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Nikola Tesla's 3-Phase AC and Motors

EV World (originally published July 11, 2006)

The history of Electricity is a very interesting one indeed.

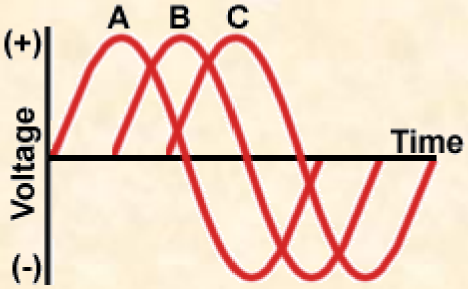
In the early 1900s, Thomas Edison is said to have hated AC simply because he didn't understand it. Edison made efforts to squash AC distribution but ultimately failed due to the economics of power generation and distribution. He just couldn't send DC very far.

Edison's rival Nikola Tesla developed and patented much of AC power generation and distribution technology used today. George Westinghouse purchased Tesla's patents and profited from them.

Even with these patents, the company Edison that founded -- General Electric -- is many times the size of Westinghouse. Telsa fell into relative obscurity. He is rarely mentioned in history books. He does not get the kind of recognition he truly deserves even though he is the creator of polyphase transformers and machinery. Nikola Tesla is the real reason why we use 3-phase distribution.

http://www.electricityforum.com/3-phase-electricity.html

… To transmit and distribute alternating current, it is more efficient to use 3 circuits that are out of sequence. This idea was discovered by **Nikola Tesla** (1856-1943). Much of its efficiency is because there is always voltage (electrons moving) in at least one wire.



He found that it is an arrangement that fits in very nicely with generator design. The 120° phasing separation allows close to the optimum spacing and size of the copper conductors around the stator bore. The compatible generator is the cheapest form to make.

This type of power is designed especially for large electrical loads where the total electrical load is divided among the three separate phasing sequences. As a result, the wire and transformers will be less expensive than if these large loads were carried on a single system.

Generators usually have 3 separate windings with each producing its own separate single-phase voltage. Since these windings are staggered around the generator circumference, each of the voltages is "out of phase" with one another. That is, each of the three reaches the maximum and minimum points in the AC cycle at different times.

Power is generated at electric utilities in this way. But if this power is better than single phase, why not 4-, 5-, or 6-phase? Theoretically, these would be even better. But equipment manufacturers would have to build motors to use it. And that just wouldn't be cost effective given the installed base of equipment that must continue to be powered.

The word is often abbreviated using the Greek letter "phi" (φ).

The most important class of load is the electric motor. An induction motor has a simple design, inherently high starting torque, and high efficiency. Such motors are applied in industry for pumps, fans, blowers, compressors, conveyor drives, and many other kinds of motor-driven equipment. A motor will be more compact and less costly than a motor of the same voltage class and rating. AC motors above 10 HP (7.5 kW) are uncommon. 3-phase motors will also vibrate less and hence last longer than motor of the same power used under the same conditions.

Large air conditioning, etc. equipment use motors for reasons of efficiency, economy, and longevity.

Resistance heating loads such as electric boilers or space heating may be connected to systems. Electric lighting may also be similarly connected. These types of loads do not require the revolving magnetic field characteristic of motors but take advantage of the higher voltage and power level usually associated with distribution. Fluorescent lighting systems also benefit from reduced flicker if adjacent fixtures are powered from different.

Large rectifier systems may have inputs; the resulting DC current is easier to filter (smooth) than the output of a rectifier. Such rectifiers may be used for battery charging, electrolysis processes such as aluminum production, or for operation of DC motors. … …

http://mysite.du.edu/~jcalvert/tech/threeph.htm

Most alternating-current (AC) generation and transmission -- and a good part of use -- take place through 3-phase circuits. If you want to understand electric power, you must know something about 3-phase. It is rather simple if you go at it the right way (though it has a reputation for difficulty).

Phase is a frequently-used term around AC. The word comes from Greek θασις ("appearance"), from θαυειυ ("to appear)". It originally referred to the eternally regular changing appearance of the Moon through each month. And then it was applied to the periodic changes of some quantity such as the voltage in an AC circuit.

Electrical phase is measured in degrees with 360° corresponding to a complete cycle. A sinusoidal voltage is proportional to the cosine or sine of the phase.

Three-phase (abbreviated 3φ) refers to three voltages or currents that that differ by a third of a cycle (or 120 electrical degrees) from each other. They go through their maxima in a regular order called the **phase sequence**. The 3 phases could be supplied over 6 wires with 2 wires reserved for the exclusive use of each phase.

However, they are generally supplied over only 3 wires. And the phase or line voltages are the voltages between the three possible pairs of wires. The phase or line currents are the currents in each wire. Voltages and currents are usually expressed as rms (or effective values) as in single-phase analysis.

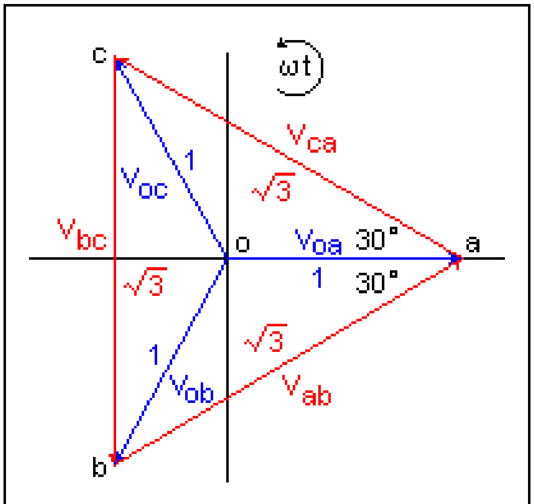
When you connect a load to the 3 wires, it should be done in such a way that it does not destroy the symmetry. This means that you need three equal loads connected across the 3 pairs of wires. This looks like an equilateral triangle (or "delta") and is called a **delta load**. Another symmetrical connection would result if you connected one side of each load together, and then the three other ends to the 3 wires. This looks like a "Y" and is called a **wye load**.

These are the only possibilities for a symmetrical load. The center of the Y connection is -- in a way -- equidistant from each of the 3 line voltages and will remain at a constant potential. It is called the **neutral** and may be furnished along with the 3 phase voltages. The benefits of 3-phase are realized best for such a symmetrical connection which is called **balanced**. If the load is not balanced, the problem is a complicated one -- one whose solution gives little insight, just numbers. Such problems are best left to computer circuit analysis.

3-phase systems that are roughly balanced (the practical case) can be analyzed profitably by a method called **symmetrical components**. Here, let us consider only balanced 3-phase circuits (which are the most important anyway).

The key to understanding 3-phase is to understand the **phasor diagram** for the voltages or currents. In the diagram at the right, **'a'**, **'b'**, and **'c'** represent the 3 lines and **'o'** represents the neutral. The **red** phasors are the line (or "delta") voltages -- the voltages between the wires. The **blue** phasors are the "wye" voltages -- the voltages to neutral. They correspond to the 2 different ways a symmetrical load can be connected.

The vectors can be imagined rotating anti-clockwise with time with angular velocity $\omega = 2\pi f$, their projections on the horizontal axis representing the voltages as functions of time. Note how the subscripts on the Vs give the points between which the voltage is measured and the sign of the voltage. $\mathbf{V_{ab}}$ is the voltage at point a relative to point **'b'**, for example.



Three-Phase Wye and Delta

The same phasor diagram holds for the currents. In this case, the line currents are the **blue** vectors and the **red** vectors are the currents through a delta load. The **blue** and **red** vectors differ in phase by 30° and in magnitude by a factor of √3 as is marked in the diagram.

Suppose we want to take two phase wires and neutral to make a 3-wire household service supplying 120V between each hot wire and ground. The neutral will become the grounded conductor and the two phases the hot conductors.

Then, the wye voltage is 120. So the delta voltage will be √3 x 120 = 208V. This is the 3-phase line voltage necessary in this case. Note that the two 120V sources are not opposite in phase and will not give 240 V between them.

On the other hand, suppose we do want a 240V service. Then this must be the line voltage and the voltages to neutral will be 139V, not 120V. A 120V 3-phase service will give only 69V from line to neutral. Note that √3 appears everywhere and that the differences in phase explain the unexpected results.

If the load consists of general impedances **Z**, the situation is described by current and voltage phasors connected by **V = IZ**, both in magnitude and phase. The diagrams are similar in shape and rotated by the phase angle between voltage and current in each impedance. Remember that the line voltages are the **red** vectors while the line currents are the **blue** vectors.

Z relates either the line voltages and delta currents -- or the wye voltages and the line currents -- depending on the connection. **Z** does not relate the line current and line voltage, which are different in phase by 30° even for unity power factor (pure resistance load).

This comes out more clearly when we consider the power **P** delivered to the load. For a resistive delta load, $\mathbf{P = 3\ V_{line}I_{delta} = \sqrt{3}\ V_{line}I_{line}}$ since $\mathbf{I_{delta} = \sqrt{3}\ I_{line}}$. For a wye load, $P = 3\ V_{wye}I_{line} = \sqrt{3}\ V_{line}I_{line}$. This is, of course, the same expression.

For other than unity power factor, this must be multiplied by **cosθ** which is the angle of **Z** -- not the phase difference between the line voltage and line current. This means (most emphatically) that our usual rule for finding the power from phasors does <u>not</u> apply to 3-phase!

If you write out the 3 phase currents as explicit functions of time -- $I_{max}\cos(\omega t)$, $I_{max}\cos(\omega t - 120°)$, and $I_{max}\cos(\omega t + 120°)$ -- square them, multiply by the resistance **R**, and then add, the result is the constant $\mathbf{(3/2)I_{max}^2R = 3\ I^2R}$. The power is applied <u>steadily</u> as in DC circuits -- not in pulses as in single-phase AC circuits. This is a great advantage, giving 3-phase machines 48% greater capacity than identical single-phase machines.

In Germany and Switzerland where 3-phase power was originated and developed, it is known as *Drehstrom* ("rotating current") for this property of constant power. Ordinary AC is called *Wechselstrom* (or "change current"). **Nikola Tesla** -- the discoverer of polyphase currents and inventor of the induction motor -- employed 2-phase current where the phase difference is 90°. This also can be used to create a **rotating magnetic field** and is more efficient than single-phase, but is not quite as advantageous as 3-phase. 2-phase power was once rather common in the United States where Tesla was important in the introduction of AC. But it has now gone completely out of use.

2-phase can be supplied over 3 wires. But there is no true neutral since the phases are not symmetrical. However, it is always easy to double the number of phases in a transformer secondary by making 2 secondary windings and connecting them in opposing phases. 4-phase does have a neutral like three-phase, but requires 4 wires. In fact, 3-phase is more economical than any other number of phases. For applications like rectifiers and synchronous converters where DC is produced, it is most efficient to use 6-phase AC input which is easily produced from 3-phase in a transformer.

If you are transmitting a certain amount of power single-phase, adding one more conductor operated at the same line voltage and current and using 3-phase will increase the power transmitted by 72% with only a 50% increase in the amount of copper and losses. The advantage is obvious. Under certain conditions, transmitting a certain amount of power by 3-phase only requires 75% of the copper of single-phase transmission. This is not the major advantage of 3-phase. But it does play a factor.

Three wires are usually seen in high-voltage transmission lines (whether on towers or poles) with pin or suspension insulators. Some high-voltage lines are now DC since solid-state devices make it easier to convert to and from AC. The DC lines are free of the problems created by phase as well as eliminating the skin effect that reduces the effective area of the conductors. It is not nearly as easy to manage long-distance electrical transmission as might be thought.

http://en.wikipedia.org/wiki/Rotating_magnetic_field

… The **rotating magnetic field** is a key principle in the operation of **alternating-current motors**. A permanent magnet in such a field will rotate so as to maintain its alignment with the external field. This effect was conceptualized by **Nikola Tesla** and later utilized in his and others' early AC (alternating-current) electric motors.

A rotating magnetic field can be constructed using 2 orthogonal coils with 90 degrees phase difference in their AC currents. However, in practice such a system would be supplied through a 3-wire arrangement with unequal currents. But this inequality would cause serious problems in standardization of the conductor size. So in order to overcome it, 3-phase systems are used where the three currents are equal in magnitude and have 120 degrees phase difference.

3 similar coils having mutual geometrical angles of 120 degrees will create the rotating magnetic field in this case. The ability of the 3-phase system to create a rotating field -- utilized in electric motors -- is one of the main reasons why three-phase systems dominate the World's electrical power supply systems.

Because magnets degrade with time, **synchronous motors** and **induction motors** use short-circuited **rotors** (instead of a magnet) following the rotating magnetic field of a multi-coiled **stator**. The short-circuited turns of the rotor develop **eddy currents** in the rotating field of the stator. These currents in turn move the rotor by the Lorentz force.

In 1882, Nikola Tesla identified the concept of the rotating magnetic field. In 1885, **Galileo Ferraris** independently researched the concept. In 1888, Tesla gained **U.S. Patent 381,968** for his work. Also in 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin.

http://electojects.com/motors/tesla-induction-motors-1.htm

Tesla Poly-Phase Induction Motors

part of "Motors" in http://electojects.com/motors/index.htm

Most AC motors are induction motors. Induction motors are favored due to their ruggedness and simplicity. In fact, 90% of industrial motors are induction motors.

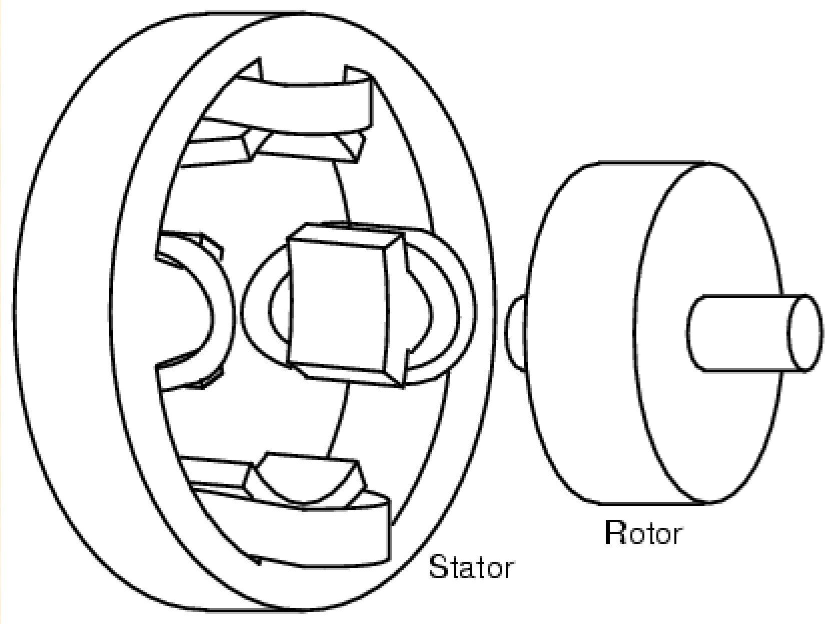
Nikola Tesla conceived the basic principals of the poly-phase induction motor in 1883 and had a half-horsepower (i.e., 400-watt) model by 1888. Tesla sold the manufacturing rights to George Westinghouse for $65,000.

Most large (e.g., >1 hp or 1 kW) industrial motors are **poly-phase induction motors**. By "poly-phase", we mean that the stator contains multiple distinct windings per motor pole, driven by corresponding time shifted sine waves. In practice, this is 2 or 3 phases.

Large industrial motors are 3-phase. While we include numerous illustrations of 2-phase motors for simplicity, we must emphasize that nearly all poly-phase motors are 3-phase. By "induction motor", we mean that the stator windings induce a current flow in the rotor conductors like a transformer (and unlike a brushed DC commutator motor).

Construction

An induction motor is composed of a rotor (known as an armature) and a stator containing windings connected to a poly-phase energy source as shown in Figure below. The simple 2-phase induction motor below is similar to the 1/2 horsepower motor which Nikola Tesla introduced in 1888.

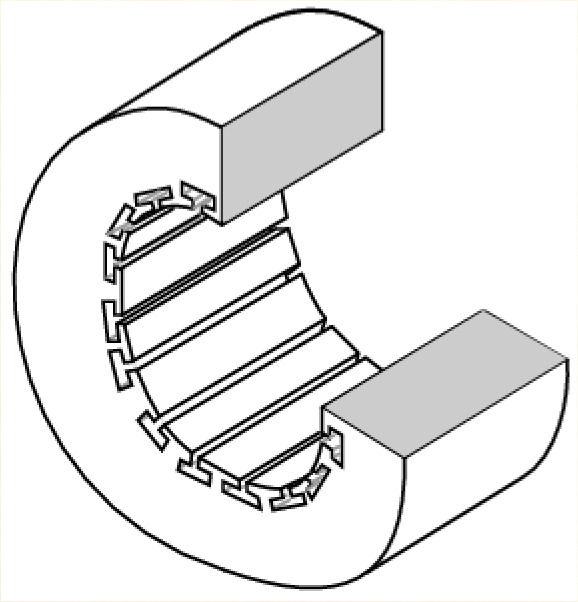


Tesla poly-phase induction motor

The stator in Figure above is wound with pairs of coils corresponding to the phases of electrical energy available. The 2-phase induction motor stator above has 2-pairs of coils -- one pair for each of the two phases of AC.

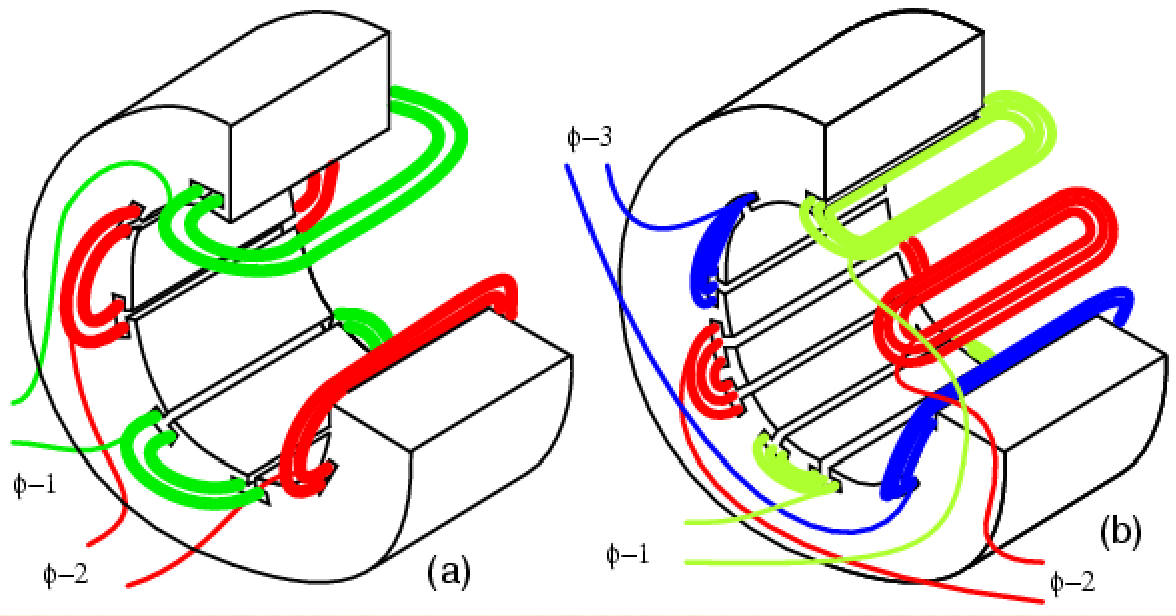
The individual coils of a pair are connected in series and correspond to the opposite poles of an electromagnet. That is, one coil corresponds to an N-pole and the other to a S-pole until the phase of AC changes polarity. The other pair of coils is oriented 90^o in space to the first pair. This pair of coils is connected to AC shifted in time by 90^o in the case of a 2-phase motor. In Tesla's time, the source of the 2 phases of AC was a 2-phase alternator.

The stator in Figure above has salient, obvious protruding poles as used on Tesla's early induction motor. This design is used to this day for sub-fractional horsepower motors (i.e., <50 watts). However, for larger motors less torque pulsation and higher efficiency results if the coils are embedded into slots cut into the stator laminations. (Figure below)



Stator frame showing slots for windings

The stator laminations are thin insulated rings with slots punched from sheets of electrical-grade steel. A stack of these is secured by end screws, which may also hold the end housings.



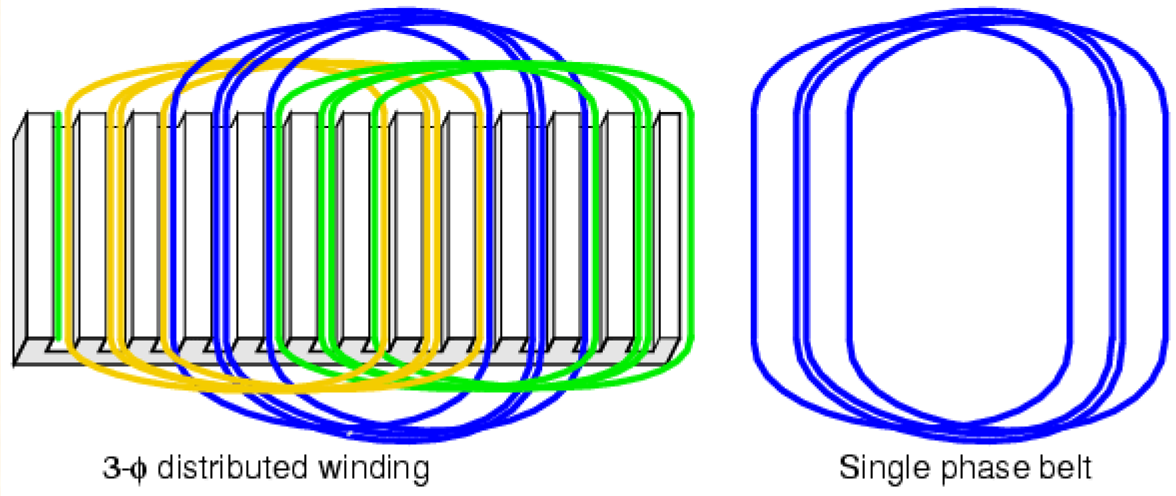
Stator with (a) 2-φ and (b) 3-φ windings

In Figure above, the windings for both a 2-phase motor and a 3-phase motor have been installed in the stator slots. The coils are wound on an external fixture and then worked into the slots. Insulation wedged between the coil periphery and the slot protects against abrasion.

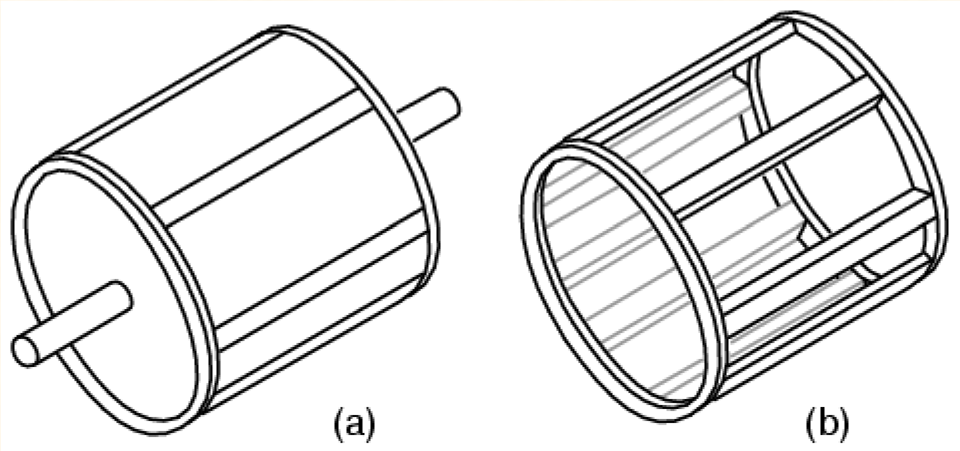
Actual stator windings are more complex than the single windings per pole in Figure above. Comparing the 2-φ motor to Tesla's 2-φ motor with salient poles, the number of coils is the same. In actual large motors, a pole winding, is divided into identical coils inserted into many smaller slots than above. This group is called a **phase belt**. See Figure below.

The distributed coils of the phase belt cancel some of the odd harmonics, producing a more sinusoidal magnetic field distribution across the pole. This is shown in the synchronous motor section.

The slots at the edge of the pole may have fewer turns than the other slots. Edge slots may contain windings from two phases. That is, the phase belts overlap.



The key to the popularity of the AC induction motor is simplicity as evidenced by the simple rotor (Figure below). The rotor consists of a shaft, a steel laminated rotor, and an embedded copper or aluminum squirrel cage shown at (b) removed from the rotor. As compared to a DC motor armature, there is no commutator. This eliminates the brushes, arcing, sparking, graphite dust, brush adjustment and replacement, and re-machining of the commutator.



Laminated rotor (a)embedded squirrel cage ; (b)Conductive cage removed from rotor

The squirrel cage conductors may be skewed, twisted, with respect to the shaft. The misalignment with the stator slots reduces torque pulsations.

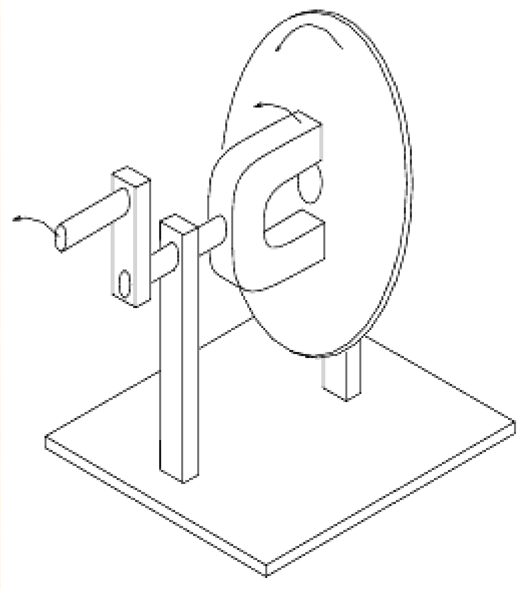
Both rotor and stator cores are composed of a stack of insulated laminations. The laminations are coated with insulating oxide or varnish to minimize eddy current losses.The alloy used in the laminations is selected for low hysteresis losses.

Theory of Operation

A short explanation of operation is that the stator creates a rotating magnetic field which drags the rotor around.

The theory of operation of induction motors is based on a rotating magnetic field. One means of creating a rotating magnetic field is to rotate a permanent magnet as shown in Figure below. If the moving magnetic lines of flux cut a conductive disk, it will follow the motion of the magnet. The lines of flux cutting the conductor will induce a voltage -- and consequent current flow 00 in the conductive disk.

This current flow creates an electromagnet whose polarity opposes the motion of the permanent magnet -- **Lenz's Law**. The polarity of the electromagnet is such that it pulls against the permanent magnet. The disk follows with a little less speed than the permanent magnet.



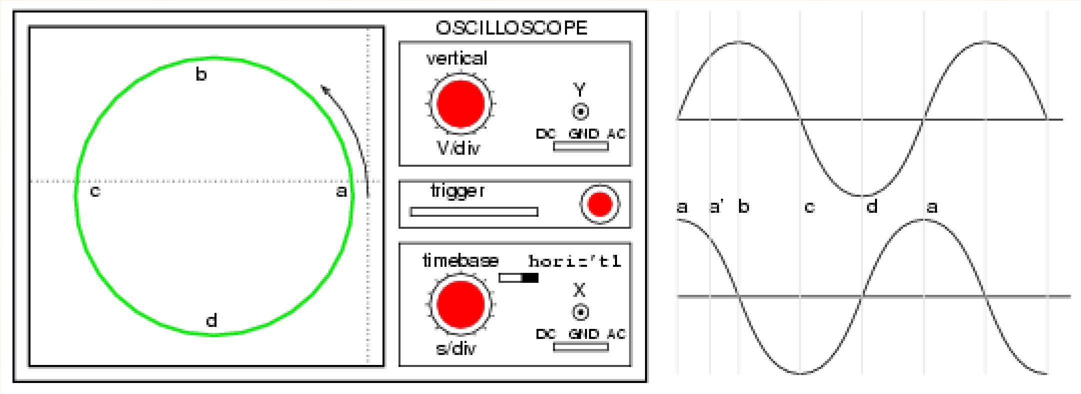
Rotating magnetic field produces torque in conductive disk

The torque developed by the disk is proportional to the number of flux lines cutting the disk and the rate at which it cuts the disk. If the disk were to spin at the same rate as the permanent magnet, there would be no flux cutting the disk, no induced current flow, no electromagnet field, no torque.

Thus, the disk speed will always fall behind that of the rotating permanent magnet so that lines of flux cut the disk induce a current and create an electromagnetic field in the disk, which follows the permanent magnet. If a load is applied to the disk, slowing it, more torque will be developed as more lines of flux cut the disk. Torque is proportional to slip, the degree to which the disk falls behind the rotating magnet. More slip corresponds to more flux cutting the conductive disk, developing more torque.

An analog automotive eddy current speedometer is based on the principle illustrated above. With the disk restrained by a spring, disk and needle deflection is proportional to magnet rotation rate.

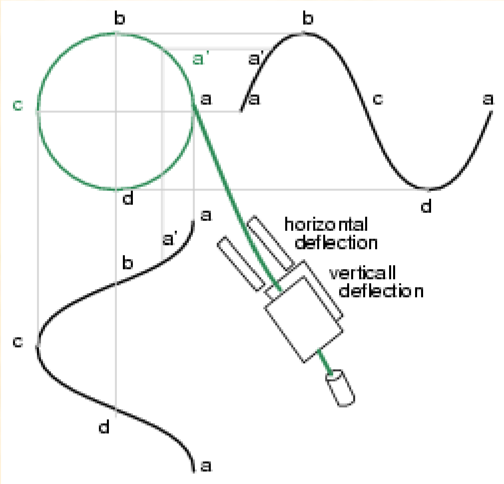
A rotating magnetic field is created by 2 coils placed at right angles to each other, driven by currents which are 90^o out-of-phase. This should not be surprising if you are familiar with oscilloscope *Lissajous* patterns.



Out-of-phase (90^o) sine waves produce circular Lissajous pattern

In Figure above, a circular *Lissajous* is produced by driving the horizontal and vertical oscilloscope inputs with 90^o out-of-phase sine waves. Starting at (a) with maximum "X" and minimum "Y" deflection, the trace moves up and left toward (b). Between (a) and (b), the two waveforms are equal to 0.707 V_{peak} at 45^o.

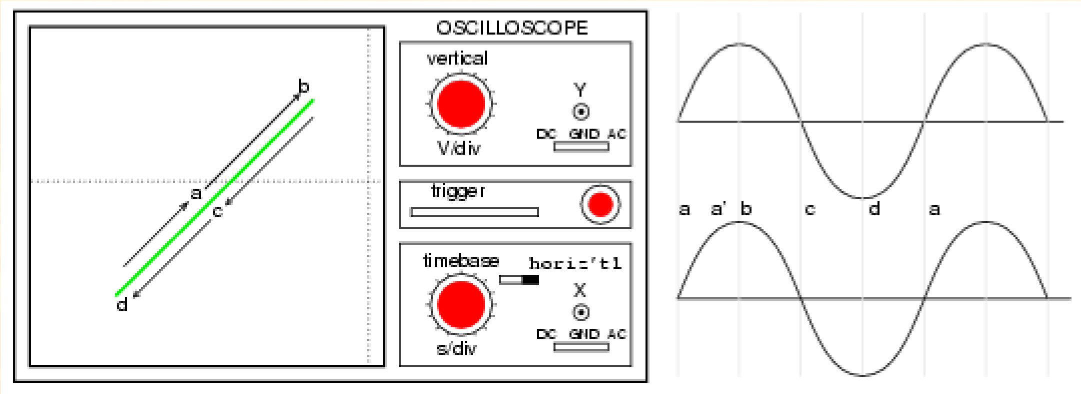
This point (0.707, 0.707) falls on the radius of the circle between (a) and (b) The trace moves to (b) with minimum "X" and maximum "Y" deflection. With maximum negative "X" and minimum "Y" deflection, the trace moves to (c). Then with minimum "X" and maximum negative "Y", it moves to (d), and on back to (a), completing one cycle.



X-axis sine and Y-axis cosine trace circle

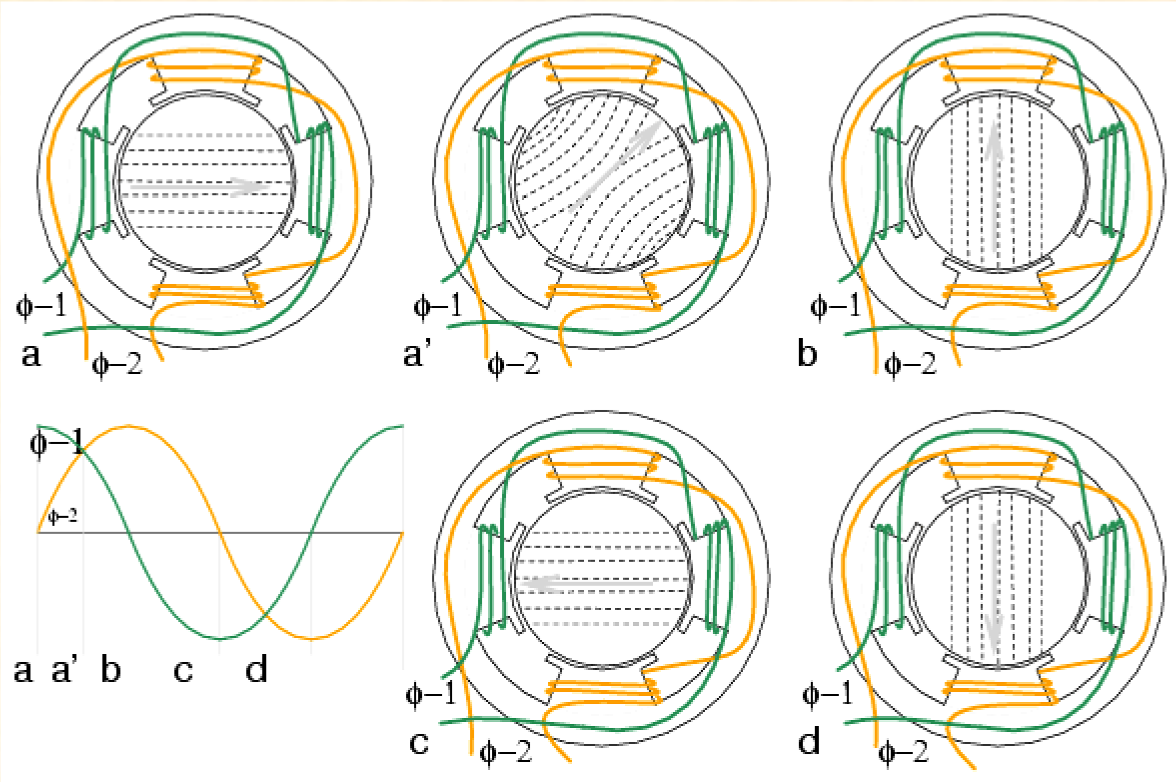
Figure above shows the two 90^o phase-shifted sine waves applied to oscilloscope deflection plates which are at right angles in space. If this were not the case, a one-dimensional line would display. The combination of 90^o phased sine waves and right angle deflection results in a 2-dimensional pattern -- a circle. This circle is traced out by a counter-clockwise rotating electron beam.

For reference, Figure below shows why in-phase sine waves will not produce a circular pattern. Equal "X" and "Y" deflection moves the illuminated spot from the origin at (a) up to right (1,1) at (b) … back down left to origin at (c) … down left to (-1.-1) at (d) … and back up right to origin. The line is produced by equal deflections along both axes; y=x is a straight line.



No circular motion from in-phase waveforms

If a pair of 90° out-of-phase sine waves produces a circular *Lissajous*, a similar pair of currents should be able to produce a circular rotating magnetic field. Such is the case for a 2-phase motor. By analogy, 3 windings placed 120° apart in space and fed with corresponding 120° phased currents will also produce a rotating magnetic field.



Rotating magnetic field from 90° phased sine waves

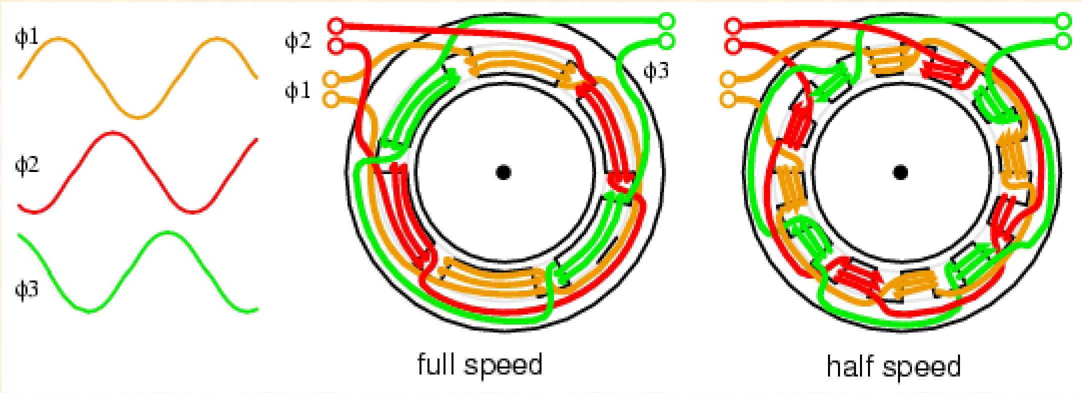
As the 90° phased sine waves (Figure above) progress from points (a) through (d), the magnetic field rotates counterclockwise (figures a-d) as follows:

- (a) φ-1 maximum, φ-2 zero
- (a') φ-1 70%, φ-2 70%
- (b) φ-1 zero, φ-2 maximum
- (c) φ-1 maximum negative, φ-2 zero
- (d) φ-1 zero, φ-2 maximum negative

Motor speed

The rotation rate of a stator rotating magnetic field is related to the number of pole pairs per stator phase. The "full speed" Figure below has a total of 6 poles or 3 pole-pairs and 3 phases. However, there is but one pole pair per phase -- the number we need. The magnetic field will rotate once per sine wave cycle.

In the case of 60 Hz power, the field rotates at 60 times per second or 3,600 revolutions per minute (rpm). For 50 Hz power, it rotates at 50 rotations per second or 3,000 rpm. The 3,600 and 3,000 rpm are the synchronous speed of the motor. Though the rotor of an induction motor never achieves this speed, it certainly is an upper limit. If we double the number of motor poles, the synchronous speed is cut in half because the magnetic field rotates 180^o in space for 360^o of electrical sine wave.



Doubling the stator poles halves the synchronous speed

The synchronous speed is given by:

$$\mathbf{N_s = 120 \cdot f/P}$$

where $\mathbf{N_s}$ = synchronous speed in rpm, **f** = frequency of applied power (Hz), and **P** = total number of poles per phase (a multiple of 2).

Example:

The "half speed" Figure above has 4 poles per phase (3-phase). The synchronous speed for 50 Hz power is:

$$\mathbf{S = 120 \cdot x\ 50/4 = 1500\ rpm}$$

The short explanation of the induction motor is that the rotating magnetic field produced by the stator drags the rotor around with it.

The longer more correct explanation is that the stator's magnetic field induces an alternating current into the rotor squirrel cage conductors which constitutes a transformer secondary. This induced rotor current in turn creates a magnetic field.

The rotating stator magnetic field interacts with this rotor field. The rotor field attempts to align with the rotating stator field. The result is rotation of the squirrel cage rotor. If there were no mechanical motor torque load, no bearing, windage, or other losses, the rotor would rotate at the synchronous speed.

However, the slip between the rotor and the synchronous speed stator field develops torque. It is the magnetic flux cutting the rotor conductors as it slips which develops torque. Thus, a loaded motor will slip in proportion to the mechanical load. If the rotor were to run at synchronous speed, there would be no stator flux cutting the rotor, no current induced in the rotor, no torque.

Torque

When power is first applied to the motor, the rotor is at rest while the stator magnetic field rotates at the synchronous speed N_s. The stator field is cutting the rotor at the synchronous speed Ns. The current induced in the rotor shorted turns is maximum as is the frequency of the current (the line frequency).

As the rotor speeds up, the rate at which stator flux cuts the rotor is the difference between synchronous speed N_s and actual rotor speed N (or N_s - N). The ratio of actual flux cutting the rotor to synchronous speed is defined as **slip**:

$$\mathbf{s = (N_s - N) / N_s}$$

where $\mathbf{N_s}$ = synchronous speed, **N** = rotor speed.

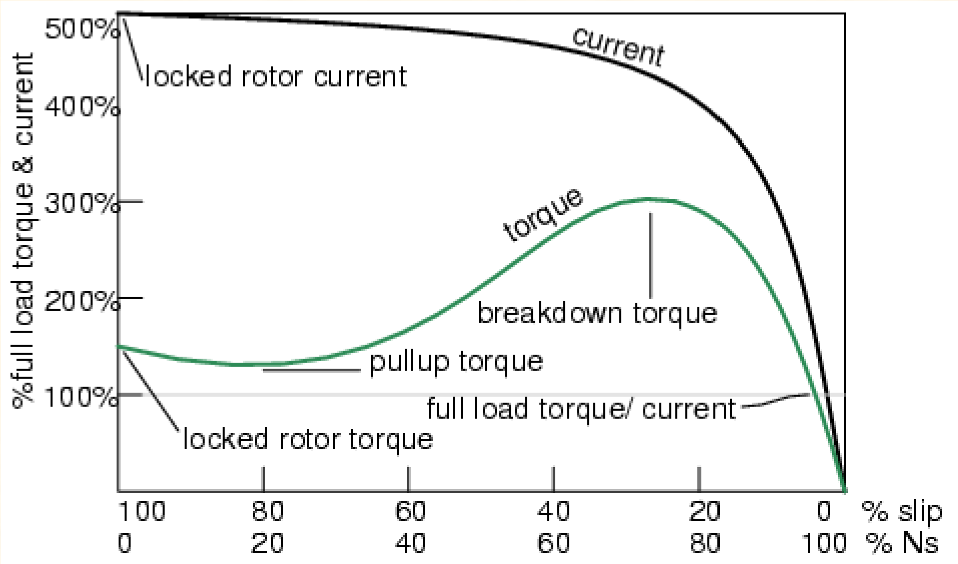
The frequency of the current induced into the rotor conductors is only as high as the line frequency at motor start, decreasing as the rotor approaches synchronous speed. **Rotor frequency** is given by:

$$\mathbf{f_r = s \cdot f}$$

where **s** = slip, **f** = stator power line frequency.

Slip at 100% torque is typically 5% or less in induction motors. Thus for f = 50 Hz line frequency, the frequency of the induced current in the rotor $f_r = 0.05 \cdot x\ 50 = 2.5$ Hz.

Why is it so low? The stator magnetic field rotates at 50 Hz. The rotor speed is 5% less. The rotating magnetic field is only cutting the rotor at 2.5 Hz. The 2.5 Hz is the difference between the synchronous speed and the actual rotor speed. If the rotor spins a little faster, at the synchronous speed, no flux will cut the rotor at all ($f_r = 0$).



Torque and speed vs %Slip. %N_s=%Synchronous Speed

The Figure above graph shows that starting torque known as **Locked Rotor Torque** (LRT) is higher than 100% of the **Full Load Torque** (FLT) -- the safe continuous torque rating. The Locked Rotor Torque is about 175% of FLT for the example motor graphed above. Starting current known as **Locked Rotor Current** (LRC) is 500% of **Full Load Current** (FLC) -- the safe running current. The current is high because this is analogous to a shorted secondary on a transformer.

As the rotor starts to rotate, the torque may decrease a bit for certain classes of motors to a value known as the **Pull-Up Torque**. This is the lowest value of torque ever encountered by the starting motor. As the rotor gains 80% of synchronous speed, torque increases from 175% up to 300% of the Full Load Torque. This **breakdown torque** is due to the larger than normal 20% slip. The current has decreased only slightly at this point. But it will decrease rapidly beyond this point.

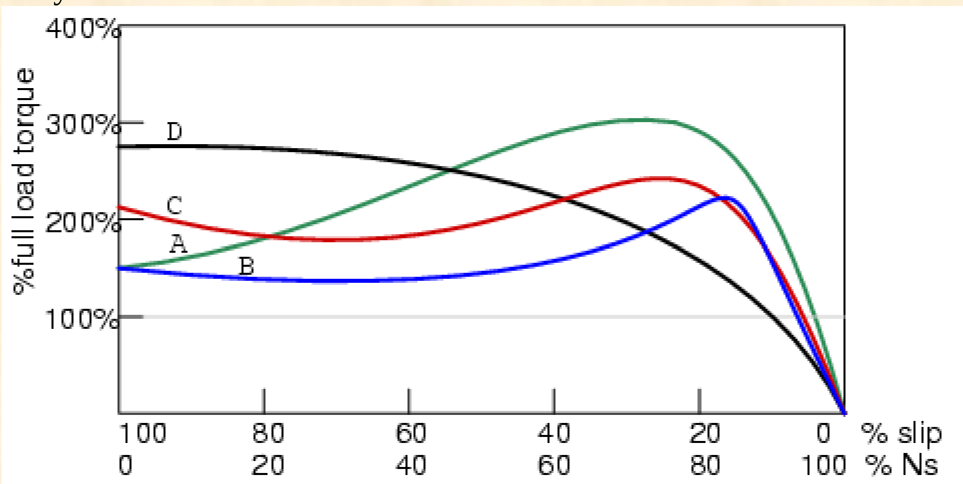
As the rotor accelerates to within a few percent of synchronous speed, both torque and current will decrease substantially. Slip will be only a few percent during normal operation. For a running motor, any portion of the torque curve below 100% rated torque is normal. The motor load determines the operating point on the torque curve.

While the motor torque and current may exceed 100% for a few seconds during starting, continuous operation above 100% can damage the motor. Any motor torque load above the breakdown torque will stall the motor. The torque, slip, and current will approach zero for a "no mechanical torque" load condition. This condition is analogous to an open secondary transformer.

There are several basic induction motor designs (Figure below) showing considerable variation from the torque curve above. The different designs are optimized for starting and running different types of loads. The Locked Rotor Torque (LRT) for various motor designs and sizes ranges from 60% to 350% of Full Load Torque (FLT). Starting current or locked rotor current (LRC) can range from 500% to 1400% of full load current (FLC). This current draw can present a starting problem for large induction motors.

NEMA design classes

Various standard classes (or designs) for motors, corresponding to the torque curves (Figure below) have been developed to better drive various type loads. The National Electrical Manufacturers Association (NEMA) has specified motor classes A, B, C, and D to meet these drive requirements. Similar International Electrotechnical Commission (IEC) classes N and H correspond to NEMA B and C designs respectively.



Characteristics for NEMA designs.

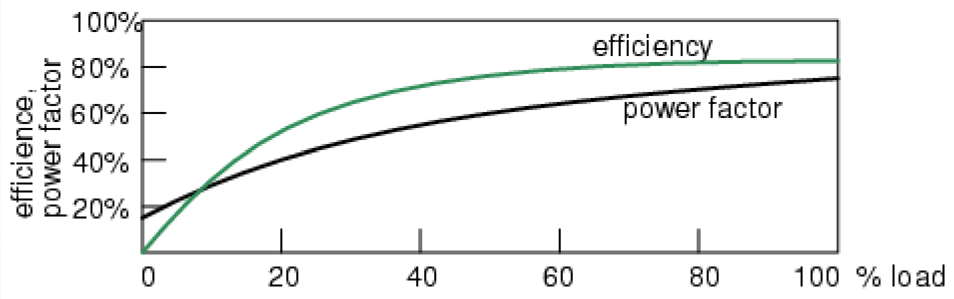
All motors except class D operate at %5 slip or less at full load.

- **Class B (IEC Class N)** motors are the default motor to use in most applications. With a starting torque of LRT = 150% to 170% of FLT, it can start most loads without excessive starting current (LRT). Efficiency and power factor are high. It typically drives pumps, fans, and machine tools.
- **Class A** starting torque is the same as Class B. Drop out torque and starting current (LRT) are higher. This motor handles transient overloads as encountered in injection molding machines.
- **Class C (IEC Class H)** has higher starting torque than class A and B at LRT = 200% of FLT. This motor is applied to hard-starting loads which need to be driven at constant speed like conveyors, crushers, and reciprocating pumps and compressors.
- **Class D** motors have the highest starting torque (LRT) coupled with low starting current due to high slip (5% to 13% at FLT). The high slip results in lower speed. Speed regulation is poor. However, the motor excels at driving highly variable speed loads like those requiring an energy storage flywheel. Applications include punch presses, shears, and elevators.
- **Class E** motors are a higher efficiency version of Class B.
- **Class F** motors have much lower LRC, LRT, and break down torque than Class B. They drive constant easily-started loads.

Power factor

Induction motors present a lagging (inductive) power factor to the power line. The power factor in large fully loaded high speed motors can be as favorable as 90% for large high speed motors. At ¾ full-load, the largest high speed motor power factor can be 92%. The power factor for small low-speed motors can be as low as 50%. At starting, the power factor can be in the range of 10% to 25%, rising as the rotor achieves speed.

Power factor (PF) varies considerably with the motor mechanical load (Figure below). An unloaded motor is analogous to a transformer with no resistive load on the secondary. Little resistance is reflected from the secondary (rotor) to the primary (stator). Thus the power line sees a reactive load as low as 10% PF. As the rotor is loaded an increasing resistive component is reflected from rotor to stator, increasing the power factor.



Induction motor power factor and efficiency

Efficiency

Large 3-phase motors are more efficient than smaller 3-phase motors and most all single phase motors. Large induction motor efficiency can be as high as 95% at full load, though 90% is more common. Efficiency for a lightly load or no-loaded induction motor is poor because most of the current is involved with maintaining magnetizing flux.

As the torque load is increased, more current is consumed in generating torque while current associated with magnetizing remains fixed. Efficiency at 75% FLT can be slightly higher than that at 100% FLT. Efficiency is decreased a few percent at 50% FLT and decreased a few more percent at 25% FLT. Efficiency only becomes poor below 25% FLT. The variation of efficiency with loading is shown in Figure above.

Induction motors are typically oversized to guarantee that their mechanical load can be started and driven under all operating conditions. If a poly-phase motor is loaded at less than 75% of rated torque where efficiency peaks, efficiency suffers only slightly down to 25% FLT.

<u>Nola power factor corrector</u>

Frank Nola of NASA proposed a power factor corrector (PFC) as an energy saving device for single phase induction motors in the late 1970s. It is based on the premise that a less than fully-loaded induction motor is less efficient and has a lower power factor than a fully loaded motor. Thus, there is energy to be saved in partially loaded motors (1-φ motors in particular).

The energy consumed in maintaining the stator magnetic field is relatively fixed with respect to load changes. While there is nothing to be saved in a full- loaded motor, the voltage to a partially-loaded motor may be reduced to decrease the energy required to maintain the magnetic field. This will increase power factor and efficiency. This was a good concept for the notoriously inefficient single-phase motors for which it was intended.

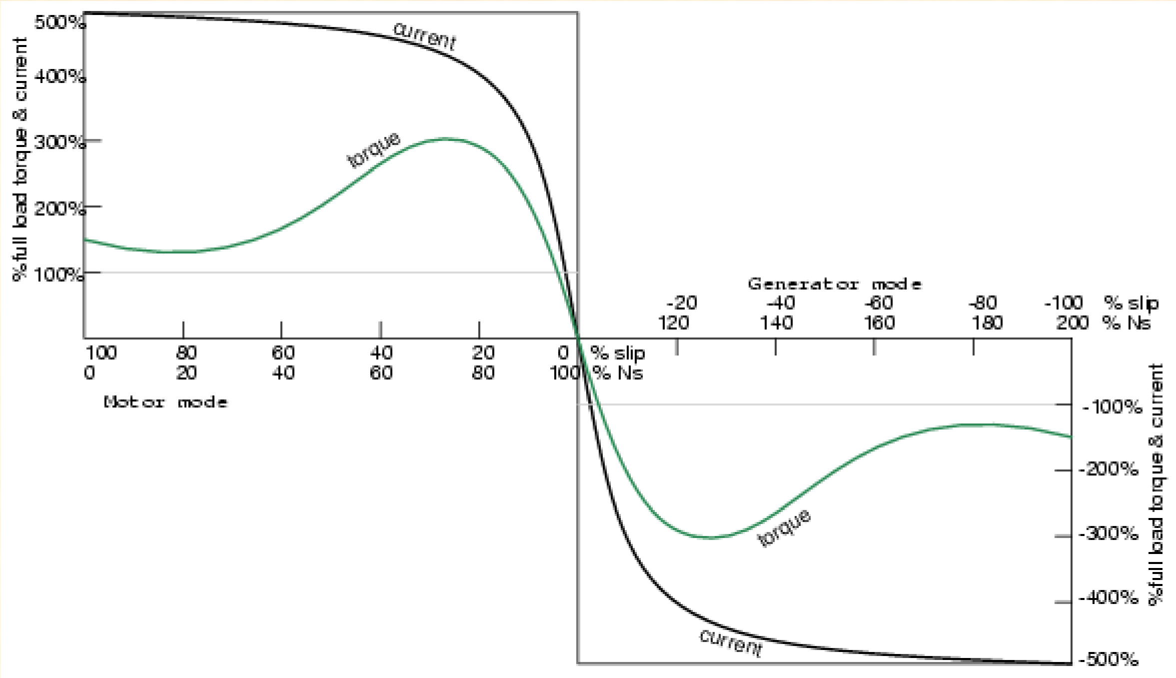
This concept is not very applicable to large 3-phase motors. Because of their high efficiency (90^{+}%), there is not much energy to be saved. Moreover, a 95% efficient motor is still 94% efficient at 50% full-load torque (FLT) and 90% efficient at 25% FLT. The potential energy savings in going from 100% FLT to 25% FLT is the difference in efficiency 95% - 90% = 5%. This is not 5% of the full load wattage but 5% of the wattage at the reduced load.

The Nola power factor corrector might be applicable to a 3-phase motor which idles most of the time (below 25% FLT) -- like a punch press. The payback period for the expensive electronic controller has been estimated to be unattractive for most applications, although it might be economical as part of an electronic motor starter or speed control.

<u>Induction motor alternator</u>

An induction motor may function as an alternator if it is driven by a torque at greater than 100% of the synchronous speed (Figure below). This corresponds to a few % of "negative" slip (say, -1% slip).

This means that as we are rotating the motor faster than the synchronous speed, the rotor is advancing 1% faster than the stator rotating magnetic field. It normally lags by 1% in a motor. Since the rotor is cutting the stator magnetic field in the opposite direction (leading), the rotor induces a voltage into the stator feeding electrical energy back into the power line.



Negative torque makes induction motor into generator

Such an **induction generator** must be excited by a "live" source of 50 or 60 Hz power. No power can be generated in the event of a power company power failure. This type of alternator appears to be unsuited as a standby power source. As an auxiliary power wind turbine generator, it has the advantage of not requiring an automatic power failure disconnect switch to protect repair crews. It is fail-safe.

Small remote (from the power grid) installations may be make self-exciting by placing capacitors in parallel with the stator phases. If the load is removed residual magnetism may generate a small amount of current flow. This current is allowed to flow by the capacitors without dissipating power. As the generator is brought up to full speed, the current flow increases to supply a magnetizing current to the stator. The load may be applied at this point. Voltage regulation is poor. An induction motor may be converted to a self-excited generator by the addition of capacitors.

Start-up procedure is to bring the wind turbine up to speed in motor mode by application of normal power line voltage to the stator. Any wind-induced turbine speed in excess of synchronous speed will develop negative torque, feeding power back into the power line and reversing the normal direction of the electric kilowatt-hour meter.

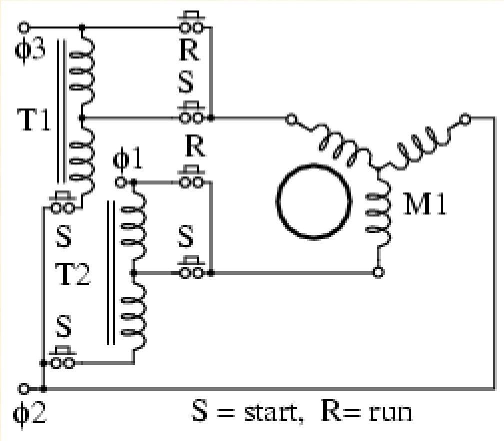
Whereas an induction motor presents a lagging power factor to the power line, an induction alternator presents a leading power factor. Induction generators are not widely used in conventional power plants. The speed of the steam turbine drive is steady and controllable as required by synchronous alternators. Synchronous alternators are also more efficient.

The speed of a wind turbine is difficult to control and subject to wind speed variation by gusts. An induction alternator is better able to cope with these variations due to the inherent slip. This stresses the gear train and mechanical components less than a synchronous generator.

However, this allowable speed variation only amounts to about 1%. Thus, a direct line connected induction generator is considered to be fixed-speed in a wind turbine. See **Doubly-fed induction generator** for a true variable speed alternator. Multiple generators or multiple windings on a common shaft may be switched to provide a high and low speed to accommodate variable wind conditions.

Motor starting and speed control

Some induction motors can draw over 1,000% of full-load current during starting (though a few hundred percent is more common). Small motors of a few kilowatts or smaller can be started by direct connection to the power line. Starting larger motors can cause line voltage sag, affecting other loads. Motor-start rated circuit breakers (analogous to "slow blow" fuses) should replace standard circuit breakers for starting motors of a few kilowatts. This breaker accepts high over-current for the duration of starting.



Autotransformer induction motor starter

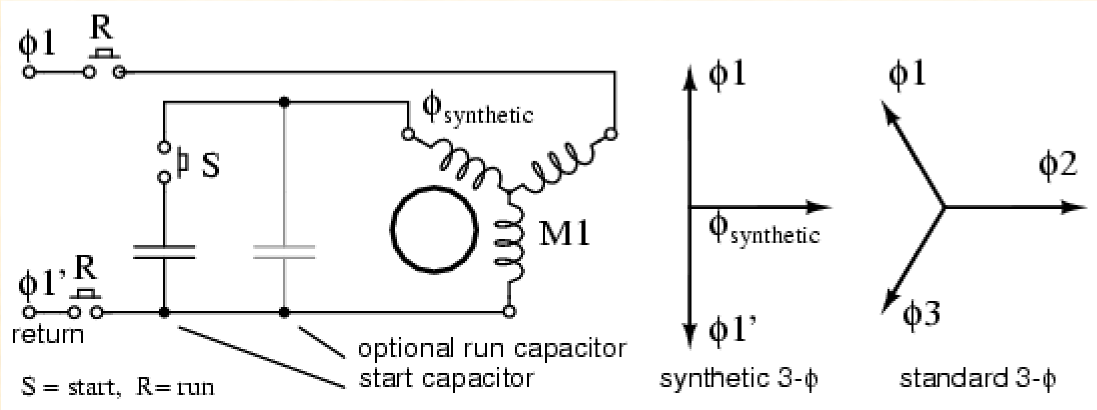
Motors over 50 kW use motor starters to reduce line current from several hundred to a few hundred percent of full-load current. An intermittent duty autotransformer may reduce the stator voltage for a fraction of a minute during the start interval, followed by application of full line voltage as in Figure above.

Closure of the S contacts applies reduced voltage during the start interval. The S contacts open and the R contacts close after starting. This reduces starting current to, say, 200% of full-load current. Since the autotransformer is only used for the short start interval, it may be sized considerably smaller than a continuous duty unit.

Running 3-phase motors on 1-phase

3-phase motors will run on single phase as readily as single-phase motors. The only problem for either motor is starting.

Sometimes 3-phase motors are purchased for use on single-phase if 3-phase power is anticipated. The power rating needs to be 50% larger than for a comparable single phase motor to make up for one unused winding. Single phase is applied to a pair of windings simultaneous with a start capacitor in series with the third winding. The start switch is opened in Figure below upon motor start. Sometimes a smaller capacitor than the start capacitor is retained while running.

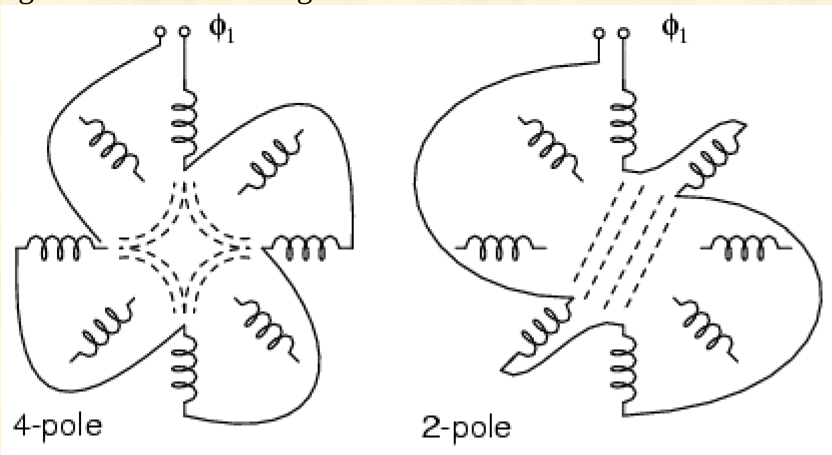


Starting a 3-phase motor on single phase

The circuit for running a 3-phase motor on single phase is known as "add a phase" or various other brand names. "Add a phase" supplies a phase approximately midway 90^o between the 180^o single-phase power source terminals.

Multiple fields

Induction motors may contain multiple field windings. For example, a 4-pole and an 8-pole winding corresponding to 1,800 and 900 rpm synchronous speeds. Energizing one field or the other is less complex than rewiring the stator coils in Figure below.



Multiple fields allow speed change

If the field is segmented with leads brought out, it may be rewired (or switched) from 4-pole to 2-pole as shown above for a 2-phase motor. The 22.5^o segments are switchable to 45^o segments. Only the wiring for one phase is shown above for clarity.

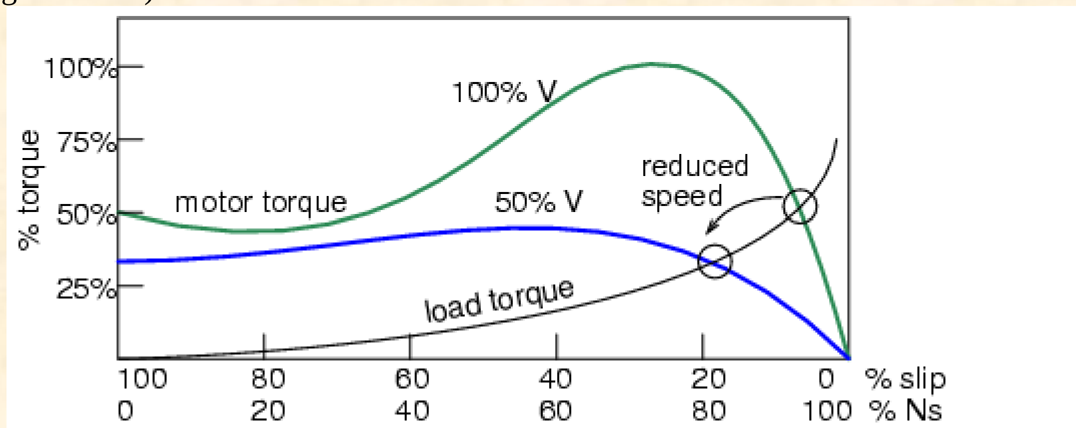
Thus, our induction motor may run at multiple speeds. When switching the above 60 Hz motor from 4 poles to 2 poles, the synchronous speed increases from 1,800 rpm to 3,600 rpm. I f the motor is driven by 50 Hz, what would be the corresponding 4-pole and 2-pole synchronous speeds?

N_s = 120 f/P = 120 x 50/4 = 1,500 rpm (4-pole)

N_s = 3,000 rpm (2-pole)

Variable voltage

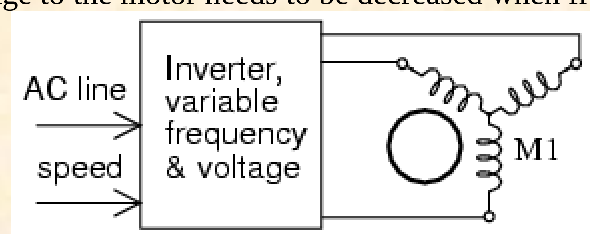
The speed of small squirrel cage induction motors for applications such as driving fans may be changed by reducing the line voltage. This reduces the torque available to the load which reduces the speed. (Figure below).



Variable voltage controls induction motor speed

Electronic speed control

Modern solid-state electronics increase the options for speed control. By changing the 50 or 60 Hz line frequency to higher or lower values, the synchronous speed of the motor may be changed. However, decreasing the frequency of the current fed to the motor also decreases reactance X_L which increases the stator current. This may cause the stator magnetic circuit to saturate with disastrous results. In practice, the voltage to the motor needs to be decreased when frequency is decreased.



Electronic variable speed drive

Conversely, the drive frequency may be increased to increase the synchronous speed of the motor. However, the voltage needs to be increased to overcome increasing reactance to keep current up to a normal value and maintain torque. The inverter (Figure above) approximates sinewaves to the motor with pulse width modulation outputs. This is a chopped waveform which is either 'on' or 'off', 'high' or 'low' with the percentage of 'on' time corresponds to the instantaneous sine wave voltage.

Once electronics is applied to induction motor control, many control methods are available varying from the simple to complex:

Summary: Speed control

- **Scalar Control** -- Low-cost method described above to control only voltage and frequency without feedback.
- **Vector Control** (also known as vector phase control) -- The flux and torque producing components of stator current are measured or estimated on a real-time basis to enhance the motor torque-speed curve. This is computation-intensive.
- **Direct Torque Control** -- An elaborate adaptive motor model allows more direct control of flux and torque without feedback. This method quickly responds to load changes.

Summary -- Tesla Poly-Phase Induction Motors

- A **poly-phase induction motor** consists of a polyphase winding embedded in a laminated stator and a conductive squirrel cage embedded in a laminated rotor.
- 3-phase currents flowing within the stator create a rotating magnetic field which induces a current, and consequent magnetic field in the rotor. Rotor torque is developed as the rotor slips a little behind the rotating stator field.
- Unlike single-phase motors, poly-phase induction motors are **self-starting**.
- **Motor starters** minimize loading of the power line while providing a larger starting torque than required during running. Starters are only required for large motors.
- **Multiple field windings** can be rewired for multiple discrete motor speeds by changing the number of poles.

Linear Induction Motor

The wound stator and the squirrel cage rotor of an induction motor may be cut at the circumference and unrolled into a linear induction motor. The direction of linear travel is controlled by the sequence of the drive to the stator phases.

The linear induction motor has been proposed as a drive for high-speed passenger trains. Up to this time, the linear induction motor with the accompanying **magnetic repulsion levitation** system required for a smooth ride has been too costly for all but experimental installations. However, the linear induction motor is scheduled to replace steam driven catapult aircraft launch systems on the next generation of naval aircraft carrier (CVNX-1) in 2013. This will increase efficiency and reduce maintenance. … … … … …

[continued at http://electojects.com/motors/wound-rotor-induction-motors.htm]

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