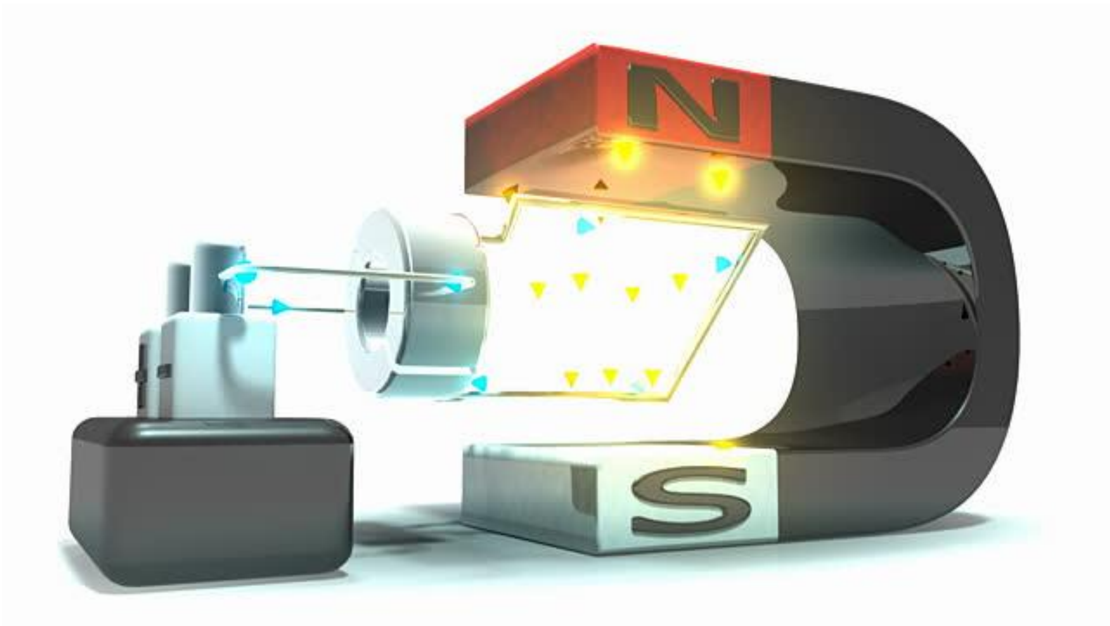
ELECTRIC MACHINE ۱۱



THE MAGNETIC FIELD

Magnetic fields are the fundamental mechanism by which energy is convel1ed from one form to another in motors, generators, and transformers. Four basic principles describe how magnetic fields are used in these devices:

1. A current-carrying wire produces a magnetic field in the area around it.

2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis of transformer action.)

3. A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of motor action.)

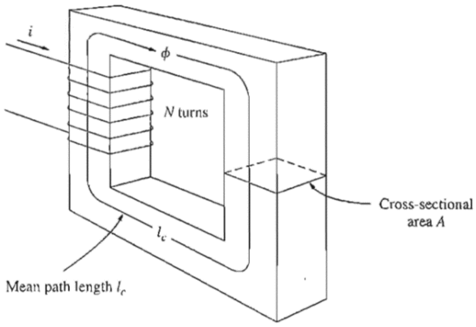
4. A moving wire in the presence of a magnetic field has a voltage induced in it. (This is the basis of generator action.)

Production of a Magnetic Field

The basic law governing the production of a magnetic field by a current is

Ampere's law:

$$\oint \mathbf{H} \cdot d\mathbf{l} = I_{\text{net}}$$



Where H is the magnetic field intensity produced by the current Inet and dl is a differential element of length along the path of integration. In SI units, I is measured in amperes and H is measured in ampere-turns per meter. To better understand the meaning of this equation, it is helpful to apply it to the simple example in Figure up. Figure up shows a rectangular core with a winding of N turns of wire wrapped about one leg of the core. If the core is composed of iron or certain other similar metals (collectively called ferromagnetic materials), essentially all the magnetic field produced by the current will remain inside the core, so the path of integration

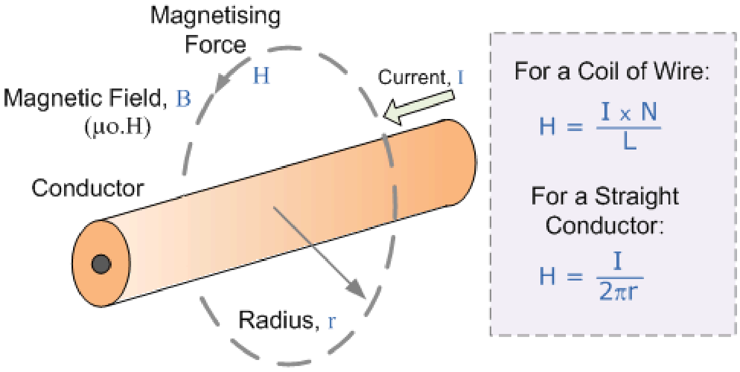
in Ampere's law is the mean path length of the core Lc. The current passing within the path of integration I ller is then Ni, since the coi1 of wire cuts the path of integration N times while carrying current i. Ampere's law thus becomes

$$Hl_c = Ni$$

Here H is the magnitude of the magnetic field intensity vector H. Therefore, the magnitude of the magnetic field intensity in the core due to the applied current is

$$H = \frac{Ni}{l_c}$$

Magnetic Field Strength for Electromagnets



- Where:
  - H – is the strength of the magnetic field in ampere-turns/metre, At/m
  - N – is the number of turns of the coil
  - I – is the current flowing through the coil in amps, A
  - L – is the length of the coil in meters, m

Then to summarize, the strength or intensity of a coils magnetic field depends on the following factors.

- The number of turns of wire within the coil.
- The amount of current flowing in the coil.

The type of core material.

The magnetic field intensity (H) is in a sense a measure of the "effort" that a current is putting into the establishment of a magnetic field. The strength of the magnetic field flux produced in the core also depends on the material of the core.

The relationship between the magnetic field intensity (H) and the resulting magnetic flux density (B) produced within a material is given by

$$\mathbf{B} = \mu \mathbf{H}$$

H =magnetic field intensity

μ= magnetic permeability of material

B =resulting magnetic flux density produced

The permeability of free space is called μ_0, and its value is

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H/m}$$

The permeability of any other material compared to the permeability of free space is called its relative permeability

$$\mu_r = \frac{\mu}{\mu_o} = \frac{\text{Flux Density in the Material}}{\text{Flux Density in a Vacuum}}$$

Relative permeability is a convenient way to compare the magnetizability of materials. For example, the steels used in modem machines have relative permeability's of 2000 to 6000 or even more. This means that, for a given amount of current, 2000 to 6000 times more flux is established in a piece of steel than in a corresponding area of air. (The permeability of air is essentially the same as the permeability of free space.) Obviously, the metals in a transformer or motor core play an extremely important part in increasing and concentrating the magnetic flux in the device.

the magnitude of the flux density is given by

$$B = \mu H = \frac{\mu N i}{l_c}$$

$$\text{Magnetic Flux Density, (tesla)} = \frac{\text{Magnetic Flux, (weber)}}{\text{Area, (m2)}}$$

Now the total flux in a given area is given by

$$\phi = \int_A \mathbf{B} \cdot d\mathbf{A}$$

Where dA is the differential unit of area. If the flux density vector is perpendicular to a plane of area A, and if the flu x density is constant throughout the area, then this equation reduces to

$$\phi = BA$$

Thus, the total flux in the core in Figure up due to the current i in the winding is

$$\phi = BA = \frac{\mu N i A}{l_c}$$

Where A is the cross-sectional area of the core.

1. Faraday's Law of Electromagnetic Induction

This basic law, due to the genius of the great English chemist and physicist

Michael Faraday (1791–1867), presents itself in two different forms:

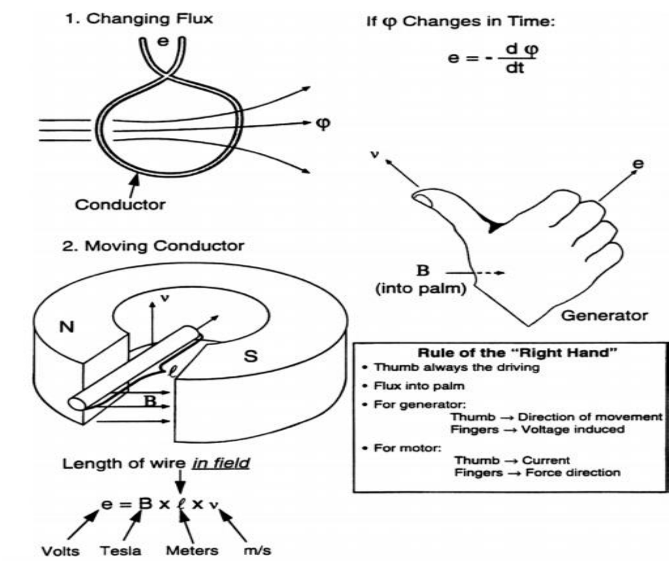
1. A moving conductor cutting the lines of force (flux) of a constant magnetic

   Field has a voltage induced in it.

2. A changing magnetic flux inside a loop made from a conductor material

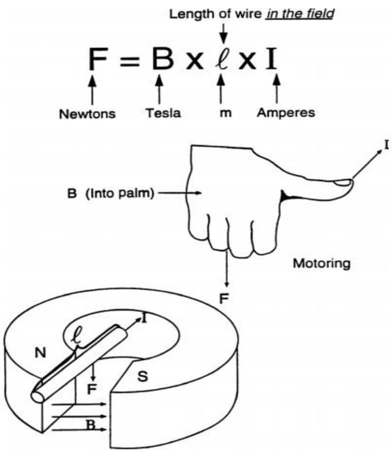
   Will induce a voltage in the loop.

In both instances the rate of change is the critical determinant of the resulting differential of potential. Figure 1.13 illustrates both cases of electromagnetic induction, and also provides the basic relationship between the changing flux and the voltage induced in the loop, for the first case, and the relationship between the induced voltages in a wire moving across a constant field, for the second case. The figure also shows one of the simple rules that can be used to determine the direction of the induced voltage in the moving conductor.



2. Ampere-BiotSavart's Law of Electromagnetic Induced Forces

This basic law is attributed to the French physicists Andre Marie Ampere (1775–1836), Jean Baptiste Biot (1774–1862), and Victor Savart (1803–1862). In its simplest form this law can be seen as the "reverse" of Faraday's law. While Faraday predicts a voltage induced in a conductor moving across a magnetic field, the Ampere-BiotSavart law establishes that a force is generated on a current carrying conductor located in a magnetic field. Figure presents the basic elements of the Ampere-BiotSavart's law as applicable to electric machines. The figure also shows the existing numerical relationships, and a simple hand-rule to determine the direction of the resultant force.



1. Lenz's Law of Action and Reaction

The direction of induce emf is such that the current produced by if sets up a magnetic field opposing the flux $e = -n(d\varphi/dt)$

☒ **In order for an EMF to be induced, three conditions must be present:**

- A magnetic field
- A current-carrying conductor
- Relative motion between the two

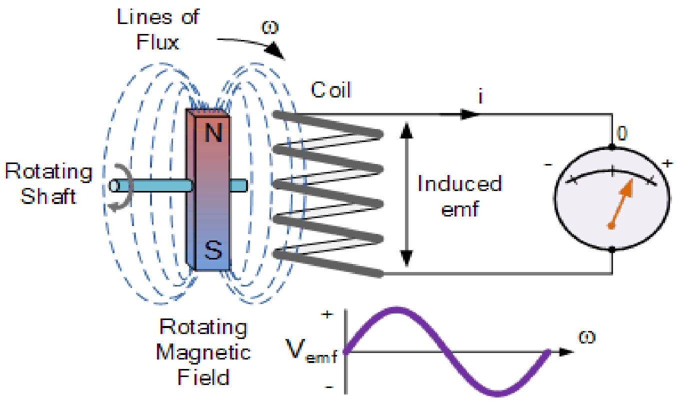
This does not mean that the conductor must be carrying current. It simply means that the conductor must consist of a closed path capable of carrying current.
An equation for EMF is:

$$EMF = \beta VL$$

Where: β = magnetic flux density in Webers per square meters
V = conductor or field velocity in meters per second
L = length of the conductor in meters

This EMF, or induced voltage, and the resultant current flow sets up its own magnetic field. The interaction of the magnetic field of the stator and the magnetic field of the rotor causes motor rotation and delivers torque. Torque is produced by the interaction of the stator and rotor fluxes. Torque in an induction motor is discussed in detail later in this article.

Simple Generator using Magnetic Induction



The simple dynamo type generator above consists of a permanent magnet which rotates around a central shaft with a coil of wire placed next to this rotating magnetic field. As the magnet spins, the magnetic field around the top and bottom of the coil constantly changes between a north and a south pole. This rotational movement of the magnetic field results in an alternating emf being induced into the coil as defined by Faraday's law of electromagnetic induction.

The magnitude of the electromagnetic induction is directly proportional to the flux density, β the number of loops giving a total length of the conductor, l in meters and the rate or velocity, ν at which the magnetic field changes within the conductor in meters/second or m/s, giving by the motional emf expression:

Faraday's Motional emf Expression

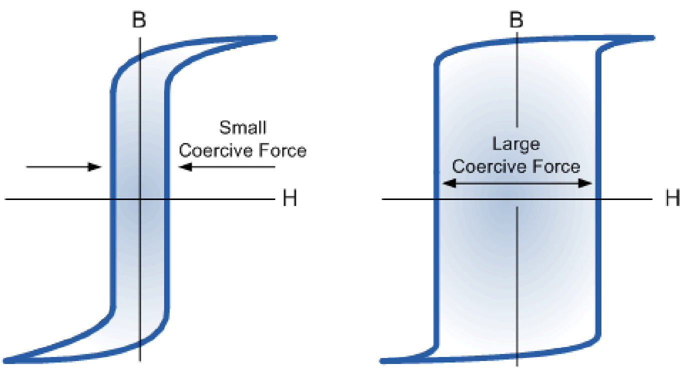
$\varepsilon = -\beta.\ell.\upsilon$ volts

If the conductor does not move at right angles (90°) to the magnetic field then the angle θ° will be added to the above expression giving a reduced output as the angle increases:

$\varepsilon = -\beta.\ell.\upsilon \sin\theta$ volts

Magnetic Hysteresis

The lag or delay of a magnetic material known commonly as Magnetic Hysteresis, relates to the magnetization properties of a material by which it firstly becomes magnetized and then de-magnetized.



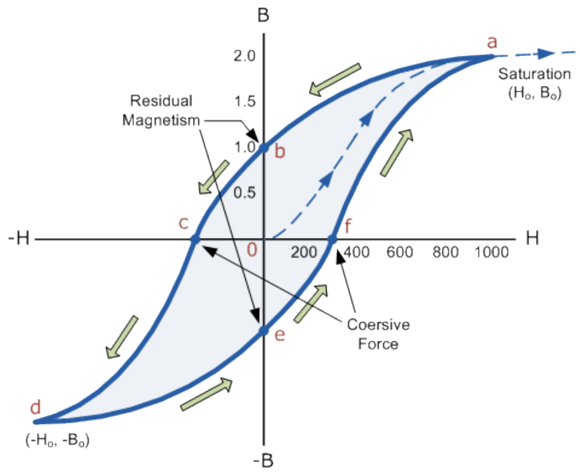
"Soft" Ferromagnetic Material "Hard" Ferromagnetic Material

Magnetic Hysteresis results in the dissipation of wasted energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. Hysteresis losses will always be a problem in AC transformers where the current is constantly changing direction and thus the magnetic poles in the core will cause losses because they constantly reverse direction.

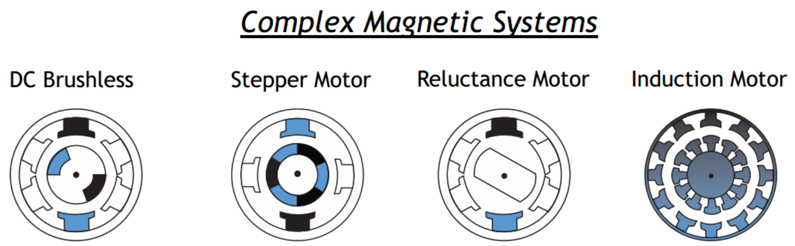
Rotating coils in DC machines will also incur hysteresis losses as they are alternately passing north the south magnetic poles. As said previously, the shape of the hysteresis loop depends upon the nature of the iron or steel used and in the case of iron which is subjected to massive reversals of magnetism, for example transformer cores, it is important that the B-H hysteresis loop is as small as possible.

In the next tutorial about electromagnetism, we will look at Faraday's Law of electromagnetic Induction and see that by moving a wire conductor within a stationary magnetic field it is possible to induce an electric current in the conductor producing a simple generator.

Magnetic Hysteresis Loop



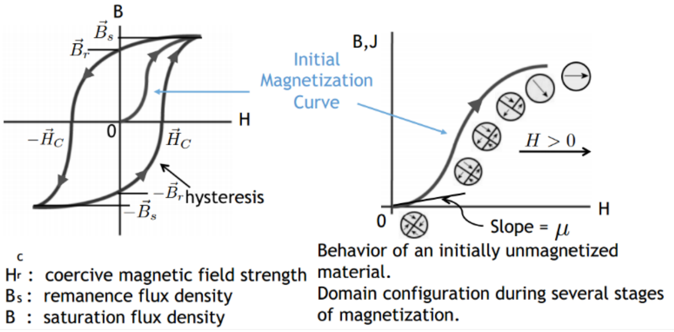
The Magnetic Hysteresis loop above, shows the behavior of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnified core both B and H will be at zero, point 0 on the magnetization curve.



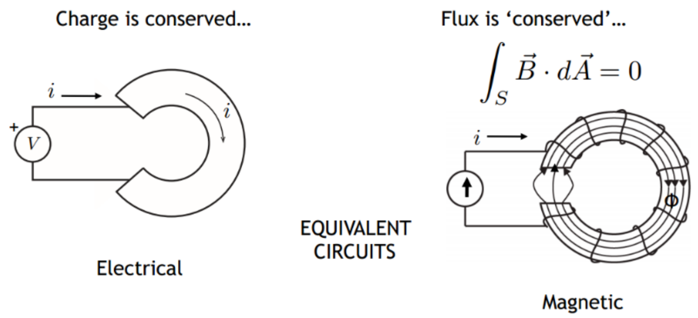
$$\int_C \vec{H} \cdot d\vec{l} = I_{enclosed} \qquad \int_S \vec{B} \cdot d\vec{A} = 0 \qquad \vec{f} = q\left(\vec{v} \times \vec{B}\right)$$

Φ -Magnetic Flux [Wb] (Webers)
B -Magnetic Flux Density [Wb/m2] = T (Tesla)
H -Magnetic Field Intensity [Amp-turn/m]

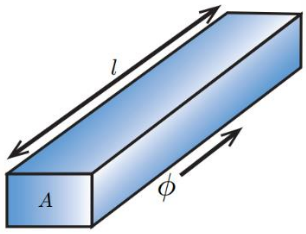
Review: Ferromagnetic Materials



Electrical Circuit Analogy



Reluctance of Magnetic Bar

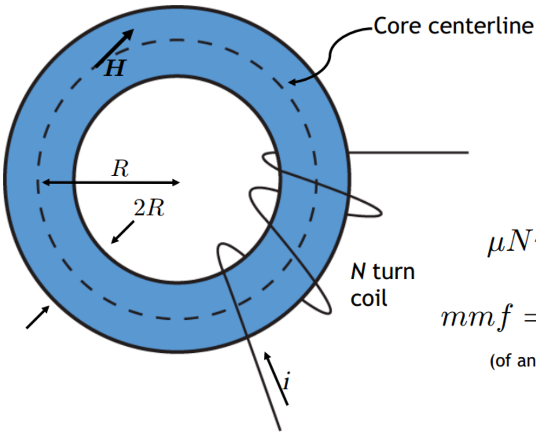


Magnetic "OHM's LAW"

$$Ni = \Phi \Re$$

$$\Re = \frac{l}{\mu A}$$

Flux Density in a Toroidal Core



$$B = \frac{\mu N i}{2\pi R}$$

$$\mu N i = 2\pi R B = l B$$

$$mmf = Ni = \frac{lB}{\mu} = \boxed{\Phi \frac{l}{\mu A}}$$

(of an N-turn coil)

$$mmf = \Phi \Re$$

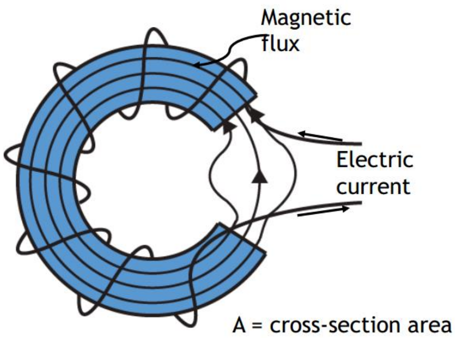
Electrical	Magnetic
Voltage v	Magnetic Force $F = Ni$
Current i	Magnetic Flux φ=BA
Resistance R	Reluctance R
Conductivity $1/\rho$	Permeability μ
Current Density J	Magnetic Flux Density $B=\mu H$ B = # H B = #
Electric Field E	Magnetic Field Intensity H

Toroid with Air Gap

$$Ni = \Phi\Re$$

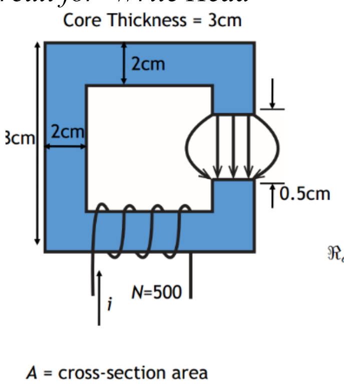
&

$$\Re = \frac{l}{\mu A} \Rightarrow \Re = \frac{2\pi R}{\mu A}$$

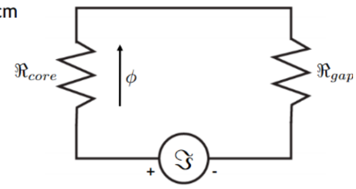


$$\Phi = BA = Ni\frac{\mu A}{2\pi R}$$

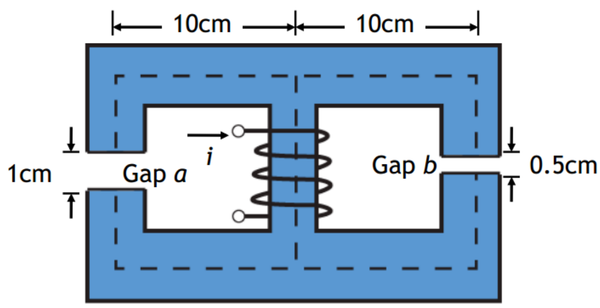
Magnetic Circuit for 'Write Head'



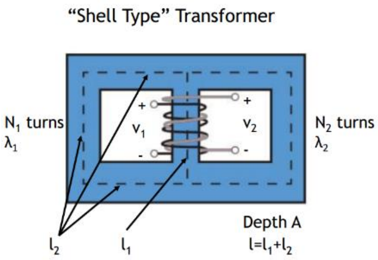
$$\Re = \frac{l}{\mu A}$$

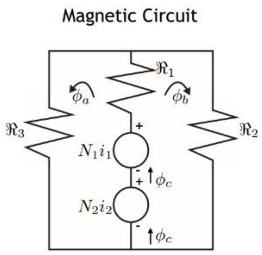


Parallel Magnetic Circuits



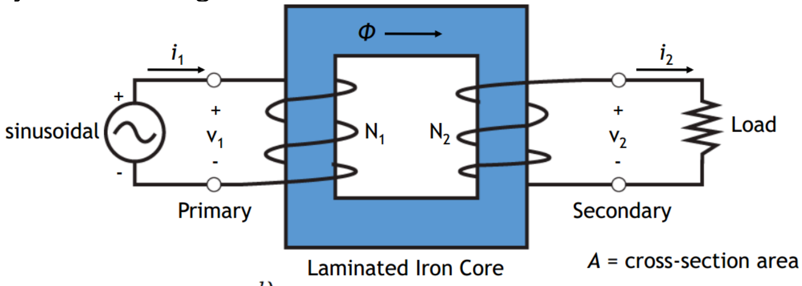
A Magnetic Circuit with Reluctances in Series and Parallel





$$\Re_1 = \frac{l_1}{\mu A} \quad \Re_2 = \frac{l_2}{\mu A}$$

Faraday Law and Magnetic Circuits



Flux linkage $\lambda = N\Phi$ $v = \frac{d\lambda}{dt}$

Example — Find the relative permeability of the typical ferromagnetic material whose magnetization curve is shown in Figure 1–10c at (a) $H = 50$, (b) $H = 100$, (c) $H = 500$, and (d) $H = 1000$ A • turns/m.

Solution

The permeability of a material is given by

$$\mu = \frac{B}{H}$$

and the relative permeability is given by

$$\mu_r = \frac{\mu}{\mu_0}$$

Thus, it is easy to determine the permeability at any given magnetizing intensity.

(a) At $H = 50$ A • turns/m, $B = 0.25$ T, so

$$\mu = \frac{B}{H} = \frac{0.25\text{ T}}{50\text{ A • turns/m}} = 0.0050\text{ H/m}$$

and

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0.0050\text{ H/m}}{4\pi \times 10^{-7}\text{ H/m}} = 3980$$

(b) At $H = 100$ A • turns/m, $B = 0.72$ T, so

$$\mu = \frac{B}{H} = \frac{0.72\text{ T}}{100\text{ A • turns/m}} = 0.0072\text{ H/m}$$

and

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0.0072\text{ H/m}}{4\pi \times 10^{-7}\text{ H/m}} = 5730$$

(c) At $H = 500$ A • turns/m, $B = 1.40$ T, so

$$\mu = \frac{B}{H} = \frac{1.40\text{ T}}{500\text{ A • turns/m}} = 0.0028\text{ H/m}$$

and

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0.0028\text{ H/m}}{4\pi \times 10^{-7}\text{ H/m}} = 2230$$

(d) At $H = 1000$ A • turns/m, $B = 1.51$ T, so

$$\mu = \frac{B}{H} = \frac{1.51\text{ T}}{1000\text{ A • turns/m}} = 0.00151\text{ H/m}$$

and

$$\mu_r = \frac{\mu}{\mu_0} = \frac{0.00151\text{ H/m}}{4\pi \times 10^{-7}\text{ H/m}} = 1200$$

EXAMPLE 1:-

The magnetic circuit shown in Fig. 1.2 has dimensions $A_c = A_g = 9\text{ cm}^2$, $g = 0.050$ cm, $l_c = 30$ cm, and $N = 500$ turns. Assume the value $\mu_r = 70{,}000$ for core material. (a) Find the reluctances $\mathcal{R}_c$ and $\mathcal{R}_g$. For the condition that the magnetic circuit is operating with $B_c = 1.0$ T, find (b) the flux ϕ and (c) the current i.

■ Solution

a. The reluctances can be found from Eqs. 1.13 and 1.14:

$$\mathcal{R}_c = \frac{l_c}{\mu_r\mu_0 A_c} = \frac{0.3}{70,000\,(4\pi \times 10^{-7})(9 \times 10^{-4})} = 3.79 \times 10^3\ \frac{\text{A} \cdot \text{turns}}{\text{Wb}}$$

$$\mathcal{R}_g = \frac{g}{\mu_0 A_g} = \frac{5 \times 10^{-4}}{(4\pi \times 10^{-7})(9 \times 10^{-4})} = 4.42 \times 10^5\ \frac{\text{A} \cdot \text{turns}}{\text{Wb}}$$

b. From Eq. 1.4,

$$\phi = B_c A_c = 1.0(9 \times 10^{-4}) = 9 \times 10^{-4}\text{ Wb}$$

c. From Eqs. 1.6 and 1.15,

1

$$i = \frac{\mathcal{F}}{N} = \frac{\phi(\mathcal{R}_c + \mathcal{R}_g)}{N} = \frac{9 \times 10^{-4}(4.46 \times 10^5)}{500} = 0.80\text{ A}$$

P r o b l e m:-

Find the flux 4) and current for Example 1.1 if (a) the number of turns is doubled to N = 1000 turns while the circuit dimensions remain the same and (b) if the number of turns is equal to N = 500 and the gap is reduced to 0.040 cm.

Solution

a. $\phi = 9 \times 10^{-4}$ Wb and $i = 0.40$ A
b. $\phi = 9 \times 10^{-4}$ Wb and $i = 0.64$ A

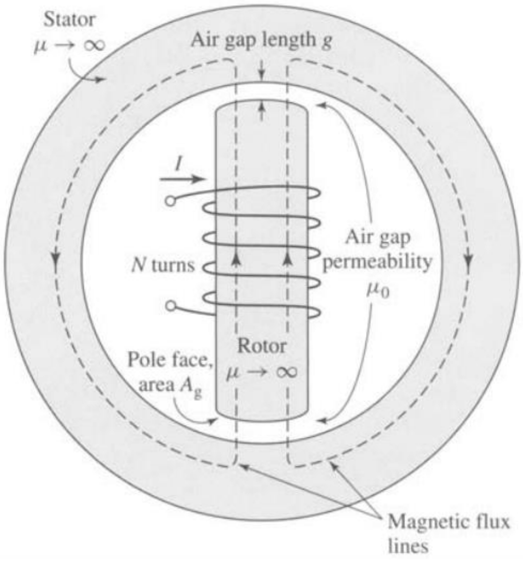
EXAMPLE 2:-

The magnetic structure of a synchronous machine is shown schematically in Fig. 1.5. Assuming that rotor and stator iron have infinite permeability ($\mu \rightarrow \infty$), find the air-gap flux ϕ and flux density B_g. For this example $I = 10$ A, $N = 1000$ turns, $g = 1$ cm, and $A_g = 2000\text{ cm}^2$.

■ Solution

Notice that there are two air gaps in series, of total length $2g$, and that by symmetry the flux density in each is equal. Since the iron permeability here is assumed to be infinite, its reluctance is negligible and Eq. 1.20 (with g replaced by the total gap length $2g$) can be used to find the flux

$$\phi = \frac{NI\mu_0 A_g}{2g} = \frac{1000(10)(4\pi \times 10^{-7})(0.2)}{0.02} = 0.13\text{ Wb}$$

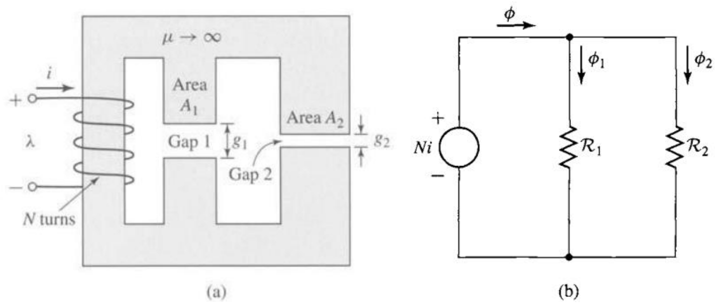


$$B_g = \frac{\phi}{A_g} = \frac{0.13}{0.2} = 0.65 \text{ T}$$

P r o b l e m -:For the magnetic structure of Fig. 1.5 with the dimensions as given in Example 2, the air-gap flux density is observed to be Bg = 0.9 T. Find the air-gap flux ~band, for a coil of N =500turns, the current required to produce this level of air-gap flux.

Solution :φ= 0.18 Wb and I= 28.6 A.

EXAMPLE 3 -: The magnetic circuit of Fig .consists of an N-turn winding on a magnetic core of infinite permeability with two parallel air gaps of lengths g1 and g2 and areas A1 and A2, respectively .Find (a) the inductance of the winding and (b) the flux density B1 in gap 1 when the winding is carrying a current i .Neglect fringing effects at the air gap.



$$B_1 = \frac{\phi_1}{A_1} = \frac{\mu_0 N i}{g_1}$$

■ **Solution**

a. The equivalent circuit of Fig. 1.6b shows that the total reluctance is equal to the parallel combination of the two gap reluctances. Thus

$$\phi = \frac{Ni}{\frac{\mathcal{R}_1\mathcal{R}_2}{\mathcal{R}_1+\mathcal{R}_2}}$$

where

$$\mathcal{R}_1 = \frac{g_1}{\mu_0 A_1} \qquad \mathcal{R}_2 = \frac{g_2}{\mu_0 A_2}$$

From Eq. 1.29,

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} = \frac{N^2(\mathcal{R}_1+\mathcal{R}_2)}{\mathcal{R}_1\mathcal{R}_2}$$

$$= \mu_0 N^2\left(\frac{A_1}{g_1}+\frac{A_2}{g_2}\right)$$

b. From the equivalent circuit, one can see that

$$\phi_1 = \frac{Ni}{\mathcal{R}_1} = \frac{\mu_0 A_1 Ni}{g_1}$$

EXAMPLE 4 -:

Assume that the core material in Example 1. is M-5 electrical steel, which has the dc magnetization curve of Fig. 1.10. Find the current i required to produce $B_c = 1$ T.

■ **Solution**

The value of H_c for $B_c = 1$ T is read from Fig. 1.10 as

$$H_c = 11 \text{ A} \cdot \text{turns/m}$$

The mmf drop for the core path is

$$\mathcal{F}_c = H_c l_c = 11(0.3) = 3.3 \text{ A} \cdot \text{turns}$$

The mmf drop across the air gap is

$$\mathcal{F}_g = H_g g = \frac{B_g g}{\mu_0} = \frac{5\times10^{-4}}{4\pi\times10^{-7}} = 396 \text{ A} \cdot \text{turns}$$

The required current is

$$i = \frac{\mathcal{F}_c+\mathcal{F}_g}{N} = \frac{399}{500} = 0.80 \text{ A}$$

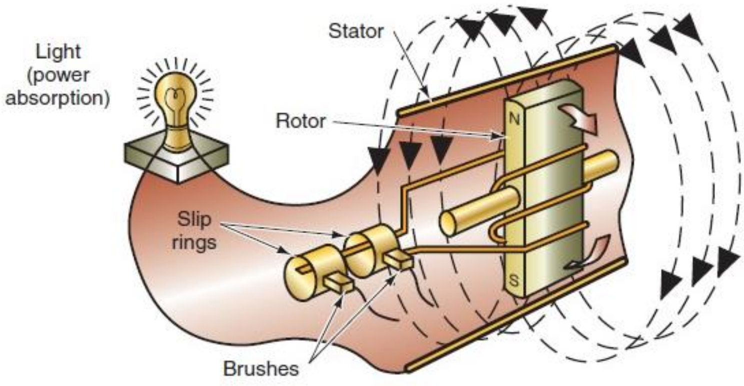
Some basic motor concepts

The magnetic field around electrical conductors can be strengthened by winding them into a coil around an iron core. When the wire is wound into a coil, all the flux lines produced by each turn of wire join up to form a single magnetic field around the coil. The greater the number of turns of the coil, the greater the strength of the magnetic field. This field has the same characteristics as a natural magnetic field, and so also has a north and a south pole. But before we dig any further into the world of magnetism, let us have a closer look at the main components of an electric motor: the stator and the rotor.

It possible to reverse the poles by reversing the direction of the current

1. Rotor:-
   The rotating part of the motor, rotates with the motor shaft by moving with the magnetic field of the stator.

2. Stator:-
   The stator is the stationary electrical part of the motor. It contains a number of windings whose polarity is changed all the time when an alternating current (AC) is applied. This makes the combined magnetic field of the stator.



Simplified AC generator indicating electromagnetic induction

Three-Phase Induction Machines

Three-phase induction motors are the motors most frequently encountered in industry. They are simple, rugged, low-priced, and easy to maintain. They run at essentially constant speed from zero to full-load. The speed is frequency-dependent and, consequently, these motors are not easily adapted to speed control. However, Three-phase induction motors are the motors most frequently encountered in industry. They are simple, rugged, low priced, and easy to maintain. They run at essentially constant speed from zero to full-load. The speed is frequency-dependent and, consequently, these motors are not easily adapted to speed control. However, variable frequency electronic drives are being used more and more to control the speed of commercial induction motors. In this chapter we cover the basic principles of the 3-phase induction motor and develop the fundamental equations describing its behavior.
We then discuss its general construction and the way the windings are made. variable frequency electronic drives are being used more and more to control the speed of commercial induction motors.
In this chapter we cover the basic principles of the 3-phase induction motor and develop the fundamental equations describing its behavior. We then discuss its general construction and the way the windings are made.

Squirrel-cage, wound-rotor ranging from a few horsepower to several thousand horsepower permit the reader to see that they all operate on the same basic principles.

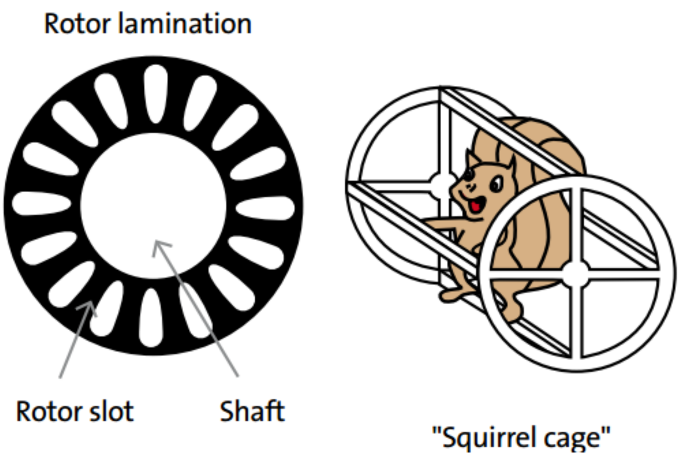
Principal components

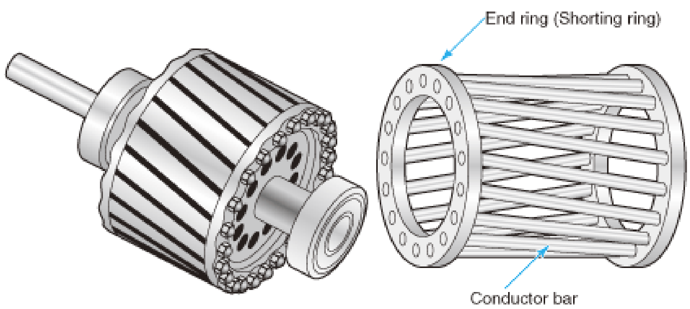
A 3-phase induction motor has two main parts: a stationary stator and a revolving rotor. The rotor is separated from the stator by a small air gap that ranges from 0.4 rum to 4 mm. depending on the power of the motor.

- The stator consists of a steel tram that supports a hollow, cylindrical core made up of stacked laminations. A number of evenly spaced slots, punched Out of the internal circumference of the laminations. Provide the space for the stator winding.
- The rotor is also composed of punched laminations. These are carefully stacked to create a series of rotor slots to provide space for the rotor winding.

We use two types of rotor windings: (I) conventional 3-phase windings made of insulated wire and (2) squirrel-cage windings. The type of winding gives rise to two main classes of motors: squirrel cage induction motors (also called cage motors) and wound-rotor induction motors.

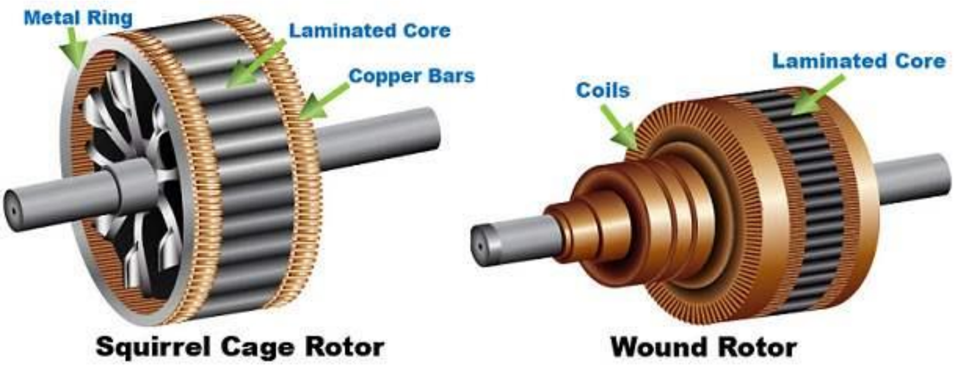
- A squirrel-cage rotor:- is composed of bare copper bars, slightly longer than the rotor, which are pushed into the slots. The opposite ends are welded to two copper end-rings, so that all the bars are short-circuited together. The entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived. In small and medium-size motors, he bars and end-rings are made of diecast aluminum. Molded to form an integral block.





(a) Rotor (b) Squirrel-cage conductor

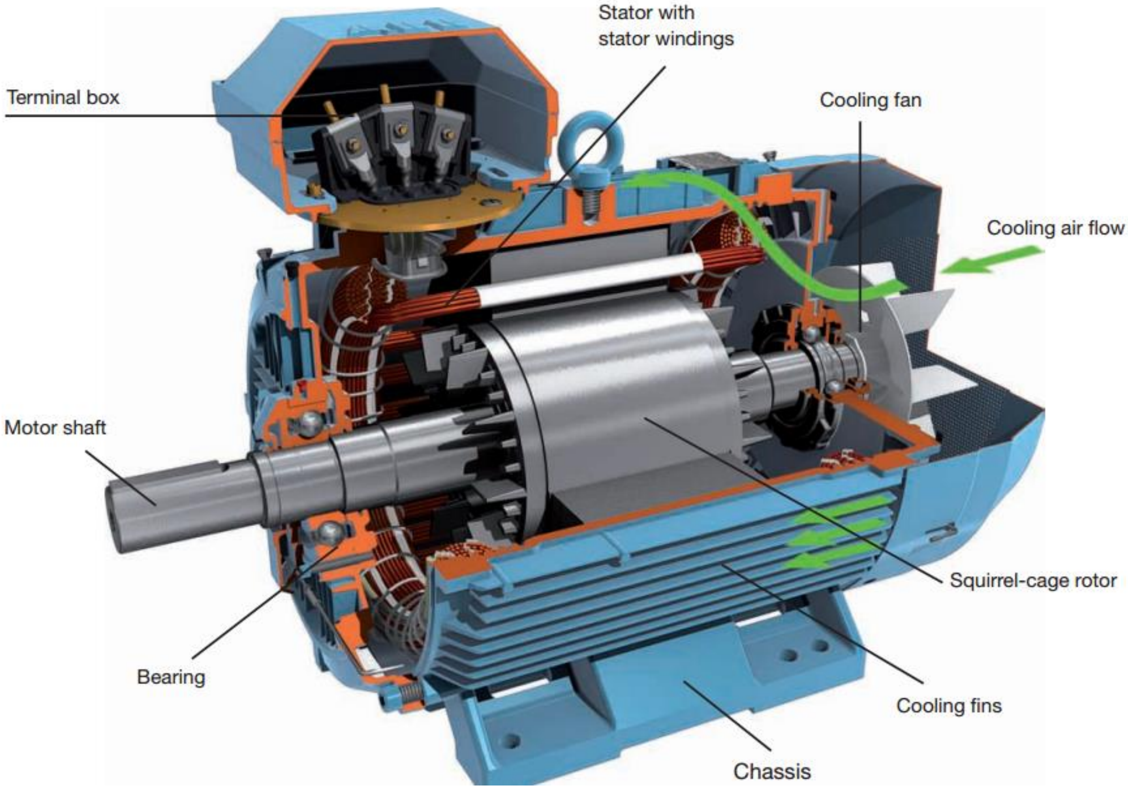
- A wound rotor:- has a 3-phase winding, similar to the one on the stator. The winding is uniformly distributed in the slots and is usually connected in 3 wire wye. The terminals are connected to three slip rings, which turn with the rotor. The revolving slip-rings and associated stationary brushes enable us to connect external resistors in series with the rotor winding. The external resistors are mainly used during the startup period: under normal running conditions, the three brushes are short-circuited.



Construction

An induction motor consists essentially of two main parts:

(a) a stator and
(b) a rotor



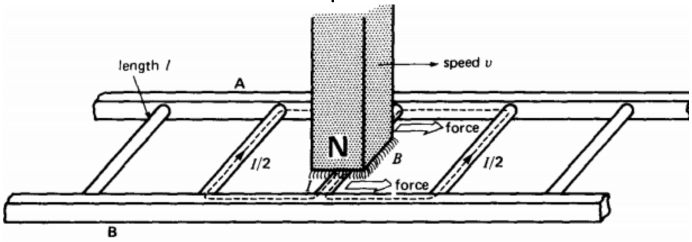
1. Frame. Made of close-grained alloy cast iron.
2. Stator and Rotor Core. Built from high-quality low-loss silicon steel laminations and flash-enameled on both sides.
3. Stator and Rotor Windings. Have moisture proof tropical insulation embodying mica and high quality varnishes. Are carefully spaced for most effective air circulation and are rigidly braced to withstand centrifugal forces and any short-circuit stresses.

4. Air-gap. The stator rabbets and bore are machined carefully to ensure uniformity of air gap.
5. Shafts and Bearings. Ball and roller bearings are used to suit heavy duty, toruble-free running and for enhanced service life.
6. Fans. Light aluminum fans are used for adequate circulation of cooling air and are securely keyed onto the rotor shaft.
7. Slip-rings and Slip-ring Enclosures. Slip-rings are made of high quality phosphor-bronze and are of molded construction.

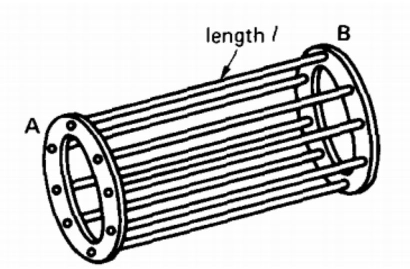
Principle of operation

The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz: force on a conductor. The behavior can readily be understood by means of the following:

Example:- Consider a series of conductors of length 1, whose extremities are short-circuited by two bars A and B. A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed y, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:



(a)



1. A voltage E=βvι is induced in each conductor while it's being cut by the flux (Faraday law).
2. The induced voltage immediately produces a current 1. which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.
3. Because the current carrying conductor lies in the magnetic field of the permanent magnet. it experiences a mechanical force(Lorentz force).
4. The force always acts in a direction to drag the conductor along with the magnetic field, If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently. The force acting on the conductors wilt also decreases, If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.

- **Why motors are known as induction motors?** an induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate of all the ac. motors, the poly phase induction motor is the one which is extensively used for various kinds of industrial drives. **It has the following main**

advantages and also some dis-advantages:

1. It has very simple and extremely rugged, almost unbreakable construction (especially squirrel cage type).
2. Its cost is low and it is very reliable.
3. It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
4. It requires minimum of maintenance.
5. It starts up from rest and needs no extra starting motor and has not to be synchronized. Its starting arrangement is simple especially for squirrel-cage type motor.

Disadvantages:

1. Its speed cannot be varied without sacrificing some of its efficiency.
2. Just like a dc. shunt motor, its speed decreases with increase in load.
3. Its starting torque is somewhat inferior to that of a dc. shunt motor.

Running Operation

If the stator windings are connected to a three-phase supply and the rotor circuit is closed, the induced voltages in the rotor windings produce rotor currents that interact with the air gap field to produce torque. The rotor, if free to do so. Will then start rotating. According to Lens law. the rotor rotates in the direction of the rotating field such that the relative speed between the rotating field and the rotor winding decreases. The rotor will eventually reach a steady-state speed n that is less than the synchronous speed ns, at which the stator rotating field rotates in the air gap. lt is obvious that at n = ns there will be no induced voltage and current in the rotor circuit and hence no torque.

$$n = \frac{2}{P} f * 60 = \frac{120 f}{p}$$

The difference between the rotor speed n and the synchronous speed ns of the rotating field is called the slip s and is defined as

$$s = \frac{n_s - n}{n_s}$$

If you were sitting on the rotor, you would find that the rotor was slipping behind the rotating field by the slip rpm = ns-n=sns. The frequency f2 0f the induced voltage and Current in the rotor circuit will correspond to this slip rpm. Because this is the relative speed between the rotating field and the rotor winding. Thus.

$$f_2 = \frac{p}{120}(n_s - n) = \frac{p}{120} s n_s = s f_1$$

This rotor circuit frequency f2, is also called slip frequency. The voltage induced in the rotor circuit at slip s is:

$$E_{2s} = 4.44 f_2 N_2 \phi_p K_{W2} = 4.44 s f_1 N_2 \phi_p K_{W2} = s E_2$$

Where E2 is the induced voltage in the rotor circuit at standstill.

that is, at the stator frequency f_1.

EXAMPLE:- A three-phase. 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%. Calculate

a) Synchronous speed

b) Rotor speed
C) Frequency of rotor current
Solution
- Synchronous speed: ns=120f/p=(120*60)/6= 1200 rpm
- Rotor speed. =(1-S)Ns=(l-0.O5)(l200)= 1140 rpm
- Frequency of rotor current: F2=sf (0.05)(60)=3 Hz

EXAMPLE:- A three-phase, 460 V, 100 hp. 60 Hz four-pole induction machine delivers rated output power at a slip of 0.05 (this can be stated as a slip of 5%). Determine the
(a.) synchronous speed.
(b.) motor speed.
(e.) frequency of the rotor circuit.
(d.) slip speed.

(a.) $n_s = 120 \frac{f}{P} = 120 \frac{60}{4} = 1800 \text{ rpm}$

(b.) $n = n_s(1 - s) = 1800(1 - 0.05) = 1710 \text{ rpm}$

(c.) $f \quad = sf = (0.05)(60) = 3 \text{ Hz}$

(d.) $n_{slip} = sn_s = (0.05)(1800) = 90 \text{ rpm}$

Example:- A 3-phase. 460 V. 100hp. 60 H: four-pole induction machine delivers rated output power at a slip of 0.05.
Determine the:
(a) Synchronous speed and motor speed.
(b) Speed of the rotating air gap field.
(c) Frequency of the rotor circuit.
(d) Slip rpm.
(e) Speed of the rotor field relative to the (I) rotor structure. (ii) Stator structure. (iii) Stator rotating field.
(f) Rotor induced voltage at the operating speed. if the
stator-to-rotor turns ratio is 1 : 0.5.

Solution:

$(a)\ n_s = \frac{120f}{p} = \frac{120*60}{4} = 1800\ rpm,$

$n = (1 - s)n_s = (1 - 0.05)*1800 = 1710\,rpm$

(b) *1800 rpm* (same as synchronous speed)

$(c)\ f_2 = sf_1 = 0.05 \times 60 = 3$ Hz.

(d) slip $rpm = s\ n_s = 0.05 * 1800 = 90\ rpm$

(e) (i) 90 *rpm* (ii) 1800 *rpm* (iii) 0 *rpm*

(f) Assume that the induced voltage in the stator winding is the same as the applied voltage. Now,

$$E_{2s} = sE_2 = s\frac{N_2}{N_1}E_1 = 0.05*0.5*\frac{460}{\sqrt{3}} = 6.64V\,/\,Phase$$

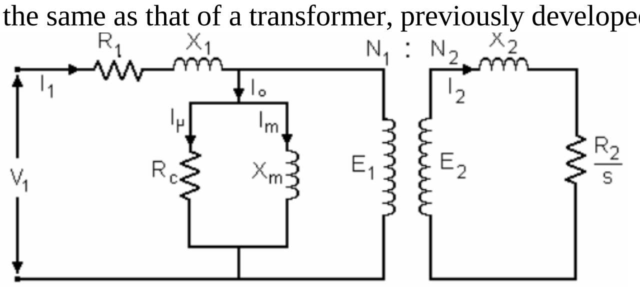
Example: A slip-ring induction motor runs at 290 rpm. at full load, when connected to

50-Hz supply. Determine the number of poles and slip.
Solution. Since N is 290 rpm; Ns has to be somewhere near it, say 300 rpm. If Ns is assumed as 300 rpm, then 300 = 120 × 50/P. Hence, P = 20. ∴ s = (300 − 290)/300 = 3.33%

Equivalent Circuit of the Induction Motor

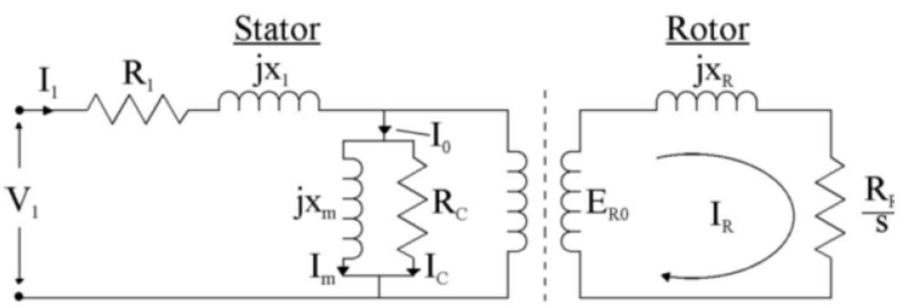
In this section we develop the equivalent circuit from basic principles. We then analyze the characteristics of a low-power and high-power motor and observe their basic differences. Finally, we develop the equivalent circuit of an asynchronous generator and determine its properties under load. A 3-phase wound-rotor induction motor is very similar in construction to a 3-phase transformer. Thus, the motor has 3 identical primary windings and 3 identical secondary windings one set for each phase. On account of the perfect symmetry, we can consider a single primary winding and a single secondary winding in analyzing the behavior of the motor.

When the motor is at standstill, it acts exactly like a conventional transformer, and so its equivalent circuit is the same as that of a transformer, previously developed.

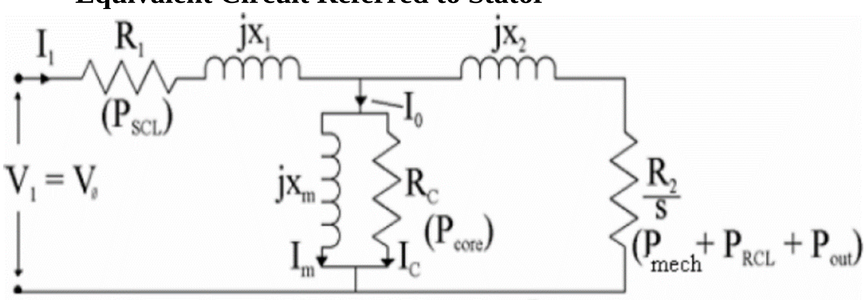


In the case of a conventional 3-phase transformer, we would be justified in removing the magnetizing branch composed of jXc, and Rc because the exciting current I_0 is negligible compared to the load current I_1. However, in a motor this is no longer true: I_0 may be as high as 40 percent of I_1, because of the air gap. Consequently, we cannot eliminate the magnetizing branch.

The Induction Motor circuit can be represented as:



Equivalent Circuit Referred to Stator



Example:
A 220-V three-phase six-pole 50-Hz induction motor is running at a slip of 3.5 percent. Find:

(a) The speed of the magnetic fields in revolutions per minute
(b) The speed of the rotor in revolutions per minute
(c) The slip speed of the rotor
(d) The rotor frequency in hertz

SOLUTION

(a) The speed of the magnetic fields is

$$n_{sync} = \frac{120\, f_{2e}}{P} = \frac{120(50 \text{ Hz})}{6} = 1000 \text{ r/min}$$

(b) The speed of the rotor is

$$n_m = (1-s)\; n_{sync} = (1-0.035)(1000 \text{ r/min}) = 965 \text{ r/min}$$

(c) The slip speed of the rotor is

$$n_{slip} = sn_{sync} = (0.035)(1000 \text{ r/min}) = 35 \text{ r/min}$$

(d) The rotor frequency is

$$f_{re} = \frac{n_{slip} P}{120} = \frac{(35 \text{ r/min})(6)}{120} = 1.75 \text{ Hz}$$

Ex: A three-phase 60-Hz induction motor runs at 715 r/min at no load and at 670 r/min at full load.
(a) How many poles does this motor have?
(b) What is the slip at rated load?
(c) What is the speed at one-quarter of the rated load?
(d) What is the rotor's electrical frequency at one-quarter of the rated load?

SOLUTION

(a) This machine has 10 poles, which produces a synchronous speed of

$$n_{sync} = \frac{120\, f_e}{P} = \frac{120(60 \text{ Hz})}{10} = 720 \text{ r/min}$$

(b) The slip at rated load is

$$s = \frac{n_{sync} - n_m}{n_{sync}} \times 100\% = \frac{720-670}{720} \times 100\% = 6.94\%$$

(c) The motor is operating in the linear region of its torque-speed curve, so the slip at ¼ load will be

$$s = 0.25(0.0694) = 0.0171$$

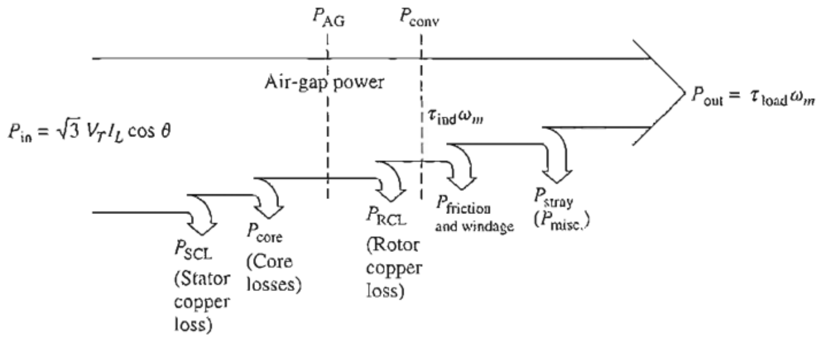
The resulting speed is

$$n_m = (1-s)\; n_{sync} = (1-0.0171)(720 \text{ r/min}) = 708 \text{ r/min}$$

(d) The electrical frequency at ¼ load is

$$f_r = sf_e = (0.0171)(60 \text{ Hz}) = 1.03 \text{ Hz}$$

Power flow in induction motor



$$P_1 = 3V_1 I_1 Cos\theta$$

$$P_g = P_1 - P_{Si}$$

$$P_m = P_g - P_{Cu2}$$

$$P_m = (1 - S)P_g$$

$$P_{Cu1} = 3I_1^2 R_1$$

$$P_{Cu2} = 3I_2'^2 R_2'$$

$$P_{Cu2} = SP_g$$

P_1: input power.
Pcu_1: copper loss in stator.
Pg: developed power in air gap.
Pcu_2: copper loss in rotor.
Pm: mechanical power
Pf: friction power

Therefore, for efficient operation of the induction machine, it should operate at a low slip so that more of the air gap power is converted into mechanical power. Part of the mechanical power will be lost to overcome the windage and friction. The remainder of the mechanical power will be available as output shaft power.

Iron Loss in Armature

Due to the rotation of the iron core of the armature in the magnetic flux of the field poles, there are some losses taking place continuously in the core and are known as Iron Losses or Core Losses. Iron losses consist of (i) Hysteresis loss and (ii) Eddy Current loss.

Example: A 480-V, 60-Hz, 50-hp, three-phase induction motor is drawing 60 A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the Stray losses are negligible. Find the following quantities:
(a) The air-gap power PAG
(b) The power converted Pconv
(c) The output power Pout
(d) The efficiency of the motor

Solution

To answer these questions, refer to the power-flow diagram for an induction motor (Figure 6–13).

(*a*) The air-gap power is just the input power minus the stator I^2R losses and core losses. The input power is given by

$$P_{in} = \sqrt{3}V_T I_L \cos\theta$$
$$= \sqrt{3}(480\text{ V})(60\text{ A})(0.85) = 42.4\text{ kW}$$

From the power-flow diagram, the air-gap power is given by

$$P_{AG} = P_{in} - P_{SCL} - P_{core}$$
$$= 42.4\text{ kW} - 2\text{ kW} - 1.8\text{ kW} = 38.6\text{ kW}$$

(*b*) From the power-flow diagram, the power converted from electrical to mechanical form is

$$P_{conv} = P_{AG} - P_{RCL}$$
$$= 38.6\text{ kW} - 700\text{ W} = 37.9\text{ kW}$$

(*c*) From the power-flow diagram, the output power is given by

$$P_{out} = P_{conv} - P_{F\&W} - P_{misc}$$
$$= 37.9\text{ kW} - 600\text{ W} - 0\text{ W} = 37.3\text{ kW}$$

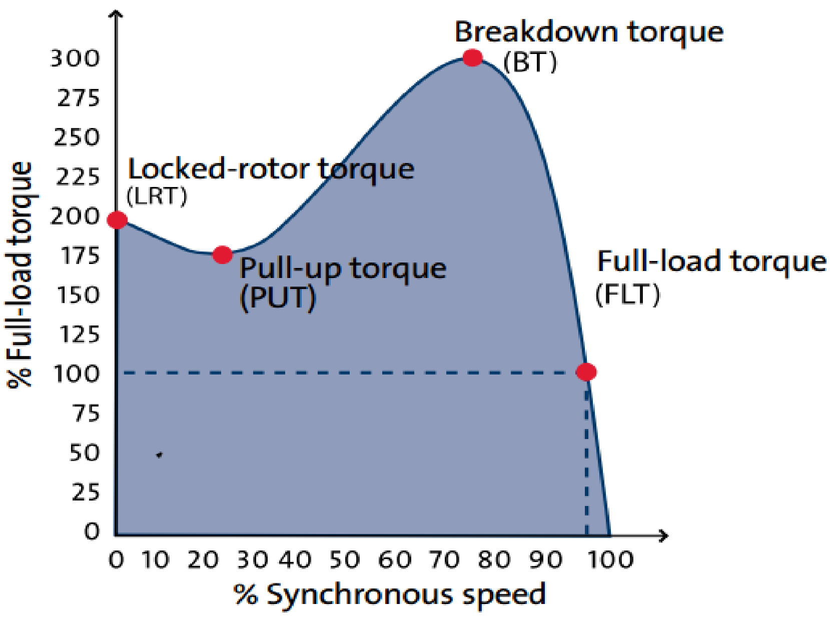
or, in horsepower,

$$P_{out} = (37.3\text{ kW})\frac{1\text{ hp}}{0.746\text{ kW}} = 50\text{ hp}$$

(*d*) Therefore, the induction motor's efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$
$$= \frac{37.3\text{ kW}}{42.4\text{ kW}} \times 100\% = 88\%$$

The Derivation of the Induction Motor Induced-Torque Equation



Torque/speed curve for an AC motor

1. Starting torque (ST) / Locked-rotor torque (LRT):

The torque produced when power is applied to a motor at rest, i .e. When the motor is energized at full voltage and the shaft is locked in place. This is the torque used to start accelerating the load.

2. **Pull-up torque (PUT):**

This term is used for the lowest point on the torque speed curve for a motor which is accelerating a load up to full speed . Most Grundfos motors do not have a separate pull-up torque value, as the lowest point is found at the locked-rotor point .As a result, pull-up torque is the same as starting torque/locked-rotor torque for the majority of all Grundfos motors.

3. **Breakdown torque (BT):**
The maximum torque that an AC motor develops with rated voltage applied at rated frequency without causing sudden drops in speed . This is also known as pull-out torque or maximum torque.

4. **Full-load torque (FLT):**
The torque required to produce rated power at full-load speed .

$$\tau_{ind} = \frac{P_{conv}}{\omega_m}$$

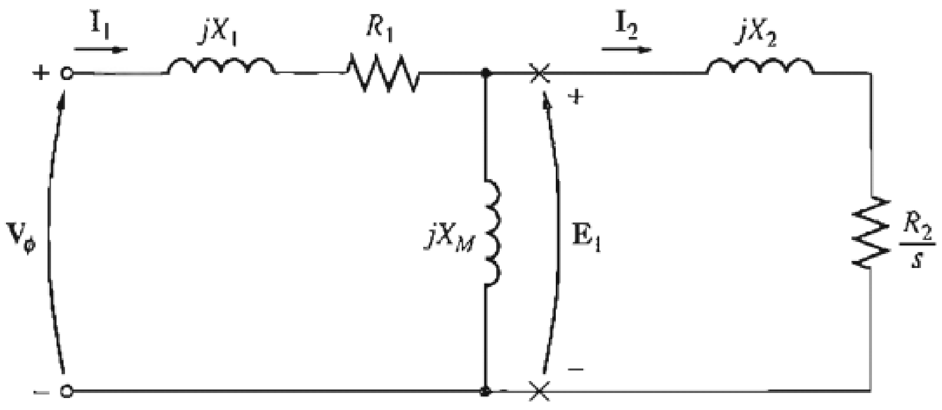
$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}}$$

$$\omega_s = \frac{2\pi\, ns}{60} \qquad \text{rad/sec.}$$

$$P_{AG,1\phi} = I_2^2 \frac{R_2}{s}$$

Therefore, the total air-gap power is

$$P_{AG} = 3I_2^2 \frac{R_2}{s}$$



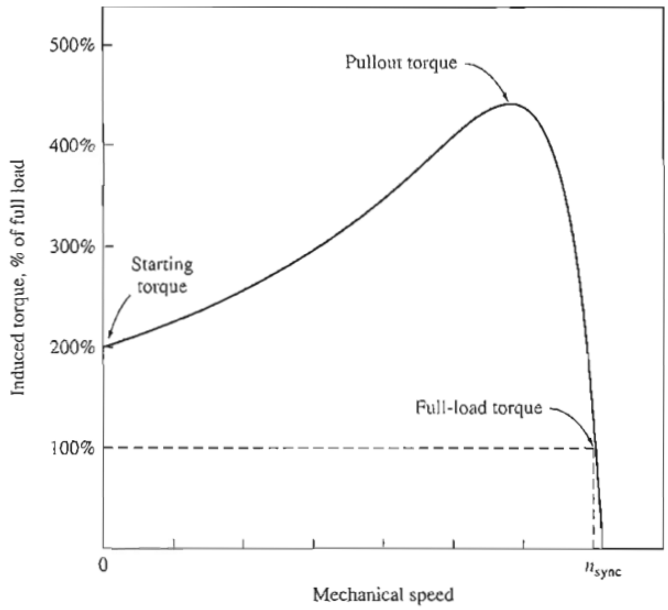
$$T = \frac{P_g}{\omega_s} = \frac{3 I_2'^2 R_2' / S}{2\pi \ ns / 60} \quad , \quad T = K \cdot I_2'^2 \cdot \frac{R_2'}{S} \qquad \text{Nm}$$

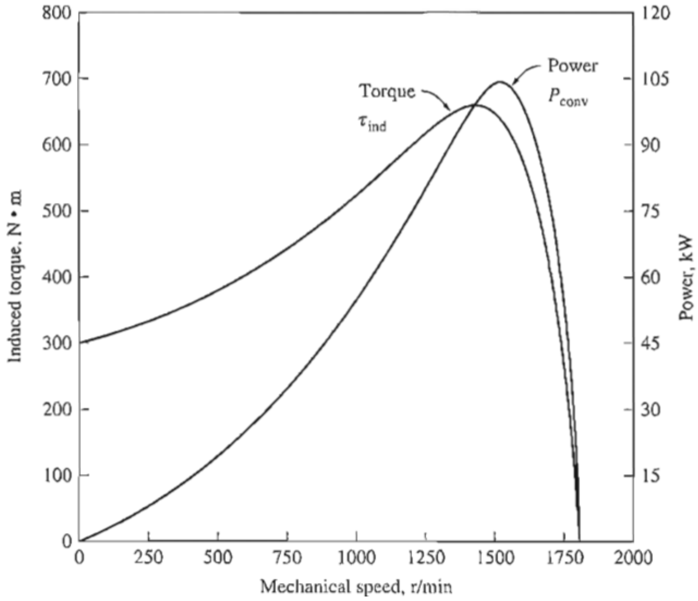
$$K = \frac{3 \times 60}{2\pi \ ns}$$

$$I_2' = \frac{V_1}{Z_{eq}} = \frac{V_1}{\sqrt{(R_1 + R_2'/S)^2 + X_{eq}^2}}$$

$$T = K \cdot \frac{V_1^2}{(R_1 + R_2'/S)^2 + X_{eq}^2} \cdot \frac{R_2'}{S}$$

Comments on the Induction Motor Torque- Speed Curve





The induction motor torque-speed characteristic curve plotted in Figures up provides several important pieces of information about the operation of induction motors. This information is summarized as follows:

1. The induced torque of the motor is zero at synchronous speed. This fact has been discussed previously.

2. The torque- speed curve is nearly linear between no load and full load. In this range, the rotor resistance is much larger than the rotor reactance, so the rotor current, the rotor magnetic field, and the induced torque increase linearly with increasing slip.

3. There is a maximum possible torque that cannot be exceeded. This torque, called the pullout torque or breakdown torque, is 2 to 3 times the rated full load torque of the motor. The next section of this chapter contains a method for calculating pullout torque.

4.The starting torque on the motor is slightly larger than its full-load torque. So this motor will start carrying any load that it can supply at full power.

5. Notice that the torque on the motor for a given slip varies as the square of the applied voltage. This fact is useful in one form of induction motor speed control that will be described later.

6. If the rotor of the induction motor is driven faster than synchronous speed, then the direction of the induced torque in the machine reverses and the machine becomes a genera tor, converting mechanical power to electric power. The use of induction machines as generators will be described later.

7. If the motor is turning backward relative to the direction of the magnetic fields, the induced torque in the machine will stop the machine very rapidly and will try to rotate it in the other direction. Since reversing the direction of magnetic field rotation is simply a matter of switching any two stator phases, this fact can be used as a way to very rapidly stop an induction motor. The act of switching two phases in order to stop the motor very rapidly is called plugging. The power converted to mechanical form in an induction motor is equal to

$$P_{conv} = \tau_{ind}\,\omega_m$$

- Notice that the peak power supplied by the induction motor occurs at a different speed than the maximum torque; and, of course, no power is converted to mechanical form when the rotor is at zero speed.

Maximum (Pullout) Torque in an Induction Motor

Since the induced torque is equal to.

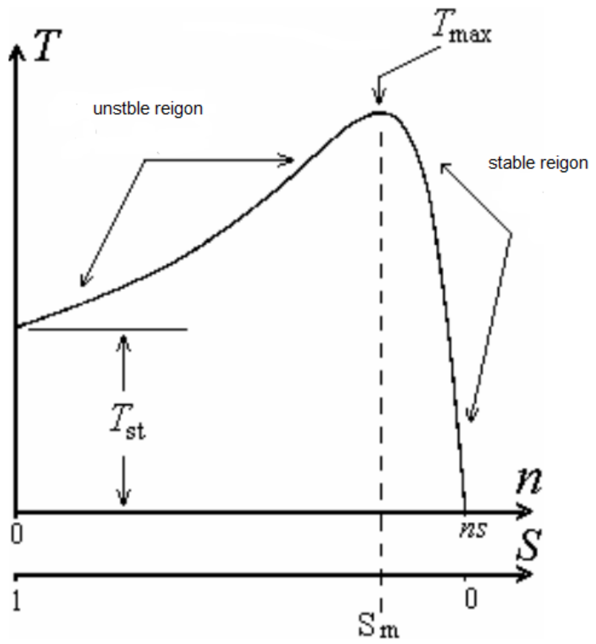
$$P_{AG} / \omega_{sync},$$

The maximum possible torque occurs when the air-gap power is maximum. Since the air-gap power is equal to the power consumed in the resistor R2 /s, the maximum induced torque will occur when the power consumed by that resistor is maximum.

$$T_{max} = K \cdot \frac{V_1^2}{2X_2'}$$

And the slip at maximum torque is:-

$$S_m = \frac{R_2'}{X_2'}$$



Starting torque at zero speed (s=1) is

$$T_{Start} = K \cdot \frac{V_1^2}{(R_1 + R_2')^2 + X_{eq}^2} \cdot R_2'$$

EX: A 50-kW, 460-V, 50-Hz, two-pole induction motor has a slip of 5 percent when operating a full-load conditions. At full-load conditions, the friction and windage losses are 700 W, and the core losses are 600W. Find the following values for full-load conditions:

(a) The shaft speed nm

(b) The output power in watts

(c) The load torque in newton-meters

(d) The induced torque Tind in newton-meters

(e) The rotor frequency in hertz

SOLUTION

(a) The synchronous speed of this machine is

$$n_{sync} = \frac{120\, f_{se}}{P} = \frac{120(50\text{ Hz})}{2} = 3000\text{ r/min}$$

Therefore, the shaft speed is

$$n_m = (1-s)\, n_{sync} = (1-0.05)(3000\text{ r/min}) = 2850\text{ r/min}$$

(b) The output power in watts is 50 kW (stated in the problem).

(c) The load torque is

$$\tau_{load} = \frac{P_{OUT}}{\omega_m} = \frac{50\text{ kW}}{(2850\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 167.5\text{ N}\cdot\text{m}$$

(d) The induced torque can be found as follows:

$$P_{conv} = P_{OUT} + P_{F\&W} + P_{core} + P_{misc} = 50\text{ kW} + 700\text{ W} + 600\text{ W} + 0\text{ W} = 51.3\text{ kW}$$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{51.3\text{ kW}}{(2850\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 171.9\text{ N}\cdot\text{m}$$

(e) The rotor frequency is

$$f_r = sf_e = (0.05)(50\text{ Hz}) = 2.5\text{ Hz}$$

EX:

A 208-V four-pole 60-Hz Y-connected wound-rotor induction motor is rated at 30 hp. Its equivalent circuit components are

$R_1 = 0.100\ \Omega$ $\quad R_2 = 0.070\ \Omega$ $\quad X_M = 10.0\ \Omega$

$X_1 = 0.210\ \Omega$ $\quad X_2 = 0.210\ \Omega$

$P_{mech} = 500\text{ W}$ $\quad P_{misc} \approx 0$ $\quad P_{core} = 400\text{ W}$

For a slip of 0.05, find

(a) The line current I_L

(b) The stator copper losses P_{SCL}

(c) The air-gap power P_{AG}

(d) The power converted from electrical to mechanical form P_{conv}

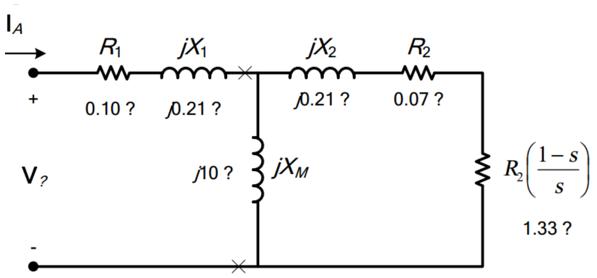
(e) The induced torque τ_{ind}

(f) The load torque τ_{load}

(g) The overall machine efficiency

(h) The motor speed in revolutions per minute and radians per second

SOLUTION: The equivalent circuit of this induction motor is shown below:



The equivalent impedance of the rotor circuit in parallel with jX_M is:

$$Z_F = \frac{1}{\frac{1}{jX_M} + \frac{1}{Z_2}} = \frac{1}{\frac{1}{j10\ \Omega} + \frac{1}{1.40 + j0.21}} = 1.318 + j0.386 = 1.374\angle 16.3^\circ\ \Omega$$

The phase voltage is $208/\sqrt{3} = 120$ V, so line current I_L is

$$I_L = I_A = \frac{V_\phi}{R_1 + jX_1 + R_F + jX_F} = \frac{120\angle 0^\circ\ \text{V}}{0.10\ \Omega + j0.21\ \Omega + 1.318\ \Omega + j0.386\ \Omega}$$

$$I_L = I_A = 78.0\angle -22.8^\circ\ \text{A}$$

(b) The stator copper losses are

$$P_{SCL} = 3I_A^2 R_1 = 3(78.0\ \text{A})^2 (0.10\ \Omega) = 1825\ \text{W}$$

(c) The air gap power is $P_{AG} = 3I_2^2 \frac{R_2}{s} = 3I_A^2 R_F$

$$P_{AG} = 3I_2^2 \frac{R_2}{s} = 3I_A^2 R_F = 3(78.0\ \text{A})^2 (1.318\ \Omega) = 24.0\ \text{kW}$$

(d) The power converted from electrical to mechanical form is

$$P_{conv} = (1-s) P_{AG} = (1-0.05)(24.0\ \text{kW}) = 22.8\ \text{kW}$$

(e) The induced torque in the motor is

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{24.0\ \text{kW}}{(1800\ \text{r/min})\left(\frac{2\pi\ \text{rad}}{1\ \text{r}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)} = 127.4\ \text{N}\cdot\text{m}$$

(f) The output power of this motor is

$$P_{OUT} = P_{conv} - P_{mech} - P_{core} - P_{misc} = 22.8\ \text{kW} - 500\ \text{W} - 400\ \text{W} - 0\ \text{W} = 21.9\ \text{kW}$$

The output speed is

$$n_m = (1-s)\ n_{sync} = (1-0.05)(1800\ \text{r/min}) = 1710\ \text{r/min}$$

$$\tau_{load} = \frac{P_{OUT}}{\omega_m} = \frac{21.9\ \text{kW}}{(1710\ \text{r/min})\left(\frac{2\pi\ \text{rad}}{1\ \text{r}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)} = 122.3\ \text{N}\cdot\text{m}$$

(g) The overall efficiency is

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100\% = \frac{P_{OUT}}{3V_\phi I_A \cos\theta} \times 100\%$$

h) The motor speed in revolutions per minute is 1710 r/min. The motor speed in radians per second is

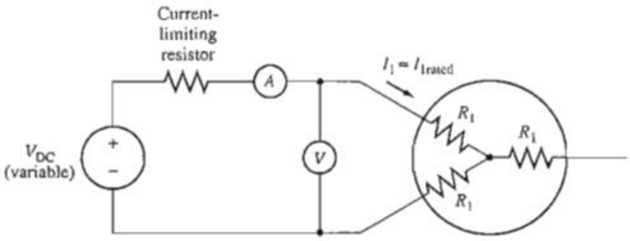
$$\omega_m = (1710\ \text{r/min})\left(\frac{2\pi\ \text{rad}}{1\ \text{r}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right) = 179\ \text{rad/s}$$

DETERMINING CIRCUIT MODEL PARAMETERS.

1. The DC Test for Stator Resistance

The rotor resistance R2plays an extremely critical role in the operation of an induction motor. Among other things, R, determines the shape of the torque-speed curve, determining the speed at which the pullout torque occurs. A standard motor test called the locked-roto r test can be used to determine the total motor circuit (resistance (this test is taken up in the next section). However, this test finds only the total resistance. To find the rotor resistance R2 accurately. it is necessary to know RI so that it can be subtracted from the total. There is a test for RI independent of R" XI and X,. This test is called the de test. Basically, a de voltage is applied to the stator windings of an induction motor. Because the current is dc, there is no induced voltage in the rotor circuit and no resulting rotor current flow. Also, the reactance of the motor is zero at direct current. Therefore, the only quantity limiting current flow in the motor is the stator resistance, and that resistance can be determined. The basic circuit for the de test is shown in Figure 6-54. This figure shows a dc power supply connected to two of the three terminals of a V-connected induction motor. To perform the test, the current in the stator windings is adjusted to the rated value, and the voltage between the terminals is measured. The current in

the stator windings is adjusted to the rated value in an attempt to heat the windings to the same temperature they would have during normal operation (remember. winding resistance is a function of temperature).



The current flow through two of the windings, so the total resistance in the current path is 2Rl' Therefore,

$$2R_1 = \frac{V_{DC}}{I_{DC}}$$

$$\boxed{R_1 = \frac{V_{DC}}{2I_{DC}}}$$

2. The No Load Test

In this motor at no-load conditions, the input power measured by the meters must equal the losses in the motor. The rotor copper losses are negligible because the current I, is extremely small [because of the large load resistance R,(I - s)/s], so they may be neglected. The stator copper losses are given by

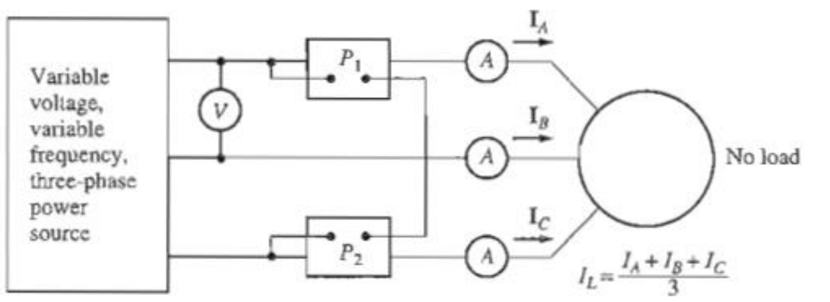
$$\boxed{P_{SCL} = 3I_1^2 R_1}$$

so the input power must equal

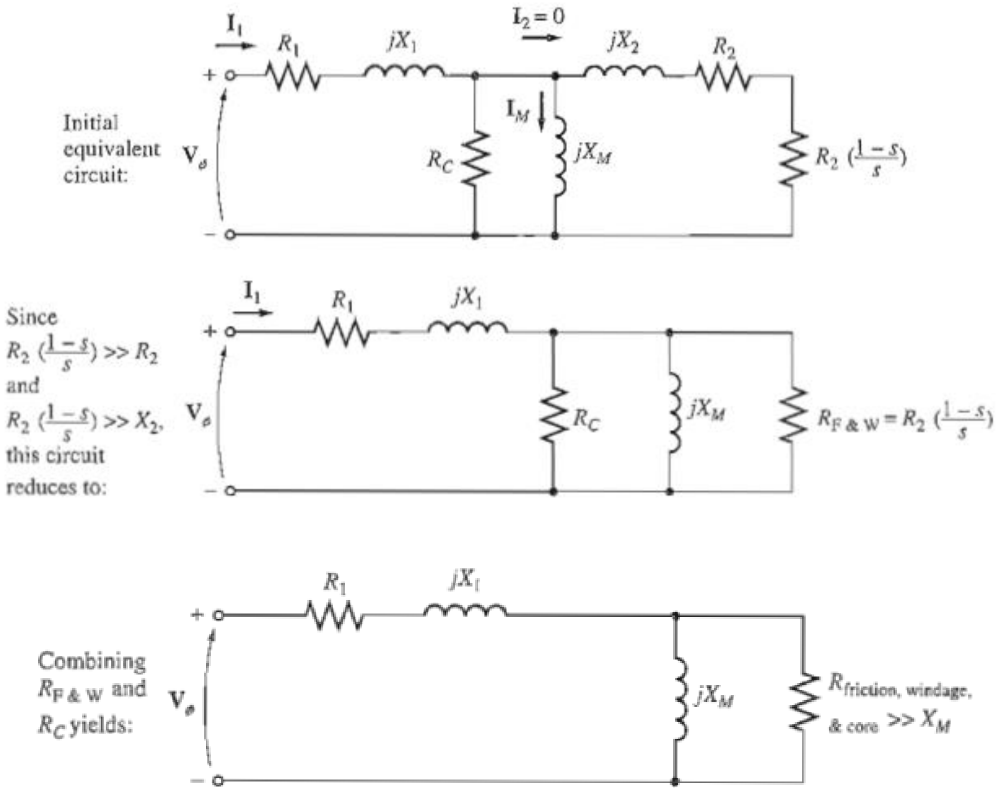
$$P_{in} = P_{SCL} + P_{core} + P_{F\&W} + P_{misc}$$
$$= 3I_1^2 R_1 + P_{rot}$$

where P_{rot} is the rotational losses of the motor:

$$P_{rot} = P_{core} + P_{F\&W} + P_{misc}$$



(a)



The equivalent circuit that describes the motor operating in this condition (contains resistors Rc and R2(] - s)/s in parallel with the magnetizing reactance XM .The current needed to establish a magnetic field is quite large in an induction motor, because of the high reluctance of its air gap, so the reactance XM will be much smaller than the resistances in parallel with it and the overall input power factor will be very small. With the large lagging current, most of the voltage drop will be across the inductive components in the circuit. The equivalent input impedance is thus approximately

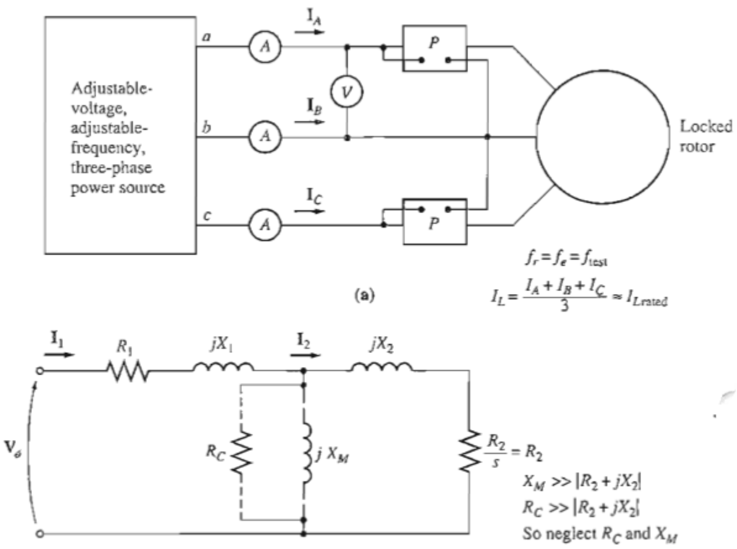
$$|Z_{eq}| = \frac{V_\phi}{I_{1,nl}} \approx X_1 + X_M$$

3. The Locked-Rotor Test

The third test that can be performed on an induction motor to determine its circuit parameters is called the locked-rotor test, or sometimes the blocked-rotor test. This test corresponds to the short-circuit test on a transformer. In this test, the rotor is locked or blocked so that it cannot move, a voltage is applied to the motor, and the resu1ting voltage, current, and power are measured.

Figure shows the connections for the locked-rotor test To perform the locked-rotor test, an ac voltage is applied to the stator, and the current flow is adjusted to be approximately full-load value, When the current is full-load value, the voltage, current, and power flowing into the motor are measured. The equivalent circuit for this test is shown in Figure 6-55b. Notice that since the rotor is not moving, the slip s = 1, and so the rotor resistance R2/s is just equal to R2 (quite a small value). Since R, and X, are so small, almost all the input current will flow through them, instead of through the much larger magnetizing reactance Xm• Therefore, the circuit under these conditions looks like a series combination of Xl> RI , Xl> and R2.

There is one problem with this test, however. In normal operation, the stator frequency is the line frequency of the power system (SO or 60 Hz). At starting conditions, the rotor is also at line frequency. However, at normal operating conditions, the slip of most motors is only 2 to 4 percent, and the resulting rotor frequency is in the range of 1 to 3 Hz. This creates a problem in that the line frequency does not represent the normal operating conditions of the rotor. Since effective rotor resistance is a strong function of frequency for design class Band C motors, the incorrect rotor frequency can lead to misleading results in this test. A typical compromise is to use a frequency 25 percent or less of the rated frequency. While this approach is acceptable for essentially constant resistance rotors (design classes A and D), it leaves a lot to be desired when one is trying to find the normal rotor resistance of a variable-resistance rotor. Because of these and similar problems, a great deal of care must be exercised in taking measurements for these tests.



$$P = \sqrt{3} V_T I_L \cos \theta$$

so the locked-rotor power factor can be found as

$$\text{PF} = \cos \theta = \frac{P_{in}}{\sqrt{3} V_T I_L}$$

$$|Z_{LR}| = \frac{V_\phi}{I_1} = \frac{V_T}{\sqrt{3} I_L}$$

The locked-rotor resistance R_{LR} is equal to

$$R_{LR} = R_1 + R_2$$

while the locked-rotor reactance X'_{LR} is equal to

$$X'_{LR} = X'_1 + X'_2$$

Example. The following test data were taken on a 7.5-hp, four-pole, 208-V, 60-Hz, design A, V-connected induction motor having a rated current of 28 A.

DC test:

$V_{DC} = 13.6$ V $\quad I_{DC} = 28.0$ A

No-load test:

$V_T = 208$ V $\quad f = 60$ Hz

$I_A = 8.12$ A $\quad P_{in} = 420$ W

$I_B = 8.20$ A

$I_C = 8.18$ A

Locked-rotor test:

$V_T = 25$ V $\quad f = 15$ Hz

$I_A = 28.1$ A $\quad P_{in} = 920$ W

$I_B = 28.0$ A

$I_C = 27.6$ A

(a) Sketch the per-phase equivalent circuit for this motor.

(b) Find the slip at the pullout torque, and find the value of the pullout torque itself.

Solution

(a) From the dc test,

$$R_1 = \frac{V_{DC}}{2I_{DC}} = \frac{13.6\text{ V}}{2(28.0\text{ A})} = 0.243\ \Omega$$

From the no-load test,

$$I_{L,av} = \frac{8.12\text{ A} + 8.20\text{ A} + 8.18\text{ A}}{3} = 8.17\text{ A}$$

$$V_{\phi,nl} = \frac{208\text{ V}}{\sqrt{3}} = 120\text{ V}$$

Therefore,

$$|Z_{nl}| = \frac{120\text{ V}}{8.17\text{ A}} = 14.7\ \Omega = X_1 + X_M$$

When X_1 is known, X_M can be found. The stator copper losses are

$$P_{SCL} = 3I_1^2 R_1 = 3(8.17 \text{ A})^2(0.243 \ \Omega) = 48.7 \text{ W}$$

Therefore, the no-load rotational losses are

$$P_{rot} = P_{in,nl} - P_{SCL,nl}$$
$$= 420 \text{ W} - 48.7 \text{ W} = 371.3 \text{ W}$$

From the locked-rotor test,

$$I_{L,av} = \frac{28.1 \text{ A} + 28.0 \text{ A} + 27.6 \text{ A}}{3} = 27.9 \text{ A}$$

The locked-rotor impedance is

$$|Z_{LR}| = \frac{V_\phi}{I_A} = \frac{V_T}{\sqrt{3}I_A} = \frac{25 \text{ V}}{\sqrt{3}(27.9 \text{ A})} = 0.517 \ \Omega$$

and the impedance angle θ is

$$\theta = \cos^{-1} \frac{P_{in}}{\sqrt{3}V_T I_L}$$
$$= \cos^{-1} \frac{920 \text{ W}}{\sqrt{3}(25 \text{ V})(27.9 \text{ A})}$$

$$= \cos^{-1} 0.762 = 40.4°$$

Therefore, $R_{LR} = 0.517 \cos 40.4° = 0.394 \ \Omega = R_1 + R_2$. Since $R_1 = 0.243 \ \Omega$, R_2 must be $0.151 \ \Omega$. The reactance at 15 Hz is

$$X'_{LR} = 0.517 \sin 40.4° = 0.335 \ \Omega$$

The equivalent reactance at 60 Hz is

$$X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = \left(\frac{60 \text{ Hz}}{15 \text{ Hz}}\right) 0.335 \ \Omega = 1.34 \ \Omega$$

For design class A induction motors, this reactance is assumed to be divided equally between the rotor and stator, so

$$X_1 = X_2 = 0.67 \ \Omega$$
$$X_M = |Z_{nl}| - X_1 = 14.7 \ \Omega - 0.67 \ \Omega = 14.03 \ \Omega$$

The final per-phase equivalent circuit is shown in Figure 6–57.

(b) For this equivalent circuit, the Thevenin equivalents are found from Equations (6–41b), (6–44), and (6–45) to be

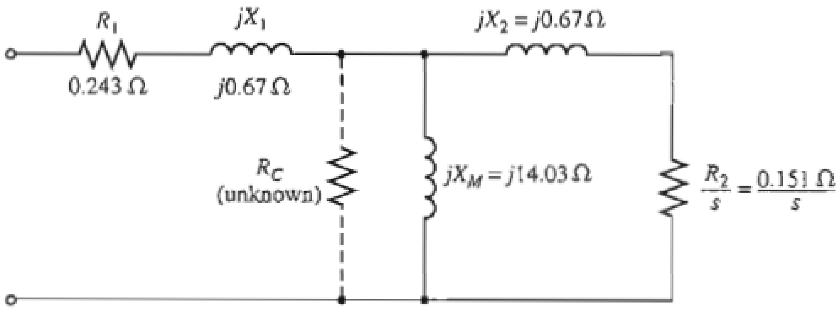
$$V_{TH} = 114.6 \text{ V} \qquad R_{TH} = 0.221 \ \Omega \qquad X_{TH} = 0.67 \ \Omega$$

Therefore, the slip at the pullout torque is given by

$$s_{max} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$
$$= \frac{0.151 \ \Omega}{\sqrt{(0.243 \ \Omega)^2 + (0.67 \ \Omega + 0.67 \ \Omega)^2}} = 0.111 = 11.1\%$$

The maximum torque of this motor is given by

$$\tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync}[R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X^2)}]}$$
$$= \frac{3(114.6 \text{ V})^2}{2(188.5 \text{ rad/s})[0.221 \ \Omega + \sqrt{(0.221 \ \Omega)^2 + (0.67 \ \Omega + 0.67 \ \Omega)^2}]}$$
$$= 66.2 \text{ N} \cdot \text{m}$$



QUESTIONS AND ANSWERS ON THREE-PHASE INDUCTION MOTORS

Q. 1. How do changes in supply voltage and frequency affect the performance of an induction motor?

Ans. High voltage decreases both power factor and slip, but increases torque. Low voltage does just the opposite. Increase in frequency increases power factor but decreases the torque. However, per cent slip remains unchanged. Decrease in frequency decreases power factor but increases torque leaving per cent slip unaffected as before.

Q. 2. What is, in brief, the basis of operation of a 3-phase induction motor?

Ans. The revolving magnetic field which is produced when a 3-phase stator winding is fed from a 3-phase supply.

Q. 3. What factors determine the direction of rotation of the motor?

Ans. The phase sequence of the supply lines and the order in which these lines are connected to the stator winding.

Q. 4. How can the direction of rotation of the motor be reversed?

Ans. By transposing or changing over any two line leads.

Q. 5. Why induction motors are called asynchronous?

Ans. Because their rotors can never run with the synchronous speed.

Q. 6. How does the slip vary with load?

Ans. The greater the load, greater is the slip or slower is the rotor speed.

Q. 7. What modifications would be necessary if a motor is required to operate on voltage different from that for which it was originally designed?

Ans. The number of conductors per slot will have to be changed in the same ratio as the change in voltage. If the voltage is doubled, the number of conductors per slot will have to be doubled.

Q. 8. Enumerate the possible reasons if a 3-phase motor fails to start.

Ans. Any one of the following reasons could be responsible:

1. one or more fuses may be blown.
2. Voltage may be too low.
3. The starting load may be too heavy.
4. Worn bearings due to which the armature may be touching field laminate, thus introducing excessive friction.

Q. 9. A motor stops after starting i.e. it fails to carry load. What could be the causes?

Ans. Any one of the following:

1. hot bearings, which increase the load by excessive friction.

2. Excessive tension on belt, which causes the bearings to heat.

3. Failure of short cut-out switch.

4. single-phasing on the running position of the starter.

Q. 10. Which is the usual cause of blow-outs in induction motors ?

Ans. The commonest cause is single-phasing.

Q. 11. What is meant by 'single-phasing' and what are its causes?

Ans. By single-phasing is meant the opening of one wire (or leg) of a three-phase circuit whereupon the remaining leg at once becomes single-phase. When a three-phase circuit functions normally, there are three distinct currents flowing in the circuit. As is known, any two of these currents use the third wire as the return path i.e. one of the three phase's acts as a return path for the other two. Obviously, an open circuit in one leg kills two of the phases and there will be only one current or phase working, even though two wires are left intact. The remaining phase attempts to carry all the load. The usual cause of single-phasing is, what is generally referred to as running fuse, which is a fuse whose current-carrying capacity is equal to the full-load current of the motor connected in the circuit. This fuse will blow-out whenever there is overload (either momentary or sustained) on the motor.

Q. 12. What happens if single-phasing occurs when the motor is running? And when it is stationary?

Ans. (i) If already running and carrying half load or less, the motor will continue running as a single-phase motor on the remaining single-phase supply, without damage because half loads do not blow normal fuses.

(ii) If motor is very heavily loaded, then it will stop under single-phasing and since it can neither restart nor blow out the remaining fuses, the burn-out is very prompt.

A stationary motor will not start with one line broken. In fact, due to heavy standstill

current, it is likely to burn-out quickly unless immediately disconnected.

OBJECTIVE TESTS

Regarding skewing of motor bars in a squirrel cage induction motor, (SCIM) which statement is false?

(a) it prevents cogging

(b) it increases starting torque

(c) it produces more uniform torque

(d) it reduces motor 'hum' during its operation.

2. The principle of operation of a 3-phase. Induction motor is most similar to that of a

(a) Synchronous motor

(b) repulsion-start induction motor

(c) Transformer with a shorted secondary

(d) capacitor-start, induction-run motor.

3. The magnetizing current drawn by transformers and induction motors is the cause of their

.........power factor.

(a) Zero (b) unity

(c) Lagging (d) leading.

4. The effect of increasing the length of air-gap in an induction motor will be to increase the

(a) Power factor

(b) speed

(c) magnetizing current

(d) air-gap flux.

5. In a 3-phase induction motor, the relative speed of stator flux with respect to ....is zero.

(a) Stator winding (b) rotor

(c) rotor flux (d) space.

6. An eight-pole wound rotor induction motor operating on 60 Hz supply is driven at 1800 rpm.by a prime mover in the opposite direction of revolving magnetic field. The frequency of rotor current is

(a) 60 Hz (b) 120 Hz

(c) 180 Hz (d) none of the above.

7. A 3-phase, 4-pole, 50-Hz induction motor runs at a speed of 1440 rpm. The rotating field produced by the rotor rotates at a speed of.......rpm. with respect to the rotor.

(a) 1500 (b) 1440

(c) 60 (d) 0.

8. In a 3-φ induction motor, the rotor field rotates at synchronous speed with respect to

(a) stator (b) rotor

(c) stator flux (d) none of the above.

9. Irrespective of the supply frequency, the torque developed by a SCIM is the same whenever........ is the same.

(a) Supply voltage (b) external load

(c) rotor resistance (d) slip speed.

10. In the case of a 3-φ induction motor having Ns= 1500 rpm and running with s = 0.04

(a) revolving speed of the stator flux is space is .....rpm

(b) rotor speed is ....rpm

(c) speed of rotor flux relative to the rotor is ....rpm

(d) speed of the rotor flux with respect to the

stator is ....rpm.

11. The number of stator poles produced in the rotating magnetic field of a 3-φ induction motor having 3 slots per pole per phase is

(a) 3 (b) 6

(c) 2 (d) 12

12. The power factor of a squirrel-cage induction motor is

(a) low at light loads only

(b) low at heavy loads only

(c) low at light and heavy loads both

(d) low at rated load only.

13. Which of the following rotor quantity in a SCIM does NOT depend on its slip?

(a) Reactance (b) speed

(c) induced emf (d) frequency.

14. A 6-pole, 50-Hz, 3-φ induction motor is running at 950 rpm and has rotor Cu loss of 5 kW. Its rotor input is ......kW.

(a) 100 (b) 10

(c) 95 (d) 5.3.

15. The efficiency of a 3-phase induction motor is approximately proportional to

(a) (1− s) (b) s

(c) N (d) Ns.

16. A 6-pole, 50-Hz, 3-φ induction motor has a full load speed of 950 rpm. At half-load, its speed would be ......rpm.

(a) 475 (b) 500

(c) 975 (d) 1000

17. If rotor input of a SCIM running with a slip of 10% is 100 kW, gross power developed by its rotor is ...... kW.

(a) 10 (b) 90

(c) 99 (d) 80

18. Pull-out torque of a SCIM occurs at that value of slip where rotor power factor equals

(a) unity (b) 0.707

(c) 0.866 (d) 0.5

19. Fill in the blanks. When load is placed on a 3-phase induction motor, its

(i) speed.......

(ii) Slip......

(iii) Rotor induced emf......

(iv) Rotor current......

(v) Rotor torque......

(vi) Rotor continues to rotate at that value of slip at which developed torque equals ...... torque.

20. When applied rated voltage per phase is reduced by one-half, the starting torque of a SCIM becomes ...... of the starting torque with full voltage.

(a) 1/2 (b) 1/4

(c) 1/ 2 (d) 3/2

21. If maximum torque of an induction motor is 200 kg-m at a slip of 12%, the torque at 6% slip would be ...... kg-m.

(a) 100 (b) 160

(c) 50 (d) 40

22. The fractional slip of an induction motor is the ratio

(a) rotor Cu loss/rotor input

(b) stator Cu loss/stator input

(c) rotor Cu loss/rotor output

(d) rotor Cu loss/stator Cu loss

23. The torque developed by a 3-phase induction motor depends on the following three factors:

(a) speed, frequency, number of poles

(b) voltage, current and stator impedance

(c) synchronous speed, rotor speed and frequency

(d) rotor emf, rotor current and rotor pf.

24. If the stator voltage and frequency of an induction motor are reduced proportionately, its

(a) locked rotor current is reduced

(b) torque developed is increased

(c) magnetizing current is decreased

(d) both (a) and (b)

25. The efficiency and pf. of a SCIM increases in proportion to its

(a) speed (b) mechanical load

(c) voltage (d) rotor torque

26. A SCIM runs at **constant** speed only so long as

(a) torque developed by it remains constant

(b) its supply voltage remains constant

(c) Its torque exactly equals the mechanical load

(d) stator flux remains constant

27. The synchronous speed of a linear induction motor does NOT depend on

(a) width of pole pitch

(b) number of poles

(c) supply frequency

(d) any of the above

28. Thrust developed by a linear induction motor depends on

(a) synchronous speed

(b) rotor input

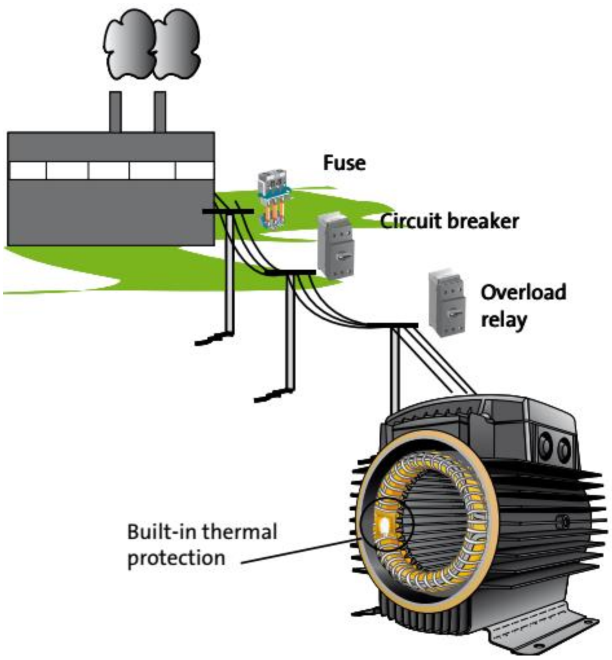
(c) number of poles

(d) both (a) and (b)

ANSWERS

1. b **2.** c **3.** c **4.** c **5.** c **6.** c **7.** c **8.** a **9.** d **10.** (i) 1500 (ii) 1440 (iii) 60 (iv) 1500 **11.** b **12.** a**13.** b **14.** a **15.** a **16.** c **17.** b **18.** b **19.** (i) Decreases (ii) increases (iii) increases (iv) increases (v) increases (vi) applied **20.** b **21.** b **22.** a **23.** d **24.** d **25.** b **26.** c **27.** b **28.** D

Motor protection



Why is motor protection necessary?

In order to avoid unexpected breakdowns, costly repairs and subsequent losses due to motor downtime, it is important that the motor is fitted with some sort of protective device. Generally speaking, motor protection can be divided into the following 3 levels:

External protection against short circuit in the whole installation. External protection

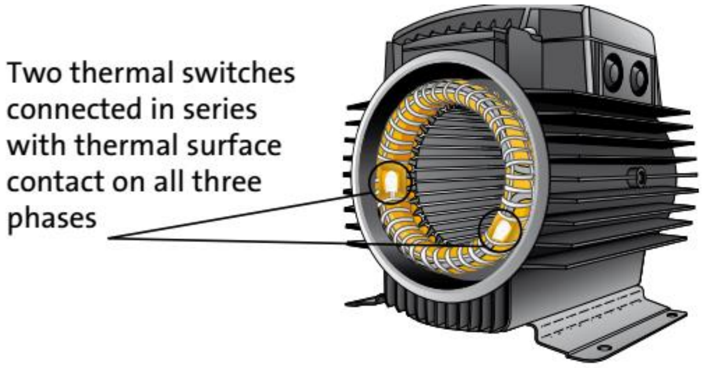
device is normally different types of fuses or short circuit relays. This kind of protection

device is compulsory and legal and placed under safety regulations.

External protection against overload of specific equipment; i.e. .to avoid overload of

pump motor and thereby prevent damage and breakdown of the motor. This type of protection reacts on current.

Built-in motor protection with thermal overload protection to avoid damage and breakdown of motor. The built-in protector always require an external circuit breaker while some built-in motor protection types even require an overload relay.



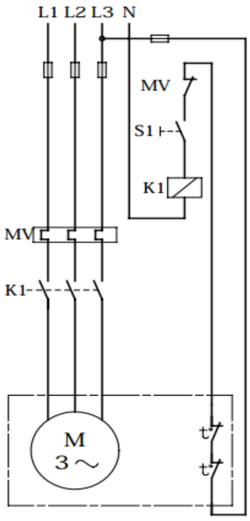
Thermal protection built into the windings

Y connection + 2 terminal thermal sensor

When it comes to pump motors, the most common TP designations are:

TP 111 – Protection against slow overload
TP 211 – protection against both rapid and slow overload.

TP designation for the diagram



Automatic reclosing

S1 On/off switch
S2 Off switch
K1 Contactor
t Thermal switch in motor
M Motor
MV Overload relay
Thermal switches can be loaded as followed:
U_{max}= 250 V AC
IN = 1 .5 A
Imax = 5 .0 A (cut-in and cut-out current)

Starting of Induction Motors

Induction motors, when direct-switched, take five to seven times their full-load current and develop only 1.5 to 2.5 times their full-load torque. This initial excessive current is objectionable because it will produce large line-voltage drop that, in turn ,will affect the operation of other electrical equipment connected to the same lines. Hence, it is not advisable to line-star motors of rating above 25 kW to 40 kW.

Methods for starting induction motors are discussed below:

Squirrel-cage motor

(a) Direct-on-line starting

(b)Primary resistors (or rheostat) or reactors
(c) Auto-transformer
(d) Star-delta switches
(e) Soft starting
in all these methods, terminal voltage of the squirrel-cage motor is reduced during starting.

Slip-ring motor

(a) Rotor rheostat

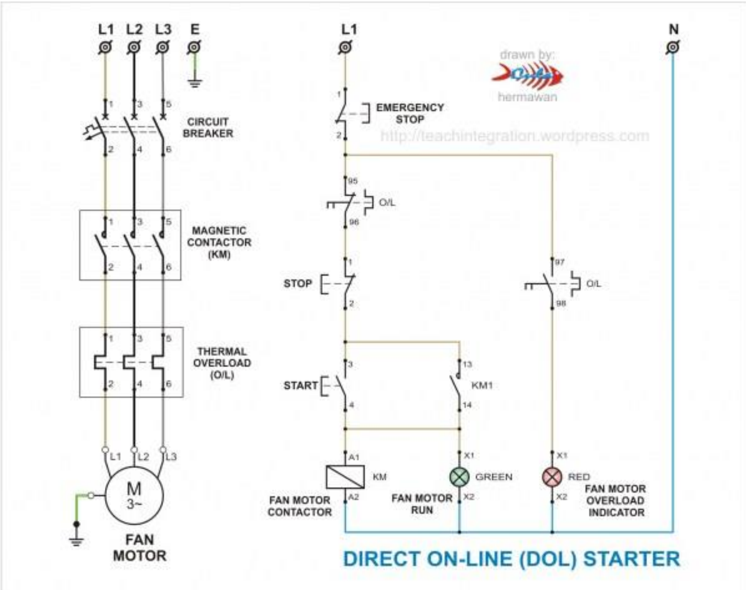
(a) Direct-on-line starting

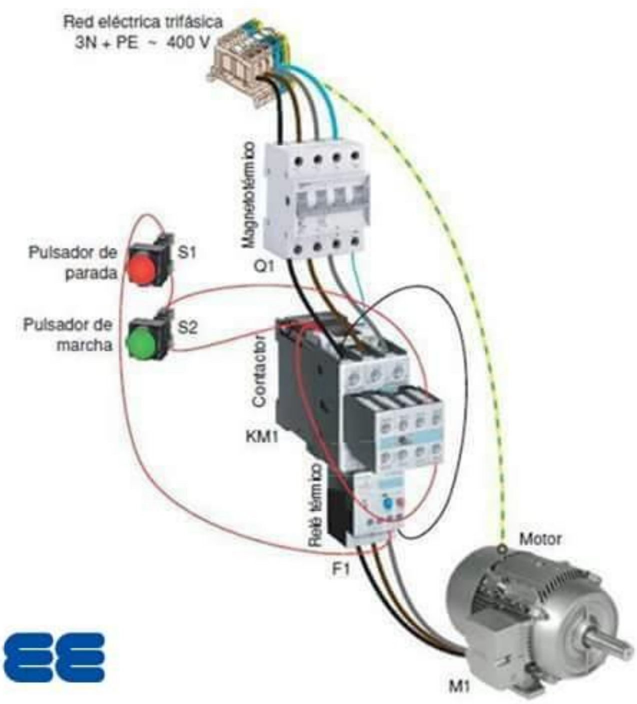
Motor Starting Characteristics on DOL Starter

Available starting current: 100%.

Peak starting current: 6 to 8 Full Load Current.

Peak starting torque: 100%





Advantages of DOL Starter

1. Most Economical and Cheapest Starter
2. Simple to establish, operate and maintain
3. Simple Control Circuitry

4. Easy to understand and trouble-shoot.

5. It provides 100% torque at the time of starting.

6. Only one set of cable is required from starter to motor.

7. Motor is connected in delta at motor terminals.

Disadvantages of DOL Starter

1. It does not reduce the starting current of the motor.
2. High Starting Current: Very High Starting Current (Typically 6 to 8 times the FLC of the motor).
3. Mechanically Harsh: Thermal Stress on the motor, thereby reducing its life.
4. Voltage Dip: There is a big voltage dip in the electrical installation because of high in-rush current affecting other customers connected to the same lines and therefore not suitable for higher size squirrel cage motors
5. High starting Torque: Unnecessary high starting torque, even when not required by the load, thereby increased mechanical stress on the mechanical systems such as rotor shaft, bearings, gearbox, coupling, chain drive, connected equipment's, etc. leading to premature failure and plant downtimes.

Features of DOL starting

For low- and medium-power three-phase motors Three connection lines (circuit layout: star or delta)

1. High starting torque

2. Very high mechanical load

3. High current peaks

4. Voltage dips

5. Simple switching devices

Direct on Line Motor Starter (DOL) is suitable for:

A direct on line starter can be used if the high inrush current of the motor does not cause excessive voltage drop in the supply circuit. The maximum size of a motor allowed on a direct on line starter may be limited by the supply utility for this reason. For example, a utility may require rural customers to use reduced-voltage starters for motors larger than 10 kW.

DOL starting is sometimes used to start small water pumps, compressors, fans and conveyor belts.

Direct on Line Motor Starter (DOL) is NOT suitable for:

1. The peak starting current would result in a serious voltage drop on the supply system.

2. The equipment being driven cannot tolerate the effects of very high peak torque loadings.

3. The safety or comfort of those using the equipment may be compromised by sudden starting as, for example, with escalators and lifts.

(b)Primary resistors

Their purpose is to drop some voltage and hence reduce the voltage applied across the motor terminals. In this way, the initial current drawn by the motor is reduced. However, it should be noted that whereas current varies directly as the voltage, the torque varies as square of applied voltage.

When applied voltage is reduced, the rotating flux Φ is reduced which, in turn, decreases rotor elf. And hence rotor current I Starting torque, which depends both on Φ and I2 suffers on two counts when impressed voltage is reduced. If the voltage applied across the motor terminals is reduced by 50%, starting current is reduced by 50%, but torque is reduced to 25% of the full-voltage value.

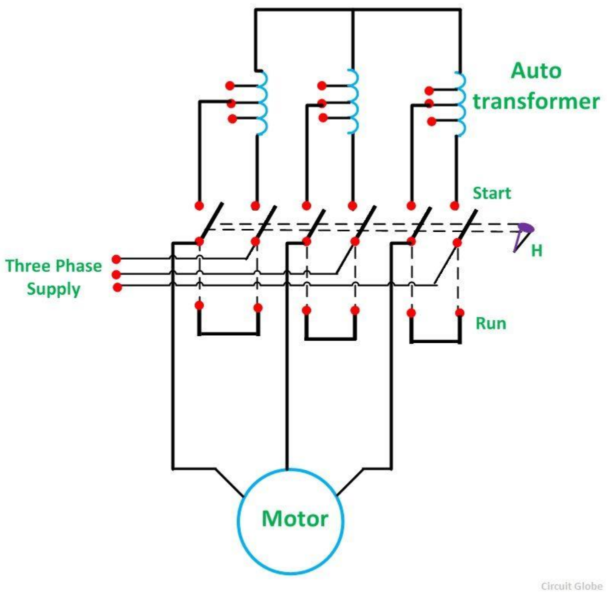
(b)Auto-transformers-:

Such starters, known variously as auto-trans compensators, consist of an auto-transformer, with necessary switches. We may use either two autotransformers connected as usage This method can be used both for star-and delta-connected motors with starting connections, a reduced voltage is applied across the motor terminals. When the motor has ran up to say, 80% of its normal speed, connections are so changed that auto-transformers are cut out and full supply voltage is applied across the motor. The switch making these changes from ‘start’ to ‘run’ may be air break (for small motors) or may be oil-immersed (for large motors) to reduce sparking. There is also provision for no-voltage and over-load protection ,along with a time dela device, so that momentary interruption of voltage or momentary over-load do not disconnect the motor from supply line. Most of the auto-starters are provided with 3 sets of taps, so as to reduce voltage to 65,80 or 50 percent of the line voltage, to suit the local conditions of supply .

Auto transformer Starter:

An Auto transformer Starter is suitable for both star and delta connected motors. In this method, the starting current is limited by using a three-phase auto transformer to reduce the initial stator applied voltage.

The figure below shows the motor with the Auto transformer starter.

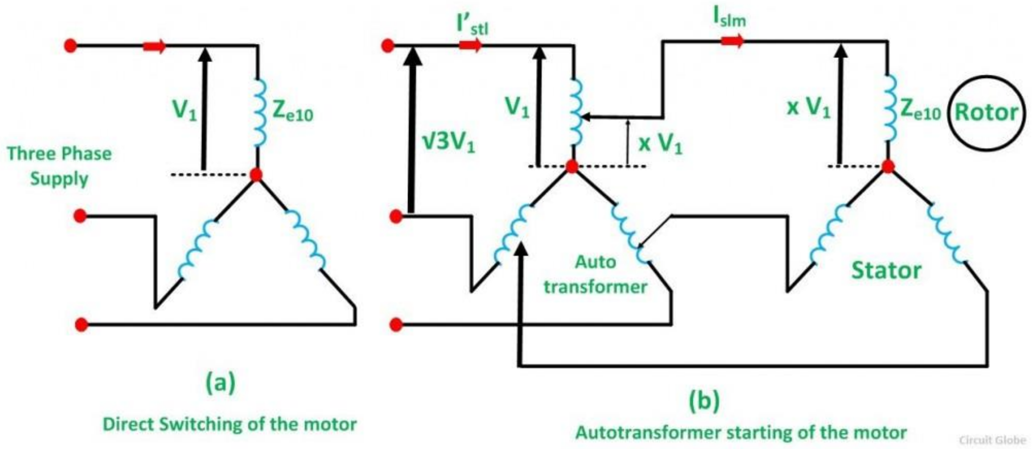


It is provided with a number of tappings. The starter is connected to one particular tapping to obtain the most suitable starting voltage. A double throw switch S is used to connect the auto transformer in the circuit for starting. When the handle H of the switch S in the START position. The primary of the auto transformer is connected to the supply line, and the motor is connected to the secondary of the auto transformer.

When the motor picks up the speed of about 80 percent of its rated value, the handle H is quickly moved to the RUN position. Thus, the auto transformer is disconnected from the

circuit, and the motor is directly connected to the line and achieve its full rated voltage. The handle is held in the RUN position by the under voltage relay.
If the supply voltage fails or falls below a certain value, the handle is released and returns to the OFF position. Thermal overload relays provide the overload protection.

Theory of Auto transformer Starter
The figure (a) shown below shows the condition when the motor is directly switched on to lines and the figure (b) shows when the motor is started with the help of auto transformer.



Let,
Ze10 is the equivalent standstill impedance per phase of the motor referred to the stator side
V1 is the supply voltage per phase.
When the full voltage V1 per phase is applied to the direct switching, the starting current drawn from the supply is given by the equation shown below.

$$I_{stl} = \frac{V_1}{Z_{e10}} \dots\dots\dots (1)$$

With auto transformer starting, if a tapping of the transformer ratio x is used, then the voltage per phase across the motor is xV1. Therefore, at the starting, the motor current is given by the equation.

$$I_{stm} = \frac{xV_1}{Z_{e10}} \dots\dots\dots (2)$$

In a transformer, the ratio of currents is inversely proportional to the voltage ratio provided that the no load current is neglected. i.e.,

$$\frac{I_1}{I_2} = \frac{V_2}{V_1} \quad \text{or}$$

$$V_1 I_1 = V_2 I_2$$

If I' stl is the current taken from the supply by the auto transformer. Then,

$$V_1 I'_{stl} = (xV_1)\, I_{stm}$$

$$I'_{stl} = x\, I_{stm} \dots\dots\dots (3)$$

Substituting the value of Istm from the equation (2) in the equation (3) we get.

$$I'_{stl} = x\left(\frac{xV_1}{Z_{e10}}\right)$$

$$I'_{stl} = \frac{x^2 V_1}{Z_{e10}} \dots\dots\dots (4)$$

Therefore,

$$\frac{\text{Starting current with autotransformer}}{\text{Starting current with direct switching}} = \frac{I'_{stl}}{I_{stl}} = \frac{(x^2 V_1/Z_{e10})}{(V_1/Z_{e10})} = x^2 \quad \ldots\ldots(5)$$

Since the torque developed is proportional to the square of the applied voltage, the starting torque with the direct switching is given as

$$T_{std} \propto V_1^2$$

$$T_{std} = k_2 V_1^2 \ldots\ldots(6)$$

Similarly, starting torque with auto transformer starter

$$T_{sta} \propto (xV_1)^2$$

$$T_{sta} = k_2 x^2 V_1^2 \ldots\ldots(7)$$

Therefore,

$$\frac{\text{Starting torque with autotransformer starter}}{\text{Starting torque with direct switching}} = \frac{k_2 x^2 V_1^2}{k_2 V_1^2} = x^2 \ldots\ldots\ldots(8)$$

With the auto transformer, at the starting, the motor current is given by the equation shown below.

$$I_{stm} = \frac{xV_1}{Z_{e10}} = xI_{sc} \ldots\ldots(9)$$

From the equation (3) and (9) we can conclude that

$$I'_{stl} = x^2 I_{sc} \ldots\ldots\ldots(10)$$

From the above equation (5) we get

$$\frac{T_{est}}{T_{efl}} = \left(\frac{I_{stm}}{I_{fl}}\right)^2 s_{fl} = \left(\frac{xI_{sc}}{I_{fl}}\right)^2 s_{fl}$$

$$\frac{T_{est}}{T_{efl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \ldots\ldots\ldots(11)$$

The above equation (5) and the equation (8) shows that with an auto transformer, the starting current I'stl from the main supply and the starting torque are reduced to the x2 times to the corresponding values with the direct online starting.
Now, comparing equation (4) and the equation (11) we get

$$x^2 = \frac{1}{3} \quad \text{or} \quad x = \frac{1}{\sqrt{3}} = 0.58$$

Thus, the star delta starter is equivalent to an auto transformer starter of the ratio **x = 0.58**. A Star Delta starter is much cheaper than an auto transformer starter and is commonly used for both small and the medium size motors.

Example: A 20 hp. (14.92 kW), 400-V, 950 rpm, 3φ, 50-Hz, 6-pole cage motor with

400 V applied takes 6 times full-load current at standstill and develops 1.8 times full-load running torque .The full-load current is 30 A.

(a) What voltage must be applied to produce full-load torque at starting?

(b) What current will this voltage produce?

(c) If the voltage is obtained by an auto-transformer, what will be the line current?

Solution.

(a)

$$\therefore \quad \left(\frac{V}{400}\right)^2 = \frac{1}{1.8} \quad \text{or} \quad V = \frac{400}{\sqrt{1.8}} = \mathbf{298.1\ V}$$

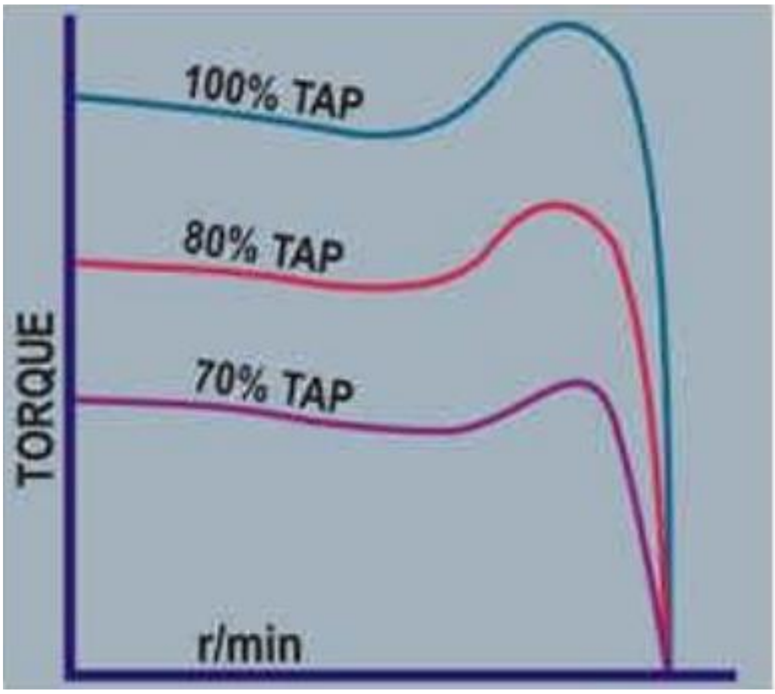
(b) Currents are proportional to the applied voltage.

$$\therefore \quad 6\,I_f \propto 400\ ;\ I \propto 298.1 \quad \therefore \quad I = 6 \times \frac{298.1}{400},\ I_f = \frac{6 \times 298.1 \times 30}{400} = \mathbf{134.2\ A}$$

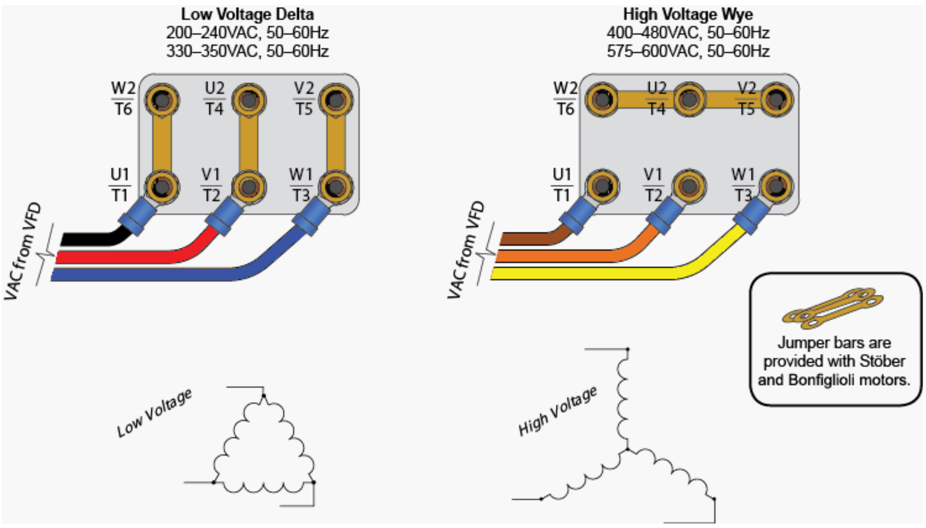
(C) Here

*LINE CURRENT= (line current M * voltage apply motor)/ line voltage*

*Line current = (134.2 * 298.1)/ (400) =100A*



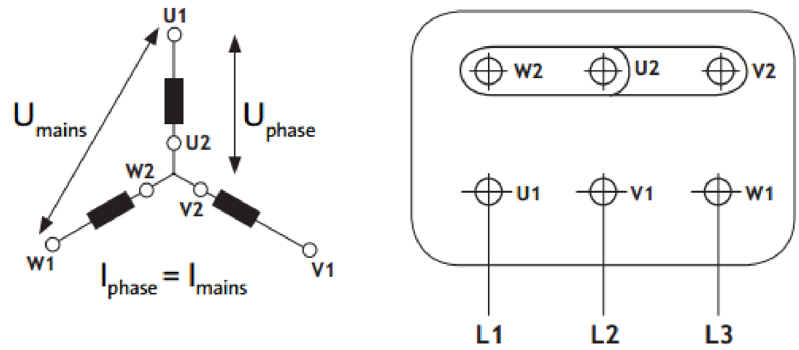
(C) Star-delta Starter-:

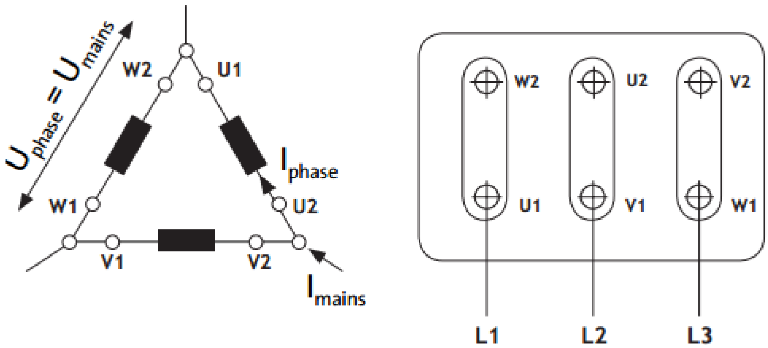


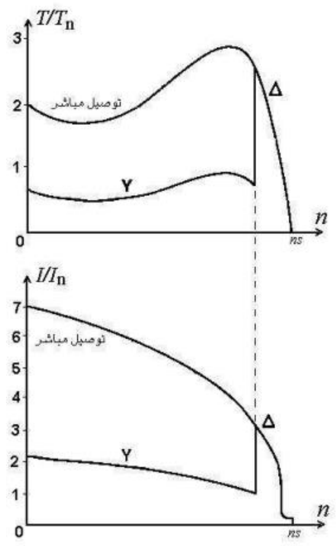
This method is used in the case of motors which are built to run normally with a delta-connected stator winding. It consists of a two-way switch which connects the motor in star for starting and then in delta for normal running. When star-connected, the applied voltage over each motor phase is reduced by a factor of 1/ 3 and hence the torque developed becomes 1/3 of that which would have been developed if motor were directly connected in delta. The line current is reduced to 1/3. Hence, during starting period when motor is Y-connected, it takes 1/3 as much starting current and develops 1/3 rd as much torque as would have been developed were it directly connected in delta.

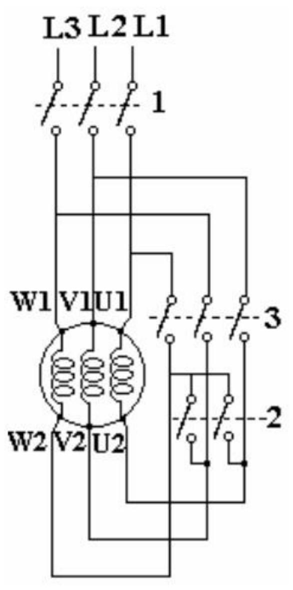
Relation between Starting and F.L. Torque

$$I_{st}\text{ per phase} = \frac{1}{\sqrt{3}} I_{sc}\text{ per phase}$$









Advantages of Star-Delta starter

The operation of the star-delta method is simple and rugged it is relatively cheap compared to other reduced voltage methods Good Torque/Current Performance. It draws 2 times starting current of the full load ampere of the motor connected.

Disadvantages of Star-Delta starter

1. Low Starting Torque (Torque = (Square of Voltage) is also reduce).

2. Break In Supply – Possible Transients

3. Six Terminal Motor Required (Delta Connected).

4. It requires 2 set of cables from starter to motor.

It provides only 33% starting torque and if the load connected to the subject motor requires higher starting torque at the time of starting than very heavy transients and stresses are produced while changing from star to delta connections, and because of these transients and stresses many electrical and mechanical break-down occurs.

In this method of starting initially motor is connected in star and then after change over the motor is connected in delta. The delta of motor is formed in starter and not on motor terminals.

High transmission and current peaks :When starting up pumps and fans for example, the load torque is low at the beginning of the start and increases with the square of the speed. When reaching approx. 80-85 % of the motor rated speed the load torque is equal to the motor torque and the acceleration ceases. To reach the rated speed, a switch over to delta position is necessary, and this will very often result in high transmission and current peaks. In some cases the current peak can reach a value that is even bigger than for a D.O.L start.

Applications with a load torque higher than 50 % of the motor rated torque will not be able to start using the start-delta starter..

Low Starting Torque :The star-delta (wye-delta) starting method controls whether the lead connections from the motor are configured in a star or delta electrical connection. The initial connection should be in the star pattern that results in a reduction of the line voltage by a factor of 1/√3 (57.7%) to the motor and the current is reduced to 1/3 of the current at full voltage, but the starting torque is also reduced 1/3 to 1/5 of the DOL starting torque.

The transition from star to delta transition usually occurs once nominal speed is reached, but is sometimes performed as low as 50% of nominal speed which make transient Sparks.

star-delta starting Features of

1. for low- to high-power three-phase motors.

2 .Reduced starting current

3 .Six connection cables

4 .Reduced starting torque

5. Current peak on changeover from star to delta

6 .Mechanical load on changeover from star to delta

Application of Star-Delta Starter

The star-delta method is usually only applied to low to medium voltage and light starting Torque motors.

The received starting current is about 30 % of the starting current during direct on line start and the starting torque is reduced to about 25 % of the torque available at a D.O.L start. This starting method only works when the application is light loaded during the start.

If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position.

Example. A 3-phase, 6-pole, 50-Hz induction motor takes 60 A at full-load speed of 940 rpm. And develops a torque of 150 N-m. The starting current at rated voltage is 300 A. What is the starting torque? If a star/delta starter is used, determine the starting torque and starting current.

Solution.

$$\frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 s_f \qquad \text{Here,} \qquad I_{st} = I_{sc} = 300 \text{ A (line value)} ;\ I_f = 60 \text{ A (line value)},$$

$$s_f = (1000 - 940)/1000 = 0.06 ;\ T_f = 150 \text{ N-m}$$

$$\therefore \quad T_{st} = 150(300/60)^2 \times 0.06 = \mathbf{225\ N\text{-}m}$$

When star/delta starter is used

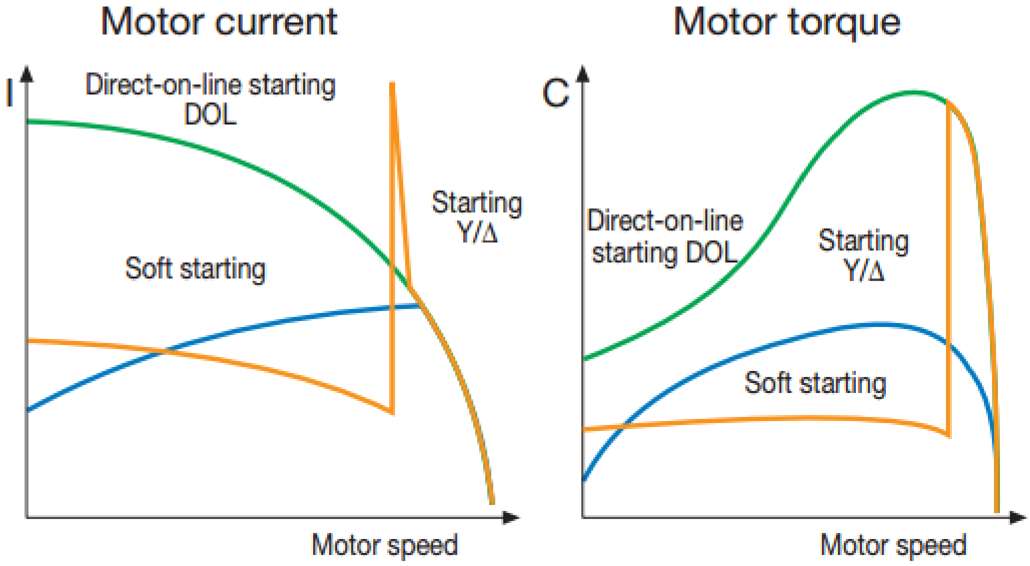
Starting current = 1/3 × starting current with direct starting = 300/3 = **100 A**

Starting torque = 225/3 = **75 N-m**

Starting of Slip-ring Motors-:

These motors are practically always started with full line voltage applied across the stator terminals. The value of starting current is adjusted by introducing a variable resistance in the rotor circuit. The controlling resistance is in the form of a rheostat the resistance being gradually cut-out of the rotor circuit, as the motor gathers speed. It has been already shown that by increasing the rotor resistance, not only is the rotor (and hence stator) current reduced at starting, but at the same time, the starting torque is also increased due to improvement in power factor. The controlling rheostat is either of stud or contactor type and may be hand-operated or automatic.

(e) Soft starting: A soft starter is, as you would expect, a device which ensures a soft start of a motor.



Advantages

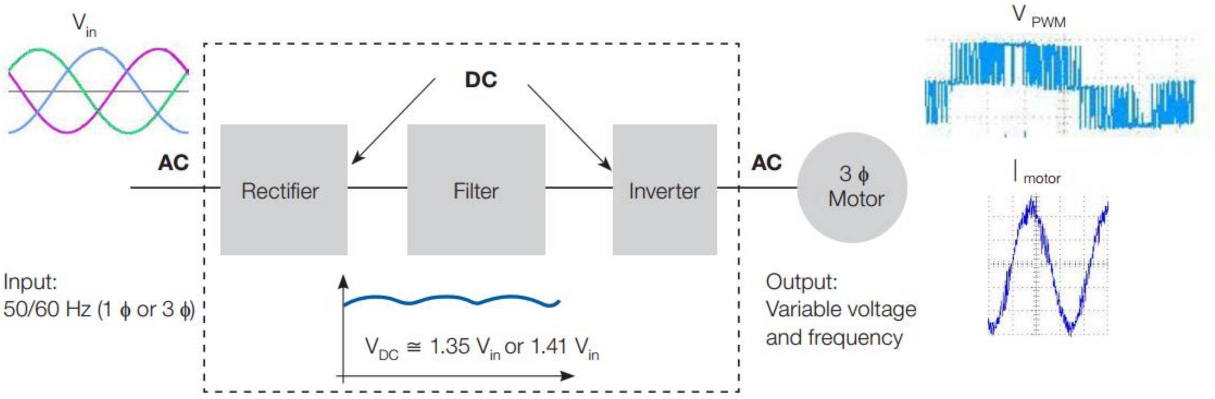
Soft starters are based on semiconductors. Via a power circuit and a control circuit, these semiconductors reduce the initial motor voltage. This results in lower motor torque. During the starting process, the soft starter gradually increases the motor voltage, thereby allowing the motor to accelerate the load to rated speed without causing high torque or current peaks. Soft starters can also be used to control how processes are stopped. Soft starters are less expensive than frequency converters.

Drawbacks

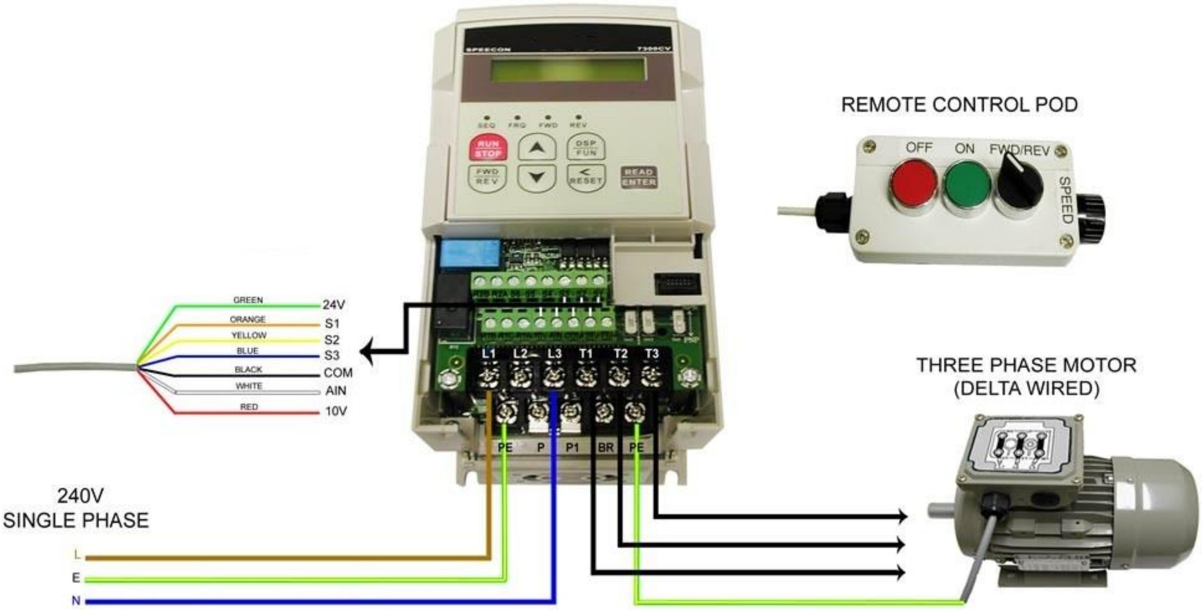
They do, however, share the same problem as frequency converters: they may inject harmonic currents into the system, and this can disrupt other processes .The starting method also supplies a reduced voltage to the motor during start-up. The soft starter starts up the motor at reduced voltage, and the voltage is then ramped up to its full value . The voltage is reduced in the soft starter via phase angle. In connection with this starting method current pulses will not occur. Run-up time and locked-rotor current (starting current) can be set .

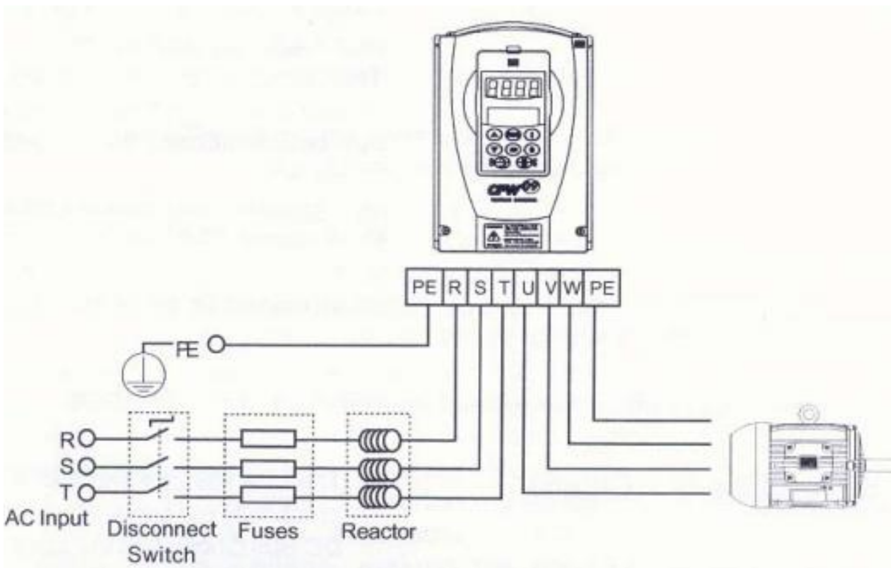
(f) Frequency converter starting

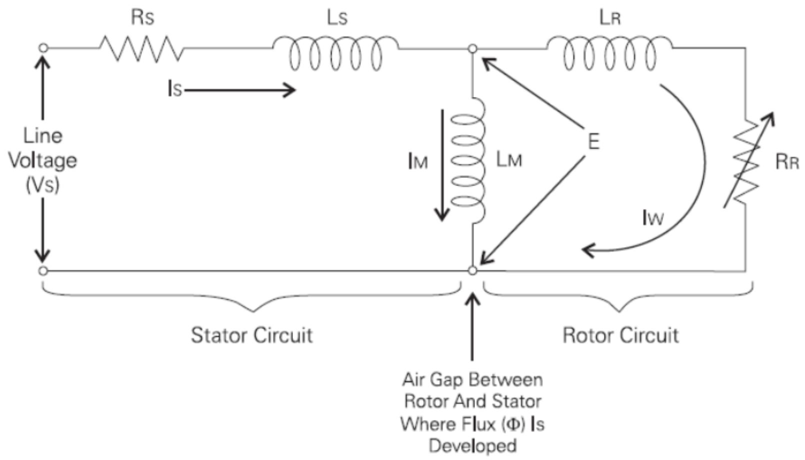
Frequency converters are designed for continuous feeding of motors, but they can also be used for start-up only.



Input line reactor connection







- **Magnetizing current: Im**

$$I_M = \frac{E}{2\pi F L_M}$$

- **Stator current : Is**

$$I_S = \sqrt{I_M^2 + I_W^2}$$

- **Flux Φ**

$$\Phi \approx \frac{E}{F}$$

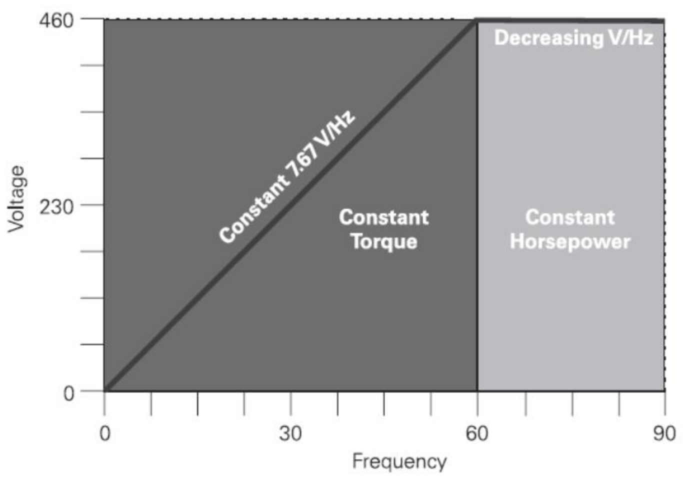
- **Constant torque**

$$T = k\Phi I_W$$

$$T \approx \Phi^2$$

- **Power constant :**

Frequency	V/Hz
30 Hz	7.67
60 Hz	7.67
70 Hz	6.6
90 Hz	5.1



Advantages
The frequency converter makes it possible to use low starting current because the motor can produce rated torque at rated current from zero to full speed. Frequency converters are becoming cheaper all the time. As a result, they are increasingly being used in applications where soft starters would previously have been used.
Drawbacks
Even so, frequency converters are still more expensive than soft starters in most cases; and like soft starters, they also inject harmonic currents into the network.

Summary
The principle objective of all methods of motor starting is to match the torque characteristics to those of the mechanical load, while ensuring that the peak current requirements do not exceed the capacity of the supply. Many starting methods are available, each of which has slightly different characteristics. The following table summarizes the main characteristics for the most popular starting methods.

Motor starting methods summary

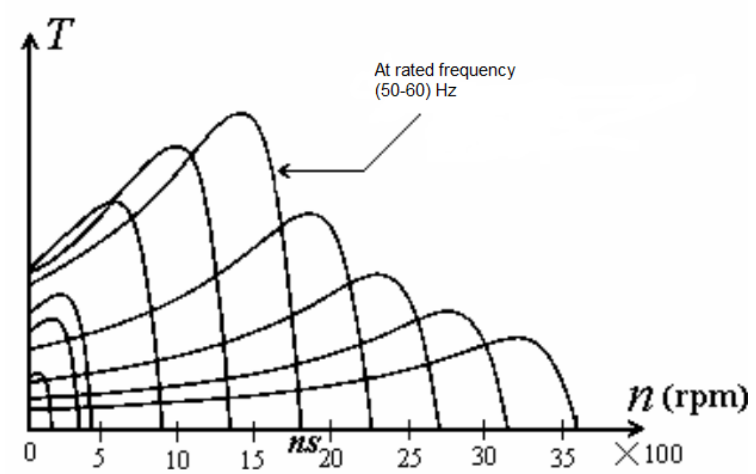
Method	Advantages	Disadvantages
Across-the –Line(DOL)	Simple, Cost-Effective	High Current Inrush High Starting Torque Abrupt Start
Reduced-voltage autotransformer	High output torque vs. starting current. Some Flexibility in starting characteristics due adjustable taps on autotransformers	Limited duty cycle Large equipment size due to autotransformers
Reduced-Voltage Resistor or Reactor	High output torque vs. starting current	Limited duty cycle Limited flexibility in starting characteristics Higher inrush current than with reduced-voltage autotransformer Large equipment size due to resistors/reactors
Wye-Delta	Relatively low inrush current Relatively simple starter construction Good for long acceleration times	Relatively low output torque vs. starting current Limited flexibility in starting characteristics Requires special motor construction
Part-Winding	Relatively Simple starter construction	Relatively low output torque vs. starting current

		Not suitable for frequent starts Requires special motor construction
Solid-state soft starter	Smooth Acceleration Low inrush current High flexibility in starting characteristics Typically offers deceleration control also Typically integrates with industrial automation infrastructure	Relatively Expensive Sensitive to power quality Heat dissipation and ambient temperature are a concern
Rotor Resistance	Smooth acceleration available Good flexibility in starting characteristics Can be used for speed control also	Complicated controller design Requires expensive wound-rotor motor construction
Adjustable Speed Drive	Smooth Acceleration Low inrush current High flexibility in starting characteristics Offers deceleration and speed control also Typically integrates with industrial automation infrastructure	Cost-prohibitive unless speed control is required also Sensitive to power quality Heat dissipation and ambient temperature are a concern Continuous harmonic currents can create power quality issues

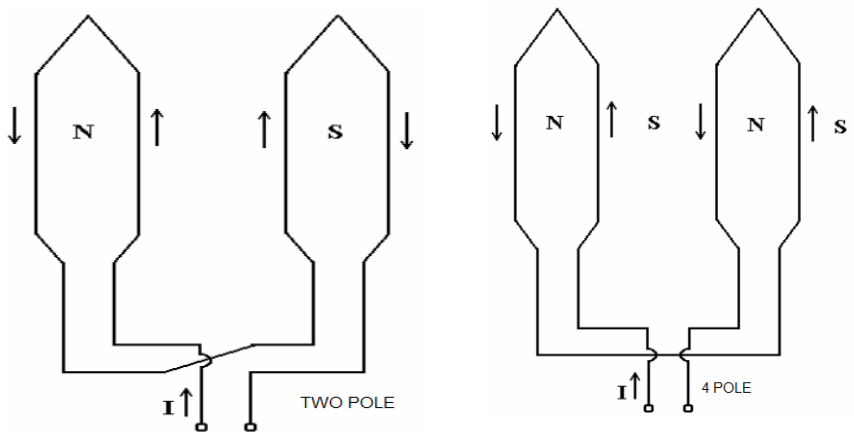
Speed Control of Induction Motor

(a) By changing the applied voltage.

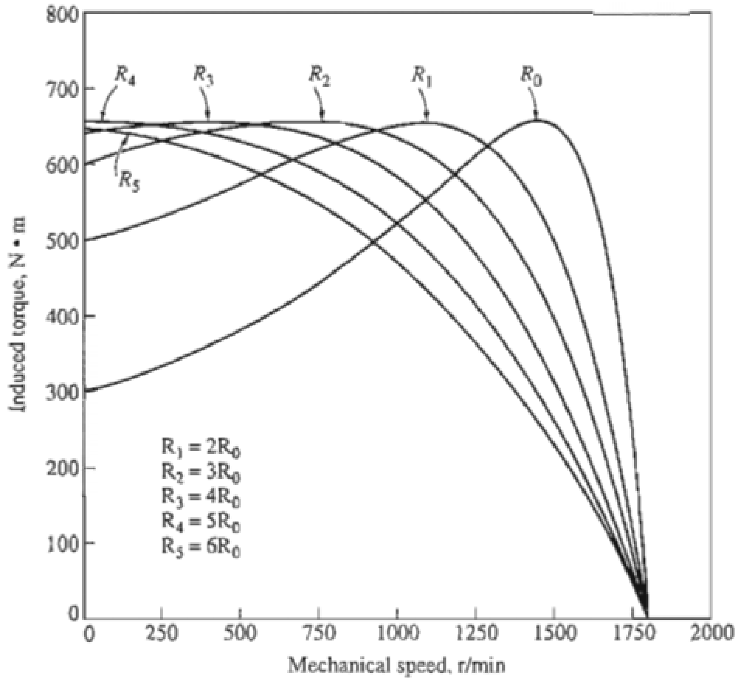
(b)By changing the applied frequency.



(C) By changing the number of stator poles .



(d) Rotor resistance control.



Induction Motor Braking

Induction motor are used at various places. Speed control of induction motor is quite difficult and that's why their use was restricted and dc motor had to be used as their speed regulation was possible. But when induction motor drives were invented and implemented, they were given preference because of many advantages over dc motor. Whenever controlling of motors is done, braking is the most important term, so as with induction motors. Induction motor braking can be done by different methods, which are

I. Regenerative braking of induction motor.
ii. Plugging Braking of induction motor.
iii. Dynamic braking of induction motor.
a) AC dynamic breaking
b) Self excited braking using capacitor
c) DC dynamic braking
d) Zero Sequence braking

1. **Regenerative Braking of Induction Motor**

   We know the power (input) of an induction motor is given as. Pin = 3VIscosφs

   Here, φs the phase angle between stator phase voltage V and the stator phase current is. Now, for motoring operation φs < 90° and for braking operation φs > 90°. When the speed of the motor is more than the synchronous speed, relative speed between the motor conductors and air gap rotating field reverses, as a result the phase angle because greater than 90° and the power flow reverse and thus regenerative braking takes place.

   It the source frequency is fixed then the regenerative braking of induction motor can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source regenerative braking of induction motor can occur for speeds lower than synchronous speed.

   The main advantage of this kind of braking can be said that the generated power is use fully employed and the main disadvantage of this type of braking is that for fixed frequency sources, braking cannot happen below synchronous speeds.

2. **Plugging Braking of Induction Motor**

   Plugging induction motor braking is done by reversing the phase sequence of the motor. Plugging braking of induction motor is done by interchanging connections of any two phases of stator with respect of supply terminals.

   And with that the operation of motoring shifts to plugging braking.

   During plugging the slip is (2 - s), if the original slip of the running motor is s, the

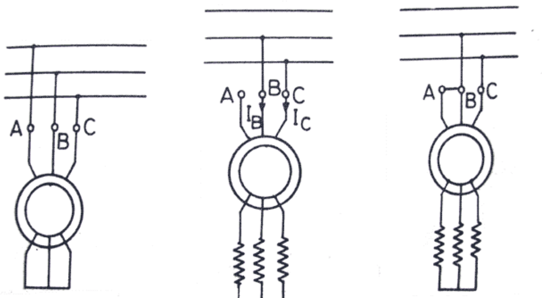
$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$

   In it can be shown in the following way. From the figure beside we can see that the torque is not zero at zero speed. That's why when the motor is needed to be stopped, it should be disconnected from the supply at near zero speed. The motor is connected to rotate in the reverse direction and the torque is not zero at zero or any other speed, and as a result the motor first decelerates to zero and then smoothly accelerates in the opposite direction.

3. **Dynamic Braking of Induction Motor**:- There are four type of dynamic braking of induction motor.

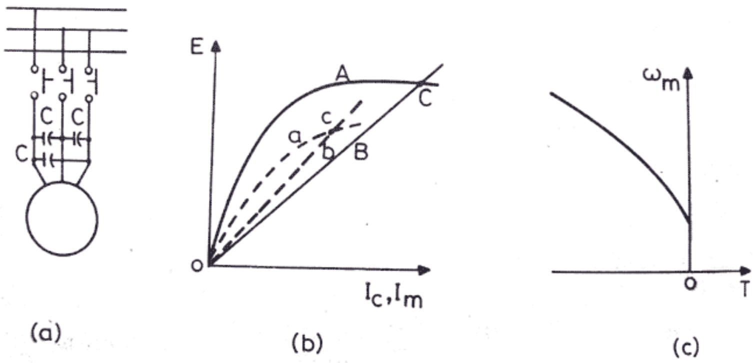
A- AC Dynamic Braking - This type of induction motor braking is obtained when the motor is made to run on a single phase supply by disconnecting any one of the three phase from the source, and it is either left open or it is connected with another phase. When the disconnected phase is left open, it is called two lead connection and when the disconnected phase is connected to another machine phase it is known as three load connection. The braking operation can be understood easily.

When the motor is running on 1-phase supply, the motor is fed by positive and negative sequence, net torque produced by the machine at that point of time is sum of torques due to positive and negative sequence voltage. At high resistance the net torque is found to be negative and braking occurs. From the figure below the two and three load connections can be understood.



(a) Motoring (b) Two lead connection (c) Three lead connection

B-Self excited braking using capacitor:-

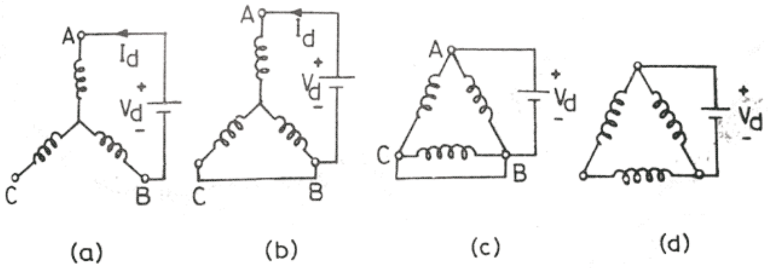


The figures above shows the circuit diagram and various characteristics of self-excited braking using capacitors.

As we can see from the figure, in this method there capacitors are kept permanently connected across the source terminals of the motor. The value of the capacitor are chosen depending upon their capability to deliver enough reactive current to excite the motor and make it work as a generator. So, that when the motor terminals are disconnected from the source the motor works as a self-excited generator and the produced torque and field is in the opposite direction and the induction motor braking operation occurs.

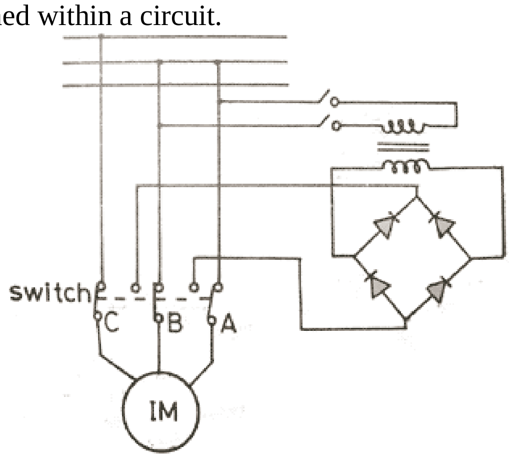
In the figure (b) the curve A represents the no load magnetization curve and line B is the current through capacitors, which is given by Here E is the stator induced voltage per phase .The speed torque characteristics under self-excited braking is shown in the figure (c). To increase the braking torque and to utilize the generated energy sometimes external electric resistance are connected across the stator terminals.

C-DC Dynamic Braking:- To obtain this type of braking the stator of a running induction motor is connected to a dc supply. Two and three load connections are the two common type of connections for star and delta connected stators.



Various stator connections for dc dynamic braking (a) and (d) are two lead connections and (b) and (c) are three lead connection

Another diagram is shown below to illustrate how by diode bridge two load connection can be obtained within a circuit.



Two loads dc dynamic braking operation Now coming to the method of operation, the moment when AC supply is disconnected and DC supply is introduced across the terminals of the induction motor , there is a stationery magnetic field generated due to the Dc current flow and as the rotor of the motor rotates in that field, there is a field induces in the rotor winding, and as a result the machine works as a generator and the generated energy dissipates in the rotor circuit resistance and dynamic braking of induction motor occurs.

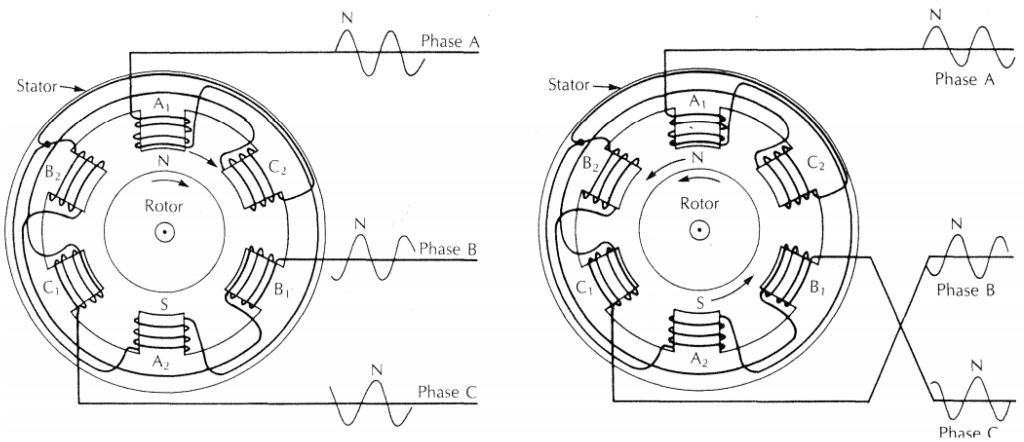
D-Zero sequence braking in this type of braking all the three stator phases are connected in series and single phase ac or dc is connected across them.

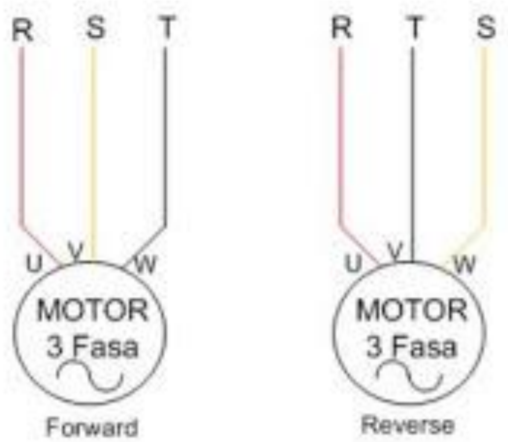
This type of connection is called zero-sequence connection. When the connected supply is ac, resultant field is stationery in space and pulsates at the frequency of supply, when the supply is dc, resultant field is stationery and is of constant magnitude. The main advantage of this induction motor braking is that all the stator phases are uniformly loaded. It does not require large rotor resistance like ac dynamic braking, it does not require large rotor resistance.

Reversing Rotation of three phase motor

Squirrel-cage:
Turning round 3-phase induction motors (forward / reverse):

To reverse the direction of rotation of 3-phase induction motor is by reversing the polarity of one of the incoming voltage to the motor. try to look at the picture below.

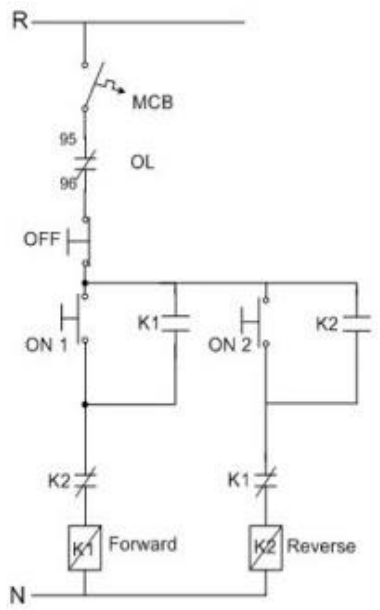




In the picture above shows that the motor will rotate to the right (forward) if the terminal winding / winding motor receives voltage RST with R connected with U, S connected to V and T connected with W. And the motor will rotate in the opposite direction (reverse) if terminal winding motor receives voltage RST with R connected with U, S connected with the W and T are connected to the voltage V. in other words RST reversed into RTS. Reversing the polarity others can also, like R with S or R to T.

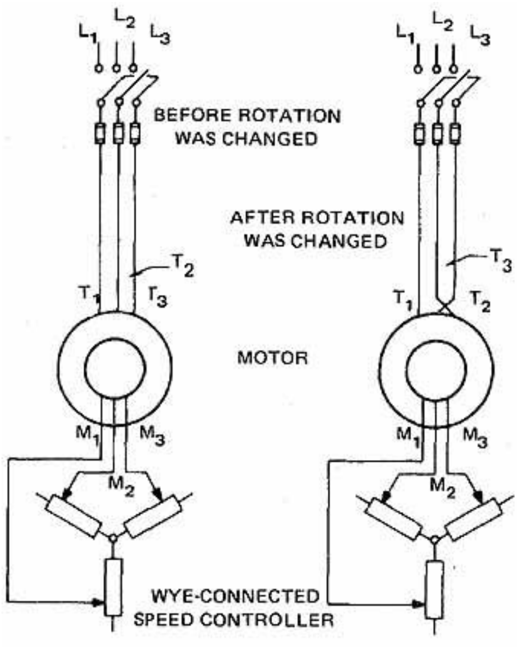
To change or reverse the polarity of the voltage that is typically used RST control circuit is a series of mechanical and magnetic contactors. And as motorcycle safety also mounted motor protection (thermal overload). Note the main diagram drawing / power forward following reverse.

- To regulate or control the two contactors are needed forward reverse control circuit. And below is a control circuit diagram of the forward reverse. Consider the following picture, and understand how it works.



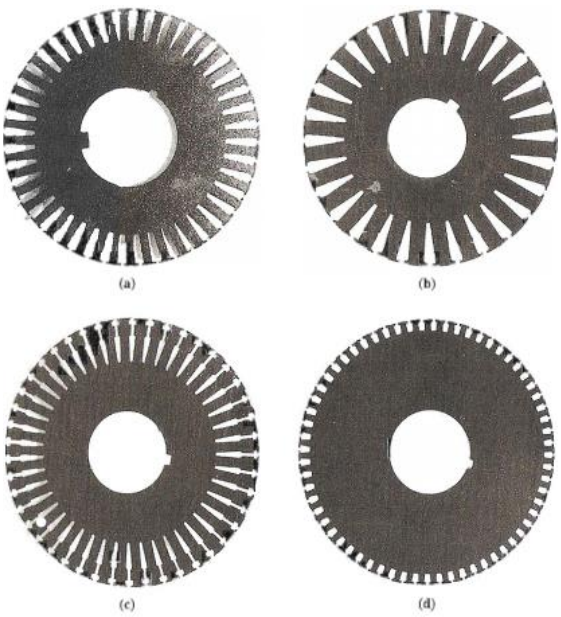
Forward reverse circuit control system

Wound-rotor:
The direction of rotation of a wound-rotor induction motor is reversed by inter changing the connections of any two of the three line leads, figure below. This procedure is identical to the procedure used to reverse the direction of rotation of a squirrel-cage induction motor.

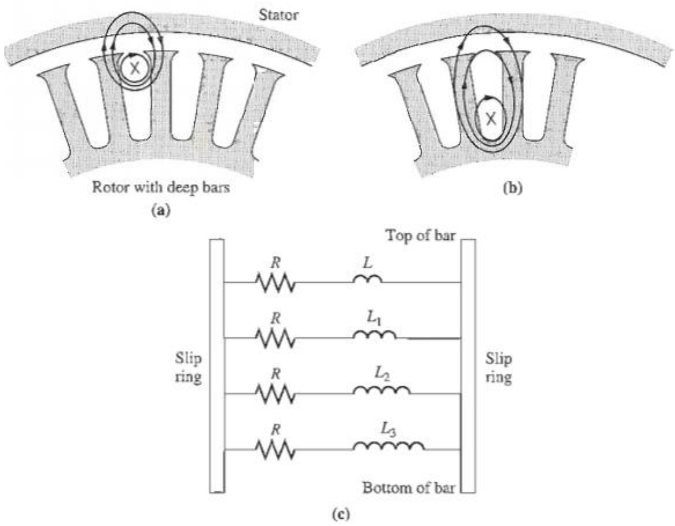


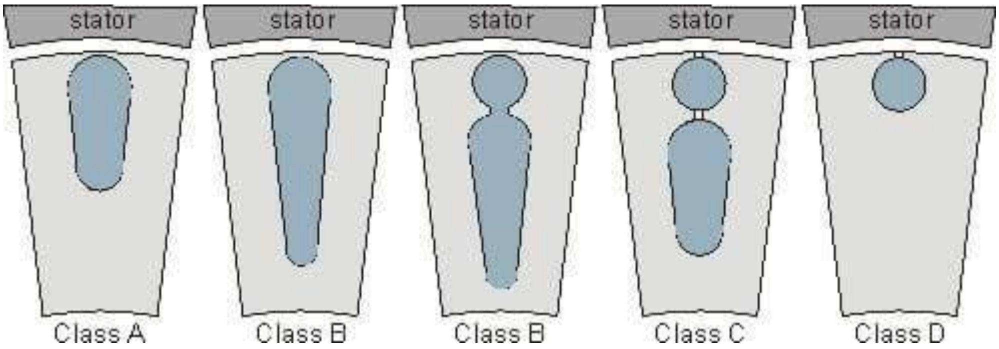
Control of Motor Characteristics by Cage Rotor Design

Laminations from typical cage induction motor rotors, showing the cross section of the rotor bars: (a) NEMA design class A- large bars near the surface; (b) NEMA design class B-large, deep rotor bars; (c) NEMA design class C-double-cage rotor design; (d) NEMA design class D-small bars near the surface.



Deep-Bar and Double-Cage Rotor Designs



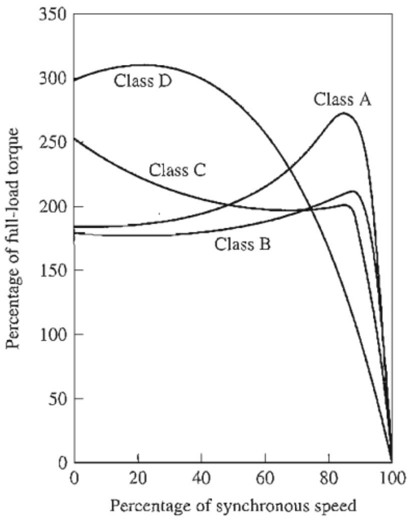


A class A design. A typical torque speed characteristic for this construction is the design class B curve in Figure A cross-sectional view of a double-cage rotor is shown in. It consists of a large, low-resistance set of bars buried deeply in the rotor and a small, high resistance set of bars set at the rotor surface. It is similar to the deep-bar rotor, except that the difference between low-slip and high-slip operation is even more exaggerated. At starting conditions, only the small bar is effective, and the rotor resistance is quite high. This high resistance results in a large starting torque. However, at normal operating speeds, both bars are effective, and the resistance is almost as low as in a deep-bar rotor. Double-cage rotors of this sort are used to produce NEMA class B and class C characteristics. Possible torque- speed characteristics for a rotor of this design are designated design class B and design class C in Figure.

Double-cage rotors have the disadvantage that they are more expensive than the other types of cage rotors, but they are cheaper than wound-rotor designs. They allow some of the best features possible with wound-rotor motors (high starting torque with a low stm1ing current and good efficiency at normal operating conditions) at a lower cost and without the need of maintaining slip rings and brushes.

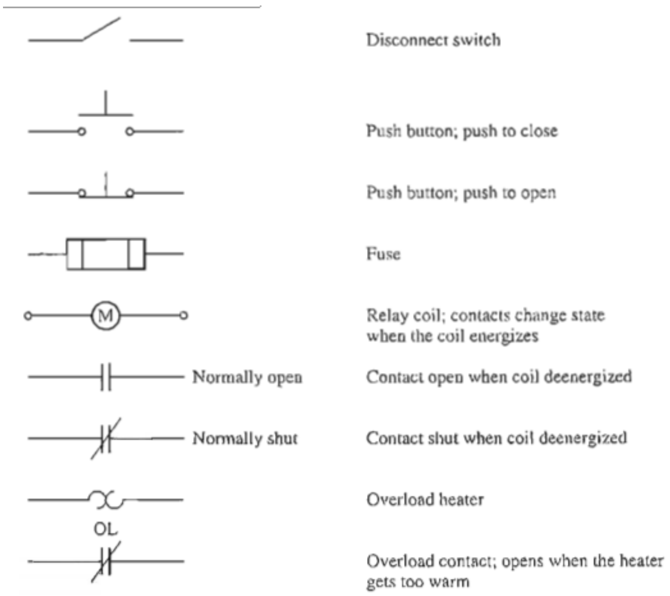
Induction Motor Design Classes

1. DESIGN CLASS A.
2. DESIGN CLASS B.
3. DESIGN CLASS C.
4. DESIGN CLASS D.

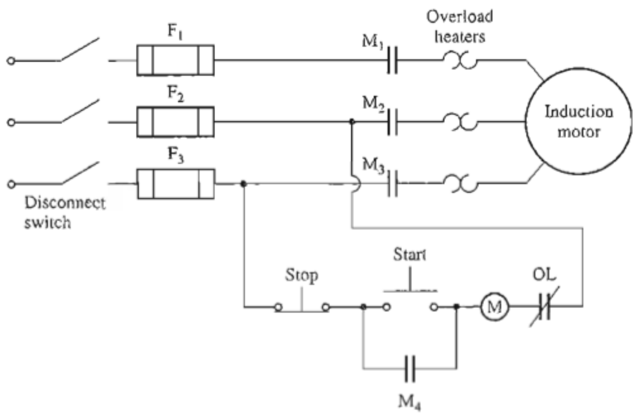


- Several techniques are used to improve the efficiency of these motors compared to the traditional standard efficiency designs. Among these techniques are:-
  1. More copper is used in the stator windings to reduce copper losses.
  2. The rotor and stator core length is increased to reduce the magnetic flux density in the air gap of the machine. This reduces the magnetic saturation of the machine, decreasing core losses.
  3. More steel is used in the stator of the machine, allowing a greater amount of heat transfer out of the motor and reducing its operating temperature. The rotor's fan is then redesigned to reduce windage losses.
  4. The steel used in the stator is a special high-grade electrical steel with low hysteresis losses.
  5. The steel is made of an especially thin gauge (i.e., the laminations are very close together), and the steel has a very high internal resistivity. Both effects tend to reduce the eddy current losses in the motor.
  6. The rotor is carefully machined to produce a uniform air gap, reducing the stray load losses in the motor.

Induction Motor Starting Circuits



Typical components found in induction motor control circuits.



IP - Ingress Protection Rating

IP - Ingress Protection rating is used to specify environmental protection - electrical enclosure - of electrical equipment
The IP rating normally has two (or three) numbers:

1. Protection from solid objects or materials (1-6).
2. Protection from liquids (water) (1-8).
3. Protection against mechanical impacts (commonly omitted, the third number is not a part of IEC 60529)

Example - IP Rating

With the IP rating IP 54

IS 5 describes the level of protection from solid objects and 4 describes the level of protection from liquids.

1. IP First number - Protection against solid objects

0	No special protection
1	Protected against solid objects over 50 mm, e.g. accidental touch by persons hands
2	Protected against solid objects over 12 mm, e.g. persons fingers
3	Protected against solid objects over 2.5 mm (tools and wires)
4	Protected against solid objects over 1 mm (tools, wires, and small wires)
5	Protected against dust limited ingress (no harmful deposit)
6	Totally protected against dust

2. IP Second number - Protection against liquids

0	No protection
1	Protection against vertically falling drops of water e.g. condensation
2	Protection against direct sprays of water up to 15° from the vertical
3	Protected against direct sprays of water up to 60° from the vertical
4	Protection against water sprayed from all directions - limited ingress permitted

5	Protected against low pressure jets of water from all directions - limited ingress
6	Protected against temporary flooding of water, e.g. for use on ship decks - limited ingress permitted
7	Protected against the effect of immersion between 15 cm and 1 m
8	Protects against long periods of immersion under pressure

NEMA Insulation Classes

Electrical insulation systems rated by standard NEMA classifications to maximize allowable operating temperatures.

Temperature Tolerance Class	Maximum Operation Temperature Allowed	Allowable Temperature Rise at full load 1.0 service factor motor[1)]	Allowable Temperature Rise 1.15 service factor motor [1)]
	°C	°C	°C
A	105	60	70
B	130	80	90
F	155	105	115
H	180	125	-

[1)] Allowable temperature rises are based upon a reference ambient temperature of *40°C*. Operation temperature is reference temperature + allowable temperature rise + allowance for "hot spot" winding.

Example Temperature Tolerance Class F:

$40^oC + 105^oC + 10^oC = \underline{155}^oC$

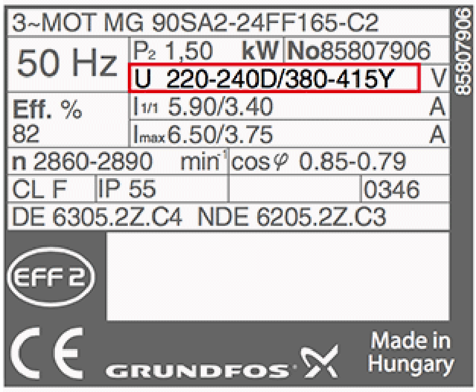
In general a motor should not operate with temperatures above the maximum. Each *10°C* rise above the rating may reduce the motor lifetime by one half. It is important to be aware that insulation classes are directly related to motor life.

Example - a motor operating at 180°C will have an estimated life of only 300 hours with Class A insulation, 1800 hours with Class B insulation, 8500 hours with Class F insulation, tens of thousands of hours with Class H insulation

Temperature Tolerance Class B is the most common insulation class used on most *60 cycle* US motors.

Temperature Tolerance Class F is the most common for international and *50 cycle* motors.

1. Voltage



2. Frequency

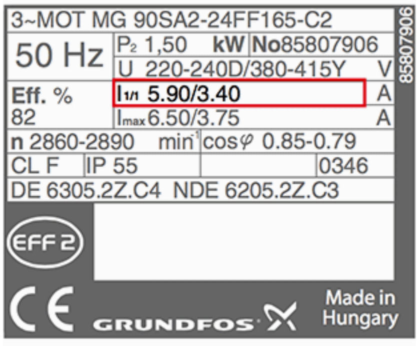
Usually for motors, the input frequency is 50 or 60 Hz. If more than one frequency is marked on the nameplate, then other parameters that will differ at different input frequencies have to be indicated on the nameplate as well.

3. Phase

This parameter represents the number of AC power lines that supply the motor. Single-phase and three-phase are considered as the standard.

4. Current

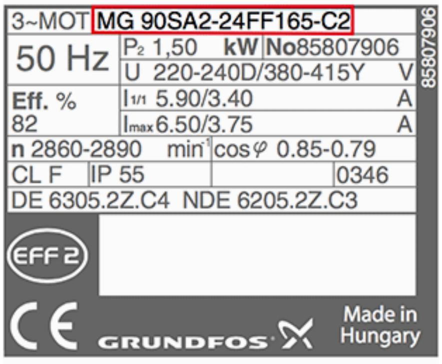
Current indicated on the nameplate corresponds to the rated power output together with voltage and frequency. Current may deviate from the nameplate amperes if the phases are unbalanced or if the voltage turns out to be lower than indicated.



5. Type

Some manufacturers use type to define the motor as single-phase or poly-phase, single-phase or multi-speed or by type of construction. Nevertheless, there are no industry standards for type.

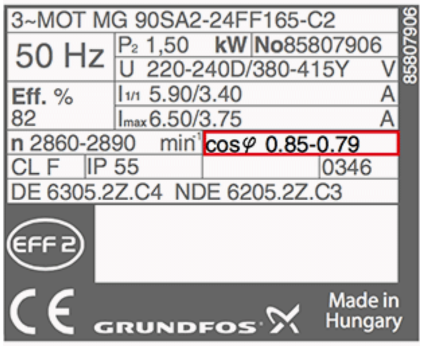
6. **Grundfos** uses the following type designation: MG90SA2-24FF165-C2.



7. Power factor

Power factor is indicated on the nameplate as either “PF” or “P .F” or cos φ . Power factor is an expression of the ratio of active power (W) to apparent power (VA) expressed as a percentage.

The motor’s nameplate provides you with the power factor for the motor at full-load.

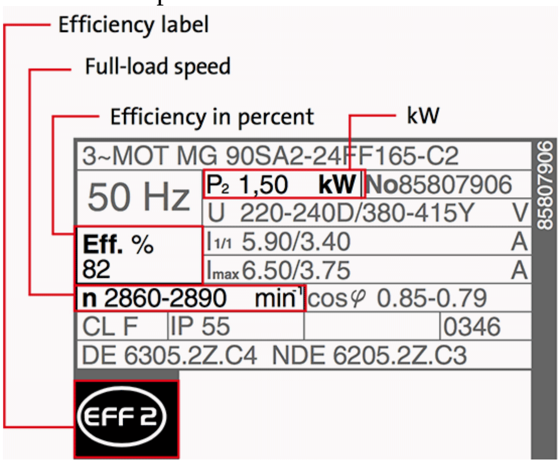


8. KW or horsepower

KW or Hp is an expression of the motor's mechanical output rating – that is its ability to deliver the torque needed for the load at rated speed.

9. Full-load speed

Full-load speed is the speed at which rated full-load torque is delivered at rated power output. Normally, the full-load speed is given in RPM. This speed is sometimes called slip-speed or actual rotor speed.



Motor efficiency label Full-load speed; Efficiency in percent and kW or horsepower.

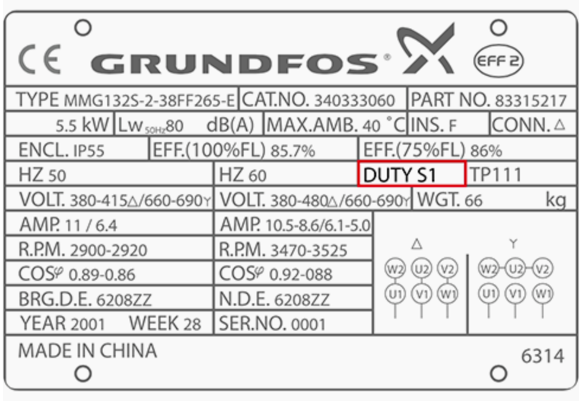
10. Efficiency

Efficiency is the motor's output power divided by its input power multiplied by 100. Efficiency is expressed as a percentage. Efficiency is guaranteed by the manufacturer to be within a certain tolerance band, which varies depending on the design standard, eg IEC or NEMA.

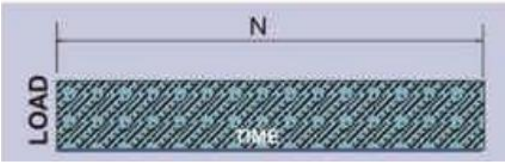
Therefore, pay attention to guaranteed minimum efficiencies, when you evaluate the motor's performance.

11. Duty

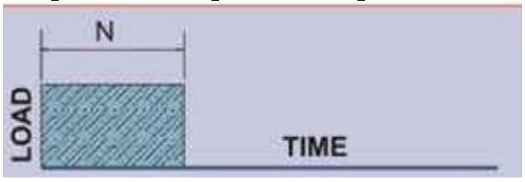
This parameter defines the length of time during which the motor can carry its nameplate rating safely. In many cases, the motor can do it continuously, which is indicated by an S1 or "Cant" on the nameplate. If nothing is indicated on the nameplate, the motor is designed for duty cycle S1.



S1:Continuous operation with a fixed load

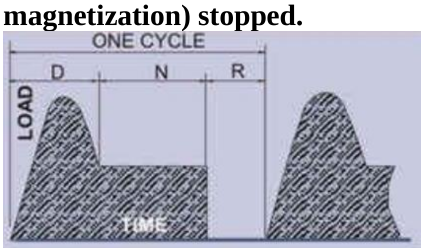


S2:Run for specific periods with constant load and after stopping the motor must degree temperature drop of air temperature and then you can start again

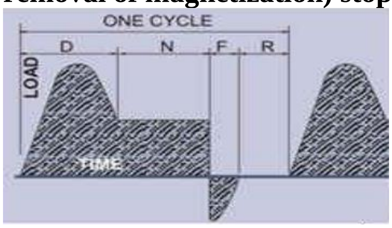


S3: Discontinuous periods of running and stopping short of her time to remove the magnetization of the motor and not for cooling

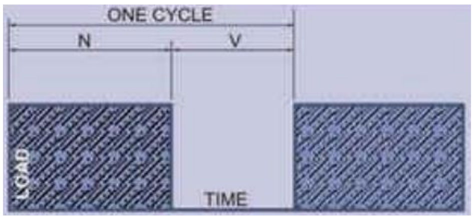
S4:Run frequently contains three periods (start - run by constant load - the removal of magnetization) stopped.



S5:**Run frequently contains four periods (start - run by constant load - braking - the removal of magnetization) stopped.**



S6: Continuous operation contains two periods first with load and the second without load



12. Insulation class

Insulation class (INSUL CLASS) is an expression of the standard classification of the thermal tolerance of the motor winding. Insulation class is a letter designation such as “B” or “F”, depending on the winding’s ability to survive a given operating temperature for a given life. The farther in the alphabet, the better the performance.

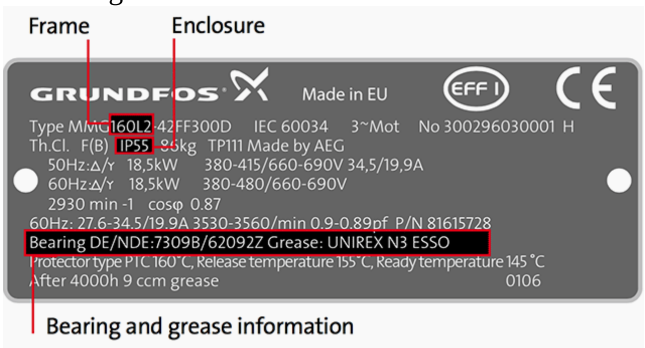
For instance, a class “F” insulation has a longer nominal life at a given operating temperature than a class “B”.

13. Maximum ambient temperature

The maximum ambient temperature at which a motor can operate is sometimes indicated on the nameplate. If not the maximum is 40°C for EFF2 motors and normally 60°C for EFF1 motors. The motor can run and still be within the tolerance of the insulation class at the maximum rated temperature.

14. Enclosure

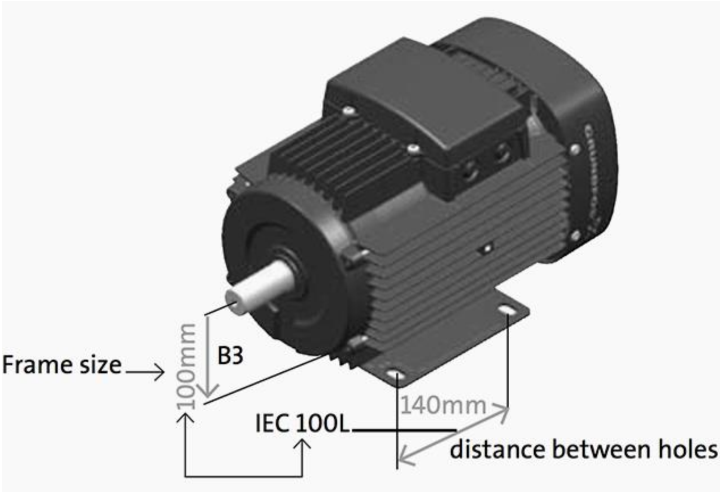
Enclosure classifies a motor as to its degree of protection from its environment and its method of cooling. Enclosure is shown as IP or ENCL on the nameplate.



Motor frame, enclosure bearing and grease information on nameplate.

15. Frame

The frame size data on the nameplate is an important piece of information. It determines mounting dimensions such as the foot hole mounting pattern and the shaft height. The frame size is often a part of the type designation which can be difficult to interpret because special shaft or mounting configurations are used.



16. Bearings
17. NEMA
The most important ones are:
Letter code.
Design letter.
Service factor.
16. Service factor

- A motor designed to operate at its nameplate power rating has a service factor of 1.0. This means that the motor can operate at 100% of its rated power.
- Some applications require a motor that can exceed the rated power. In these cases, a motor with a service factor 1.15 can be applied to the rated power. A 1.15 service factor motor can be operated at 15% higher than the motor's nameplate power.

However, any motor that operates continuously at a service factor that exceeds 1 will have reduced life expectancy compared to operating it at its rated power.

How you can Test a Motor without Nameplate Information?

All motors originate from the manufacturer with a name or data plate affixed to the motor casing. This nameplate contains information that is essential to an effective motor testing program. It provides the operating characteristics and design parameters for that particular motor.

Occasionally you may be tasked to test a motor when no nameplate information is provided or readily available. For de-energized testing this doesn't pose much of a problem as the data we are collecting is compared between phases, for balance, on poly phase motors. DC and single phase motors are more problematic as we don't have the ability for phase comparison.

When testing a poly phase motor without nameplate information, we will not know the number of poles unless we perform a rotor influence check. The best way to do that is to test the motor as the rotor is stepped in 5 degree increments. When a complete cycle for inductance or impedance is obtained you can easily determine the number of poles. If a complete cycle is obtained in 45 degrees of rotation it is an 8 pole, 60 degrees 6 pole, 90 degrees 4 pole, and 180 degrees a 2 pole.

Another disadvantage to not having nameplate information is that we lose the ability to compare to like motors. This applies to both energized and de-energized testing.

Energized testing is extremely difficult without nameplate data. If similar motors are used for the same process you can use the nameplate data off of one of them. It may not be fully accurate, but-will get you in the ball park. If no similar units are available and you are not familiar with the process, talk to the operators. Use a strobe tachometer to determine motor RPM and then set up a generic motor in the database for that RPM. If loading cannot be provided by the operator use the acquired data and RPM to approximate loading. You can view the power factor for a value around 88 to 92 to approximate full load.

Testing without proper nameplate information is not desirable, but-possible. With a proper understanding of motor theory and operational characteristics of a motor, reliable data collection is still attainable.

Induction Generator

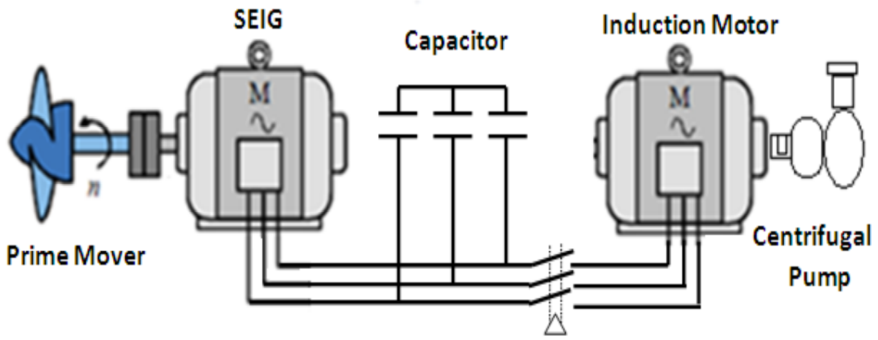
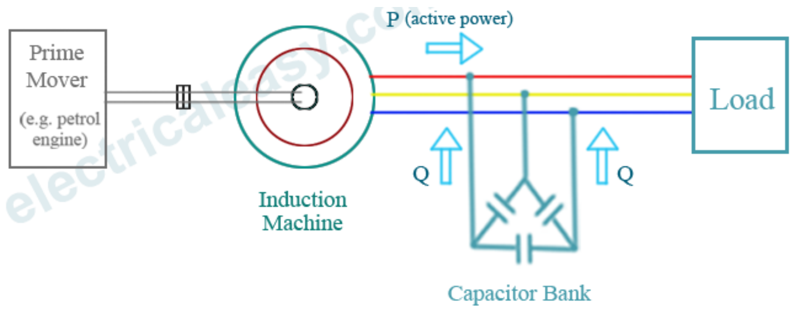
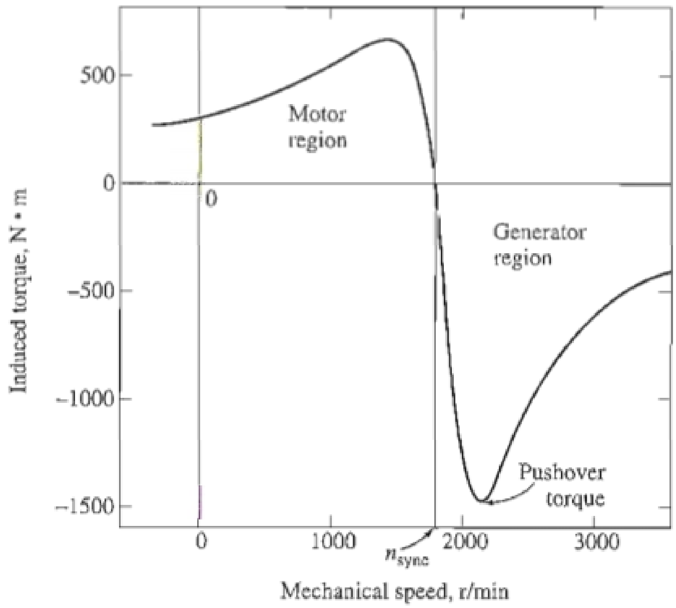


Fig.1 Wind Electric Pumping System





When the induction machine will behave as an induction generator are written below:

(a) Slip becomes negative due to this the rotor current and rotor emf attains negative value.

(b) The prime mover torque becomes opposite to electric torque. Isolated Induction Generator

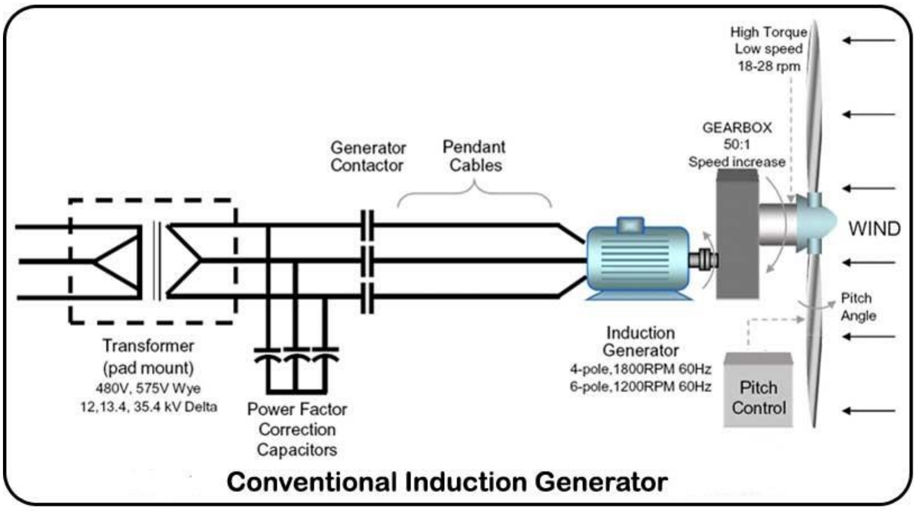
This type of generator is also known as self-excitation generator. Now why it is called self-excited? It is because it uses capacitor bank which is connected across its stator terminals as Shown in the diagram given below, the function of the capacitor bank is to provide the lagging reactive power to the induction generator as well as load. So mathematically we can write total reactive power provided by the capacitor bank is equals to the summation of the reactive power consumed by the induction generator as well as the load.

- **Application of Induction Generator**

We have two types of induction generator:-

1-separately: Externally excited generators are widely used for regenerative breaking of hoists driven by the three phase induction motor.

2-Self excited generators are used in the wind mills.



Advantages	**Disadvantages**
Cheap	Need Q source
Less maintenance	Consume more Q
Automatically synchronous with system	Can't control with output voltage
No need Dc excitation system	Low efficiency

Application of Synchronous Motor

- As synchronous motor is capable of operating under either leading or lagging power factor, it can be used for power factor improvement. A synchronous motor under no-load with leading power factor is connected in power system where static capacitors cannot be used.
- It is used where high power at low speed is required. Such as rolling mills, chippers, mixers, pumps, pumps, compressor etc.

QUESTIONS

1. What are slip and slip speed in an induction motor?

2. How does an induction motor develop torque?

3. Why is it impossible for an induction motor to operate at synchronous speed?

4. Sketch and explain the shape of a typical induction motor torque-speed characteristic curve.

5. What equivalent circuit element has the most direct control over the speed at which the pullout torque occurs?

7. Describe the characteristics and uses of wound-rotor induction motors and of each

NEMA design class of cage motors.

8. Why is the efficiency of an induction motor (wound-rotor or cage) so poor at high slips?

9. Name and describe four means of controlling the speed of induction motors.

10. Why is it necessary to reduce the voltage applied to an induction motor as electrical frequency is reduced?

11. Why is terminal voltage speed control limited in operating range?

12. What are starting code factors? What do they say about the starting current of an induction motor?

13. How does a resistive starter circuit for an induction motor work?

14. What information is learned in a locked-rotor test?

15. What information is learned in a no-load test?

16. What actions are taken to improve the efficiency of modern high-efficiency induction motors?

17. What controls the terminal voltage of an induction generator operating alone?

18. For what applications are induction generators typically used?

19. How can a wound-rotor induction motor be used as a frequency changer?

20. How do different voltage-frequency patterns affect the torque-speed characteristics of an induction motor?

21. Two 480-V, IOO-hp induction motors are manufactured. One is designed for 50-Hz operation, and one is designed for 60-Hz operation, but they are otherwise similar. Which of these machines is larger?

OBJECTIVE TESTS

1. In the circle diagram for a 3-φ induction motor, the diameter of the circle is determined by

(A) rotor current

(b) Exciting current

(c) Total stator current

(d) Rotor current referred to stator.

2. Point out the WRONG statement. Blocked rotor test on a 3-φ induction motor helps to find

(a) Short-circuit current with normal voltage

(b) Short-circuit power factor

(c) Fixed losses

(d) Motor resistance as referred to stator.

3. In the circle diagram of an induction motor, point of maximum input lies on the tangent drawn parallel to

(a) Output line

(b) Torque line

(c) Vertical axis

(d) Horizontal axis.

4. An induction motor has a short-circuit current 7 times the full-load current and a full-load slip of 4 per cent. Its line-starting torque is ....times the full-load torque.

(a) 7 (b) 1.96

(c) 4 (d) 49

5. In a SCIM, torque with autostarter is .... times the torque with direct-switching.

(a) K2 (b) K

(c) 1/K2 (d) 1/K

Where K is the transformation ratio of the autostarter.

6. If stator voltage of a SCIM is reduced to 50 per cent of its rated value, torque developed is reduced by .... per cent of its full-load value.

(a) 50 (b) 25

(c) 75 (d) 57.7

7. For the purpose of starting an induction motor, a Y-Δ switch is equivalent to an auto-starter of ratio.......per cent.

(a) 33.3 (b) 57.7

(c) 73.2 (d) 60.

8. A double squirrel-cage motor (DSCM) scores over SCIM in the matter of

(a) Starting torque

(b) High efficiency under running conditions

(c) Speed regulation under normal operating conditions

(D) all of the above.

9. In a DSCM, outer cage is made of high resistance metal bars primarily for the purpose

Of increasing its

(a) Speed regulation (b) Starting torque

(c) Efficiency (d) Starting current.

10. A SCIM with 36-slot stator has two separate windings: one with 3 coil groups/ phase/pole and the other with 2 coil groups/phase/pole. The obtainable two motor speeds would be in the ratio of

(a) 3 : 2 (b) 2 : 3

(c) 2 : 1 (d) 1 : 2

11. A 6-pole 3-φ induction motor taking 25 kW from a 50-Hz supply is cumulatively cascaded to a 4-pole motor. Neglecting all losses, speed of the 4-pole motor would be .... rpm.

(a) 1500 (b) 1000

(c) 600 (d) 3000.

And its output would be .... kW.

(e) 15 (f) 10

(g) 50/3 (h) 2.5.

12. Which class of induction motor will be well suited for large refrigerators?

(a) Class E (b) Class B

(c) Class F (d) Class C

13. In a Schrage motor operating at super synchronous speed, the injected emf and the Standstill secondary induced emf

(a) Are in phase with each other

(b) Are at 90º in time phase with each other

(c) Are in phase opposition

(d) None of the above.

14. For starting a Schrage motor, 3-φ supply is connected to

(a) Stator

(b) Rotor via slip-rings

(c) Regulating winding

(d) Secondary winding via brushes.

15. Two separate induction motors, having 6 poles and 5 poles respectively and their cascade combination from 60 Hz, 3-phase supply can give the following synchronous speeds in rpm

(a) 720, 1200, 1500 and 3600 (b) 720, 1200 1800

(c) 600, 1000, 15000 (d) 720 and 3000

16. Mark the WRONG statement .A Schrage motor is capable of behaving as a/ an

(a) Inverted induction motor (b) slip-ring induction motor
(c) Shunt motor

(d) Series motor (e) Synchronous motor.

17. When a stationary 3-phase induction motor is switched on with one phase disconnected

(a) It is likely to burn out quickly unless immediately disconnected

(b) It will start but very slowly

(c) It will make jerky start with loud growing noise

(d) Remaining intact fuses will be blown out due to heavy inrush of current

18. If single-phasing of a 3-phase induction motor occurs under running conditions, it

(a) Will stall immediately (b) will keep running though with slightly increased slip

(c) May either stall or keep running depending on the load carried by it

(d) Will become noisy while it still keeps running.

ANSWERS

1. c **2.** c **3.** d **4.** b **5.** a **6.** c **7.** b **8.** d **9.** b **10.** a **11.** c, f **12.** d **13.** a **14.** b **15.** a

16. d **17.** a **18.** c

AC winding design

The windings used in rotating electrical machines can be classified as -: Concentrated Windings

•All the winding turns are wound together in series to form one multi turn coil

•All the turns have the same magnetic axis

•Examples of concentrated winding are

–field windings for salient-pole synchronous machines

–D.C. machines

–Primary and secondary windings of a transformer

Distributed Windings-:

• All the winding turns are arranged in several full-pitch or fractional-pitch coils.

• These coils are then housed in the slots spread around the air-gap periphery to form phase or commutator winding.

• Examples of distributed winding are

– Stator and rotor of induction machines

– The armatures of both synchronous and D.C. machines

Armature windings, in general, are classified under two main heads, namely:

1 .Closed Windings

•There is a closed path in the sense that if one starts from any point on the winding and traverses it, one again reaches the starting point from where one had started

•Used only for D.C. machines and A.C. commutator machines

2 .Open Windings

•Open windings terminate at suitable number of slip-rings or terminals

•Used only for A.C. machines, like synchronous machines, induction machines ,etc.

Some of the terms common to armature windings are described below-:

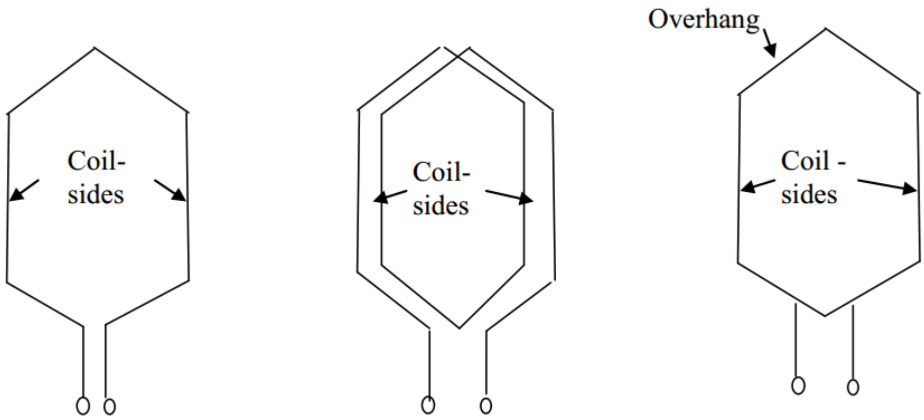
1 .Conductor. A length of wire which takes active part in the energy conversion process is a called a conductor.

2 .Turn. One turn consists of two conductors.

3 .Coil. One coil may consist of any number of turns.

4 .Coil –side. One coil with any number of turns has two coil-sides.

The number of conductors (C) in any coil-side is equal to the number of turns (N) in that coil.

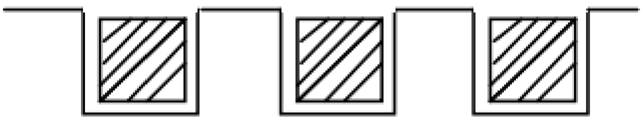


One-turn coil two-turn coil multi-turn coil

5 .Single- layer and double layer windings.

Single -layer winding

• One coil-side occupies the total slot area



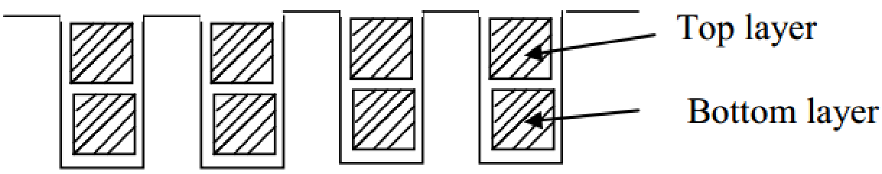
one coil-side per slot

• Used only in small ac machines

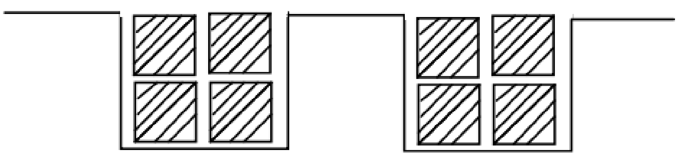
Double -layer winding

• Slot contains even number (may be 2,4,6 etc.) of coil-sides in two layers

• Double-layer winding is more common above about 5kW machines



Two coil –sides per slot



4-coil-sides per slot

The advantages of double-layer winding over single layer winding are as follows:

a. Easier to manufacture and lower cost of the coils

b. Fractional-slot winding can be used

c. Chorded-winding is possible

d. Lower-leakage reactance and therefore , better performance of the machine

e. Better emf waveform in case of generators

6 .Pole – pitch. A pole pitch is defined as the peripheral distance between identical points on two adjacent poles. Pole pitch is always equal to 180o.

7 .Coil–span or coil-pitch. The distance between the two coil-sides of a coil is called coil-span or coil-pitch. It is usually measured in terms of teeth, slots or electrical degrees electrical.

8 .Chorded-coil -:If the coil-span (or coil-pitch) is equal to the pole-pitch, then the coil is termed a full-pitch coil.

In case the coil-pitch is less than pole-pitch, then it is called Chorded, short-pitch or fractional-pitch coil.If there are S slots and P poles ,then pole pitch

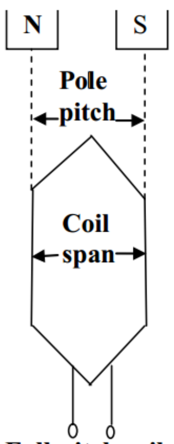
$$Q = \frac{S}{P}$$

Slots per pole.If coil-pitch it results in full-pitch winding In case coil-pitch

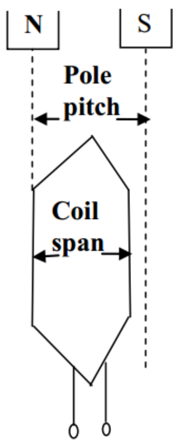
$$y < \frac{S}{P}$$

It results in chorded ,short-pitched or fractional-pitch the slot angle pitch is given by

$$\gamma = \frac{180^o}{Slots\ per\ pole} = \frac{180^o}{6} = 30^o$$



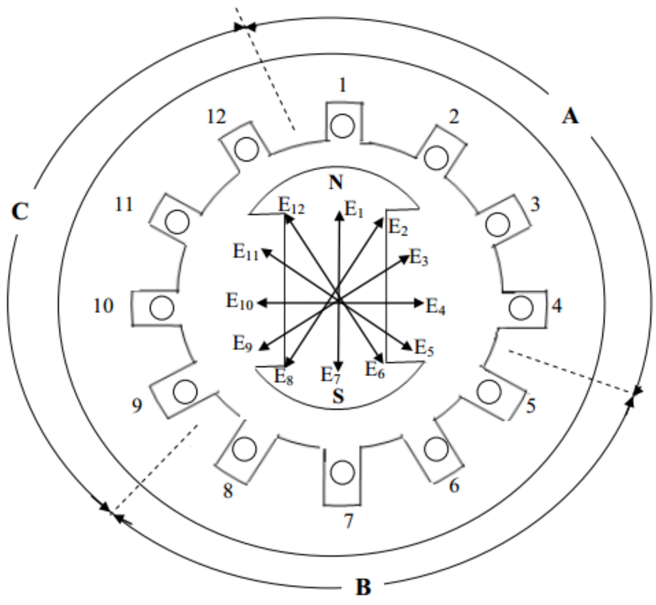
Full-pitch coil



Short-pitched or chorded coil

Phase spread-:

Where field winding on the rotor to produce 12 poles and the stator carries 12 conductors housed in 12 slots.



3-phase winding - phase spread is 120°

-The phase band may be defined as the group of adjacent slots belonging to one phase under one pole-pair

Conductors 1, 2, 3 and 4 constitute first phase group (A)

Conductors 5, 6, 7 and 8 constitute second phase group (B)

Conductors 9, 10, 11 and 12 constitute third phase group(C)

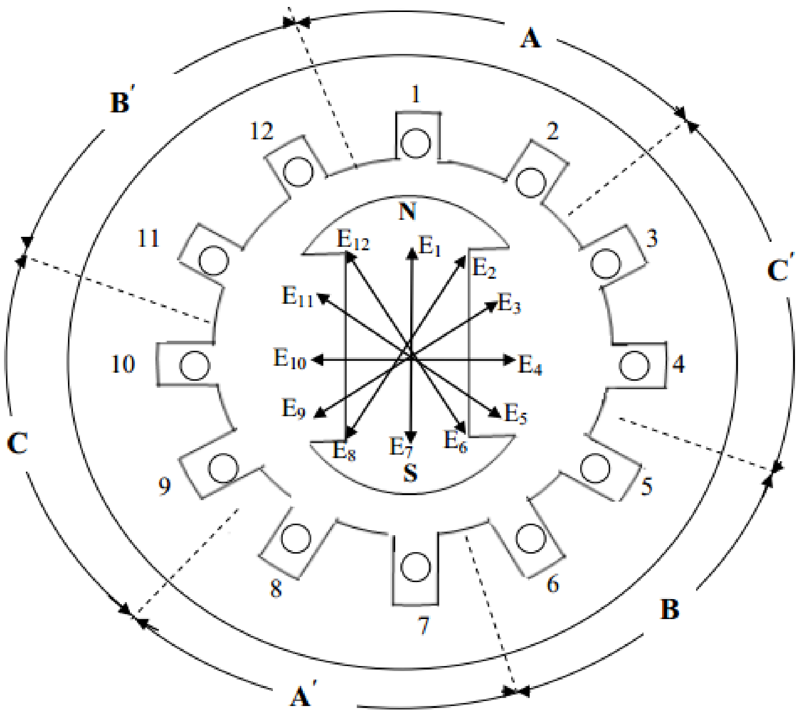
The angle subtended by one phase group is called phase spread, symbol $\sigma = q\gamma$ where

$$q = number\ of\ slots\ per\ pole\ per\ phse = \frac{S}{Pm}$$

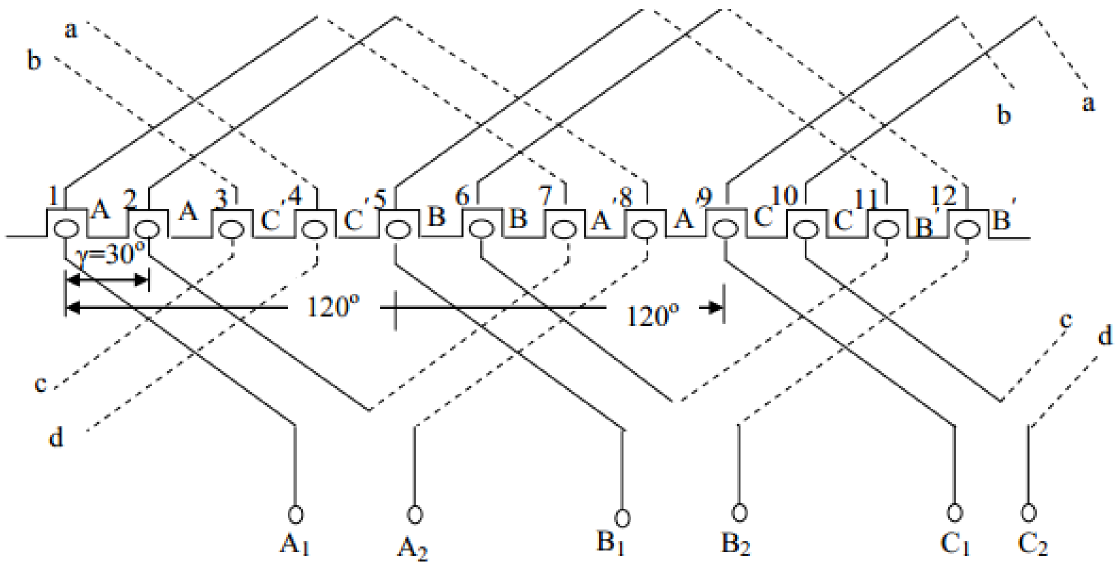
Sequence of phase-belts (groups)

Let 12-conductors can be used to obtain three-phase single – layer winding having a phase spread of 60o $(\sigma{=}60)$

- coil pitch or coil span $\boldsymbol{y}$= pole pitch $\boldsymbol{\tau} = \frac{S}{P} = \frac{12}{2} = 6$
- for 12 slots and 2 poles, slot angular pitch γ =**30°**
- for $\sigma = 60^o$, two adjacent slots must belong to the same phase



3-phase winding, phase spread is 60°



Double Layer Winding-:

- synchronous machine armatures and induction –motor stators above a few kW, are wound with double layer windings
- if the number of slots per pole per phase $q = \frac{S}{mP}$ is an integer, then the winding is called an ***integral-slot winding***
- in case the number of slots per pole per phase, q is not an integer, the winding is called ***fractional-slot winding.*** For example
  - *a 3-phase winding with 36 slots and 4 poles is an integral slot winding, because* $q = \frac{36}{3\times4} = 3$ *is an integer*
  - *a 3-phase winding with 30 slots and 4 poles is a fractional slot winding, because* $q = \frac{30}{3\times4} = \frac{5}{2}$ *is not an integer*
- the number of coils ***C*** is always equal to the number of slots ***S***, ***C=S***

Integral Slot Winding

Example :make a winding table for the armature of a 3-phase machine with the following specifications:

Total number of slots = 24 Double – layer winding

Number of poles = 4 Coil-span = full-pitch

Solution: slot angular pitch, $\gamma = \frac{4\times180^o}{24} = 30^o$

Phase spread, $\sigma = 60^o$

Number of slots per pole per phase, $q = \frac{24}{3\times4} = 2$

Coil span = full pitch = $\frac{24}{4} = 6$

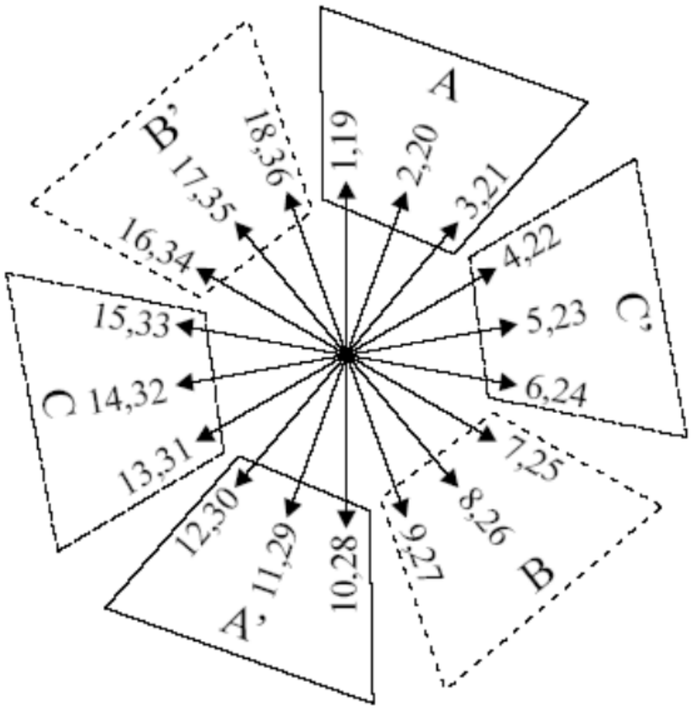
2 .Integral slot chorded winding (Short pitch)

- Coil span (coil pitch) < pole pitch ($y < \tau$)
- The advantages of using chorded coils are:
  - To reduce the **amount of copper** required for the end-connections (or over hang)
  - To reduce the **magnitude of certain harmonics** in the waveform of phase emfs and mmfs
- The coil span generally varies from **2/3 pole pitch** to **full pole pitch**

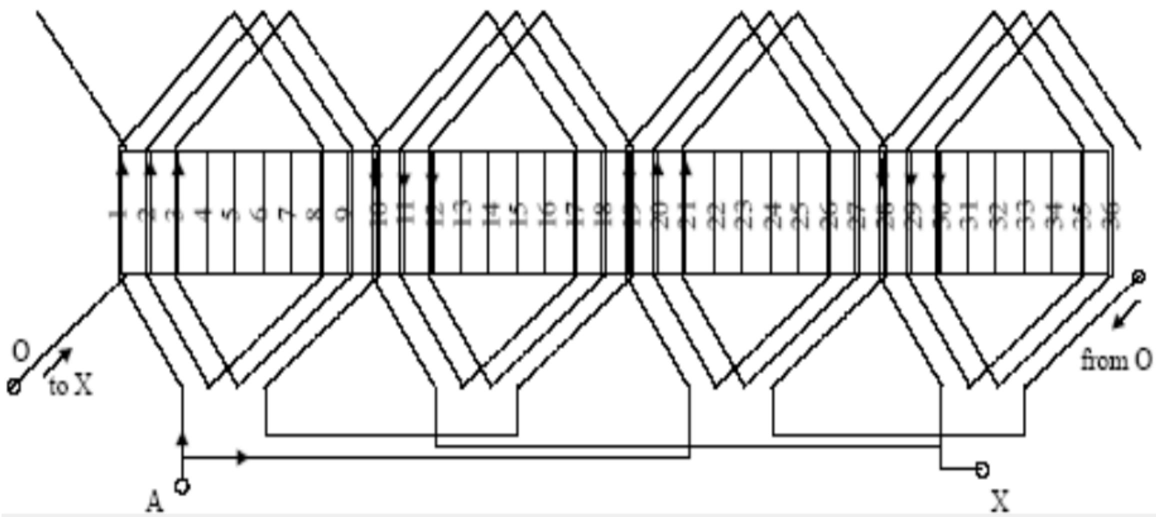
Disadvantages of short pitch coil (chorded coil)-:

The total voltage around the coils is reduce

Example. Let us consider a double-layer three-phase winding with q =3, p = 4, (S = 36 slots), chorded coils y/τ = 7/9



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
layer1	A	A	A	C'	C'	C'	B	B	B	A'	A'	A'	C	C	C	B'	B'	B'	A	A	A	C'	C'	C'	B	B	B	A'	A'	A'	C	C	C	B'	B'	B'
layer2	A	C'	C'	C'	B	B	B	A'	A'	A'	C	C	C	B'	B'	B'	A	A	A	C'	C'	C'	B	B	B	A'	A'	A'	C	C	C	B'	B'	B'	A	A



3. Fractional Slot Windings

If the number of slots q of a winding is a fraction, the winding is called a fractional slot winding.

- Advantages of fractional slot windings:-
  1. A great freedom of choice with respect to the number of slot a possibility to reach a suitable magnetic flux density
  2. This winding allows more freedom in the choice of coil span

3. If the number of slots is predetermined, the fractional slot winding can be applied to a wider range of numbers of poles than the integral slot winding the segment structures of large machines are better controlled by using fractional slot windings
4. This winding reduces the high-frequency harmonics in the EMF and MMF waveforms.

Winding Factor (Coil Pitch and Distributed Windings):-

Pitch Factor or Coil Pitch

The ratio of phasor sum of induced emfs per coil to the arithmetic sum of induced emfs per coil is known as pitch factor (KP) or coil span factor (Kc) which is always less than unity.

Let the coil have a pitch short by angle θ electrical space degrees from full pitch and induced emf in each coil side be E ,If the coil would have been full pitched, then total induced emf in the coil would have been 2E When the coil is short pitched by θ electrical space degrees the resultant induced emf ,ER in the coil is phasor sum of two voltages ,θ apart $ER = 2E\cos(\theta/2)$

$$\textbf{Pitch factor,}\quad K_p = \frac{\textit{Phasor sum of coil side emfs}}{\textit{Arithmetic sum of coil side emfs}} = \frac{2E\cos\frac{\theta}{2}}{2E} = \cos\frac{\theta}{2}$$

Example. The coil span for the stator winding of an alternator is 120°. Find the chording factor of the winding.

Solution: Chording angle, $\theta = 180^o - coil\ span = 180^o - 120^o = 60^o$

Chording factor, $K_p = \cos\frac{\theta}{2} = \cos\frac{60^o}{2} = 0.866$

Factor Distribution

The ratio of the phasor sum of the emfs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the emfs induced (or to the resultant of emfs induced in all coils concentrated in one slot under one pole) is known distribution factor Kd.

1-The distribution factor is always less than unity

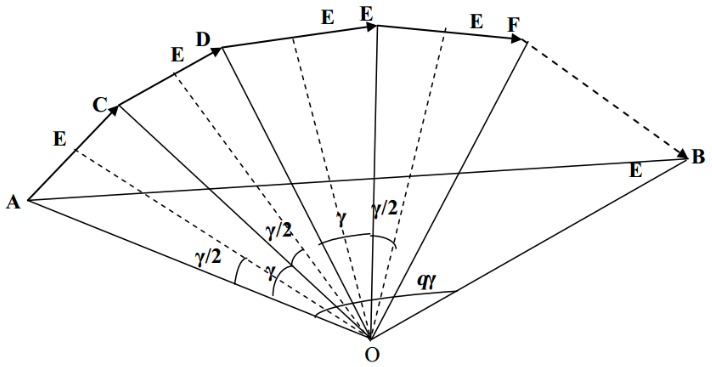
2- Let # of slots per pole = Q and no. of slots per pole per phase= q Induced emf in each coil side = E

3-Angular displacement between the slots

$$\gamma = \frac{180^o}{Q}$$

4-The emf induced in different coils of one phase under one pole are

Represented by side AC, CD, DE, EF… Which are equal in magnitude (say each equal E_c) and differ in phase (say by γ_o) from each other.



∴ The resultant distribution factor Kd

$$= \frac{\sin \frac{q\gamma}{2}}{q \sin \frac{\gamma}{2}}$$

Example. Calculate the distribution factor for a 36-slots, 4-pole, single layer 3-phase winding.

Solution: No. of slots per pole, $Q = \frac{36}{4} = 9$

No. of slots per pole per phase, $q = \frac{Q}{Number \ \ of \ phases} = \frac{9}{3} = 3$

Angular displacement between the slots, $\gamma = \frac{180^o}{Q} = \frac{180^o}{9} = 20^o$

Distribution factor, $K_d = \frac{\sin \frac{q\gamma}{2}}{q \sin \frac{\gamma}{2}} = \frac{\sin \frac{3\times 20^o}{2}}{3 \sin \frac{20^o}{2}} = \frac{1}{3} \frac{\sin 30^o}{\sin 10^o} = 0.96$

Example1. A 3-phase, 8-pole, 750 rpm. star-connected alternator has 72 slots on the armature. Each slot has 12 conductors and winding is short chorded by 2 slots. Find the induced emf between lines, given the flux per pole is 0.06 Wb.

Solution:

Flux per pole, $\emptyset = 0.06\ Wb$

$$f = \frac{pn}{60} = \frac{4 \times 750}{60} = 50\ Hz$$

Number of conductors connected in series per phase,

$$Z_s = \frac{Number\ \ of\ \ conductors\ \ per\ \ slot\ \times number\ \ of\ \ slots}{Num\,ber\ \ of\ \ phases}$$

$$= \frac{12 \times 72}{3} = 288$$

Number of turns per phase, $T = \frac{Z_s}{2} = \frac{288}{2} = 144$

Number of slots per pole, $Q = \frac{72}{8} = 9$

Number of slots per pole per phase, $q = \frac{Q}{3} = \frac{9}{3} = 3$

Angular displacement between the slots, $\gamma = \frac{180^o}{Q} = \frac{180^o}{9} = 20^o$

Distribution factor, $K_d = \frac{\sin\frac{q\gamma}{2}}{q\sin\frac{\gamma}{2}} = \frac{\sin\frac{3\times 20^o}{2}}{3\sin\frac{20^o}{2}} = \frac{1}{3}\frac{\sin 30^o}{\sin 10^o} = 0.96$

Chording angle, $\theta = 180^o \times \frac{2}{9} = 40^o$

Pitch factor, $K_p = \cos\frac{\theta}{2} = \cos\frac{40^o}{2} = \cos 20^o = 0.94$

Induced emf between lines, $E_L = \sqrt{3} \times 4.44 \times K_d \times K_p \times \emptyset \times f \times T$

$$= \sqrt{3} \times 4.44 \times 0.96 \times 0.94 \times 0.06 \times 50 \times 144 = 2998\ V$$

Winding factor (Kw):- Kω =Kd.Kp

Synchronous Generators

SIEMENS's 2 pole generators customized for the use on gas and steam turbines

Synchronous machines are principally used as alternating current (AC) generators. They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural, and domestic.

Synchronous generators usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers.

Synchronous generators are built in large units, their rating ranging from tens to hundreds of megawatts.

Synchronous generator converts mechanical power to ac electric power. The source of mechanical power, the prime mover, may be a diesel engine, a steam turbine, a water turbine, or any similar device.

- For high-speed machines, the prime movers are usually steam turbines employing fossil or nuclear energy resources.
- Low-speed machines are often driven by hydro-turbines that employ water power for generation.

Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers.

- **Types of Synchronous Machine**:-

According to the arrangement of the field and armature windings, synchronous machines may be classified as rotating-armature type or rotating-field type.

1. Rotating-Armature Type: The armature winding is on the rotor and the field system is on the stator.
2. Rotating-Field Type: The armature winding is on the stator and the field system is on the rotor.

According to the shape of the field, synchronous machines may be classified as cylindrical-rotor (non-salient pole) machines and salient-pole machines

Round Rotor Machine

• The stator is a ring shaped laminated iron-core with slots.

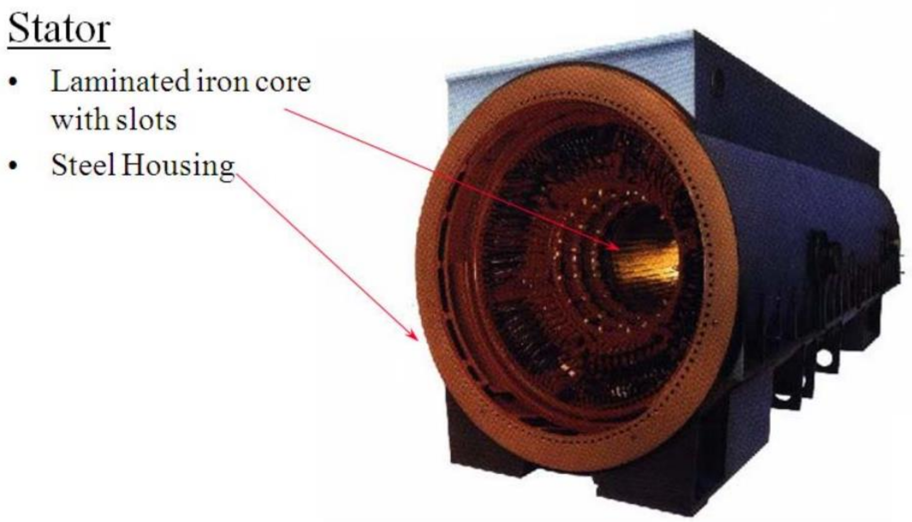
• Three phase windings are placed in the slots.
• Round solid iron rotor with slots.
• A single winding is placed in the slots. Dc current is supplied through slip rings

Salient Rotor Machine
• The stator has a laminated iron-core with slots and three phase windings placed in the slots.
• The rotor has salient excited by dc current.
• DC current is supplied to the rotor through slip-rings and brushes.
• The number of poles varies between 2-128.

- **Construction**:-

1. The winding consists of copper bars insulated with mica and epoxy resin.
2. The conductors are secured by steel wedges.
3. The iron core is supported by a steel housing.

Round rotor



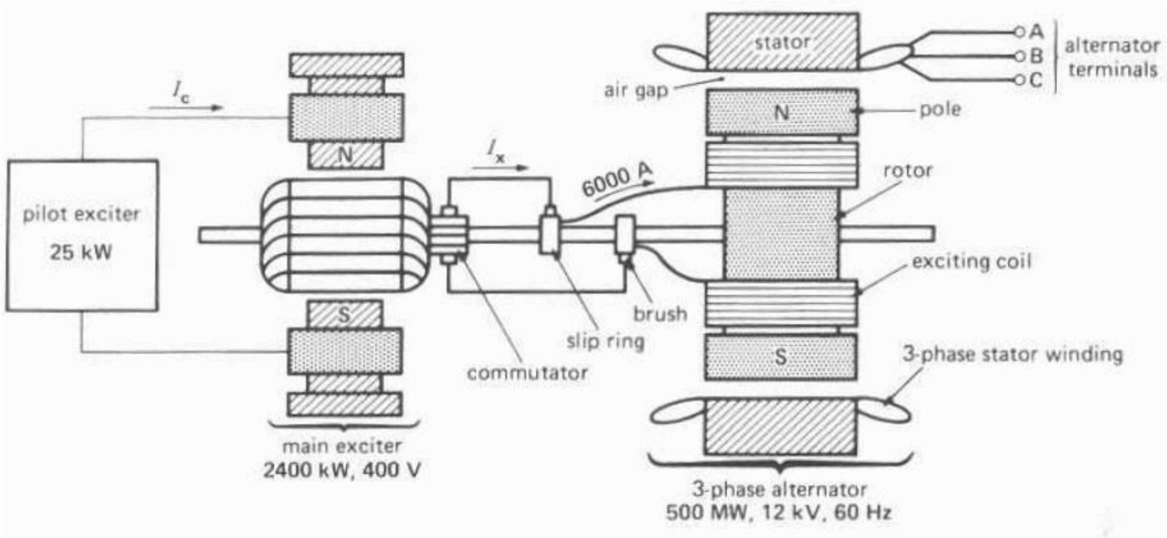
• The round rotor is used for large high speed (3600rpm) machines.
• A forged iron core (not laminated, DC) is installed on the shaft.
• Slots are milled in the iron and insulated copper bars are placed in the slots.
. The slots are closed by wedges and re-enforced with steel rings.

Salient pole rotor construction
• The poles are bolted to the shaft.
• Each pole has a DC winding.
• The DC winding is connected to the slip-rings (not shown).
• A DC source supplies the winding with DC through brushes pressed into the slip ring.
• A fan ‹s installed on the shaft to assure air circulation and effective cooling.
- Low speed, large hydro-generators may have more than one hundred poles
- These generators are frequently mounted vertically

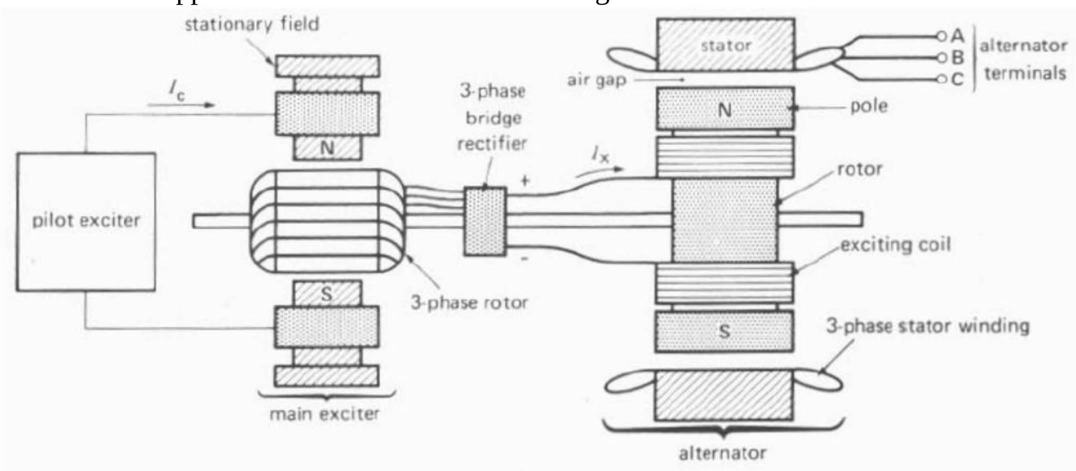
Field Excitation and Exciters:-
• DC field excitation is an important part of the overall design of a synchronous generator
• The field excitation must ensure not only a stable AC terminal voltage, but must also respond to sudden load changes.
• Rapid field excitation response is important.

Three methods of excitation

1. Slip rings link the rotor's field winding to an external dc source.



2. Dc generator exciter.
• A dc generator is built on the same shaft as the ac generator's rotor.
• A commutator rectifies the current that is sent to the field winding.
3. Brushless exciter
An Ac generator with fixed field winding and a rotor with a three phase circuit. Diode/SCR rectification supplies dc current to the field windings



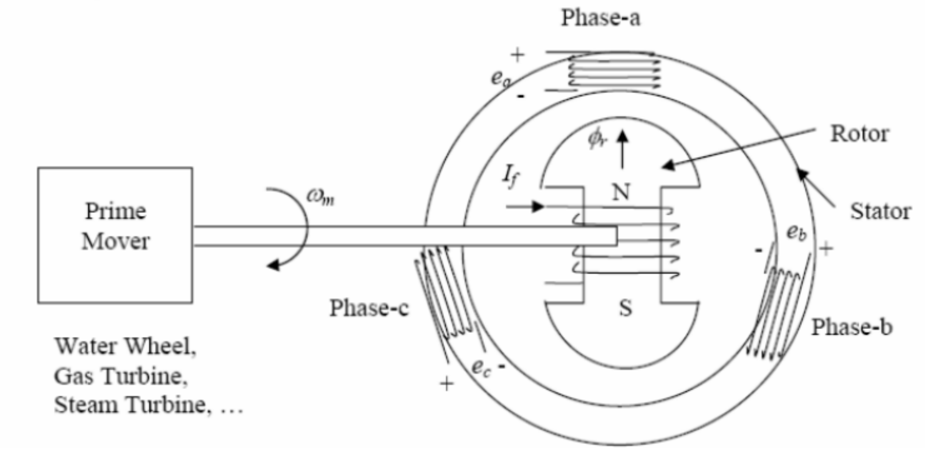
Typical brushless exciter system

- **Ventilation or Cooling of an Alternator:-**

The slow speed salient pole alternators are ventilated by the fan action of the salient poles which provide circulating air.
• Cylindrical rotor alternators are usually long, and the problem of air flow requires very special attention.
• The cooling medium, air or hydrogen is cooled by passing over pipes through which cooling water is circulated and ventilation of the alternator.
• Hydrogen is normally used as cooling medium in all the turbine-driven alternators because hydrogen provides better cooling than air and increases the efficiency and decreases the windage losses.
• Liquid cooling is used for the stators of cylindrical rotor generators.

Principle of Operation

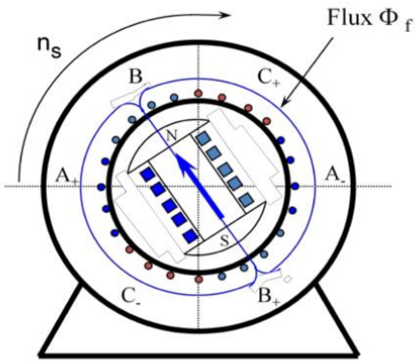
1) From an external source. The field winding is supplied with a DC current > excitation.
2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



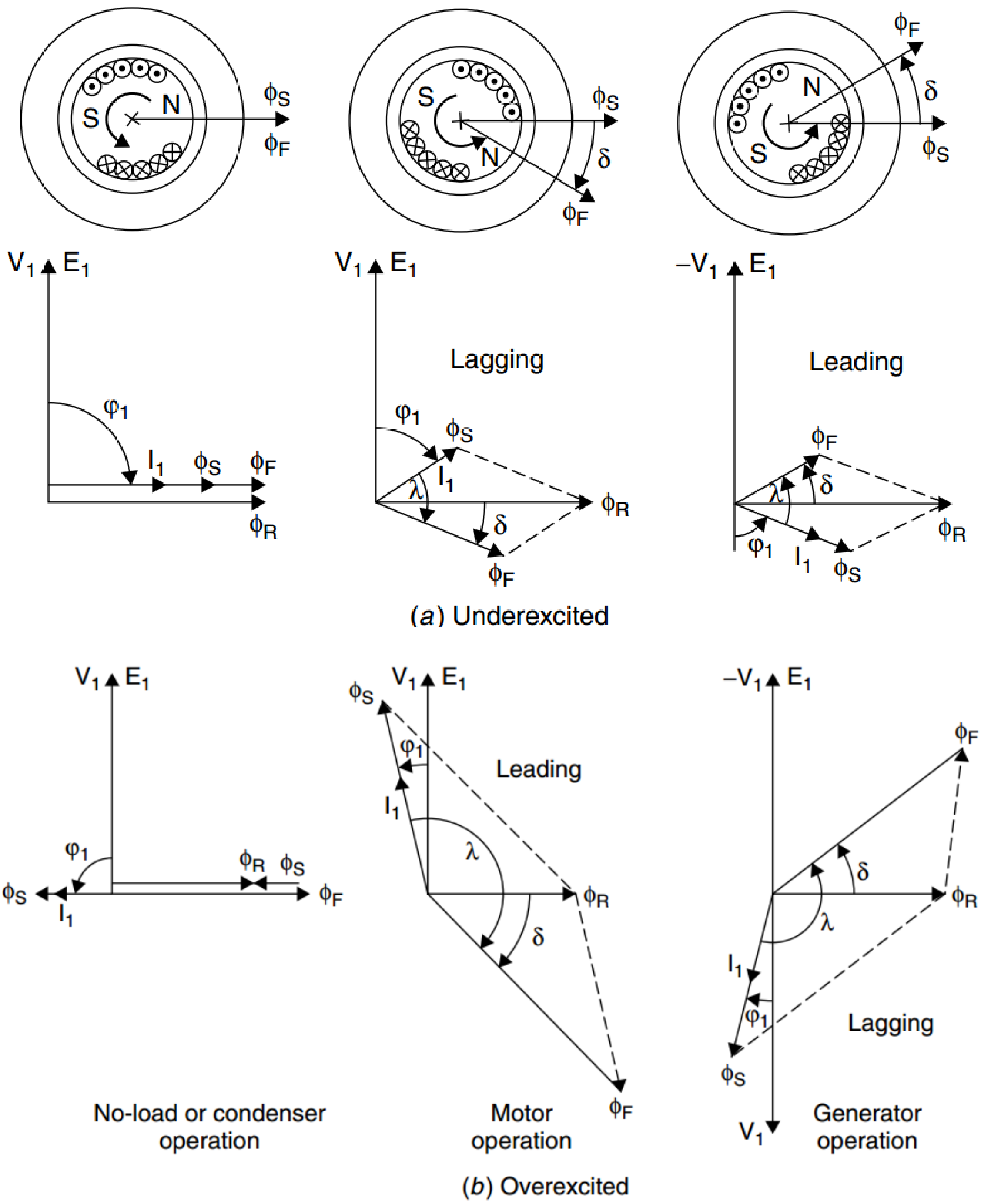
Operation concept

- The rotor is supplied by DC current I_f that generates a DC flux Φ_f.
- The rotor is driven by a turbine with a constant speed of n_s.
- The rotating field flux induces a voltage in the stator winding.
- The frequency of the induced voltage depends upon the speed.

Operation (two poles)



- The frequency - speed relation is $f = (p / 120)\, n = p\, n / 120$
  p is the number of poles.
- Typical rotor speeds are 3600 rpm for 2-pole, 1800 rpm for 4 pole and 450 rpm for 16 poles.



Phasor diagrams for a synchronous cylindrical-rotor *ideal* machine.

- **The rms. value of the induced voltages are:**

$$E_{rms} = \frac{k_w \, \omega \, N_a \, \Phi_f}{\sqrt{2}} = 4.44 \;\; f \; N_a \; \Phi_f \; k_w$$

k_w = 0.85-0.95 is the winding factor.

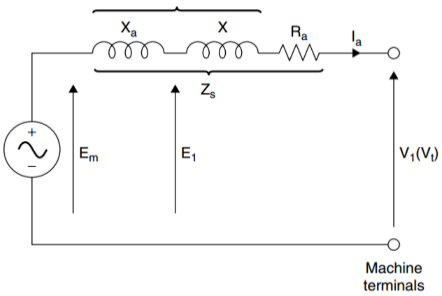
Armature Reaction in Synchronous Machines

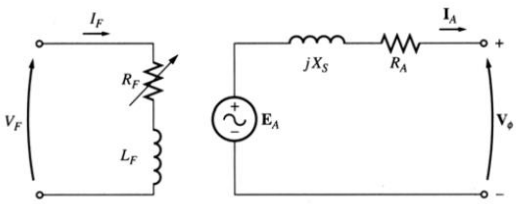
Armature reaction refers to
• The influence on the magnetic field in the air gap when the phase windings a, b, and c on the stator are connected across a load.
• The flux produced by the armature winding reacts with the flux set up by the poles on the rotor, causing the total flux to change.

What is the relationship between the two voltages?
The answer to these questions yields the equivalent circuit model of a synchronous generator.
There are a number of factors that cause the difference between EA and Vt:
1. The distortion of the air-gap magnetic field by the current flowing in the stator, called armature reaction.
2. The self-inductance of the armature coils.
3. The resistance of the armature coils.
4. The effect of salient-pole rotor shapes.

Synchronous Generators Equivalent Circuit (round rotor)

1) DC current in the field winding produces the main flux, ϕ_f.
2) ϕ_f induces an emf, E_G, in the armature winding.
3) Depending on the load condition, the armature current I_A is established. In the following discussions, it is assumed to be a lagging power factor.
4) I_A produces its own flux due to armature reaction, E_{AR} is the induced emf by ϕ_{AR}.
5) The resulting phasor, $E_{resultant} = E_G + E_{AR}$ is the "true" induced emf that is available.





If the machine is 3 phase, the same equivalent circuit is used. After solving the single-phase circuit, then proper 3 phase values (Line-line voltage or 3-pahse power) should be calculated.

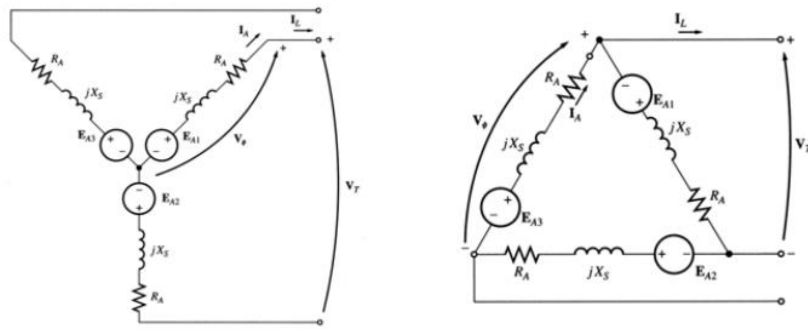
Phasor Diagrams (single phase):

$$V_t = E_A - I_A jX_A - I_A jX_{AR} - I_A R_A = E_A - jX_s I_A - I_A R_A$$

$$V_t = E_A - I_A\left(R_A + jX_s\right)$$

where, $(X_{AR} + X_A)$ = synchronous reactance, X_s.

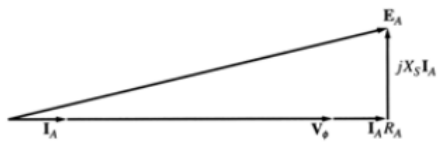
A synchronous generator can be Y- or Δ-connected:



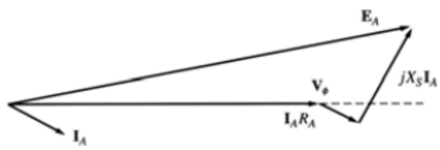
- ## Phasor diagram of a synchronous generator:-

Since the voltages in a synchronous generator are AC voltages, they are usually expressed as phasors. A vector plot of voltages and currents within one phase is called a phasor diagram.

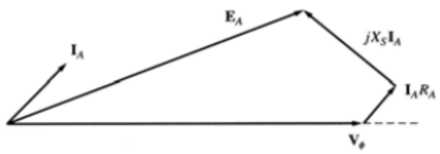
A phasor diagram of a synchronous generator with a unity power factor (resistive load) ⟶



Lagging power factor (inductive load): a larger than for leading PF internal generated voltage E_A is needed to form the same phase voltage.



Leading power factor (capacitive load).



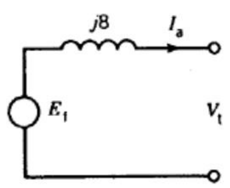
For a given field current and magnitude of load current, the terminal voltage is lower for lagging loads and higher for leading loads.

Example:-

A 3ϖ, 5 kVA, 208 V, four-pole, 60 Hz, star-connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 8Ω per phase at rated terminal voltage. Determine the excitation voltage and the power angle when the machine is delivering rated kVA at 0.8 PF lagging. Draw the phasor diagram for this condition.

Solution

The per-phase equivalent circuit for the synchronous generator



$$V_t = \frac{208}{\sqrt{3}} = 120 \text{ V/phase}$$

Stator current at rated kVA;

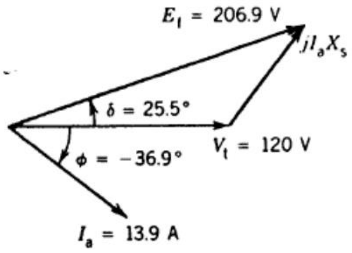
$$I_a = \frac{5000}{\sqrt{3} \times 208} = 13.9 \text{ A}$$

$$\phi = -36.9^\circ \quad \text{for lagging pf of 0.8}$$

$$E_f = V_t\angle 0^\circ + I_a jX_s$$
$$= 120\angle 0^\circ + 13.9\angle -36.9^\circ \cdot 8\angle 90^\circ$$
$$= 206.9\angle 25.5^\circ$$

Excitation voltage $E_f = 206.9$ V/phase

Power angle $\delta = +25.5^\circ$



EXAMPLE:-

A four pole, three-phase synchronous generator is rated 250 MVA, its terminal voltage is 24 kV, the synchronous reactance is: 125%.

- Calculate the synchronous reactance in ohm.
- Calculate the rated current and the line to ground terminal voltage.
- Draw the equivalent circuit.
- Calculate the induced voltage, Ef at rated load and pf = 0.8 lag.

(Ans: X_{syn}=2.88Ω, I_g=6.01∟-36.87°KA, E_{gn}=27.93∟29.74KV)

• Power and torque in synchronous generators:-

A synchronous generator needs to be connected to a prime mover whose speed is reasonably constant (to ensure constant frequency of the generated voltage) for various loads.

The applied mechanical power

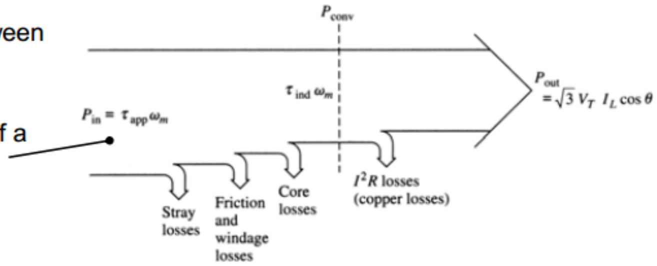
$$P_{in} = \tau_{app}\omega_m$$

is partially converted to electricity

$$P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma$$

Where γ is the angle between E_A and I_A.

The power-flow diagram of a synchronous generator.



The real output power of the synchronous generator is

$$P_{out} = \sqrt{3}V_T I_L \cos\theta = 3V_\phi I_A \cos\theta$$

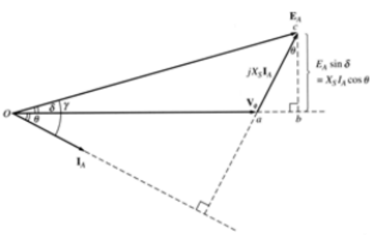
The reactive output power of the synchronous generator is

$$Q_{out} = \sqrt{3}V_T I_L \sin\theta = 3V_\phi I_A \sin\theta$$

Recall that the power factor angle θ is the angle between V_ϕ and I_A and **not** the angle between V_T and I_L.

In real synchronous machines of any size, the armature resistance $R_A \ll X_S$ and, therefore, the armature resistance can be ignored. Thus, a simplified phasor diagram indicates that

$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S} \qquad (7.23.3)$$



Then the real output power of the synchronous generator can be approximated as

$$P_{out} \approx \frac{3V_\phi E_A \sin\delta}{X_S}$$

We observe that electrical losses are assumed to be zero since the resistance is neglected. Therefore:

$$P_{conv} \approx P_{out}$$

Here δ is the torque angle of the machine – the angle between V_ϕ and E_A.

The maximum power can be supplied by the generator when $\delta = 90^0$:

$$P_{\max} = \frac{3V_\phi E_A}{X_S}$$

the induced torque is

$$\tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_S}$$

EXAMPLE:-

The internal generated voltage of a 2-pole, □-connected, 60 Hz, three phase synchronous generator is 14.4 kV, and the terminal voltage is 12.8 kV. The synchronous reactance of this machine is 4 □, and the armature resistance can be ignored. *EA,VT.*

(a) If the torque angle of the generator δ = 18°, how much power is being supplied by this generator at the current time?

(b) What is the power factor of the generator at this time?

(c) Sketch the phasor diagram under these circumstances.

(d) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at these conditions?

SOLUTION

(a) If resistance is ignored, the output power from this generator is given by

$$P = \frac{3V_\phi E_A}{X_S}\sin\delta = \frac{3(12.8\text{ kV})(14.4\text{ kV})}{4\ \Omega}\sin 18° = 42.7\text{ MW}$$

(b) The phase current flowing in this generator can be calculated from

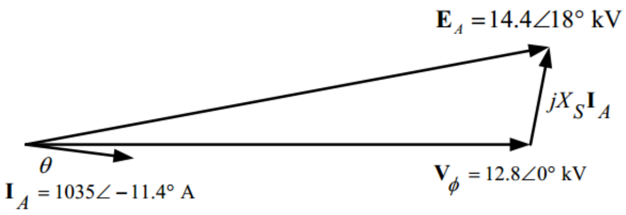
$$\mathbf{E}_A = \mathbf{V}_\phi + jX_S\mathbf{I}_A$$

$$\mathbf{I}_A = \frac{\mathbf{E}_A - \mathbf{V}_\phi}{jX_S}$$

$$\mathbf{I}_A = \frac{14.4\angle 18°\text{ kV} - 12.8\angle 0°\text{ kV}}{j4\ \Omega} = 1135\angle -11.4°\text{ A}$$

Therefore the impedance angle $\theta = 11.4°$, and the power factor is $\cos(11.4°) = 0.98$ lagging.

(c) The phasor diagram is



(d) The induced torque is given by the equation

$$P_{\text{conv}} = \tau_{\text{ind}}\omega_m$$

With no losses,

$$\tau_{\text{app}} = \tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{42.7 \text{ MW}}{2\pi(60 \text{ hz})} = 113{,}300 \text{ N•m}$$

EXAMPLE:-

A 100-MVA, 14.4-kV, 0.8-PF-lagging, 50-Hz, two-pole, Y-connected synchronous generator has a per unit synchronous reactance of 1.1 and a per-unit armature resistance of 0.011. (a) What are its synchronous reactance and armature resistance in ohms? (b) What is the magnitude of the internal generated voltage EA at the rated conditions? What is its torque angle □ at these conditions? (c) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at full load?

SOLUTION The base phase voltage of this generator is $V_{\phi,\text{base}} = 14{,}400/\sqrt{3} = 8314$ V. Therefore, the base impedance of the generator is

$$Z_{\text{base}} = \frac{3\,V_{\phi,\text{base}}{}^2}{S_{\text{base}}} = \frac{3(8314 \text{ V})^2}{100{,}000{,}000 \text{ VA}} = 2.074\ \Omega$$

(a) The generator impedance in ohms are:

$$R_A = (0.011)(2.074\ \Omega) = 0.0228\ \Omega$$

$$X_S = (1.1)(2.074\ \Omega) = 2.281\ \Omega$$

(b) The rated armature current is

$$I_A = I_L = \frac{S}{\sqrt{3}\,V_T} = \frac{100 \text{ MVA}}{\sqrt{3}(14.4 \text{ kV})} = 4009 \text{ A}$$

The power factor is 0.8 lagging, so $\mathbf{I}_A = 4009\angle -36.87°$ A. Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$
$$\mathbf{E}_A = 8314\angle 0° + (0.0228\ \Omega)(4009\angle -36.87° \text{ A}) + j(2.281\ \Omega)(4009\angle -36.87° \text{ A})$$
$$\mathbf{E}_A = 15{,}660\angle 27.6° \text{ V}$$

Therefore, the magnitude of the internal generated voltage E_A = 15,660 V, and the torque angle δ = 27.6°.

(c) Ignoring losses, the input power would equal the output power. Since

$$P_{\text{OUT}} = (0.8)(100 \text{ MVA}) = 80 \text{ MW}$$

and

$$n_{\text{sync}} = \frac{120 f_{se}}{P} = \frac{120(50 \text{ Hz})}{2} = 3000 \text{ r/min}$$

the applied torque would be

$$\tau_{\text{app}} = \tau_{\text{ind}} = \frac{80{,}000{,}000 \text{ W}}{(3000 \text{ r/min})(2\pi \text{ rad/r})(1 \text{ min}/60 \text{ s})} = 254{,}700 \text{ N}\cdot\text{m}$$

Machine Losses:-

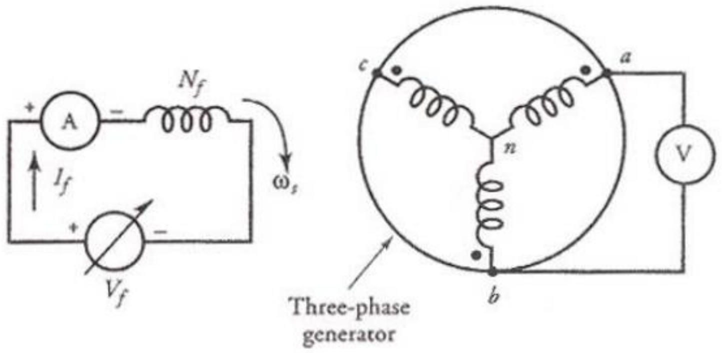
Winding Losses (Copper Losses).
•1^2R stator loss
. 1^2R rotor loss
• Eddy and circulating current loss in winding (parasitic currents induced in the windings)
Iron Losses.
• Mainly stator losses due to hysteresis loss and eddy current loss in stator laminations
Parasitic Eddy Losses.

. Induced currents in all metallic component (bolts, frame. etc.)
. Friction and windage loss
. Losses in fans, rotor and stator cooling vents
. Losses in bearings
Exogenous Losses.
. Losses in auxiliary equipment
Excitation
Lubrication oil pumps
H2 seal oil pumps
112 and water cooling pumps
And so on
. Iso-phase or lead losses

Synchronous Generator Tests

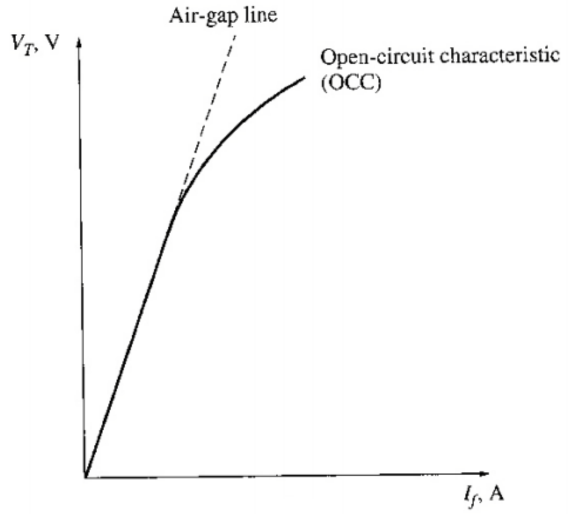
To obtain the parameters of a synchronous generator, we perform three simple tests as described below.

1. **The Resistance Test**:-
This test is conducted to measure-winding resistance of a synchronous generator when it is at rest and the field winding is open. The resistance is measured between two lines at a time and the average of the three resistance readings is taken to be the measured value of the resistance from line to line. If the generator is Y connected, the per-phase resistance is
Ra = 0.5 RL
2. **The Open-Circuit Test**:-
The open-circuit test, or the no-load test, is performed by
a) Generator is rotated at the rated speed.
b) No load is connected at the terminals.
c) Field current is increased from 0 to maximum.
d) Record values of the terminal voltage and field current value.



With the terminals open, IA=0, so EA = Vφ. It is thus possible to construct a plot of EA or VT vs IF graph. This plot is called open-circuit characteristic (OCC) of a generator. With this

characteristic, it is possible to find the internal generated voltage of the generator for any given field current.
The OCC follows a straight-line relation as long as the magnetic circuit of the synchronous generator does not saturate. Since, in the linear region, most of the applied mmf is consumed by the air-gap, the straight line is appropriately called the air-gap line.

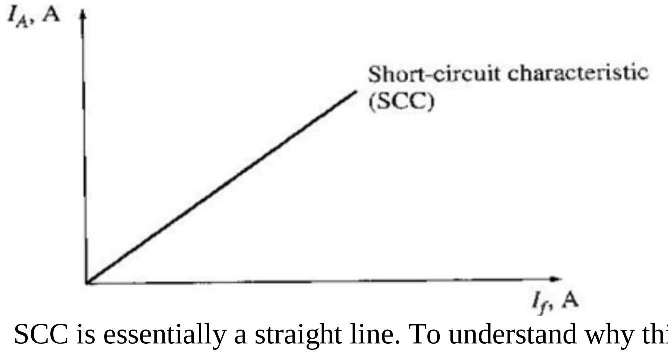


Open-circuit characteristic (OCC) of a generator

3. **The Short-Circuit Test**:-

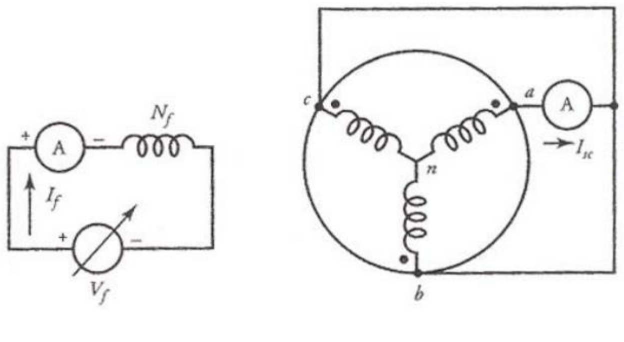
The short-circuit test provides information about the current capabilities of a synchronous generator. It is performed by;

a. Generator is rotated at rated speed.
b. Adjust field current to 0
c. Short circuit the terminals.
d. Measure armature current or line current as the field current is increased.



SCC is essentially a straight line. To understand why this characteristic is a straight line, look at the equivalent circuit below when the terminals are short circuited.

- When the terminals are short circuited, the armature current IA is:



$$I_A = \frac{E_A}{R_A + jX_S}$$

➔ ***From both tests,*** here we can find the internal machine impedance (E_A from OCC, I_A from SCC):

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

Since $X_s >> R_A$, the equation reduces to:

$$X_s \approx \frac{E_A}{I_A} = \frac{V_{\phi oc}}{I_A}$$

Short Circuit Ratio

Ratio of the field current required for the rated voltage at open circuit to the field current required for rated armature current at short circuit.

$$SCR = \frac{I_{f,OC}}{I_{f,SC}}$$

$$So, SCR = \frac{1}{X_s}$$

Example. A 200-kVA, 480-V, 50-Hz, Y-connected synchronous generator With a rated field current of 5 A was tested, and the following data were taken:

1. Vt. oc at the rated IF was measured to be 540 V.
2. IL. SC at the rated IF was found to be 300 A.
3. When a de voltage of 10 V was applied to two of the terminals, a current of 25 A was measured. Find the values of the armature resistance and the approximate synchronous reactance in ohms that would be used in the generator model at the rated conditions.

Solution

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings. Therefore, the resistance is given by

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{V_{DC}}{2I_{DC}} = \frac{10\text{ V}}{(2)(25\text{ A})} = 0.2\ \Omega$$

The internal generated voltage at the rated field current is equal to

$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}}$$

$$= \frac{540\text{ V}}{\sqrt{3}} = 311.8\text{ V}$$

The short-circuit current I_A is just equal to the line current, since the generator is Y-connected:

$$I_{A,SC} = I_{L,SC} = 300\text{ A}$$

$$X_S = \frac{E_A}{I_A} = \frac{311.8\ V}{300\ A} = 1.04\ \Omega$$

$$\sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = \frac{311.8\ V}{300\ A}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = 1.039\ \Omega$$

$$0.04 + X_S^2 = 1.08$$

$$X_S^2 = 1.04$$

$$X_S = 1.02\ \Omega$$

Example:- A 480 V, 50 Hz, Y-connected six-pole synchronous generator has a per-phase synchronous reactance of 1.0 **Ω**. Its full-load armature current is 60 A at 0.8 PF lagging. Its friction and windage losses are 1.5 kW and core losses are 1.0 kW at 60 Hz at full load. Assume that the armature resistance (and, therefore, the I2R losses) can be ignored. The field current has been adjusted such that the no load terminal voltage is 480 V.

a. What is the speed of rotation of this generator?

b. What is the terminal voltage of the generator if

It is loaded with the rated current at 0.8 PF lagging & 0.8 PF leading &1.0 PF?

c. What is the efficiency of this generator (ignoring the unknown electrical losses) when it is operating at the rated current and 0.8 PF lagging?

d. How much shaft torque must be applied by the prime mover at the full load?
How large is the induced counter torque?

e. What is the voltage regulation of this generator at 0.8 PF lagging? At 1.0 PF? At 0.8 PF leading?

Solution:-

Since the generator is Y-connected, its phase voltage is

$$V_\phi = V_T / \sqrt{3} = 277\ V$$

At no load, the armature current $I_A = 0$ and the internal generated voltage is $E_A =$ 277 V and it is constant since the field current was initially adjusted that way.

a. The speed of rotation of a synchronous generator is

$$n_m = \frac{120}{P} f_e = \frac{120}{6} 50 = 1000\ rpm$$

which is $$\omega_m = \frac{1000}{60} 2\pi = 104.7\ rad/s$$

b.1. For the generator at the rated current and the 0.8 PF lagging, the phasor diagram is shown. The phase voltage is at 0^0, the magnitude of E_A is 277 V, and that $jX_S I_A = j \cdot 1 \cdot 60\angle -36.87° = 60\angle 53.13°$

Two unknown quantities are the magnitude of V_ϕ and the angle δ of E_A. From the phasor diagram:

$$E_A^2 = \left(V_\phi + X_S I_A \sin\theta\right)^2 + \left(X_S I_A \cos\theta\right)^2$$

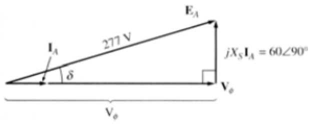
Then:

$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta\right)^2} - X_S I_A \sin\theta = 236.8\ V$$

Since the generator is Y-connected,

$$V_T = \sqrt{3}V_\phi = 410\ V$$

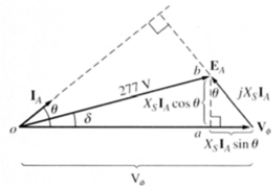
b.2. For the generator at the rated current and the 1.0 PF, the phasor diagram is shown. Then:



$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta\right)^2} - X_S I_A \sin\theta = 270.4\ V$$

and $$V_T = \sqrt{3}V_\phi = 468.4\ V$$

b.3. For the generator at the rated current and the 0.8 PF leading, the phasor diagram is shown. Then:



$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta\right)^2} - X_S I_A \sin\theta = 308.8\ V$$

and $$V_T = \sqrt{3}V_\phi = 535\ V$$

The induced countertorque of the generator is

$$\tau_{app} = \frac{P_{conv}}{\omega_m} = \frac{34.1}{125.7} = 271.3\ \ N\text{-}m$$

e. The voltage regulation of the generator is

Lagging PF: $$VR = \frac{480-410}{410}\cdot 100\% = 17.1\%$$

Unity PF: $$VR = \frac{480-468}{468}\cdot 100\% = 2.6\%$$

Lagging PF: $$VR = \frac{480-535}{535}\cdot 100\% = -10.3\%$$

c. The output power of the generator at 60 A and 0.8 PF lagging is

$$P_{out} = 3V_\phi I_A \cos\theta = 3\cdot 236.8\cdot 60\cdot 0.8 = 34.1\ kW$$

The mechanical input power is given by

$$P_{in} = P_{out} + P_{elec\ loss} + P_{core\ loss} + P_{mech\ loss} = 34.1 + 0 + 1.0 + 1.5 = 36.6\ kW$$

The efficiency is

$$\eta = \frac{P_{out}}{P_{in}}\cdot 100\ \% = \frac{34.1}{36.6}\cdot 100\% = 93.2\%$$

d. The input torque of the generator is

$$\tau_{app} = \frac{P_{in}}{\omega_m} = \frac{36.6}{125.7} = 291.2\ \ N\text{-}m$$

Example: A 3-phase synchronous generator produces an open-circuit line voltage of 6928 V when the do exciting current is 50 A. The ac terminals are then short—circuited, and the three line current are found to be 800 A.
a. Calculate the synchronous reactance per phase.
b. Calculate the terminal voltage if three 12 .0 resistors are connected in wye across the terminals.

Solution:

a. The line-to-neutral induced voltage is

$$E_o = E_L / \sqrt{3} = 6928 / \sqrt{3} = 4000V$$

When the terminals are short-circuited, the only impedance limiting the current flow is that due to the synchronous reactance. Consequently,

$$X_S = E_o / I = 4000 / 80 = 5\Omega$$

b. The equivalent circuit per phase is shown in Fig. 1

The impedance of the circuit is:

$$Z = \sqrt{R^2 + X_S^2} = \sqrt{12^2 + 5^2} = 13\Omega$$

The current is :

$$I = E_o / Z = 4000 / 13 = 308A$$

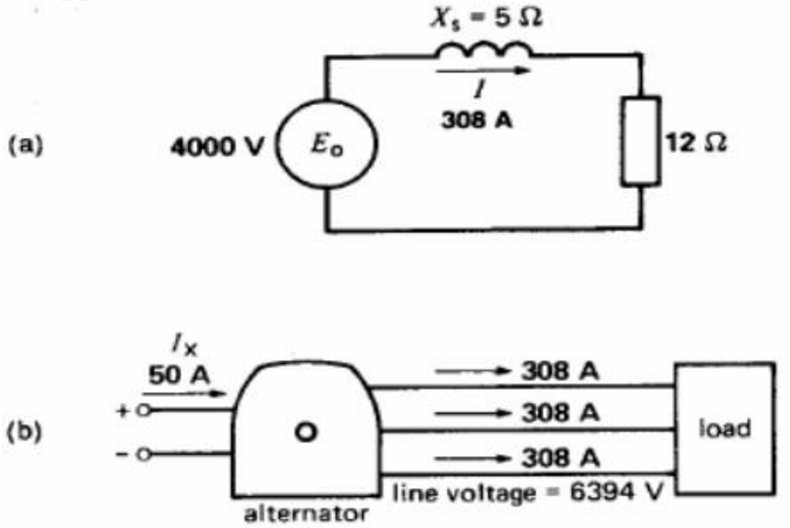
The voltage across the load resistor is

$$E = IR = 308 * 12 = 3696\ V$$

The line voltage under load is:

$$E_L = \sqrt{3}E = \sqrt{3} * 3696 = 6402\ V$$

The schematic diagram of Fig. 1 helps us visualize what is happening in the actual circuit.



Example 4–1. A 200-kVA, 480-V, 50-Hz, Y-connected synchronous generator with a rated field current of 5 A was tested, and the following data were taken:

1. $V_{T,OC}$ at the rated I_F was measured to be 540 V.
2. $I_{L,SC}$ at the rated I_F was found to be 300 A.
3. When a dc voltage of 10 V was applied to two of the terminals, a current of 25 A was measured.

Find the values of the armature resistance and the approximate synchronous reactance in ohms that would be used in the generator model at the rated conditions.

Solution

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings. Therefore, the resistance is given by

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{V_{DC}}{2I_{DC}} = \frac{10\ V}{(2)(25\ A)} = 0.2\ \Omega$$

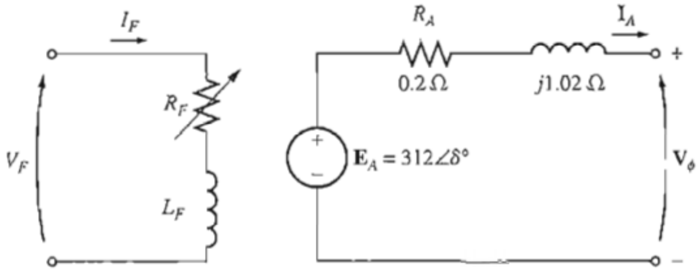
The internal generated voltage at the rated field current is equal to

$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}}$$

$$= \frac{540\ V}{\sqrt{3}} = 311.8\ V$$

The short-circuit current I_A is just equal to the line current, since the generator is Y-connected:

$$I_{A,SC} = I_{L,SC} = 300\ A$$



$$\sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = \frac{311.8\ V}{300\ A}$$

$$\sqrt{(0.2\ \Omega)^2 + X_S^2} = 1.039\ \Omega$$

$$0.04 + X_S^2 = 1.08$$

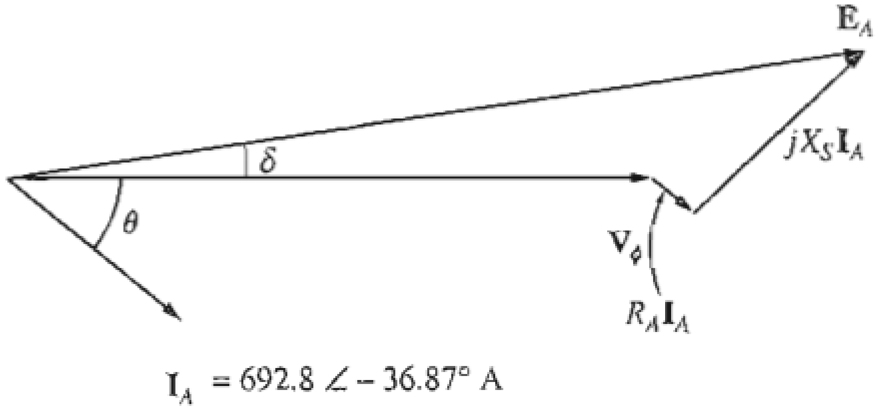
$$X_S^2 = 1.04$$

$$X_S = 1.02\ \Omega$$

How much effect did the inclusion of R_A have on the estimate of X_S? Not much. If X_S is evaluated by Equation (4–26), the result is

$$X_S = \frac{E_A}{I_A} = \frac{311.8\ V}{300\ A} = 1.04\ \Omega$$

Example 4–2. A 480-V, 60-Hz, Δ-connected, four-pole synchronous generator has the OCC shown in Figure 4–23a. This generator has a synchronous reactance of 0.1 Ω and an armature resistance of 0.015 Ω. At full load, the machine supplies 1200 A at 0.8 PF lagging. Under full-load conditions, the friction and windage losses are 40 kW, and the core losses are 30 kW. Ignore any field circuit losses.



(b)

(a) What is the speed of rotation of this generator?

(b) How much field current must be supplied to the generator to make the terminal voltage 480 V at no load?

(c) If the generator is now connected to a load and the load draws 1200 A at 0.8 PF lagging, how much field current will be required to keep the terminal voltage equal to 480 V?

(d) How much power is the generator now supplying? How much power is supplied to the generator by the prime mover? What is this machine's overall efficiency?

(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?

(f) Finally, suppose that the generator is connected to a load drawing 1200 A at 0.8 PF *leading*. How much field current would be required to keep V_T at 480 V?

Solution

This synchronous generator is Δ-connected, so its phase voltage is equal to its line voltage $V_\phi = V_T$, while its phase current is related to its line current by the equation $I_L = \sqrt{3} I_\phi$.

(a) The relationship between the electrical frequency produced by a synchronous generator and the mechanical rate of shaft rotation is given by Equation (3–34):

$$f_{se} = \frac{n_m P}{120} \qquad (3\text{–}34)$$

Therefore,

$$n_m = \frac{120 f_{se}}{P}$$

$$= \frac{120(60\text{ Hz})}{4\text{ poles}} = 1800\text{ r/min}$$

(b) In this machine, $V_T = V_\phi$. Since the generator is at no load, $\mathbf{I}_A = 0$ and $\mathbf{E}_A = \mathbf{V}_\phi$. Therefore, $V_T = V_\phi = E_A = 480$ V, and from the open-circuit characteristic, $I_F = 4.5$ A.

(c) If the generator is supplying 1200 A, then the armature current in the machine is

$$I_A = \frac{1200\text{ A}}{\sqrt{3}} = 692.8\text{ A}$$

The phasor diagram for this generator is shown in Figure 4–23b. If the terminal voltage is adjusted to be 480 V, the size of the internal generated voltage $\mathbf{E}_A$ is given by

$$\begin{aligned}
\mathbf{E}_A &= \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A \\
&= 480\angle 0°\text{ V} + (0.015\ \Omega)(692.8\angle -36.87°\text{ A}) + (j0.1\ \Omega)(692.8\angle -36.87°\text{ A}) \\
&= 480\angle 0°\text{ V} + 10.39\angle -36.87°\text{ V} + 69.28\angle 53.13°\text{ V} \\
&= 529.9 + j49.2\text{ V} = 532\angle 5.3°\text{ V}
\end{aligned}$$

To keep the terminal voltage at 480 V, $\mathbf{E}_A$ must be adjusted to 532 V. From Figure 4–23, the required field current is 5.7 A.

(d) The power that the generator is now supplying can be found from Equation

$$\begin{aligned}
&= \sqrt{3}(480\text{ V})(1200\text{ A})\cos 36.87° \\
&= 798\text{ kW}
\end{aligned}$$

To determine the power input to the generator, use the power-flow diagram (Figure 4–15). From the power-flow diagram, the mechanical input power is given by

$$P_{in} = P_{out} + P_{elec\ loss} + P_{core\ loss} + P_{mech\ loss} + P_{stray\ loss}$$

The stray losses were not specified here, so they will be ignored. In this generator, the electrical losses are

$$\begin{aligned}
P_{elec\ loss} &= 3I_A^2R_A \\
&= 3(692.8\text{ A})^2(0.015\ \Omega) = 21.6\text{ kW}
\end{aligned}$$

The core losses are 30 kW, and the friction and windage losses are 40 kW, so the total input power to the generator is

$$P_{in} = 798\text{ kW} + 21.6\text{ kW} + 30\text{ kW} + 40\text{ kW} = 889.6\text{ kW}$$

Therefore, the machine's overall efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{798\text{ kW}}{889.6\text{ kW}} \times 100\% = 89.75\%$$

(e) If the generator's load were suddenly disconnected from the line, the current $\mathbf{I}_A$ would drop to zero, making $\mathbf{E}_A = \mathbf{V}_\phi$. Since the field current has not changed, $|\mathbf{E}_A|$ has not changed and $\mathbf{V}_\phi$ and V_T must rise to equal $\mathbf{E}_A$. Therefore, if the load were suddenly dropped, the terminal voltage of the generator would rise to 532 V.

(*f*) If the generator were loaded down with 1200 A at 0.8 PF leading while the terminal voltage was 480 V, then the internal generated voltage would have to be

$$\begin{aligned} \mathbf{E}_A &= \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A \\ &= 480\angle 0^\circ \text{ V} + (0.015\ \Omega)(692.8\angle 36.87^\circ \text{ A}) + (j0.1\ \Omega)(692.8\angle 36.87^\circ \text{ A}) \\ &= 480\angle 0^\circ \text{ V} + 10.39\angle 36.87^\circ \text{ V} + 69.28\angle 126.87^\circ \text{ V} \\ &= 446.7 + j61.7 \text{ V} = 451\angle 7.1^\circ \text{ V} \end{aligned}$$

Therefore, the internal generated voltage E_A must be adjusted to provide 451 V if V_T is to remain 480 V. Using the open-circuit characteristic, the field current would have to be adjusted to 4.1 A.

Which type of load |(leading or lagging) needed a larger field current to maintain the rated voltage? Which type of load (leading or lagging) placed more thermal stress on the generator? Why?

Voltage regulation of Alternator

The voltage regulation of an Alternator is defined as the change in terminal voltage from no-load to load condition expressed as per-unit or percentage of terminal voltage at load condition; the speed and excitation conditions remaining same.

$$\text{Voltage Regulation, V. R.} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

EXAMPLE . *A 3-phase, 1500 kVA, star-connected, 50-Hz, 2300 V alternator has a resistance between each pair of terminals as measured by direct current is 0.16 Ω. Assume that the effective resistance is 1.5 times the ohmic resistance. A field current of 70 A produces a short-circuit current equal to full-load current of 376 A in each line. The same field current produces an e.m.f. of 700 V on open circuit. Determine the synchronous reactance of the machine and its full load regulation at 0.8 power factor lagging.*

SOLUTION. $Z_s = \dfrac{\text{open-circuit e.m.f. per phase}}{\text{short circuit armature current}}$

$$= \frac{(700/\sqrt{3})}{376} = 1.075\ \Omega$$

Ohmic resistance per phase $= \dfrac{0.16}{2} = 0.08\ \Omega$

Effective resistance per phase

$$R_a = 1.5 \times 0.08 = 0.12\ \Omega$$

Synchronous reactance

$$X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{1.075^2 - 0.12^2} = 1.068\ \Omega$$

$$S_{3\Phi} = \sqrt{3}\ V_L I_L$$

$$1500 \times 10^3 = \sqrt{3} \times 2300 I_L,\ I_L = 376\ \text{A}$$

Rated voltage per phase

$$V_p = 2300\sqrt{3} = 1328\ \text{V}$$

Phase current $I_{ap} = I_L = 376$ A

$$\mathbf{E_p} = \mathbf{V_p} + \mathbf{I_{ap}Z_s}$$

Let $\mathbf{V_p}$ be taken as reference phasor :

$$\mathbf{V_p} = V_p \angle 0° = 1328\angle 0°\ \text{V} = 1328 + j0\ \text{V}$$

$$\mathbf{I_{ap}} = I_{ap} \angle -\cos^{-1} 0.8 = 376 \angle -36.87°\ \text{A}$$

$$\mathbf{Z_s} = R_a + jX_s = 0.12 + j1.068 = 1.075 \angle 83.59°\ \Omega$$

$$\mathbf{E_p} = 1328 + j0 + (376 \angle -36.87°)(1.075 \angle 83.59°) = 1328 + 404.2\angle 46.72°$$

$$= 1328 + 277.1 + j\,294.26 = 1605.1 + j294.26 = 1631 \angle 10.39°\ \text{V}$$

Percentage regulation

$$= \frac{E_p - V_p}{V_p} \times 100$$

$$= \frac{1631 - 1328}{1328} \times 100 = 22.8\%$$

Alternative method of calculating E_p

$$E_p = \sqrt{(V_p \cos\phi + I_a R_a)^2 + (V_p \sin\phi + I_a X_s)^2}$$

$$= \sqrt{(1328 \times 0.8 + 376 \times 0.12)^2 + (1328 \times 0.6 + 376 \times 1.068)^2} = 1631\ \text{V}$$

EXAMPLE . *A 3-phase, star-connected alternator is rated at 1600 kVA, 13500 V. The armature effective resistance and synchronous reactance are 1.5 Ω and 30 Ω respectively per phase. Calculate the percentage regulation for a load of 1280 kW at power factors of (a) 0.8 leading; (b) unity; (c) 0.8 lagging.*

SOLUTION. (*a*) $P_{3\phi} = \sqrt{3} V_L I_L \cos\phi$

$$1280 \times 10^3 = \sqrt{3} \times 13500 I_L \times 0.8$$

$$I_L = \frac{1280 \times 10^3}{\sqrt{3} \times 13500 \times 0.8} = 68.43 \text{ A} = I_a$$

$$\cos\phi = 0.8, \quad \sin\phi = 0.6$$

$$R_a = 1.5\ \Omega,\ X_s = 30\ \Omega, \quad V_p = \frac{13500}{\sqrt{3}} = 7794.5 \text{ V}$$

For leading power factor

$$E_p^2 = (V_p \cos\phi + I_a R_a)^2 + (-V_p \sin\phi + I_a X_s)^2$$

$$= (7794.5 \times 0.8 + 68.43 \times 1.5)^2 + (-7794.5 \times 0.6 + 68.43 \times 30)^2$$

$$= (6338)^2 + (-2623.8)^2$$

$$E_p = 6859.6 \text{ V}$$

$$\text{Voltage regulation} = \frac{E_p - V_p}{V_p} \times 100 = \frac{6859.6 - 7794.5}{7794.5} \times 100 = -11.99\%$$

(*b*) *Unity power factor*

$$\cos\phi = 1, \sin\phi = 0$$

$$P_{3\phi} = \sqrt{3} V_L I_L \cos\phi$$

$$1280 \times 10^3 = \sqrt{3} \times 13500 I_L \times 1$$

$$I_L = \frac{1280 \times 10^3}{\sqrt{3} \times 13500} = 54.74 A = I_a$$

$$E_p^2 = (V_p + I_a R_a)^2 + (I_a X_s)^2$$

$$= (7794.5 + 54.74 \times 1.5)^2 + (54.74 \times 30)^2 = (7876.6)^2 + (1642.2)^2$$

$$E_p = 8046 \text{ V}$$

Voltage regulation

$$= \frac{E_p - V_p}{V_p} \times 100 = \frac{8046 - 7794.5}{7794.5} \times 100 = 3.227\%$$

(*c*) *Power factor 0.8 lagging*

$$E_p^2 = (V_p \cos\phi + I_a R_a)^2 + (V_p \sin\phi + I_a X_s)^2$$

$$= (7794.5 \times 0.8 + 68.43 \times 1.5)^2 + (7794.5 \times 0.6 + 68.43 \times 30)^2$$

$$= (6338)^2 + (6729.6)^2$$

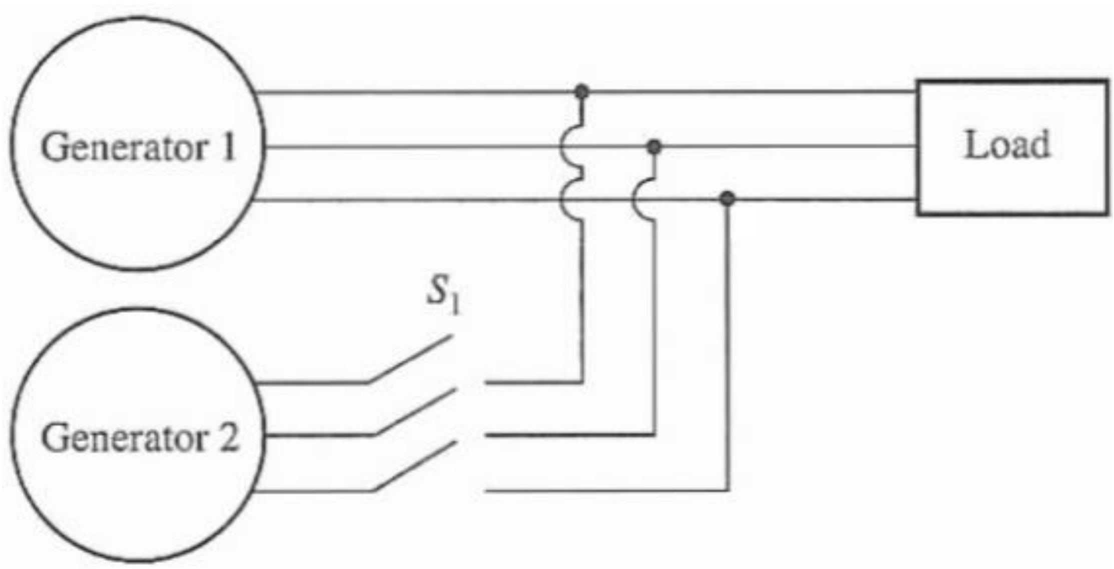
$$E_p = 9244.4 \text{ V}$$

$$\text{Voltage regulation} = \frac{E_p - V_p}{V_p} \times 100 = \frac{9244.4 - 7794.5}{7794.5} \times 100 = 18.6\%$$

PARALLEL OPERATION OF AC GENERATORS

In today's world, an isolated synchronous generator supplying its awn load independently of other generators is very rare. Such a situation is found in only a few out-of-the-way applications such as emergency generators. For all usual generator applications, there is more than one generator operating in parallel to supply the power demanded by the loads. An extreme example of this situation is the U.S. power grid, in which literally thousands of generators share the load on the system.

Why are synchronous generators operated in parallel?
1. Several generators can supply a bigger load than one machine by itself.
2. Having many generators increases the reliability of the power system, since the failure of anyone of them does not cause a total power loss to the load.
3. Having many generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.
4. If only one generator is used and it is not operating at near fun load, then it (will be relatively inefficient. With several smaller machines in parallel, it is possible to operate only a fraction of them. The ones that do operate are operating near full load and thus more efficiently.



- **The Conditions Required for Paralleling**:-

1. The rms line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of the two a phases must be equal.
4. The frequency of the new generator, called the oncoming generator, must be slightly higher than the frequency of the running system.

- These paralleling conditions require some explanation. Condition 1 is obvious- in order for two sets of voltages to be identical, they illustrate of course have the same rms magnitude of voltage. The voltage in phases a and a' will be
- Operation of Generators in Parallel with Large Power Systems When a synchronous generator is connected to a power system, the power system is often so large that nothing the operator of the generator does will have much of an effect on the power system. An example of this situation is the connection of a single generator to the U.S. power grid. The U.S. power grid is

so large that no reasonable action on the pat1 of the one generator can cause an observable change in overall grid frequency.

- To summarize, when a generator is operating in parallel with an infinite bus:

1. The frequency and terminal voltage of the generator are controlled by the system to which it is connected.

2. The governor set points of the generator control the real power supplied by the generator to the system.

3. The field current in the generator controls the reactive power supplied by the generator to the system.

To summarize, in the case of two generators operating together:

1. The system is constrained in that the total power supplied by the two generators together must equal the amount consumed by the load. Neither fs nor VT is constrained to be constant.

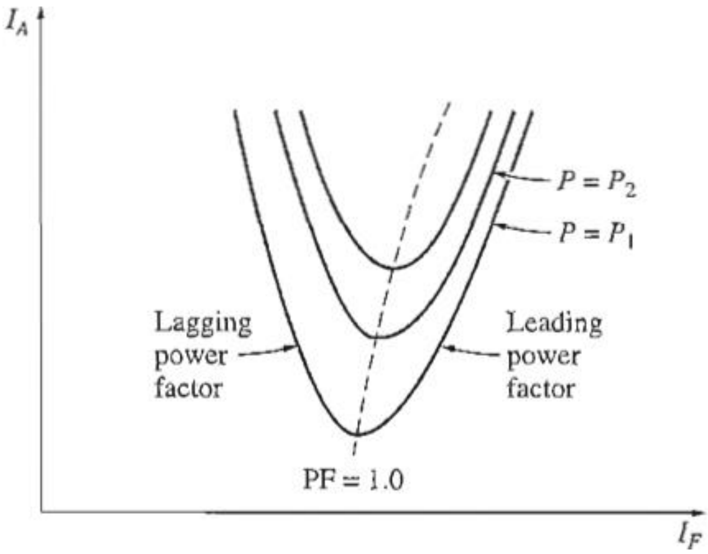
2. To adjust the real power sharing between generators without changing fs simultaneously increase the governor set points on one generator while decreasing the governor set points on the other. The machine whose governor set point was increased will assume more of the load.

3. To adjust fs without changing the real power sharing, simultaneously increase or decrease both generators' governor set points.

4. To adjust the reactive power sharing between generators without changing VT, simultaneously increase the field current on one generator while decreasing the field current on the other. The machine whose field current was increased will assume more of the reactive load.

5. To adjust Vr without changing the reactive power sharing, simultaneously increase or decrease both generators' field currents.

The Effect of Field Current Changes on a Synchronous Motor



A plot of IA versus IF for a synchronous motor is shown in Figure up Such a plot is called a synchronous motor V curve, for the obvious reason that it is shaped like the letter V. There are several V curves drawn, corresponding to different real power levels. For each curve, the minimum armature current occurs at unity power factor, when only real power is being supplied to the motor. At any other point on the curve, some reactive power is being supplied to or by the motor as well. For field Currents less than the value giving minimum lA, the armature current is lagging, consuming Q. For field currents greater than the value giving the minimum lA' the armature current is leading, supplying Q to the power system as a capacitor would. Therefore, by controlling the field current of a synchronous.

The Synchronous Motor and Power-Factor Correction

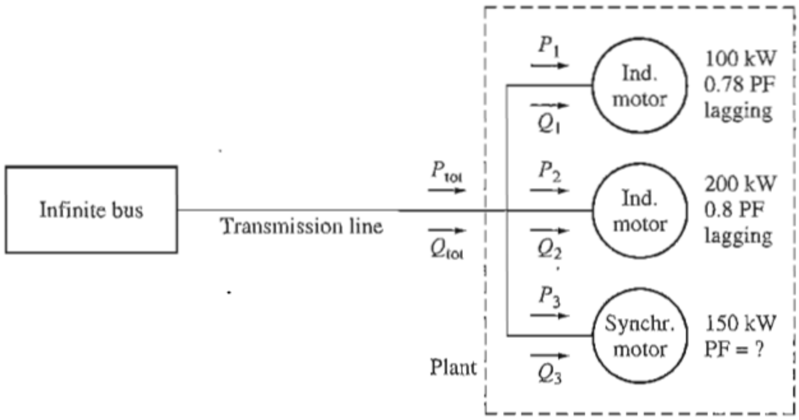


FIGURE 5–13

Example 5–3. The infinite bus in Figure 5–13 operates at 480 V. Load 1 is an induction motor consuming 100 kW at 0.78 PF lagging, and load 2 is an induction motor consuming 200 kW at 0.8 PF lagging. Load 3 is a synchronous motor whose real power consumption is 150 kW.

(a) If the synchronous motor is adjusted to operate at 0.85 PF lagging, what is the transmission line current in this system?

(b) If the synchronous motor is adjusted to operate at 0.85 PF leading, what is the transmission line current in this system?

(c) Assume that the transmission line losses are given by

$$P_{LL} = 3I_L^2 R_L \qquad \text{line loss}$$

where LL stands for line losses. How do the transmission losses compare in the two cases?

Solution

(a) In the first case, the real power of load 1 is 100 kW, and the reactive power of load 1 is

$$\begin{aligned} Q_1 &= P_1 \tan\theta \\ &= (100\text{ kW}) \tan(\cos^{-1} 0.78) = (100\text{ kW}) \tan 38.7° \\ &= 80.2\text{ kVAR} \end{aligned}$$

The real power of load 2 is 200 kW, and the reactive power of load 2 is

$$\begin{aligned} Q_2 &= P_2 \tan\theta \\ &= (200\text{ kW}) \tan(\cos^{-1} 0.80) = (200\text{ kW}) \tan 36.87° \\ &= 150\text{ kVAR} \end{aligned}$$

The real power load 3 is 150 kW, and the reactive power of load 3 is

$$\begin{aligned} Q_3 &= P_3 \tan\theta \\ &= (150\text{ kW}) \tan(\cos^{-1} 0.85) = (150\text{ kW}) \tan 31.8° \\ &= 93\text{ kVAR} \end{aligned}$$

Thus, the total real load is

$$\begin{aligned} P_{tot} &= P_1 + P_2 + P_3 \\ &= 100\text{ kW} + 200\text{ kW} + 150\text{ kW} = 450\text{ kW} \end{aligned}$$

and the total reactive load is

$$\begin{aligned} Q_{tot} &= Q_1 + Q_2 + Q_3 \\ &= 80.2\text{ kVAR} + 150\text{ kVAR} + 93\text{ kVAR} = 323.2\text{ kVAR} \end{aligned}$$

The equivalent system power factor is thus

$$\begin{aligned} \text{PF} &= \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{323.2\text{ kVAR}}{450\text{ kW}}\right) \\ &= \cos 35.7° = 0.812\text{ lagging} \end{aligned}$$

Finally, the line current is given by

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L \cos\theta} = \frac{450\text{ kW}}{\sqrt{3}(480\text{ V})(0.812)} = 667\text{ A}$$

(b) The real and reactive powers of loads 1 and 2 are unchanged, as is the real power of load 3. The reactive power of load 3 is

$$\begin{aligned} Q_3 &= P_3 \tan\theta \\ &= (150\text{ kW}) \tan(-\cos^{-1} 0.85) = (150\text{ kW}) \tan(-31.8°) \\ &= -93\text{ kVAR} \end{aligned}$$

Thus, the total real load is

$$\begin{aligned} P_{tot} &= P_1 + P_2 + P_3 \\ &= 100\text{ kW} + 200\text{ kW} + 150\text{ kW} = 450\text{ kW} \end{aligned}$$

and the total reactive load is

$$\begin{aligned} Q_{tot} &= Q_1 + Q_2 + Q_3 \\ &= 80.2\text{ kVAR} + 150\text{ kVAR} - 93\text{ kVAR} = 137.2\text{ kVAR} \end{aligned}$$

The equivalent system power factor is thus

$$\begin{aligned} \text{PF} &= \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{137.2\text{ kVAR}}{450\text{ kW}}\right) \\ &= \cos 16.96° = 0.957\text{ lagging} \end{aligned}$$

Finally, the line current is given by

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L \cos\theta} = \frac{450\ \text{kW}}{\sqrt{3}(480\ \text{V})(0.957)} = 566\ \text{A}$$

(c) The transmission losses in the first case are

$$P_{LL} = 3I_L^2 R_L = 3(667\ \text{A})^2 R_L = 1{,}344{,}700\ R_L$$

The transmission losses in the second case are

$$P_{LL} = 3I_L^2 R_L = 3(566\ \text{A})^2 R_L = 961{,}070\ R_L$$

Notice that in the second case the transmission power losses are 28 percent less than in the first case, while the power supplied to the loads is the same.

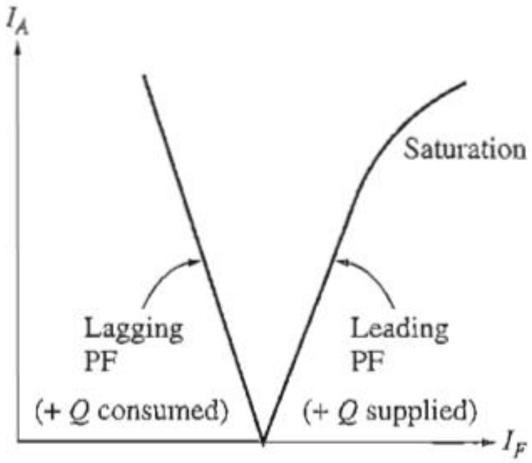
Overexcited synchronous motors on the system can be useful for the following reasons:

1. A leading load can supply some reactive power Q for nearby lagging loads, instead of it coming from the generator. Since the reactive power does not have to travel over the long and fairly high-resistance transmission lines, the transmission line current is reduced and the power system losses are much lower. (This was shown by the previous example.)

2. Since the transmission lines carry less current, they can be smaller for a given rated power flow. A lower equipment current rating reduces the cost of a power system significantly.

3. In addition, requiring a synchronous motor to operate with a leading power factor means that the motor must be run overexcited. This mode of operation increases the motor's maximum torque and reduces the chance of accidentally exceeding the pullout torque.

The use of synchronous motors or other equipment to increase the overall power factor of a power system is called power-factor correction. Since a synchronous motor can provide power-factor correction and lower power system costs, many loads that can accept a constant-speed motor (even though they do not necessarily need one) are driven by synchronous motors. Even though a synchronous motor may cost more than an induction motor on an individual basis, the ability to operate a synchronous motor at leading power factors for power-factor correction saves money for industrial plants. This results in the purchase and user of synchronous motors. Any synchronous motor that exists in a plant is run overexcited as a matter of course to achieve power-factor correction and to increase its pullout torque.



STARTING SYNCHRONOUS MOTOR

Three basic approaches can be used to safely start a synchronous motor:

1. Reduce the speed of the stator magnetic field to a low enough value that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field's rotation. This can be done by reducing the frequency of the applied electric power

2. Use an external prime mover to accelerate the synchronous motor up to synchronous speed. Go through the paralleling procedure, and bring the machine on the line as a generator. Then, turning off or disconnecting the prime mover will make the synchronous machine a motor.

3. Use damper windings. The function of damper windings and their use in motor starting torque

OBJECTIVE TESTS

1. The frequency of voltage generated by an alternator having 4-poles and rotating at 1800 rpm is ....hertz.

(a) 60 (b) 7200

(c) 120 (d) 450.

2. A 50-Hz alternator will run at the greatest possible speed if it is wound for .... poles.

(a) 8 (b) 6

(c) 4 (d) 2.

3. The main disadvantage of using short-pitch winding in alternators is that it

(a) reduces harmonics in the generated voltage

(b) reduces the total voltage around the armature coils

(c) produces asymmetry in the three phase windings

(d) increases Cu of end connections.

4. Three-phase alternators are invariably Y-connected because

(a) magnetic losses are minimized

(b) less turns of wire are required

(c) smaller conductors can be used

(d) higher terminal voltage is obtained.

5. The winding of a 4-pole alternator having 36 slots and a coil span of 1 to 8 is short-pitched by .... degrees.

(a) 140 (b) 80

(c) 20 (d) 40.

6. Squirrel-cage bars placed in the rotor pole faces of an alternator help reduce hunting

(a) above synchronous speed only

(b) below synchronous speed only

(c) above and below synchronous speeds both

(d) none of the above.

7. Regarding distribution factor of an armature winding of an alternator which statement is false?

(a) it decreases as the distribution of coils (slots/pole) increases

(b) higher its value, higher the induced e.m.f. per phase

(c) it is not affected by the type of winding either lap, or wave

(d) it is not affected by the number of turns per coil.

8. When speed of an alternator is changed from 3600 rpm. to 1800 rpm, the generated

emf/phases will become

(a) one-half (b) twice

(c) four times (d) one-fourth.

9. The magnitude of the three voltage drops in an alternator due to armature resistance, leakage reactance and armature reaction is solely determined by

(a) load current, Ia

(b) pf. of the load

(c) whether it is a lagging or leading pf. load

(d) field construction of the alternator.

10. Armature reaction in an alternator primarily affects

(a) rotor speed

(b) terminal voltage per phase

(c) frequency of armature current

(d) generated voltage per phase.

11. Under no-load condition, power drawn by the prime mover of an alternator goes to

(a) produce induced emf. in armature winding

(b) meet no-load losses

(c) produce power in the armature

(d) meet Cu losses both in armature and rotor windings.

12. As load pf. of an alternator becomes more leading, the value of generated voltage required to

give rated terminal voltage

(a) increases

(b) remains unchanged

(c) decreases

(d) varies with rotor speed.

13. With a load pf. of unity, the effect of armature reaction on the main-field flux of an alternator is

(a) distortional (b) magnetizing

(c) demagnetizing (d) nominal.

14. At lagging loads, armature reaction in an alternator is

(a) cross-magnetizing (b) demagnetizing

(c) non-effective (d) magnetizing.

15. At leading p.f., the armature flux in an alternator .... the rotor flux.

(a) opposes (b) aids

(c) distorts (d) does not affect.

16. The voltage regulation of an alternator having 0.75 leading pf. load, no-load induced emf. of 2400V and rated terminal voltage of 3000V is .... percent.

(a) 20 (b) − 20

(c) 150 (d) − 26.7

17. If, in a 3-φ alternator, a field current of 50A produces a full-load armature current of 200 A on short-circuit and 1730 V on open circuit, then its synchronous impedance is .... ohm.

(a) 8.66 (b) 4

(c) 5 (d) 34.6

18. The power factor of an alternator is determined by its

(a) speed

(b) load

(c) excitation

(d) prime mover.

19. For proper parallel operation, a.c. polyphase alternators must have the same

(a) speed (b) voltage rating

(c) kVA rating (d) excitation.

20. Of the following conditions, the one which does not have to be met by alternators working in

parallel is

(a) terminal voltage of each machine must be the same

(b) the machines must have the same phase rotation

(c) the machines must operate at the same frequency

(d) the machines must have equal ratings.

21. After wiring up two 3-φ alternators, you checked their frequency and voltage and found them to

be equal. Before connecting them in parallel, you would

(a) check turbine speed

(b) check phase rotation

(c) lubricate everything

(d) check steam pressure.

22. Zero power factor method of an alternator is used to find its

(a) efficiency

(b) voltage regulation

(c) armature resistance

(d) synchronous impedance.

23. Some engineers prefer `lamps bright' synchronization to ‘lamps dark’ synchronization because

(a) brightness of lamps can be judged easily

(b) it gives sharper and more accurate synchronization

(c) flicker is more pronounced

(d) it can be performed quickly.

24. It is never advisable to connect a stationary alternator to live bus-bars because it

(a) is likely to run as synchronous motor

(b) will get short-circuited

(c) will decrease bus-bar voltage though momentarily

(d) will disturb generated emfs. Of other alternators connected in parallel.

25. Two identical alternators are running in parallel and carry equal loads. If excitation of one alternator is increased without changing its steam supply, then

(a) it will keep supplying almost the same load

(b) kVAR supplied by it would decrease

(c) its pf. will increase

(d) kVA supplied by it would decrease.

26. Keeping its excitation constant, if steam supply of an alternator running in parallel with another identical alternator is increased, then

(a) it would over-run the other alternator

(b) its rotor will fall back in phase with respect

to the other machine

(c) it will supply greater portion of the load

(d) its power factor would be decreased.

27. The load sharing between two steam-driven alternators operating in parallel may be adjusted by varying the

(a) field strengths of the alternators

(b) power factors of the alternators

(c) steam supply to their prime movers

(d) speed of the alternators.

28. For a machine on infinite bus active power can be varied by

(a) changing field excitation

(b) changing of prime cover speed

(c) both (a) and (b) above

(d) none of the above .

ANSWERS

1. a **2.** d **3.** b **4.** d **5.** d **6.** c **7.** b **8.** a **9.** a **10.** d **11.** b **12.** c **13.** a **14.** d **15.** b **16.** b **17.** c **18.** b **19.** b **20.** d **21.** b **22.** b**23.** b **24.** b **25.** a**26.** c **27.** c **28.** B

Single Phase Induction Motor

A Single Phase Induction Motor consists of a single phase winding which is mounted on the stator of the motor and a cage winding placed on the rotor. A pulsating magnetic field is produced, when the stator winding of the single phase induction motor is energized by a single phase supply.

The word Pulsating means that the field builds up in one direction falls to zero and then builds up in the opposite direction. Under these conditions, the rotor of an induction motor does not rotate. Hence, a single phase induction motor is not self-starting. It requires some special starting means.

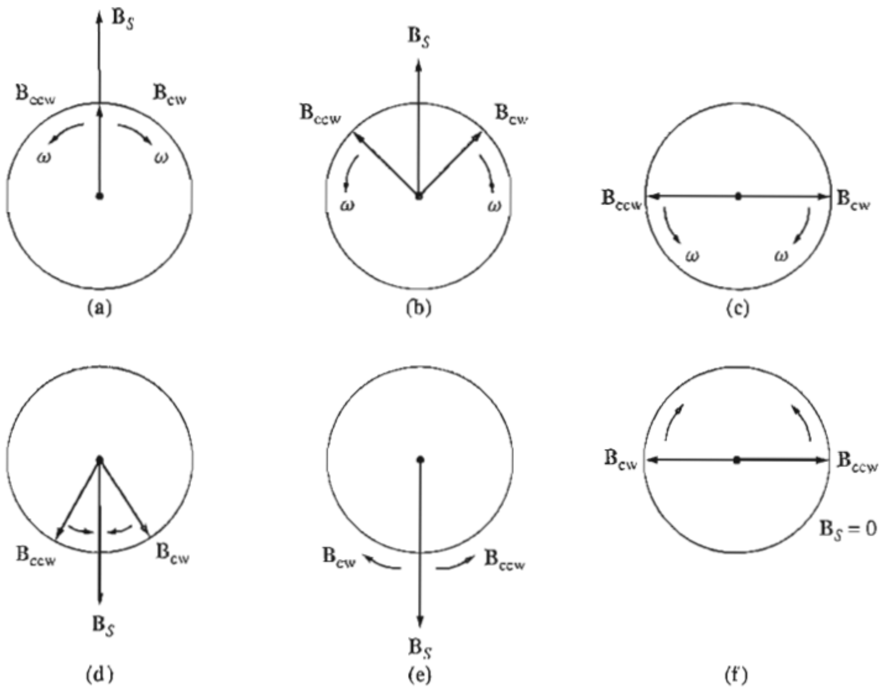
If a 1 phase stator winding is excited and the rotor of the motor is rotated by an auxiliary means and the starting device is then removed, the motor continues to rotate in the direction in which it is started.

The performance of the single phase induction motor is analyzed by the two theories. One is known as the Double Revolving Field Theory ,and the other is Cross Field Theory .Both the theories are similar and explains the reason for the production of torque when the rotor is rotating.

Double Revolving Field Theory of Single Phase Induction Motor

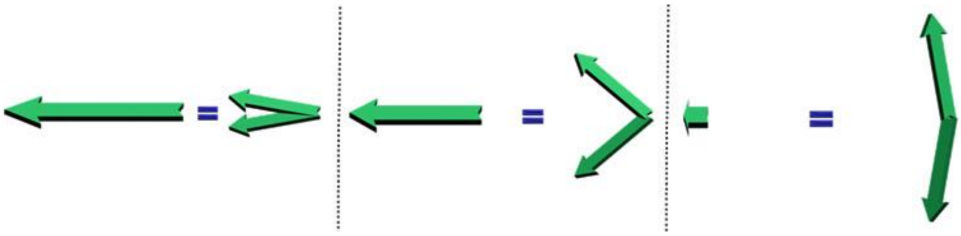
The double-revolving-field theory of single-phase induction motors basically states that a stationary pulsating magnetic field can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions. The induction motor responds to each magnetic field separately, and the net torque in the machine will be the sum of the torques due to each of the two magnetic fields. Figure down shows how a stationary pulsating magnetic field can be resolved into two equal and oppositely rotating magnetic fields. The flux density of the stationary magnetic field is given by

$$\mathbf{B}_S(t) = (\mathbf{B}_{max} \cos \omega t)\,\hat{\mathbf{j}}$$



- Notice that the sum of the clockwise and counterclockwise magnetic fields is equal to the stationary pulsating magnetic field Bs:

$$\mathbf{B}_S(t) = \mathbf{B}_{CW}(t) + \mathbf{B}_{CCW}(t)$$



Why Single Phase Induction Motor is not Self Starting?

According to double field revolving theory, any alternating quantity can be resolved into two components, each component have magnitude equal to the half of the maximum magnitude of the alternating quantity and both these component rotates in opposite direction to each other. For example - a flux, φ can be resolved into two components

$$\frac{\phi_m}{2} \text{ and } -\frac{\phi_m}{2}$$

Each of these components rotates in opposite direction i. e if one φ_m / 2 is rotating in clockwise direction then the other φ_m / 2 rotates in anticlockwise direction. When a single phase ac supply is given to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude φ_m /2. Each of these components will rotate in opposite direction, with the synchronous speed, N_s. Let us call these two components of flux as forward component of flux, φ_f and backward component of flux, φ_b. The resultant of these two component of flux at any instant of time, gives the value of instantaneous stator flux at that particular instant

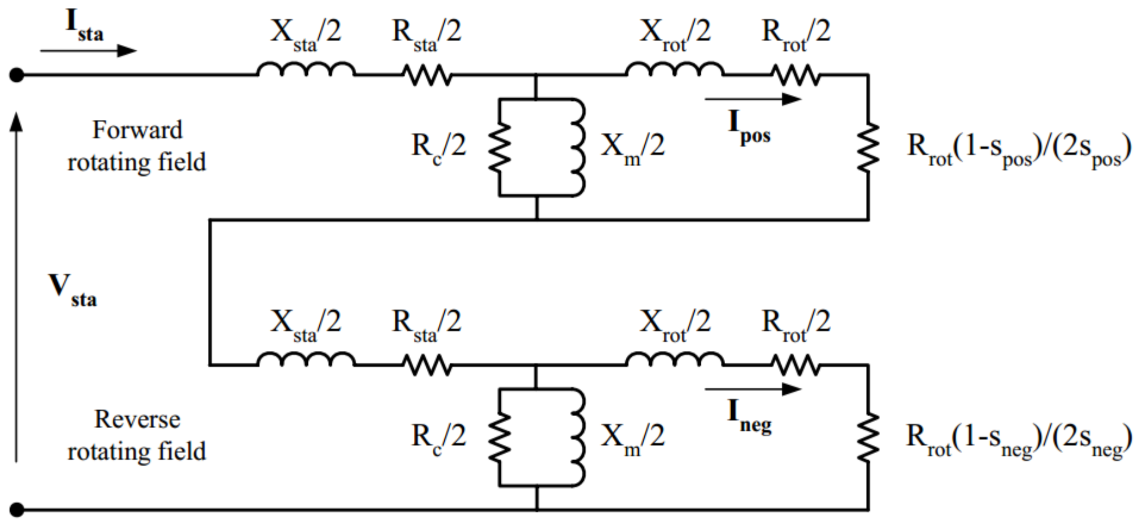
$$i.e. \phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \text{ or } \phi_r = \phi_f + \phi_b$$

Now at starting, both the forward and backward components of flux are exactly opposite to each other. Also both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at starting is zero. So, the single phase induction motors are not self-starting motors.

The phase shift is achieved by connecting

– a resistance, an inductance, or a capacitance

THE CIRCUIT MODEL OF ASINGLE-PHASE INDUCTION MOTOR

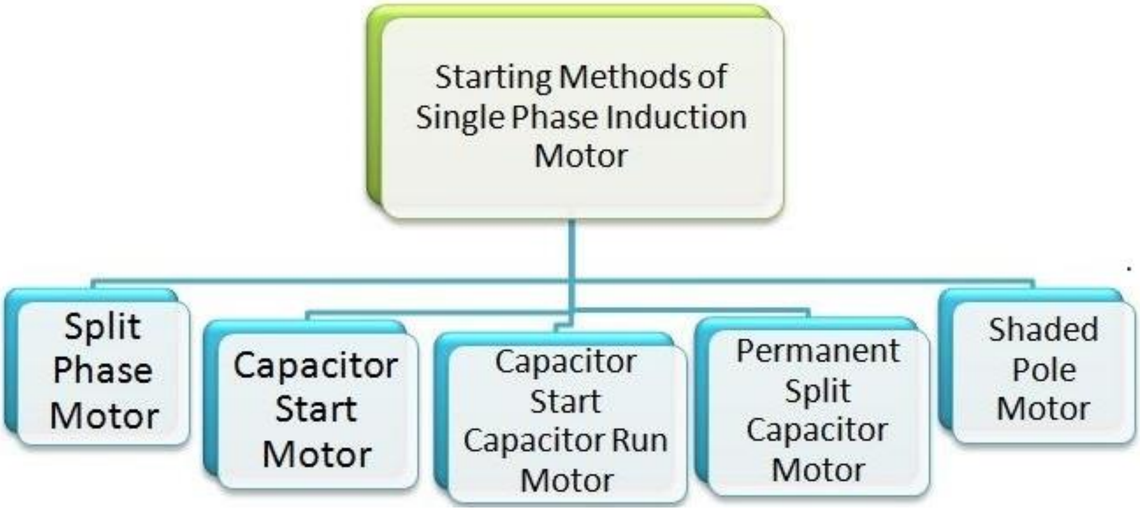


Different between single and three phase induction motor are :

- As the name itself shows, the Single Phase induction motor uses single phase supply, for its operation and 3 Phase induction motor uses three phase supply.
- The Starting Torque of Single Phase induction motor is low, whereas the starting torque of Three Phase Induction motor is high.
- Single Phase motors are easy to repair and maintain, but the maintenance of three phase motors difficult.
- Single Phase motors are simple in construction, reliable and economical as compared to three phase induction motors.
- The efficiency of single phase motor is low, whereas the efficiency of three phase induction motors is high.
- The power factor of Single Phase Induction motor is low as compared to that of three-phase induction motor.
- Single Phase motors are mostly used in domestic appliances such as mixer grinder, fans, compressors, etc. Three phase induction motors are mostly used in the industries.

BASIS	SINGLE PHASE INDUCTION MOTOR	THREE PHASE INDUCTION MOTOR
Supply	Single Phase induction motor uses single phase supply, for its operation.	Three Phase induction motor uses three phase supply, for its operation.
Starting torque	The starting torque is low.	The starting torque is high.
Maintenance	They are easy to repair and maintain.	Difficult to repair and maintain.
Features	Simple in construction, reliable and economical as compared to three phase induction motors.	Complex in construction and costly.
Efficiency	Efficiency is less	Efficiency is high
Power factor	Power factor is low	Power factor is high
Examples	They are mostly used in domestic appliances such as mixer grinder, fans, compressors etc	Three phase induction motors are mostly used in industries.

Methods for Making Single Phase Induction as Self Starting Motor

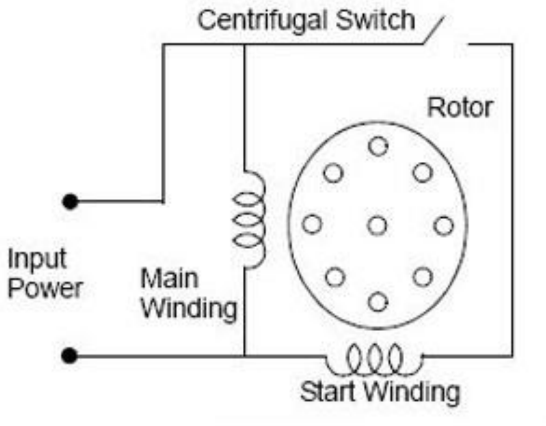


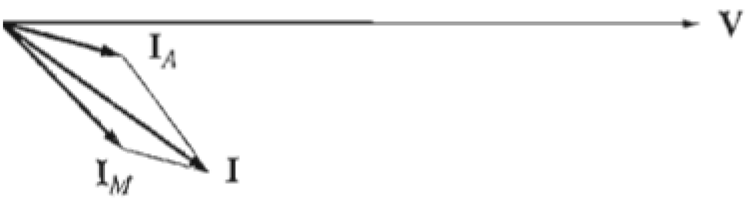
1. Split phase induction motor.
2. Capacitor start inductor motor.
3. Capacitor start capacitor run induction motor.
4. Shaded pole induction motor.
5. Permanent split capacitor motor or single value capacitor motor.

1. Split phase induction motor.

The Split Phase Motor is also known as a Resistance Start Motor. It has a single cage rotor, and its stator has two windings known as main winding and starting winding. Both the windings are displaced 90degrees in space. The main winding has very low resistance and a high inductive reactance whereas the starting winding has high resistance and low inductive reactance.

The Connection Diagram of the motor is shown below.





Applications of Split Phase Induction Motor

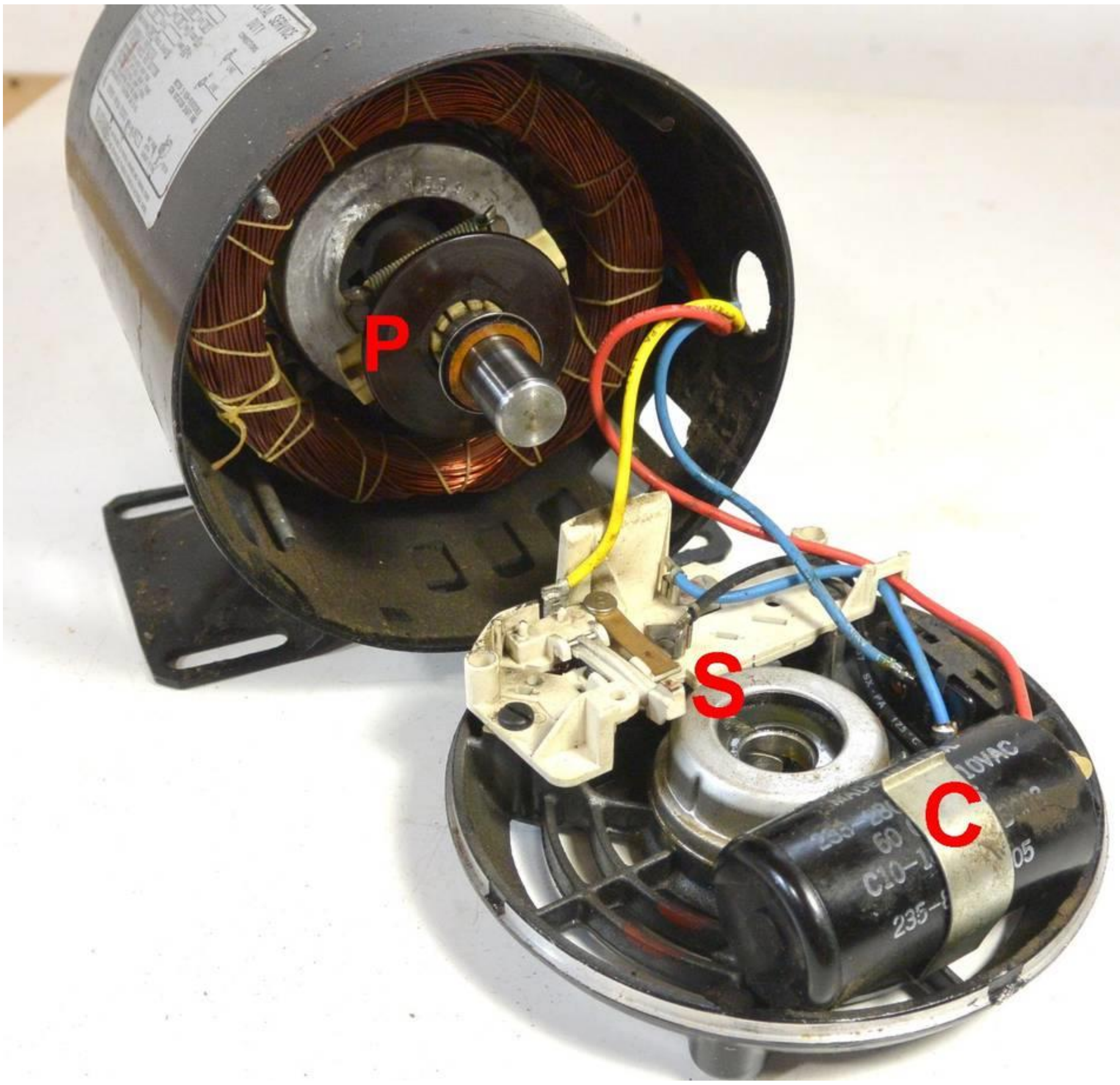
This type of motors are cheap and are suitable for easily starting loads where the frequency of starting is limited. This type of motor is not used for drives which require more than 1 KW because of the low starting torque. The various applications are as follows:-

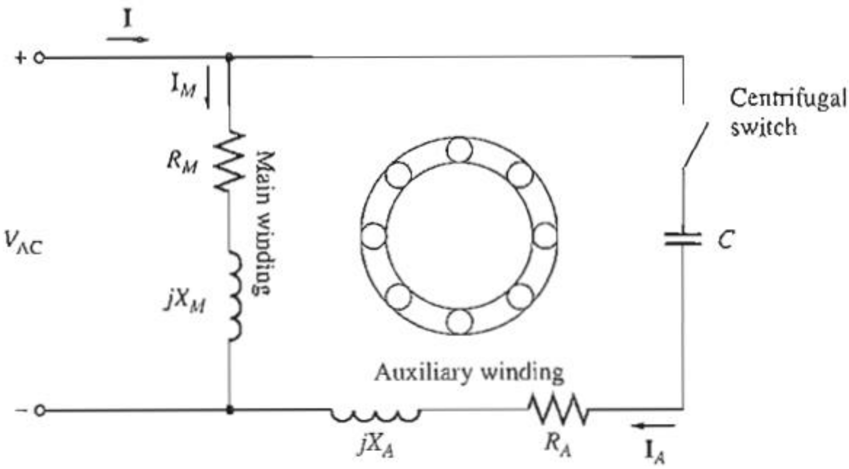
- Used in the washing machine, and air conditioning fans.
- The motors are used in mixer grinder, floor polishers.
- Blowers, Centrifugal pumps
- Drilling and lathe machine.

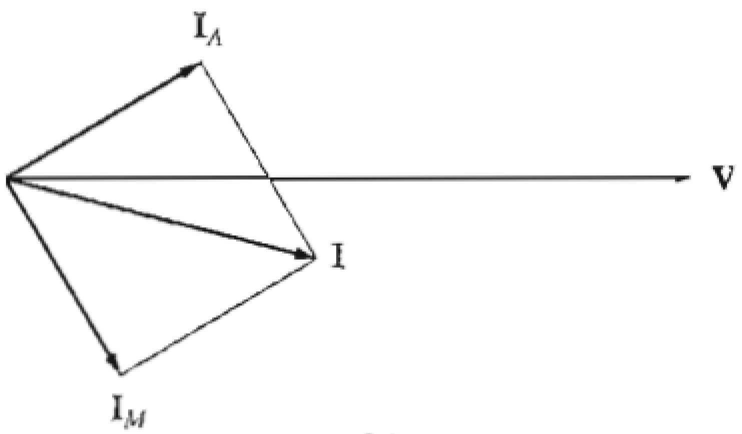
2. Capacitor start induction motor.

A Capacitor Start Motors are the single phase Induction Motor that employs a capacitor in the auxiliary winding circuit to produce a greater phase difference between the current in the main and the auxiliary windings. The name capacitor starts itself shows that the motor uses a capacitor for the purpose of the starting.

This starter winding is in series with a capacitor (C), and a centrifugal switch (S). In this motor, the starter capacitor is mounted inside the main housing. More typically, the starter capacitor is mounted on top of the housing under a metal dome.
The centrifugal switch (S) is mounted to the back plate and is activated by a disk (P) that pushes against a tab on the switch (just left of the S in the photo).


P
S
C

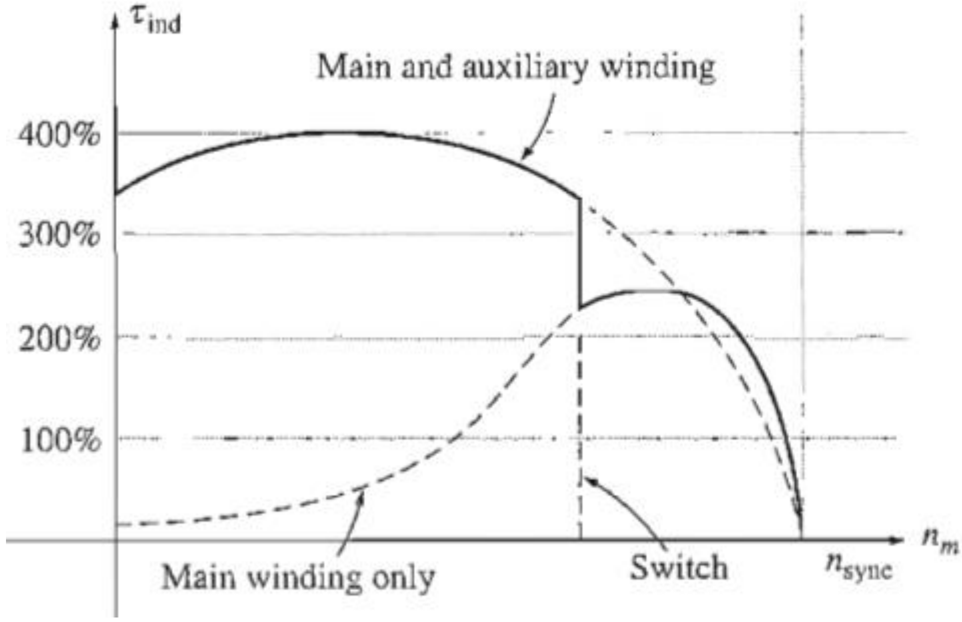

I
+
I_M
R_M
Main winding
V_{AC}
jX_M
Centrifugal switch
C
Auxiliary winding
−
jX_A
R_A
I_A



Applications of the Capacitor Start Motor

The various applications of the motor are as follows:-

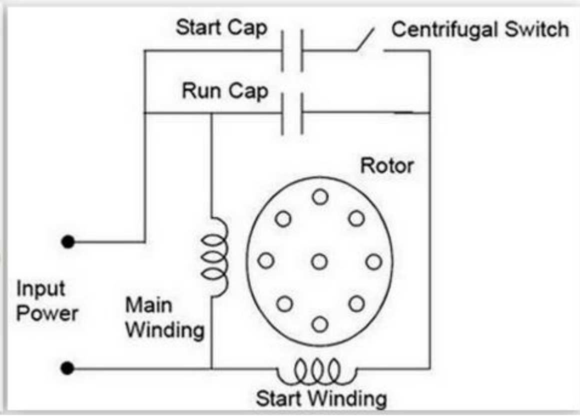
- These motors are used for the loads of higher inertia where frequent starting is required.
- Used in pumps and compressors
- Used in the refrigerator and air conditioner compressors.
- They are also used for conveyors and machine tools.

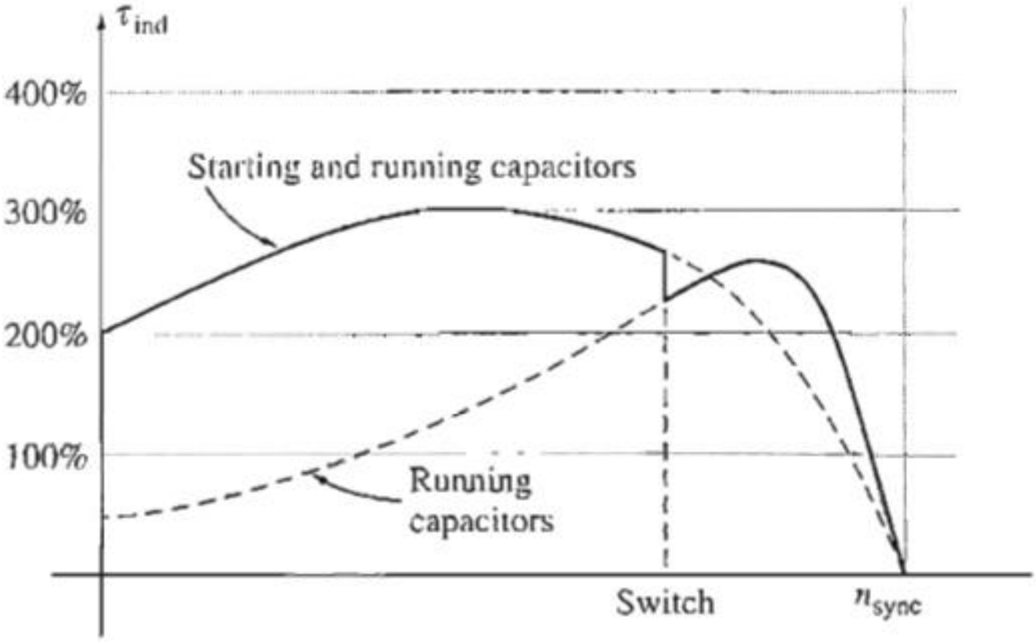


3. Capacitor start Capacitor run induction motor.

The Capacitor Start Capacitor Run Motor has a cage rotor, and its stator has two windings known as Main and Auxiliary Windings. The two windings are displaced 90 degrees in space. There are two capacitors in this method one is used at the time of the starting and is known as starting capacitor. The other one is used for continuous running of the motor and is known as RUN capacitor.

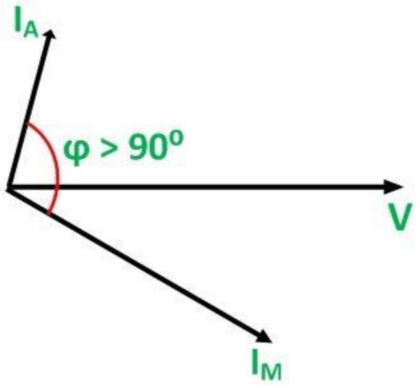
So this motor is named as Capacitor Start Capacitor Run Motor. This motor is also known as Two Value Capacitor Motor. Connection diagram of the Two valve Capacitor Motor is shown below.

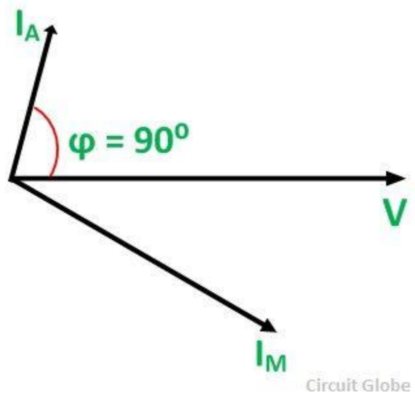




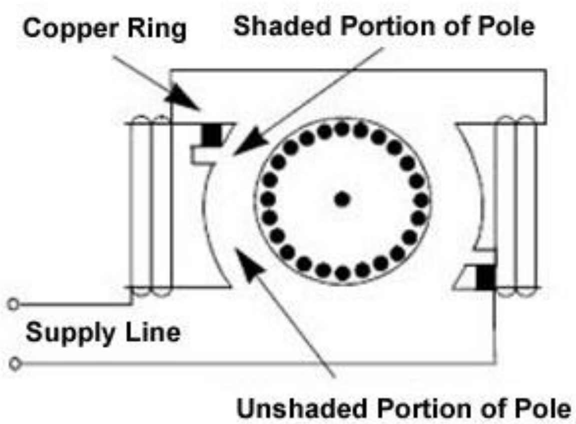
Phasor Diagram of the Capacitor Start Capacitor Run Motor.

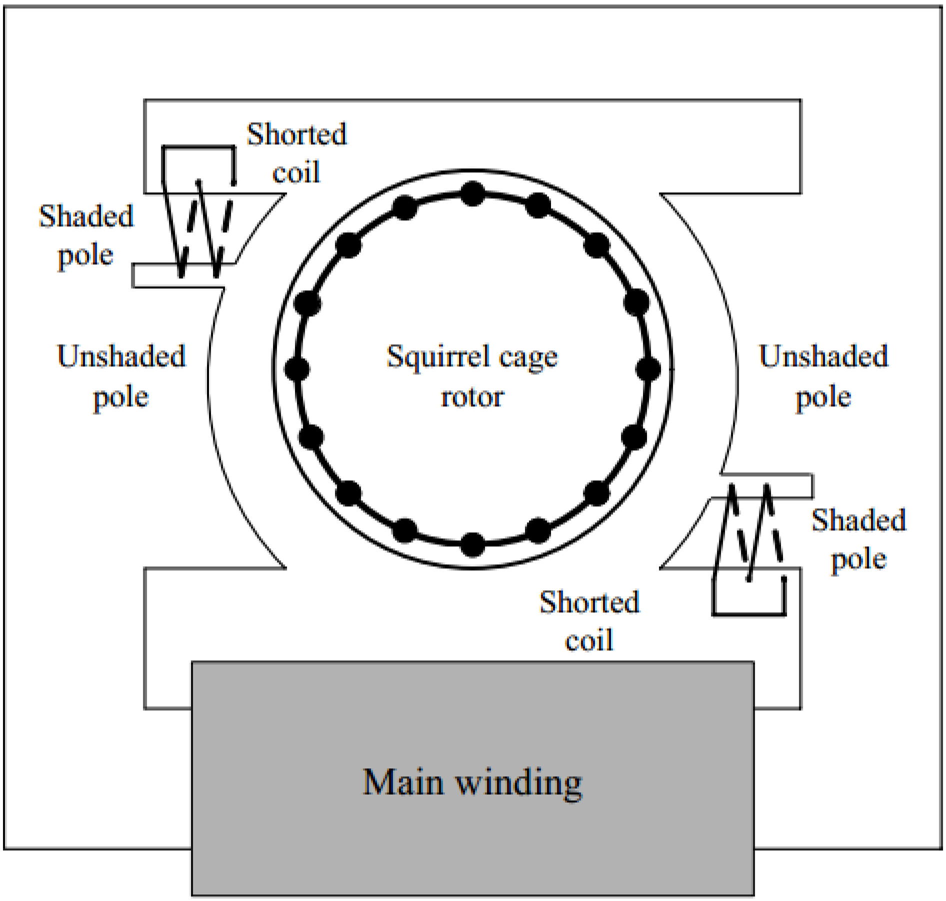
This type of motor is quiet and smooth running. They have higher efficiency than the motors that run on the main windings only. They are used for loads of higher inertia requiring frequent starts where the maximum pull-out torque and efficiency required are higher. The Two Value Capacitor Motors are used in pumping equipment, refrigeration, air compressors, etc.

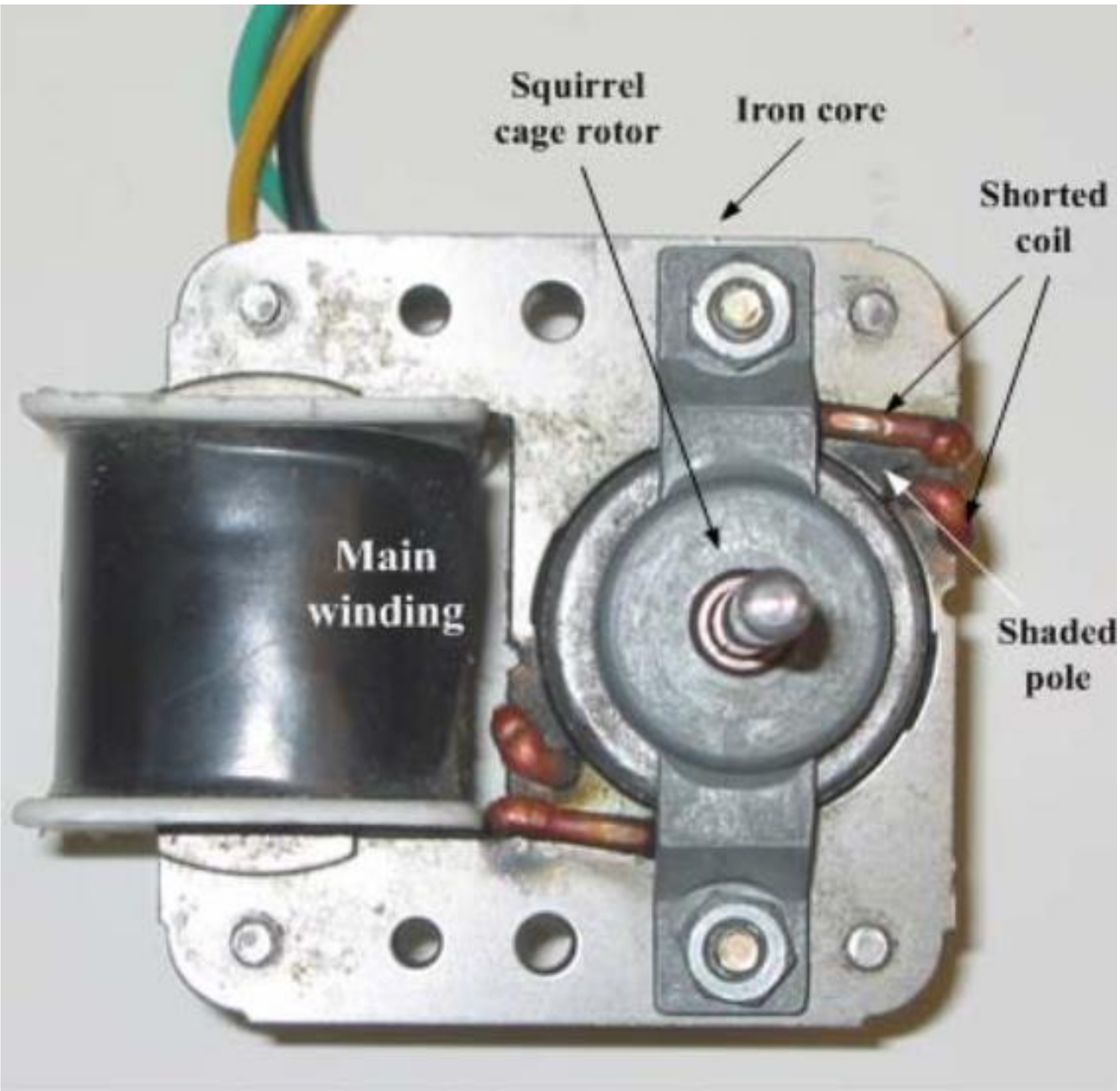


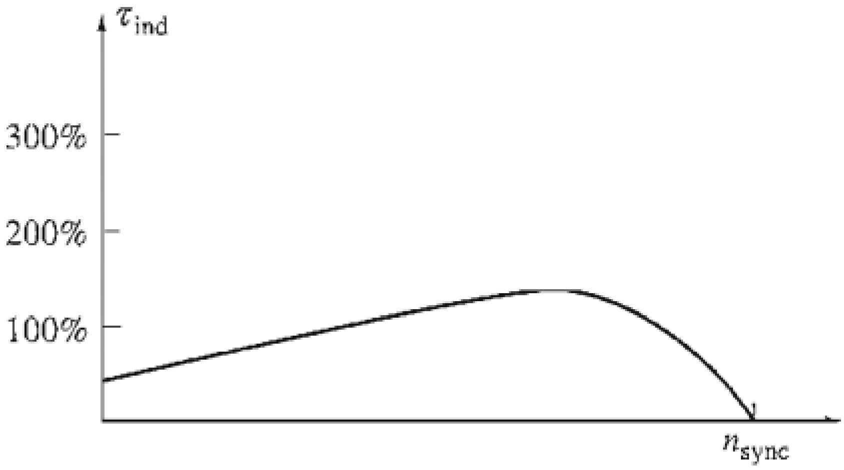


4. Shaded pole induction motor.




Shorted
coil
Shaded
pole
Unshaded
pole
Squirrel cage
rotor
Unshaded
pole
Shaded
pole
Shorted
coil
Main winding

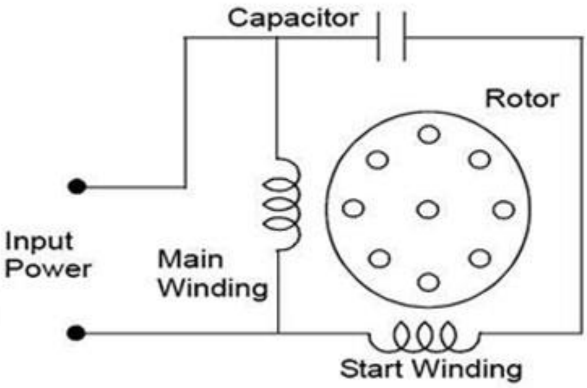


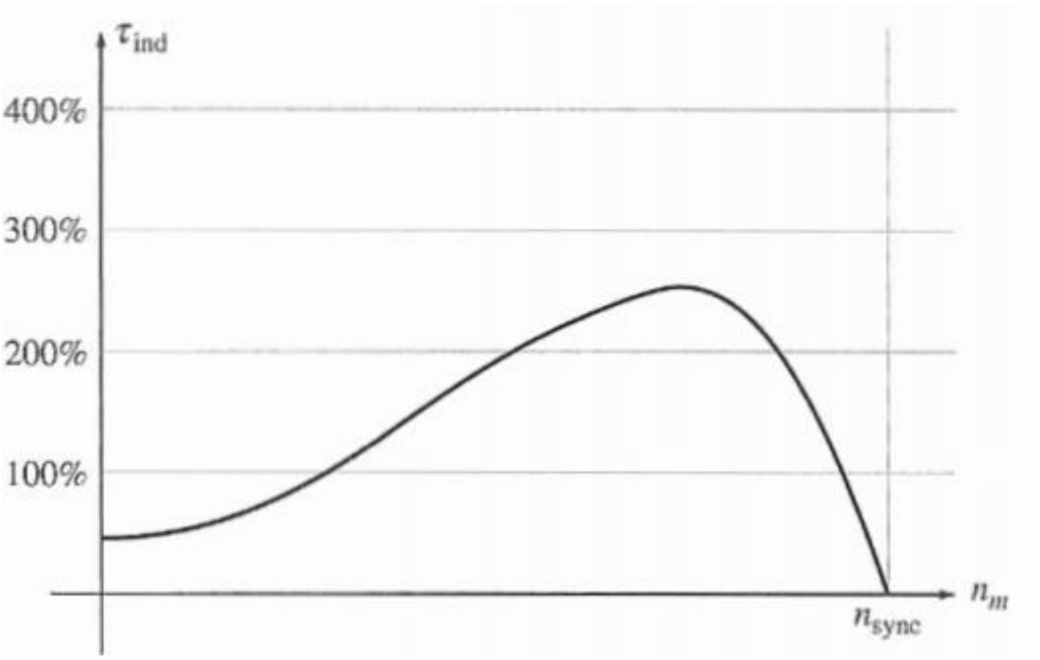


5. Permanent split capacitor motor or single value capacitor motor.

The Permanent Split Capacitor motor also has a cage rotor and the two windings named as main and auxiliary windings similar to that of a Capacitor start Capacitor run induction motor It has only one capacitor connected in series with the starting winding. The capacitor C is permanently connected in the circuit both at the starting and the running conditions.

The connection diagram of a Permanent Split Capacitor Motor is shown below.





Advantages of The Single Value Capacitor Motor has following advantages.

No centrifugal switch is required.

Efficiency is high.

As the capacitor is connected permanently in the circuit, the power factor is high.

It has a higher pullout torque.

Limitations of Permanent split capacitor motor

The limitations of the motor are as follows:-

The paper capacitor is used in the motor as an Electrolytic capacitor cannot be used for continuous running. The cost of the paper capacitor is higher, and size is also large as compared to the electrolytic capacitor of the same ratings. It has low starting torque, less than full load torque.

Applications of Permanent split capacitor motor

The various applications of the split motor are as follows:-

Used in fans and blowers in heaters and air conditioners.

Used in refrigerator compressors.

Used in office machinery.

SPEED CONTROL OF SINGLE PHASE INDUCTION MOTORS

1. Vary the stator frequency.

2. Change the number of poles.

3. Change the applied terminal voltage V

In practical designs involving fairly high-slip motors, the usual approach to speed control is to vary the terminal voltage of the motor. The voltage applied to a motor may be varied in one of three ways:

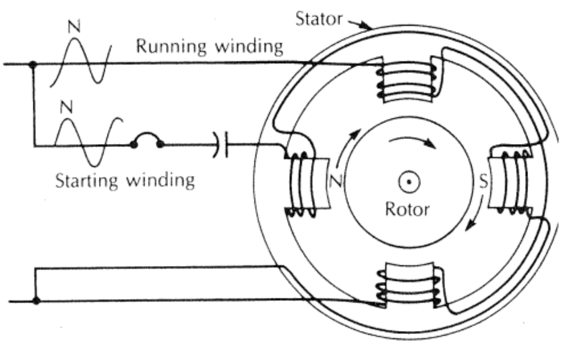
1. An autotransformer may be used to continually adjust the line voltage. This is the most expensive method of voltage speed control and is used only when very smooth speed control is needed.

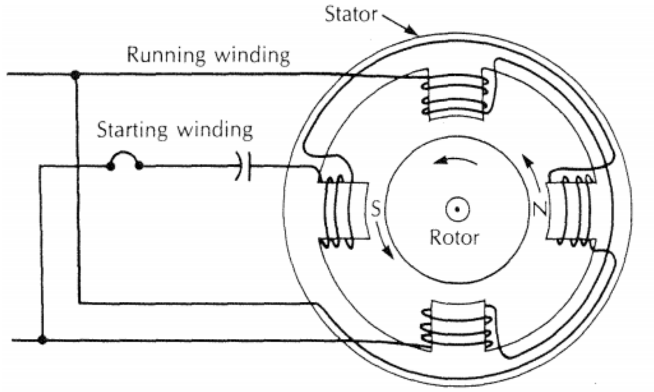
2. A solid-state controller circuit may be used to reduce the rms voltage applied to the motor by ac phase control. Solid-state control circuits are considerably cheaper than autotransformers and so are becoming more and more common.

3. A resistor may be inserted in series with the motor's stator circuit. This is the cheapest method of voltage control, but it has the disadvantage that considerable power is lost in the resistor, reducing the overall power conversion efficiency.

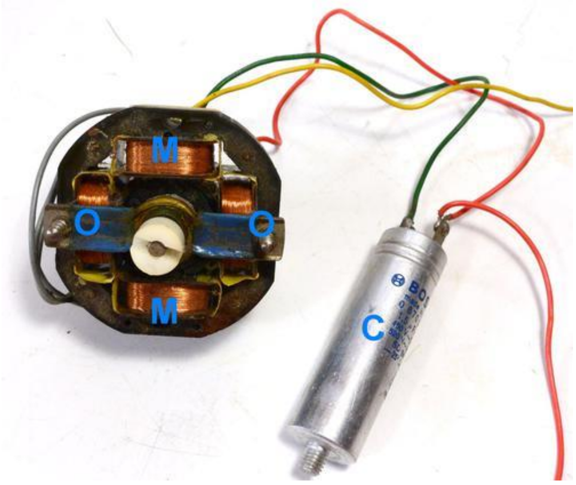
Reverse of Rotation single phase induction motor

Reversing the lead wires to the starting winding reverses the direction of rotation of the rotor

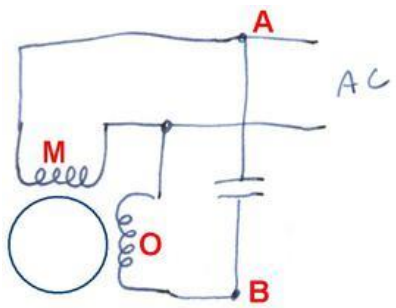




I. **Reversing a split phase motor**

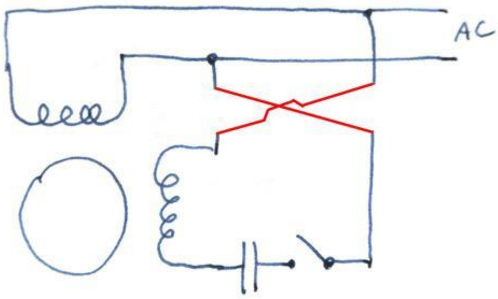


Reversing the motor is simply a matter of moving the power connection so that the other winding is directly on AC. Essentially, moving one side of the power connection from (A) to (B), causing winding (O) to be the main winding and winding (M) to be the phase shifted one. Split phase motors are typically smaller motors, less than 1/4 horsepower.



II. **Reversing a capacitor start motor**

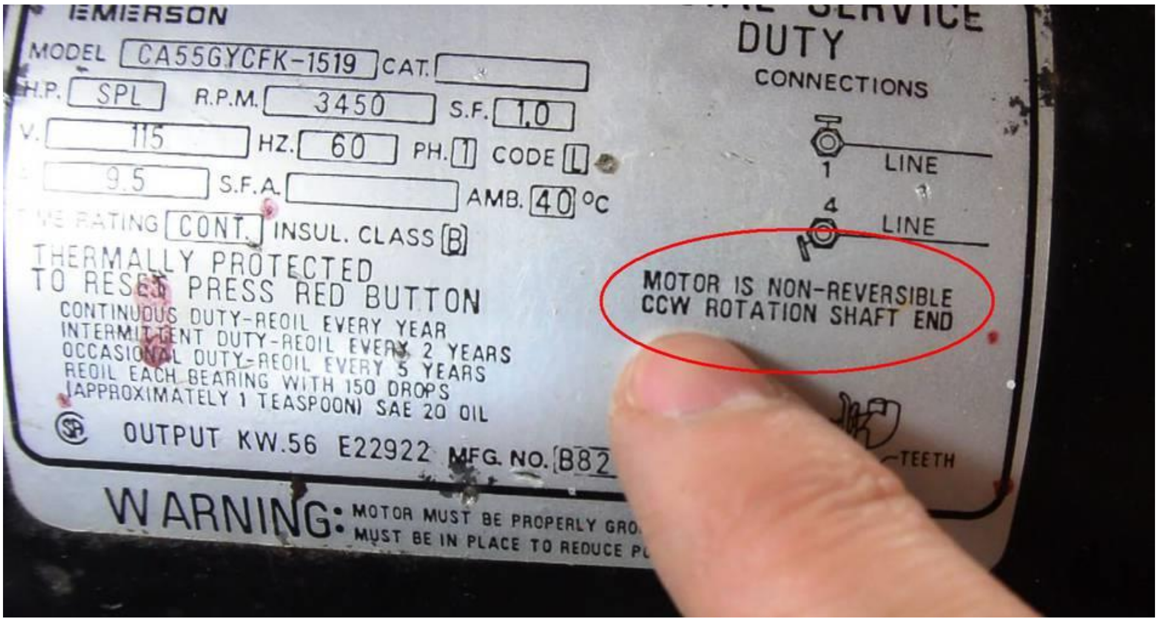
So how do we reverse a capacitor start motor? Once started, a single phase induction motor will happily run in either direction. To reverse it, we need to change the direction of the rotating magnetic field produced by the main and starter windings. And this can be accomplished by reversing the polarity of the starter winding. Basically, we need to swap the connections on either end of the starter winding. Sometimes it's just the winding, Sometimes the winding, switch and capacitor are reversed. The order of the switch and capacitor don't matter, as long as they are in wired in series.



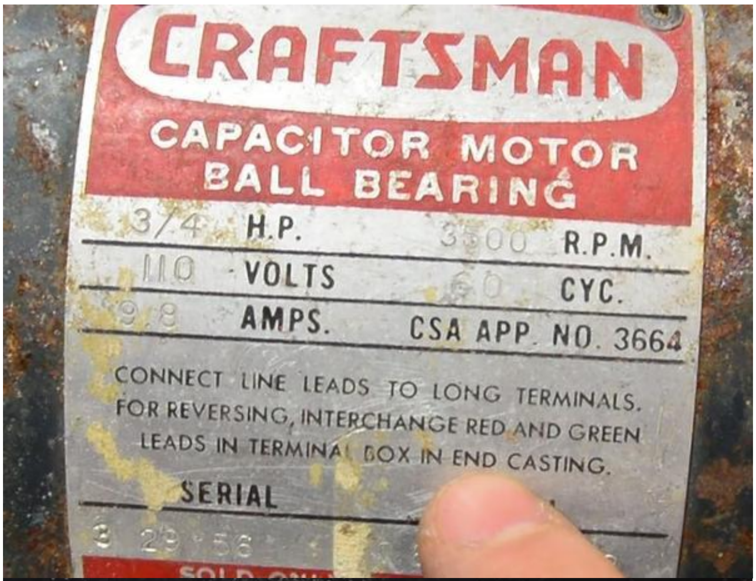
You could also reverse the motor by reversing the main winding (same effect).

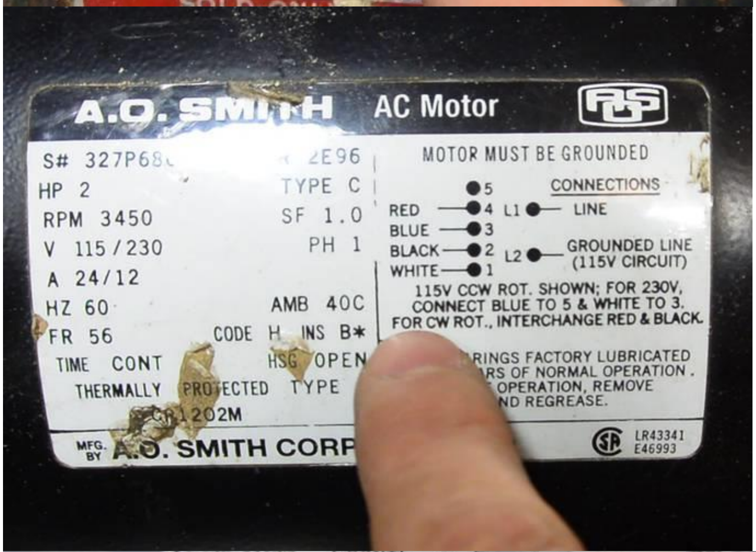
If you were to switch the main and starter windings, as one does with a split phase motor, the motor will also reverse. However, it will not run at full power and is also likely to burn out. The starter winding is not suitable for continuous operation.

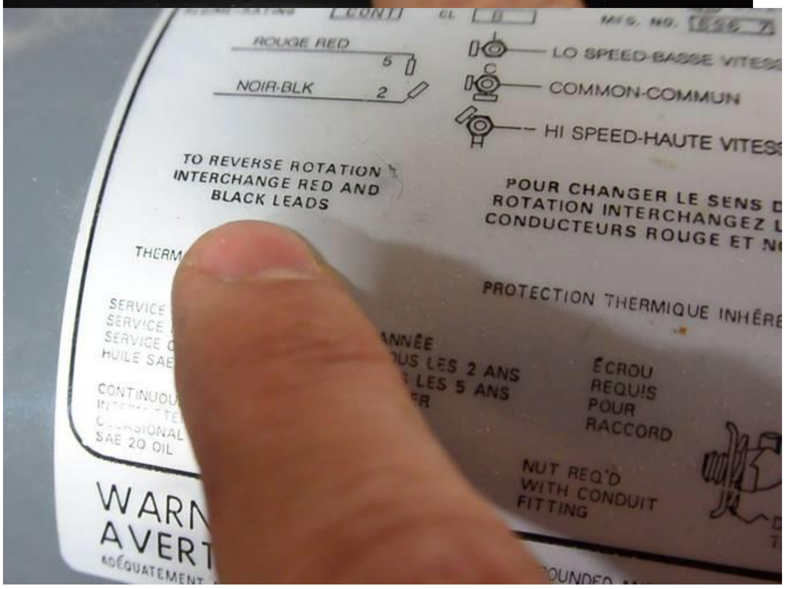
The label on this motor indicates "MOTOR IS NON-REVERSIBLE"



But on motors that are reversible, the label always indicates to swap two wires to reverse it

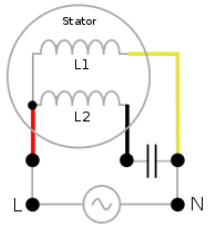

CRAFTSMAN
CAPACITOR MOTOR
BALL BEARING
3/4 H.P.
3500 R.P.M.
110 VOLTS
60 CYC.
9.8 AMPS.
CSA APP. NO. 3664
CONNECT LINE LEADS TO LONG TERMINALS.
FOR REVERSING, INTERCHANGE RED AND GREEN
LEADS IN TERMINAL BOX IN END CASTING.
SERIAL


A.O. SMITH
AC Motor
S# 327P68
2E96
HP 2
TYPE C
RPM 3450
SF 1.0
V 115/230
PH 1
A 24/12
HZ 60
AMB 40C
FR 56
CODE H
INS B*
TIME CONT
HSG OPEN
THERMALLY PROTECTED TYPE
MOTOR MUST BE GROUNDED
CONNECTIONS
RED
BLUE
BLACK
WHITE
L1
LINE
L2
GROUNDED LINE
(115V CIRCUIT)
115V CCW ROT. SHOWN; FOR 230V,
CONNECT BLUE TO 5 & WHITE TO 3.
FOR CW ROT., INTERCHANGE RED & BLACK.
MFG. BY A.O. SMITH CORP
LR43341
E46993

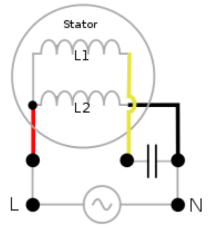

ROUGE RED
NOIR-BLK
LO SPEED-BASSE
COMMON-COMMUN
HI SPEED-HAUTE
TO REVERSE ROTATION
INTERCHANGE RED AND
BLACK LEADS
POUR CHANGER LE SENS
ROTATION INTERCHANGEZ
CONDUCTEURS ROUGE ET
PROTECTION THERMIQUE
ÉCROU
REQUIS
POUR
RACCORD
NUT REQ'D
WITH CONDUIT
FITTING
SAE 20 OIL

The wires to reverse are always the wires that lead to the starter winding.
If you have a motor where the label is missing, the starter winding typically has about three times the electrical resistance of the main winding and is always in series with the starter switch and capacitor (if there is one). If you can isolate both ends of this winding and swap them, you can reverse the motor. If however there are only three wires coming out of the windings, then the main and starter windings have one end tied together and the motor is not reversible.

For a 1/2 hp 120 volt motor, the main winding will typically have about 1.5 ohms, and the starter winding about 4 ohms. For 240 volt 1/2 hp motors (240 volt only), you should expect about 6 ohms on the main winding, and 16 ohms on the starter winding. Expect the resistance of the windings to be inversely proportional with horsepower.
A lot of motors will have a few extra wires coming off the windings. Often, a thermal switch is attached to the windings, and this switch may be partially tied to one of the windings. Also, if the motor can be rewired for 120 and 240 volt, the main winding will consist of two 120 volt windings that can be wired either in series or parallel. So there can be quite a few wires coming off the windings. It can take a bit of time and probing around to figure it out.
For motors that can be wired at both 120 volts and 240 volts, the starter winding is a 120 volt winding. When these motors are wired for 240 volts, the main winding is used as an autotransformer to make the 120 volts for the starter winding. Otherwise, rewiring the motor from 120 to 240 volts would be much more complex!



1) Wiring of the fan in question.
Capacitor in series with L2



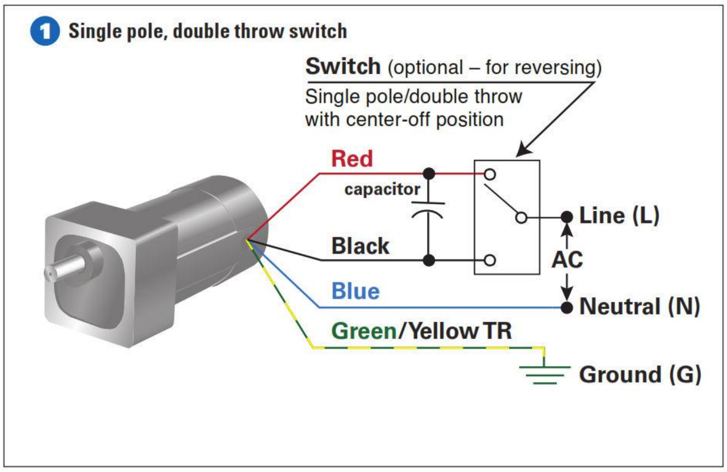
2) Black & Yellow interchanged.
Capacitor now in series with L1

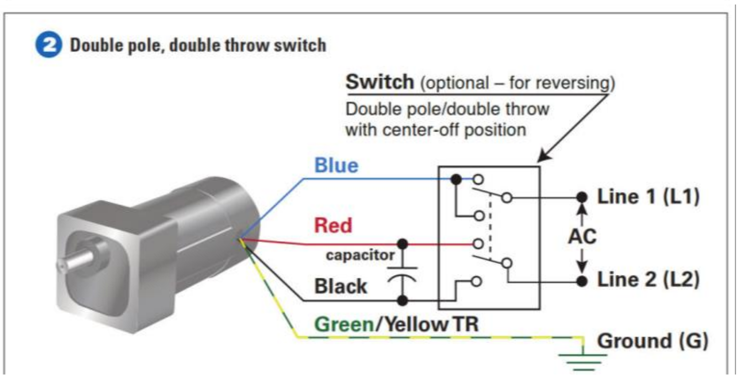
How to Wire an Optional Reversing Switch to a 3- or 4-wire AC (PSC) Motor or Gear motor (115VAC/60Hz Models)

Optional switch to reverse the direction of a 3- or 4-wire Bodine permanent split capacitor (PSC) motor/gear motor. All the wiring diagrams use variations of a double throw switch, with a center-off position. The purpose of the center-off position is to bring the gear motor to a complete stop before reversing its direction of rotation. This is necessary to prevent gearing damage. Table 1 (below) shows examples of switch manufacturers, part numbers and specifications recommended for use with Bodine products.

3- Wire-Reversible Bodine AC Motor or Gear motor

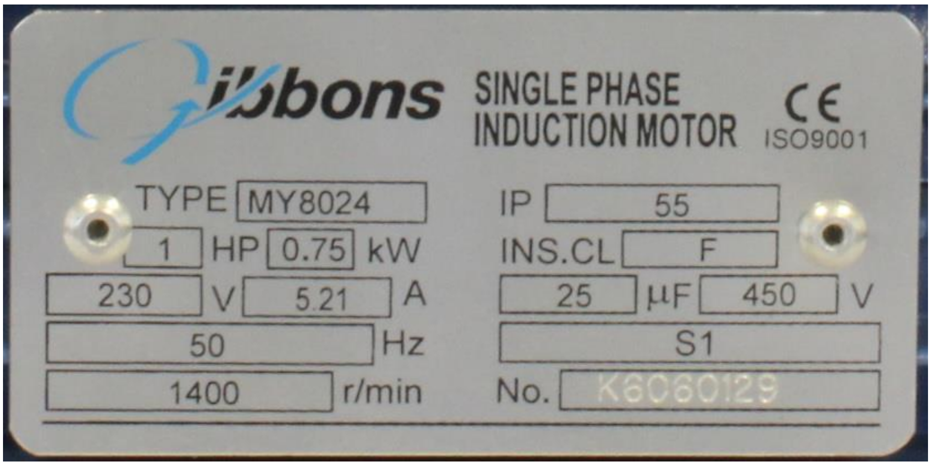
Examples 1 & 2 show how to connect a single- or double-pole switch to our 3-wire, PSC, fixed-speed AC gear motors or motors.





Reversal of Rotation**.** The concentrated-pole (or salient-pole) type universal motor may be reversed by reversing the flow of current through either the armature or field windings. The usual method is to interchange the leads on the brush holders.

Nameplate on a typical single-phase squirrel cage induction motor



1. HP

This is the rated horsepower. 1hp = 746 watts.

2. KW

   The rated output in kilowatts.

3. V

   The rated voltage.

4. A
   The full-load current (amps).
5. Hz
   Frequency. This is always 50 Hz in the UK and Europe, though some countries in Asia, the Middle East and the Americas use 60Hz.
6. r/min
   Shaft speed (revolutions per minute).
7. IP
   Ingress Protection rating of a motor enclosure from objects, dust and moisture. The digits represents protection against ingress of solid objects and liquids respectively.
8. INS. CL
   This is the insulation class which indicates resistance to thermal failure. It is commonly F, covering temperatures up to 155°C, although motors can be rated H for a maximum 180°C.
9. μF/V
   These represent the rating of the capacitor in microfarads (μF) and volts (V).
10. S1
    This box denotes the duty cycle rating according to the International Standard IEC 60034-1. This ranges from S1 to S10, with S1 being continuous duty and S2-S10 providing shorter duties.
11. No.
    The manufacturer's unique serial/reference number. This helps the company that produced the motor diagnose faults and provide an identical replacement if necessary.

Universal Motor

A universal motor is defined as a series DC motor which may be operated either on direct or single-phase ac. supply at approximately the same speed and output.

Speed/Load Characteristic. The speed of a universal motor varies just like that of a dc. Series motor i.e. low at full-load around 7000 rpm and high on no-load (about 20,000 rpm. in some cases). In fact, on no-load the speed is limited only by its own friction and windage load. Usually, gear trains are used to reduce the actual load speeds to proper values.

Applications. Universal motors are used in vacuum cleaners where actual motor speed is the load speed. Other applications where motor speed is reduced by a gear train are drink and food mixers, portable drills and domestic sewing machine etc.

OBJECTIVE TESTS

1. The starting winding of a single-phase motor is placed in the

(a) rotor (b) stator

(c) armature (d) field.

2. One of the characteristics of a single- phase motor is that it

(a) is self-starting

(b) is not self-starting

(c) requires only one winding

(d) can rotate in one direction only.

3. after the starting winding of a single- phase Induction motor is disconnected from supply, it continues to run only on ....winding.

(a) Rotor (b) compensating

(c) Field (d) running

4. If starting winding of a single-phase induction motor is left in the circuit, it will

(a) Draw excessive current and overheat

(b) Run slower

(c) Run faster

(d) Spark at light loads.

5. The direction of rotation of a single-phase motor can be reversed by

(a) Reversing connections of both windings

(b) Reversing connections of starting winding

(c) Using a reversing switch

(d) Reversing supply connections.

6. If a single-phase induction motor runs slower than normal, the more likely defect is

(a) Improper fuses (b) shorted running winding

(c) Open starting winding (d) Worn bearings.

7. The capacitor in a capacitor-start induction- run ac motor is connected in series with ......winding.

(a) Starting (b) running

(c) squirrel-cage (d) compensating

8. A permanent-split single-phase capacitor motor does not have

(a) Centrifugal switch (b) Starting winding

(c) squirrel-cage rotor (d) High power factor.

9. The starting torque of a capacitor-start induction-run motor is directly related to the

Angle α between its two winding currents by the relation

(A) cos α (b) sin α

(c) Tan α (d) sin α/2.

10. In a two-value capacitor motor, the capacitor Used for running purposes is a/an

(a) dry-type ac electrolytic capacitor (b) paper-spaced oil-filled type

(c) air-capacitor (d) Ceramic type.

11. If the centrifugal switch of a two-value capacitor motor using two capacitors fails to

Open, then

(a) Electrolytic capacitor will, in all probability, suffer breakdown

(b) Motor will not carry the load

(c) Motor will draw excessively high current

(d) Motor will not come up to the rated speed.

12. Each of the following statements regarding a shaded-pole motor is true **except**

(a) Its direction of rotation is from un- shaded to shaded portion of the poles

(b) It has very poor efficiency

(c) It has very poor pf.

(d) It has high starting torque.

13. Compensating winding is employed in an ac series motor in order to

(a) Compensate for decrease in field flux

(b) Increase the total torque

(c) reduce the sparking at brushes

(d) Reduce effects of armature reaction.

14. A universal motor is one which

(A) is available universally

(b) Can be marketed internationally

(c) Can be operated either on dc or ac supply

(d) Runs at dangerously high speed on no-load.

ANSWERS

1. b **2.** b **3.** d **4.** a **5.** b **6.** d **7.** a **8.** a **9.** b **10.** b **11.** a **12.** d **13.** d **14.** c