unknown quantity with your finger and the remaining uncovered boxes will reveal formula for determining the unknown quantity.

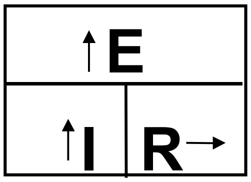
Say, for example, we wanted to calculate the current in a circuit where the voltage is 100 volts and a 40Ω load, (meaning the load-resistance is 40Ω). We could simply cover the quantity we want to solve for with our finger (in this case current), and the graphic tells us that to determine current, we would need to divide the voltage by the resistance.

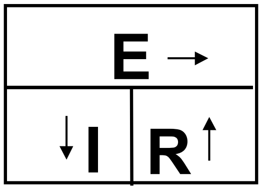


$$\frac{100V\ (E)}{40\ \Omega\ (R)} = 2.5\ A\ (I)$$

In this example, correct usage of Ohm's law tells us that a circuit having an applied voltage of 100V and a resistance of 40 Ω will have 2½ amps of current flowing through it.

In general, if resistance remains constant, then current will be *directly proportional* to the voltage. If voltage goes up, then the current goes up.



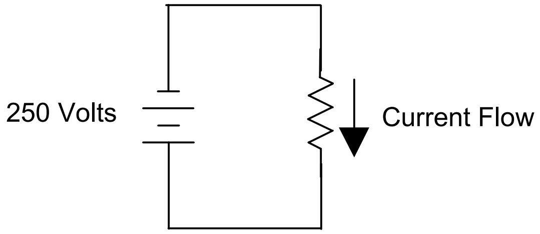


If the voltage remains constant while resistance varies, the amount of current will be *indirectly proportional* to the resistance. If the resistance to current flow goes up, the current will go down proportionally.

Motor Current

Suppose we had a motor that had a data plate telling us that it was rated to operate at 250V and draw a maximum of 5 amps of current. As the windings of a motor are essentially a piece of wire, they inherently have a rather low internal resistance, (generally 10Ω or less).

Using 10Ω (general maximum for a standard electric motor) as our value of resistance, we can draw an equivalent motor circuit, as shown at below:



Using Ohm's law, we can calculate the amount of current that will flow through a 10Ω load when 250 volts is applied:

$$\frac{250\text{V}}{10\ \Omega}\ \frac{(E)}{(R)} = 25\text{ A}\ \ (I)$$

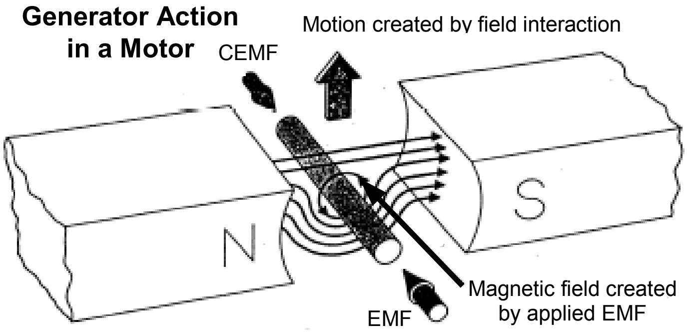
The 25 amps calculated is about 5 times, or 500% the amount of current the motor is rated to handle. Obviously, something besides the miniscule resistance of the motor windings must be involved in limiting the current flow through them.

Counter Electromotive Force (CEMF)

Counter EMF (CEMF) acts as a load to the voltage source powering the motor, so that the inherently low internal resistance of the motor windings is not the only factor limiting motor current. When full voltage is first applied to a standard motor, the motor rotor is not turning and the motor will indeed, draw 500% to 600% of it's full load amp rating on startup. This is called *inrush current*. (High efficiency motor windings generally have much lower internal resistance and therefore their *inrush current* draw can generally be as much as 1500% full load amps on startup.)

But, just as soon as the rotor starts turning, CEMF begins being created. As the armature begins rotating through the magnetic field, the physical motion of the windings cutting through the magnetic field will cause a voltage to be developed across the windings, in the opposite polarity to the applied voltage, (EMF).

In essence, this CEMF that is developed as the windings cut through the magnetic field of the stator tends to try to induce current flow in the opposite direction from that drawn from the voltage source, thus subtracting from and reducing the overall current within the windings.

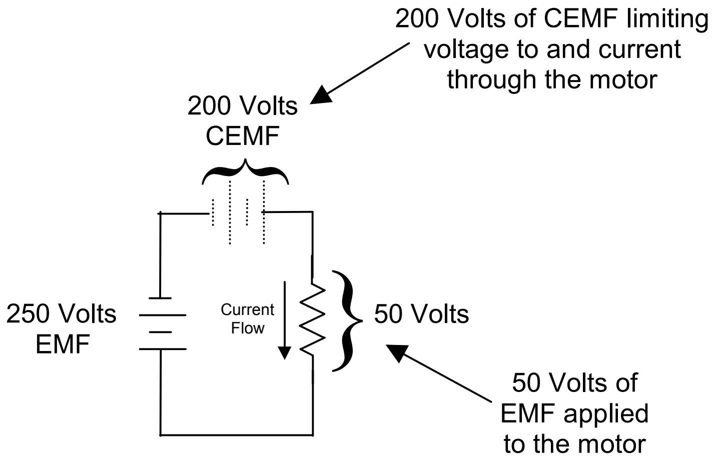


As this is the same phenomenon that creates the voltage output of electrical generators and alternators, the creation of CEMF within a motor is sometimes referred to as *generator action.*

Now we can go back to our earlier example and using Ohm's law, we can calculate the effect that CEMF plays in this motor circuit. If the motor is rated to draw a maximum of 5 full load amps at full rated speed, then to calculate the amount of voltage actually dropped across the motor windings when running at full speed:

$$E = I \times R \quad \text{therefore} \quad E = 5A \times 10\Omega = 50 \text{ volts}$$

When the motor is running at full rated speed, CEMF is developing 200 volts worth of counter potential in the opposite polarity with the applied voltage, effectively dropping the 250 volts applied down to only 50 volts actually producing current flow within the motor. With only 50 volts applied to the motor's inherent 10Ω winding resistance, only 5 amps of current will be flowing in the motor windings when running at rated speed.



Locked Rotor Current

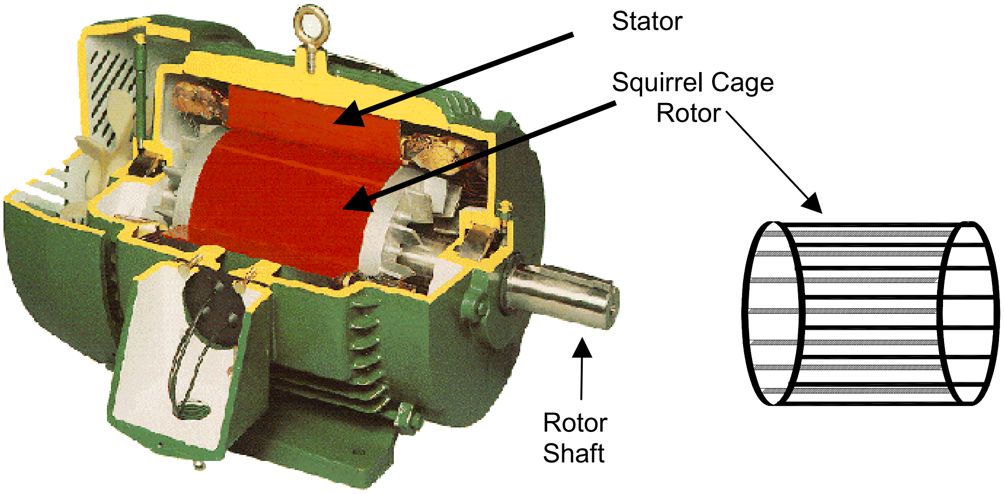
CEMF is the primary factor in limiting motor current and CEMF is <u>only</u> created when the motor is rotating. If the rotor is mechanically locked (not free to turn), then CEMF will not be created and 500% to 1500% FLA (full load amps) will be drawn <u>continuously</u>.

Excessive heat will be created by continuous current levels of 5 to 15 times the motor's full-load amp rating, which can not only severely damage the motor, but is also a fire hazard. Circuit breakers should normally be employed on the input motor leads, whenever there the possibility exists that the motor's mechanical load could prevent motor rotation while under power.

AC Induction Motors

Most of the motors in use today are AC induction motors. AC motors basically operate by creating a magnetic field that rotates around the rotor. The rotor in induction motors is often called a *squirrel cage rotor*, as it is generally made up of aluminum or copper conductors (bars) that form a cage that resembles a small animal exercise wheel.

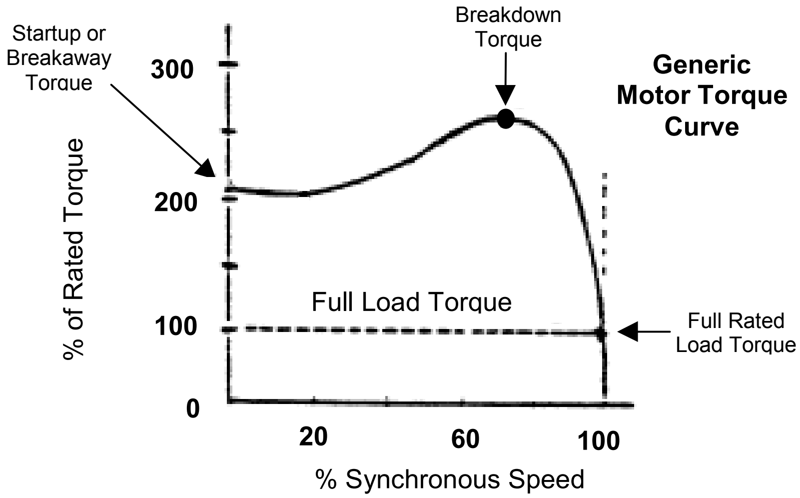
AC Induction Motor



When commercial AC power is applied to the stator, a rotating magnetic field is generated that induces voltage and current flow within the rotor bars. The current flowing within the rotor conductors cause a magnetic field to be created around them, which will interact with the stator field.

When AC power is first applied to the stator, the speed differential between to rotating stator field and the stationary rotor will cause very high currents to flow within the rotor, creating a very strong magnetic field to build up around the rotor bars. The interaction of these two strong magnetic fields will produce very high *torque*, causing the rotor to turn in the same direction as the rotating field generated by the stator.

As the rotor rotation speed begins approaching that of the stator field, the speed differential between them becomes less, causing less current to be induced in the rotor bars, which in turn reduces the strength of the magnetic field around them. As the strength of the magnetic field around the rotor bars decreases, so does the amount of torque delivered to the rotor shaft.

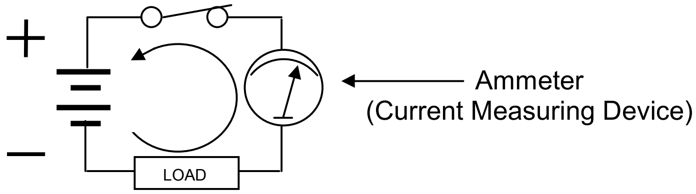


The rotor of an induction motor will never turn at exactly the same speed (synchronous speed) as the rotating stator field, as it is the *difference* in speed between them that creates motor *torque*, (the force that causes the rotor to turn). If the *difference* in speed between them were zero, then there would be no torque developed to cause the motor shaft to turn. The difference between synchronous speed and actual speed is known as *slip*.

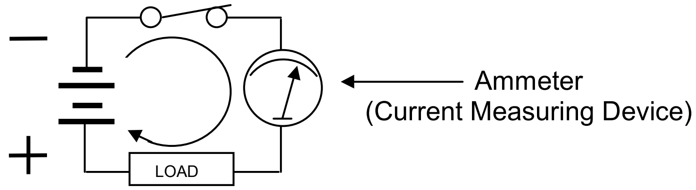
AC (Alternating Current)

Unlike a battery that provides a constant, (unvarying) amount of voltage and a constant direction of current flow, (DC) AC voltages are constantly varying in their instantaneous voltage level and reversing the direction of current flow on a cyclical basis.

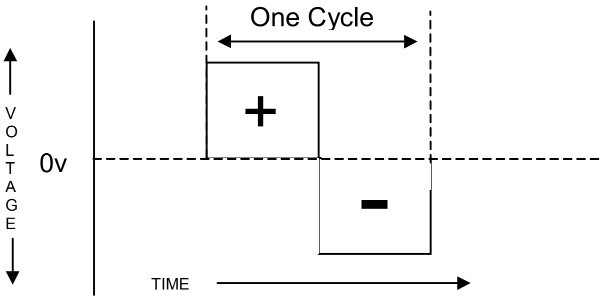
Suppose we were to reverse the direction (or *polarity*) of the battery on a repetitive basis. Part of the time, the current would flow in one direction.



…and then, the current would change direction and flow back in the opposite direction.



If amount of time the current was flowing in each direction was the same and we then drew an X-Y plot where voltage changes in the vertical, while time expands in the horizontal, we could plot the behavior of the voltage, in respect to time:



This type of an electrical signal, which causes the current to continually reverse direction in a rhythmic pattern, is called *alternating current* (or AC for short) because the direction of current flow alternates. One complete pattern from 0 to up to the maximum + voltage, back to 0, then down to the maximum - voltage, and then up to 0 again is called one complete *cycle* of the AC voltage signal. (Because of its appearance, the voltage waveform illustrated above is called a *square wave*.)

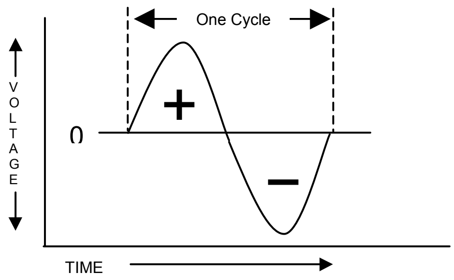
Sinewave

AC power generators at the utility company produce an AC power signal that is *sinusoidal* in nature and is therefore called a *sinewave*.

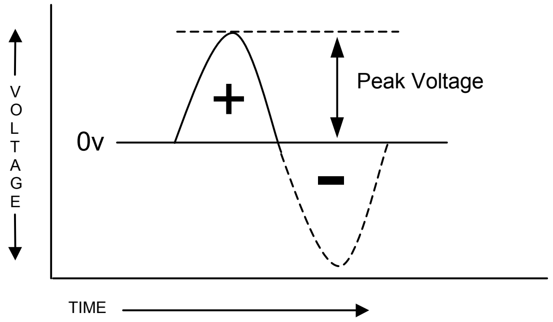
When charted on ax X-Y plot, (voltage vs. time) a sine wave would look like the illustration on the right:

Again, one complete positive-to-negative-to-positive transition of the voltage is called a *cycle*.

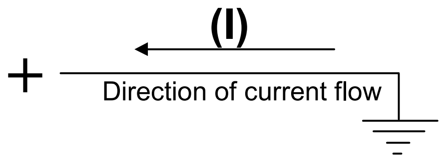
During the positive half-cycle, the voltage rises from zero to a maximum positive level and then falls from that maximum positive level, back to zero again.



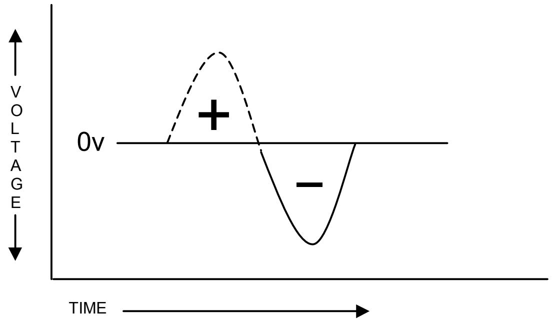
The difference in voltage potential between zero and its maximum positive level is called the *peak voltage*.

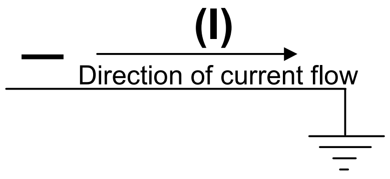


During the positive half-cycle, current will flow from ground, (zero volt potential) towards the positive voltage source. (The amount of current flowing during any given instant in time will be dependent upon the exact voltage at that time, in relation to the resistance per Ohm's Law, as previously discussed.)



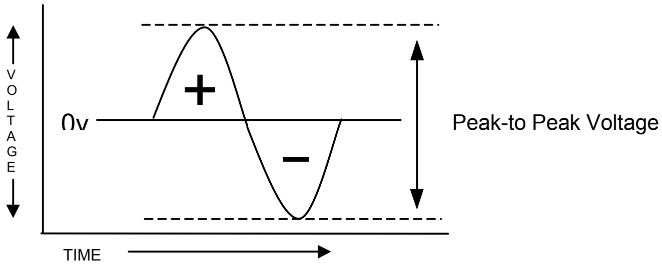
During the negative half-cycle, current will reverse direction and flow from the negative voltage source towards ground, (zero volt potential). (Again, the amount of current flowing during any given instant in time will be dependent upon the exact voltage at that time, in relation to the resistance per Ohm's Law, as previously discussed.)



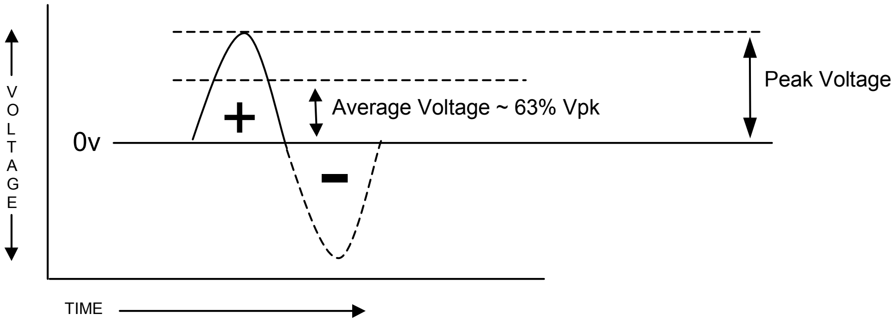


The "average" voltage of one complete cycle always equals zero, as for every instant in time during the positive half-cycle, there will be an exact equal and opposite voltage during the negative half-cycle.

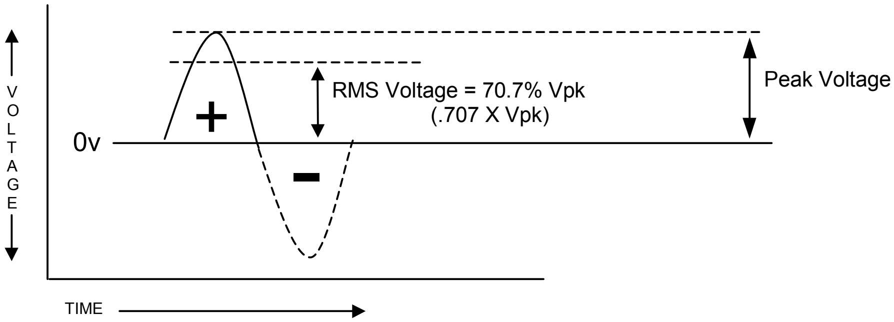
The difference in voltage potential between the maximum positive peak value and the maximum negative voltage peak value is called the *peak-to-peak voltage*.



As the rate at which the voltage varies in a sine wave is sinusoidal in nature, the *average* voltage of each half-cycle of a sine wave is 0.637 of the peak voltage.



But this *average voltage* cannot be used as an accurate measure of AC voltage levels however, as there would be differences in power dissipation through a resistive load, when compared to an equal amount of DC voltage. To keep from having to have separate power ratings (one for DC and another for AC) for components and wiring, AC voltages are measured as RMS volts, (Root-Mean, Squared).



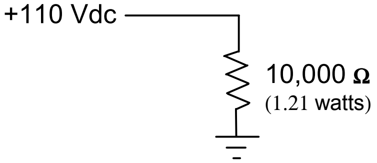
When measuring the voltage of an AC sine wave, (like AC power) with an AC voltmeter, the meter will display RMS voltage, which is 70.7% of the peak voltage, (.707 x V_{pk}). It is not really important that one truly understand the mathematics behind the derivation of RMS. ($V_{RMS} = V_{pk}$ multiplied times the reciprocal of the square-root of 2.)

$$V_{rms} = V_{pk} \times \frac{1}{\sqrt{2}}$$

The main thing that one needs to remember is that when measuring the voltage of sinusoidal AC signals, (like AC power) the meter will display the RMS voltage, which is 70.7% of the peak voltage, ($.707 \times V_{pk}$). The purpose of using the RMS value is to equalize the power dissipation across a resistive load, when the same amount of voltage is applied, regardless of whether it is AC or DC.

For example:

To calculate the power that would be dissipated when +110 volts DC is applied to a 10,000 ohm load:

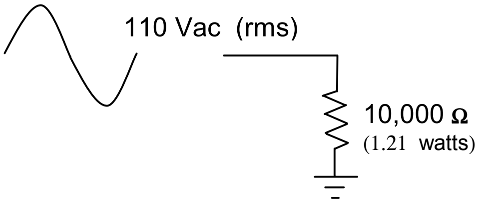


As discussed previously, $P = \frac{E^2}{R}$ therefore $P = \frac{12{,}100}{10{,}000}$ (110 x 110)

OR

1.21 watts

When 110 Vac (rms) is applied to the same 10,000 ohm load, exactly the same 1.21 watts of power will be dissipated across the load as when 110 Vdc was applied.



Keeping the power constant through a resistive load for the same amount of AC and DC voltage is why AC voltages are measured as RMS. As AC (sine wave) voltages are expressed in RMS terms, (V_{rms}) their corresponding current values will also be expressed in RMS terms, (I_{rms}).

In some technical documentation, RMS volts may also be referred to as *effective voltage*.

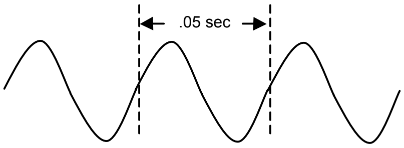
Frequency

The term *frequency* refers to the number of complete cycles of an AC signal that occur during a single second of time. Frequency is measured in units called *hertz*, where one hertz is equal to one cycle-per-second. The standard AC power frequency in the United States 60 hertz, (60Hz) meaning that sixty complete cycles will occur every second. (In Europe, a 50Hz standard is commonly used.)

Frequency can be expressed as the reciprocal of the time of one cycle, expressed in seconds:

$$F = \frac{1 \text{ (cycle)}}{T \text{ (time in seconds)}}$$

Therefore, if the time it takes for a single cycle to occur is .05 seconds, then:



$$F = \frac{1}{.05} = 20\text{Hz}$$

If the frequency is known, then the time of one cycle can be calculated as the reciprocal of the frequency. For example, using the AC power frequency of 60Hz, we can calculate the time a one cycle by:

$$T = \frac{1}{F} = \frac{1}{60} = .0167 \text{ seconds}$$

This means that each cycle of the AC power line frequency, (often just referred to *as line frequency*) occurs in:

$$\frac{16.7}{1000} \text{ of a second}$$

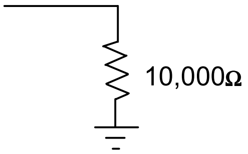
Prefixes

In order to simplify discussion of very large, or very small numbers of various units of measurement, prefixes are often utilized to modify the basic unit by some power factor of 10. Prefixes generally change the base unit in increments of 10 to the plus or minus 3, giving us separate prefix names to distinguish units grouped by thousands, millions, billions, etc., or their reciprocals:

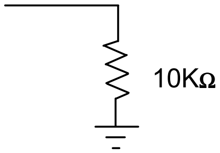
1/Thousandths =	milli	(m)	= x 10^{-3}	= x 0.001
1/Millionths =	micro	(µ or u)	= x 10^{-6}	= x 0.000001
1/Billionths =	nano	(n)	= x 10^{-9}	= x 0.000000001
1/Trillionths =	pico	(p)	= x 10^{-12}	= x 0.000000000001
Thousands =	Kilo	(K)	= x 10^{3}	= x 1,000
Millions =	Mega	(M)	= x 10^{6}	= x 1,000,000
Billions =	Giga	(G)	= x 10^{9}	= x 1,000,000,000
Trillions =	Tera	(T)	= x 10^{12}	(very rarely used)

So, as the time of a single cycle of AC line frequency is expressed in 1/1000's of a second, instead of saying 0.0167 seconds, we can use the prefix *milli* and call it 16.7 *milliseconds*, (16.7ms) which is generally easier to talk about.

Going back to our earlier example when we were utilizing a 10,000 ohm resister:



This value would be more commonly referred to verbally and on diagrams as 10 Kilo-ohms, which is generally shortened to just, ten "kay" ohms (10KΩ), which means the same thing as saying ten-thousand ohms.

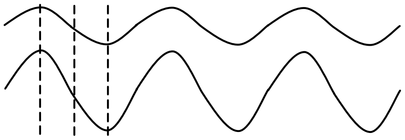


Phase Relationships

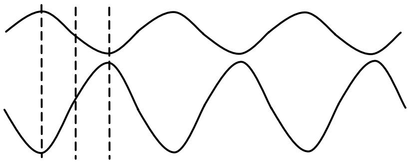
Whenever dealing with multiple AC signals of the same frequency, we need to be aware of the *phase* relationship between them. The term "phase" refers to the time of occurance that one signal does something, in respect to when another similar signal (of the same frequency) does the same thing.

For example:

The illustration below-right, shows two AC sinewaves of the same frequency, but having different peak-to-peak voltage levels. (Voltage levels do not effect the phase relationship between signals.) Note that both sinewaves reach their positive and negative peaks at exactly the same time. They also reach their respective *zero-crossing points* at exactly the same time. If not for differences in volatge levels, these two signals would be identical, as they are both doing exactly the same thing at exactly the same time. These two signals are said to be *in-phase*, one with another.



In-Phase Signals

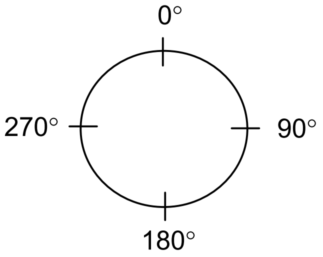


Out-of-Phase Signals

Pictured on the left is an illustration of two signals that are not *in-phase*, so are therefore said to be *out-of-phase*, one with another. While their zero-crossing points are happening at the same instant in time, when one signal is at it's maximum positive peak, the other is at its maximum negative peak and vice versa. They are doing the exact opposite of one another!

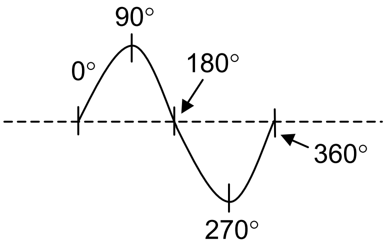
To create a unit of measurement for comparing out-of-phase signals, the geometric system for plotting points of a circle has been borrowed.

From the reference point labeled 0°, a circle is divided up into 360 equal increments called *degrees*. One quarter of the way around the circle (from the 0° reference) is called the 90° point. Half way around the circle (from the 0° reference) is called the 180° point. The three-quarter point around the circle (from the 0° reference) is called the 270° point and eventually the plot ends at the 360° point, which is the same point on the circle as the 0° reference we started with.

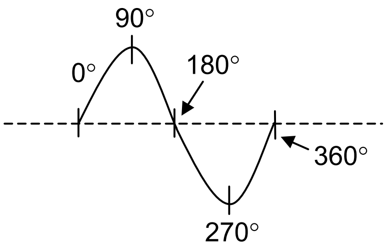


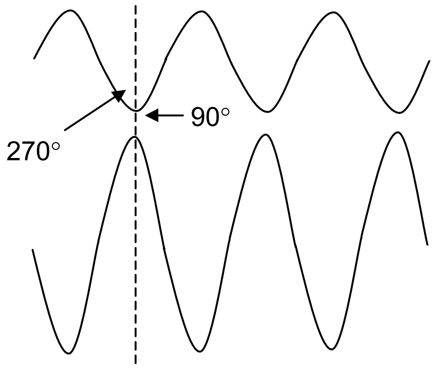
Since sinewaves are created by an electrical alternator whose armature is turning in a circle, various points along a sinewave can be plotted in exactly the same way:

Using these method, the phase relationship between two similar signals of the same frequency can be discussed. Using a similar illustration for the out of phase two signals that we were doing just the opposite of one another, we can calculate the phase differential by subtracting the degree values of each of the two signals, for a given instant in time.



For example: In the illustration below, if we pick the time at which the upper waveform is at its' 270° point, the lower waveform is at its' its' 90° point. To calculate the phase difference between them, we simply subtract 90° from 270°, giving us a phase differential of 180°. Thus, we can say that these two signals are 180° out-of-phase with each other.

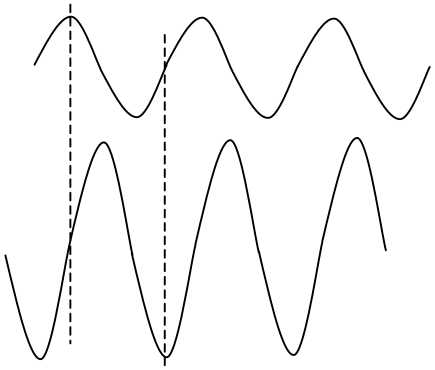




270° – 90° = 180° Out-of-Phase

180° Out-of-Phase Signals

Below is another illustration of out-of-phase signals that are 90° out-of-phase with each other. When the lower waveform is at its' 0° point, the upper waveform is at its' 90° point, so therefore we can say that these two signals are 90° out-of-phase with each other.



90° – 0° = 90° Out-of-Phase

90° Out-of-Phase Signals

What is the farthest apart similar signals of the same frequency can be away from each other, in terms of phase? The answer is similar to the old adage about the farthest one can walk into the forrest: → Half-way, because to go further, one would be coming back out again on the other side.

The farthest two similar signals of the same frequency can be away from each other in terms of phase, is 180°.

(If the phase differential were shifted any more, they would be starting to come closer to becoming in-phase again as one waveform would begin catching up with the next cycle of the other waveform.)

Power

Energy is generally defined as "the ability to do work." Physicists define *work* as a force applied to some form of matter (an object) multiplied by the distance that this object travels.

Work = Force x Distance (W = F x D)

Energy exists in various forms and is measured in various units of measurement, depending upon which form being utilized. One *newton* is the force needed to accelerate (or move) a mass weighting one kilogram, one meter in one second, (in a vacuum with no friction). The amount of energy (work) required to move an object with the force of one *newton* over a distance of one meter is called a *joule*. In physics, *work* is defined as the product of force and distance and is measured in *foot-pounds*.

For example:

If one pound were lifted one foot, then one *foot-pound* of work has been performed. By adding the element of time into this scenario, then we could measure the rate at which the work is being performed:

If a one pound weight were being raised one foot once every second, the rate at which the work is being performed would be expressed as "one foot-pound per second".

In electrical circuits the measurement of the rate that work is being performed is called *power*. Power is measured in units called *watts* and is generally represented with the letter "P" in mathematical expressions. (One *watt* is equal to one *joule* of energy being expended every second.)

Power in resistive circuits is calculated by multiplying the applied voltage times the current:

$$P = I \times E$$

For example, if the circuit was pulling 2.5 amps at 110 volts the power consumed would be:

2.5 amps X 110 volts = 275 watts of power

In the above example, the 275 watts represents the amount of power being expended every second. To find the total amount of *energy* being expended by an electrical circuit, the *wattage* (or rate of expenditure) must be multiplied by the time that the circuit is expending this amount of power:

275 watts X 6 hours = 1,650 watt / hours of energy

This is why our electric bills show usage in terms of *kilowatt/hours*, (the prefix "kilo" meaning "thousand.") So for the example shown above, we can say that over a period of 6 hours, a 110v circuit, drawing 2.5A of current will expend 1.65 *kilowatt/hours* of energy.

A commonly used memory jogger for remembering how to calculate power in a resistive circuit is to remember the word, "PIE." ($P = I \times E$) There are other ways to calculate power if one of these two values is unknown. By transposing the equation we can also say that:

$$P = I^2 \times R \quad \text{AND} \quad P = \frac{E^2}{R}$$

Using any of these three equations will result in the same answer, when calculating power.

Heat Losses

There is no such thing as a "perfect" (zero ohms) conductor of electricity. All conductors will have some amount of inherent *resistance* to current flow. Although the internal resistance within a conductor (like copper wire) it is usually quite small, it plays the predominate role in determining how much current a given conductor can safely carry.

When considering the internal resistance of a wire, there are two things we need to keep in mind. As stated previously:

1. The greater the length of the wire, the more internal resistance it has.
2. The greater the diameter of the wire, the less internal resistance it has.

The internal resistance of wires is important because it relates directly to the amount of heat that will be built up within a wire when electric current flows through it. As electrons flow through any material which is "resisting" the current flow, a certain amount of heat will begin building up within the material. The greater the current, (or the greater the resistance) the greater the amount of heat.

As previously noted, $P = I^2 \times R$, so the higher the internal resistance of a component or a piece of wire, the more power that will be lost and dissipated in the form of heat as current flows through it. This heat within the conductive material is generally is generally shed, (*dissipated*) into the air by *thermal conduction*, due to the heated surface area of the material being in physical contact with the air. The larger the surface area of the conductor, the more heat it can dissipate and the cooler it will be for any given amount of current.

Example: Most everyone can relate to about how much heat that a 100-watt light bulb gives off. Suppose this same 100-watt light bulb was the size of a water tower. Do you think it would even feel warm to the touch? -- *No!*

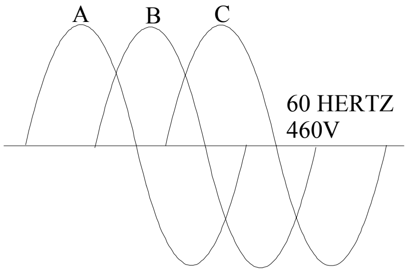
Now, suppose we tried dissipating that same amount of heat in an object the size of a thimble. How hot do you think it would get? -- *Red hot!*

For this reason, wires that are intended to carry larger amounts of current are physically larger in diameter than those intended for smaller amounts of current flow. (The larger diameter also helps reduce the amount of heat generated for a given amount of current flow, in that the larger wire will also have a smaller internal resistance.)

This is also why most high wattage components, (like resisters) are physically larger, to maximize their surface area to assist in heat dissipation.

3-Phase AC Power

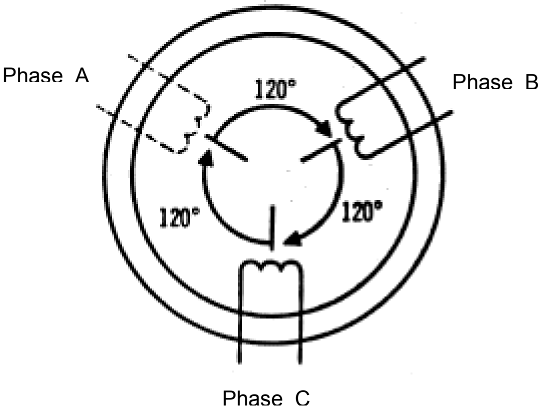
Residential and some commercial electrical circuits are typically configured as 115 Vac, single-phase circuits, but this is impractical in most industrial environments. Because of the amount of power required to drive large industrial applications, 460 Vac, 3-phase power is commonly utilized, as it is much more efficient and can result in significant cost savings. (The higher the voltage, the lower the current for a given amount of power.)



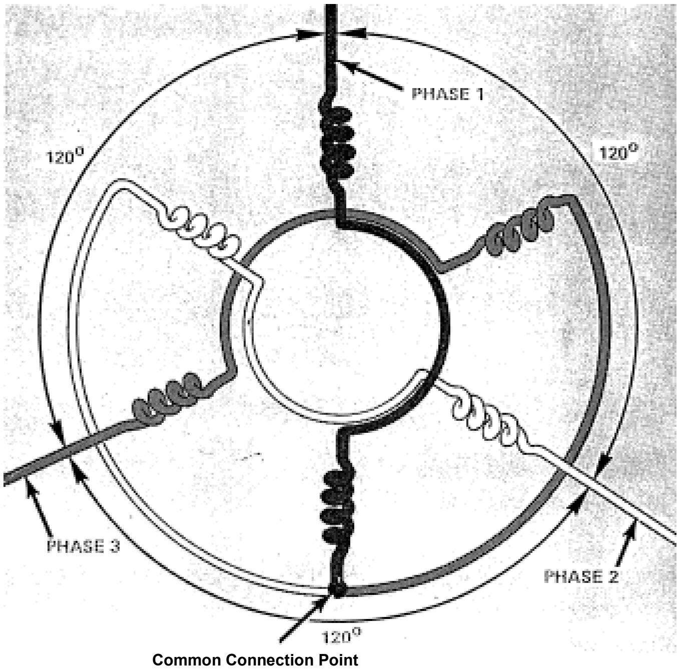
In 3-phase, 460 Vac power systems, there are generally three separate "hot" leads and a safety earth ground wire within every power line. These three "hot" wires are generally called Phase-A, Phase-B and Phase-C and will be at a 460 Vac_{RMS} potential in respect to one another. (NOT in respect to the earth ground safety wire.)

The three hot phases of three-phase power are 120° out-of-phase with each other, as shown in the illustration on the upper-right:

Polyphase Induction Motors



3-phase induction motors normally contain multiple sets of stator windings which can be used to determine the actual speed the motor shaft will turn in *revolutions per minute* (RPM) when a power signal is applied, depending on how it is wired.



Motor Poles

3-phase motors will have a minimum of three motor windings, each having two connections as shown in the illustration above. They may also have many other windings (in some multiple of three) which can be wired up in various ways to vary the speed of the motor at 60Hz.

The number of winding connections wired into each phase is referred to as motor *poles*. In the illustration on the left, the motor only has three separate windings (each having two connections), one for each phase.

Any motor wired in this arrangement is called *2-pole* motor.

Motor Speed

The synchronous speed of the motor shaft can be calculated as 60 seconds per minute, multiplied times the applied frequency, divided by 1/2 the number of motor poles:

$$\text{RPM} = \frac{60\ (\text{sec/min}) \times \text{Frequency}}{1/2 \text{ the \# of Motor Poles}}$$

So, for a 2-pole motor running at 60Hz, it's synchronous speed would be:

$$\text{RPM} = \frac{60\ (\text{sec/min}) \times 60\text{Hz}}{1/2 \text{ of } 2} = 3600\ \text{RPM}$$

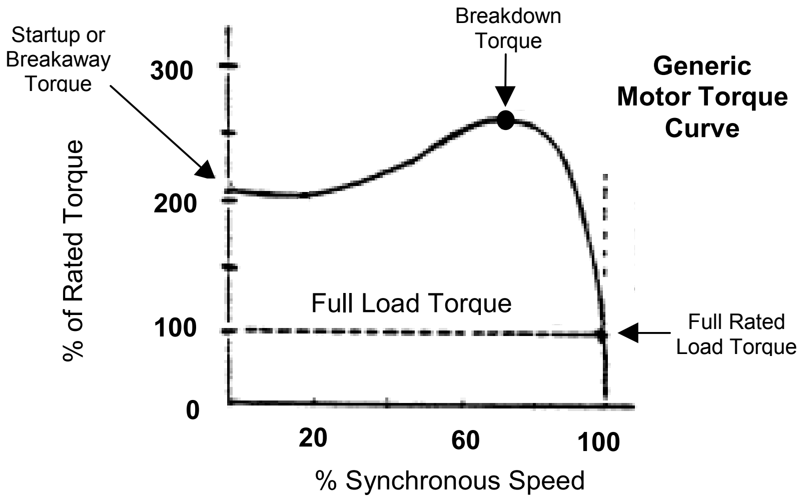
For a 6-pole motor running at 60Hz, it's synchronous speed would be:

$$\text{RPM} = \frac{60\ (\text{sec/min}) \times 60\text{Hz}}{1/2 \text{ of } 6} = 1200\ \text{RPM}$$

Motor Overload

As discussed previously, at full rated torque, the rotor of an AC induction motor can never run at exactly synchronous speed, as with no speed differential, no torque is developed. As a general rule, an AC induction motor rotor will turn at approximately 97% of synchronous speed, as shown in the torque curve illustrated below:

If the mechanical load applied to the motor were to increase, (overload condition) the motor will initially slow down. As the motor slows down, less CEMF is developed causing more current to flow. As more current flows, the magnetic fields get stronger, creating more torque. If enough torque is developed to overcome the inertia of the additional load, the motor will again speed up, causing CEMF to again increase and motor current to go back down to normal.



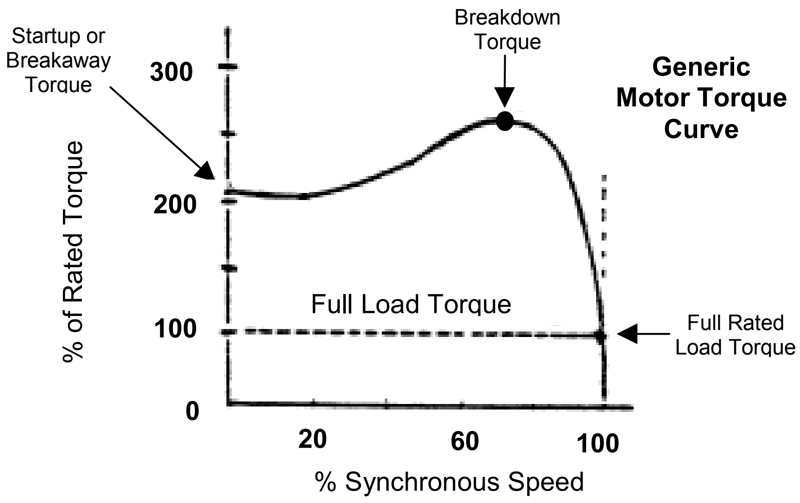
If not, the mechanical overload will continue slowing the motor, causing the rotor to slow down even more, creating even less CEMF, higher motor current and even more torque.

WARNING!

Although motors are rated to allow for operating in a minor overloaded condition for a short time, it should be noted that the fan blades to provide cooling for the motor are mounted on the rotor. When the rotor is rotating more slowly due to overload, not only will additional heating be incurred due to higher than normal levels of motor current, the slower turning fan blades will be providing less air for cooling. Motor heating can rise quickly if allowed to continue in an over-current condition for very long and a catastrophic motor failure can occur.

There is a theoretical maximum level of torque that any motor can develop called "*breakdown torque*."

Breakdown torque can be noted on the motor torque curve on the right, as the peak on the curve. Further loading of the motor beyond the breakdown torque level, will cause the motor's torque level to decrease in spite of additional motor current, causing the motor to "stall" (stop) suddenly.



If this occurs, the motor will continuously draw 500% to 1500% of it's full load current rating and a catastrophic motor failure (with the possibility of fire) can occur very quickly.

For this reason, motors often utilize some kind of circuit breaker on their inputs, to protect the motor from a prolonged over-current condition.

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Basic Drives

Module - 2

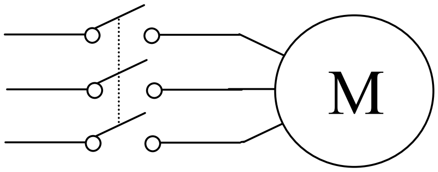
Introduction

When operated directly from utility power, motor's run at a constant speed determined by the physical characteristics of the motor (the number of poles wired in) and the frequency of the AC power signal. In many applications, turning the motor on & off is simply accomplished using a contactor to apply or disconnect utility power.

Contactors

A contactor is basically a mechanical or electromechanical device used to apply power to other devices. Illustrated below is the schematic (drawing) representation of a 3-line (3-phase) contactor, connected to a motor. (The dotted line indicates that the three contacts are <u>not</u> independent of each other, but are mechanically interlocked so that all three of the contacts move together.)

When the contactor closes, 3-phase AC utility power is applied to the motor and the motor will begin rotating. This is called an "across the line" start.

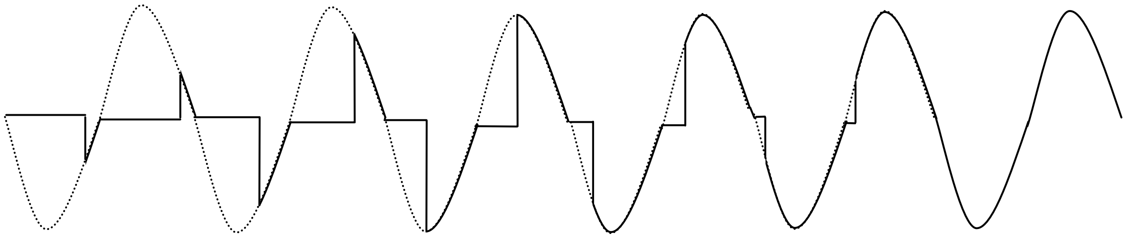


As discussed in the previous module, when starting a motor across the line, the *inrush current* will initially be 500% to 1500% of the motor's full load amp rating, for the short period of time before the motor comes up to speed. (Although the level of *inrush current* is 5-15 times normal, it usually doesn't last long enough for circuit breakers to respond, so they normally do not trip.)

As a contactor basically just applies or removes power; there is no control of the motor, other than on-off. While *inrush current* normally will not trip a current limiting device like an input circuit breaker, it is essentially wasted power that can not only increase utility costs, but can introduce unnecessary heating within the motor, that can reduce the motor's expected service life.

Soft-Starters

Inrush current and mechanical shock to the motor's load can be reduced by a certain extent by utilizing an electronic control device called a soft-starter, on the input to the motor. Instead of applying the entire sinusoidal AC voltage signal to the motor all at once (like a contactor does), a soft-starter applies only portions of the AC power signal to the motor, in increasing increments, over the period of a few cycles of the AC power frequency. An example of a soft-starter output to a motor is shown below:



In this way, a soft-starter gradually increases the voltage applied to the motor over a period of time, and depending upon the inertia of the load, allowing the motor to start without drawing quite as high an amount of initial inrush current. But the primary purpose of using soft-starters however, is to provide a mechanical load a relatively gentle acceleration up to normal run speed, as compared to an across the line start. Soft-starters cannot control (vary) a motor's speed or direction of rotation. For variable speed and direction control of a motor, a more sophisticated electronic controller know as a motor “drive” is utilized.

AC Motor Drives

To vary motor speed, the *frequency* of the “drive” signal applied to a motor must also be varied.

$$\text{RPM} = \frac{60\ (\text{sec/min}) \times \text{Frequency}}{1/2 \text{ the \# of Motor Poles}}$$

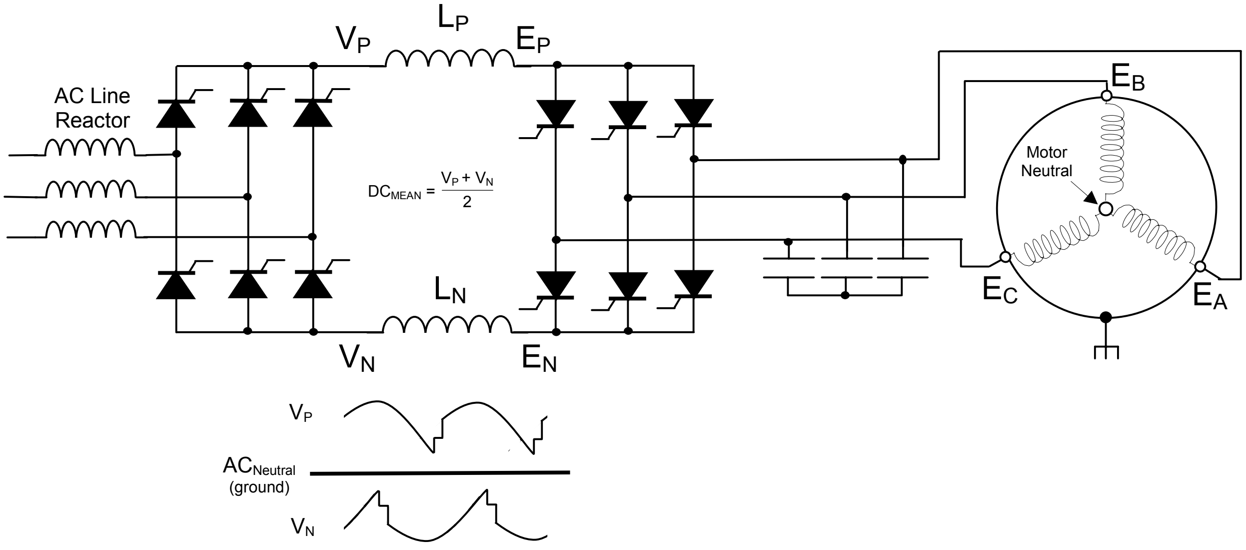
As discussed previously, for a given amount of voltage applied to a motor, motor current will increase as a motor slows down (thus increasing torque) due to reduced CEMF. Therefore in order to reduce the current draw and thereby avoid excessive heat build up within a motor operating at a slower than normal speed (RMP), a *motor drive* must also be able to vary the voltage applied to the motor.

There are two basic families of AC motor drives currently on the market:

1. Current Source drives
2. Voltage Source drives

Current Source Drives

Early AC motor drives were *current source* drives, which controlled the motor by direct control of the current flowing through the motor windings.



Typical Current Source AC Motor Drive Configuration

Current source drives generally utilize active thyrister control on both ends (input and output) to create an output signal to drive the motor. Except for older installations and the largest of medium voltage applications, current source drives have generally been superceded in the marketplace by newer *voltage source* AC motor drives.

Voltage Source Drives

Voltage source AC motor drives do not control motor current directly, but they do control two different aspects of the motor drive signal that indirectly effect motor current:

1. Voltage
2. Frequency

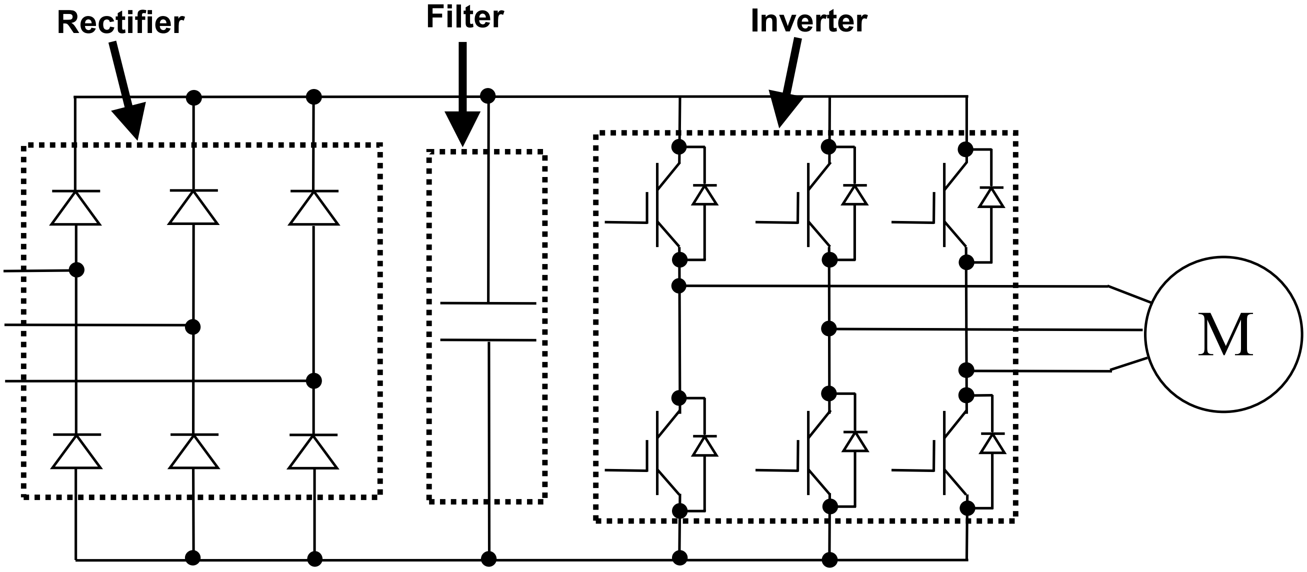
Voltage source AC Motor drives are referred to by a number of different terms and acronyms:

1. VFD's (variable frequency drive)
2. ASD's (adjustable speed drives)
3. Inverters (a misnomer, better suited to describing the output section of a drive)

Voltage source drives utilize an AC-DC-AC topology, meaning that incoming AC power is converted into DC, which is then converted back into AC again. All voltage source AC motor drives (regardless of manufacturer) are comprised of the same three basic drive components:

1. Rectifier
2. Filter
3. Inverter

Illustrated below is a schematic diagram for a generic voltage source drive, showing the three basic power components:



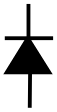
The input section of the "generic" voltage source VFD illustrated on page 2-3 is called a 3-phase, full-wave bridge rectifier. The individual components within the rectifier section are sometimes called *rectifiers* (because that is what they do) or *diodes*.

Rectifiers (Diodes)

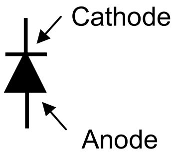
A *rectifier* (or *diode*) is a passive device that will conduct in only one direction. In essence, a diode acts like a polarity sensitive switch. The term *diode* is a left over from the early days of electronics and was created from the prefix *di* – meaning two, and the last portion of the word *electrode*. The term diode was first coined to describe the simplest form of vacuum tube that contained only two electrodes. This type of vacuum tube was unique in that it would only conduct electrical current in one direction only.

By today's standards, these vacuum tube diodes are obsolete and have been replaced by *solid state* devices that behave in exactly the same way as their earlier tube counterparts. Today, *diodes* still only conduct current in one direction, but they are much smaller and cheaper than the early tube versions displaying the same behavior.

The schematic symbol for a diode is shown on the right:

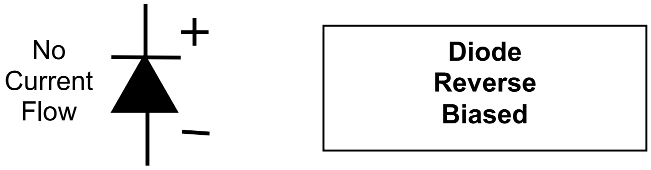


Even the names of the two leads are the same as their tube counterparts. The side toward the back of the arrowhead is called the *anode* and the side toward the line across the point of the arrowhead is called the *cathode*.

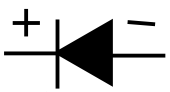


A diode will only conduct when the voltage on it's cathode is more negative, (less positive) than the voltage on it's anode. When the voltage conditions required to make a diode conduct are met, the diode will be *forward biased* and current will flow against the arrow.

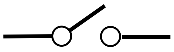
When the voltage conditions required to make a diode conduct are not met, the diode will be *reverse biased* and no current will flow through the diode.



A diode acts like a polarity sensitive switch. When the diode is reverse biased, it will not conduct much like when a switch is open:

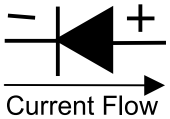


No Current Flow

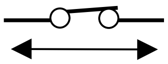


No Current Flow

When the diode is forward biased, it will conduct much like when a switch is closed:



Current Flow



Current Flow

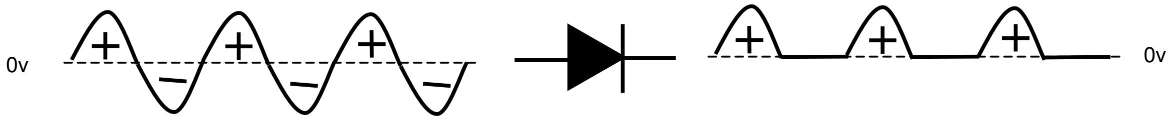
One of the major differences between a diode and a switch is that when a switch is closed, current can flow in either direction, but in a diode current can only flow in one direction.

Voltage Drop

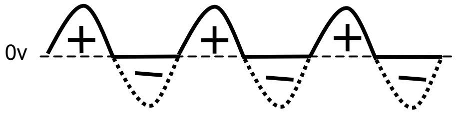
Another difference between diodes and switches is the amount of voltage dropped across them when they are conducting. As a closed switch has a very low resistance, it has little, (if any) discernable voltage drop across the switch when current is flowing through it. But diodes will have a definite and consistent voltage drop across it whenever it is in full conduction. Depending on the exact materials that it is made from, **a conducting diode will generally create a voltage drop ranging from 0.2 to 0.7 volts**.

Rectification

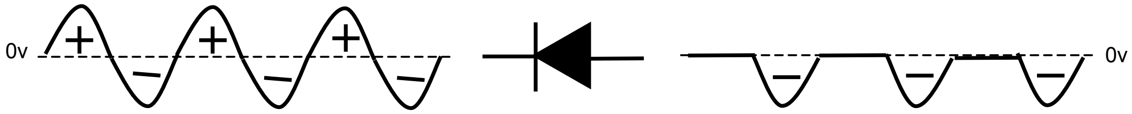
When a *sinewave* is put into a diode, the diode will be forward biased and conduct for one half-cycle, but will be reverse biased and turned off, (not conducting) for the other half-cycle:



With the sinewave being applied to the anode, during the positive half-cycle the diode will be forward biased and will conduct, passing the positive half-cycle of the input sinewave through the diode and out of the cathode lead, as shown in the illustration above. During the negative half-cycle, the anode is driven negative, reverse biasing the diode. The diode stops conducting and there will be zero volts on the output of the diode (the cathode) during the entire negative half-cycle of the input sinewave, as shown in the illustration below:



To pass only the negative half-cycle, we simply input the sinewave into the cathode end of the diode:



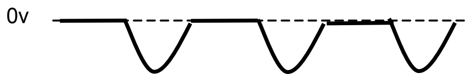
The process of removing one complete polarity swing of an AC signal is called *rectification*, so diodes are also often called *rectifiers*.

In fact, when *solid state* diodes were first introduced, tube-type diodes were still commonly used and to avoid confusion, *solid state* diodes were originally called *crystal rectifiers*. The output of a *rectifier* no longer has voltage swings in both the positive and negative direction, but only in one direction or the other, so it is no longer an AC signal. It is now *pulsating DC*.

Half-Wave Rectification

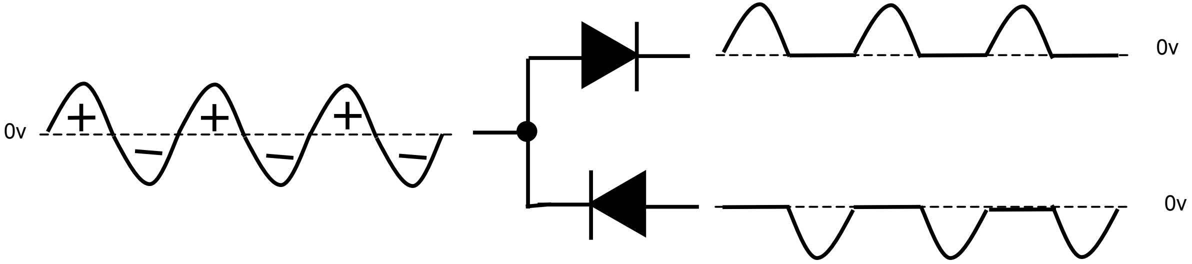
When a *sinewave* is rectified only in one direction, (either positive or negative) like we have been discussing, this is called *half-wave rectification*.

OR



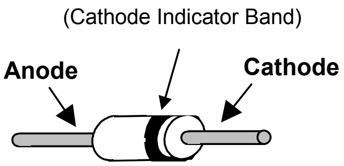
Full-Wave Rectification

Often, multiple diodes will be used together to rectify a sinewave on both half-cycles:

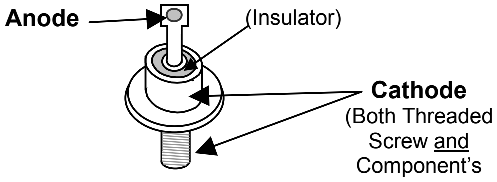


At any given instant, one of the two diodes will be forward biased (conducting) while the other is reversed biased (not conducting). Rectification is the primary means of converting AC power into DC, so therefore diode rectifiers are one of the primary components of a type of electronic circuit known as a DC power supply.

Illustrated below are the two most commonly used diode body types. A low-power, *signal diode* is an axial leaded component with a band marking to denote the cathode lead. *Power diodes* are normally metal-bodied components with a threaded screw connection on the cathode end and a solder eyelet on the anode. The entire metal body of a *power diode* is directly connected to the cathode and can present a shock hazard if touched while the diode is under power!



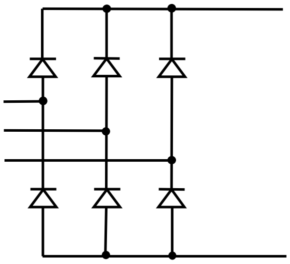
Signal Diode



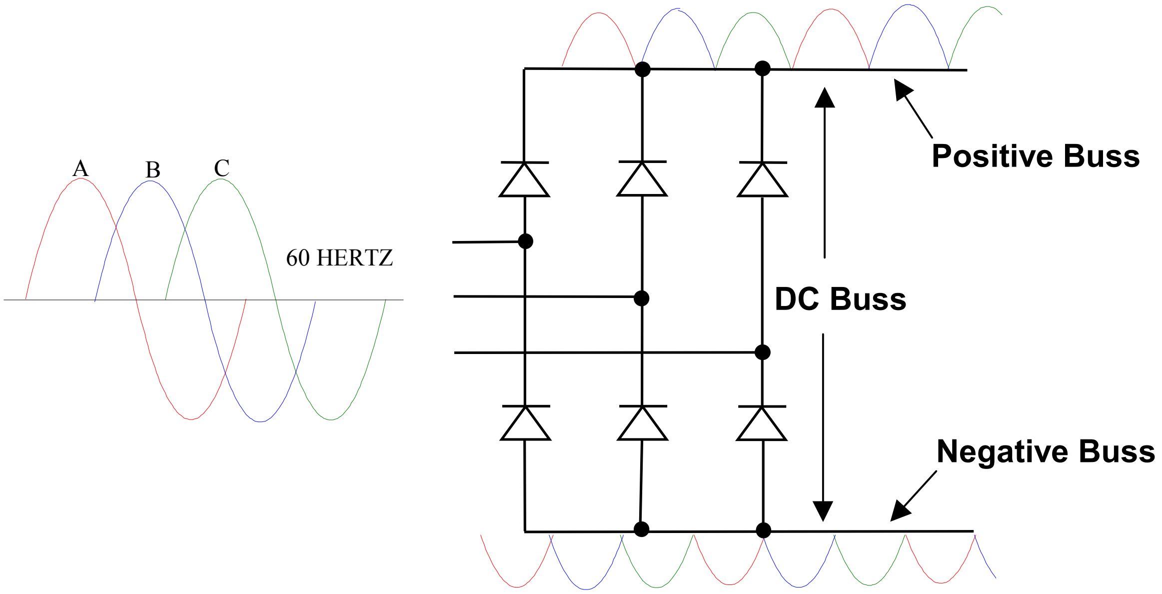
Power Diode

Multi-Phase Rectification

3-phase AC power is often rectified into DC using a 3-phase, full-wave bridge rectifier circuit, as shown in the illustration on the right:



When 3-phase AC power is fed into a 3-phase, full-wave bridge rectifier, their positive and negative peaks will pass through the diode bridge to the common DC buss outputs of the diodes in the form of pulsating DC, as shown below:



The DC voltage across the DC buss (measured between the positive and negative busses) will be the full peak-to-peak voltage of the input AC, or calculated another way, the RMS voltage multiplied times 1.414. Therefore, if the input voltage is 3-phase, 460Vac (RMS), then the DC buss voltage will be:

$$460\ VAC_{RMS} \times 1.414 = 650.44\ VDC, \text{ or } \sim 650 \text{ volts DC.}$$

If the input voltage is half that (230Vac), then the DC buss level will be ~325Vdc.

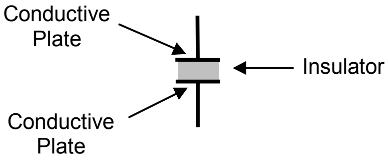
Filters

As illustrated above, the output of a full-wave bridge rectifier is pulsating DC. This pulsating DC is obviously not a continuous, unvarying level of DC like that coming out of a battery. A *DC filter* is often employed to "smooth out" the voltage pulsations in pulsating DC, changing it into a DC voltage source having much less voltage variation.

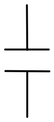
The most commonly used form of DC filter is a *capacitive filter*.

Capacitors

A capacitor is a passive electronic component that stores energy in the form of an *electrostatic charge*. A *capacitor* is a device made from two, parallel plates of conductive material that are separated from one another by an insulator.

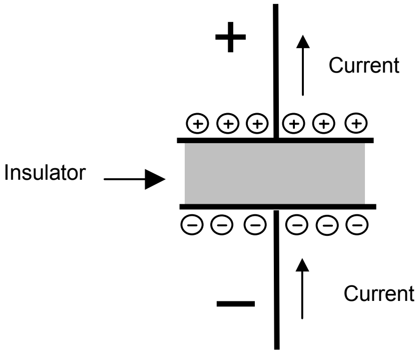


The schematic symbol for a capacitor does not show the insulator, but is very indicative of its' composition, as shown below:



Capacitor Symbol

When a difference in voltage potential is placed across the plates of a capacitor, current (electrons) will flow into the plate connected to the more negative (less positive) voltage. As this current flows into the plate negative *ions* are created as the plate's atoms accept these additional electrons flowing in from the negative voltage source and causing the plate to take on an overall negative electrostatic charge.



As current is flowing into the plate connected to the negative voltage source, electrons are also drawn out of the other plate, (current) by the positive voltage source. As electrons leave this plate, positive ions are formed as the electrons are lost, giving this plate an overall positive electrostatic charge.

The process by which a capacitor takes on an electrostatic charge is called *charging* and the charging process will continue until difference in voltage potential across the capacitor's two plates is equal to the applied voltage. While there is <u>no</u> actual current that flows between a capacitor's two plates (because of the insulator separating them), current <u>will</u> flow into and out of the plates during the time the capacitor is charging up to the applied voltage potential.

Farads

As resisters have different values in units called ohms, capacitors also have different values, measured in units called *farads*. As previously discussed, the ampere one amp of current is defined as one coulomb of charge, (approximately 6.24 x 10^{18} or 6.24 quintillion electrons) flowing past a given point in one second.

One *farad* is the amount of capacitance where one amp of current (one coulcomb of electrons flowing for one second) will produce one volt of charge. The *farad* is an extremely large unit of measurement for capacitance and in actual practice, capacitors with values this large are very rarely used.

In common electrical and electronic circuits capacitors are more commonly valued in *microfarads*, (µf) where 1 µf = 10^{-6} farads, or *picofarads*, (pf) where 1 pf = 10^{-12} *farads*.

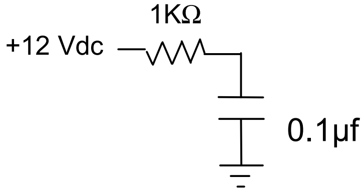
Some capacitors may still be labeled with an older measurement of µµf, (micro-microfarads) but this means the same as *picofarads*. Capacitance values will normally vary between very tiny amounts, such as 1 pf for radio frequency applications to as much as 10,000 µf in some power supply applications.

RC Time Constants

Capacitors do not "charge up" instantaneously, but require some amount of time to acquire the same electrostatic charge potential as the applied voltage. As all electrical conductors have some inherent amount of finite resistance to current flow, any amount of circuit resistance will have an effect on the amount of time that it will take a capacitor to fully charge up to the applied voltage. The charge rate of a capacitor is measured by its' *RC* (Resistance-Capacitance) *time constant*.

The time of one *RC time constant* is calculated by multiplying the amount of resistance in the capacitor's charge path, (in ohms) times the value of the capacitor being charged.

For example:



When +12 Vdc is first applied to the RC circuit shown above, the capacitor will begin charging. But how long will it take before the capacitor will charge to the full 12 volts level being applied?

TC (time constant) = R x C = 1,000Ω x .00000001f = 0.00001 seconds or 10 µsec (microseconds)

The RC time constant (TC) for this circuit is 10 µsec (microseconds). Does this mean that the capacitor will be fully charged to the applied 12 volt level after 10 µsec? -- **NO!**

During each time constant, (in this case 10 µsec) the capacitor will charge to approximately 63% of the applied voltage. So, after the first 10 µsec the capacitor will be charged to 63% of +12 volts, or ~+7.56 volts. During the second *RC time constant*, (another 10 µsec) the capacitor will charge ~63% of the <u>difference</u> between its' current +7.56 volt charge level and the 12 volts being applied:

12v – 7.56v = 4.44 volts x 63% = 2.7972 v

So, during the second *time constant* the capacitor will charge up another ~+2.8 volts on top of the +7.56 volt level achieved during the first time constant. This means that after two time constants, (in this case 20 µsec) the capacitor will be charged to:

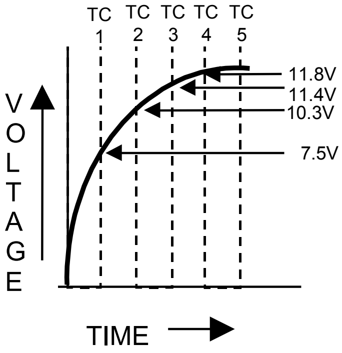
7.56v + 2.8v = ~10.36 volts

After five complete time constants the capacitor will reach over 99.3% of the applied voltage and so, is <u>considered to be fully charged after five complete time constants</u>:

1-TC = 7.56 V
2-TC = 10.36 V
3-TC = 11.39 V
4-TC = 11.78 V
5-TC = 11.92 V

Therefore, it will take ~50 µsec for the capacitor to completely charge up to the applied 12 volt level in our example.

The charging pattern of a capacitor can be plotted graphically on an X-Y plot, where the voltage changes are plotted in the vertical and time expands in the horizontal, as illustrated above. The curve representing the time-voltage relationship of a charging capacitor is logarithmic in nature.



Charging and Discharging of Capacitors

As we've seen, whenever the voltage applied to a capacitor increases, additional current will flow and the capacitor will charge up to the new voltage level, after a small delay. Likewise, if the voltage applied to a charged capacitor were to decrease, the capacitor will *discharge* (current flows in the opposite direction) to allow the capacitor voltage to change to the new voltage level after a small delay. (RC time constants apply to the discharging of capacitors also.)

When the capacitor is discharging, it acts as a *current source* for other components in the same circuit and the delay in the voltage change (due to the RC Time constant) will tend to keep the voltage near its' previous level for a small period of time. Thus, it is said that ***capacitors tend to resist a change in voltage across them.***

AC-DC Relationships in Capacitors

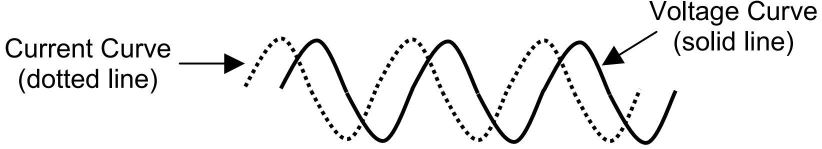
Once a capacitor is fully charged up to an applied DC voltage level, current flow stops. Therefore, once charged, *capacitors are said to "block" (not pass) a DC signal.*

As the voltage of an AC signal is constantly varying in both voltage level and polarity, a capacitor will constantly charge and discharge in accordance to the varying AC voltage signal applied to it and the effects of this signal are seen to pass through the device from one lead to the other. Therefore, *capacitors are said to pass an AC signal.*

Voltage-Current Relationships in Capacitors

In a purely resistive circuit, the voltage and current are always "in-phase" with one another. But when capacitors are utilized, the voltage and current will be shifted out-of-phase with each other. To effect a voltage change across the plates of a capacitor, current must first flow to ionize the plates. As previously discussed, it will take five complete time constants for full voltage to be developed across the capacitor; therefore it is said that *in capacitors, the current will lead the resulting voltage.*

When an AC signal is applied to a capacitor, the voltage across the capacitor will lag the current, as illustrated below:



Voltage-Current Relationship in Capacitors

As seen in the illustration, there is a definite phase-shift of the voltage across the capacitor, in respect to the current.

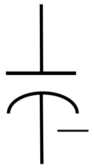
Polarized Capacitors

Non-polarized capacitors generally utilize solid insulators (like paper or mylar) between their plates and can be installed into a circuit in either direction. The majority of capacitors in use today are *electrolytic capacitors* that use special electrolytes (chemicals) or electrolytic oils as the primary insulating agent between their plates. *Electrolytic* capacitors are unique in their internal construction, in order to achieve larger capacitance values and higher voltage ratings with the smallest possible physical body size.

Electrolytic capacitors are *polarized* devices, meaning that extreme care must be taken to ensure that they are installed into the circuit properly.

One or both of the terminals will be labeled with a + or – symbol, denoting the polarity of the voltage that terminal is designed to accommodate. This does <u>not</u> mean that one has to have a positive voltage while the other a negative voltage, in respect to ground. It just means that the voltage on the "negative" terminal must be more negative (or less positive) than the voltage on the positive terminal. **If only one terminal is marked, it will <u>always</u> be the negative terminal that is marked.**

Polarized capacitors have a slightly different schematic symbol than the non-polarized variety. The lower plate will generally be drawn as a curved line, denoting the negative terminal of the cap.

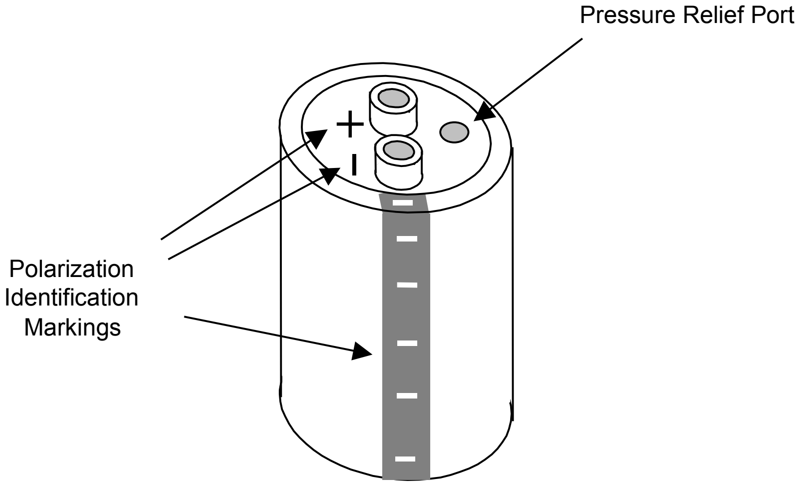


Polarized Capacitor Symbol

Can-Type Capacitors

Large value, high voltage (rated for over 50 volts) capacitors (like those used in power supplies) are almost always *electrolytic* capacitors having a *can-type* body style.

If for some reason a can-type, electrolytic capacitor were to have a plate-to-plate voltage applied that is greater than it's rated voltage level, the internal insulator between the plates can begin to break down allowing current to begin flowing between them. This current flow within the electrolyte is a form of *electric arc* which will raise the temperature with the capacitor to levels that can "flash" (instantly gasify) some of the liquid insulator resulting in an extreme pressure rise due to the rapidly expanding gas.



Can-Type Capacitor

As a safety feature, can-type capacitors generally have a *pressure relief port* installed to relieve excessive pressure that could occur if gasification of the liquid insulator should occur. **Should a pressure build-up within the capacitor become too severe, the *pressure relief port* is designed to <u>rupture</u>, allowing hot, pressurized liquid to spew out of the port.**

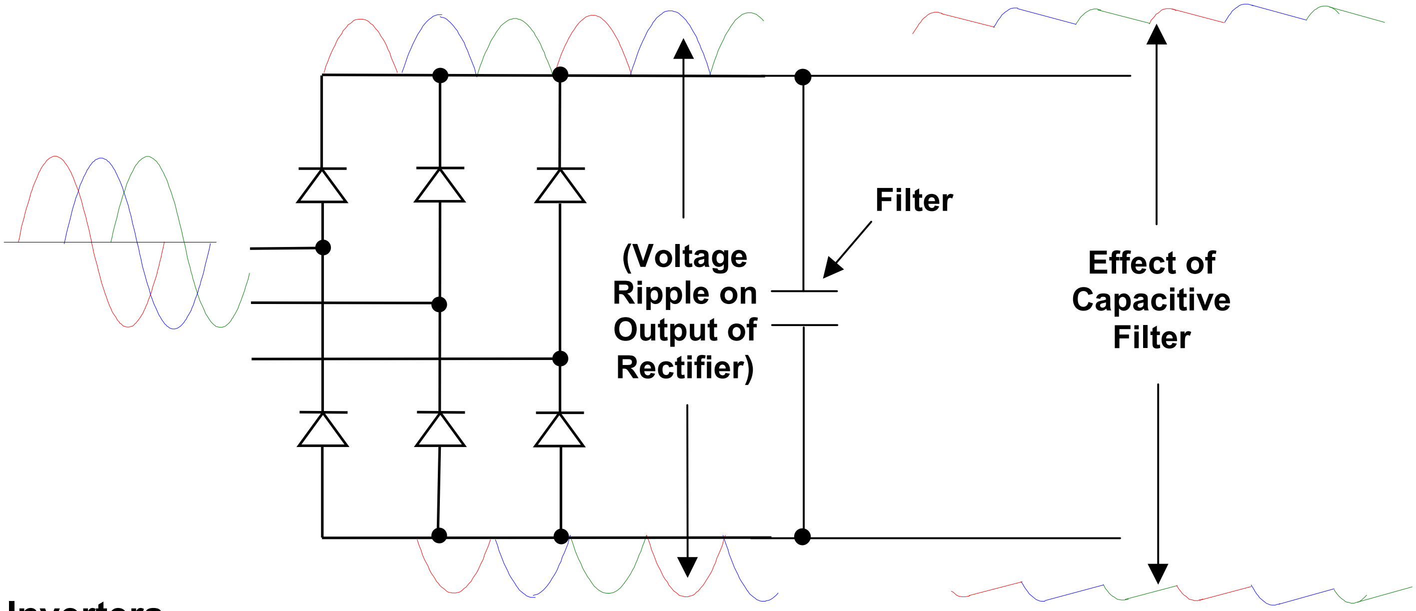
SAFETY ALERT!
It is imperative that maintenance personnel be aware that under the right conditions, hot liquid may come gushing out of the pressure relief ports unexpectedly. **For safety purposes, safety glasses and face shields should be utilized whenever working in proximity to these types of capacitors whenever power is applied.**

It should also be noted, however, that reverse biasing of a polarized capacitor (making the negative plate more positive than the positive plate) can cause the component to fail catastrophically, giving insufficient time for the pressure port to react and result in component explosion.

WARNING!
Reverse biasing a polarized capacitor, (applying voltage to the negative terminal that is more positive than that on the positive terminal) **can lead to explosive failure of the component!**

Capacitive Filtering

Whenever pulsating DC is applied across a capacitor, the RC time constant of the capacitor will cause the voltage pulsations (ripple) to be dampened significantly.



Inverters

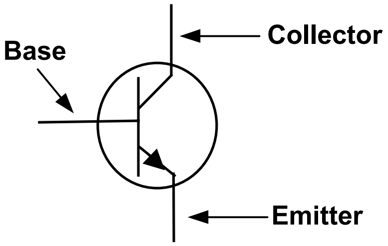
As we have seen, a rectifier is a semiconductor device used to convert AC into DC. An *inverter* is an electronic circuit that converts DC into AC.

Bipolar Transistors

As Early voltage source AC motor drives utilized *bipolar transistors* as the primary power component in their inverter sections.

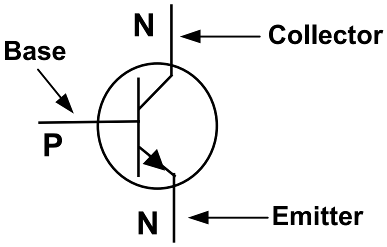
The schematic symbol for a bipolar transistor is shown on the right:

The three leads on a bipolar transistor are called the *Base*, the *Emitter* and the *Collector*. There are two different types of bipolar transistors, called NPN transistors and PNP transistors. They can generally be differentiated by the direction of the arrow shown on the schematic symbol.



Schematic Symbol for a Bipolar Transistor

The arrow always points toward the "N" part of the transistor, so as it is pointing toward the *Emitter* in the illustration on the right, this would indicate an NPN transistor. (If the arrow were pointing toward the *Base*, that would indicate a PNP type transistor.)



Schematic Symbol for a Bipolar Transistor

The polarity relationship between the *Base* and *Emitter* voltage potentials determines whether the transistor will conduct *Emitter-to-Collector*. We can think of the "N" and "P" designations as denoting "negative" and "positive" and therefore, in an NPN transistor, if the voltage on the *Base* is more positive than the voltage applied to the Emitter, the transistor is forward biased and current will flow *Emitter-to-Base* and *Emitter-to-Collector*.

(As *Emitter* current is the total of both *Emitter-to-Base* and *Emitter-to-Collector* currents, the *Emitter-to-Base* current is generally referred to simply as *Base current* and the *Emitter-to-Collector* current is generally referred to simply as *Collector current*.)

In a PNP transistor, polarities are opposite of those required by an NPN, so a PNP transistor will conduct only when the *Base* is more negative than the *Emitter*. If the transistor is reversed biased, there is no conduction within the transistor at all.

A bipolar transistor is a current controlled device that is basically a *current amplifier*. Every bipolar transistor type has an inherent current gain called "beta" (β). As stated previously, whenever the transistor is forward biased, both *Base current* and *Collector current* will flow. But, how much current will flow?

Base current (I_B) is determined by voltage and resistance values in the base-to-emitter circuit external to the transistor as defined by Ohm's law. Collector current (I_C) on the other hand is always an exact multiple of the *Base current*, as defined by the inherent current gain of the transistor (β).

$$I_C = I_B \times \beta$$

The β of any transistor can be found in the manufacturer's data book.

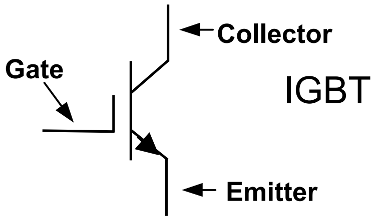
When used in the inverter section of a voltage source AC motor drive, bipolar transistors are used as "saturation amplifiers" as they are turned either full-on (maximum Collector current) or full-off (zero Collector current). In this way, they are utilized to act as an electronically controlled switch.

IGBT's

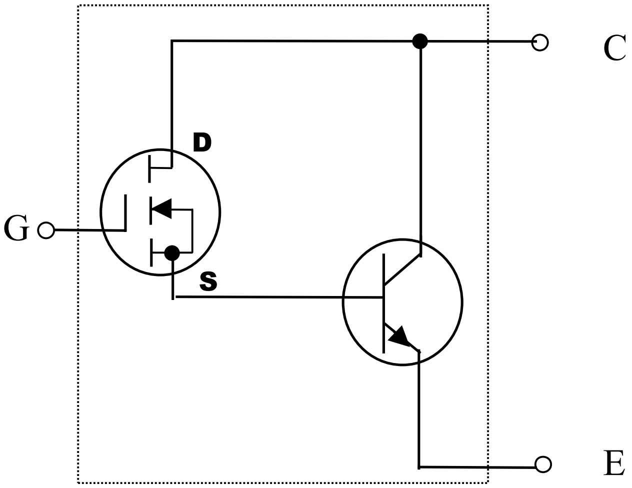
The use of bipolar transistors in the *inverter* section has been abandoned in most modern voltage source AC motor drive designs, in favor of a newer device called an *Insulated Gate Bipolar Transistor*, or IGBT.

Illustrated below is the basic schematic symbol used to denote an IGBT:

The three leads of an IGBT are called the *Gate*, the *Emitter* and the *Collector*. Note the similarities to the names of the three leads of a bipolar transistor. Only the name of the control lead, has been change from "base" to "gate".



That is primarily because an IGBT is basically a *Field Effect Transistor* (FET), controlling a bipolar transistor current driver, as illustrated below:

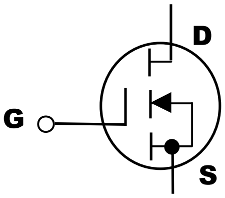


IGBT - Simplified Equivalent Circuit

The bipolar transistor on the output of the simplified equivalent circuit illustrated above is obvious, but the Field Effect Transistor (FET) on the input is new and requires some explanation.

FET's

Illustrated on the right, is the schematic symbol for the most predominate type FET, known as a MOSFET (Metal Oxide Semiconductor Field Effect Transistor). A MOSFET has three leads called the Gate, the Source and the Drain. The similarities in the naming of the three leads to those of a bipolar transistor are indicative of their similar function.

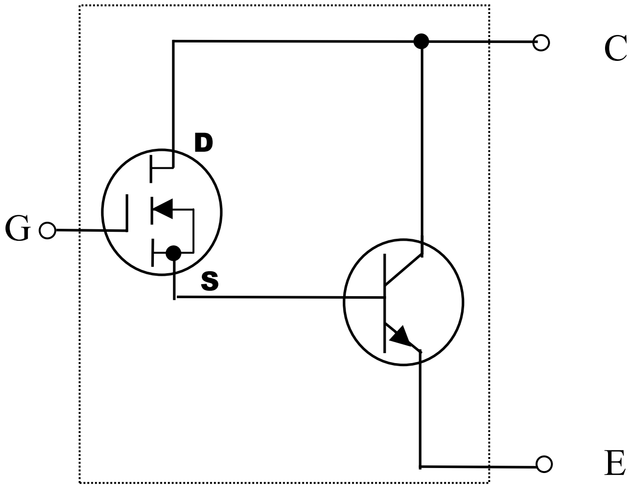


Like the base of a bipolar transistor, the *Gate* the control lead on an FET. The *Source* acts similar to the emitter and the *Drain* acts similar to the collector.

Just like the base-emitter voltage relationship determines the conductivity of a bipolar transistor, the *Gate-Source* voltage relationship determines whether an FET will conduct (*Source-to-Drain*) or not. The major difference between them is the fact that while a bipolar transistor is a current controlled device, an FET is a true *voltage control* device.

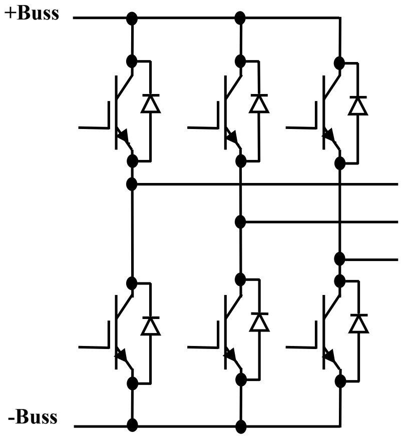
In a bipolar transistor, the voltage source controlling the base circuit must be able to provide all of the base current necessary to drive the transistor into full conduction (in drive inverter applications). Using an FET, no current is drawn from the voltage source controlling the Gate at all! This allows an FET to be controlled by lower voltage signals that have very limited current capabilities and provides for faster switching times as well. The main drawback is that FET's generally do not have the current carrying capacity of a regular bipolar transistor.

By combining the characteristics of both, an IGBT can provide faster switching with lower power consumption than can be achieved using a standard bipolar transistor.

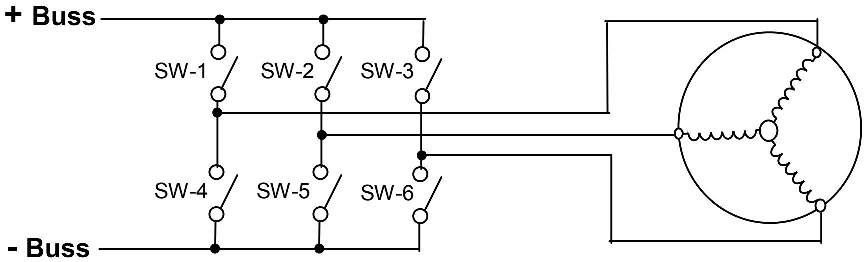


IGBT - Simplified Equivalent Circuit

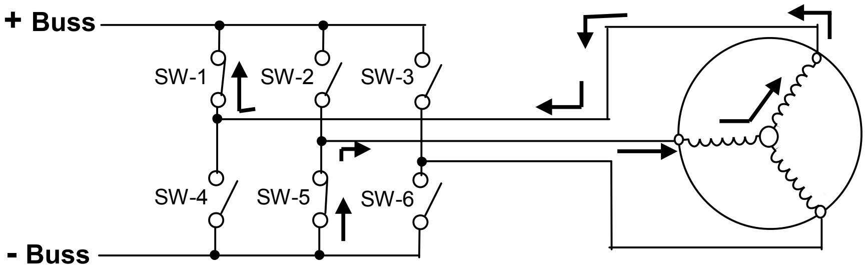
The inverter section of a modern, 3-phase voltage source AC motor drive is basically comprised of six IGBT's, as illustrated on the right:



Like the bipolar transistors used earlier, IGBT's are used as electronic switches that are either full-on (maximum conduction) or full-off (zero conduction). Illustrated below is a simplified equivalent circuit to the inverter section of a modern, voltage source AC motor drive:

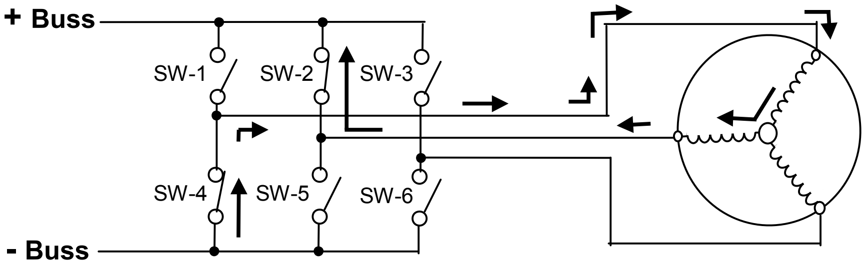


To run an AC motor, the inverter output of an AC motor drive must be able to get current to flow through the same winding in both directions. To illustrate how this can be done, let's say that switches 1 and 5 were to be closed, while the rest remain open:



We will now have a path for current to flow from the negative buss through Switch-5, through the motor windings and then through Switch-1 to the positive buss. In effect, we have just shorted out the DC buss through the motor winding.

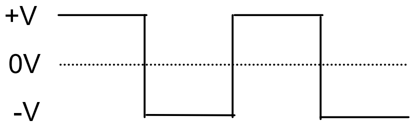
Now to reverse the direction of current flow through the same winding, let's say that Switches 1 and 5 were to open and Switches 2 and 4 were to close:

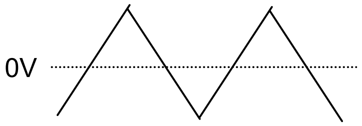


Now we have a path for current to flow from the negative buss through Switch-4, through the same motor windings and then through Switch-2 to the positive buss. Again, we have just shorted out the DC buss through the same motor winding, but this time current is flowing in the opposite direction.

Although the voltage to the motor was not sinusoidal, current has indeed flowed in both directions, so we have satisfied the definition of *alternating current*. Because AC power from the utility company is sinusoidal, we naturally tend to equate sinewaves with AC. But sinewaves are not the only waveforms that satisfy the requirement that current alternates in direction.

Illustrated below are a *squarewave* (on the left) and a *triangle-wave* (on the right). Note that both go positive and negative, in respect to the zero volt level and are therefore legitimate AC signals.

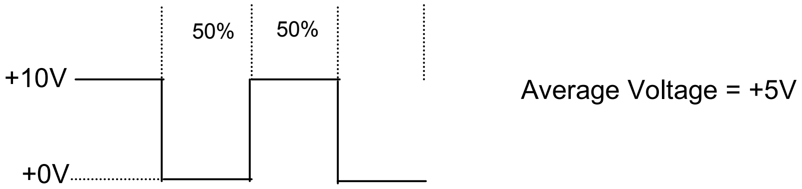




The AC output of the inverter section of a voltage source AC motor drive is not a sinewave (like that seen on the input to the rectifier), but is what is known as a PWM (Pulse Width Modulation) waveform.

PWM (Pulse Width Modulation)

Suppose that a signal were at a +10V level for a certain period of time and then at zero volts for the same period of time and then the pattern repeats, +10V half the time and zero volts half the time:

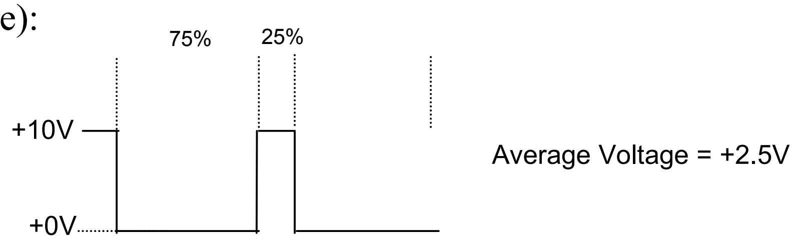


When +10V is applied 50% of the time and zero volts is applied for the other 50% of the time, then the *average* voltage applied will be +5V:

$$(10 \times .5) + (0 \times .5) = 5 + 0 = 5$$

The repetitive waveform illustrated above is called a squarewave and because it is "active" (at +10V) for 50% of the time, it is said to have a 50% "duty cycle."

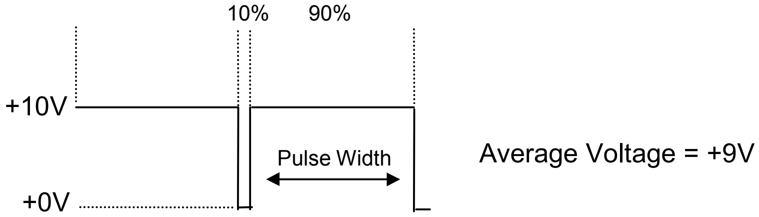
Now imagine another squarewave having a 25% duty cycle, (at +10V, 25% of the time and at zero volts 75% of the time):



When +10V is applied 25% of the time and zero volts is applied for the other 75% of the time, then the *average* voltage applied will be +2.5V:

$$(10 \times .25) + (0 \times .75) = 2.5$$

If we were to vary the duty cycle to 90%, (at +10V, 90% of the time and at zero volts 10% of the time):

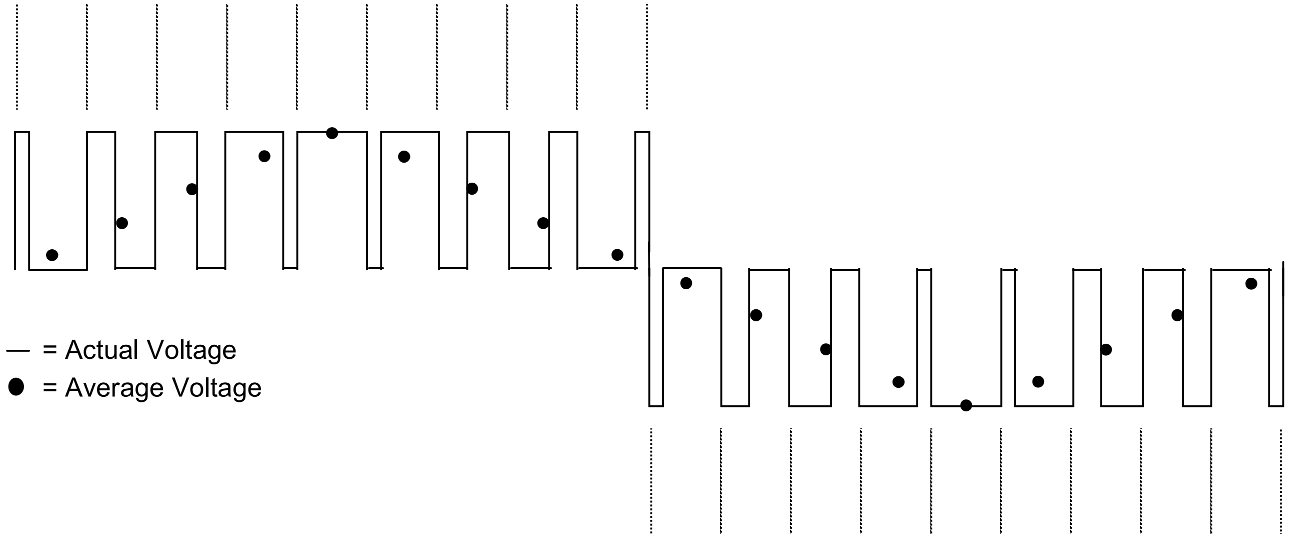


When +10V is applied 90% of the time and zero volts is applied for the other 10% of the time, then the *average* voltage applied will be +9V:

$$(10 \times .9) + (0 \times .1) = 9$$

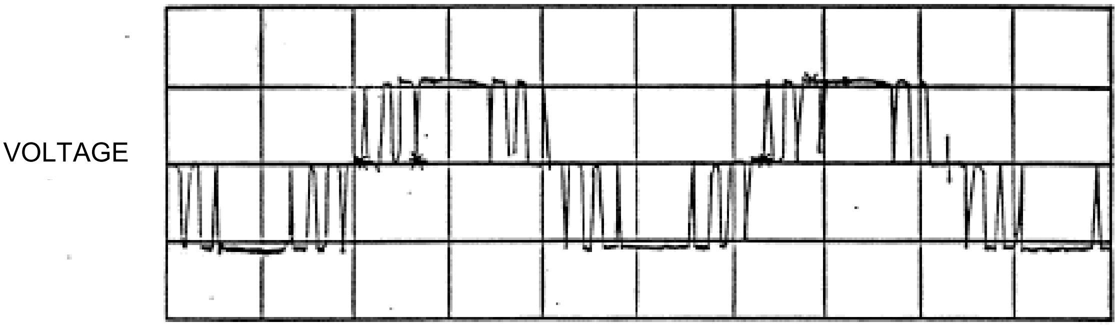
Thus, we can see that by varying the "width" of the positive going "pulse" (changing the amount of time the +10V signal is applied) we can change the *average voltage* being sent to the load to any desired level, between zero and +10V. This is the basic theory behind a type of signal known as *Pulse Width Modulation*.

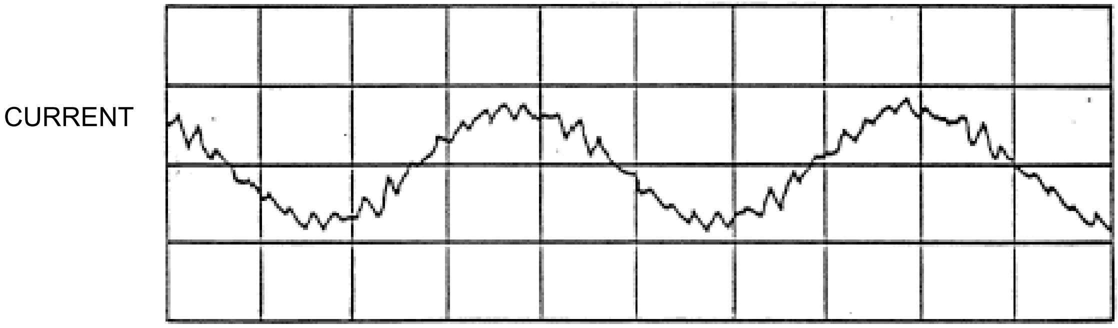
The actual PWM output of a voltage source, AC motor drive will gradually increase the pulse width of the output signal (gradually increasing the average voltage) until it reaches a maximum (100% duty cycle) level. Then the output begins to gradually reduce the pulse width (gradually decreasing the average voltage) until the average is near the zero volt level, as shown in the illustration below:



The pattern is then repeated with current flowing in the opposite direction through the same motor windings, to create the negative half-cycle of the output PWM waveform, as illustrated above.

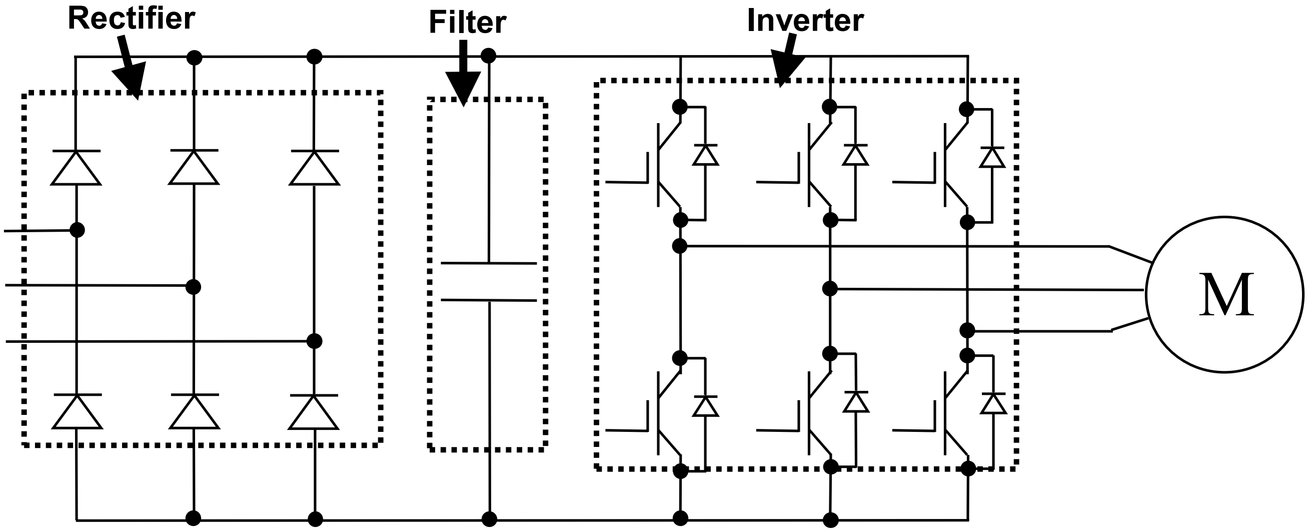
While the voltage (PWM signal) applied to the motor windings is not sinusoidal, the motor current is a function of the *average voltage* applied so the motor current is very sinusoidal in nature, as illustrated below:



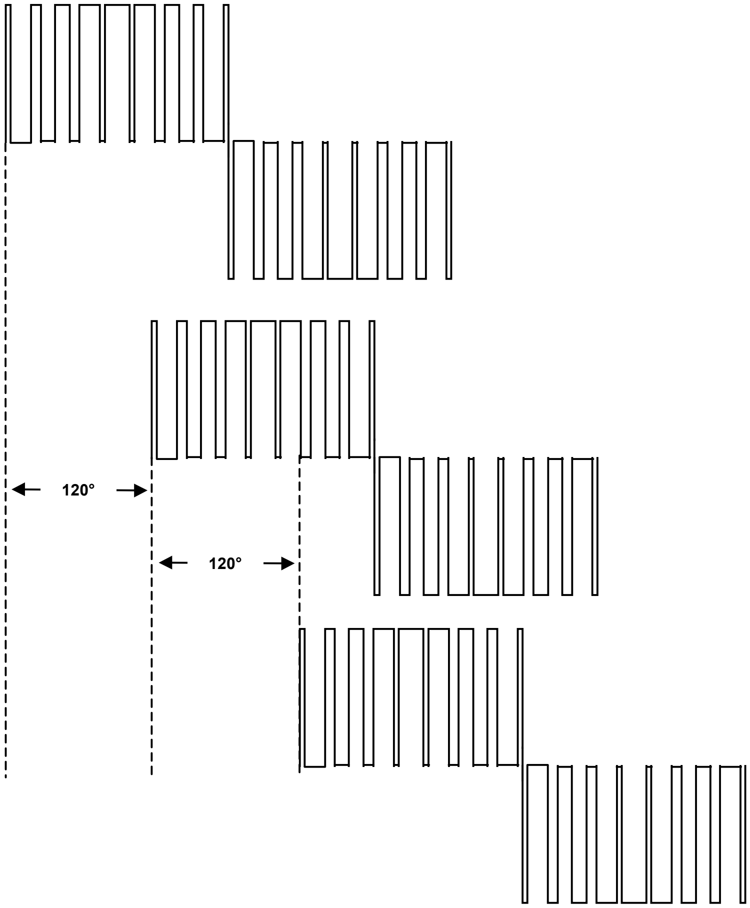


3-Phase PWM

As seen previously, it took us 4 switches to create a signal that could cause current to flow through the same motor winding in both directions. By simply adding two additional switches, it is possible to create a 3-phase PWM output to a 3-phase motor. Illustrated below is the schematic diagram for the main power circuitry of a "generic" voltage source AC motor drive:



The firing pattern of the six IGBT's is microprocessor controlled to create three PWM waveforms on the three outputs (measured phase-to-phase) that are 120° out of phase with each other, as illustrated below:



Volts-per-Hertz Curve

While it is motor current that creates the magnetic fields that interact and cause the motor rotor to turn, a voltage source AC motor drive cannot control motor current directly. Voltage source drives can only control the frequency and the voltage of the motor drive signal. Motor speed is a function of the frequency of the drive signal and motor torque is a function of voltage level of the drive signal. Although a voltage source drive cannot control motor currently directly, by controlling both the voltage and the frequency of the output signal to the motor, both motor speed and motor torque can be directly controlled.

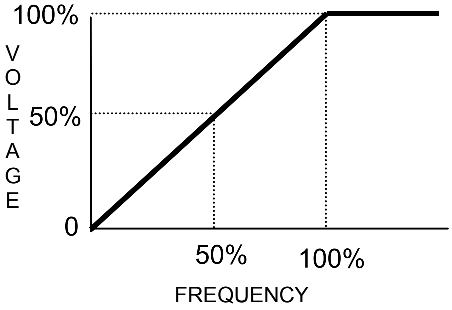
The voltage-to-frequency relationship in the motor drive signal can be represented by a *Volts-per-Hertz curve* that represents the way they relate to each other. There are two different *volts-per-hertz* curves that are in predominate usage for general voltage source AC drive applications:

1. Constant Torque Curve
2. Variable Torque Curve

Constant Torque Curve

Whenever the motor load requires a consistent amount of torque to be applied bringing a motor up to speed, a *constant torque* curve is generally selected for the output waveform.

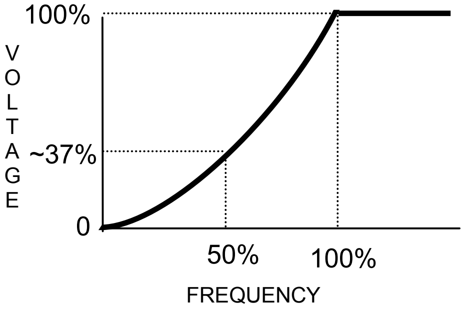
In a constant torque application, the voltage-to-frequency relationship is linear, meaning that they constantly track together between 0V/0Hz up to full-voltage/full-speed. When the drive is running at exactly half speed, the output voltage will be exactly half of its full voltage level. A constant torque volts-per-hertz curve is illustrated below:



When the drive receives an externally applied "RUN" command (either from the drive's front panel controls or an externally applied signal) the drive output will begin firing the IGBT's in such a way that both the output voltage and the output frequency begin ramping upward from zero, towards a point where the motor is running at full voltage and full speed. If the drive were to receive an externally applied command to cause the motor to slow down, the output voltage will also decrease proportionally (along with the lowered frequency) to keep torque constant.

Variable Torque Curve

Whenever the load is know to vary, a *variable torque* curve will often be selected for drives installed in these applications. A variable torque curve is illustrated below:



When using a *variable torque* volts-per-hertz curve, the frequency of the output signal will increase at a slightly higher rate than the voltage at the low end of the curve. At half speed, the output voltage will be approximately 37% of full output voltage. As the speed nears the higher end of the curve, the voltage will begin rising at a rate faster than the frequency is increasing so that they both will reach 100% at the same time.

Torque Boost

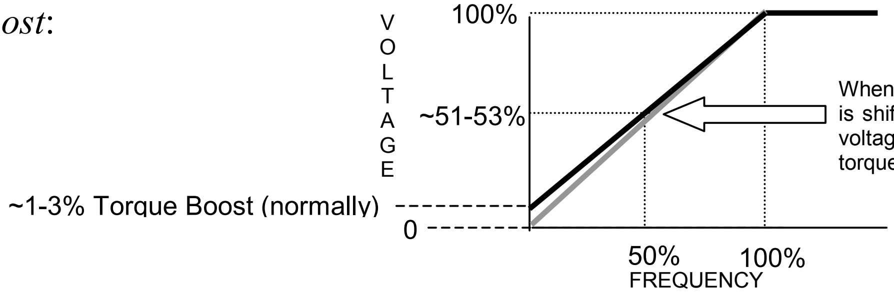
As discussed previously, when voltage is first applied to an induction motor's stator winding, the resulting current which flows within the stator winding causes a magnetic field to build up around the stator winding. This expanding stator field cuts through the "squirrel cage" conductors within the rotor, causing a voltage differential to be created across the rotor bars. This voltage differential causes current to flow within the rotor bars, which in turn, causes a magnetic field to build up around the rotor. The magnetic field around the rotor will interact with the magnetic field around the stator and when the their respective field strength is sufficient for their magnetic attraction/repulsion forces to overcome friction and inertia of the rotor, physical motion (rotation) of the rotor will result.

This initial current flow within the motor windings that is used to build the magnetic fields necessary to create rotary motion in the rotor is called *excitation current*. During the time interval while excitation current is building the stator and rotor fields, the voltage and frequency of the output signal are both increasing without a corresponding change in motor torque and speed, as the rotor is not yet rotating.

In order to build the stator and rotor fields more quickly and thereby create rotary motion in the rotor at a lower relative frequency, instead of the initial output voltage starting zero volts, a small amount of "offset voltage" often employed at the extreme low end of the motor speed range. Instead of zero volts at zero hertz (as shown in the volts per hertz curves on the previous page), the initial output voltage is "boosted" to a higher level than zero at zero hertz. Depending upon the actual horsepower rating of the drive, factory defaults will often include a *voltage boost* of between 1% to 3% of the output voltage range (~4.6 Vac to ~13.8Vac for a 460Vac drive) at zero hertz, and will increase from that level to 100% output voltage as the drive accelerates the motor up to it's normal operating speed. As the output voltage controls motor torque, this *voltage boost* is often referred to as *torque boost*.

Constant Torque Curve using Torque Boost

Below is the *voltage per hertz curve* for a *constant torque* application, employing *torque boost*:

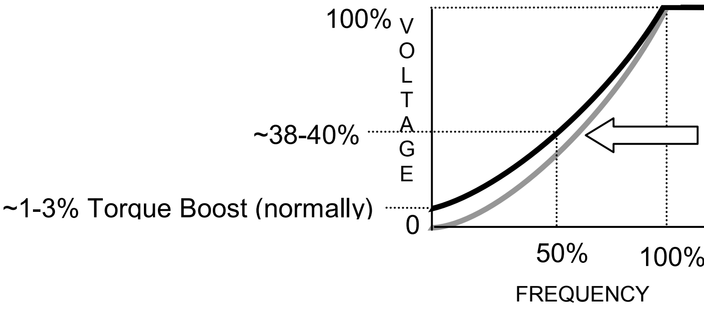


When torque boost used, the entire volts/hertz curve is shifted upwards slightly. At half speed, the output voltage is just under 50% + the specified amount of torque boost employed.

When the drive receives a "RUN" command, the drive output will begin firing the IGBT's and the output frequency will begin ramping upward from zero hertz, but instead of starting at zero volts, the initial output voltage will begin ramping upwards from the voltage specified as the amount desired *torque boost*, as shown above.

Variable Torque Curve using Torque Boost

Below is the *voltage per hertz curve* for a *variable torque* application, employing *torque boost*:



When torque boost used, the entire volts/hertz curve is shifted upwards slightly. At half speed, the output voltage is just under 37% + the specified amount of torque boost employed.

Again, when the drive receives a "RUN" command, the drive output will begin firing the IGBT's and the output frequency will begin ramping upward from zero hertz, but instead of starting at zero volts, the initial output voltage will begin ramping upwards from the voltage specified as the amount desired *torque boost*, as shown above. As seen before, when using a *variable torque* volts-per-hertz curve, the frequency of the output signal will increase at a slightly higher rate than the voltage at the low end of the curve. At half speed, the output voltage will be approximately 37% of full output voltage, plus the amount *torque boost* employed.