THE THREE PHASE INDUCTION MOTOR

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INTRODUCTION

"A chicken in every pot and an eagle in every pocket" or so went one slogan during the Great Depression. Had Thomas Edison won the battle over power distribution, we could have added "and a power plant on every corner".

Edison was a proponent of DC power and fought the use of AC bitterly. He invented the incandescent lamp in 1879 and began immediately to develop a power generating and distribution system to promote it. His first power plant opened in new York City in 1882 and several others were built over the next few years. Most of the power generated by Edison's plants went to lighting customers; however, DC motors were in use in industry by the 1880's. Although Edison's efforts were a limited financial success, it was soon recognized that DC systems suffered heavy power losses in transmissions over any distance.

The great advantage of AC power is that voltage can be easily stepped up or down by use of a transformer. This advantage is due to the relationship of the volt and amp. Power in watts is equal to volts times amps. If we wanted to transmit 1,000,000 (mega) watts we could use any number of volt - amp combinations. For example a current intensity of 1000 amps at 1000 volts would equal 1 megawatt. 100 amps at 10,000 volts is also a megawatt. Why not 10 amps at 100,000 volts? When transmitting power over long distances we want to use the highest voltage practical because the energy expended (heat) in maintaining current flow increases as the square of the current intensity. Once AC power reaches its point of use it is then stepped down to a more usable voltage.

Edison's principal opponent at the time was George Westinghouse, a staunch supporter of AC power. Long distance transmission of high voltage AC was made practical by the work of the Croatian-American engineer Nikola Tesla. Tesla not only improved the AC generator and did much of the work on the transformer, but also invented the AC induction motor. He was backed by Westinghouse who, in 1893 won the right to set up an AC hydroelectric plant at

Niagara Falls. It was the flexibility of AC and Tesla's invention of the AC induction motor that finally sealed the fate of the DC transmission system.

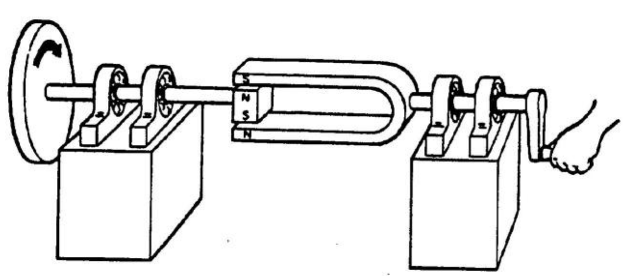
Today about 90% of all industrial motor applications use three phase induction motors. Why? Because they are simple in design, easy to maintain, and are less costly than other designs.

MAGNETISM

A magnet is defined quite simply as something that attracts iron and the force that it exhibits is called magnetism. Although undoubtedly discovered in prehistoric times, it was not until 600 BC that the early Greek Philosopher Thales reported its properties. He studied a sample of iron ore (loadstone) from the town of Magnesia which was on the Aegean coast of what is now Turkey. He called it "ho magnetes lithos" or simply the Magnesian rock. Thales also discovered that amber (a fossilized resin called elektron by the Greeks), when rubbed, exhibited an attractive force. It was different though because its attractive forces were not limited to iron but would attract any number of objects including feathers and parchment. In the latter case he had unknowingly discovered what we call electrostatics, or electricity at rest.

An object that exhibits magnetism without the aid of electricity is referred to as a permanent magnet. Permanent magnets have two areas of maximum attraction which are referred to as their North and South seeking Poles. Although a number of rules apply, the most basic is that opposite poles attract and like poles repel.

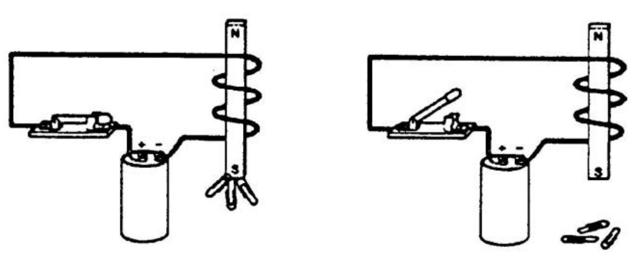
Below, we see the poles of a horseshoe magnet interacting with the poles of a bar magnet. When one is rotated, torque is transmitted to the other without making contact due to the attractive forces of the opposing poles. A similar application is used to couple pumps and motors where shaft seals cannot be used.



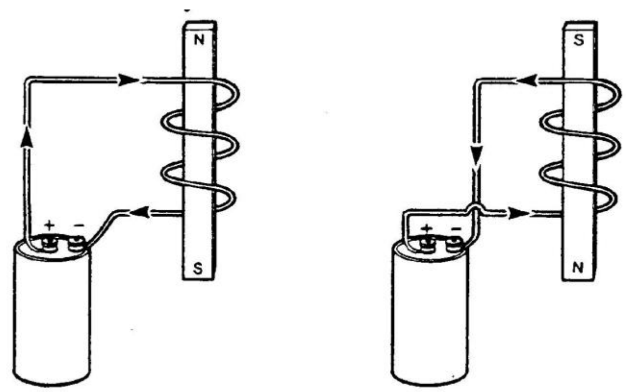
Magnetic fields are also important because of their relationship to electricity. A moving electric charge produces a magnetic field and a magnetic field exerts a force on a moving electric charge. This relationship is the basis for motors, generators, and many other electrical devices.

Before the 19th century, electricity and magnetism were thought to be independent forces. In 1819; however, Hans Christian Oersted performed an accidental experiment that demonstrated that they are intimately related. His experiment occurred during a lecture when he accidentally placed a wire connected to a battery over the face of a compass parallel to the needle. He noticed that the needle moved quickly to the right. He then reversed the battery connections only to see the needle swing to the left. He had accidentally discovered the interaction between electric current and a magnet.

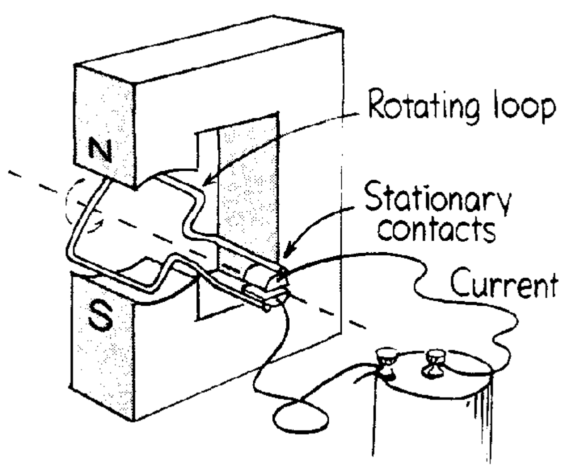
The French Physicist Andre Ampere, for whom the unit of current intensity is named, went on to demonstrate that a magnetic force generated by an electric current was indistinguishable from that of a permanent magnet. He began with two parallel wires each connected to a separate battery. One wire was fixed while the other was free to slide toward or away from its neighbor. When current traveled in the same direction in both wires, the movable wire slid toward the stationary one. When current traveled in opposite directions, the movable wire slid away. This demonstrated that an electric current could exhibit the same attractive and repulsive forces as the permanent magnet. The electromagnet is an elegantly simple device that demonstrates that a moving charge generates a magnetic field. In the figure below, a DC current is flowing through a wire that is coiled around an iron bar. The flowing current causes the bar to become magnetized. When the current is removed the bar loses its magnetic properties. Electromagnets can be constructed so that they are far more powerful than permanent magnets.



An important feature of the electromagnet is its ability to change polarity via a change in the direction of current flow. As shown below, reversing the connections to the battery causes current to flow in the opposite direction and thus changes the polarity of the iron bar. This figure also demonstrates that Benjamin Franklin's bad guess is still alive and well. It shows current flowing from the positive to the negative terminal of the battery as opposed to the proper direction. Franklin replaced Du Fay's two fluid theory of electricity with his single fluid model. A positive charge, according to him, resulted from an excess of electrical fluid and would therefore flow to a region of fluid deficiency (negative). Although incorrect, it made sense at the time as it was analogous to water running down hill. Unfortunately it is still perpetuated by some in the electrical community.



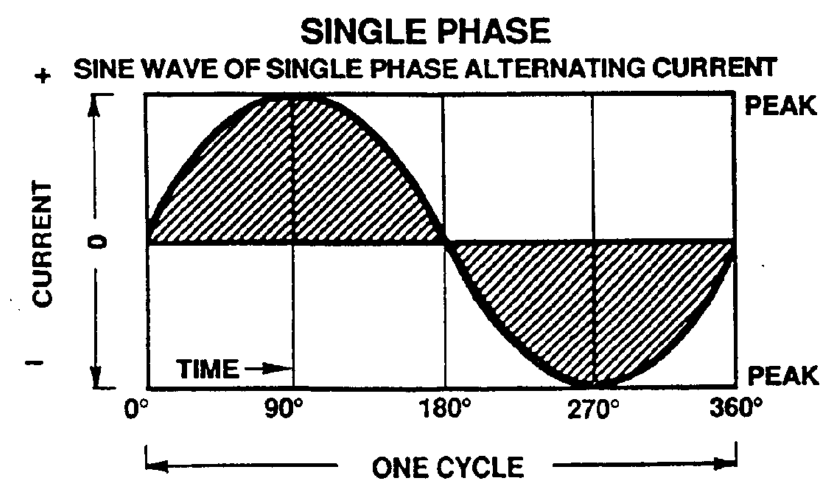
This ability to change polarity is the basis for the simple DC motor that many of us built in elementary school. Below, we see a loop of wire (rotor) within a permanent magnetic field (stator) and connected to a battery via contacts that change current direction every half rotation (commutator). When current passes



through the loop, it flows in one direction in the upper half and in the opposite direction in the lower half. If the upper half is forced to the left, then the lower half is forced to the right (Just like Oersted's compass needle and Ampere's wires). But unlike their experiments, the current entering the loop changes direction every half rotation. This keeps the forces on the upper and lower portions of the loop oriented in the same direction and thus allows continuous rotation.

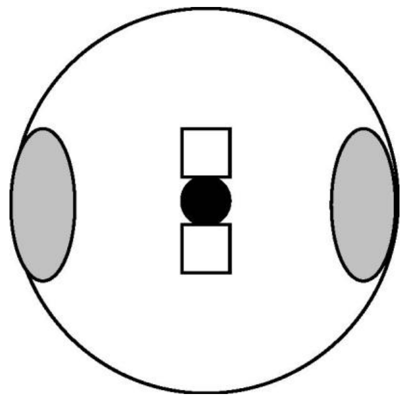
ALTERNATING CURRENT

One of the advantages of AC motors is that we do not have to come up with a means, mechanical or otherwise, to change polarity. This takes place during the normal voltage reversals of AC power.



During one 360 degree cycle of AC, current (and voltage) is 0 at 0 degrees, + max at 90 degrees, 0 again at 180 degrees, - max at 270 degrees, and 0 again at 360 degrees. Both current and voltage varies at every point in between. In the US this cycle occurs 60 times each second. In some other countries it is reduced to 50 times per second.

If we were to bond the N pole of permanent magnet to one side of a shaft, bond the S pole to the other side (a rotor), place it in a housing with two coils of wire 180 degrees apart (a stator), and energize the coils with single phase power we would have a simple 2 pole motor. (Of course this would be impossible because all magnets have two poles. Cut one in half and you get two complete but smaller magnets.) An example is shown on the following page. Since alternating current changes direction every half cycle (and in this case every half rotation), it will keep the forces on the north and south poles of the rotor oriented in the same direction through a complete rotation just as the commutator did for our DC motor. The difference is that no mechanical intervention is required.



Since our electric current changes direction 60 times per second, our 2 pole motor's synchronous speed will be 3600 rotations (not revolutions) per minute (RPM). The full load speed (or slip speed) will be somewhat less - - usually between 95 and 99% of synchronous speed.

If we were to wire the stator with four coils 90 degrees apart we would have a 4 pole motor with a synchronous speed of 1800 RPM. Use 6 coils and we get 1200 RPM and so on. This speed change occurs because it takes one complete AC cycle to traverse two coils, two cycles to traverse four coils, and three to traverse six coils. Synchronous speed in RPM is always equal to a constant of 120 times the power frequency divided by the number of poles in the motor. (Constants allow us to express quantities in alternate units. For example, angular velocity is normally expressed in radians/sec. The constant, 120, allows the alternate unit, rotations per minute, to be used.)

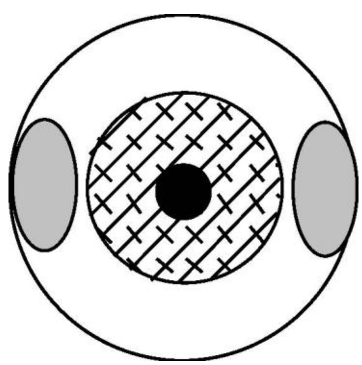
Speed = 120 * Frequency / # Poles

INDUCED CURRENT

Our discussion so far has been limited to motors that use some combination of permanent and electromagnets to create magnetic fields on the rotor or stator. Permanent magnets are limited in the size of the fields they can produce and at some point become too large to be practical. Wire wound rotors (electromagnets) can produce large fields but require some sort of mechanical intervention to change polarity. There is a simpler way.

I said earlier that a moving electric charge creates a magnetic field. If the magnetic field is intense enough, it can create a current in a nearby metallic object. This created current will produce its own magnetic field which will then interact with the magnetic field that created it. This may seem a bit incestuous, but quite economical never the less. Creation of a current via a magnetic field is called induction and is the basis for the AC induction motor. Induction is a far simpler way of creating an electromagnetic field than mechanical devices such as a commutator. Essentially an induction motor has but one moving part if you consider the bearings to be an integral part of the rotor.

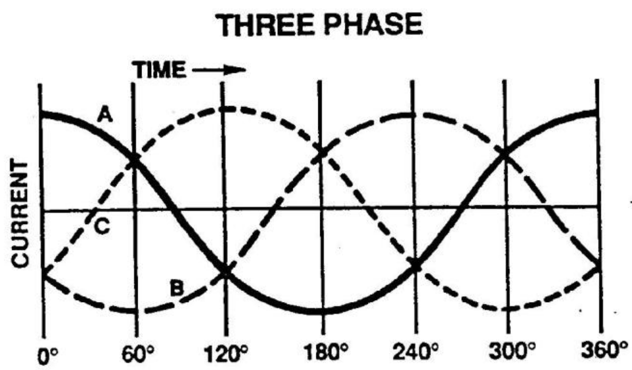
The figure on the following page is a cross sectional diagram of a single phase, two pole induction motor. The black circle represents the motor shaft and the larger circle, with hatches, concentric to it is the rotor. The egg shaped items are the coiled wire poles of the stator. As current flows through the coils of wire in the motor's stator high intensity magnetic fields are created. These fields induce currents in the rotor's bars which, in turn, create magnetic fields that interact with the fields of the stator. As current flows from coil to coil a new field is induced and since the current changes direction every half rotation, the electromagnetic and induced forces remain properly oriented and therefore allow continuous rotation. See my "Single Phase Induction Motor" tutorial for more information on the operation and the rotational fields generated by both single and three phase motors.



THREE PHASE POWER

Although versatile in a residential environment, single phase power has its limitations in motor applications. One limitation is power. Due to current draw and practical limitations on physical size most single phase motors tend to be 2

HP or smaller. They are; however, generally available up to 10 HP. Another limitation is cost. Single phase motors cost more to buy and run than their three phase counterparts. Finally, single phase motors often require special starting arrangements such as capacitors, additional windings and switches in order to get them turning under load. Three phase power overcomes these limitations.



The three phase power curve is made up of three single phase sine waves separated by 120 electrical degrees or 1/3 of a cycle. This not only reduces the current load per phase, but also increases the number of magnetic coils in a motor stator. The single phase, two pole motor has but two coils 180 degrees apart. Its three phase counterpart has two coils per phase or a total of six only 60 degrees apart. The four pole motor has twelve and so on. These additional coils makes starting much easier, especially under load. The three phase motor is also more efficient in its use of power than the single phase.

A LITTLE SIMPLE PHYSICS

Now that we have a reasonable understanding of the operation of the AC induction motor, lets discuss some application considerations.

WORK & POWER

We all know that an electric motor is a machine designed to transform electrical energy into mechanical energy so that work can be performed. Work, in a translational system, is defined as the force applied multiplied by the distance traveled. In the English system force is measured in pounds and distance is measured in feet.

$w = fd$

If we were to lift 100 pounds to a height of 10 feet, we will perform 1000 lb-ft of work. We would perform the same amount of work if we lifted a 200 pound object to a height of 5 feet or,for that matter, a 50 pounder 20 feet. (Just for grins, work in the mks system is the Joule or newton-meter and in the cgs system it is the Erg or dyne-cm. A newton is a kg-m/sec/sec and a dyne is a g-cm/sec/sec. A fig newton is not a unit of force.)

Work is a somewhat unfortunate term because in order for work to be performed, we must actually move an object in a direction that is opposite of the force acting upon it. For example, if we lift a suitcase off the ground we have performed work because the force we applied overcame the force of gravity that was holding it to the ground. Carrying it across the room; however, is not work for we are not moving it in a direction that is opposite the force acting upon it. Try telling that to someone with a thirty pound suitcase in each hand. He or she may expend energy but they do no work. The equation for work tells us how much work is done but it says nothing about how quickly it gets done. If we carry a 50 pound object up a flight of stairs 10 feet high we will perform 500 lb-ft of work. It makes no difference if we do it in five seconds or five days, the same amount of work is performed. The rate at which work is done is power. Power is equal to work divided by time. $p = w/t$

In the late eighteenth century, James Watt made some major improvements to the steam engine --improvements that made it a viable alternative to other sources of power. One of the power hungry applications in Scotland at the time was that of pumping water from coal mines. The pumps were powered by horses and Watt needed a way to relate the power of his engine to that of a team of horses. Through experimentation he determined that the average horse could lift 150 pounds to a height of 220 feet in one minute. The work performed is 33000 lb-ft (fd). Power or, in this case, horsepower (HP) is 33000 lb-ft/min. This rather cumbersome number is equal to 745.7 Joules/sec in the mks system. One joule/sec was called a watt in his honor. One HP then is equal to approximately 746 watts. In the United States we rate a motor's power in horsepower. In most other countries, it is the kilowatt (KW).

TORQUE

Torque is defined as the force that gives rise to rotational motion. It is also the result of rotational motion. Torque is equal to force times the radius through which it acts (The radius is sometimes referred to as the length of the lever arm.).

$T = fr$

Torque in a rotational system is analogous to force in a translational system. The straight line distance of the translational system; however, is replaced with an angular quantity. Work then in a rotational system is:

$W = T\phi$ where ϕ is angle through which the rotating object turns

For any given HP, torque varies inversely with rotational speed. For example a 100 HP motor operating at 3600 RPM produces a torque of approximately 150 lb-ft. At 1800 RPM torque would be about 300 lb-ft and at 1200 RPM about 450 lb-ft. This is exactly what one would expect since HP (power) is the rate at which work is done. If an 1800 RPM motor is to accomplish the same amount of work in the same amount of time as one turning at 3600 RPM, it must do twice the work per rotation. It is for this reason that the "U" dimension of the 900 RPM motor shown in the Puzzler is larger than that of the 3600 RPM model. Lower RPM motors utilize larger diameter shafts to accommodate the higher torque required to do the same amount of work in fewer rotations.

Earlier we defined horsepower as w/t and expressed it in lb-ft or watts. It can also be defined in terms of torque and speed.

$HP = T \times S(rpm) / 5250$

We can also express torque in terms other than force and the radius through which it travels. Rearranging the previous equation we get:

$T = HP \times 5250 / S(rpm)$

These last two equations are probably more useful in daily work than are the earlier ones.

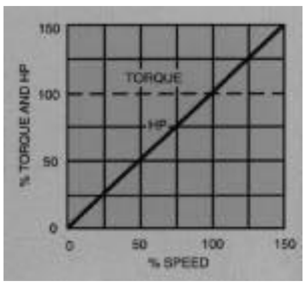
LOAD TYPES

There are three basic load types (applications) for electric motor installations. These are constant torque, constant HP, and variable torque.

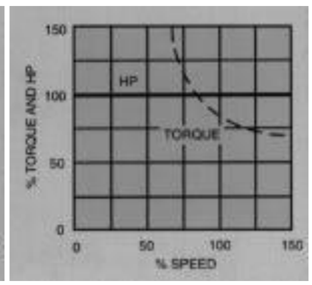
Constant torque applications require the same amount of torque regardless of the operating speed. Horsepower; however, varies directly with speed. About 90% of all applications involve constant torque loads. Examples include compressors, positive displacement pumps, conveyors, and hoists.

Constant horsepower applications require higher torque at lower speeds, and lower torque at higher speeds. A typical application would be a lathe where slow speeds are required for deep cuts and high speeds are needed for finish cuts. Other examples include milling machines and drill presses.

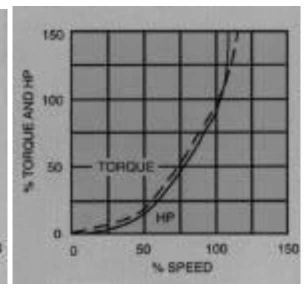
Variable torque applications follow the laws of affinity. Torque varies as the square of speed and horsepower varies as the cube of speed. Examples include centrifugal pumps, fans, and compressors.



Constant Torque



Constant HP



Variable Torque