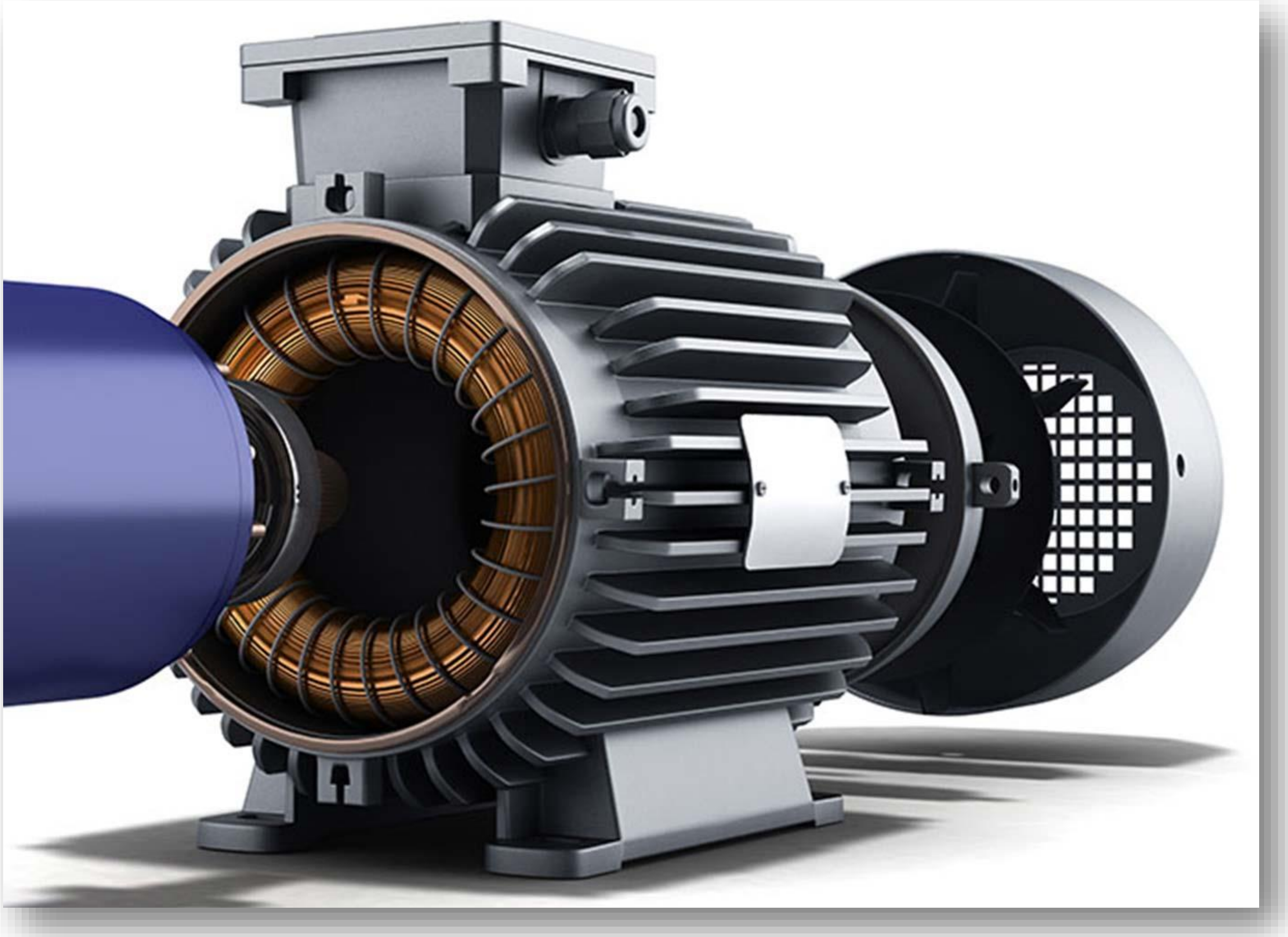
THE THREE-PHASE INDUCTION MACHINE AS MOTOR AND GENERATOR



Picture credit: Induction Generator An Ultimate Guide, www.linquip.com

John Cowdrey

hydroman303@msn.com

THE THREE-PHASE INDUCTION MACHINE AS MOTOR AND GENERATOR

John Cowdrey

PART ONE. THE INDUCTION MOTOR

DC machine shortcomings. By 1886 DC motors had reached a stage of development where they were in widespread use, especially in traction (streetcar) applications, elevators, and industry. They had high starting and running torque and good speed control. In March 1888, Nikola Tesla gave a lecture to the AIEE titled "A New System of Alternate Current Motors and Transformers." First, he explained the shortcomings of the commutators used in DC machines. A commutator is a high-speed rotary switch that periodically reverses the current direction. It is basically a mechanical full-wave rectifier. He described the DC machine's commutator as an "unreliable device" and "the source of most of the troubles experienced in the operation of the machines". The DC currents produced by the generator's commutator "cannot be utilized in the motor, but they must -- again by means of a similar unreliable device -- be reconverted into their original state of alternate currents ". "In reality, therefore, all machines are alternate current machines, the currents appearing as continuous only in the external circuit during their transit from generator to motor". His goal was to eliminate the troublesome commutator. But he noted that the DC commutator provided a vital motor function – it produced a progressive shifting or rotation of the poles. This shifting must somehow be maintained in his commutator-less motor to cause rotation [1].

Single-phase -- The double revolving field theory. Inventors initially constructed AC motors like DC motors, but numerous problems were encountered due to lack of starting torque. The double revolving field theory states that for a two-pole machine, the mmf of a single-phase winding excited by a source of alternating current can be resolved into two oppositely rotating (traveling) waves F^+ and F^-. Each traveling wave is trying to rotate the machine in the opposite direction. So, with single phase AC excitation of an induction motor, the resultant magnetic field is the phasor sum of F^+ and F^-. It pulsates -

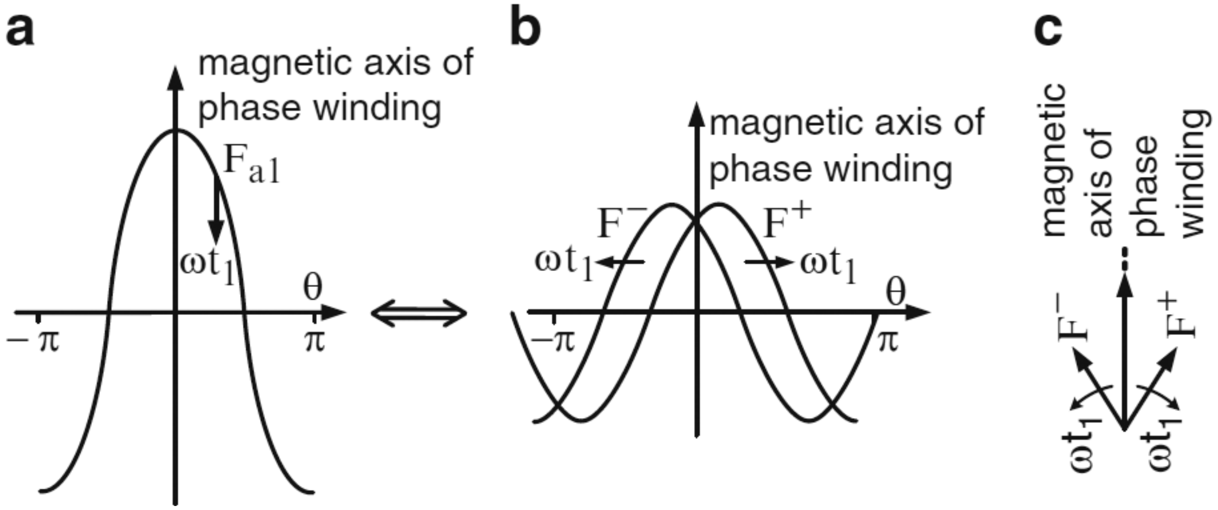


Figure 1 -- A single phase alternating wave decomposed into forward and backward travelling waves. [2]

- grows and shrinks in strength -- but does not rotate [2]. The torque speed curve for a single-phase induction machine can be drawn as the sum of two torque speed curves - one trying to drive the machine in the forward direction, one trying to drive the machine backwards. At standstill with two equal and opposing rotating fields, the net torque will be zero. This idea is shown in Fig. 2. However, if the rotor is pushed, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to rated speed, but the single-phase motor is not self-starting.

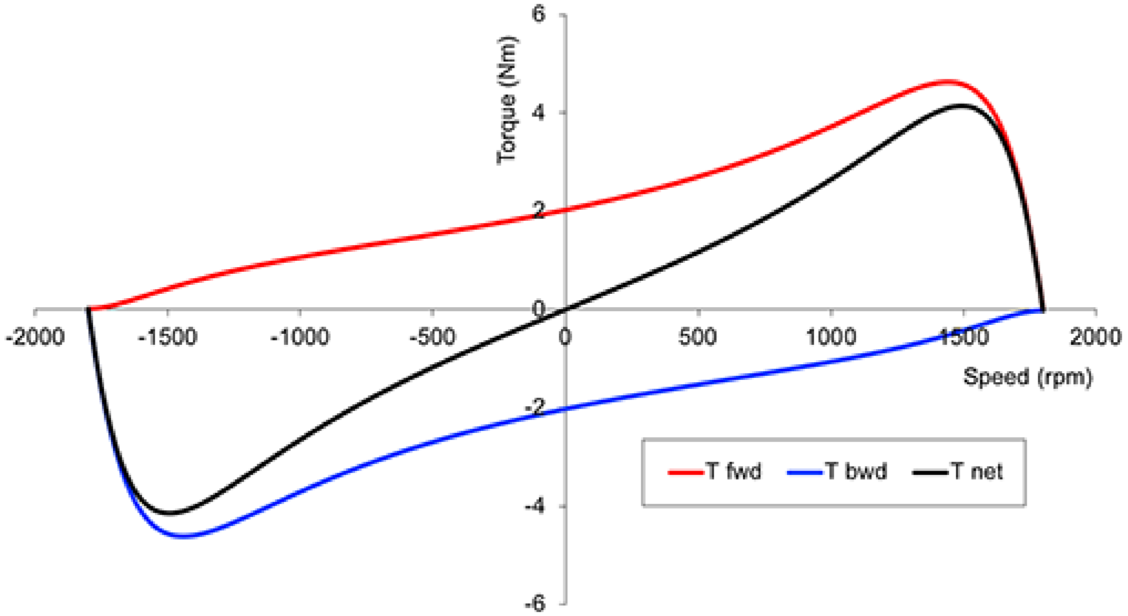
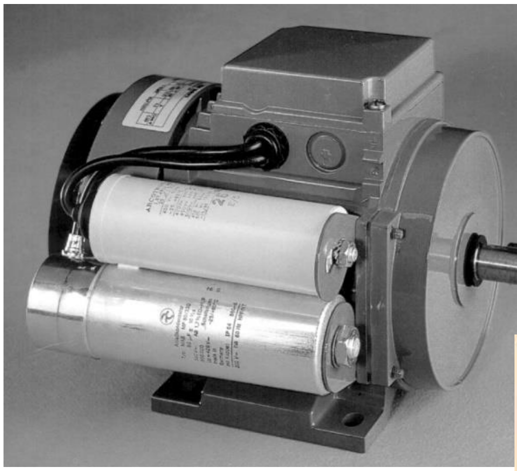


Figure 2 -- Forward and backward single-phase induction motor torques, and the resultant. Source:**Single-Phase Induction Machines, Dr. Andy Knight, University of Calgary. https://people.ucalgary.ca/~aknigh/electrical_machines/other/spim.html**

Starting the single-phase motor. The single-phase induction motor must have a second starting or running winding with a phase difference from the main winding. Several methods can provide this produced rotating field – split phase, capacitor start-induction run, capacitor start and run, and shaded pole. With capacitor start motor, a start winding, capacitor and centrifugal switch are connected in



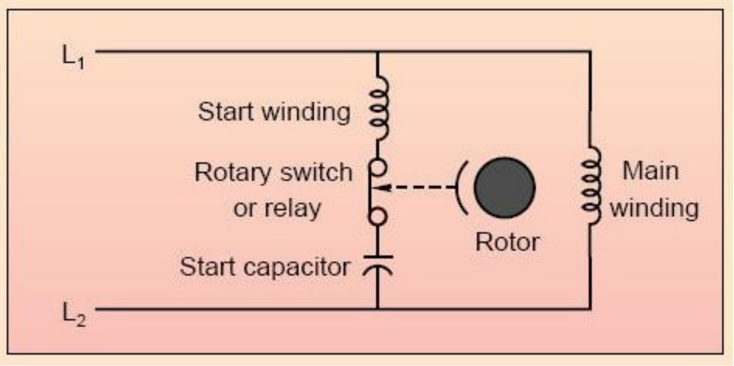


Figure 3 -- Capacitor start run induction motor and capacitor start schematic.
Picture credit Studyelectrical.com and ABB

parallel with the main winding, which will make about an 80° phase difference when the switch is closed and current flows through both coils. With this phase difference, the rotor will generate a starting torque and it will start to rotate. When the motor reaches about 75% of the full load speed, the centrifugal switch opens and disconnects the starter winding and the capacitor from the main winding. Single-phase motors are typically less than 1 horsepower.

The performance of a 3-phase motor is superior in every respect to a single-phase for the same frame size. It has a higher maximum torque at lower slip and the losses are lower. In a single-phase motor, a single main or running winding carries all the current so stator copper-losses are higher. Further, the backward rotating field in a single-phase motor consumes volt-amperes without producing useful forward torque. All this results in single-phase motors having larger frame size, lower efficiency and higher temperature rise for a given power and speed rating. However, most motors manufactured are single-phase since the standard household power is single-phase.

Polyphase power and the rotating field. For a motor, the requirement is to maintain a uniform smooth magnetic field rotation, which minimizes torque pulsations in a motor. In March 1888, Italian professor Galileo Ferraris published a paper showing that producing two alternating currents of the same amplitude and frequency but with a phase displacement of 90°, produced a steadily revolving magnetic field. Independently, and at about the same time, Nikola Tesla filed his first patent for a two-phase induction motor in November 1887, which patent was granted in May 1888. This patent application showed how a polyphase system could produce a rotating magnetic field [3]. For two- or three-phase power, the negative-traveling (rotating) flux (mmf) waves of the three windings add up to zero while the positive-traveling mmf waves reinforce (add up), giving a single positive traveling (rotating) circular mmf (flux) wave. [2]

A polyphase system has two or more alternating current phases with a phase angle between the voltages in those phases. In his lecture, Tesla then explained the theory behind his two-phase induction motor invention. He accomplished the desired magnetic field rotation by generating two voltages with a one-quarter cycle or 90° phase difference between them, and by applying these two independent sinusoidal voltages to two independent motor windings separated in space by the same 90^o. The stator's electric energy is converted into magnetic energy. The magnetic energy travels through the air gap of the motor. By this method, a smoothly rotating magnetic field of constant magnitude and a varying direction is produced without the need for the DC machine's commutator. Physically, the stator is not moving. It is the magnetic field created within the stator that is moving at synchronous speed [5]. Furthermore, Tesla noted that his motor could be very rapidly reversed "if the connections of either one of the circuits in the ring are reversed" [1]. Since the two circuits were independent, two separate circuits and four wires, two for each phase, were required, although two of the wires could be combined into a common conductor if the ampacity of the single wire was increased by 1.414 times.

This **rotating magnetic field** is a key requirement for the operation of the induction machine. The basic idea of any AC electric motor, synchronous or induction, is to use this stator magnetic field, which originates from the stator currents, and which rotates at a synchronous speed that is dictated by the number of poles of the motor and the power system frequency. Then a second magnetic field is generated in the rotor. The rotor will constantly be trying to align its magnetic field with that of the stator field. In the induction motor, an emf is induced in the rotor from the rotating magnetic field of the stator winding, which produces a current in the rotor. This rotor current sets up the second field.

The motor's actual field is a combination of these two fields. The stator field, interacting with the second field induced in the rotor, supplies torque in the direction of the rotating stator magnetic field, which drives the motor. The action of the induction machine is the same as a transformer with a shorted secondary winding. Unlike the transformer, however, the rotor current's frequency is different from the stator current's frequency due to slip, which is discussed later. The rotor's voltage is also slip-dependent. Since the secondary winding, the rotor, is shorted, there is no electrical output, only mechanical torque. Tesla and other early inventors preferred two-phase power to the three-phase system we use today. In a three-phase motor, three AC voltage waveforms 120º out of phase in time are applied to three-phase armature windings 120º out of phase in space.

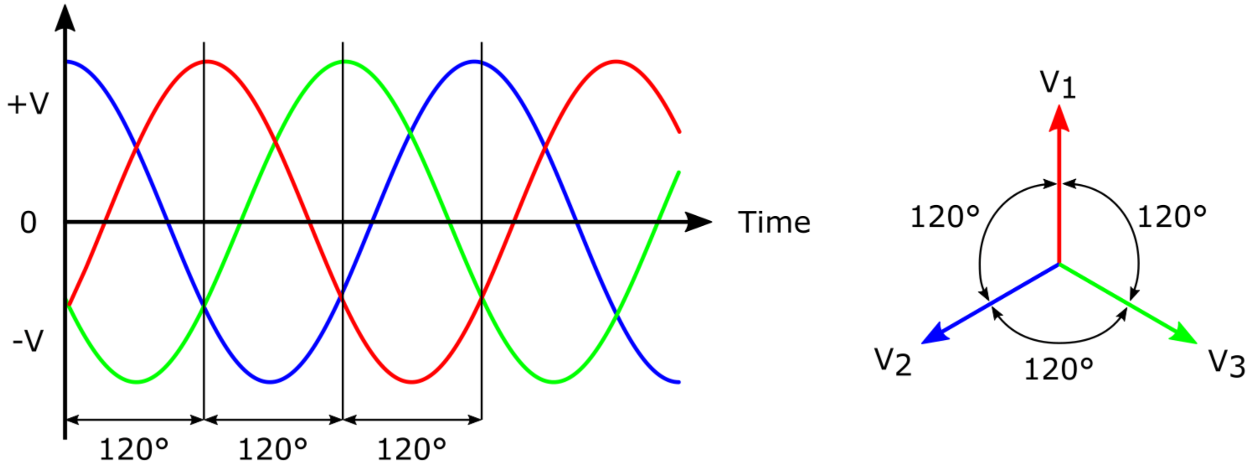


Figure 4 -- A balanced three-phase power system. *Credit: Savree.com*

Thomas Blalock in his IEEE paper *The First Polyphase System*, states that "the theoretical complexity of the superior three-phase system delayed its complete acceptance in the early days of electric power system development. During the early 1890s, understanding the behavior of simple single-phase ac was enough of a challenge. It was not until Charles P. Steinmetz, the legendary General Electric scientist, developed the concept of the use of the "j" operator (unity magnitude at a 90°phase angle) and complex numbers for ac circuit calculations that the behavior of voltages and currents in ac circuits and machines was truly understandable.

Likewise, it was not until the introduction of what eventually came to be known as "symmetrical components," during the early 20th century, that the calculation of three-phase voltages and currents became relatively straightforward. This technique utilized an "a" operator that was of unity magnitude at a 120° phase angle (–0.5 +j0.866). This operator was of significant value since, in a balanced three phase system, the voltages and currents are at 120° phase relationships to each other" [4].

Induction motor advantages and disadvantages.

The three-phase induction motor, the "workhorse of the industry", is the simplest of all motors. According to the U.S. Department of Energy (DoE), 70% of electricity is used by industrial motors, and in a typical industry 80% of the load consists of three-phase AC induction motors. It is usually a singly excited machine, as opposed to the doubly excited synchronous machine.

Induction Machine advantages:

- Simple, inexpensive, rugged design.
- Low cost and reliable –needs minimal maintenance.
- Good efficiency.
- Self-starting.
- No excitation equipment and no brushes, except for the wound-rotor design. Can be used in explosive environments – no sparking.
- Extremely reliable.
- Low speed droop -- it runs at nearly constant speed from zero to full load. Variable speed operation possible with a Variable Speed Drive (VFD) or wound-rotor design.
- Direct connection to an AC power source.

Induction Machine Disadvantages:

- Lagging power factor.
- High inrush current. Nominally six times the full-load current. A soft starter can be used.
- It is essentially a constant speed motor, unless a VFD or wound rotor is used. Note that this induction motor characteristic – essentially constant speed-- is an advantage or a disadvantage depending on whether variable speed is desired.
- Lower efficiency than synchronous motor.
- Starting is abrupt, unless a VFD or soft starter is used. VFD soft-start capability reduces the inrush current at motor start-up, thus improving motor performance and reducing stress on the motor.
- Its starting torque is less than a dc motor – not good for high-inertia loads, like traction applications (motors used for propulsion of a vehicle).

Motor and Generator construction. Induction generators and motors are made up of two principal parts, the **armature,** and the **field**. The armature carries alternating currents and, by its interaction with the field, generates electrical power in a generator, and absorbs power to produce a rotating torque when operated a motor. The magnetic iron structure of a motor's rotor or stator is called the core.

Figure 5 -- Rotor laminations on the left, the finished AC induction motor rotor with bearings pressed on the shaft, and the squirrel cage [43].

Why rotate the field? Motors and generators can be built either with a stationary armature and a rotating field or a rotating armature and a stationary field. Due to the need for a mechanical rotating commutator to change AC to DC, early DC machines used a stationary field, and rotated the armature and commutator together on a common shaft. Early AC machines, evolving from these DC designs, used this same arrangement (with slip rings on the output voltage instead of the commutator). Today, the low-power field circuit is mounted on the rotating shaft, so it is often called the rotor. The shaft extends through the motor housing and passes the rotor's rotating torque to drive a given piece of machinery. We keep the high-power armature (stator) stationary. The advantages of having the low-power field circuit rotate and keeping the high-power armature stationary are:

- Stationary armature coils can be braced more easily to withstand short-circuit currents.
- Direct connection to the external circuit permits higher voltages and load currents. It is difficult to make efficient high-voltage high-power connections through slip rings.
- The low-voltage field has less insulation and is therefore easier to balance.

The machine's steel core. The most common material for electrical machine applications consists of circular laminations punched out of electrical-grade non-oriented silicon iron (NO SiFe), usually with a thickness of 0.3 mm to 1 mm for power-frequency devices. Non-oriented means that the material has the same permeability when measured in different directions. Other metals can be added to the iron silicon alloy such as aluminum, nickel, cobalt, vanadium to adjust the material's properties [6].

Iron loss (heating) of the material is a key factor in the machine design. The main components of iron loss are the hysteresis loss due to the change of magnetization, and the eddy current loss from induced voltages in the electrically conducting magnetic steel. Whereas the hysteresis loss increases linearly with the frequency and thus the speed of the machine, the eddy current loss increases with the square of the frequency and thus machine speed. The laminations limit the eddy current losses in the steel due to the alternating flux that the core carries. Lower iron losses not only increase machine efficiency, but they also reduce the necessary heat dissipation and cooling system of the machine [6]. Recent energy efficient NEMA Premium motor designs use thinner and higher quality steel laminations in the rotor and stator core allow the motor to operate with substantially lower magnetization losses. The laminations are insulated from each other, usually by a varnish layer like in a transformer. They are arranged to provide cooling air passages. A rigidly braced framework provides mechanical stability to the armature. Three-phase windings are imbedded in the armature slots.

The Armature (stator). The armature is the stator in modern AC machines. Armatures are built with the proper number of coils to meet design criteria. The windings are arranged so that groups of coils are 120 electrical degrees apart for 3-phase construction. If there is more than one slot/phase/pole, it is said to be "distributed." Where there is only one slot/phase/pole, it is called "concentrated." Distributed windings provide lower voltages across each coil. The construction of the armature is largely identical for both induction and synchronous machines. We previously noted that applying polyphase voltages to the armature produced a rotating magnetic field within the stator. For a balanced three-phase circuit, it can be shown that mathematically the rotating flux does not change magnitude with time, even though all the voltages applied to the stator, and the resulting stator currents, are all time-varying (sinusoidal). The magnitude of this rotating magnetic field $B_{\mathbf{net}}$ is constant and equal to 3/2 times one phase's magnetic field peak. Figure 6a shows a balanced three-phase system, created in Excel. The magnitude of all the phase-to-neutral voltages and currents are of the form ($\sqrt{2}/\sqrt{3}$) sin Θ, which is an RMS value of 1 line-to-line. The power contribution from each phase is shown on the bottom curves. Since the individual phase power curves are the result of multiplying two sine waves together (current and voltage), the resultant curves are of a sine² shape. When the areas under the three curves are added up, the sum gives the resultant three-phase power of √3 Watts (the area under the green line, P = √3 IV). This constant power is advantageous to motors because there are no torque pulsations, and the shaft torque is theoretically constant [2].

If the power factor is not unity, as shown in Figure 6b below for the 0.8 lagging power factor typically found in an induction motor, the power transferred is still constant. But there are areas below the axis where reactive "wattless" power is shuttling back and forth between the motor and the source, lowering the real power transferred. In this case the power transferred is:

P = √3 IV cos Θ = 0.8 X √3 W = 1.39 W.

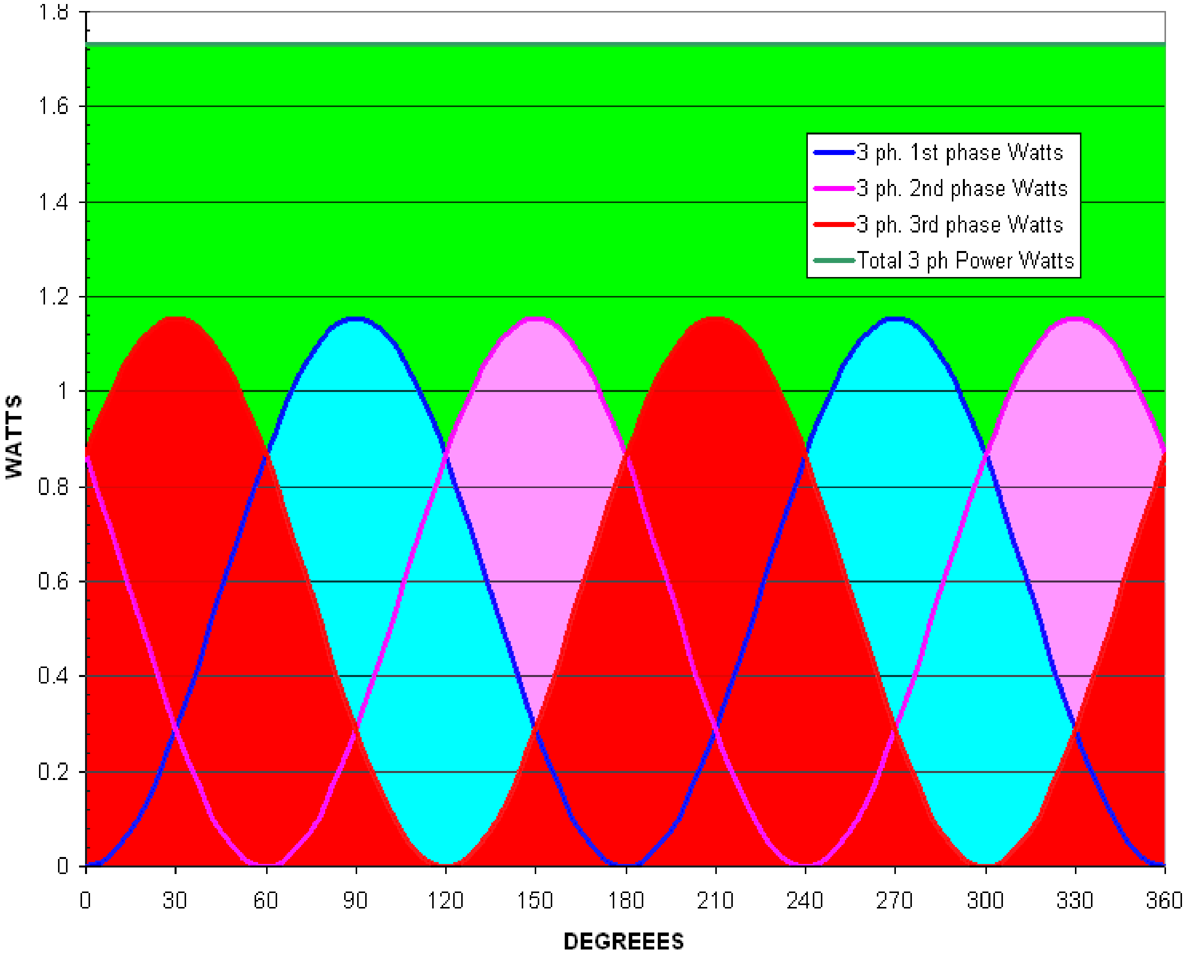


Figure 6a -- Three-phase power. A balanced three phase system will have constant power output (the area under the green curve) even though the power output of the three phases is time-varying.

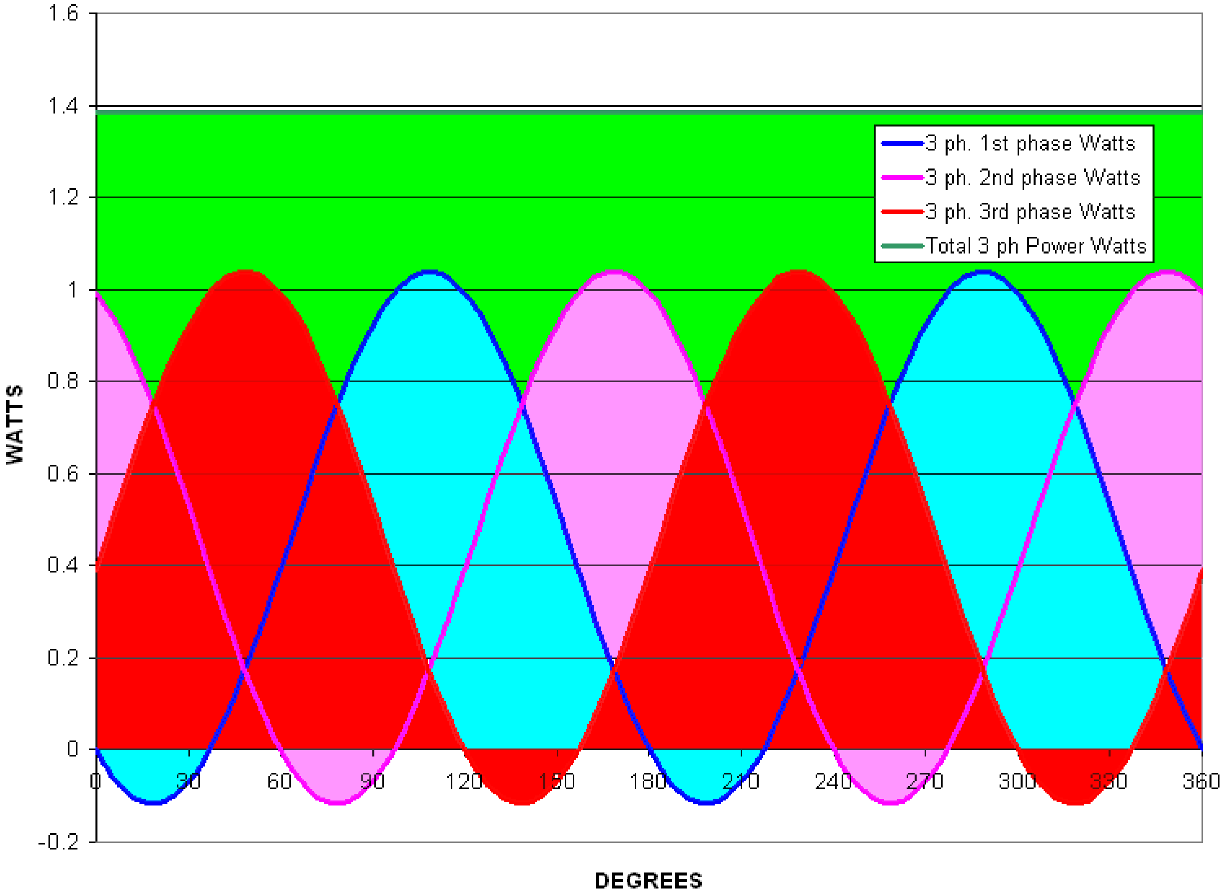


Figure 6b – Three-phase power. Power factor 0.8 lagging.

A power factor of 0.8 lagging results in less real power being transferred.

As previously noted, applying these three-phase voltages to the armature results in a rotating magnetic flux or mmf. The flux is common between the stator and rotor and produces a counter-emf of self-induction in the stator and a mutually induced emf in the rotor. The total air gap flux is due to the summation of the flux created by the currents in the rotor windings and the stator windings.

The mmf rotates at synchronous speed, set by supply frequency and the number of poles in the machine. The synchronous speed of a two-pole motor operated at 60 Hz is:

60 cycles/second X 60 seconds/minute = 3600 revolutions/minute.

The synchronous rotational speed n_S of the magnetic field is given by the formula:

$$n_s = \frac{120 f_e}{P}$$

where, f_e = frequency of the supply and P = the number of poles, an even number, 2, 4, 6, 8, etc.

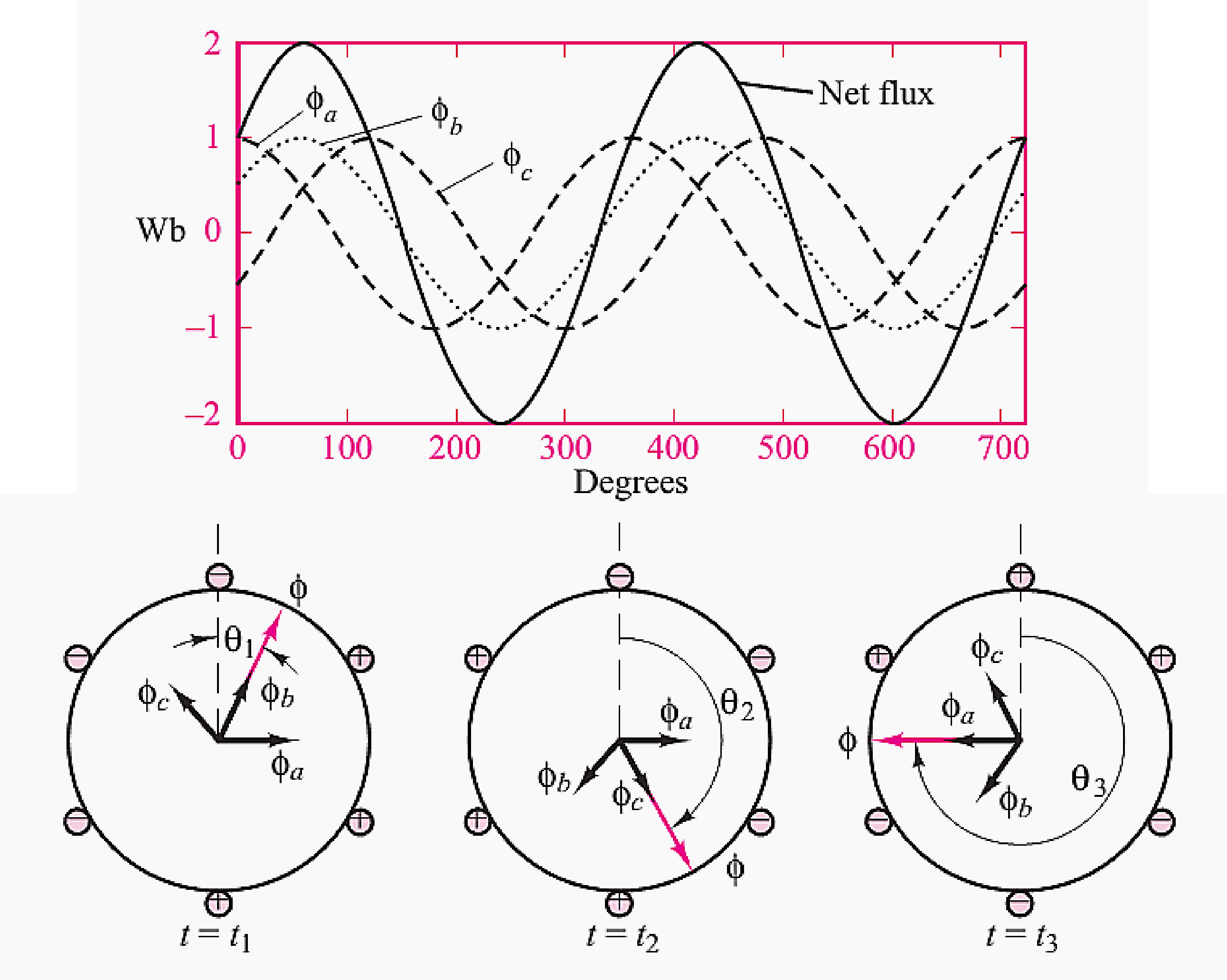
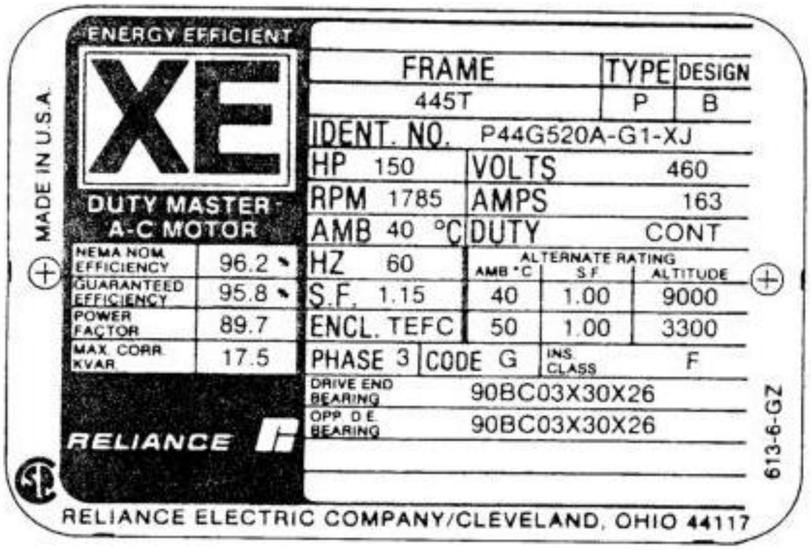


Figure 7 --Applying polyphase voltages to the armature produces a rotating magnetic field within the stator equal to 1.5 times the maximum value of the flux due to any phase

Source -- https://electrical-engineering-portal.com/rotating-magnetic-field-ac-machines.

This relationship shows that by varying the number of poles, the motor can operate at different fixed speeds, 3600 rpm, 1800 rpm, 1200 rpm etc. at 60 Hz, and 3000 rpm, 1500 rpm and 1000 rpm etc. at 50 Hz. The magnitude of the resultant flux of a three-phase machine revolving at speed n_s is of constant value and is 1.5 times the maximum value of the flux due to any phase. You can also use a variable-frequency drive (VFD) to change the motor's speed, as discussed later.

An easy way to remember the relationship between the number of poles and the speed is that at 60 Hz, 120 X f_e = 7200. So, the number of poles times the speed equals 7200. Just divide 7200 by the unknown quantity. A ten-pole machine would therefore rotate at 720 rpm. The number is 6000 at 50 Hz.



ENERGY EFFICIENT

XE

DUTY MASTER A-C MOTOR

MADE IN U.S.A.

NEMA NOM. EFFICIENCY	96.2 %
GUARANTEED EFFICIENCY	95.8 %
POWER FACTOR	89.7
MAX. CORR. KVAR	17.5

FRAME		TYPE	DESIGN
445T		P	B

IDENT. NO. P44G520A-G1-XJ

HP 150	VOLTS		460
RPM 1785	AMPS		163
AMB 40 °C	DUTY		CONT
	ALTERNATE RATING		
	AMB °C	S.F.	ALTITUDE
HZ 60			
S.F. 1.15	40	1.00	9000
ENCL. TEFC	50	1.00	3300
PHASE 3	CODE G	INS. CLASS	F

DRIVE END BEARING 90BC03X30X26

OPP. D.E. BEARING 90BC03X30X26

RELIANCE

613-6-GZ

RELIANCE ELECTRIC COMPANY/CLEVELAND, OHIO 44117

Figure 8 -- We will see that the induction motor runs slightly slower than synchronous speed. So, the synchronous speed for this machine would be 1800 rpm, making it a four-pole machine, 7200/1800 = 4.

www.slideserve.com/chumani/induction-motor-nameplate

Synchronous and asynchronous machines – two ways to produce the field. In a synchronous motor or generator, the machine's two fields are synchronized, i.e., the rotor normally rotates at the same speed as the revolving field in the machine, except momentarily during sudden load changes. This second magnetic field of the synchronous machine is produced by excitation -- supplying a direct current to the field winding. In smaller synchronous motors, a permanent magnet can be used for the field. In the induction motor, the current to produce the field is induced into the rotor, as described below.

There are two types of armature windings:

Random-wound armature -- round, insulated magnet wire, wound either by machine or hand. This insulation system is used in smaller motors and generators, below 1000 volts. The random-wound winding has two parts.

(1) The wire is insulated with turn-to-turn insulation, which is thin due to the low voltage between turns.
(2) A slot liner called the ground-wall insulation, which is between the copper and the steel core to insulate the windings from the steel.

There is additional phase- to-phase insulation, which is like the ground-wall insulation. [8]

Random wound generators and motors can be manufactured at a lower cost compared to form-wound due to lower wire cost and mechanization of the process. Although the turn-to-turn voltage is small, the turns are randomly distributed. A turn could be near other turns of different potential – the first turn could be next to the last turn -- which increases the electrical stress on the insulation.

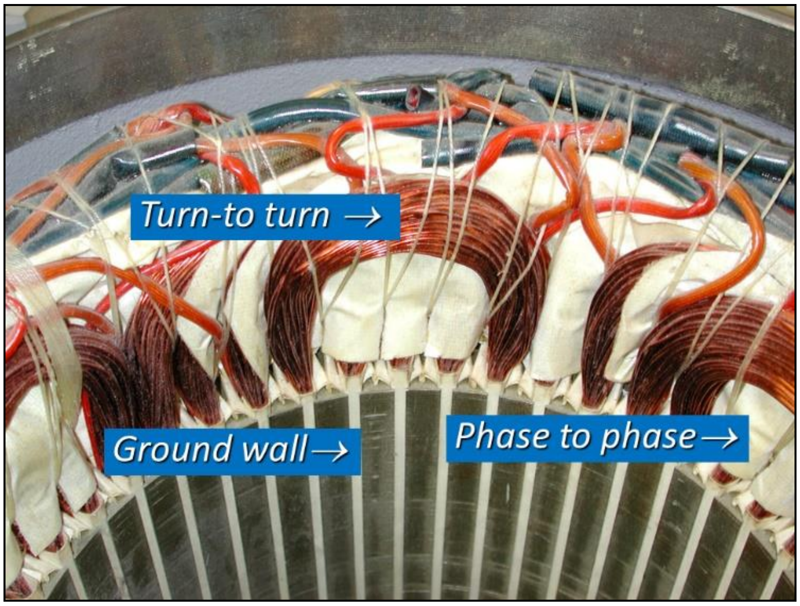


Figure 9 - Random Wound Insulation [46] and [10]

Form wound armatures are used on the larger machines and higher voltages. At terminal voltages larger than 1 kV, the voltage between adjacent turns in random wound stators becomes significant. This problem is addressed using form-wound coils. In this system, insulated, flat bar copper is bent into the required shape in a form. The form is wrapped, and later vacuum impregnated. Individual turns are arranged in precise location with respect to each other. That is, turn one is always next to turn two, turn two is always next to turn three, and so on. The winding is pressed into slots in the armature and held in place by wedges. In generators larger than 100 MW, form-wound stators are constructed with what are known as half-turn coils, also referred to as Roebel bars, since full form-wound coils become so stiff that it is nearly impossible to insert them into the narrow stator slots without damaging the coils.

Figure 10 - Form wound insulation.

The Field (rotor).

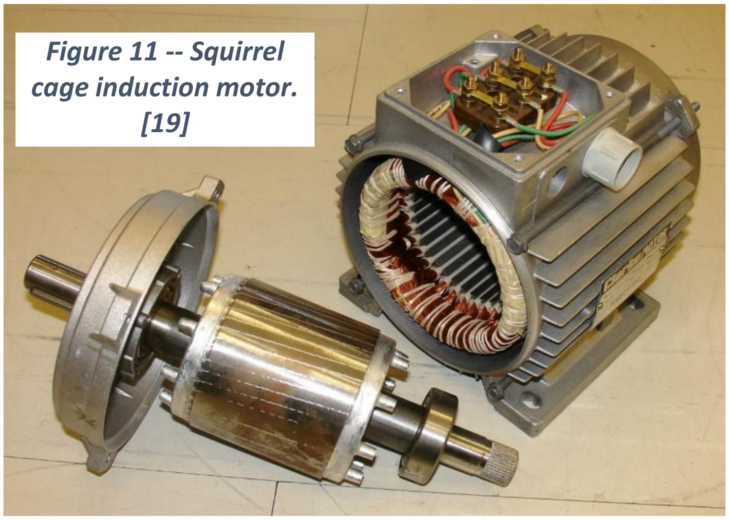


Figure 11 -- Squirrel cage induction motor. [19]

Tesla's original induction motor invention had a wound rotor. He sold his patent to George Westinghouse, and Tesla, along with Westinghouse engineers, worked on making the design practical. But surprisingly, it was Russian-born engineer Michael Dolivo-Dobrowolsky who gave us the squirrel-cage rotor design that is still used today. This design did not deliver high starting torque. The solution was another invention of his, the slip ring wound rotor motor which will be discussed later.

Today's rotor, which is the only moving part, is usually of this squirrel-cage type, and includes the shaft, the laminated iron, and the squirrel cage. It has a laminated core in which heavy conductors are embedded in slots around the perimeter and may be slightly skewed with respect to the shaft. The conductors or bars are usually aluminum and sometimes copper. The embedded conductors are short-circuited on the ends by shorting rings. With the core removed, the rotor conductors resemble the cylindrical cages used to exercise pet rodents. There are no brushes or slip rings. The rotor has both resistance and reactance. The rotor's resistance does not vary with frequency, except for skin effect. The rotor's reactance will vary with frequency.

Ococcasionally you may encounter a non-laminated solid-steel rotor, sometimes coated with copper. These motors rely on the production of eddy currents in the rotor, and are used for high-speed, high starting torque, low-vibration, low noise applications. They are low-cost to manufacture, but they suffer from high rotor eddy-current losses and therefore have lower efficiency. Their output power is lower, they have higher slip, and lower power factor [18].

The air gap.

There is an actual physical gap in an electric motor between the moving rotor and the stator. This air gap needs to be large enough to prevent contact between the rotor and stator, considering machine manufacturing tolerances of the motor and bearings, bearing wear, and other movement during operation. For example, a larger motor's rotor weight will cause the shaft to sag when not running for a period of time. The rotor will run eccentrically for a while when started and could scrape the stator. Also, during machine maintenance, the rotor may have to be removed, which becomes more difficult when the air gap is small. Large air gaps minimize manufacturing costs, increase motor cooling, and decrease pulsation loss. The MMF required for producing and sending the flux through the air gap depends on the flux density and the air-gap length. A smaller air gap is used in energy efficient motors to improve the power factor and to reduce the no-load losses in the motor. The motor with a small air gap length draws less magnetizing current, and the power factor of the motor is better than the motor having large air gap. A larger air gap increases the reluctance of the magnetic circuit, which will demand more MMF to produce the required flux in the motor. To meet the additional requirement of MMF, the stator magnetizing current increases, the motor's power factor worsens, maximum available torque decreases and the slip increases.

It is also extremely important that the air gap be uniform. When the air gap is eccentric, the air gap between the rotor and stator is smaller on one side, and larger on the other side. There will be more flux on the side with the smaller air gap, and greater pull due to the magnetic forces. The motor is going to vibrate and make noise. If the eccentricity is large enough, the magnetic pull can become unbalanced and lead to rubbing between the rotor and stator. The air gap variation should never exceed +/- 10% of the average air gap. [25]

The induction machine uses slip to produce the field.

The induction machine, either a motor or a generator, is an asynchronous device that uses Faraday's famous law of electromagnetic induction to produce the field in the rotor. When a conductor experiences a changing magnetic field, a voltage will be induced in the conductor. One way to produce this changing magnetic field is by relative motion between the conductor and the magnetic field of force.

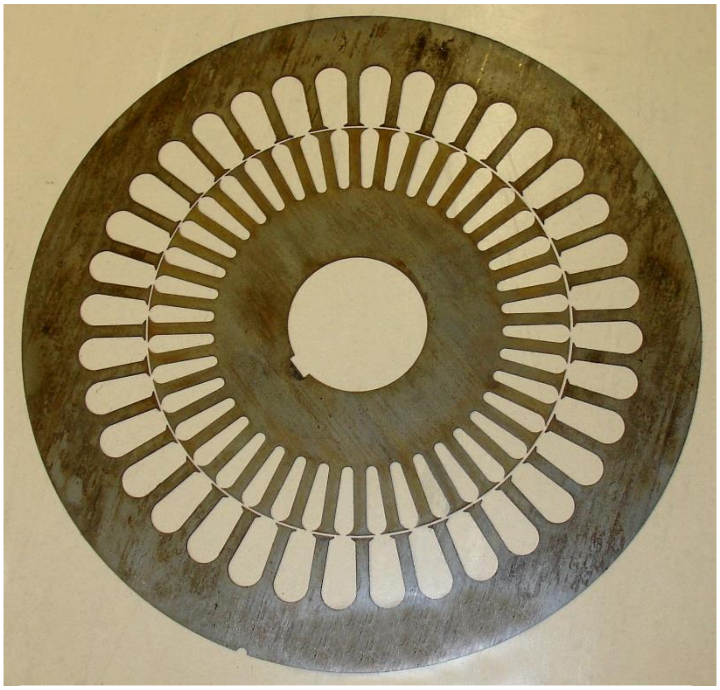


Figure 12 – Rotor and stator laminations, with 36 slots for the stator and 40 slots for the rotor [19]

Either the magnetic field, the conductor, or both can move. The magnitude of this induced voltage is proportional to the rate of change of the flux. The polarity of the voltage is predicted using Fleming's right-hand rule, which shows the relationship between field flux, conductor motion and the current flow. Reversing the direction of motion will reverse the polarity of the induced voltage. The magnitude of the induced voltage is determined by the strength of the field and is proportional to the number of flux lines being cut each second. So, moving a conductor more rapidly through a magnetic field will cut more flux lines per second, and induce more voltage. Likewise, moving a conductor more slowly through a magnetic field will cut fewer flux lines per second, and induce less voltage. If this conductor with the induced voltage is connected in such a manner as to create a closed circuit, current will flow. The direction of flow is in response to the polarity of the voltage. The rotor's opposition to the flow (resistance, impedance) limits the current. For the motor's rotor to have current flow in the bars and produce a field, it must run at a slightly slower speed than the rotating magnetic field. The embedded bars in the rotor cut the rotating field and a voltage is induced in them. The rotor slots and their enclosed bars are usually not exactly in parallel with the rotor, but slightly skewed (Figure 5). This method prevents "cogging", which is the phenomenon of magnetic locking between the stator and rotor, which may result when the rotor bars are placed parallel to the stator slots. There is a tendency of the parallel rotor teeth to remain under the stator teeth due to magnetic attraction between the two. [20]. With skewing, the next bar starts cutting the magnetic flux before the previous bar finishes, so that the rotor bars cut the flux uniformly. This continuous flux cutting results in a continuous rotor torque, which eliminates the chance of magnetic locking, and reduces magnetic hum, noise and vibration [13]. The rotor resistance can be increased due to the longer rotor conductor bars. The number of rotor slots is usually less than the number of stator slots as another way to prevent the rotor from locking at startup and to reduce torque fluctuations. The number of stator slots must not be a multiple of the number of rotor slots.

Being short-circuited at each end, the embedded conductors form completed circuits in which heavy currents can flow. The rotor's enclosed magnet iron, encircled by the adjacent conductors, forms a magnetized pole piece. The amount of speed below synchronous speed required to produce a given load, is called "slip", a dimensionless number which is the relative speed of the rotor to the synchronous speed on a per unit basis. The motor's torque will be proportional to the slip. Characteristically, the unit is rated by "percent slip" or percent of system speed. Typical slip is two to five percent. The percent slip for full load is the rated slip of the motor. The motor's no-load slip approaches zero, i.e., the speed will be 99.5% of synchronous speed (slip = 0.005), just enough to overcome friction and windage. As load increases, the speed decreases a few percent from speed-no-load, and the slip increases up to the rated slip (3 to 5%). For a four- pole induction motor a typical full-load speed is 1760 rpm. Slip is unity at the moment of startup (locked rotor) since the mechanical rotor speed n_m is zero.

The motor's starting current is very large (5 to 7 times $I_{F.L}$), and the rotor starting current lags behind the rotor voltage by a large angle. The rotor's reactance is large at standstill because the rotor frequency equals the supply frequency, resulting in a poor starting torque per ampere. As a result, starting torque is only about 1.5 times the full-load torque.

Slip is variously defined as:

Slip speed = the difference between synchronous speed n_{sync} and the rotor speed n_m:

$$n_{slip} = n_{sync} - n_m$$

Slip as a percentage:

= (synchronous speed – mechanical rotor speed) X 100% / (synchronous speed)

$$s = \frac{n_{sync} - n_m}{n_m} \; (100\%)$$

The rotor speed $n_m = (1-s)\, n_{sync}$

The induced rotor voltage and the rotor current frequency are both proportional to slip.

The slip frequency in the rotor fr = sf_s so the rotor frequency will equal the supply frequency f_s at startup (locked rotor), and the induced voltage will be highest. The induced frequency will be zero Hz and zero voltage at synchronous speed.

Although the rotor will be turning slower than the stator field to produce the slip, both the rotor and stator fields rotate synchronously, which means that they are stationary with respect to each other. The rotor itself and the two flux vectors all rotate in the same direction. The rotor's field is rotating at slip speed relative to the rotor itself.

Starting the squirrel cage induction motor.

The most common, least expensive and simplest method of starting a three-phase induction motor is called full-voltage, across the line, or direct-on-line (DOL) starting. Since full line voltage is applied to the motor initially, the electrical power system must be able to handle the high starting current inrush, which can cause a voltage drop in the power line. When the normally open start pushbutton PB_1 is pressed, the contactor coil (M1), is energized, causing the four normally open contacts M_1 to close. Three of the contacts are heavy-duty, and apply full-voltage to the motor through overload relays. When the start pushbutton is released, the relay coil M1 remains energized due to the fourth lighter-duty M1 contact, which is called a holding contact, This holding contact provides a current path around the normally open start push-button PB_2 "sealing in" the circuit. When the stop pushbutton is pressed, or any of the overload relays trip, this circuit is opened, deenergising the coil M1, and opening all four M1 contacts. The overload relays provide long-term overload protection, while the fuses (or a circuit breaker) provide short circuit protection. The contactor stays in the open position until all overload relays are reset, and the start pushbutton PB_2 is pressed. In larger machines with higher voltages and currents, a circuit breaker can provide both starting contacts and overload protection.

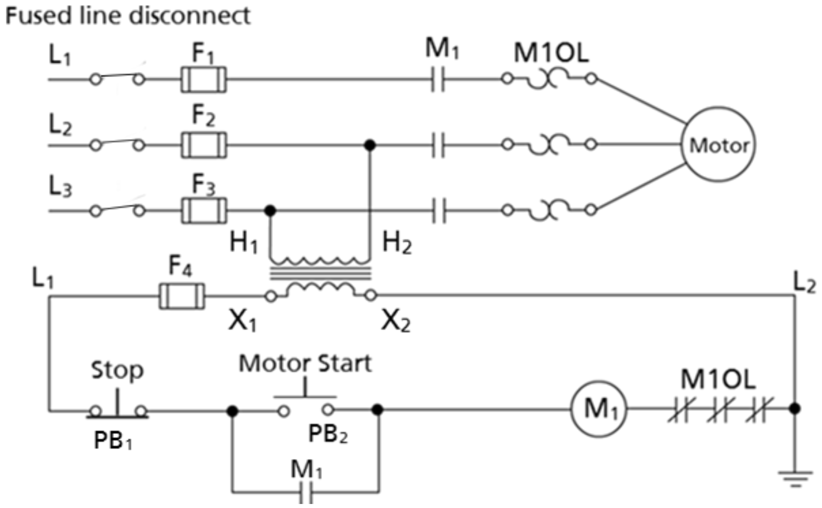


Figure 13-- Full-voltage DOL motor starter *[www.wisc-online.com]*

The basic principles of induction motor action -- Faraday's Law and the Lorentz Force.

A magnet moving above a conducting ladder, let's say aluminum, induces a voltage E=BlV in the rungs underneath it. If there is a complete circuit through end bars A and B, there will be current according to Faraday's law, even if the ladder is a non-magnetic conductor. The current-carrying ladder's rungs will experience a Lorentz force (the left-hand rule) which will drag the ladder in the same direction the moving magnet. If the ladder is rolled into a circle, it would resemble the induction motor squirrel cage. The physical magnet is replaced by a rotating magnetic field from the stator. So the stator cage will turn in the same direction as the rotating magnetic field.

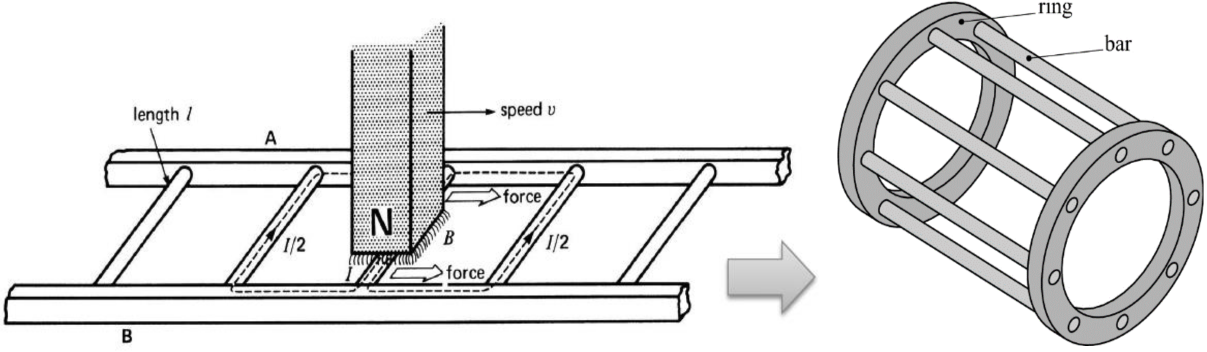


Figure 14 -- Even though the ladder is non-magnetic aluminum, it will experience a force and move in the same direction as the magnet.

Which way does the motor turn? Several different approaches. At startup the rotor speed is zero. The slip is unity, and we will assume the stator magentic field is rotating clockwise at synchronous speed. The law of energy conservation says that energy cannot be created or destroyed. Lenz's Law, in the case of generators, applies to the electromagnetic induction that is taking place. The generator's rotating magnetic field cuts the stationary rotor bars and, according to Lenz's Law, induces an opposing EMF and current flow which opposes the motion that produced it. Since the rotor bars are short circuited, large circulating currents are created in rotor bars by these induced voltages. The rotor currents are at a maximum at the instant of startup because the magnetic field has the maximum speed relative to the rotor. The large rotor current produces a second magnetic field in the rotor. A torque is produced as a result of the interaction of those two magnetic fields. The rotor will rotate in the direction of the stator field due to Lorentz forces as indicated in the ladder example above. Once the rotor starts rotating, its speed relative to the field will decrease, so its currents and Lorentz forces will decrease.

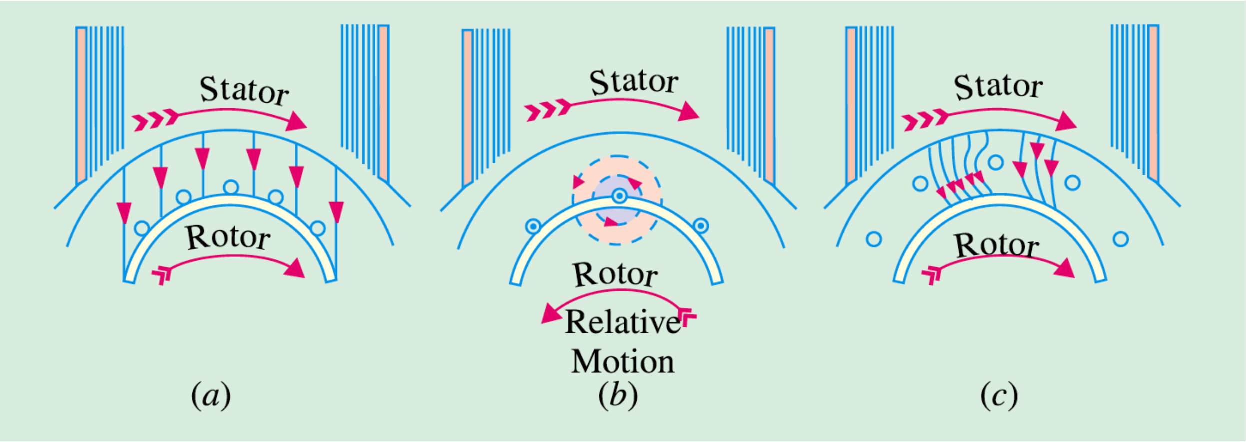


Figure 15 --Why the rotor turns in the same direction as the stator field [20].

Figure 15(a) shows the stator field rotating clockwise and cutting the top rotor bars. Since the motor's rotor always runs slower than the stator field, as shown in Figure 15(a), the field is moving clockwise, but so far as the rotor conductor is concerned, it is as if the stator field were stationary and the rotor conductor was moving counterclockwise 15(b). The current direction from the right-hand rule is outwards from the page, and the corresponding rotor bar magnetic field is as shown. The Lorentz force (left-hand rule) acting on the rotor bar in 15(c) rotates it in a clockwise direction -- the same direction as the stator flux.

Another approach -- using the combined field theory, you can also see in 15(c) that the combined field is reinforced and stretched on the left hand side of the rotor bar, and weakened on the right hand side [20]. The stretched field acts like a rubber band and pushes the rotor clockwise.

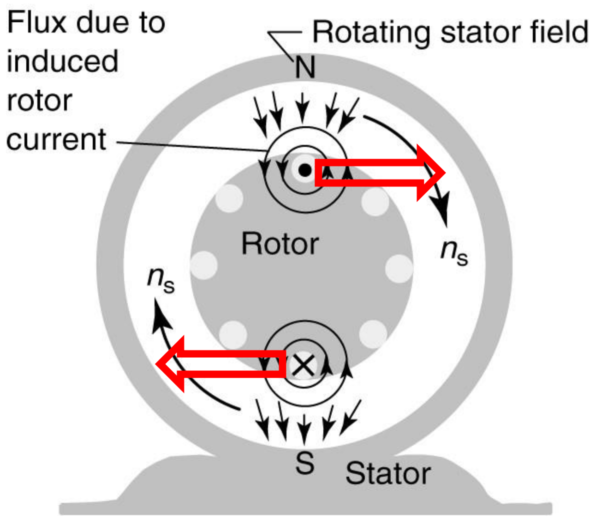


Fig 16 -- The torque on the rotor accelerates it [31].

The same thing is happening with the lower rotor bar, except this time the current direction is into the page, and the force is to the left (Figure 16). These forces produce torque on the rotor. If the rotor is free to move (and if the force is enough to overcome friction and inertia), the rotor will begin to turn.

Yet another way to look at the direction of rotation is that the rotor currents obey Lenz's Law and oppose the cause that produces them. The cause of the rotor currents is the relative velocity between the rotor and stator fluxes. To reduce the relative speed between them, the rotor starts turning in the same direction as the stator flux and tries to catch up with it [20].

A final way to look at the rotor's direction at startup is to notice that due to the high slip frequency and the rotor's reactance, the rotor's flux density will lag the stator flux density, therefore the torque will be in the same direction as the rotation of the stator's magnetic field.

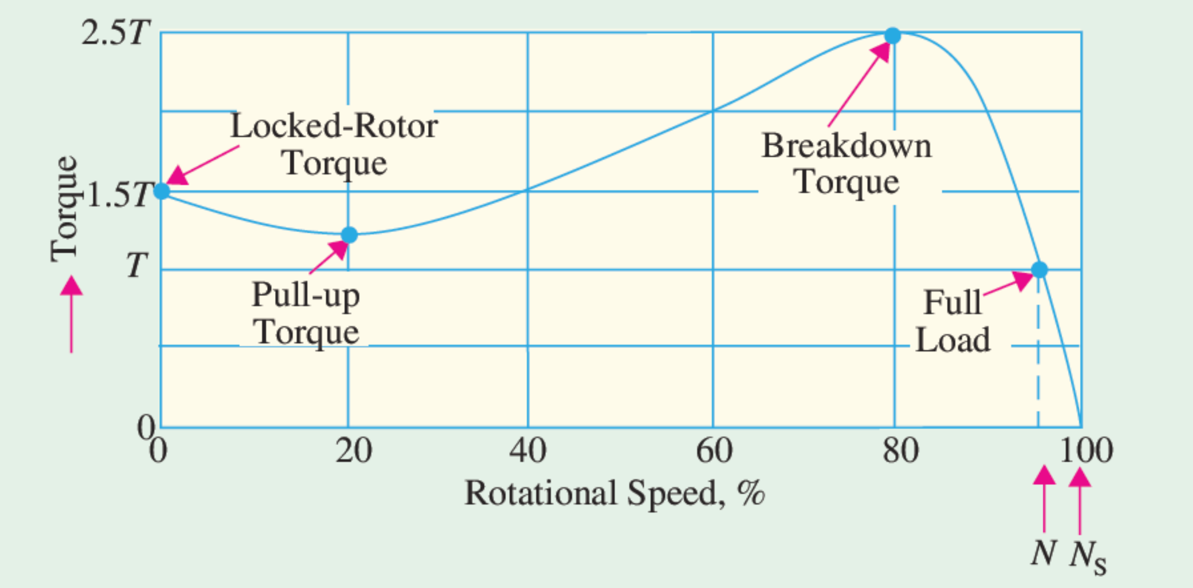


Figure 17 – Induction motor torque speed characteristic showing operating region [20]

Induction motor torque-speed characteristic. The torque equation for a motor is:

$P = \omega_m T_m$

Where = T ω_m = the mechanical angular velocity = $2\pi Nr / 60$ (rad/sec), and

T_m = the motor torque in N m, and

P= power in Watts.

The induction motor torque-speed curve, Figure 17, shows the non-linear relationship between the torque and the speed of an induction motor, to predict the machine's behavior in electrical motor applications. It is derived from the motor's equivalent circuit. The starting torque of the motor is also called the locked-rotor torque and is shown on the left. The starting condition has the greatest potential for rotor damage. The rotor must never remain locked for more than a few seconds, because when the motor current is 5-6 times the full-load current, I^2R losses are 25-36 times higher than normal. The high current produces a large force on the coils which is proportional to the square of the current, which can cause coil movement and damage. Inadequate motor starting torque can cause too long a start-up time, causing excessive temperature rise in the motor because the temperature depends on the product of the time and the square of the current. As discussed later, various motor designs can affect the shape of this curve. The maximum possible torque the machine can produce is called the pullout torque or the breakdown torque, which does not depend on rotor resistance. The motor must have sufficient breakdown torque to overcome peak loads without stalling. The slip at which the maximum torque occurs does depend on the rotor resistance and gives rise to the NEMA torque-speed curves. If the load torque is increased beyond the point of maximum torque, the motor's torque will decrease, and the motor will slow down and eventually stop. The curve is nearly linear in the normal steady-state operating region which is on the right. This range, between full-load rotor speed N and synchronous speed Ns is the motor's entire normal steady state operating range. The motor-load system is stable when the developed motor torque equals the load torque, and the motor returns to stable steady-state operation at fixed speed after a change in the load torque. The torque of the motor is zero at synchronous speed.

Wound Rotor motor. When a high-inertia load is started, a standard squirrel-cage design may accelerate slowly or stall and suffer damage due to the heavy currents in the rotor and stator.

Dobrowolsky was able to introduce an asynchronous motor with high starting torque in 1891.

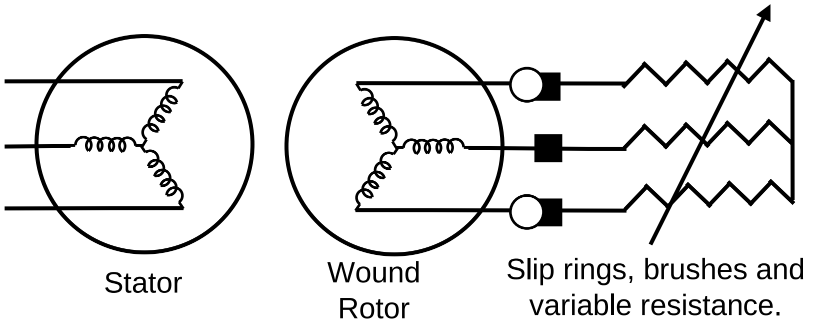


Figure 18. The wound rotor induction motor [10]

He brought the three-phase Y connected rotor circuit to the outside via slip rings and brushes as shown in Figure 18. The motor's rotor currents are, therefore, accessible at the brushes. A variable Y-connected resistance is connected to the slip rings via the brushes. In this manner, the resistance of the rotor circuit can be changed with the motor running. Adding external resistance at startup provided the ability to gradually bring high-inertia equipment and large loads up to speed smoothly and easily. The reason for adding resistance is that a high-resistance rotor develops high starting torque (up to 250%) with low inrush, but with high slip and lower efficiency.

The resistance can be gradually removed with the motor running, so the motor develops low slip and high full-load efficiency, behaving much like a NEMA Design B motor. In fact, under normal running conditions, a sliding contact bar may short the slip rings, just like the squirrel-cage rotor. The brushes can be lifted to reduce friction and wear [20]. Adding external resistance will not change the maximum torque of the motor but will change the speed at which it occurs (Figure 19). With the slip ring motor, the secondary external resistors can be selected to provide the optimum torque curves. The maximum motor torque occurs at the maximum air-gap power, which is also the point where the source impedance equals the load impedance in the equivalent circuit discussed below.

A secondary use of the wound rotor motor is to provide a means of speed control over a limited range. If you continue to increase the resistance connected to the rotor beyond the point where the maximum torque occurs at zero speed, the torque curve will continue to shift to the left, and the slip will increase. When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. The slip losses dissipated in the external resistors can be very high, and the speed regulation is poor. The wound-rotor

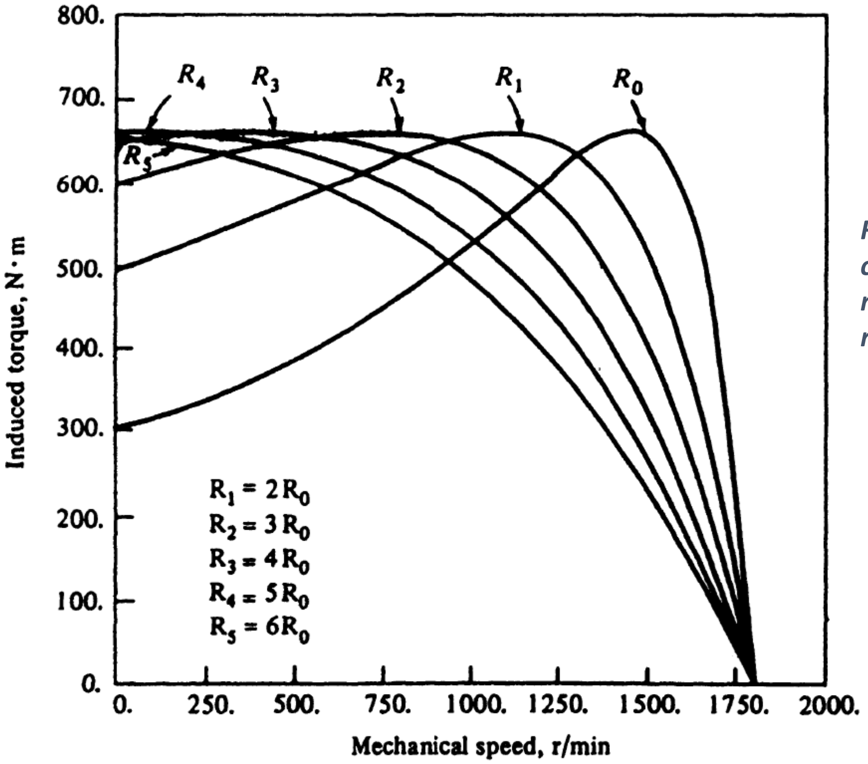


Figure 19 – Torque-speed characteristic for a wound-rotor motor with increasing external resistance [7].

disadvantages are added expense (1.5 to 2 times the cost of a squirrel-cage design), and more maintenance due to slip rings and brushes. However, they are still used on cranes and elevators where frequent starting, stopping and speed control is necessary.

A more modern application of the wound-rotor machine is the doubly-fed induction motor, where both the stator and rotor are supplied externally. Later, we will discuss a newer application of the wound rotor, the doubly-fed induction machine used as a generator. Use of the wound-rotor motor for speed control has largely been eliminated by using variable-speed drives.

Variable Frequency Drive (VFD). In mechanical applications with variable power needs, there can be very significant savings from using VFDs with intelligent control, coupled with a premium efficiency motor. The VFD regulates the output torque and speed of the motor to match the system mechanical loads. However, such control systems need a significant amount of power to operate and should not be used in fixed output power applications. In such applications, they will incur more energy losses and impose higher costs than a properly sized fixed-speed system.

Since the motor speed is a function of the frequency (120f/p), you can use frequency to control speed. A variable frequency drive (VFD) controls the speed, torque, and direction of an AC induction motor. It is among the simplest and cheapest control systems for the induction motor. A rectifier and filter convert the AC input to DC. The inverter VFDs utilize pulse width modulation (PWM) to synthesize a three-phase output voltage whose current and frequency can be changed. There is one more important thing: since $X_L= 2\pi f L$, at low frequencies the voltage must be reduced to avoid overcurrent and saturation. Therefore, in VFDs, the voltage applied to the motor is also reduced in proportion to the frequency to prevent the motor from overheating. The ratio that must be maintained is Volts per Hertz (V/Hz). For example, the Volt per Hertz ratio for a 480 Volt, 60 Hz motor will be 8 V/Hz. Maintaining this V/Hz ratio will maintain a constant flux in the air gap, keeping the motor's torque fairly constant. The torque-speed curve will maintain the same shape but will be shifted along the X axis. VFD's can also provide such benefits as soft-starting and overspeed capability.

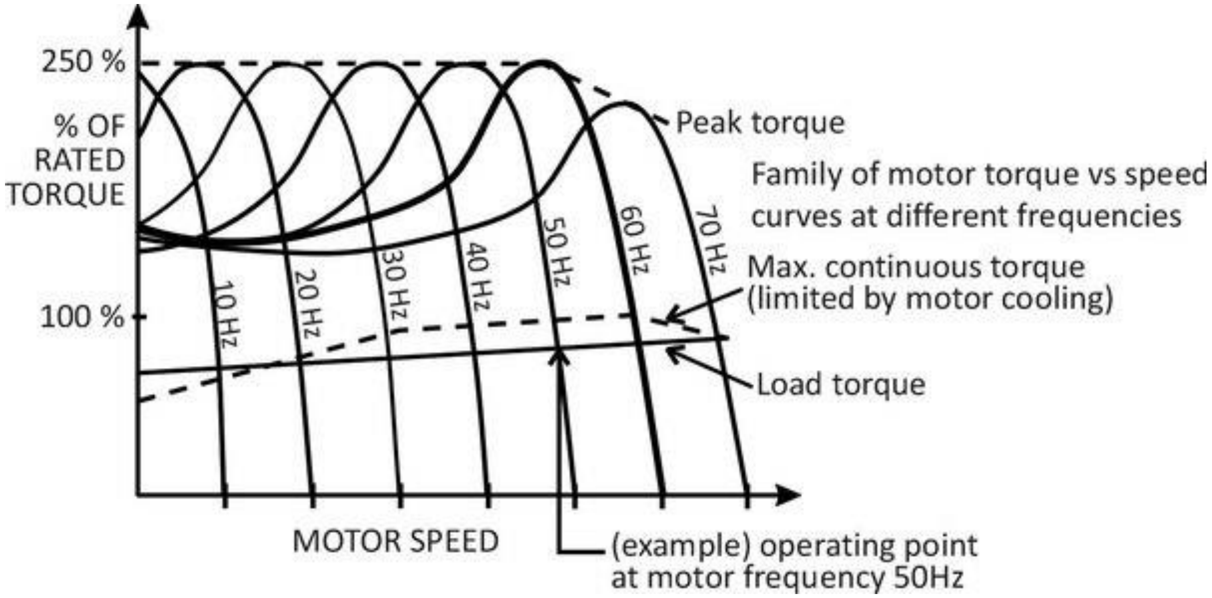


Figure 20 --Family of Torque speed curves with a VFD [44]

Another consideration for a motor driven by a VFD at reduced speed is that there is less cooling air from the motor's fan. For this reason, inverter grade motors have a defined range of speeds they may operate within to avoid over temperature, as shown by the dotted line in the figure.

The DC motor dominated the market for transportation and other markets because of variable speed and high starting torque until about 1985, when the insulated-gate bipolar transistor (IGBT) PWM (Pulse Width Modulation) inverter was provided for efficient frequency changing. However, fast switching rates of modern power semiconductors produce steep-fronted voltage waves (high dV/dt), which can lead to voltage overshoots and other power supply problems, like harmonics pollution in the power grid and electromagnetic interference (EMI) in the environment. Motor cables over fifteen feet can cause higher amplitude standing waves with voltage spikes as high as 2,150 V in a 480-V system. These voltage spikes can rapidly damage a motor's insulation system resulting in premature motor failure unless filters or limitations on cable length are used.

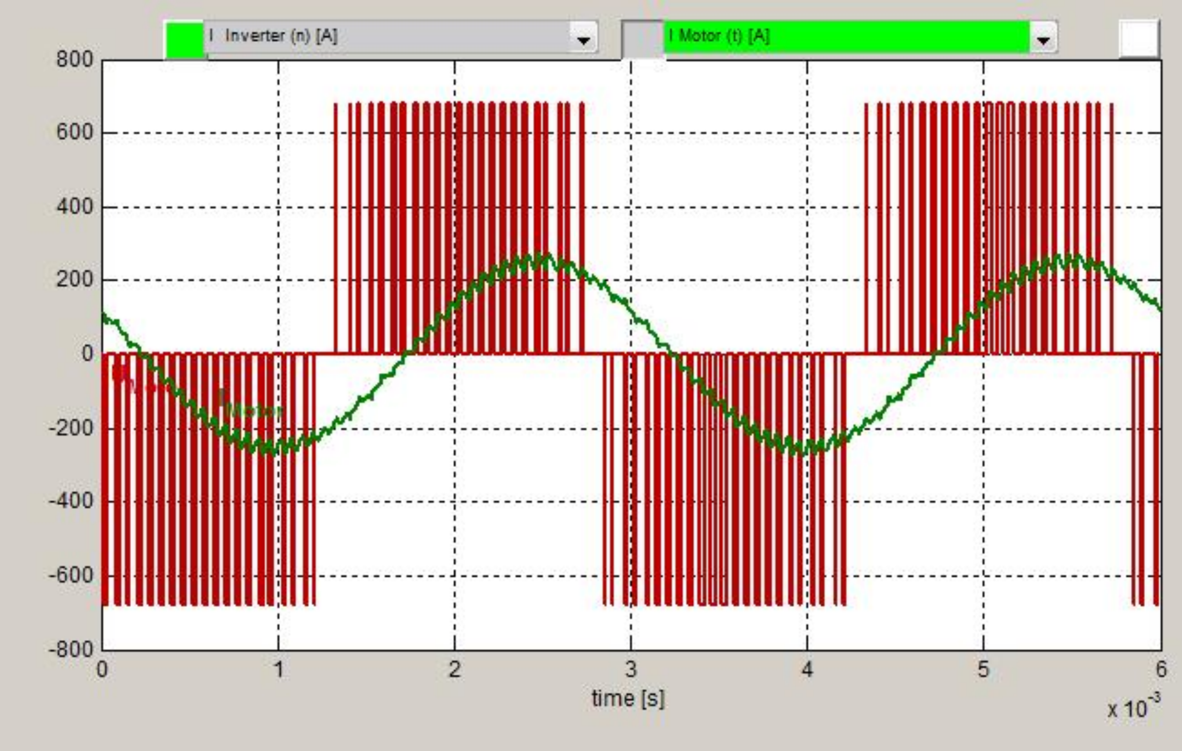


Figure 21 --VFD switching frequency and output. [15]

A more sophisticated variable speed drive is the flux vector drive, which uses a closed loop feedback from the motor, and the motor's rotor position and speed is monitored by the drive's microprocessor to control the speed, torque, and power.

The Equivalent Circuit. A per-phase equivalent circuit model of a three-phase induction motor can be modeled by using a steady-state equivalent circuit. The development of this model can be readily found in electrical machinery textbooks [7] and will not be repeated here.

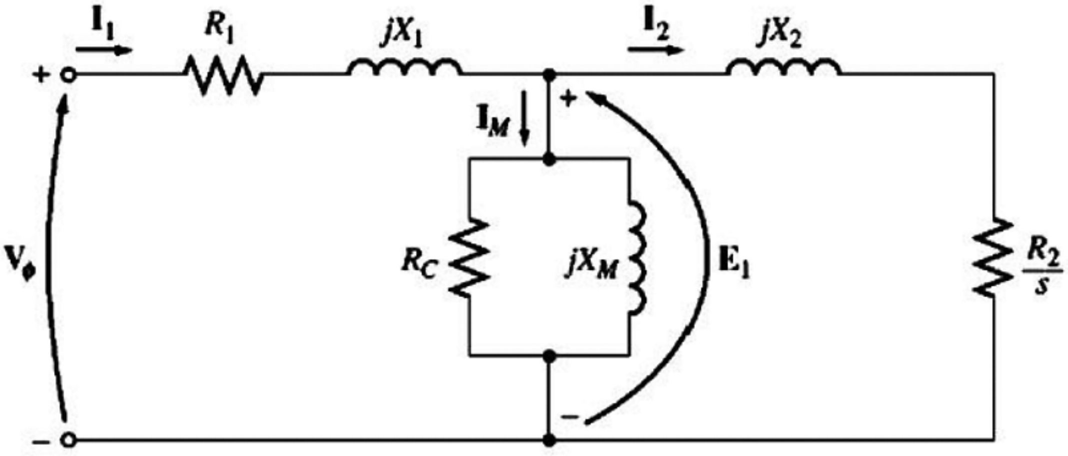


Figure 22 -Per phase steady-state simplified equivalent circuit model of a three-phase induction motor [7]

The inputs to the stator and rotor are electrical, but the rotor has a mechanical output. So, it is necessary to replace the mechanical load by an equivalent electrical load, which gives us the induction motor transformer equivalent circuit.

The no-load current I_M of an induction machine has two components:

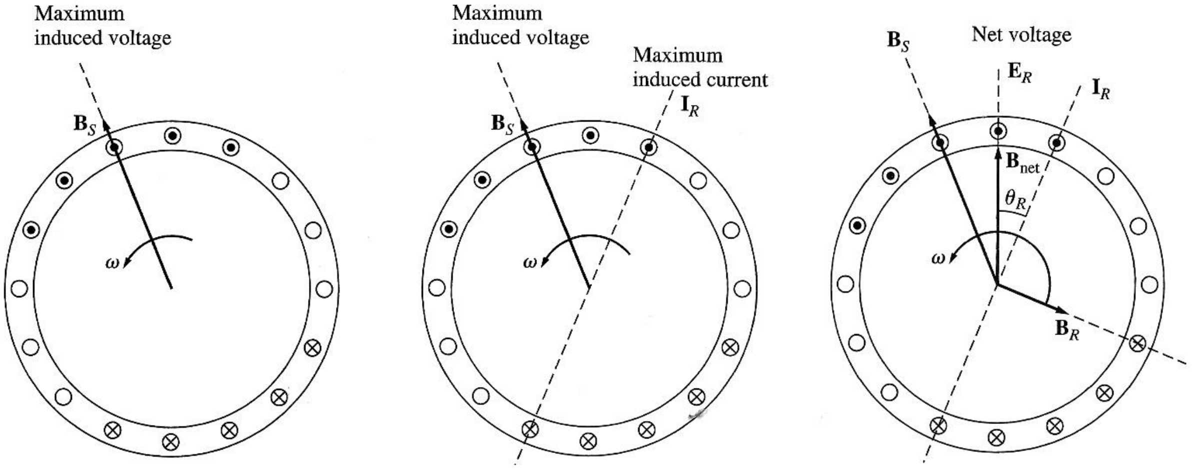
> V_Φ is the applied line-to-neutral phase voltage. The first component, through R_C, is in phase with the applied voltage, and accounts for the core losses in the motor -- eddy current losses and hysteresis losses. Sometimes the core-losses R_c are neglected to further simplify the circuit.
>
> The second component of I_M through jX_M sets up the magnetic flux in the motor's core, which lags the applied voltage by 90 degrees, and is responsible for producing torque.

The frequency of the stator voltages and current is *f*, but the frequency of the rotor voltages and current is s*f*. So, when the secondary elements are referred to the stator side, you must compensate for the difference in frequency. The stator and rotor resistance and reactance are shown with the rotor parameters referred to the stator side by the effective turns ratio of the motor a_{eff}, and the transformed rotor voltage is E_1. All the speed variation effects are concentrated in the impedance term R_2/S. At low slip, the rotor resistance predominates, and this is the linear region of the torque-speed curve. R_2/s is the electrical equivalent of the mechanical load. The value of R_2/s will vary from R_2 to infinity as the motor goes from start-up (s=1) to Ns (s=0).

Not all the flux across the air gap links with the rotor conductors. This leakage flux decreases torque production since only the air gap flux produces torque, and also reduces rotor current. A small air gap will minimize leakage flux. Even though the frequencies of stator and rotor currents are different, the magnetic fields due to them rotate at synchronous speed Ns.

A few comments about the practical application of this equivalent circuit are in order. First, this circuit determines the shape of the torque-speed curves previously presented. In the right-hand operating region of the curve, the slip is low and increases approximately linearly with the load, i.e., the motor has a linear speed droop. The rotor frequency, and therefore its reactance is low, so its power factor is approximately unity. This is the normal steady-state operating range of the motor. [5]

As slip increases (for increasing load on the motor), the torque also increases and becomes maximum when $s = R_2/X_2$. This torque is known as 'pull-out' or 'breakdown' torque. Any further increase in motor load results in a decrease of torque developed by the motor. The result is that the motor slows down and eventually stops [20]. High "locked rotor" current can damage the motor.



The rotating stator field Bs induces a voltage in the rotor bars.

Rotor current lags voltage because of rotor inductance.

Rotor current produces a rotor magnetic field B_R lagging 90°. B_R interacts with B_{net} to produce a CW torque.

Figure 23 -- Induction Motor Induced Torque. [7]

The equivalent circuit is like that of a transformer. The rotor current frequency is, however, different from the stator current frequency, so they cannot be drawn in one phasor diagram. An important difference between the motor and transformer equivalent circuit has to do with the fact that the induction motor consumes significant magnetizing current. For the transformer, the magnetizing current is low, typically one to four percent of the full-load current [5]. In the development of the transformer approximate equivalent circuit, the magnetizing branch could be moved to the primary side of the circuit with little error, and the primary and secondary impedances were combined for simplicity. However, the air gap in the induction motor greatly increases the reluctance of the flux path, and a higher magnetizing current of around 30% of the full-load current is required to obtain a given flux level. In Figure 24, if you extrapolate the current to speed-no-load condition, the magnetizing current is over 30%. The same is true for an induction generator, as we will see later.

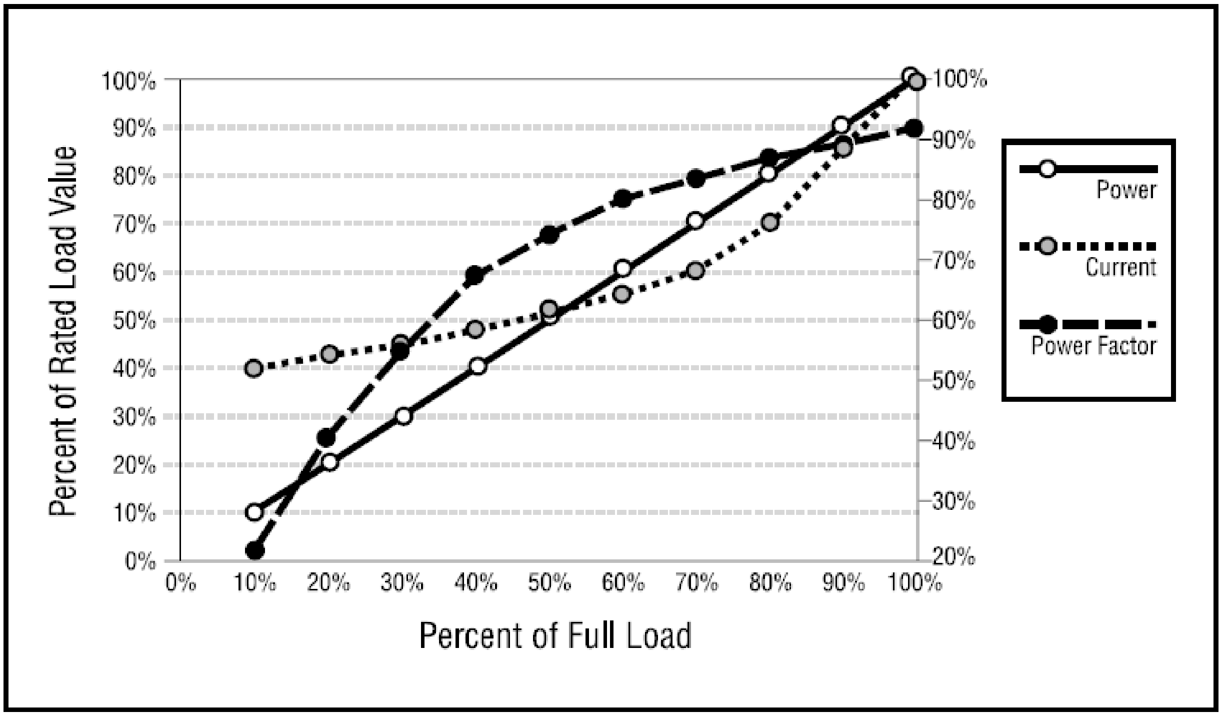


Figure 24 -- Relationships Between Power, Current, Power Factor and Motor Load [12]

The result of the high magnetizing current is that a partially loaded induction motor or generator will have a low power factor. Most electric motors are designed to run most efficiently at 50 to 100% of full load, with the optimum efficiency between 60% to 80% of full load. A motor's efficiency and power factor decrease dramatically below about 50% load [12].

The inexperienced engineer might calculate that a 5-hp motor is needed, then put in a 10 hp motor "just in case". Studies conducted by the Electric Power Research Institute reveal that over 60% of industrial motors are operating below 60% of their rated load capacity, continuously wasting electrical energy. The power factor will be poor. The induction machine should be properly sized to operate at 70 to 100 percent of its full-load torque, also taking into consideration breakdown torque and starting torque, and altitude derating discussed next. Larger motors have better full-load power factors and less full-load slip than their smaller counterparts, due to the relatively smaller air gap.

Starting current. When a squirrel-cage induction motor is connected to an energized line, there is an inrush of reactive current to magnetize the motor's iron and coils. The motor is behaving like a transformer with a short-circuited secondary winding, so the maximum amount of current is being induced into the rotor bars. As shown earlier, the force that turns and accelerates the rotor is in the same direction as the direction of the rotating magnetic field. The force comes from the interaction of the field associated with the rotor's induced currents and the poles of the rotating magnetic field. The rotor and stator frequencies are different.

There is a frequency in the motor's rotor that is proportional to the slip:

$f_r = s\, f_s$ where f_r is the rotor frequency, and f_s is the system frequency (50 or 60 Hz)

At standstill (locked rotor), the slip is unity, and the rotor's inductive reactance is comparatively high, since 60 Hz rotor currents are induced if the motor is operating at 60 Hz. Therefore, the rotor currents lag behind the flux with the result that the starting torque is low, and the starting current is heavy. With the wound-rotor machine, the resistance of the rotor can be increased during startup. This added resistance will increase the power factor of the rotor, the rotor current will be more in-phase with the stator flux, and there will be maximum starting torque. In the standard squirrel-cage machine, however, the rotor resistance is fixed.

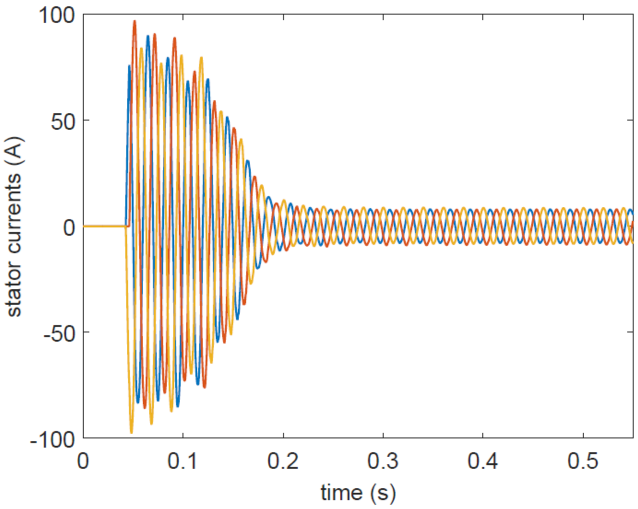


Figure 25 -- Induction motor inrush current [17]

For the rotor to turn, the electric torque produced by the machine must overcome the mechanical torque of the load. The accelerating torque is the difference in torque between the motor's torque speed curve and the load's torque-speed curve. As the rotor's speed approaches synchronous speed, the frequency of the induced rotor current decreases. Therefore, the inductive reactance of the rotor decreases, since $X_R = 2\,\pi\, f\, L_R$. The rotor currents are practically in phase with the stator flux, and the torque reaches a maximum.

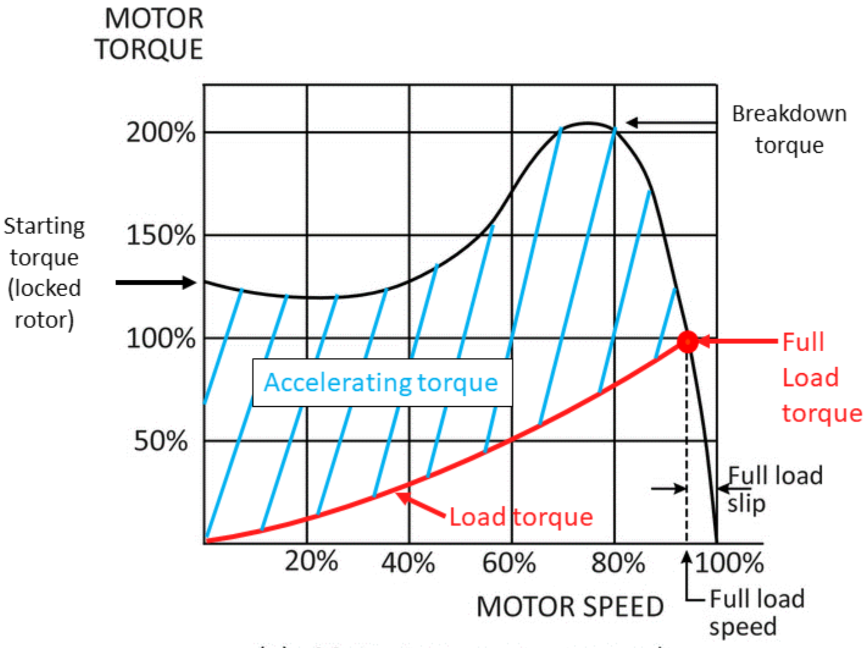


Figure 26 -- Motor torque-speed curve showing accelerating region.

The connected system must be very stable to tolerate the voltage dip resulting from the high inrush current of the induction motor. The actual starting current is identified on the nameplate as Code___. In the blank is a letter from A to V on a per-horsepower basis. The actual current may be calculated by looking up the Code letter in a table in NEMA MG1-10.37.2. This locked rotor kVA will allow you to calculate the locked rotor (starting) current [24]. The starting current is independent of motor load. The motor load only determines how long the starting current remains at the locked-rotor value.

Motor starter contactors are designed so that they close very quickly and energetically to reduce arcing. This causes them to slam against each other mechanically and produce “contact bounce”, causing the circuit to be opened and closed perhaps several times as they rebound. The problem, besides generating some arcing, is that the motor circuit is highly inductive, so when the circuit is opened, you have a large di/dt, and consequent voltage spike. An EPRI Study showed that spikes occur as the 2nd contact closes and bounces. Voltage spikes of 4 to 5 times normal are created upon starting, which cumulatively stress the insulation [8].

Methods are sometimes employed to reduce the inrush current from direct-on-line (DOL) starting, usually by reducing the supply voltage, such as using Wye-Delta starting, which reduces the starting voltage by $V_L/\sqrt{3}$. Since the starting currents are directly proportional to the voltage, this method can be effective. However, the starting torque is reduced by the square of the voltage, so the system must be evaluated to see if the reduced starting torque will be acceptable. Other methods to reduce the starting inrush are stator resistance starting, autotransformer starting, and the use of a double-cage induction motor.

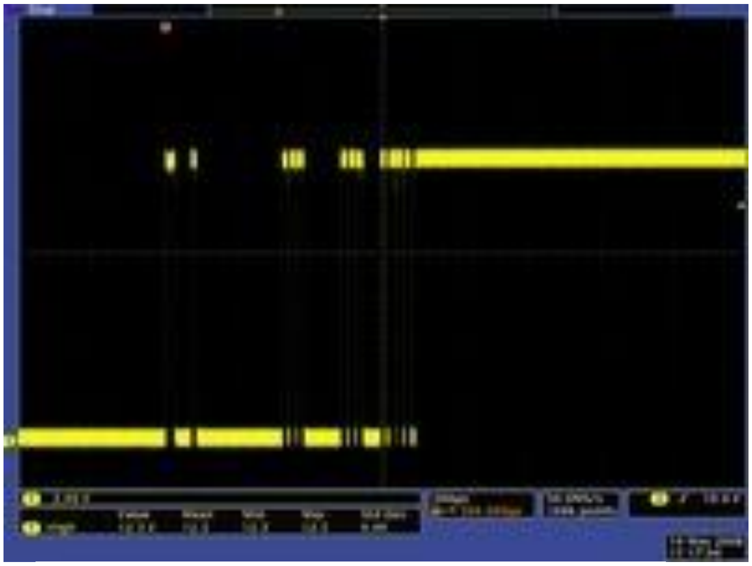


Figure 27 - Contact bounce on a large switch [30]

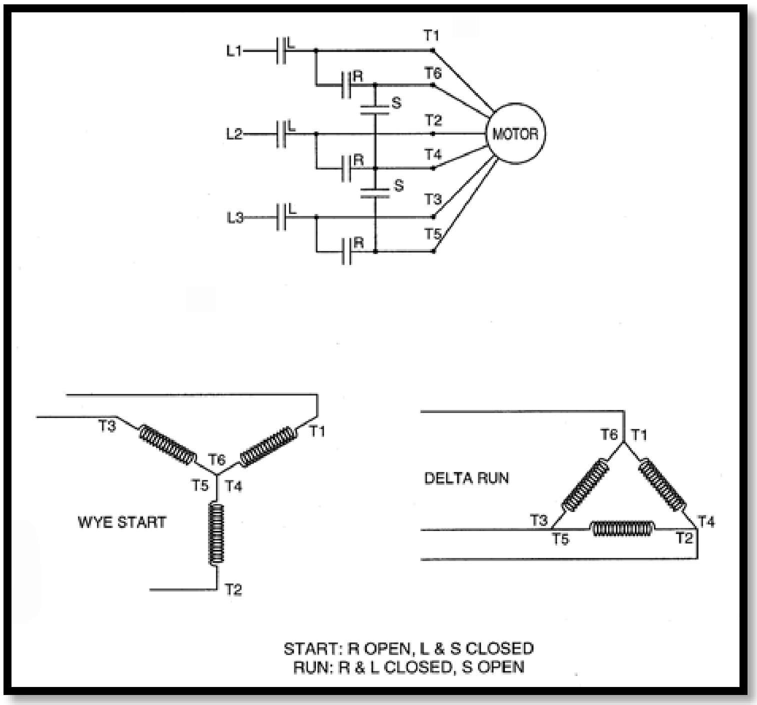


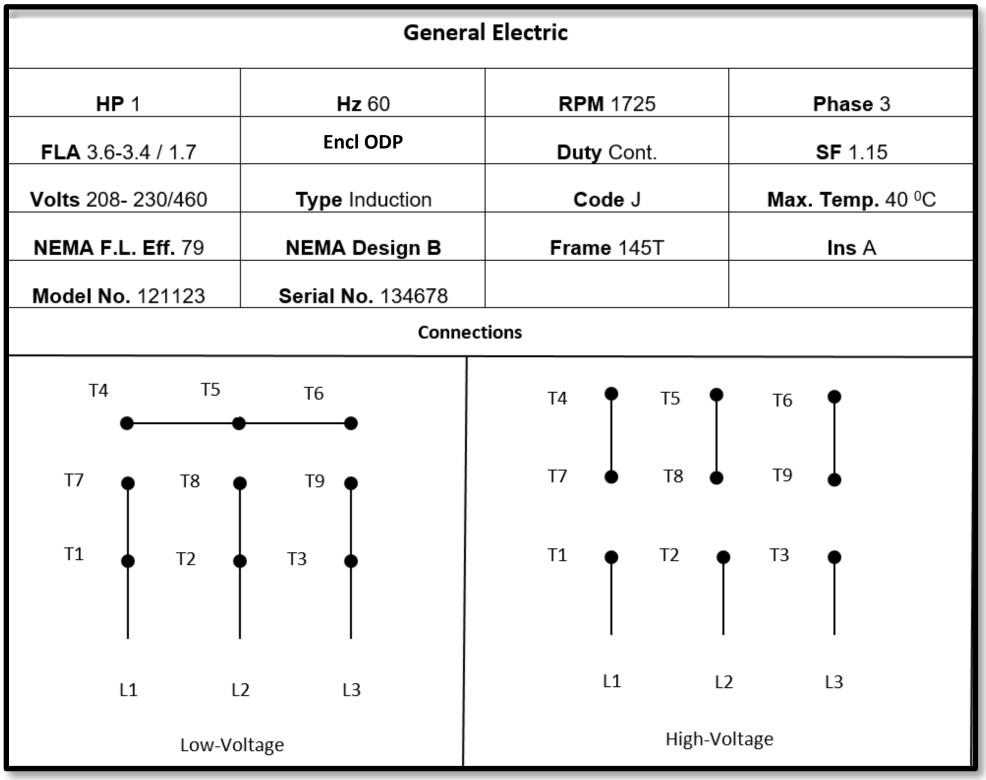
Figure 28 - Wye-Delta starting of a three-phase induction motor [21].

There is even a higher motor inrush current, perhaps 20 times $I_{F.L.}$ for a few cycles, that is rarely mentioned. The same phenomenon can happen when an induction generator is energized, as discussed in the generator section [8].

Nameplate. The National Electrical Manufacturers Association (NEMA) specifies the following data is to be listed on the individual motor nameplates. Because NEMA is an association and not a government agency, it should be noted that not all electric motor manufacturers comply with the NEMA specifications [23].

- Duty Cycle or Time Rating indicates is a measure of how long a motor can operate at a given output without overheating. It is usually expressed as a percentage of the total time period. The motor is rated for continuous duty unless otherwise specified.
- Frame size is a set of physical dimensions indicating the type and size of the motor frame for interchangeability between manufacturers.
- Frequency -- 50 or 60 Hz, which together with the number of poles, establishes the motor's synchronous speed.
- Full-Load Current (FLC) or Full-Load Amps (FLA) is the current drawn by the electric motor when operating at the rated load, rated voltage, and rated frequency.
- Full-Load Speed indicates the speed at which the electric motor will operate at rated load and voltage, which will be lower than synchronous speed due to slip. In the example in Figure 29 the full-load speed is 1725 rpm.
- Horsepower is the amount of output torque the motor can produce at its rated speed.
- Locked Rotor Indicating Code Letter is discussed under starting current below.
- Manufacturer's name.
- NEMA Design Code, letters A, B, C, and D characterize the operating characteristics of AC induction motor based on factors such as starting current, % of slip, breakdown torque, and locked rotor torque.
- Number of Phases
- Rated Voltage. Note that a nominal 480-volt motor may have a nameplate voltage of 460 V to allow for the cable voltage drop will allow the proper voltage of 460 V at the motor terminals. All motors are designed to operate successfully with limited voltage and frequency variations. However, voltage variation (voltage high or low) must be limited to ±10% with rated frequency [24]. Voltage variation is different from voltage unbalance (different voltage between phases), which will be discussed later.
- Service Factor gives the allowable horsepower overloading of the electric motor which may be operated. Sometimes service factor is used to compensate for altitude derating.
- Insulation System Class classifies insulation by its resistance to thermal aging and failure. They are designated as Class A, Class B, Class F, or Class H. These specific letters indicate the temperature each type of insulation is designed to handle over a 20,000-hour period with the electric motor operating at full load. The 20,000 hours is the rated life of the insulation – it can easily last longer.
- Temperature Rise is the rise in temperature in the motor above the ambient temperature at the full load condition. NEMA MG-1 standard establishes four classes of motor insulation. Insulation class and temperature rise are discussed further below.

- Efficiency is the percentage of electrical energy supplied to the electric motor that is converted into kinetic energy. The remaining power loss is mostly converted into heat. The NEMA full-load efficiency indicates the overall efficiency of the AC induction motor. A more detailed discussion is given below.



General Electric

HP 1	**Hz** 60	**RPM** 1725	**Phase** 3
FLA 3.6-3.4 / 1.7	**Encl ODP**	**Duty** Cont.	**SF** 1.15
Volts 208- 230/460	**Type** Induction	**Code** J	**Max. Temp.** 40 ^{0}C
NEMA F.L. Eff. 79	**NEMA Design B**	**Frame** 145T	**Ins** A
Model No. 121123	**Serial No.** 134678		

Connections

Figure 29 -- Nameplate from a small dual-voltage induction motor showing the phase connections. The wiring diagram to the left on the is for either 208 or 230 VAC. The higher 460 VAC connection is shown the right [14].

Enclosures

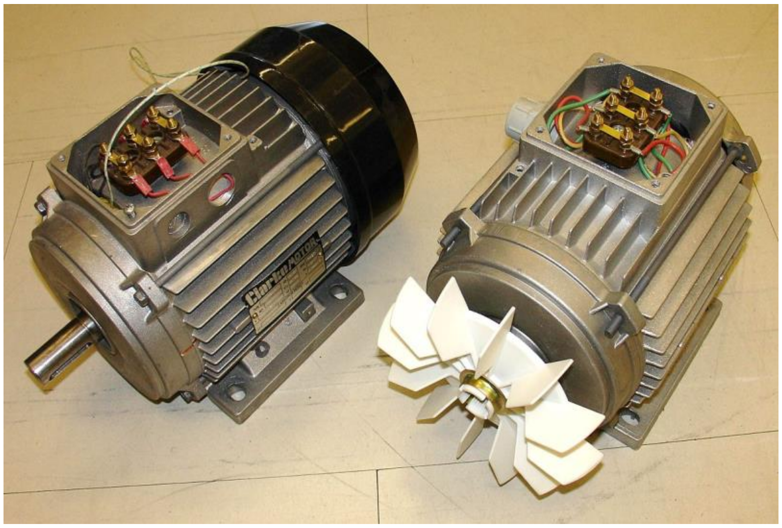


Figure 30-- TEFC motor with fan shroud removed. Picture by Zureks - Pinterest.com

Depending on the application, electric motors will have different types of enclosures. Some of the common enclosures include:

- Explosion-proof (EXP) — these enclosures are designed for areas that have hazardous atmospheres; the end bells and the cylindrical motor housing are totally enclosed and non-vented.

- Open Drip Proof (ODP) — these enclosures are probably the most commonly used. The end bells of the cylindrical motor housing have openings to permit ventilation through the motor windings. The nameplate shown in Figure 14 indicates the motor enclosure is rated ODP.
- Totally Enclosed Fan Cooled (TEFC) — these enclosures are also in common use. The end bells and the cylindrical motor housing are sealed to prevent the entrance of moisture or dirt. Often the outer surface of the cylindrical motor housing is molded with fins to increase the outer surface area of the housing. A fan is normally mounted externally on a jackshaft on the non-drive end of the motor with a protective fan shroud to help cool the motor.
- Totally Enclosed Non-vented (TENV) — these enclosures are designed to be frequently hosed down. TENV electric motors are generally used in harsh environments such as chemical or food-processing plants [23].

Induction Motor Torque.

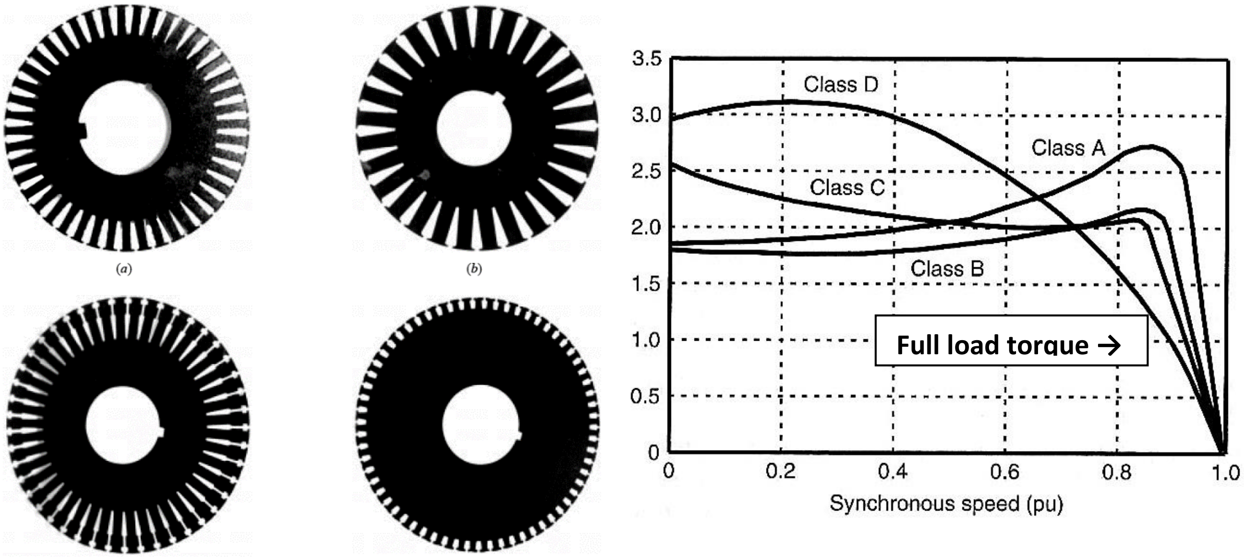


Figure 31 – Laminations from rotor bars and Rotor Torque-speed characteristics for NEMA standard machines A, B, C, & D. [7]

As was noted for the wound-rotor motor, changing the resistance of the rotor produces different motor characteristics. For the squirrel-cage rotor design, different torque characteristics can be achieved primarily by changing the rotor bar design (resistance and reactance). NEMA (The National Electrical Manufacturers Association) is the leading trade association in the U.S and publishes over 500 standards. In NEMA MG-1, they have established a Code letter designation to classify motors by the ratio of locked rotor kVA per horsepower. NEMA MG-1 has standard motor designs with torque, slip and current characteristics to meet the requirements of different loads. NEMA assigns the letters A, B, C and D to identify the torque characteristics [24]. The torque varies from start-up to steady-state speed and is provided in torque-speed graphs. It is not enough to just look at the motor's full-load rating when choosing an induction motor. Of course, the motor must have appropriate full-load torque for continuous operation. But it is also vital that the motor has sufficient starting and pull-up torque to bring the load up to operating speed (the left part of the curve). In addition, it must have sufficient breakdown torque (the right-hand peak of the curve) to overcome peak loads without stalling.

It is desirable for induction motors to have high starting torque and low stating inrush. For good efficiency there needs to be low slip at normal speed. Increasing rotor resistance increases the starting torque and reduces the starting current. But the increased resistance increases the slip, which reduces the converted mechanical power and efficiency, since $P_{CONV} = (1-S)\,P_{AG}$. So, there is a conflict between these two design requirements. To overcome these conflicting requirements, various rotor bar designs are utilized to get the various NEMA torque-speed curves. We want to add extra rotor impedance at start and remove it during normal running, like the wound-rotor design, but without slip rings and brushes or control circuits. It is possible to accomplish desired motor characteristics by taking advantage of leakage reactance and slip frequency in designing the induction motor rotor. Leakage reactance is due to the rotor flux lines that do not couple with the stator windings, shown as jX_2 in the equivalent circuit. The farther away from the stator a rotor bar or part of a bar is, the greater its leakage reactance. For example, in some induction motors, deep bars distribute the rotor currents unevenly due to eddy currents. When the rotor is stationary or turning slowly the frequency of rotor currents is relatively high, and the currents crowd to the top of the rotor bar, and the resistive part of impedance is relatively high. By choosing bar cross-sectional dimensions, it is possible to obtain a starting rotor resistance (60-Hz resistance) that is many times the running rotor resistance (which is almost the dc value). As the rotor speeds up to a value close to synchronous, the rotor current frequency becomes very low, the reactances of all parts of the bar become almost equal, and the current density over the conductor cross-section becomes nearly uniform so that it offers a resistance almost equal to its dc value.

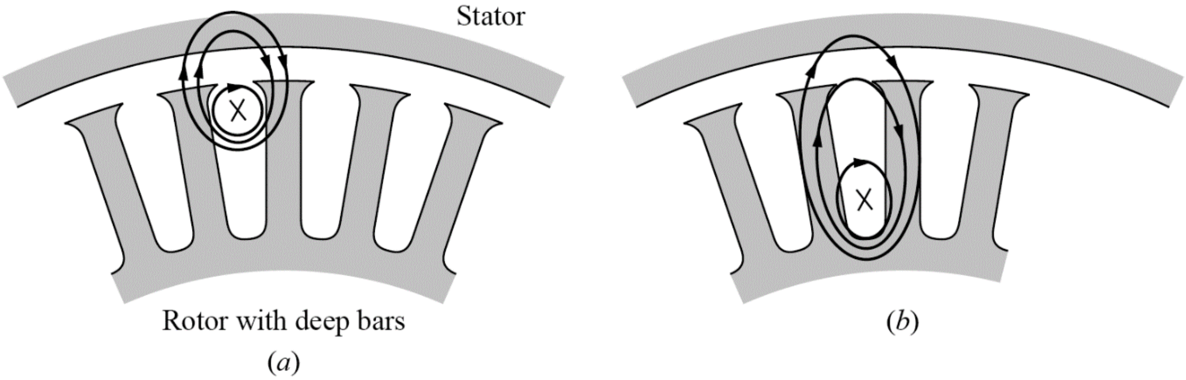


Figure 32 -- If the bars of the cage rotor are placed near the surface of the rotor, they will have small leakage flux and X_2 in the equivalent circuit will be small. If the bars of the cage rotor are placed deeper into the rotor surface, there will be more leakage and X_2 will be larger. Illustration [7] & caption [9]

- **NEMA B** is the most common torque characteristic. The starting torque is low, about 140% of full-load torque. Starting current is also low, less than five times the full-load current. The slip is less than 5%. This design uses deep bars with skin effect, or double-cage rotors. Typical applications: general use, machine tools, and fans. If the motor must handle heavy overloads for a short duration, like an injection molding machine, **NEMA A** can be used, as its breakdown torque is very high (300%). However, the starting current will also be high, as much as eight times the full-load current. This design has low slip and high efficiency due to its low-resistance rotor.

- **NEMA C** has greater rotor resistance and is the most expensive. It is considered to be a constant torque motor. It starts and accelerates at 225% of full load and has greater slip at full load. Its rotor is typically constructed as a deep bar or double-cage design (also invented by Dolivio-Dobrovolsky), with large, low-resistance bars buried deep in the rotor and small, high-resistance bars near the rotor's surface. Because one of the cages contains smaller conductors, it cannot tolerate long acceleration times. Typical applications: loaded compressors and conveyors.
- **NEMA D** motors have even more rotor resistance, so the maximum torque occurs at near zero speed, giving it a strong starting-torque. But it has greater losses at full-load and high slip. Starting torque is 270% of full load torque. This characteristic is accomplished using a single high-resistance cage with bars near the surface. Typical application: punch presses, flywheel energy storage and lifting apparatus. [7] [8] [33].

Broken rotor bars. Although the squirrel-cage rotor is very robust, one of the most common faults is broken rotor bars, which account for approximately 10% of the total induction motor failures. The rotor will show torque and speed oscillations under load, which disappear when the load is removed and the motor is coasting, because a broken rotor bar cannot carry current.

Repeated starting, thermal expansion and centrifugal forces are some of the causes of breakage. Also, during starting, rapidly alternating forces are applied to each rotor bar by the rotating magnetic stator field, diminishing in intensity and frequency as the motor accelerates. The longer the starting period, the more cyclic forces the rotor cage must endure. The broken bars unbalance the geometry and magnetic flux of the motor and may cause sparking. The healthy adjacent bars are forced to carry additional current leading to rotor core damage from persistent elevated temperatures. A motor current analysis,

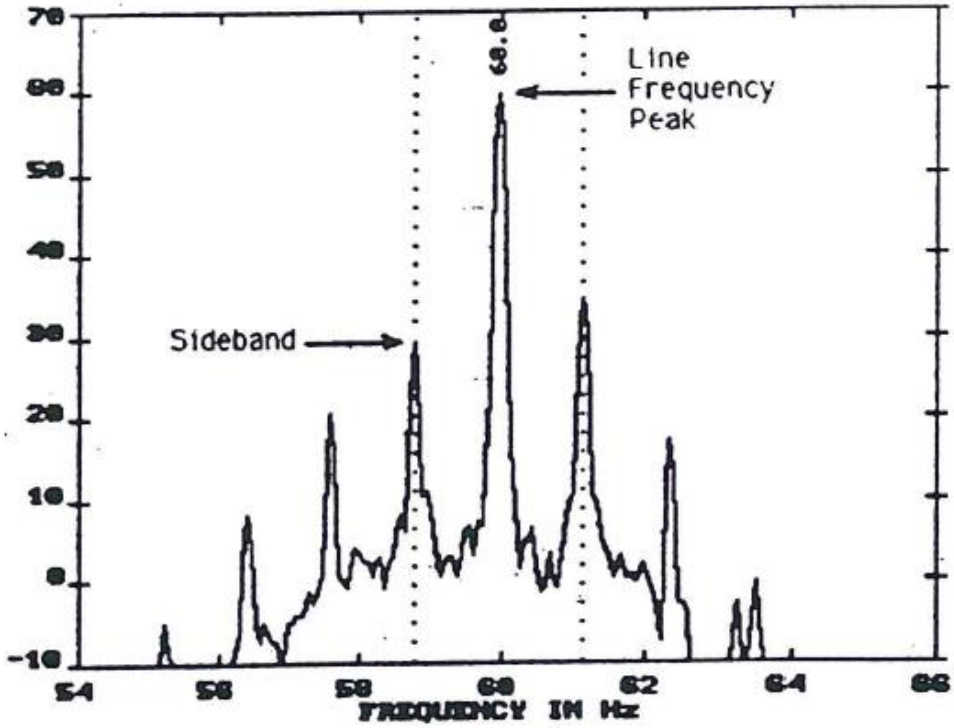


Figure 33 -- Current spectrum of a bad rotor under load showing sideband frequencies.
[Credit: Methods of Detecting Cracked Rotor Bars in Electric Motors Heconic.com]

called a current spectrum test, can be performed while the motor is under 50 - 100% load. The stator currents due to the broken bars appear as side band frequency components ($(1 \pm 2s)f_s$) Hz where f_s is the supply line frequency and s is the slip. By comparing the sideband amplitudes, you can estimate the number of broken rotor bars. This test is the most accurate and reliable.

Voltage unbalance. Voltage unbalance can be defined as a voltage variation in a power system in which the voltage magnitudes or the phase angle differences between them are not equal. Three phase induction motors are designed and manufactured to operate with balanced supply. Unbalanced line voltages are usually due to single phase loads not connected evenly across the three-phase system, and due to generation faults, unmatched impedance on transformer banks, high-resistance connections, worn starter contacts, overloads failing, a blown capacitor or the opening of one fuse. Voltage unbalance can pose serious problems to the induction motors. Excess power loss, excessive temperature rise, torque reduction, and torque vibrations are the major consequences of the unbalanced voltage. When an induction machine is supplied with a three-phase balanced voltage supply, it creates a circular rotating magnetic flux in the air gap, as shown in Figure 39.

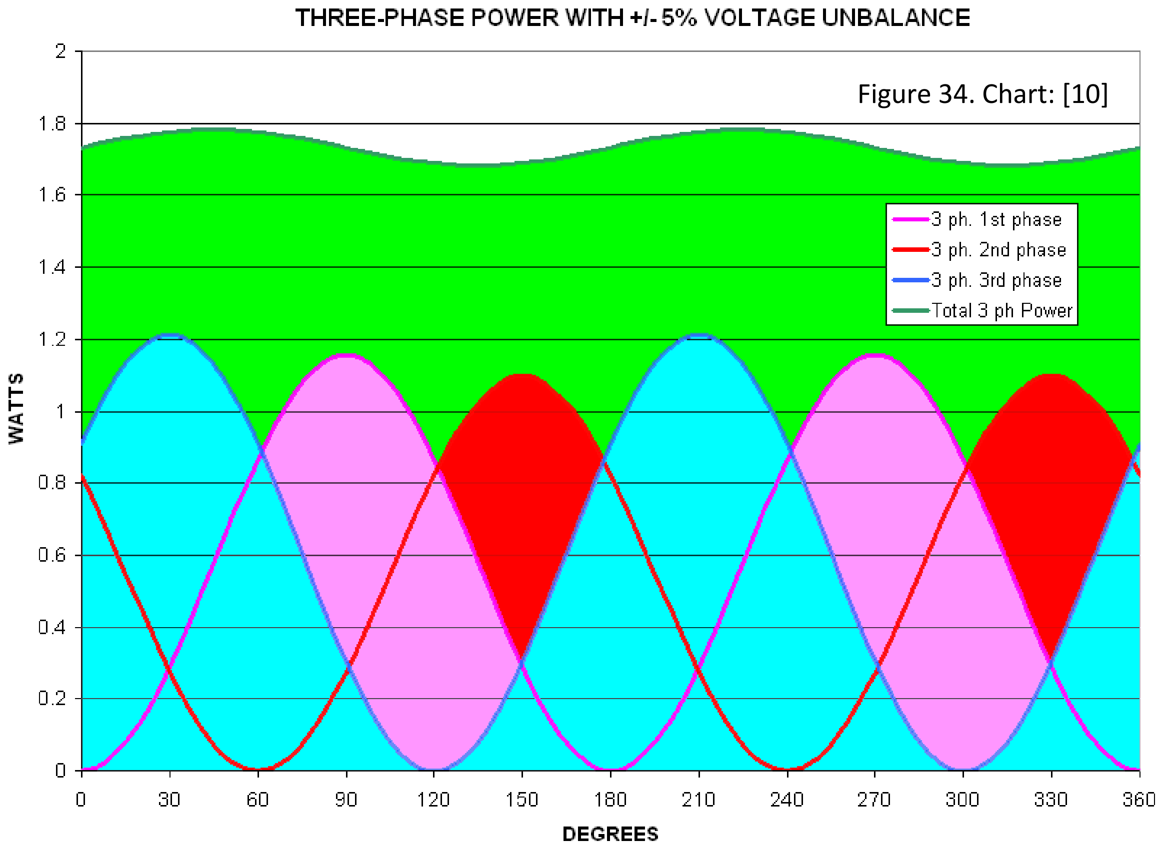


Figure 34. Chart: [10]

When applied to the stator of a polyphase motor, unbalanced sinusoidal voltages result in unbalanced currents in the stator windings, and unequal power contributions from each phase. Figure 34 shows the pulsations in the three-phase power (the area under the green curve), using phase voltages and currents of +5%, 0% and -5%. The power contribution from each phase is shown in the three lower curves.

For solving unbalanced polyphase circuits, symmetrical components analysis, first proposed by C.L. Fortescue in 1918, is normally used. Unbalanced voltages in a three-phase power system can be represented by the superposition of three balanced symmetrical three-phase systems -- two have opposite phase sequences. So, in addition to the forward (positive sequence) rotating field, there is a negative-rotating field. There is a third non-rotating field of zero phase sequence, i.e., ordinary single-phase current or voltage. Here we are considering a three-wire machine, so the zero-sequence component does not exist. The positive sequence torque is in the same direction as the supply voltage (A→B→C), while the negative sequence torque is in the opposite direction (A→C→B). Both of those currents produce rotating magnetic fields of their own. The total power crossing the air gap is the sum of the power of the positive and the negative sequences. The negative-sequence current produces a backward (negative sequence) air-gap flux that rotates against the direction of rotor, producing a braking torque and high currents. The negative sequence component cannot contribute to energy delivery in the positive direction. So, the negative sequence power crossing the air gap totally contributes to the machine's losses. This means there will be a reduction in the overall torque when the supply is unbalanced.

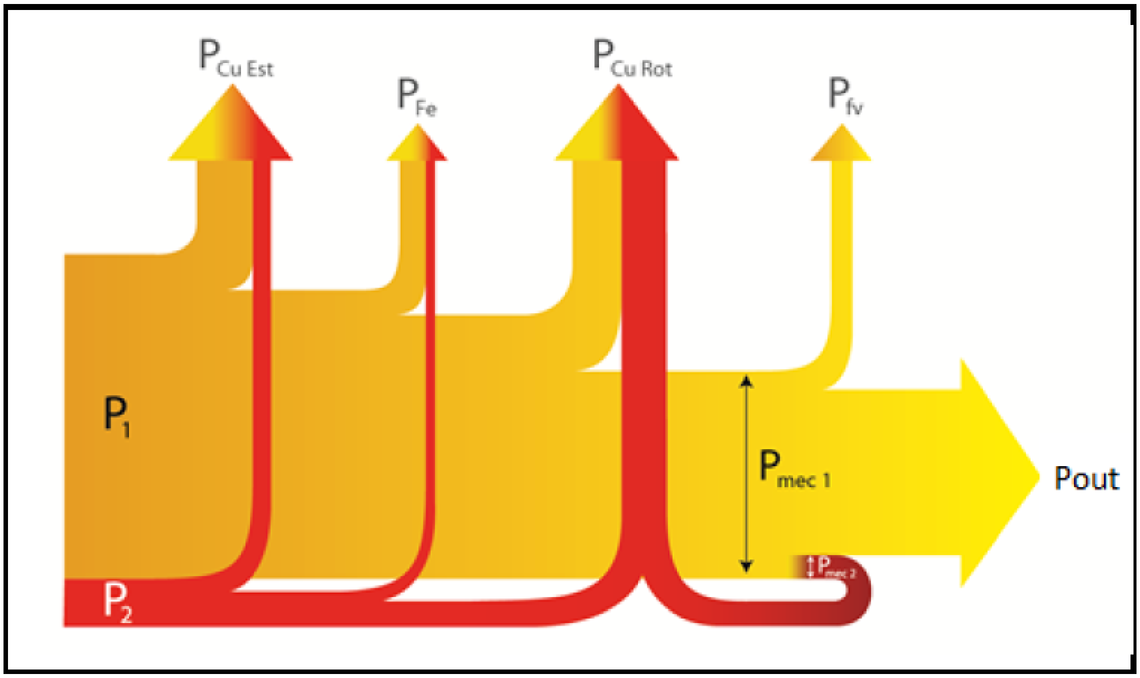


Fig 35 Induction motor power flow operating under unbalanced conditions using the positive and negative sequence equivalent circuit. [45]

Power dissipated as losses in the negative sequence rotor resistance has two sources: the air gap power of the negative sequence source and extra positive-sequence torque which is expended in overcoming the torque produced by the negative sequence magnetic field. The ripple in the power output is at double the line frequency (100 or 120 Hz). It causes vibration, acoustic noise, and shortening of the machine's life. Although induction motors are designed to tolerate a small level of unbalance, they must be derated if the unbalance is excessive. Even a small negative sequence voltage may produce a much larger percentage of negative-sequence currents, resulting in currents considerably more than those present under balanced voltage conditions. This excess current increases the temperature rise, causes increased I^2R losses, increases the slip, and decreases the locked-rotor, rotating and accelerating torques [34]. The negative sequence component cannot convey energy to the motor mechanical load. This energy is dissipated as losses. The positive and negative sequence impedances are different, with the negative sequence impedance being much smaller.

Even if the unbalanced voltage applied to the motor is small, a high amount of negative sequence current can flow because of high slip and relatively low negative sequence impedance [34]. The motor rotates at a different slip with respect to the negative sequence voltage. The negative sequence voltage has a speed of -Ns and tries to rotate the motor in the opposite direction, resulting in a decreased percentage of productive current, and poor motor efficiency. Our formula for positive sequence slip is S_1 = (Ns-Nr)/Ns. So, the slip for the negative sequence is S_2 = (-Ns-Nr)/-Ns = 2-S_1 [36].

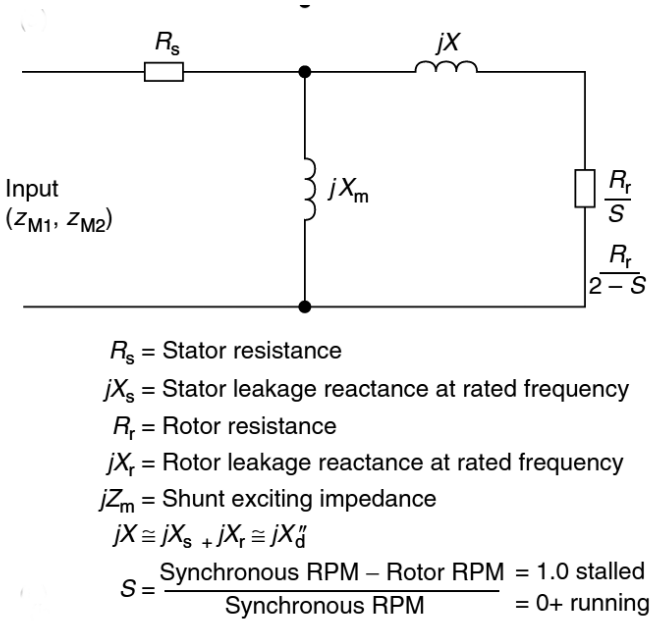


Figure 36 -- Simplified equivalent circuit showing different positive and negative sequence impedances. [35]

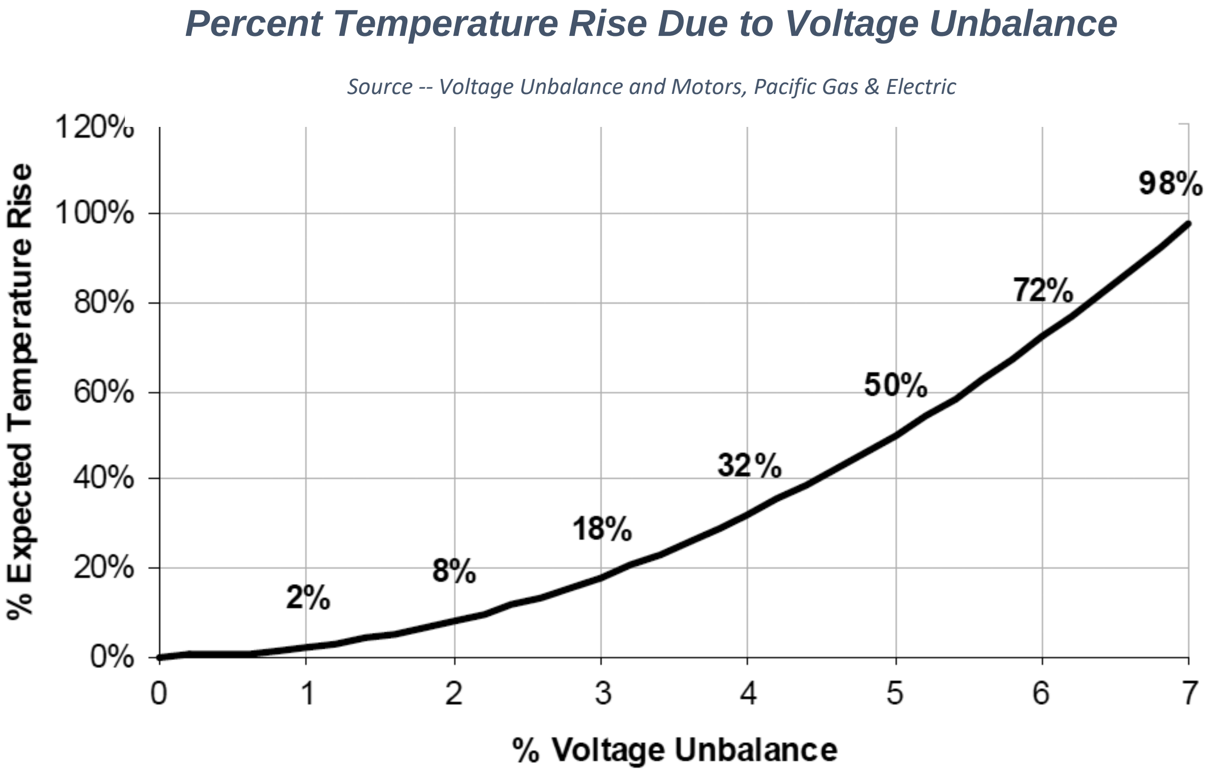
The positive sequence slip S_1 is normally very small (close to zero), the negative sequence slip S_2 is much larger (close to 2). For our motor in Figure 14 with Ns = 1800 rpm and Nr = 1725 rpm, the positive sequence slip S_1 is 0.0416, and the negative sequence slip S_2 is (2 – 0.0416) = 1.96. The negative-sequence-generated magnetic flux induces high-frequency currents in the rotor. The negative sequence rotor frequency in this example is $fr = Sf$ = 1.96 X 60 =117.5 Hz, i.e., almost double the line frequency. The resistance for negative sequence current is about 1/6th of the positive sequence current which means a small unbalance in voltage waveform will produce a negative sequence voltage that will cause a high amount of negative sequence current to flow in the rotor and produce larger losses. A three percent voltage unbalance results in a 17% current unbalance. Thus, an induction machine can be regarded as an amplifier of current imbalance. Although 3% voltage unbalance may not seem like much, a current unbalance of 17% is very high. [33]. Any unbalance above 3% hampers the motor's efficiency. If the motor is fully loaded, some stator phase windings and the rotor itself will carry this extra negative-sequence current, causing extra motor losses. The motor's torque and speed will fluctuate, causing more vibration.

Voltage Unbalance factor according to NEMA = VUF = 100 x $\frac{Maximum\ Voltage\ Deviation}{Average\ Voltage}$

For our example of Figure 34, if the voltages are 95V, 100V and 105V, the average is 100V, and the maximum voltage deviation is 5V, giving 5% voltage unbalance.

At 4% imbalance, the de-rating is about 0.82 meaning that almost 20% of the current flowing to the motor will not be producing real power. The motor's current will increase to match the equipment's torque needs, the machine's speed will be reduced to meet the load requirement, and the slip will increase, lowering efficiency. The extra current will result in proportional copper losses in motor and cable. The relationship is exponential and increases by approximately twice the square of the percent of voltage unbalance. A 3.5% voltage unbalance will cause an approximate 25% increase in temperature rise in the phase with the highest current [32]. NEMA standards state: "Operation of the motor with more than 5% voltage unbalance is not recommended". The international counterpart of NEMA is the IEC. IEC 60034-26 has its own definition of the Voltage Unbalance Factor, which is the ratio of the negative to the positive sequence voltage components.

In the next section, we will discuss the effect of temperature rise on insulation life.



Percent Temperature Rise Due to Voltage Unbalance

Source -- Voltage Unbalance and Motors, Pacific Gas & Electric

Figure 37 -- Expected temperature rise with each percent voltage unbalance.

An induction machine is designed to work under sinusoidal symmetrical voltages, creating a circular rotating magnetic flux in the air gap of the machine. The magnitude of this rotating magnetic field is equal to 3/2 times of one phase's magnetic field peak value.

When the voltages are asymmetrical, the motor's positive- and negative-sequence fields resulting from those currents produce an elliptical rotating magnetic field in the air gap rather than a circular one as shown in Figure 39. [37]

Single Phasing of a three-phase motor. The worst possible case of phase voltage unbalance is the total loss of one of the three phases which is called "single phasing". If the motor is star connected, the phase B current will be the negative of the phase C current, because phase A is no longer available, and the two remaining phases are now in series. Single phasing produces an extreme elliptical rotating magnetic field in the air gap as shown by the red curve in Figure 38.

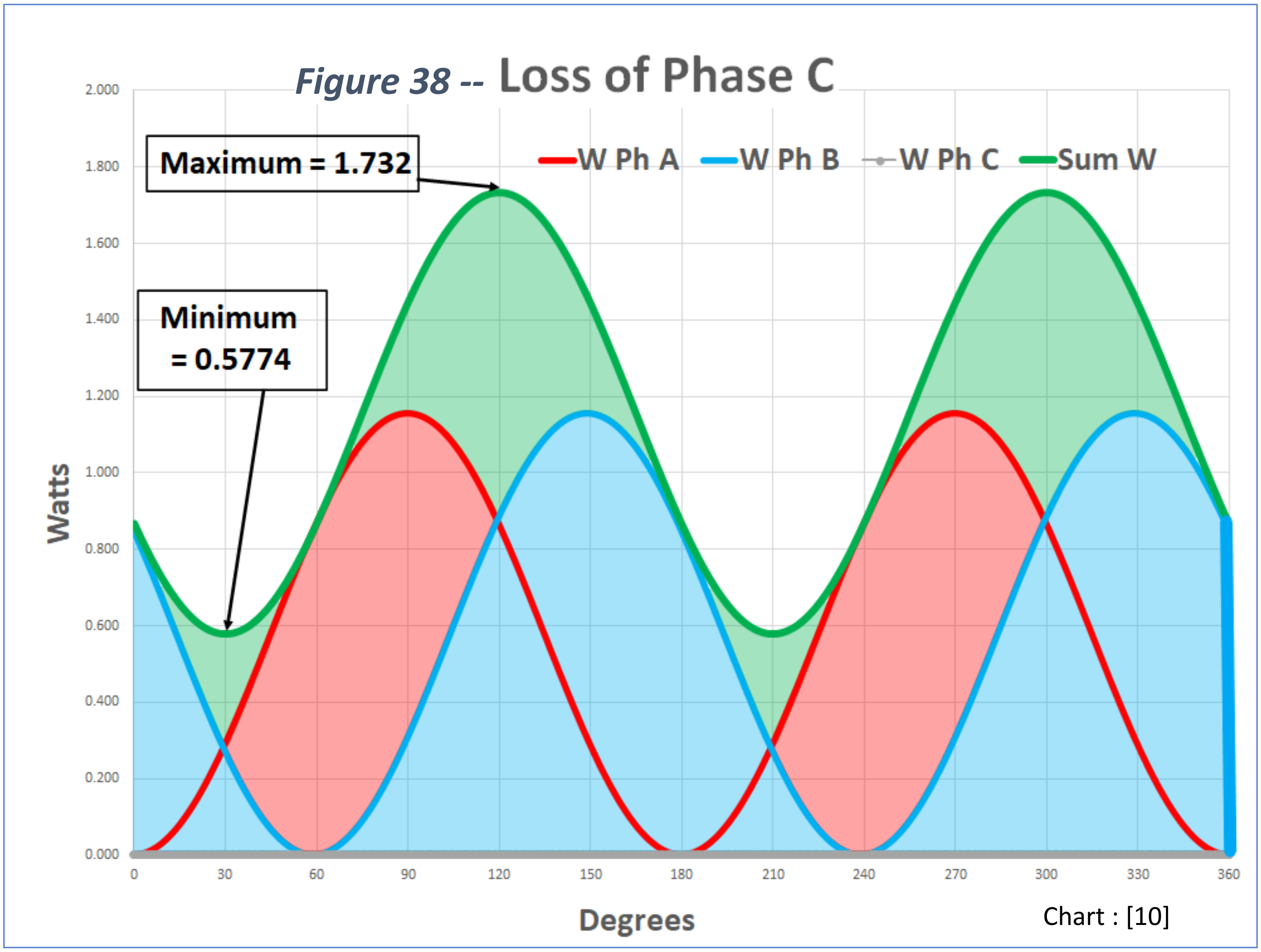


Chart : [10]

If the motor is single phased, it loses all starting torque, leaving the equipment in a high-current 'locked rotor' condition, which will overheat and damage the motor rapidly. Breakdown torque will be reduced to 40 to 50% of full-voltage values.

If a motor is already running, it will attempt to deliver enough horsepower to continue to drive the load. At low to moderate load, the motor will continue to operate with increased slip, but the current in the remaining connected windings will increase to try to maintain the power required by the load. There will be heavy noise and double-frequency pulsation. Total rotor heating loss is the sum of positive and negative sequence rotor I^2R losses. As current unbalance increases, negative sequence rotor I^2R losses increase rapidly. Rotor heating due to negative sequence I^2R losses is just as real as heating due to positive sequence current. The motor winding temperature will rapidly increase, which breaks down motor insulation causing cumulative and permanent damage to the motor. At higher load, near to the rated load, motor's load will exceed the reduced breakdown torque, and the speed will drop gradually to zero with correspondingly high locked-rotor current. Low voltage motors typically use heaters and bimetallic or solder trip elements to attempt to duplicate motor heating characteristics. If properly sized, and applied to trip all three phases, the motor starter's thermal overload relay should trip, and stop the motor before it burns up. [38], [39] and [40]

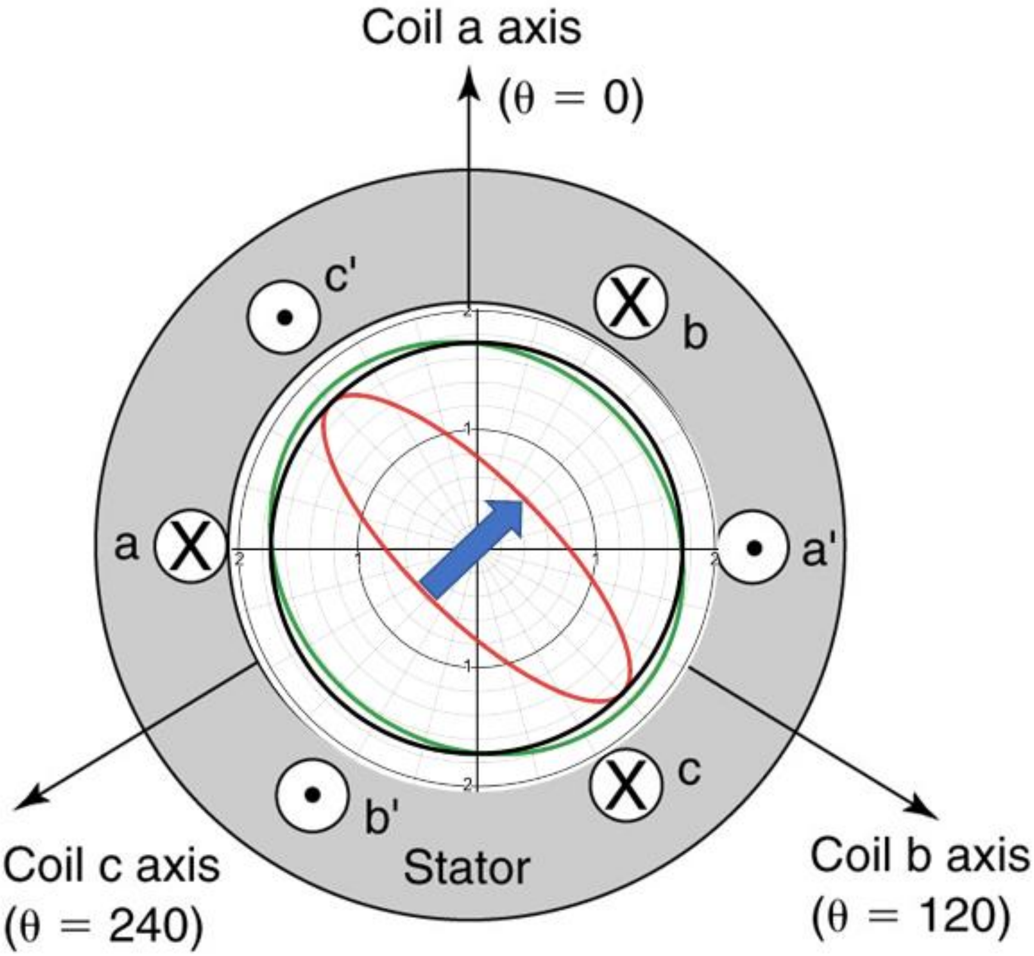


Figure 39 – Black curve – A balanced three-phase magnetic field will be circular. Green curve – Elliptical magnetic field caused by unbalance in the three-phase voltage and currents of 95%, 100% and 105%. Red curve – loss of one phase. [10]

In NEMA MG1 20.24.1, they have developed a derating curve as shown by Figure 40. Section 20.24.2 gives the formula for calculating the percent voltage unbalance, which is defined as the ratio of the maximum phase deviation to the average phase value, in percent. This curve assumes that the motor is already delivering the rated load. According to this curve it is required that any motor should be built to handle 1% unbalance, and thereafter it should be derated depending on the level of unbalance.

If the induction motor is oversized to accommodate the extra current, it may not operate at the best efficiency and power factor. Otherwise, a higher class of insulation must be used.

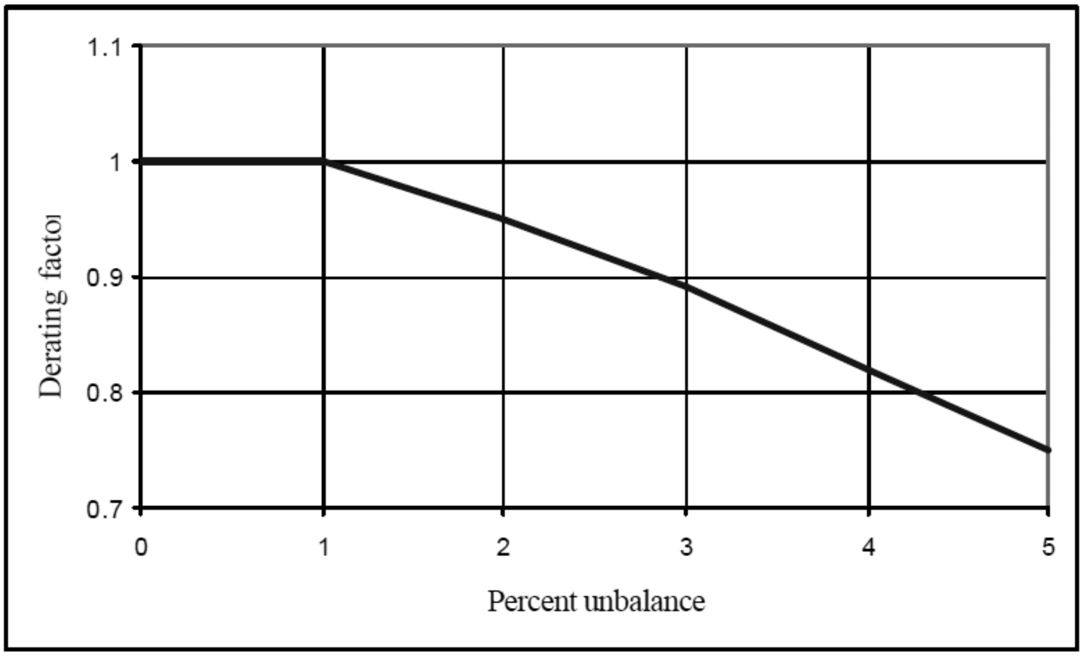


Figure 40 -- NEMA induction motor derating curve for voltage unbalance*. NEMA MG 1-2016 Large Machines—Induction Machines 20.24.1, Effect on Performance—General*

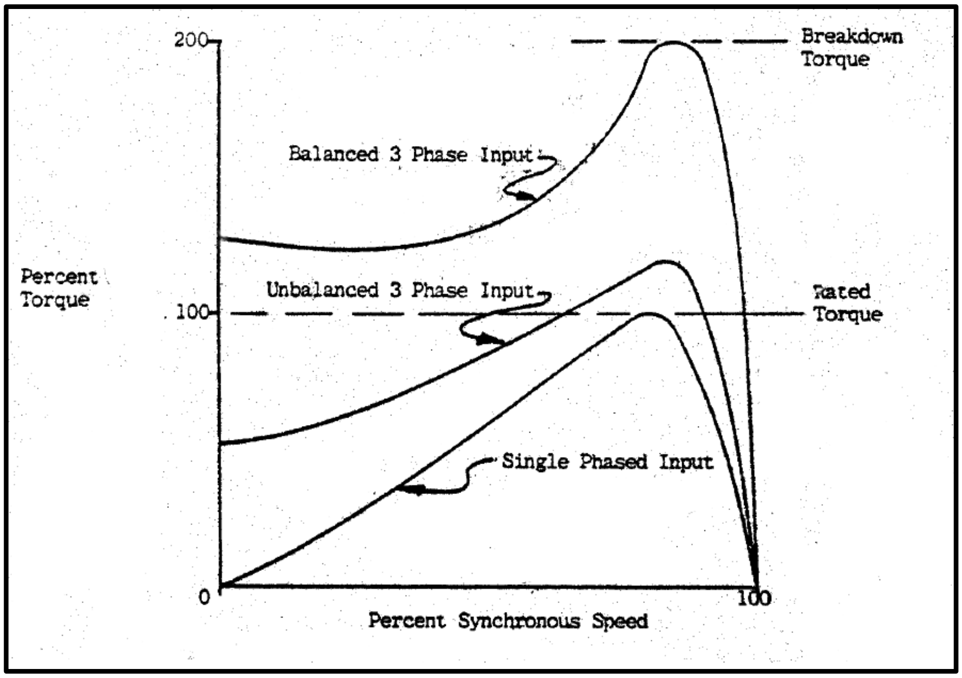


Figure 41 -- Speed torque curve for balanced and unbalanced supply voltages [39]

Harmonics. Power electronic equipment and computer power supplies commonly present in the power system are also responsible for causing current and voltage distortion.

Insulation [8] . . . is a critical part of a motor or generator. Insulation repairs are extremely difficult and expensive. No insulation is perfect (has infinite resistance), so some current flows along the insulation or through it to ground. Good insulation has high resistance to current flow and the ability to maintain that high resistance over time. Causes of insulation failure include:

- System disturbances, such as stress due to lightning, voltage spikes and VFDs.
- Mechanical movement caused by thermal expansion or contraction which can wear away the insulation. The same magnetic forces that turn the motor's rotor cause winding movement during normal operation, at startup and during faults (heavy currents). Movement is greatest at startup and at hot temperatures.
- Mechanical damage -- nicks and blemishes in the insulation during manufacturing, coil winding or maintenance.
- Thermal aging. Insulation ages exponentially with respect to an increase in operating temperature. Higher temperatures cause lower insulation resistance.
- Overloading, high ambient temperature, contamination, or obstructed ventilation, increasing the insulation temperature and reducing thermal life.

Insulation Temperature – How hot is too hot? Insulation life refers to the gradual aging and degradation of the system's insulating properties. If the insulation degrades to a point where it cannot withstand the applied voltage, a short-circuit of the windings can occur. High winding temperature is one of these degrading factors. Thermal deterioration occurs when insulation is heated beyond its design temperature, causing the breakdown of chemical bonds in the insulation material, and making it brittle. All motors are rated for 40^0 C ambient, which is the maximum surrounding air temperature. A fully-loaded motor adds a certain amount of temperature rise to the ambient temperature. NEMA has four commonly used insulation classes designated by letters A, B, F, and H. These classifications are directly related to maximum temperature and motor life. The temperature capabilities of each insulation class are defined as being the maximum temperature at which the insulation can be operated to yield an average life of 20,000 hours. Operating a CLASS F unit at a hot spot temperature of 155 C does not mean the insulation will only last 2.3 years. This is simply the 50% loss of strength point, not the end of life. The insulation can easily last longer. There is a "ten-degree rule" that applies to motors, generators, and transformers. For these pieces of air-cooled equipment operating at above-rated temperatures, insulation life is cut approximately in half for each 10° C. Want to know why? Look up the Arrhenius equation of 1899. Likewise, for each 10 degrees of unused insulation temperature capability, insulation life will be doubled. Therefore, Class F insulation with a Class B temperature rise gives us a thermal margin of 25°C, potentially increasing the life of the motor by up to 5 times 100,000 hours). The temperature rise for the insulation classes, including a hot spot allowance, is shown below.

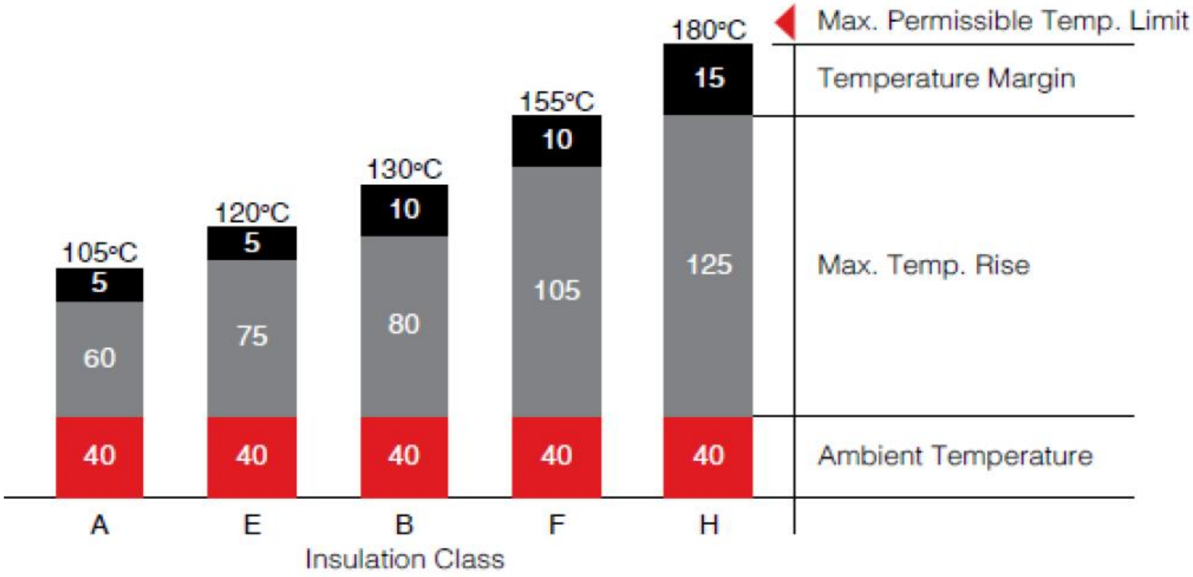
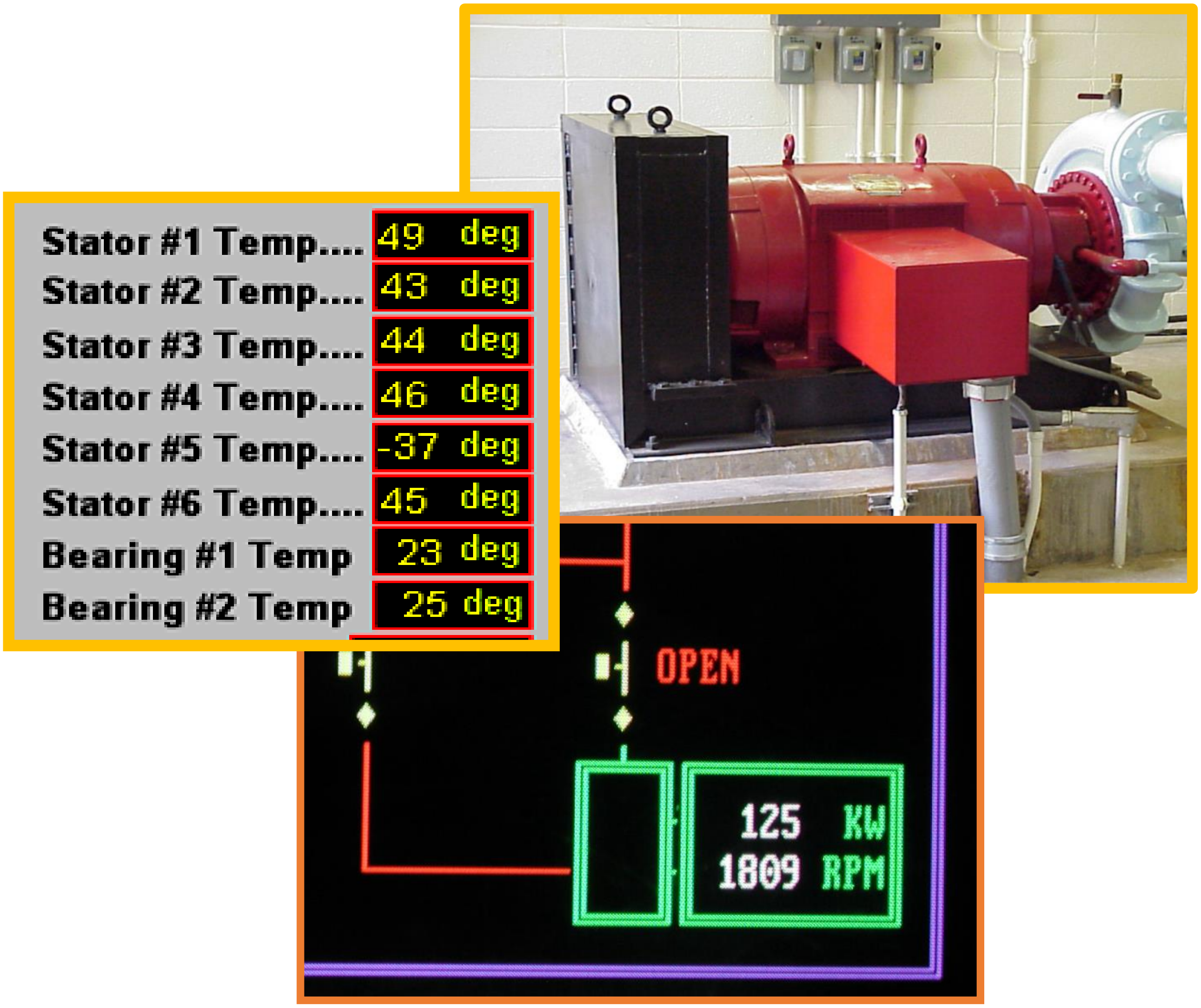


Figure 42 – Insulation Class and Total Temperature. *Image credit Ebitt Motor Katalog R01 Europe*

The most common method of measuring temperature rise of a motor involves taking the difference between the cold and hot ohmic resistances of the motor winding once the motor has achieved thermal equilibrium under load and applying a formula. The resistance of the winding is a function of the winding's temperature. This test gives the average temperature change of the entire winding including the cooler motor leads and end turns, as well as wire placed deep inside the stator slots. Since some of these spots will be hotter than others, an allowance factor is an attempt to correct the average temperature to give a reflection of what the temperature might be at the hottest spot. This Temperature Margin is called the "hot spot allowance", and is 5° to 15° degrees C.

Many motors and generators utilize an RTD (Resistance Temperature Detector) which is a passive sensor whose resistance increases as the temperature of the sensor increases. These sensors are embedded in the windings. Knowing the sensor's resistance change per degree of temperature change, the sensor's resistance can be converted to temperature. The resistance of the sensor is measured by passing a small electrical current through the sensor to generate a voltage. Three-wire sensors are common, with the third conductor added to allow the measurement to factor out the resistance of the leads. It is good to have two RTDs per phase, in case one goes bad. Bearing temperatures should likewise be monitored.



Stator #1 Temp.... 49 deg
Stator #2 Temp.... 43 deg
Stator #3 Temp.... 44 deg
Stator #4 Temp.... 46 deg
Stator #5 Temp.... -37 deg
Stator #6 Temp.... 45 deg
Bearing #1 Temp 23 deg
Bearing #2 Temp 25 deg

Figure 43 -- 225 kW Induction machine used as a generator. RTD readout. One RTD has failed. [10]

Derating for altitude. The air's heat-transfer capacity determines an air-cooled motor's ability to cool itself. The usual derating factor for output power (kW or horsepower in NEMA MG-1 is based on altitude, but this is an approximation. The rule of thumb is that you should de-rate your motor by 3% for every five hundred meters (1,640 feet) of altitude gain above 1000 meters (3,280 feet) above sea level. There is no derating between sea level and one thousand meters altitude. The rating of standard motors assumes a 40^{0}C ambient (immediate surroundings or vicinity).

Reference [11] states that: "ANSI Standards describe an "unusual service condition," as "altitudes above 1000 m (3300 ft). This condition is not a bit unusual in Colorado and Wyoming, and the machine must be derated accordingly." Actually, the constraint is a combination of temperature, humidity and barometric pressure which together determine the relative air density. "Motors having a service factor of at least 1.15 will operate satisfactorily at a unity service factor at an ambient temperature of 40°C up to an altitude of 2740 m (9000 ft)" [11]. There is also a complex calculation you can do to find the exact amount of de-rating you need to apply for your specific motor and altitude, or you can find manufacturers tables which give a de-rating percentage. An increase of one insulation class, for example from B to F, can make the motor suitable for operation in high elevations [29].

Infrared thermal inspection. Infrared cameras, also called thermal imagers, are a good screening tool for inspecting motors, generators, switchgear, and bearings. You can see what is going on while the equipment is running and locate normally invisible abnormal heat patterns. The equipment should be operating at least 40% load and no more than 40 degrees C.

The insulation is subject to normal day-to-day voltage spikes which it can withstand if it is in good condition. A common failure point in the form-wound insulation system is the “knuckle”, where the coil is bent into the required shape during manufacturing. This bending mechanically stresses the insulation. Furthermore, the knuckle is suspended in the air and unsupported by the stator core. Other factors deteriorating the insulation are mechanical movement and rubbing of the windings, torque transients, heat, contamination, and other environmental contaminants. Once the dielectric strength of this insulation falls below the incoming voltage spikes, a spike will puncture the insulation and cause a short circuit to occur. At this point a turn-to-turn or hard-welded short develops between conductors of the same phase winding. This fault causes a large circulating current to flow in the shorted turns, since it acts like a short-circuited autotransformer. Usually, the hot insulation then fails to ground.

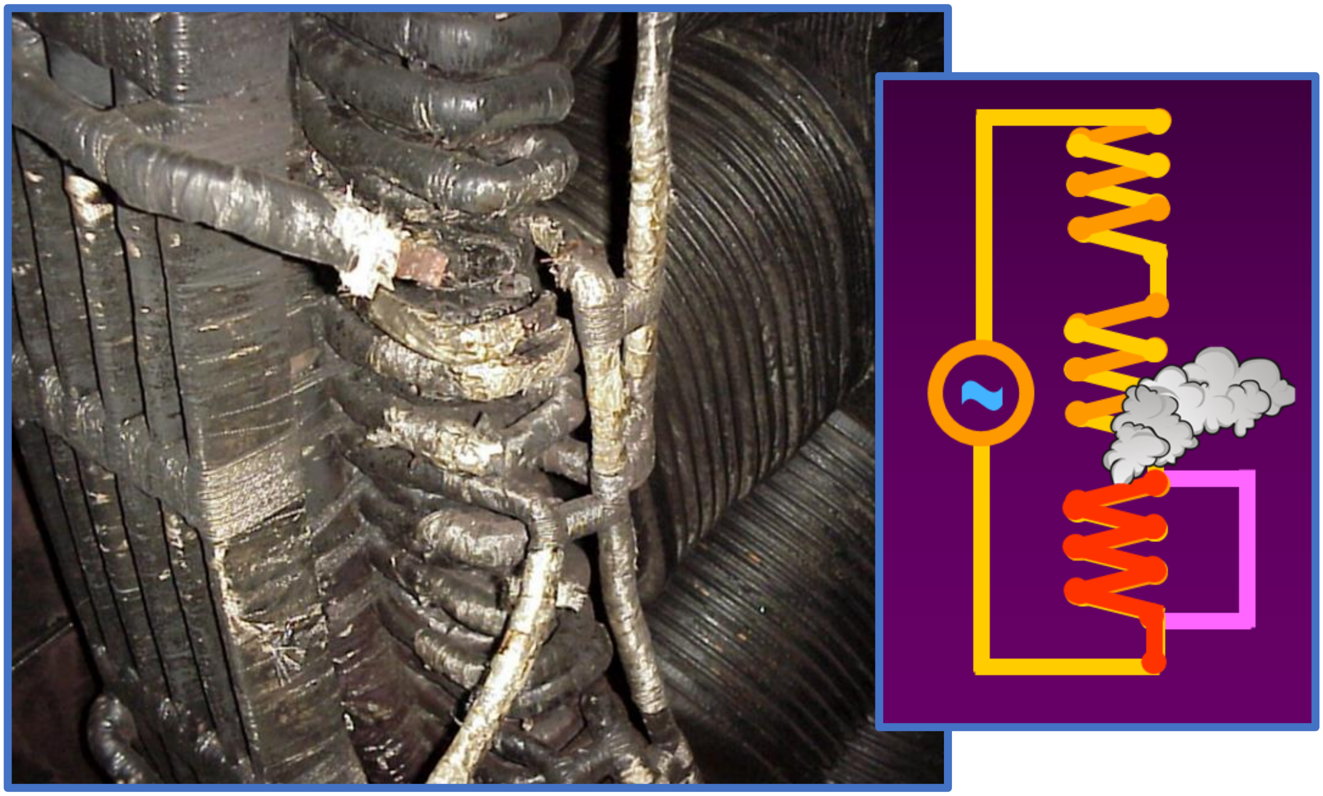


Figure 44 -- Knuckle blown out by a fault on a 3 MW generator after 30 years of operation. The turn-to-turn short makes the winding act like an autotransformer. [10]

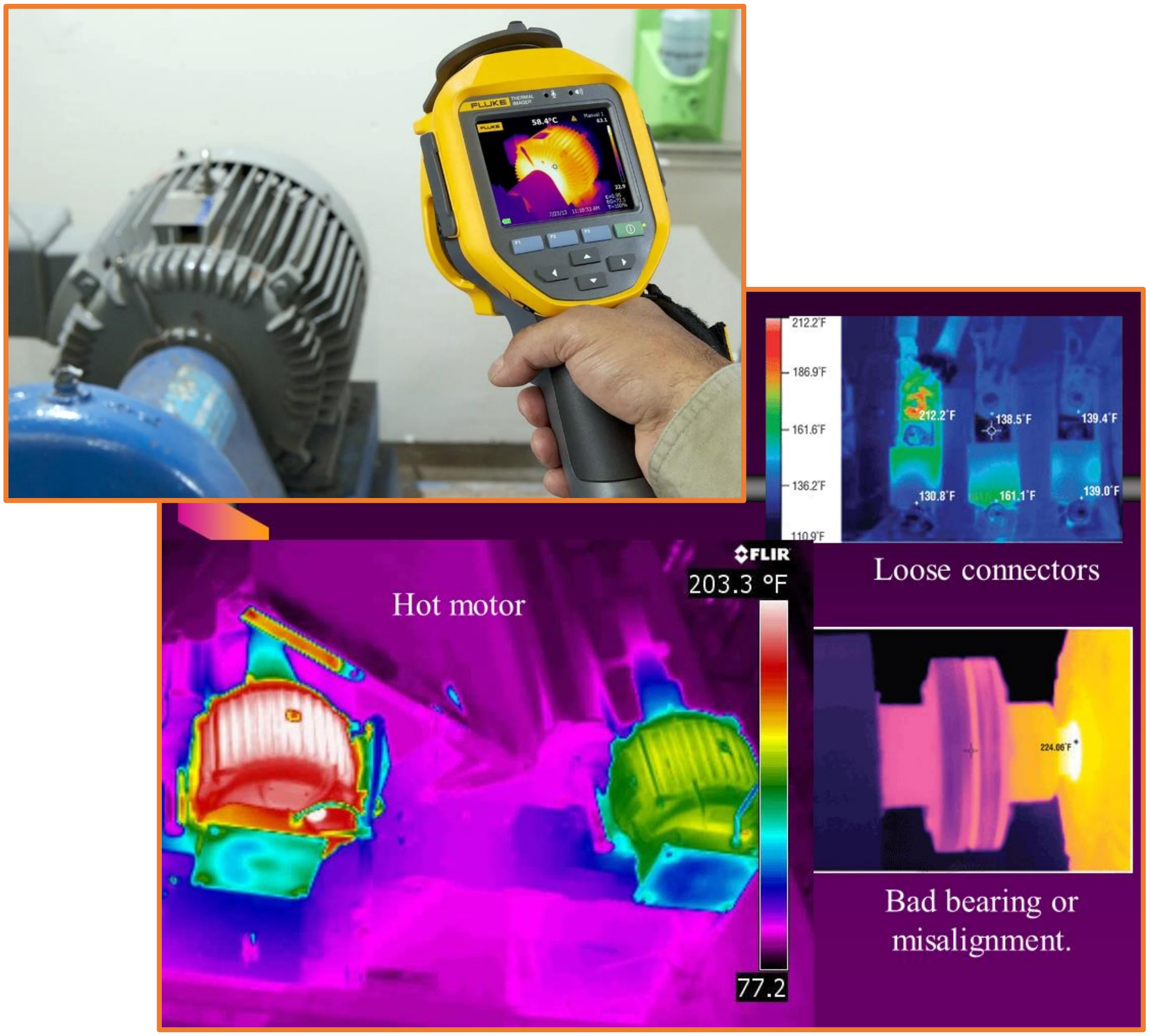


Figure 45 -- Infrared inspection shows hot motor, loose electrical connection, and hot bearing. [10] and Fluke Corp.

Amortisseur winding. The induction motor is self-starting, which means that it will turn in the direction of the stator's rotating magnetic field without any external force to the machine. We have seen that the induction motor turns in the same direction as the stator flux and tries to catch up with it [20].

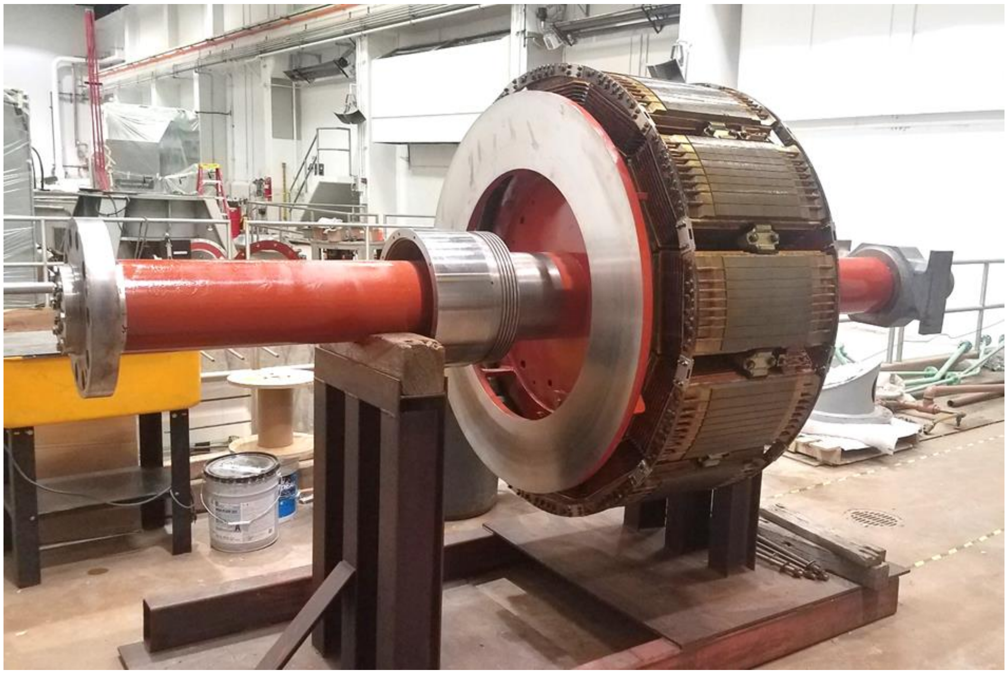


Figure 46 -- Amortisseur winding on a 3 MW synchronous generator. [10]

The synchronous motor cannot start itself due to the rotor's inertia. It's rotor usually has an additional feature – a cage winding called an amortisseur winding (shock absorber or damper in French). It has two purposes. It functions like an induction motor squirrel-cage to allow starting the synchronous motor as an induction motor. The amortisseur winding also dampens "hunting", or successive overshooting and undershooting of speed during sudden load changes, when the motor is operating in synchronous mode. If the motor overshoots the synchronous speed, the amortisseur winding will act like a generator, and the induced currents will slow the rotor down. Likewise, if the rotor momentarily undershoots the synchronous speed, the amortisseur winding will act like a motor and speed the rotor up. The amortisseur winding can sometimes be found on a synchronous generator. Since a synchronous generator is normally brought up to synchronous speed using the prime mover, the use of an amortisseur winding is generally not required unless the synchronous generator is subject to sudden load changes.

Phase rotation for an induction motor or generator. For pumps and other devices driven by an induction motor, it is important that the motor is turning in the desired direction for the connected load. The direction of rotation is determined by the phase sequence. To determine the correct phase rotation, there is a NEMA standard – induction motors and generators have an A-B-C phase sequence when the shaft is rotating counter-clockwise as viewed from opposite motor or generator's drive end. The nameplate or instructions will show the expected connection. However, this phase rotation should be confirmed during startup and after maintenance.

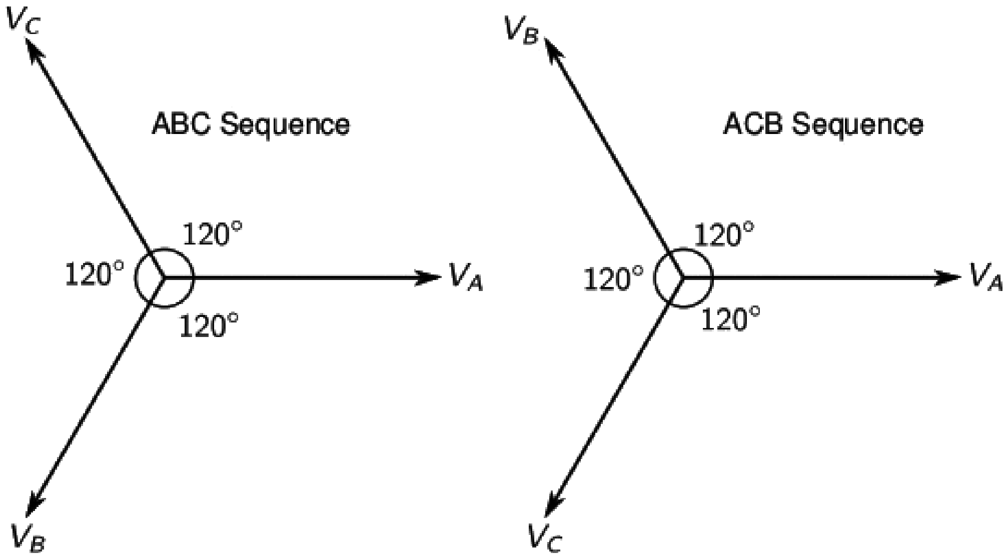


Figure 47 -- Phase rotation can be changed by reversing any two leads in a three-phase system [13]

For an induction motor, just "bump" the machine briefly as a motor, i.e., connect it briefly to the power source and verify that it is turning in the expected direction to verify that the phase rotation is correct. For a turbine/generator, this step is especially important, as the prime mover brings the generator to synchronous speed prior to closing the breaker. The generator must turn in the same direction as when driven by the turbine. According to the turbine manufacturer Gilkes, the torque on the generator shaft can approach twenty times the running torque if the breaker is closed with the phase rotation backwards. If the phase rotation is incorrect, simply switch any two of the three phase conductors.

Efficiency Issues and losses within the motor. According to the U.S. Department of Energy (DOE), electric motors consume more 50 percent of all electrical energy in the United States and more than 85 percent of industrial production electrical energy. The diagram below shows the constant (fixed) and variable losses within the motor, which are similar to a transformer:

CONSTANT. Core loss in the stator and the rotor --hysteresis and eddy currents. Core losses are decreased using improved permeability electromagnetic (up to four percent silicon) steel and by lengthening the core and rotor to reduce magnetic flux densities. Lower flux density will result in lower iron losses. Eddy current losses are decreased by using thinner steel laminations with better interlaminar insulation. In addition, bearing friction and windage losses associated with rotation, which are constant regardless of the load, are improved by bearing and seal selection, and airflow and fan design.

VARIABLE. Stator and rotor copper losses. Stator losses appear as heating due to I^2R losses, which can be decreased by modifying the stator slot design or by decreasing insulation thickness to increase the volume of wire in the stator. Rotor losses are I^2R losses due to heating of the rotor winding. Rotor losses can be reduced by increasing the size of the conductive bars and end rings to produce a lower resistance. This will produce less slip and higher efficiency but will also reduce starting torque.

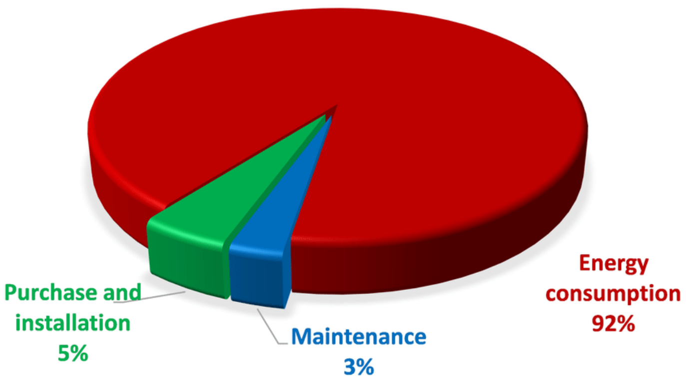


Figure 48 -- Induction Motors Typical life cycle costs of a motor installation for 25-years, [6]

Prior to 1975 most motors were designed and constructed for a low purchase price, and not efficiency. However, energy represents more than 92 percent of total motor life-cycle cost over the motor's lifetime. The only way to improve motor efficiency is to reduce motor losses. The price premium for an energy efficient motor is typically 15 to 30 percent above the cost of a standard motor. When you buy a motor, you are obligating yourself to purchase the electricity to operate it. A $4640 75-hp TEFC motor operating at 75% of full-rated load for 8,000 hours, with energy and demand charges of $0.08/kWh and $8.00/kW-month respectively, are $1,230 per year, with a simple payback of four years. [41]

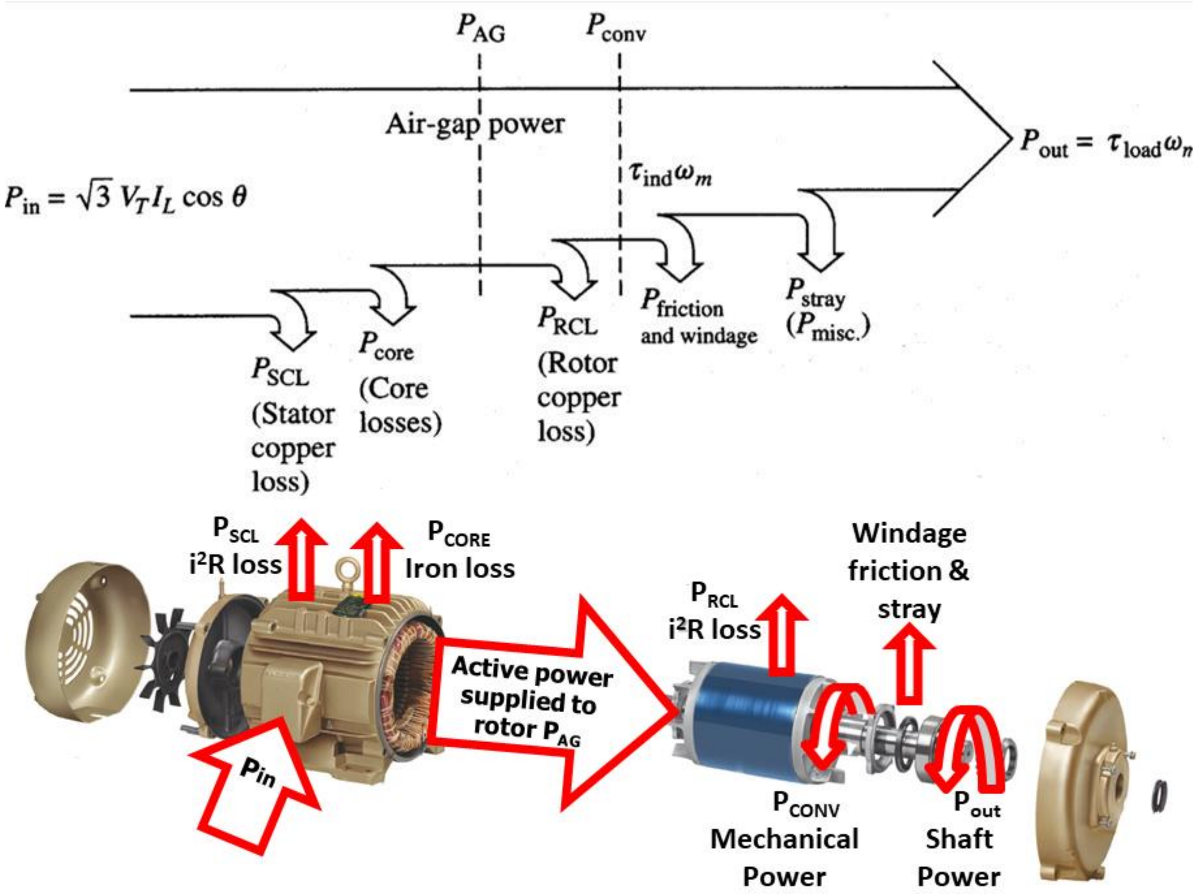


Figure 49 -- Induction motor losses – *[7] and [28]*

The International Energy Agency (IEA) and NEMA have issued standards for energy efficient motors. Beginning June 1, 2016, newly manufactured 1 to 500 horsepower industrial electric motors are required to meet “NEMA Premium efficiency standards, which use improved design, materials, and construction. IEC60034-30 sets forth new energy-efficiency classes for single-speed, three-phase, cage-induction motors. Typical operation will often pay for its purchase price in reduced energy bills within a year or two, after which they will continue to accumulate savings worth many times their purchase cost for as long as they remain in service. The energy-efficiency classes in the standard are:

- IE1 (standard efficiency)
- IE2 (high efficiency)
- IE3 (premium efficiency), equal to NEMA Premium Efficiency. Premium efficiency motors cost approximately 15% to 30% more than their energy efficient counterparts.
- IE4 (super premium efficiency), not yet enforced

Stator losses make up about 66% of power losses, and it is here that motor manufacturers have achieved significant gains in efficiency. Since increasing the mass of stator windings lowers their electrical resistance (and therefore reduces I^2R losses), highly efficient motors typically contain about 20% more copper than standard efficiency models of equivalent size and rating. Increasing the outer diameter of the stator increases surface area, allowing more effective cooling. This in turn means that a smaller, lower power fan can be used. Rotor losses are reduced by decreasing the degree of slip [29]. Stray-load losses are reduced by carefully machining the rotor to produce a uniform air gap.

A variable-speed drive system coupled with premium efficiency motor is capable of matching the motor’s power output to the work required.

Figure 50 – Older motor with thick laminations.

Photo credit: Baldor Electric Company

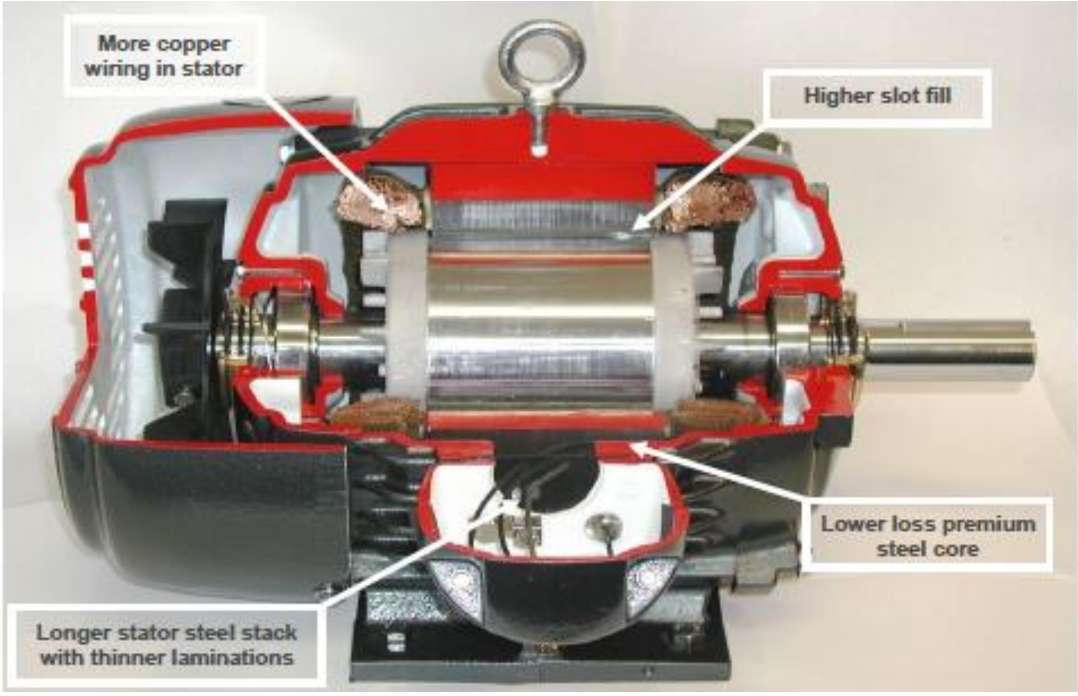


Figure 51 – Construction details that go into a high-efficiency motor. [26]

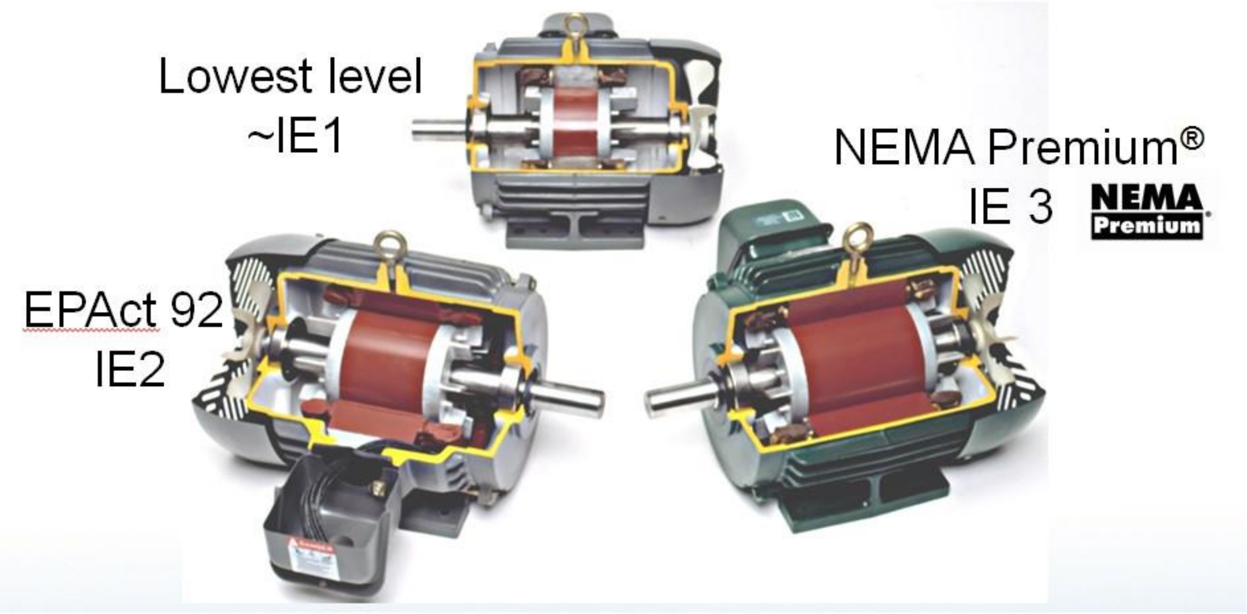


Figure 52 -- Three different efficiencies for the same horsepower rating. Top: standard-efficiency pre-EPAct motor; lower left: EPAct-level motor; lower right: NEMA Premium efficiency motor. Notice that the rotor and stator lengthen (and the amount of copper in the motor rises) as efficiency increases. Lengthening the lamination stack reduces the flux density within the stack, also reduces core losses. [22 & 27]

[1] N. Tesla, "A new system of alternate current motors and transformers," in *Proceedings of the IEEE*, vol. 72, no. 2, pp. 165-173, Feb. 1984, doi: 10.1109/PROC.1984.12838.

[2] Power Conversion of Renewable Energy Systems, Ewald F. Fuchs & Mohammad A.S. Masoum, Section 10.3, Springer, New York, 2nd printing 2012.

[3] G. Neidhofer, "Early three-phase power [History]," in *IEEE Power and Energy Magazine*, vol. 5, no. 5, pp. 88-100, Sept.-Oct. 2007, doi: 10.1109/MPE.2007.904752.

[4] Blalock, T.J., (2004). The first polyphase system: a look back at two-phase power for AC distribution. Power and Energy Magazine, IEEE. 2. 63 - 66. 10.1109/MPAE.2004.1269626.

[5] Supplemental Class Notes and Handouts, Dr. P.K. Sen, Colorado School of Mines EGGN389

[6] Soft Magnetic Material Status and Trends in Electric Machines, September by Krings, Boglietti, di Torino, Cavagnino & Sprague, 2016, IEEE Transactions on Industrial Electronics PP(99):1-1

[7] Electric Machine Fundamentals, Chapman, Stephen J., 5th ed.

[8] Thanks to Joe Leoni for much of the material in this section from his Electrical Machinery Lab experiments at the Colorado School of Mines, and his insulation test instrument presentation.

[9] Renewable Energy Systems Design and Analysis with Induction Generators, Simoes and Farret, 2004.

[10] Illustration by the author.

[11] High-Altitude Considerations for Electrical Power Systems and Components, John P. Nelson, IEEE Transactions on Industry Applications, vol. iA-20, No. 2, March/April 1984

[12] Determining Electric Motor Load and Efficiency, DOE fact sheet 10097517

[13] Three-phase Circuits Workshop on Basic Electrical Engineering held at VVCE, Mysuru, on 30-April-2016.

[14] electricala2z.com, Electric Motor Nameplate Details Explained, https://electricala2z.com/motors-control/electric-motor-nameplate-details-explained-electric-motor-specifications/

[15] VFD switching frequency, Mike Glampe, October 17th, 2017 KEB Technology, https://www.kebamerica.com/blog/vfd-switching-frequency/

[16] Why the Rotor of Induction Motor is Skewed?, no author, ETechnoG, https://www.etechnog.com/

[17] Stanislav Kocman, Petr Orsag, Pavel Pecinka, Simulation of Start-Up Behaviour of Induction Motor with Direct Online Connection, Power Engineering and Electrical Engineering Volume: 15, Number: 5, December 2017

[18] Performance Calculation for a High-Speed Solid-Rotor Induction Motor, Jacek F. Gieras and Juha Saari, IEEE Transactions on Industrial electronics, Vol. 59, No. 6, June 2012

[19] Stator and rotor laminations from an induction motor, Photo by Zureks - Own work, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.

[20] A Textbook of Electrical Technology Volume II: AC and DC Machines, Chapter 34, Fig 34.22, Induction Motor, BL and AK Theraja, Publisher S Chand.

[21] How Electronic soft starter better than star delta starter for starting an Induction motor?, Gilbert Applebee EE student, Drexel Univ., https://www.quora.com/

[22] Introduction to Premium Efficiency Motors, https://www.copper.org/environment/sustainable-energy/electric-motors/education/motor_text.html

[23] Electric Motor Nameplate Details Explained -- Electric Motor Specifications, https://electricala2z.com/motors-control/electric-motor-nameplate-details-explained-electric-motor-specifications.

[24] AC Motor Selection and Application Guide, GE Industrial Systems, no author listed, http://ocw.uniovi.es/mod/resource/view.php?id=4530

[25] Importance of Air Gap in Electric Motors, Steve Mazziotta, HECO Electric Motors, Heco Blog 2020, https://www.hecoinc.com/blog/importance-of-air-gap-in-electric-motors .

[26] Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, Paul Waide and Conrad u. Brunner, January 2011

[27] Premium Efficiency Rules, US Motors, https://acim.nidec.com/motors/usmotors/energy-efficiency/2016-doe-nema-premium-efficiency-rule

[28] [5] and and ABB Motors and Generators NEMA Super-E® premium efficient motors https://library.e.abb.com/public/e35d57ce4df3160285257d6d00720f51/9AKK106369_SuperE_1014_WEB.pdf

[29] Baldor Basics: Motors, Edward Cowern, P.E. , Power Transmission Engineering, March 2017

[30] Understanding Destructive Voltage Spikes, #4 Switch Bouncing, Pololu Robotics and Electronics, https://www.pololu.com/docs/0J16/4

[31] Three Phase Induction Motor Working Principle, no author cited, https://electricalacademia.com/induction-motor/three-phase-induction-motor-working-principle/

[32] Current and Voltage Unbalance- causes and counter measures By Amarjeet Singh July 29, 2014, https://zenatix.com/current-and-voltage-unbalance-causes-and-counter-measures/

[33] Negative-Sequence Overcurrent Considerations for Induction Motor Loads, Miles Dupuis, Nick Mahoney, Aadityaa Padmanabhan, and Krithika Bhuvaneshwaran, Cleco Power LLC, https://cms-cdn.selinc.com/assets/Literature/Publications/Technical%20Papers/6779_NegativeSequence_NM_20170209_Web3.pdf?v=20171110-231733

[34] Effect of Unbalanced Voltage on Operation of Induction Motors and Its Detection by Mirabbasi, Seifossadat, and Heidari

[35] Protective Relaying: Principles and Applications, Fourth Edition 4th Edition by J. Lewis Blackburn, CRC press 2014

[36] Technical Note No. 6, Voltage Unbalance, October 2002, Power Quality Centre, University of Wollongong

[37] Effects of Unbalanced Voltages on the Energy Performance of Three-phase Induction Motors. Quispe, Enrique & Lopez, Ivan. (2015). DOI 10.1109/PEPQA.2015.7168237.

[38] What happens to three phase induction motor when one of the three phases of supply voltage is lost -- https://www.quora.com/

[39] Unbalanced Voltages & Single Phase Operation Of Squirrel Cage Induction Motors, General Electric Company, R. F. Cota, January 1978, https://www.fs.fed.us/database/acad/elec/greenbook/18_3phase_votage_unbalanced.pdf

[40] Causes and Effects of Single-Phasing Induction Motors, W. H. Kersting, Life Fellow, IEEE. Milsoft Utility Solutions, IEEE Transactions on Industry Applications, Volume: 41 Issue: 6

[41] The Premium Efficiency Motor Selection and Application Guide, U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, page 3-9.

[42] What is the relation between line current and voltage of an induction motor and its torque?, Ian McKenzie, https://www.quora.com/

[43] Picture source: AC Induction Motors with Squirrel Cage Rotors, https://www.bodine-electric.com/blog/ac-induction-gearmotors/

[44] Family of Motor Torque Speed curves at various frequencies, https://www.quora.com/Why-do-some-motors-have-constant-load-torque-and-some-have-variable

[45] Quispe, Enrique & Lopez, Ivan. (2015). Effects of Unbalanced Voltages on the Energy Performance of Three-phase Induction Motors.

[46] Author’s picture from Megger Baker Instruments insulation testing course.