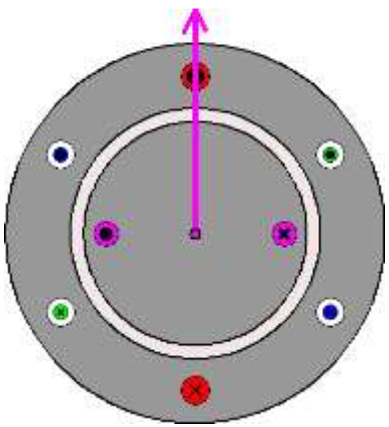
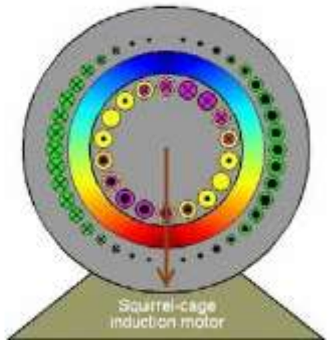
GGS CMT, Kharar

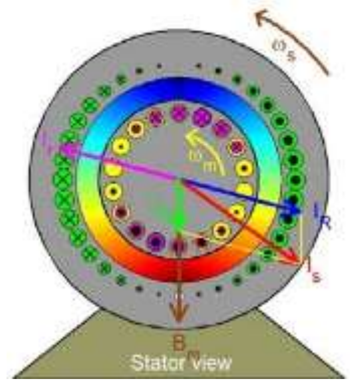
Lecture Notes

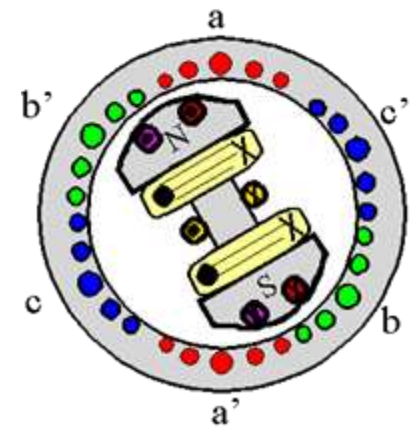
Electrical Machines-II
Subject code – BTEE-402-18
4th Semester
Electrical Engineering

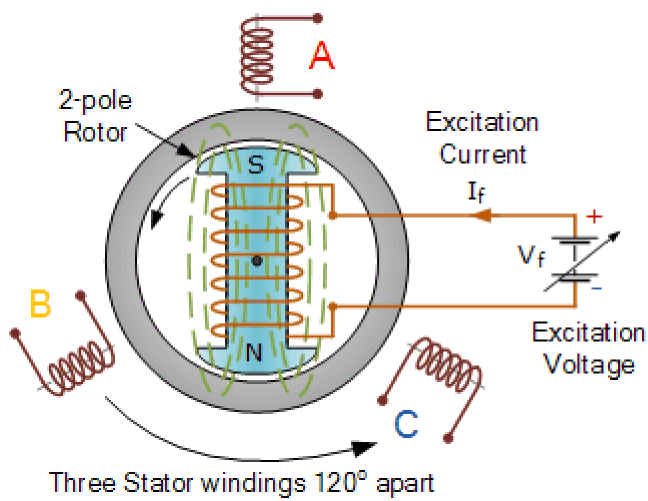
Electrical Machines II
AC machinery fundamentals

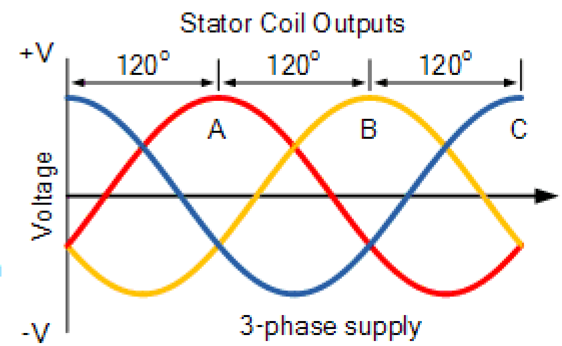










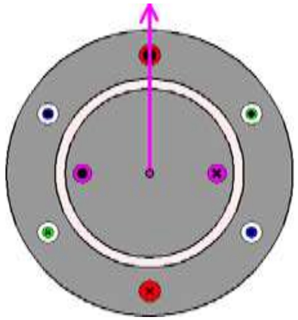


AC machinery fundamentals
Preliminary notes

- AC machines are AC motors and AC generators.
- There are two types of AC machines:
- **Synchronous machines** – the magnetic field current is supplied by a separate DC power source;
- **Induction machines** – the magnetic field current is supplied by magnetic induction (transformer action) into their field windings.
- The field circuits of most AC machines are located on their rotors.
- Every AC (or DC) motor or generator has two parts: rotating part (rotor) and a stationary part (stator).

The rotating magnetic field

- The basic idea of an electric motor is to generate two magnetic fields: rotor magnetic field and stator magnetic field and make the stator field rotating. In this situation, the rotor will constantly turning to align its magnetic field with the stator field.
- The fundamental principle of AC machine operation is to make a 3-phase set of currents, each of equal magnitude and with a phase difference of 120o, to flow in a 3-phase winding. In this situation, a constant magnitude rotating field will be generated.
- The 3-phase winding consists of 3 separate windings spaced 120o apart around the surface of the machine.

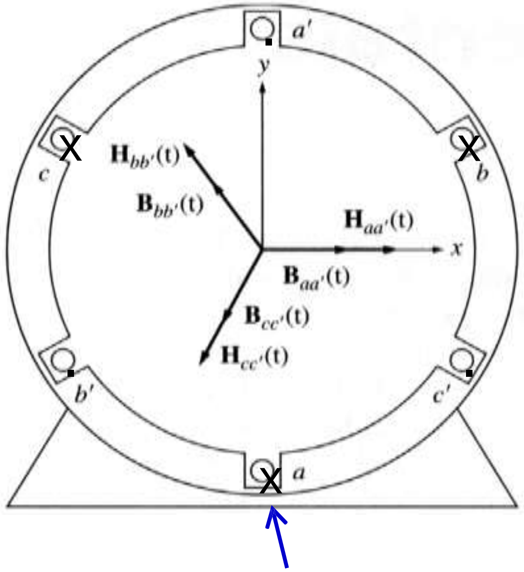


The rotating magnetic field

Consider a simple 3-phase stator containing three coils, each 120^0 apart. Such a winding will produce only one north and one south magnetic pole; therefore, this motor would be called a two-pole motor.

Assume that the currents in three coils are:

$$\begin{cases} i_{aa'}(t) = I_M \sin\omega t \\ i_{bb'}(t) = I_M \sin\left(\omega t - 120^0\right) \\ i_{cc'}(t) = I_M \sin\left(\omega t - 240^0\right) \end{cases}$$



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The directions of currents are indicated.

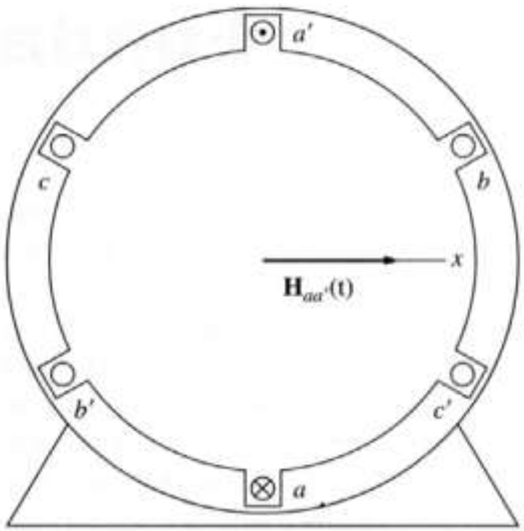
Therefore, the current through the coil *aa'* produces the magnetic field intensity

$$H_{aa'}(t) = H_M \sin\omega t\angle 0^\circ$$

The rotating magnetic field

where the magnitude of the magnetic field intensity is changing over time, while 0^0 is the spatial angle of the magnetic field intensity vector. The direction of the field can be determined by the right-hand rule.

Note, that while the magnitude of the magnetic field intensity $H_{aa'}$ varies sinusoidally over time, its direction is always constant. Similarly, the magnetic fields through two other coils are



$$H_{bb'}(t) = H_M \sin\left(\omega t - 120°\right)\angle 120°$$

$$H_{cc'}(t) = H_M \sin\left(\omega t - 240°\right)\angle 240°$$

The magnetic flux densities resulting from these magnetic field intensities can be found from

$$B = \mu H$$

The rotating magnetic field

$$B_{aa'}(t) = \mu H_M \sin \omega t \angle 0°$$
$$B_{bb'}(t) = \mu H_M \sin\left(\omega t - 120°\right) \angle 120°$$
$$B_{cc'}(t) = \mu H_M \sin\left(\omega t - 240°\right) \angle 240°$$

At the time $t = 0$ ($\omega t = 0$) :

$$B_{aa'}(t) = 0$$
$$B_{bb'}(t) = \mu H_M \sin\left(-120°\right) \angle 120°$$
$$B_{cc'}(t) = \mu H_M \sin\left(-240°\right) \angle 240°$$

The total magnetic field from all three coils added together will be

$$B_{net} = B_{aa'} + B_{bb'} + B_{cc'} = 0 + \left(-\frac{\sqrt{3}}{2}\mu H_M\right)\angle 120° + \left(\frac{\sqrt{3}}{2}\mu H_M\right)\angle 240° = 1.5\mu H_M \angle -90°$$

The rotating magnetic field

At the time when $\omega t = 90^0$:

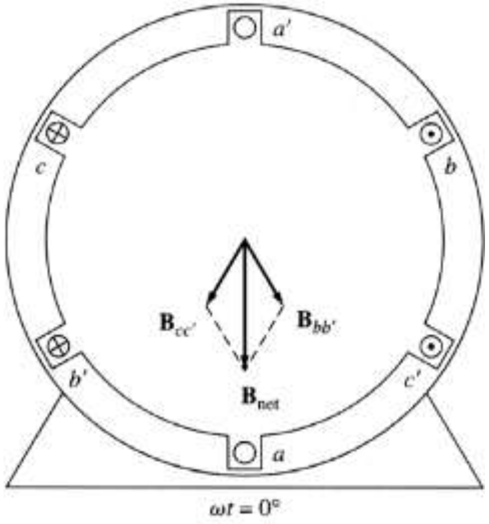
$$B_{aa'}(t) = \mu H_M \angle 0°$$
$$B_{bb'}(t) = \mu H_M \sin\left(-120°\right)\angle 120° = -0.5\mu H_M \angle 120°$$
$$B_{cc'}(t) = \mu H_M \sin\left(-240°\right)\angle 240° = -0.5\mu H_M\, 240°$$

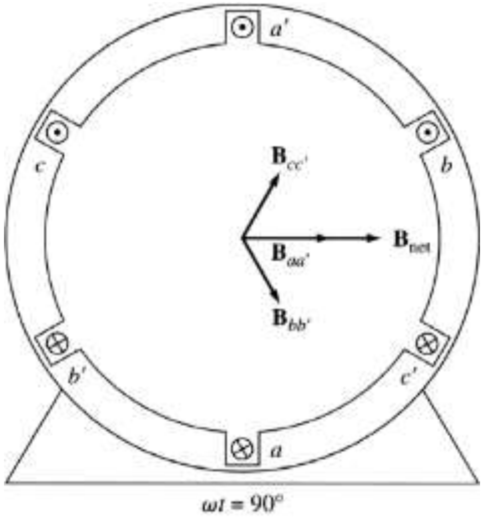
The total magnetic field from all three coils added together will be

$$B_{net} = B_{aa'} + B_{bb'} + B_{cc'} = \mu H_M \angle 0° + \left(-0.5\mu H_M\right)\angle 120° + \left(-0.5\mu H_M\right)\angle 240°$$
$$= 1.5\mu H_M \angle 0°$$

We note that the magnitude of the magnetic field is constant but its direction changes.

Therefore, the constant magnitude magnetic field is rotating in a counterclockwise direction.

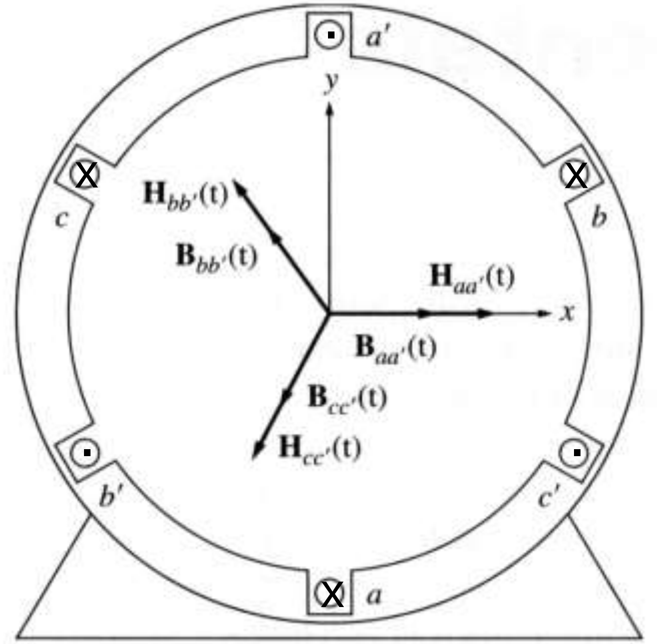




The rotating magnetic field

The magnetic flux density in the stator at any arbitrary moment is given by

$$B_{net}(t) = B_{aa'}(t) + B_{bb'}(t) + B_{cc'}(t)$$
$$= \mu H_M \sin \omega t \angle 0° + \mu H_M \sin(\omega t - 120°) \angle 120°$$
$$+ \mu H_M \sin(\omega t - 240°) \angle 240°$$



Each vector can be represented as a sum of *x* and *y* components:

$$B_{net}(t) = \mu H_M \sin \omega t \, \hat{x}$$
$$-0.5 \mu H_M \sin(\omega t - 120°) \hat{x} + \frac{\sqrt{3}}{2} \mu H_M \sin(\omega t - 120°) \hat{y}$$
$$-0.5 \mu H_M \sin(\omega t - 240°) \hat{x} - \frac{\sqrt{3}}{2} \mu H_M \sin(\omega t - 240°) \hat{y}$$

The rotating magnetic field

Which can be rewritten in form

$$B_{net}(t) = \left[\left[\mu H_M \sin\omega t - 0.5\mu H_M \sin\left(\omega t - 120^\circ\right) - 0.5\mu H_M \sin\left(\omega t - 240^\circ\right)\right]\right]\hat{x}$$
$$+\left[\frac{\sqrt{3}}{2}\mu H_M \sin\left(\omega t - 120^\circ\right) - \frac{\sqrt{3}}{2}\mu H_M \sin\left(\omega t - 240^\circ\right)\right]\hat{y}$$
$$=\left[\mu H_M \sin\omega t + \frac{1}{4}\mu H_M \sin\omega t + \frac{\sqrt{3}}{4}\mu H_M \cos\omega t + \frac{1}{4}\mu H_M \sin\omega t - \frac{\sqrt{3}}{4}\mu H_M \cos\omega t\right]\hat{x}$$
$$+\left[-\frac{\sqrt{3}}{4}\mu H_M \sin\omega t - \frac{3}{4}\mu H_M \cos\omega t + \frac{\sqrt{3}}{4}\mu H_M \sin\omega t - \frac{3}{4}\mu H_M \cos\omega t\right]\hat{y}$$

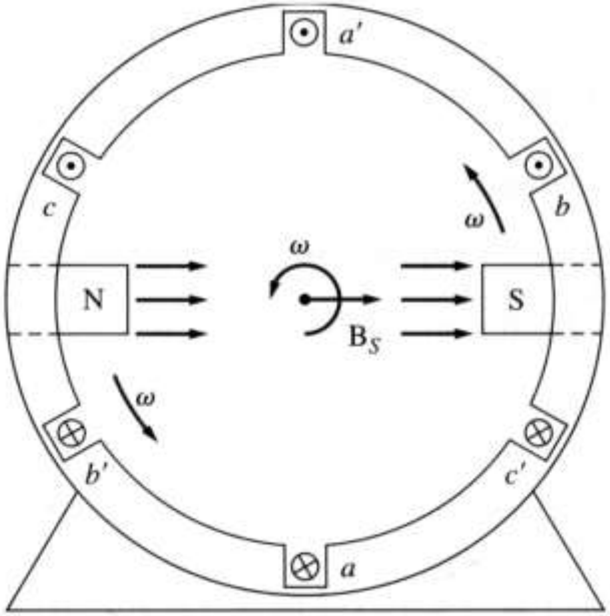
Finally:

$$B_{net}(t) = \left[1.5\mu B_M \sin\omega t\right]\hat{x} - \left[1.5\mu B_M \cos\omega t\right]\hat{y}$$

The net magnetic field has a constant magnitude and rotates **counterclockwise** at the angular velocity ω.

Relationship between electrical frequency and speed of field rotation

The stator rotating magnetic field can be represented as a north pole and a south pole. These magnetic poles complete one mechanical rotation around the stator surface for each electrical cycle of current. Therefore, the mechanical speed of rotation of the magnetic field equals to the electrical frequency.

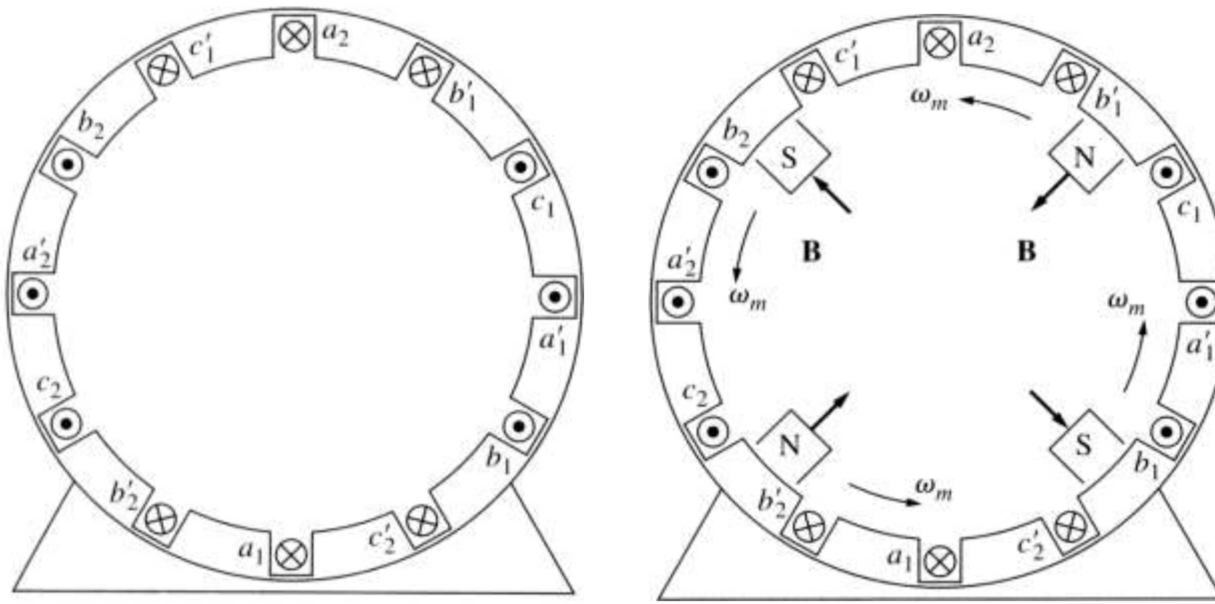


$$\left.\begin{aligned} f_e\,[Hz] &= f_m\,[rps] \\ \omega_e\,[rad/s] &= \omega_m\,[rad/s] \end{aligned}\right\} \text{two poles}$$

The magnetic field passes the windings of a two-pole stator in the following counterclockwise sequence: *a-c'-b-a'-c-b'*. What if 3 additional windings will be added? The new sequence will be: *a-c'-b-a'-c-b'-a-c'-b-a'-c-b'* and, when 3-phase current is applied to the stator, two north poles and two south poles will be produced. In this winding, a pole moves only halfway around the stator.

Relationship between electrical frequency and speed of field rotation

The relationship between the electrical angle θ_e (current's phase change) and the mechanical angle θ_m (at which the magnetic field rotates) in this situation is:



$$\theta_e = 2\theta_m$$

Therefore, for a four-pole stator:

$$\left.\begin{aligned} f_e\,[Hz] &= 2 f_m\,[rps] \\ \omega_e\,[rad/s] &= 2\omega_m\,[rad/s] \end{aligned}\right\}\quad \textit{four poles}$$

Relationship between electrical frequency and speed of field rotation

For an AC machine with *P* poles in its stator:

$$\theta_e = \frac{P}{2}\theta_m$$

$$f_e = \frac{P}{2} f_m$$

$$\omega_e = \frac{P}{2}\omega_m$$

Relating the electrical frequency to the motors speed in *rpm*:

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

Reversing the direction of field rotation

If the current in any two of the three coils is swapped, the direction of magnetic field rotation will be reversed. Therefore, to change the direction of rotation of an AC motor, we need to switch the connections of any two of the three coils.

In this situation, the net magnetic flux density in the stator is

$$\begin{aligned} B_{net}(t) &= B_{aa'}(t) + B_{bb'}(t) + B_{cc'}(t) \\ &= B_M \sin \omega t \angle 0° + B_M \sin\left(\omega t - 240°\right) \angle 120° + B_M \sin\left(\omega t - 120°\right) \angle 240° \end{aligned}$$

$$\begin{aligned} B_{net}(t) = B_M \sin \omega t \, \hat{x} - \left[0.5 B_M \sin\left(\omega t - 240°\right)\right] \hat{x} + \left[\frac{\sqrt{3}}{2} B_M \sin\left(\omega t - 240°\right)\right] \hat{y} \\ - \left[0.5 B_M \sin\left(\omega t - 120°\right)\right] \hat{x} + \left[\frac{\sqrt{3}}{2} B_M \sin\left(\omega t - 120°\right)\right] \hat{y} \end{aligned}$$

Reversing the direction of field rotation

$$B_{net}(t) = \left[\left[B_M \sin\omega t - 0.5 B_M \sin(\omega t - 240°) - 0.5 B_M \sin(\omega t - 120°) \right] \right] \hat{x}$$
$$+ \left[\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240°) + \frac{\sqrt{3}}{2} B_M \sin(\omega t - 120°) \right] \hat{y}$$

Therefore:

$$B_{net}(t) = \left[B_M \sin\omega t + \frac{1}{4} B_M \sin\omega t - \frac{\sqrt{3}}{4} B_M \cos\omega t + \frac{1}{4} B_M \sin\omega t - \frac{\sqrt{3}}{4} B_M \cos\omega t \right] \hat{x}$$
$$+ \left[-\frac{\sqrt{3}}{4} B_M \sin\omega t + \frac{3}{4} B_M \cos\omega t + \frac{\sqrt{3}}{4} B_M \sin\omega t + \frac{3}{4} B_M \cos\omega t \right] \hat{y}$$

Finally:

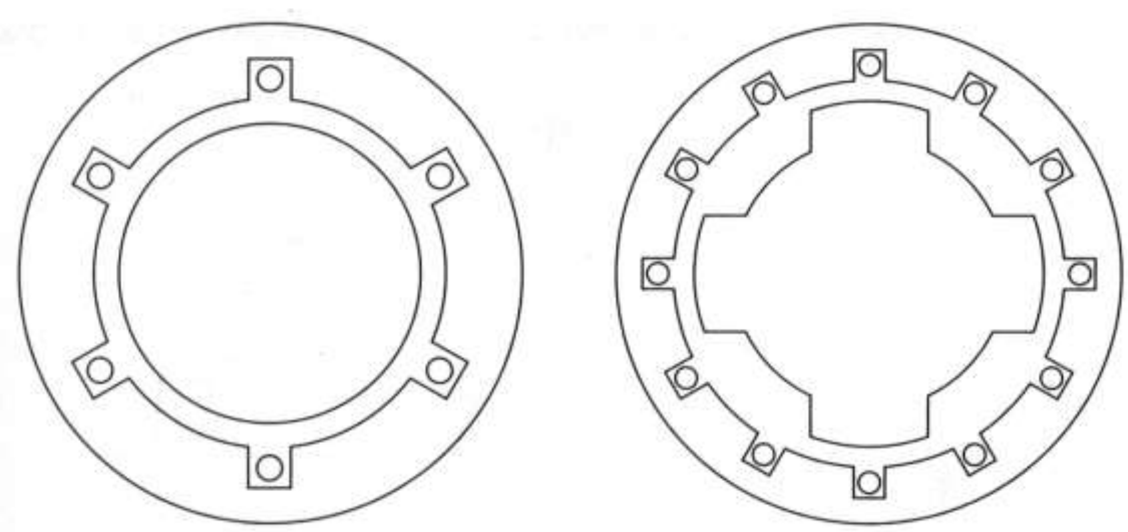
$$B_{net}(t) = \left[1.5\mu B_M \sin\omega t \right] \hat{x} + \left[1.5\mu B_M \cos\omega t \right] \hat{y}$$

The net magnetic field has a constant magnitude and rotates **clockwise** at the angular velocity ω. Switching the currents in two stator phases reverses the direction of rotation in an AC machine.

Magnetomotive force and flux distribution on an AC machine

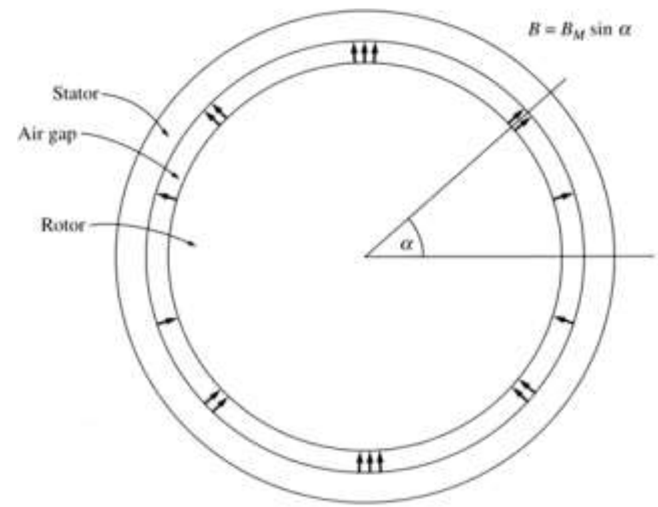
In the previous discussion, we assumed that the flux produced by a stator inside an AC machine behaves the same way it does in a vacuum. However, in real machines, there is a ferromagnetic rotor in the center with a small gap between a rotor and a stator.

A rotor can be cylindrical (such machines are said to have non-salient poles), or it may have pole faces projecting out from it (salient poles). We will restrict our discussion to non-salient pole machines only (cylindrical rotors).

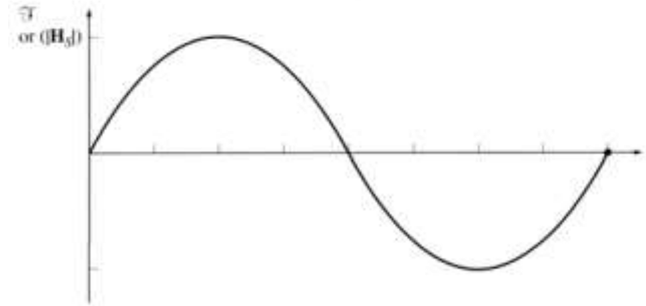


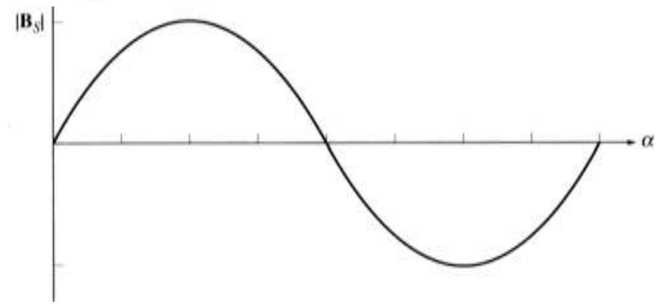
Magnetomotive force and flux distribution on an AC machine

The reluctance of the air gap is much higher than the reluctance of either the rotor or the stator; therefore, the flux density vector *B* takes the shortest path across the air gap: it will be perpendicular to both surfaces of rotor and stator.



To produce a sinusoidal voltage in this machine, the magnitude of the flux density vector *B* must vary sinusoidally along the surface of the air gap. Therefore, the magnetic field intensity (and the mmf) will vary sinusoidally along the air gap surface.





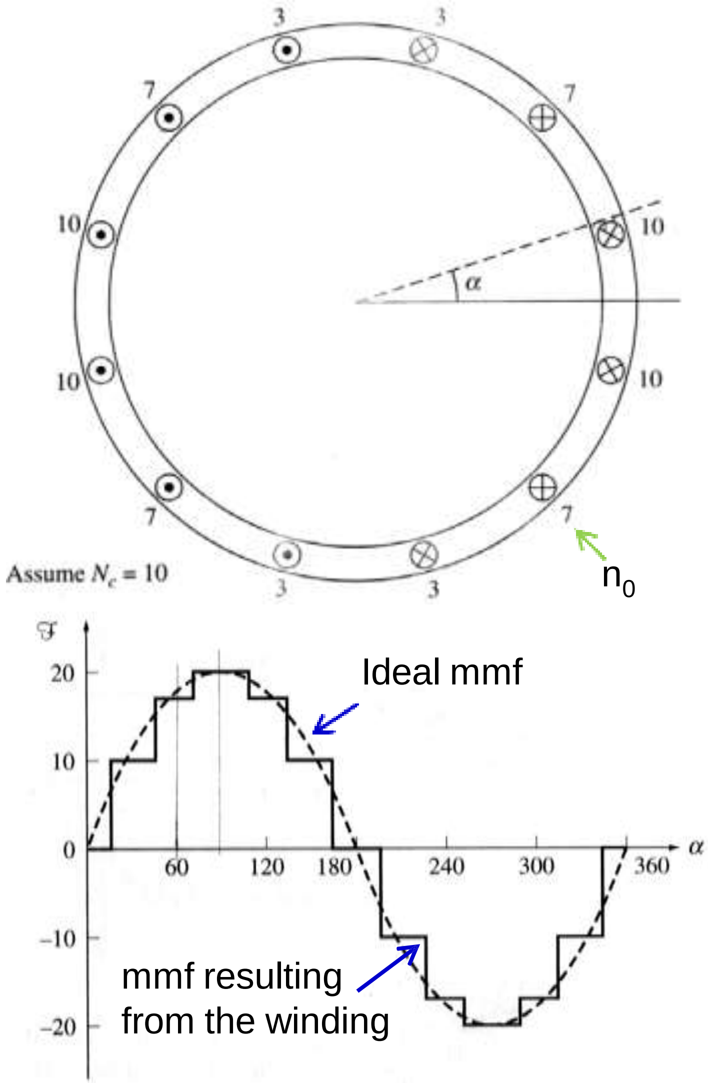
Magnetomotive force and flux distribution on an AC machine

One obvious way to achieve a sinusoidal variation of mmf along the air gap surface would be to distribute the turns of the winding that produces the mmf in closely spaced slots along the air gap surface and vary the number of conductors in each slot sinusoidally, according to:

$$n_c = N_c \cos\alpha$$

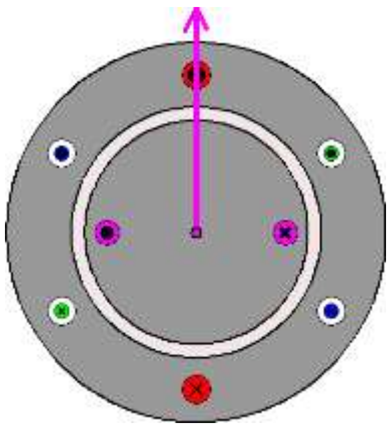
where N_c is the number of conductors at the angle of 0^0 and α is the angle along the surface.

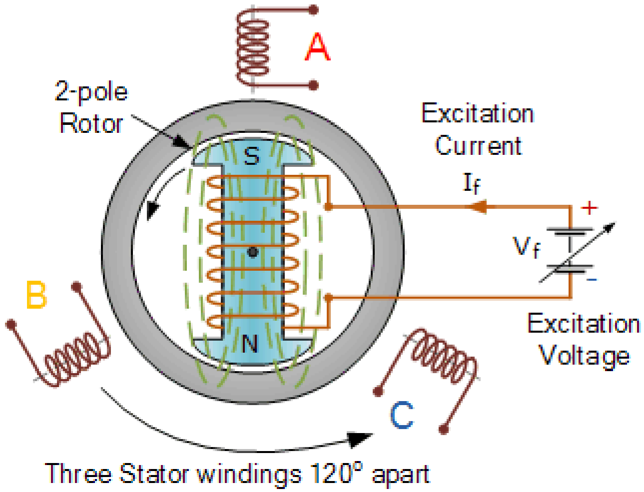
However, in practice, only a finite number of slots and integer numbers of conductors are possible. As a result, real mmf will approximate the ideal mmf if this approach is taken.

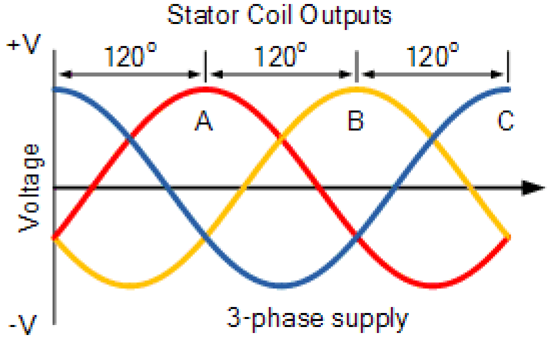


Induced voltage in AC machines

Just as a 3-phase set of currents in a stator can produce a rotating magnetic field, a rotating magnetic field can produce a 3-phase set of voltages in the coils of a stator.

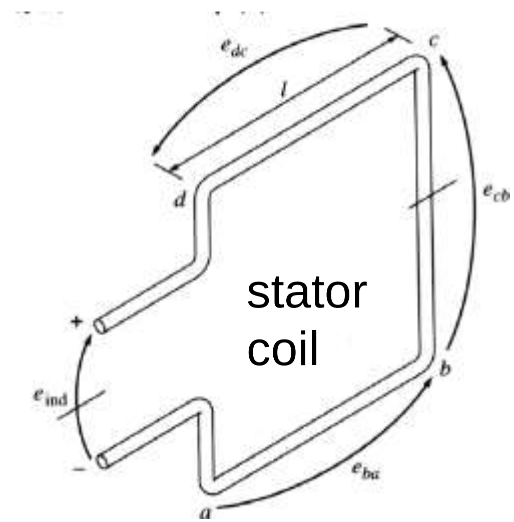






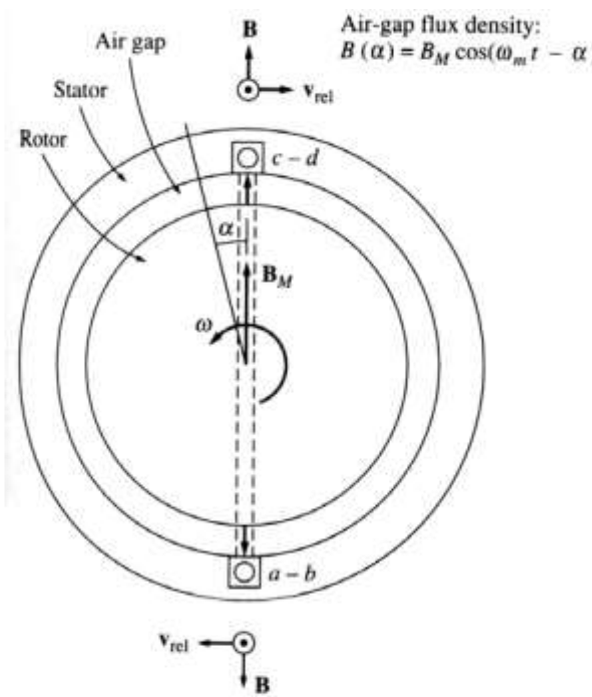
The induced voltage in a single coil on a two-pole stator

Assume that a rotor with a sinusoidally distributed magnetic field rotates in the center of a stationary coil.



stator coil

We further assume that the magnitude of the flux density *B* in the air gap between the rotor and the stator varies sinusoidally with mechanical angle, while its direction is always radially outward.

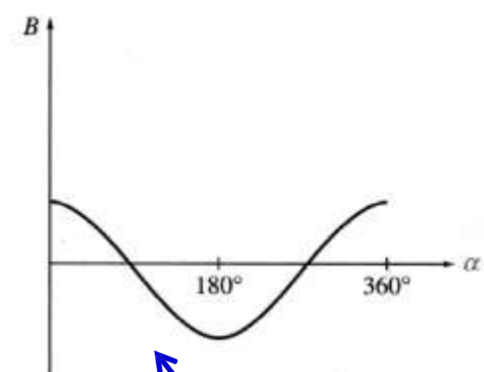


Note, that this is an ideal flux distribution.

The magnitude of the flux density vector at a point around the rotor is

$$B = B_M \cos\alpha$$

Where α is the angle from the direction of peak flux intensity.



Flux density in a gap

The induced voltage in a single coil on a two-pole stator

Since the rotor is rotating within the stator at an angular velocity ω_m, the magnitude of the flux density vector at any angle α around the stator is

$$B = B_M \cos(\omega t - \alpha)$$

The voltage induced in a wire is $$e_{ind} = (v \times B) \cdot l$$

Here v is the velocity of the wire relative to the magnetic field
B is the magnetic flux density vector
l is the length of conductor in the magnetic field

However, this equation was derived for a moving wire in a stationary magnetic field. In our situation, the wire is stationary and the magnetic field rotates. Therefore, the equation needs to be modified: we need to change reference such way that the field appears as stationary.

The induced voltage in a single coil on a two-pole stator

The total voltage induced in the coil is a sum of the voltages induced in each of its four sides. These voltages are:

1. Segment *ab*: $\alpha = 180^0$; assuming that *B* is radially outward from the rotor, the angle between *v* and *B* is 90^0, so

$$e_{ba} = (v \times B) \cdot I = -vB_M l \cos(\omega_m t - 180°)$$

2. Segment *bc*: the voltage will be zero since the vectors (*v* x *B*) and *l* are perpendicular.

$$e_{cb} = (v \times B) \cdot I = 0$$

3. Segment *cd*: $\alpha = 0^0$; assuming that *B* is radially outward from the rotor, the angle between *v* and *B* is 90^0, so

$$e_{dc} = (v \times B) \cdot I = vB_M l \cos(\omega_m t)$$

4. Segment *da*: the voltage will be zero since the vectors (*v* x *B*) and *l* are perpendicular.

$$e_{ad} = (v \times B) \cdot I = 0$$

The induced voltage in a single coil on a two-pole stator

Therefore, the total voltage on the coil is:

$$e_{ind} = e_{ba} + e_{dc} = -vB_M l \cos(\omega_m t - 180°) + vB_M l \cos\omega_m t$$
$$= \{\cos\theta = -\cos(\theta)\} = 2vB_M l \cos\omega_m t$$

Since the velocity of the end conductor is $v = r\omega_m$

Then: $e_{ind} = 2rlB_M\omega_m \cos\omega_m t$

The flux passing through a coil is $\phi = 2rlB_M$

Therefore: $e_{ind} = \phi\omega_m \cos\omega_m t$

Finally, if the stator coil has N_C turns of wire, the total induced voltage in the coil:

$$e_{ind} = N_C\phi\omega_m \cos\omega_m t$$

The induced voltage in a 3-phase set of coils

In three coils, each of N_C turns, placed around the rotor magnetic field, the induced in each coil will have the same magnitude and phases differing by 120^0:

$$e_{aa'}(t) = N_C \phi \omega_m \cos \omega_m t$$

$$e_{bb'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 120°\right)$$

$$e_{cc'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 240°\right)$$

A 3-phase set of currents can generate a uniform rotating magnetic field in a machine stator, and a uniform rotating magnetic field can generate a 3-phase set of voltages in such stator.

The rms voltage in a 3-phase stator

The peak voltage in any phase of a 3-phase stator is:

$$E_{\max} = N_C \phi \omega_m$$

For a 2-pole stator:

$$\omega_m = \omega_e = \omega = 2\pi f$$

Thus:

$$E_{\max} = 2\pi N_C \phi f$$

The rms voltage in any phase of a 2-pole 3-phase stator is:

$$E_A = \frac{2\pi}{\sqrt{2}} N_C \phi f = \sqrt{2}\pi N_C \phi f$$

The rms voltage at the terminals will depend on the type of stator connection: if the stator is Y-connected, the terminal voltage will be $\sqrt{3}E_A$.
For the delta connection, it will be just E_A.

Induced voltage: Example

Example 6.1: The peak flux density of the rotor magnetic field in a simple 2-pole 3-phase generator is 0.2 T; the mechanical speed of rotation is 3600 rpm; the stator diameter is 0.5 m; the length of its coil is 0.3 m and each coil consists of 15 turns of wire. The machine is Y-connected.

a)What are the 3-phase voltages of the generator as a function of time?
b)What is the rms phase voltage of the generator?
c)What is the rms terminal voltage of the generator?

The flux in this machine is given by

$$\phi = 2rlB = dlB = 0.5 \cdot 0.3 \cdot 0.2 = 0.03\, Wb$$

The rotor speed is

$$\omega = \frac{3600 \cdot 2\pi}{60} = 377 \frac{rad}{s}$$

Induced voltage: Example

a) The magnitude of the peak phase voltage is

$$E_{\max} = N_C \phi \omega = 15 \cdot 0.03 \cdot 377 = 169.7\ V$$

and the three phase voltages are:

$$e_{aa'}(t) = 169.7 \sin\left(377t\right)$$

$$e_{bb'}(t) = 169.7 \sin\left(377t - 120°\right)$$

$$e_{cc'}(t) = 169.7 \sin\left(377t - 240°\right)$$

b) The rms voltage of the generator is

$$E_A = \frac{E_{\max}}{\sqrt{2}} = \frac{169.7}{\sqrt{2}} = 120\ V$$

c) For a Y-connected generator, its terminal voltage is

$$V_T = \sqrt{3} \cdot 120 = 208\ V$$

Induced torque in an AC machine

In an AC machine under normal operating conditions two magnetic fields are present: a field from the rotor and a field from the stator circuits. The interaction of these magnetic fields produces the torque in the machine.

Assuming a sinusoidal stator flux distribution peaking in the upward direction

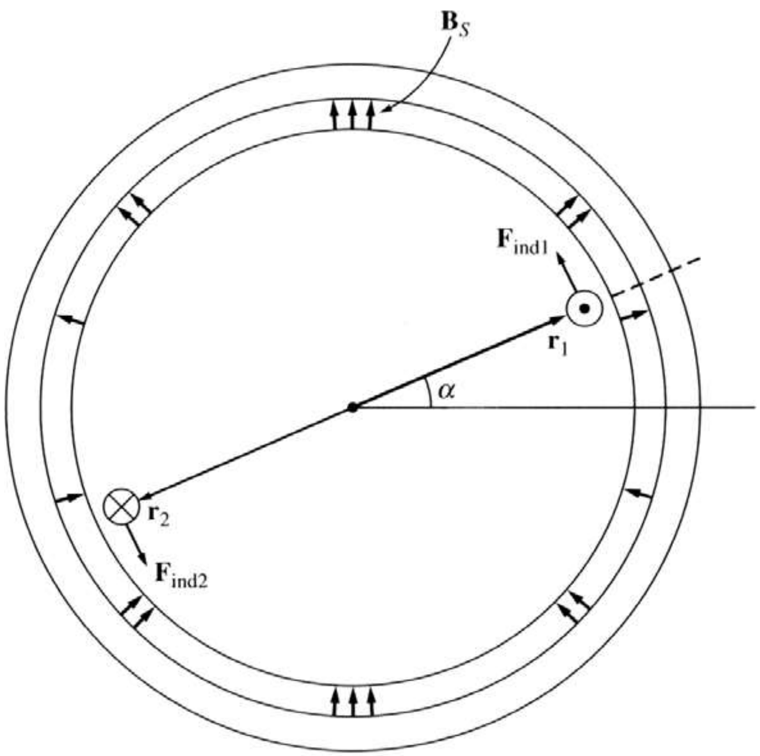
$$B_S(\alpha) = B_S \sin\alpha$$

(where B_S is the magnitude of the peak flux density) and a single coil of wire mounted on the rotor, the induced force on the first conductor (on the right) is

$$F = i(\mathbf{l} \times \mathbf{B}) = ilB_S \sin\alpha$$

The torque on this conductor is (counter-clockwise)

$$\tau_{ind,1} = \mathbf{r} \times \mathbf{F} = rilB_S \sin\alpha$$



$B_S(\alpha) = B_S \sin\alpha$

Induced torque in an AC machine

The induced force on the second conductor (on the left) is

$$F = i\left(\mathbf{l} \times \mathbf{B}\right) = ilB_S \sin\alpha$$

The torque on this conductor is (counter-clockwise)

$$\tau_{ind,2} = \mathbf{r} \times \mathbf{F} = rilB_S \sin\alpha$$

Therefore, the torque on the rotor loop is

$$\tau_{ind} = 2rilB_S \sin\alpha$$

We may notice the following:

1.The current i flowing in the rotor coil produces its own magnetic field H_R, whose magnitude is proportional to the current and direction can be found via the RHR.

2.The angle between the peak of the stator flux density B_S and the peak of the magnetic field intensity H_R is γ.

Induced torque in an AC machine

Furthermore,

$$\gamma = 180° - \alpha$$

$$\sin\gamma = \sin(180° - \alpha) = \sin\alpha$$

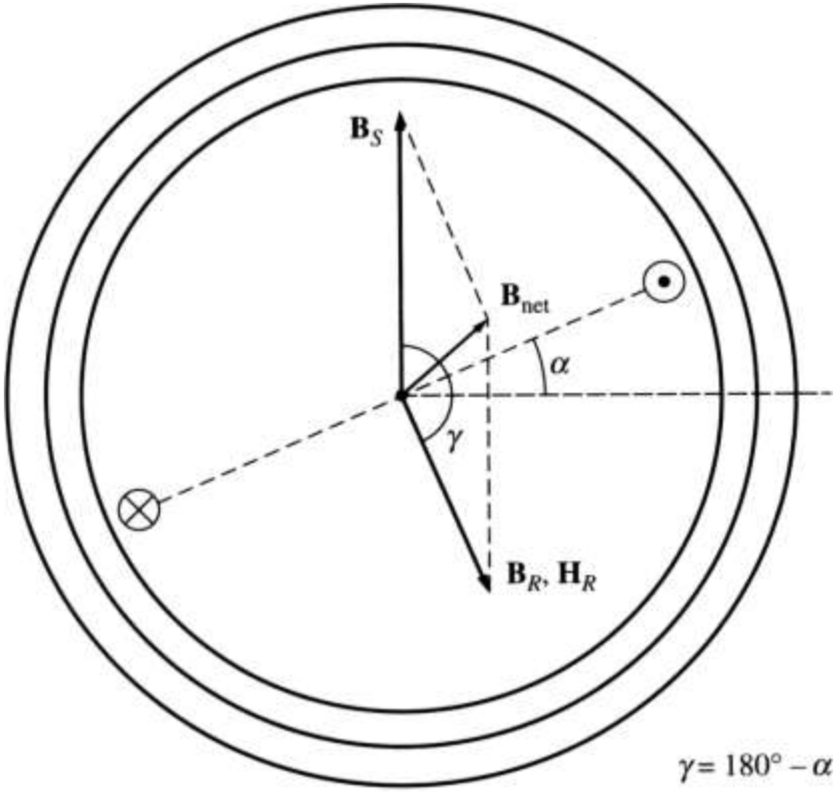
Therefore, the torque on the loop is

$$\tau_{ind} = KH_R B_S \sin\alpha$$

Here *K* is a constant dependent on the machine design. Therefore:

$$\tau_{ind} = KH_R \times B_S$$

Since $B_R = \mu H_R$



$$\tau_{ind} = kB_R \times B_S$$

Induced torque in an AC machine

Assuming no saturation, the net magnetic field is a vector sum of rotor and stator fields:

$$B_{net} = B_R + B_S$$

$$\tau_{ind} = kB_R \times \left(B_{net} - B_R\right) = k\left(B_R \times B_{net}\right) - k\left(B_R \times B_R\right)$$

Since the cross-product of any vector with itself is zero:

$$\tau_{ind} = kB_R \times B_{net}$$

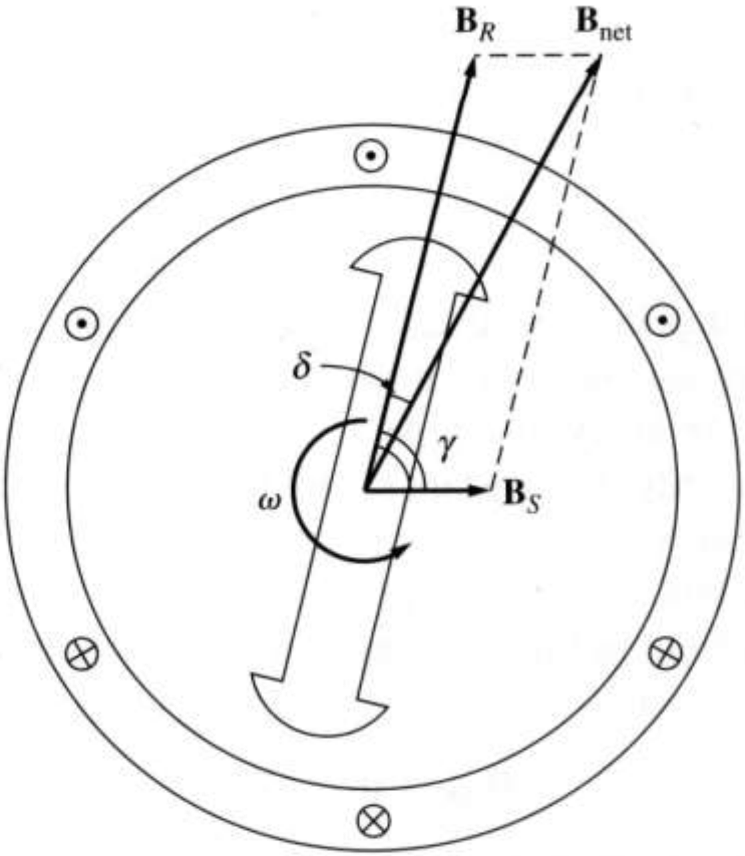
Induced torque in an AC machine

Assuming that the angle between the rotor B_R and stator B_S magnetic fields is δ:

$$\tau_{ind} = kB_R B_{net} \sin\delta$$

Assume that the rotor of the AC machine is rotating counter-clockwise and the configuration of magnetic fields is shown.

The torque will be clockwise, i.e. opposite to the direction of rotation of the rotor. Therefore, this machine must be acting as a generator.



Winding insulation in AC machines

- Winding insulation is of critical importance. If insulation of a motor or generator breaks down, the machine shorts out and the repair is expensive and sometimes even impossible. Most insulation failures are due to overheating.
- To limit windings temperature, the maximum power that can be supplied by the machine must be limited in addition to the proper ventilation.
- ROT: the life expectancy of a motor with a given type of insulation is halved for each 10^{o}C rise above the rated winding temperature

AC machine power flows and losses

The efficiency of an AC machine is defined as

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\%$$

Since the difference between the input and output powers of a machine is due to the losses occurring inside it, the efficiency is

$$\eta = \frac{P_{in} - P_{loss}}{P_{in}} \cdot 100\%$$

AC machine power losses

Losses occurring in an AC machine can be divided into four categories:

1. Electrical or Copper losses

These losses are resistive heating losses that occur in the stator (armature) winding and in the rotor (field) winding of the machine. For a 3-phase machine, the stator copper losses and synchronous rotor copper losses are:

$$P_{SCL} = 3I_A^2 R_A$$

$$P_{RCL} = 3I_F^2 R_F$$

Where I_A and I_F are currents flowing in each armature phase and in the field winding respectively. R_A and R_F are resistances of each armature phase and of the field winding respectively. These resistances are usually measured at normal operating temperature.

AC machine power losses

2. Core losses

These losses are the hysteresis losses and eddy current losses. They vary as B^2 (flux density) and as $n^{1.5}$ (speed of rotation of the magnetic field).

3. Mechanical losses

There are two types of mechanical losses: friction (friction of the bearings) and windage (friction between the moving parts of the machine and the air inside the casing). These losses are often lumped together and called the no-load rotational loss of the machine. They vary as the cube of rotation speed n^3.

4. Stray (miscellaneous) losses

These are the losses that cannot be classified in any of the previous categories. They are usually due to inaccuracies in modeling. For many machines, stray losses are assumed as 1% of full load.

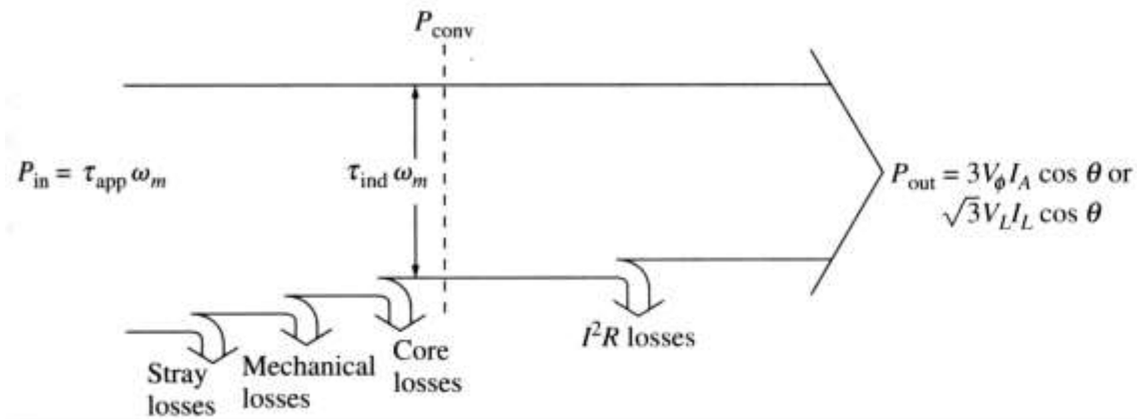
The power-flow diagram

On of the most convenient technique to account for power losses in a machine is the power-flow diagram.

AC generator:

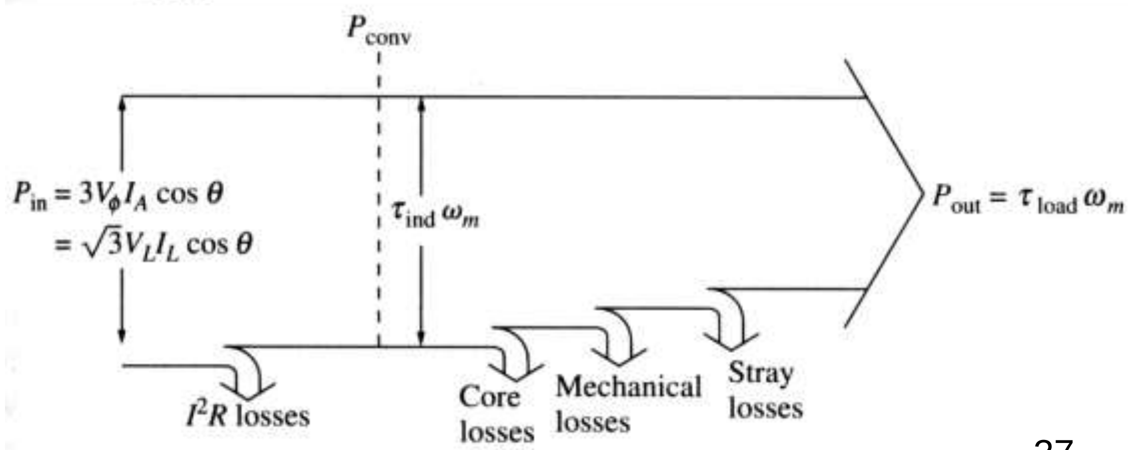
The mechanical power is input, and then all losses but cupper are subtracted. The remaining power P_{conv} is ideally converted to electricity:

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



AC motor:

Power-flow diagram is simply reversed.



Voltage regulation

Voltage regulation (VR) is a commonly used figure of merit for generators:

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \cdot 100\%$$

Here V_{nl} and V_{fl} are the no-load full-load terminal voltages of the generator. VR is a rough measure of the generator's voltage-current characteristic. A small VR (desirable) implies that the generator's output voltage is more constant for various loads.

Speed regulation

Speed regulation (SR) is a commonly used figure of merit for motors:

$$SR = \frac{n_{nl} - n_{fl}}{n_{fl}} \cdot 100\%$$

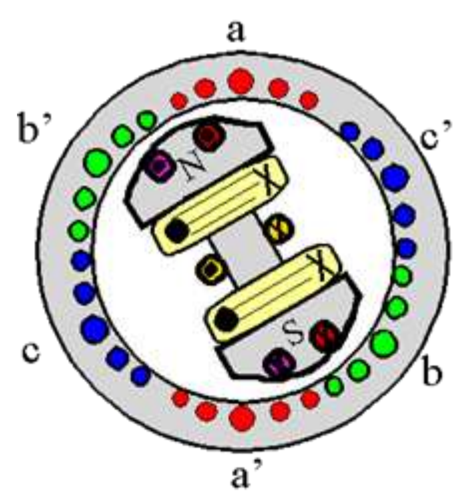
$$SR = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \cdot 100\%$$

Here n_{nl} and n_{fl} are the no-load full-load speeds of the motor. SR is a rough measure of the motor's torque-speed characteristic. A positive SR implies that a motor's speed drops with increasing load. The magnitude of SR reflects a steepness of the motor's speed-torque curve.

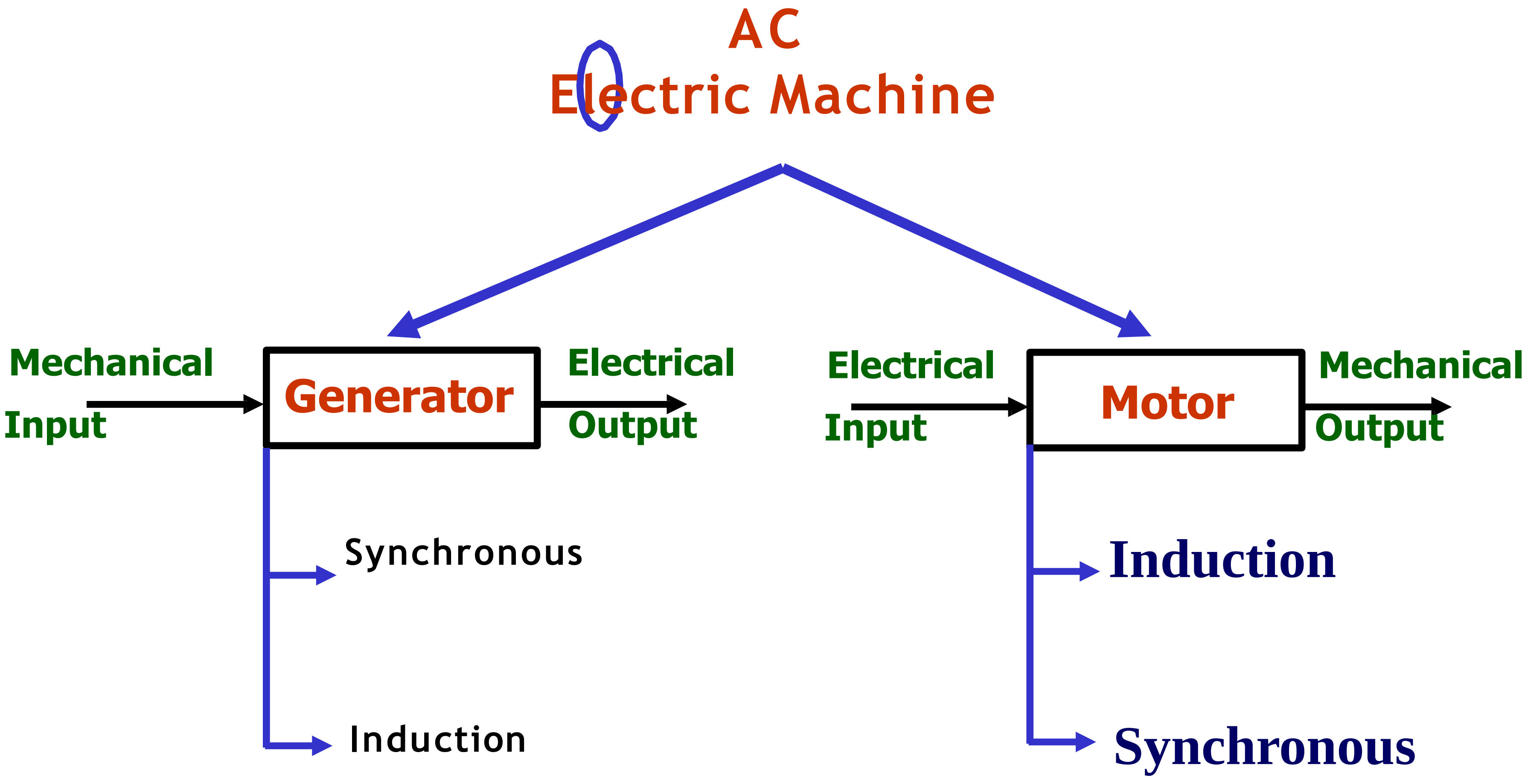
EE471-Electrical Machines II
Topic 1: Synchronous Motors

LEARNING GOALS

- **Introduction**
- **Motor Equivalent Circuit**
- **Power-angle and other Performance Characteristics (Motor)**
- **Starting of Synchronous Motor**

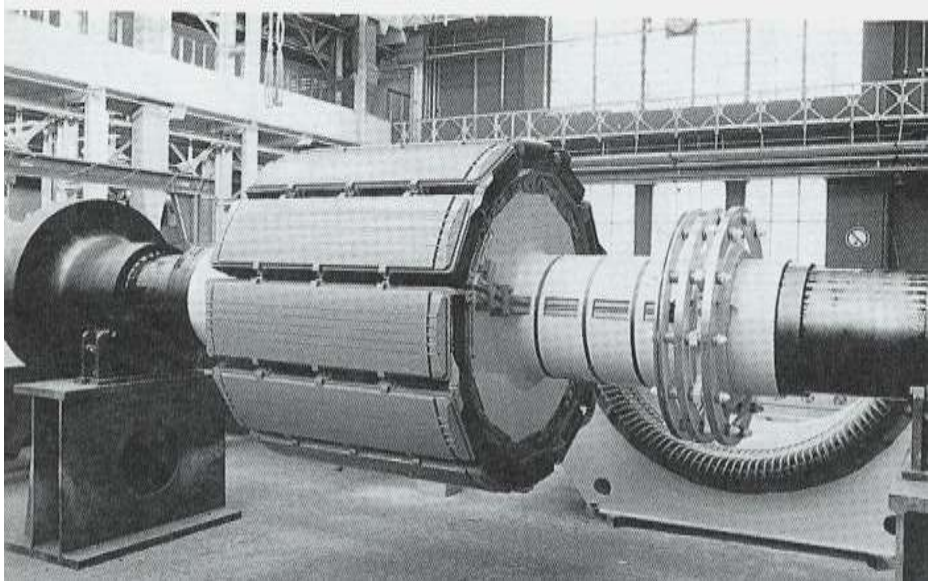


Introduction



Construction of Synchronous Machine

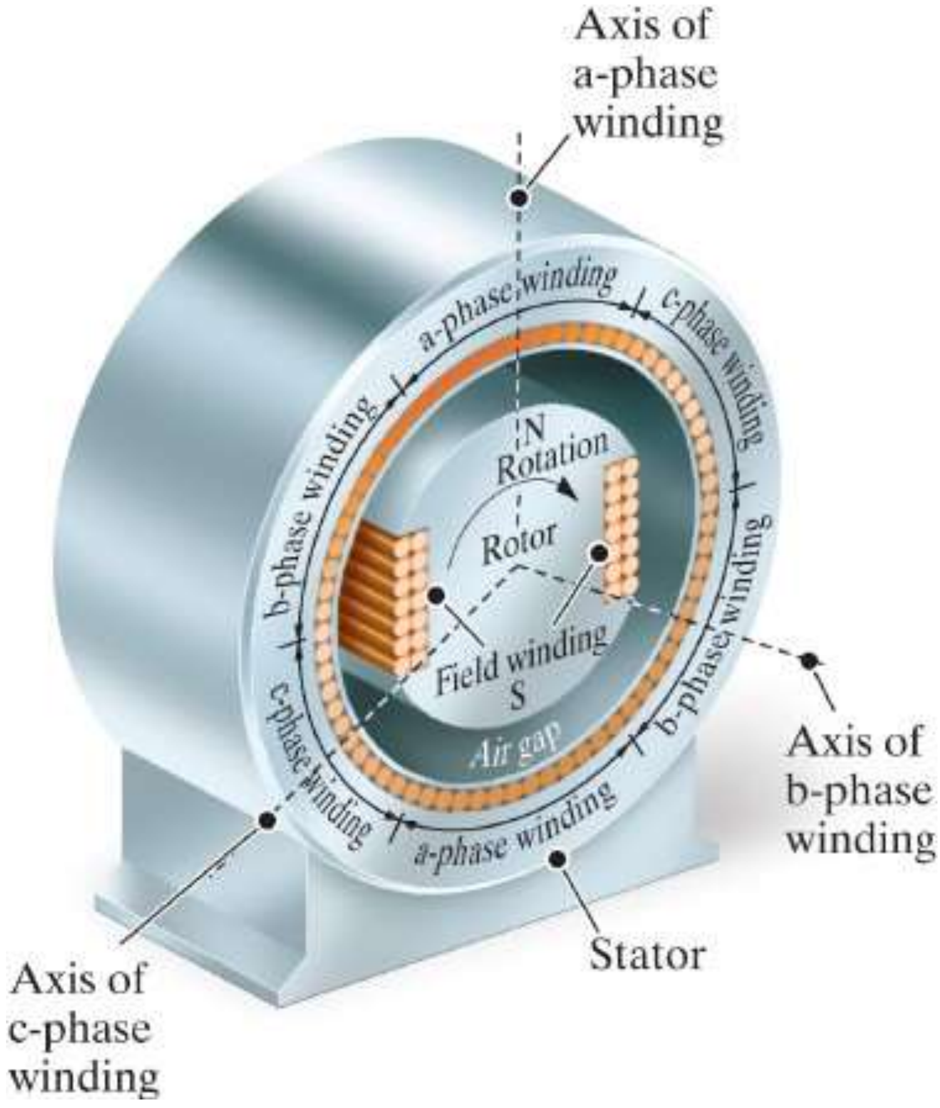
- Synchronous machine is a doubly excited machine.
- It consists of:

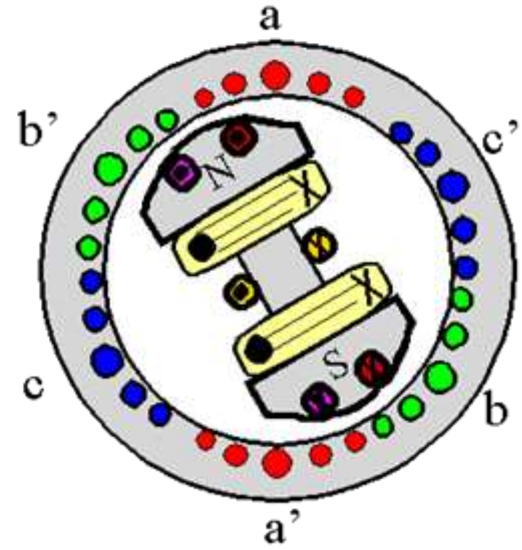


Stator

Rotor

Construction of Synchronous Machine

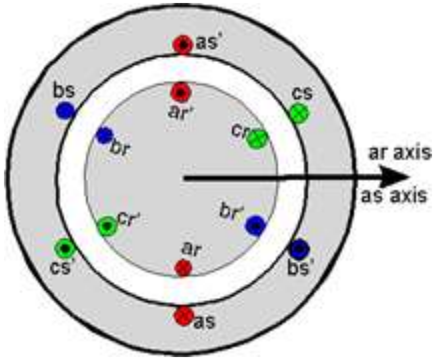




Construction of synchronous machines

Synchronous machines are AC machines that have a field circuit supplied by an external DC source.

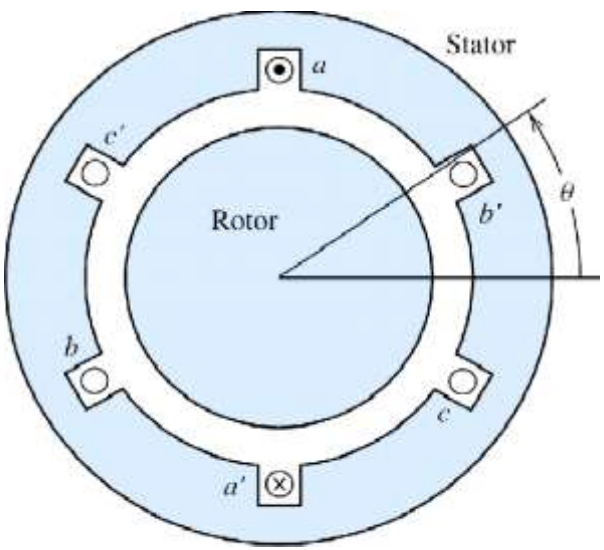
In a synchronous motor, a 3-phase set of stator currents produces a rotating magnetic field causing the rotor magnetic field to align with it. The rotor magnetic field is produced by a DC current applied to the rotor winding.



Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

Synchronous Machine: Stator

A three-phase windings is placed in slots cut on the inner surface of the stationary part. The ends of these windings can be connected in star or delta to form a three phase connection. These windings are fed from a three-phase ac supply (Motor) or connected to a three-phase ac load (Gen) .



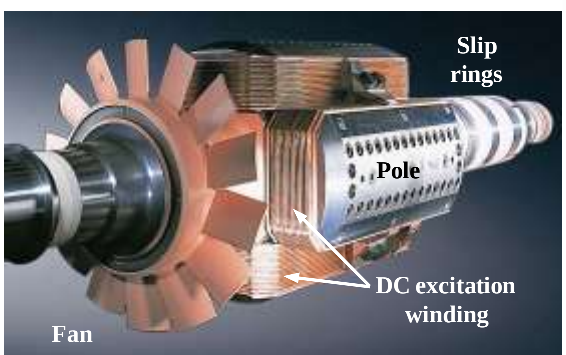
Synchronous Machine: Rotor

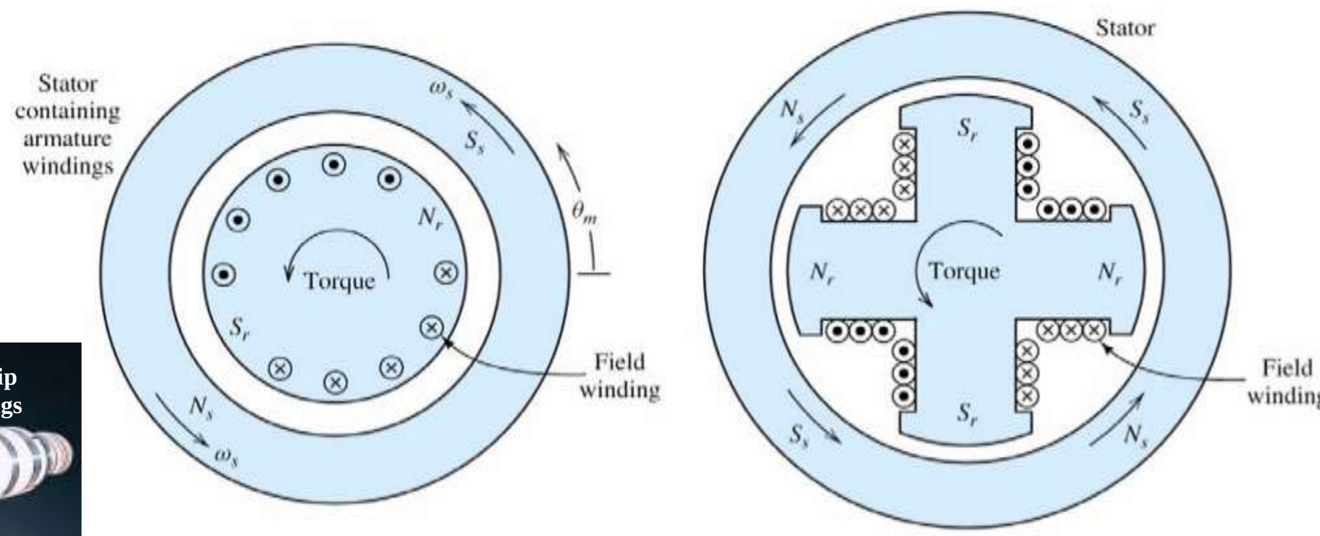
The Rotor winding is known as the field winding or excitation winding

Synchronous machine rotor consists of even numbers of poles excited from a dc supply. It can be either:

A) Cylindrical rotor

B) Salient rotor

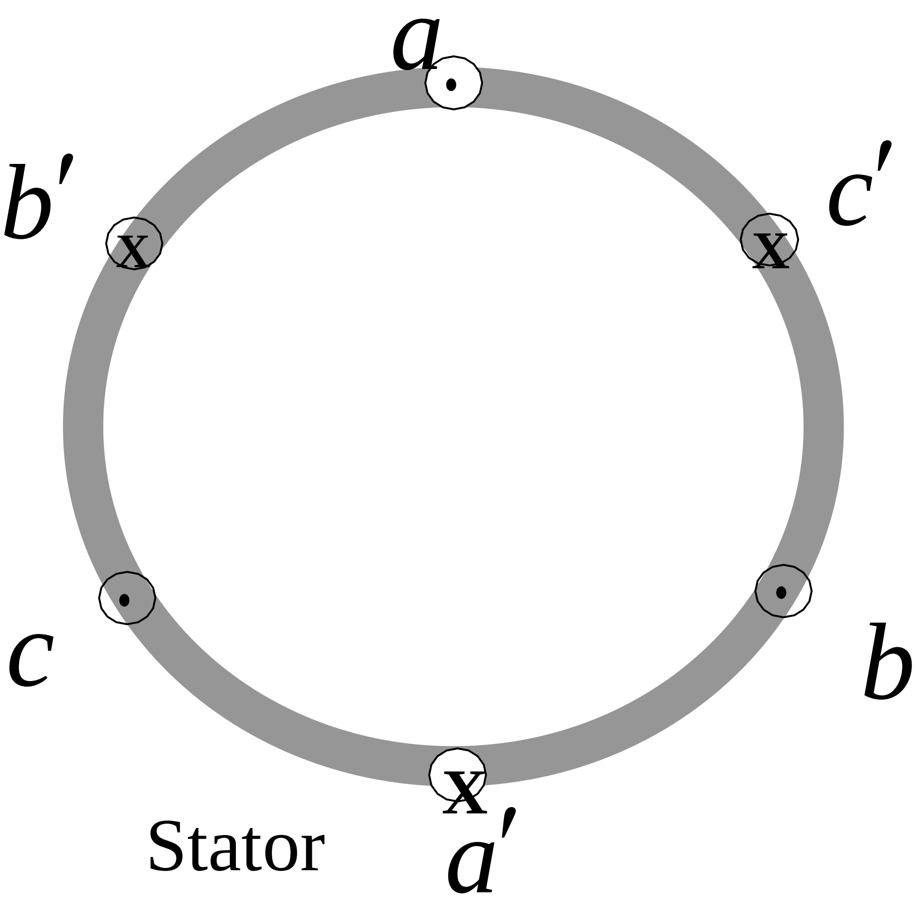


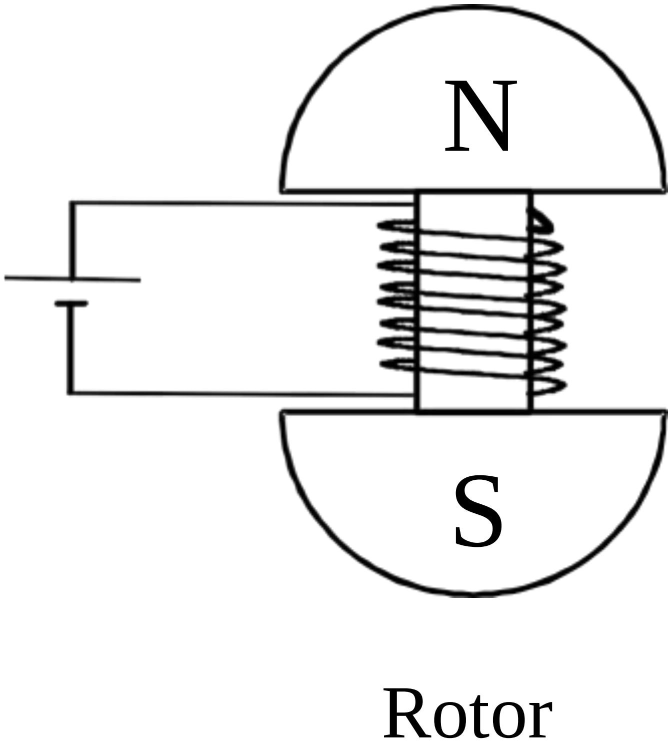


(a) Two-pole cylindrical rotor machine (b) Four-pole salient rotor machine

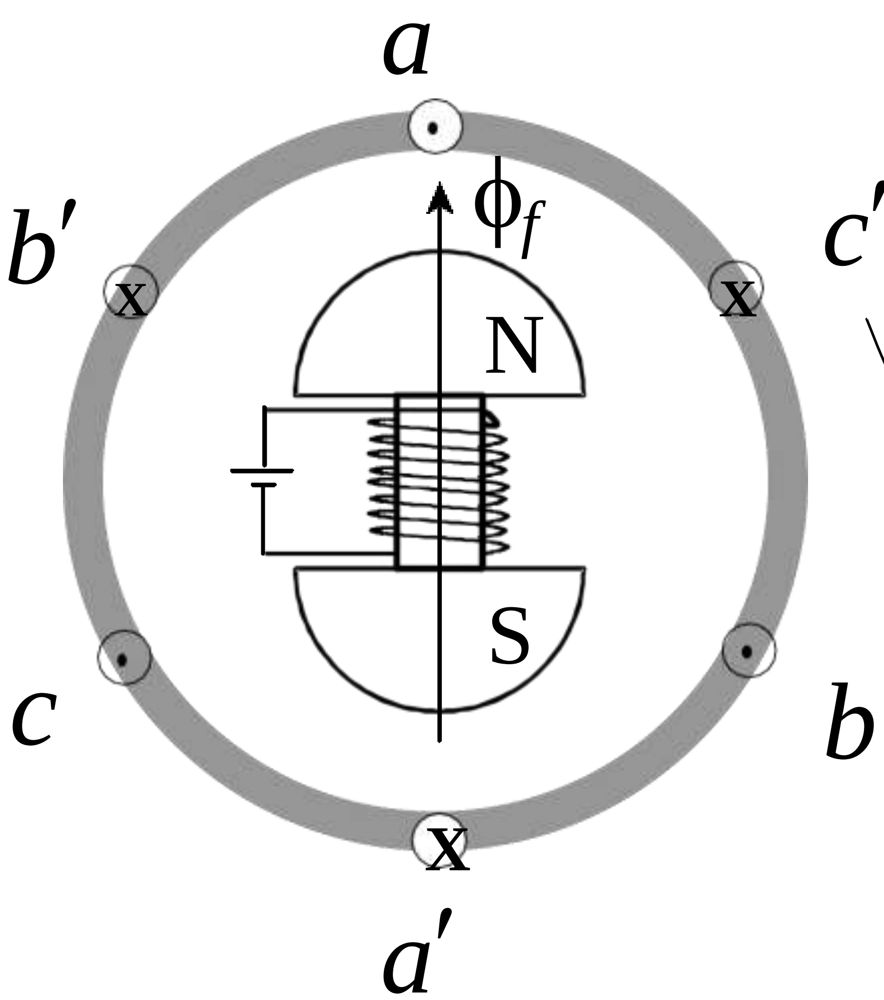
Synchronous Machine: Rotor

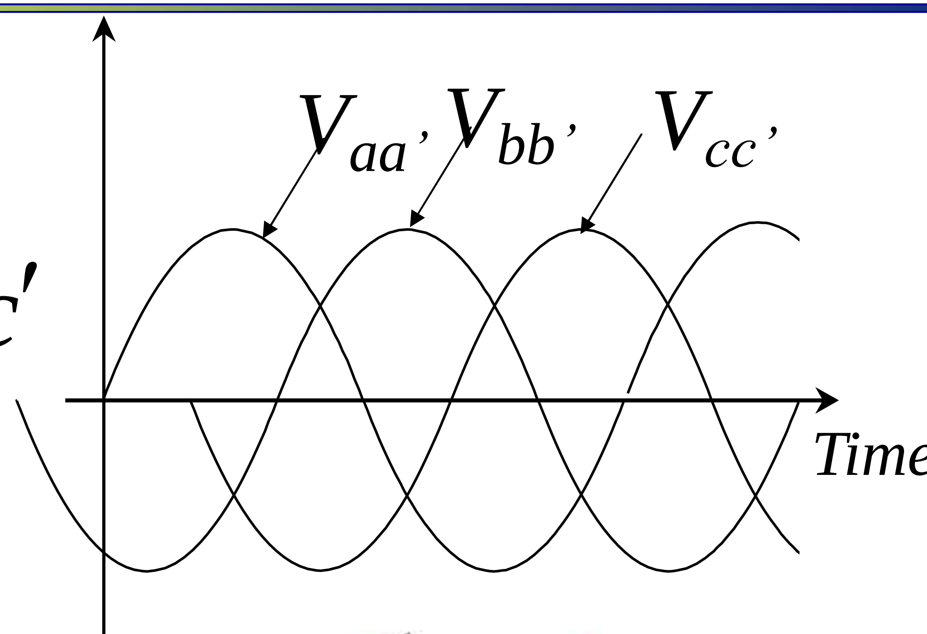
The Rotor winding is known as the field winding or excitation winding

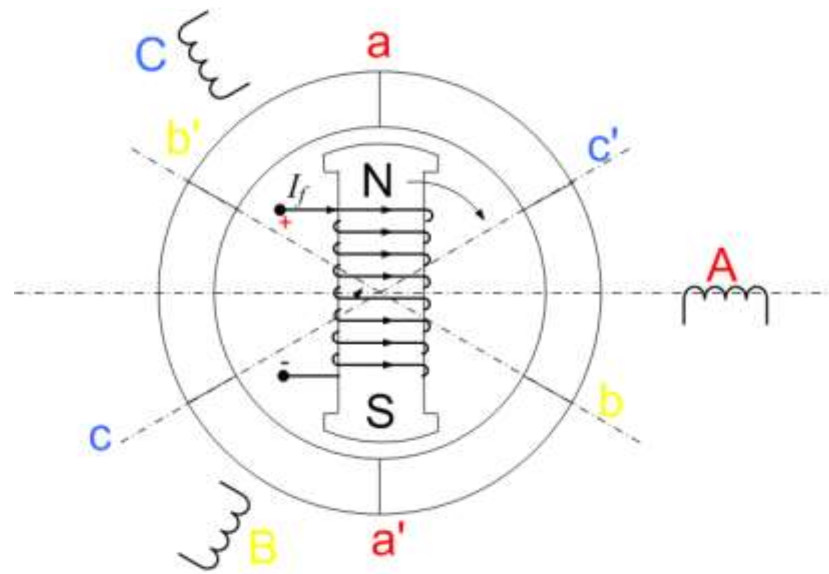




Synchronous Machine: Rotor







Principle of Operation: Generator

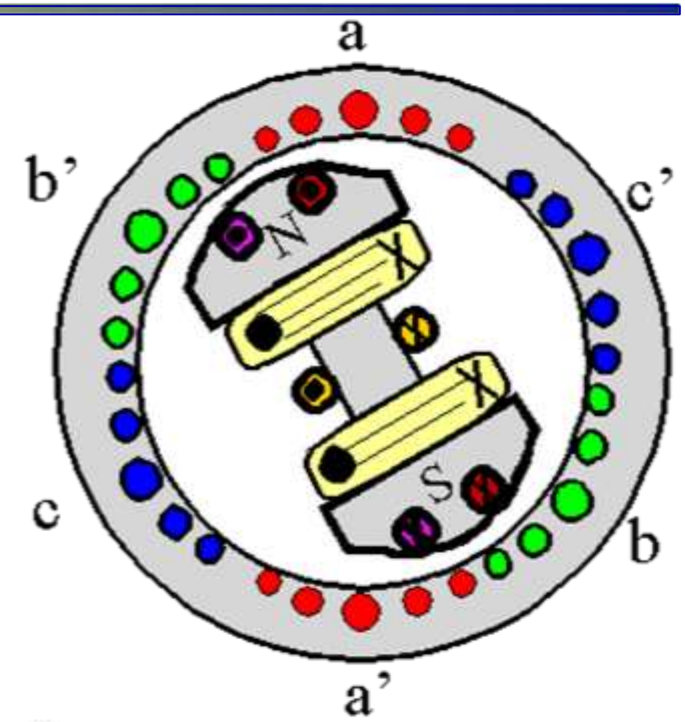
When a dc field current flows through the rotor field winding it establishes a flux in the air-gap.

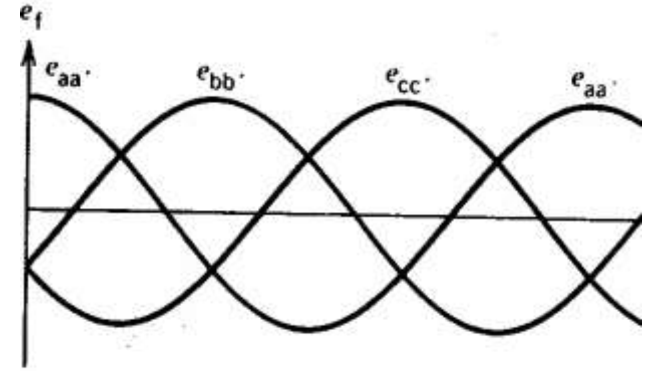
If the rotor is now rotating, a revolving field is produced in the air-gap.

The rotating flux will link the armature windings aa', bb', and cc' and will induce voltages in these stator windings.

These induced voltages have the same magnitudes but are phase-shifted by 120 electrical degrees.

The rotor speed and the frequency of the induced voltages are related by:





$$n_s = \frac{120\ f_s}{p}$$

where

f_s is the frequency of the induced voltage.

p is the total number of poles.

Induced EMF

The instantaneous value of the induced voltage in *N* turns coil is given by:

$$e = N \frac{d\phi}{dt}$$

$$\text{Let } \phi = \phi_m \sin(\omega t)$$

$$e = N \omega \phi_m \cos(\omega t)$$

The r.m.s. value of the induced voltage per phase is

$$E_{rms} = 4.44 f N_{ph} \Phi_p K_w$$

where

N_{ph} is the number of turns in series per phase

f is the frequency

ϕ_p is the flux per pole

K_w is the winding factor

Principle of Operation: Motor

when a three-phase balanced current is applied to a three-phase stator winding, a rotating magnetic flux is produced. The speed at which the magnetic flux rotates is called the synchronous speed:

$$n_s = \frac{120 f_s}{p}$$

Now if the rotor poles are excited by a dc field current , the rotor poles will be locked to opposite stator poles and will then run at synchronous speed.

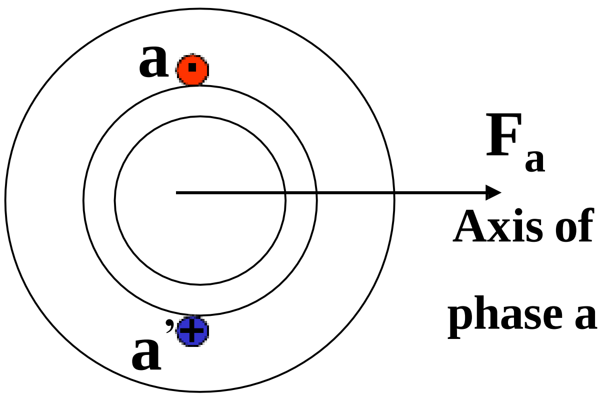
Example 1

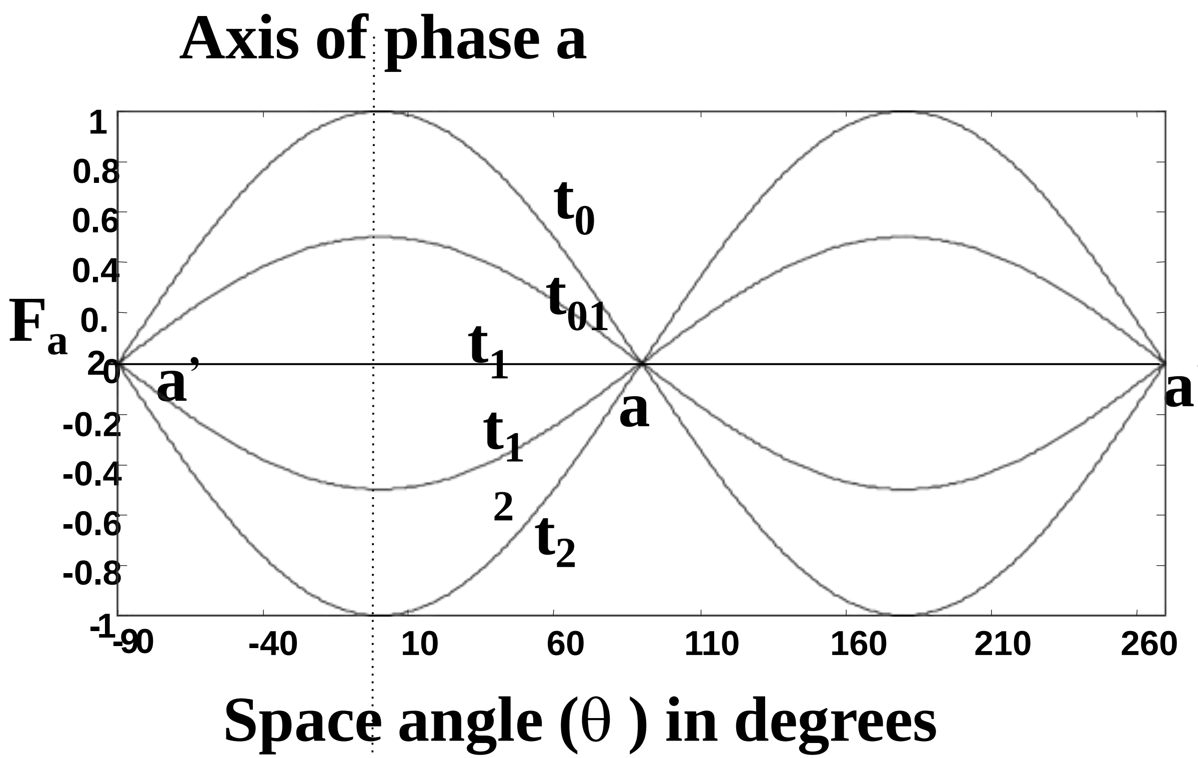
- For 60 Hz motor list three possible combination of number of poles and speeds.

$$n_s = \frac{120 f_s}{p}$$

Number of poles (p)	***Speed n_s (rpm)***
2	**3600**
4	**1800**
6	**1200**

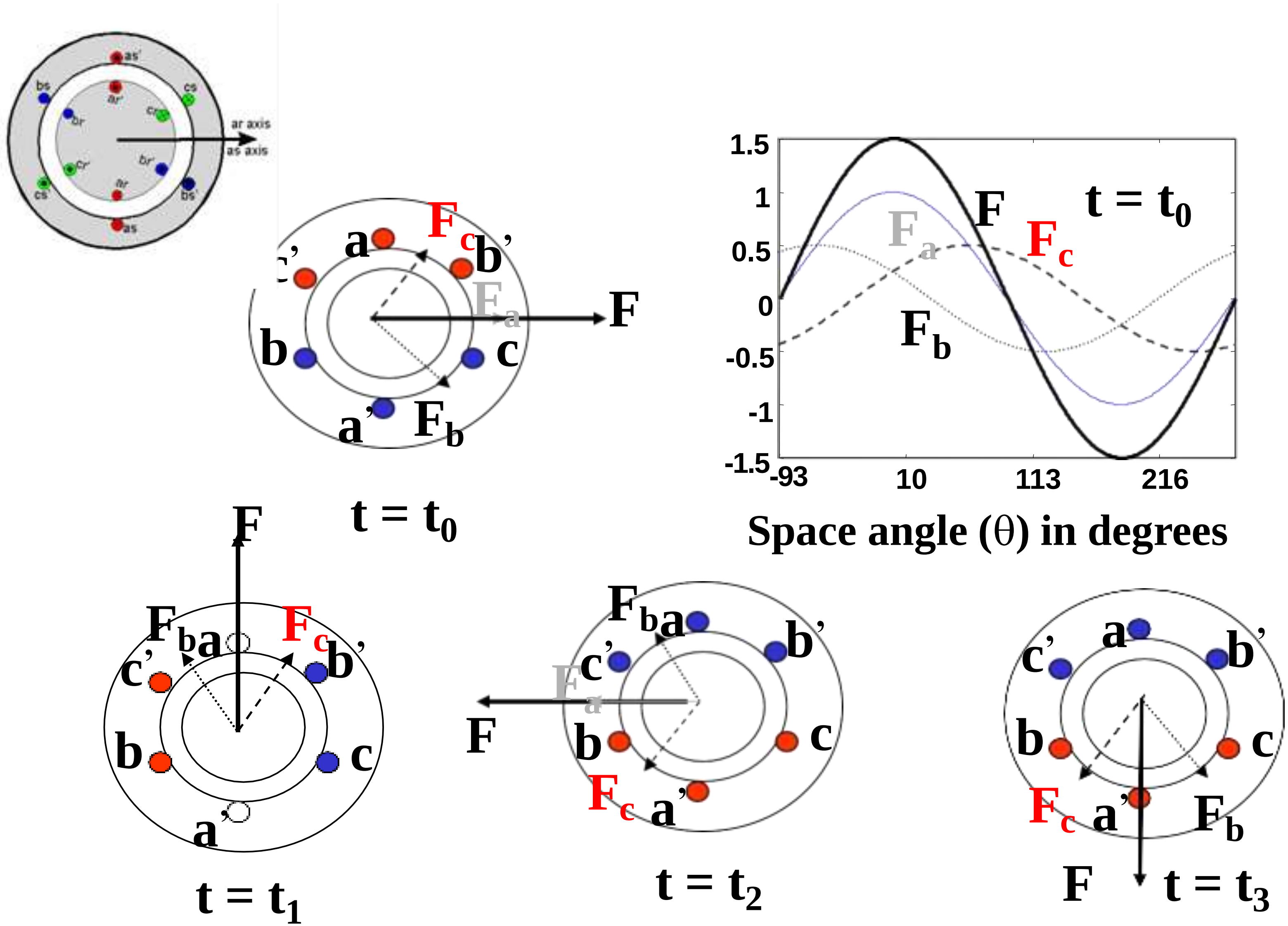
MMF due to ac current in phase “a”





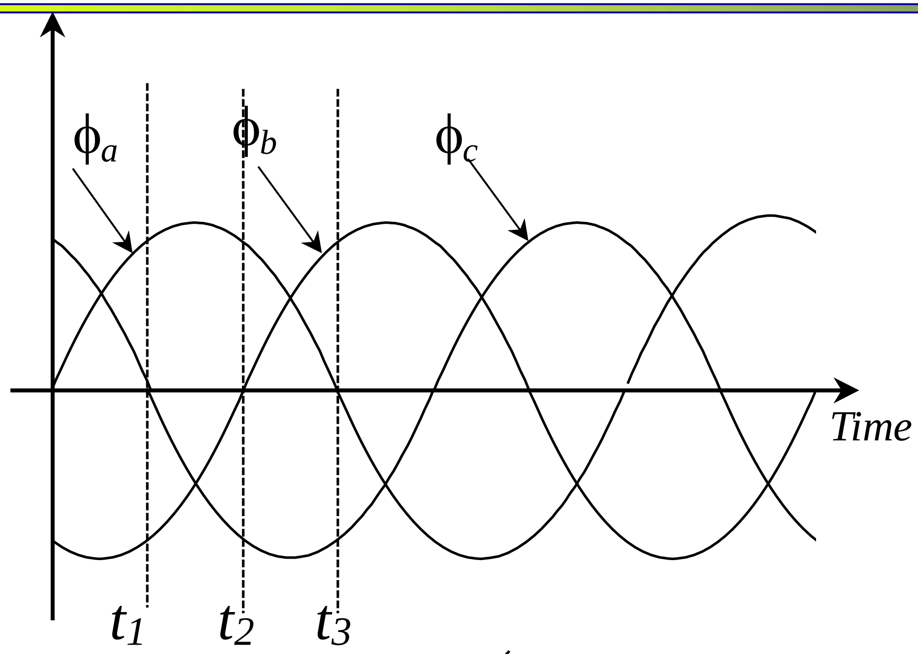
Pulsating mmf

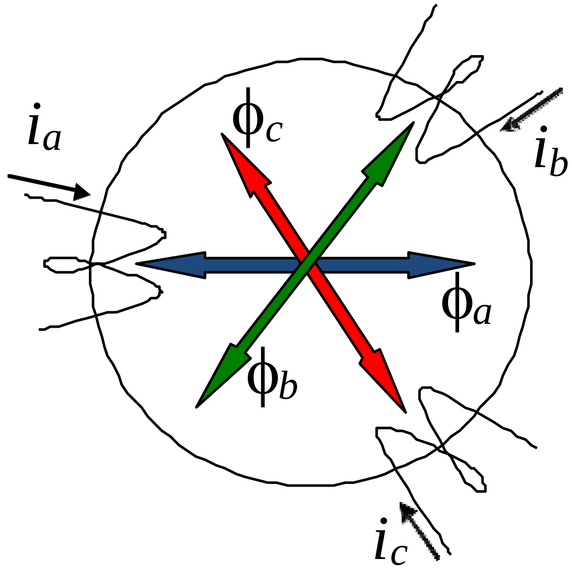
MMF due to three-phase currents in 3-ph winding

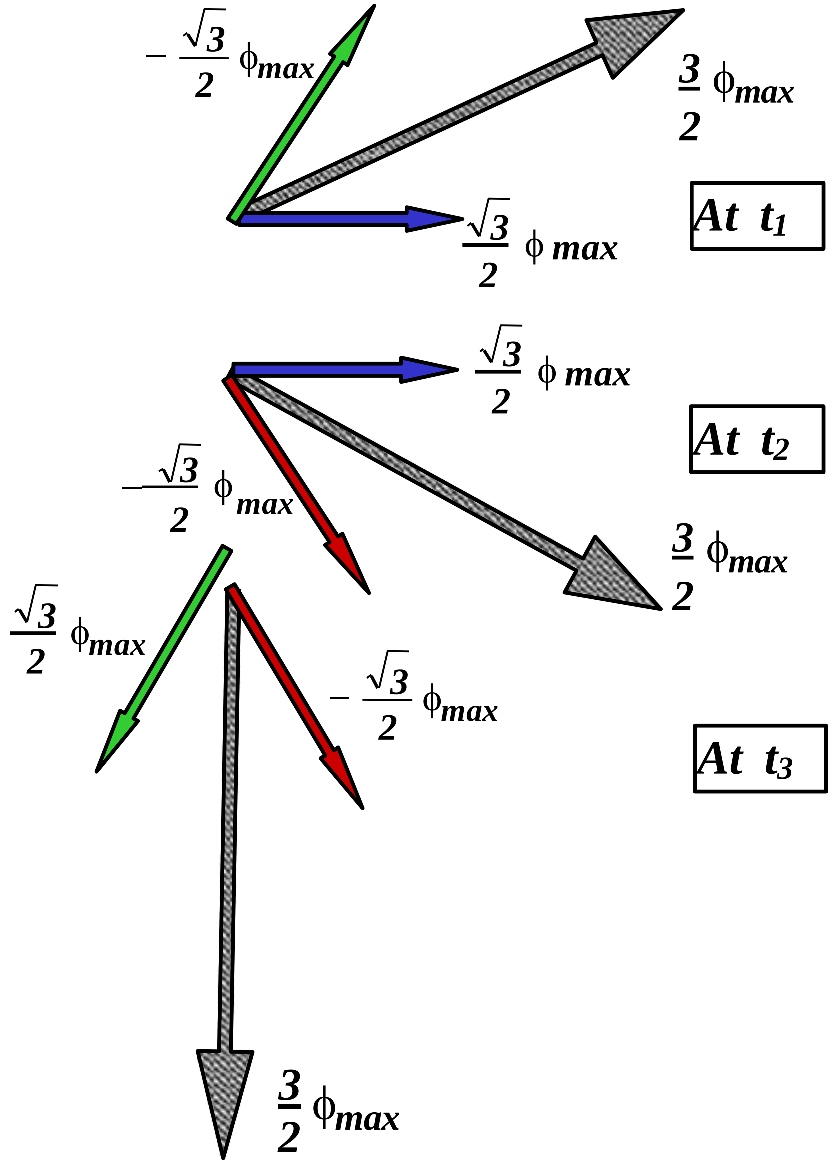


MMF's at various instant (***Rotating mmf***)

Rotating Magnetic Field





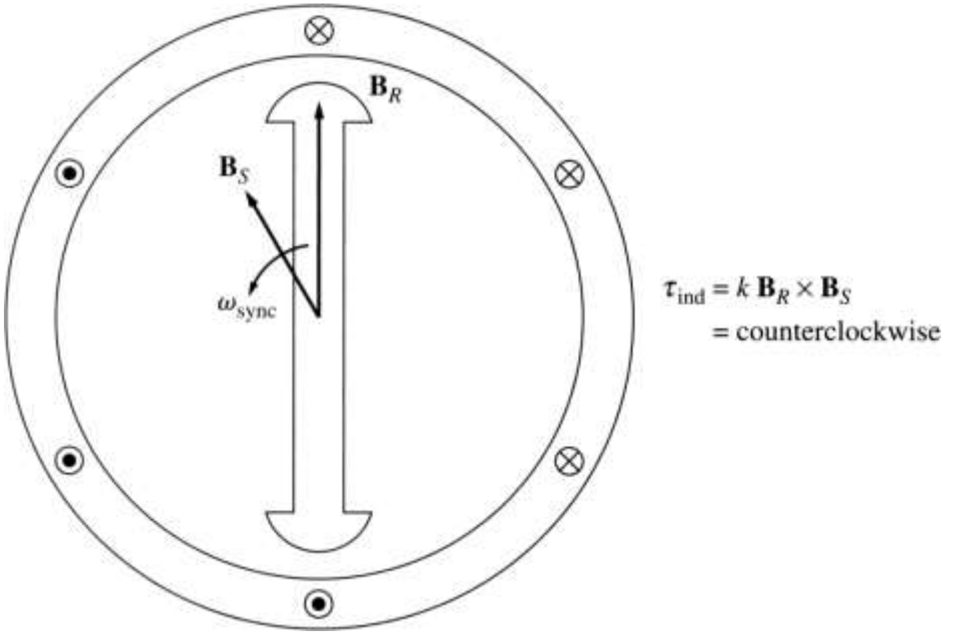


Synchronous motors

The field current I_F of the motor produces a steady-state rotor magnetic field B_R.

A 3-phase set of voltages applied to the stator produces a 3-phase current flow in the windings.

A 3-phase set of currents in an armature winding produces a uniform rotating magnetic field B_s.

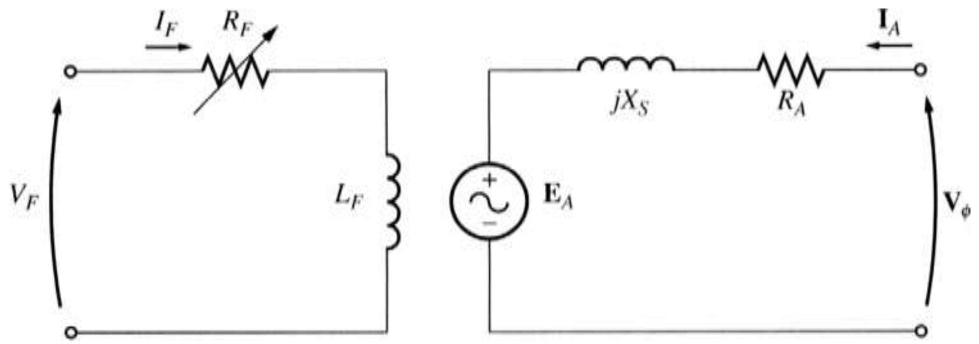


Two magnetic fields are present in the machine, and the rotor field tends to align with the stator magnetic field. Since the stator magnetic field is rotating, the rotor magnetic field will try to catch up pulling the rotor.

The larger the angle between two magnetic fields (up to a certain maximum), the greater the torque on the rotor of the machine.

Synchronous motor equivalent circuit

A synchronous motor has the same equivalent circuit as synchronous generator, except that the direction of power flow (and the direction of I_A) is reversed. Per-phase circuit is shown:



A change in direction of I_A changes the Kirchhoff's voltage law equation:

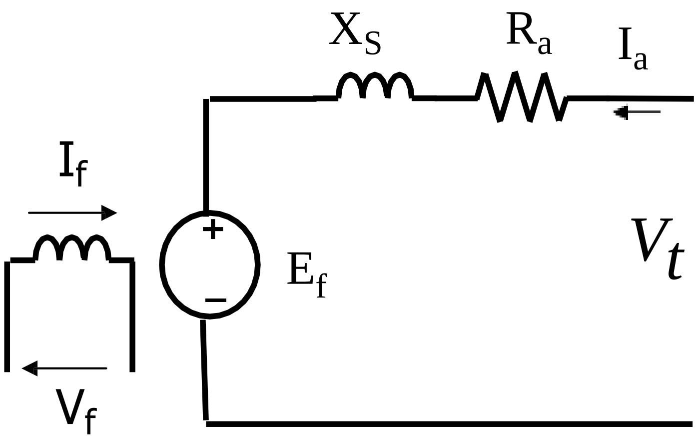
$$V_\phi = E_A + jX_S I_A + R_A I_A$$

Therefore, the internal generated voltage is

$$E_A = V_\phi - jX_S I_A - R_A I_A$$

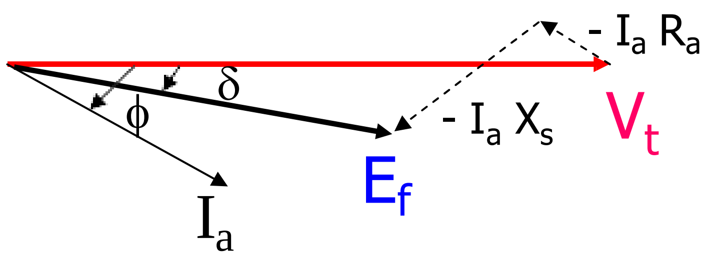
Motor Equivalent Circuit

$$\overline{E}_f = \overline{V}_t - \overline{I}_a(Ra + jXs)$$

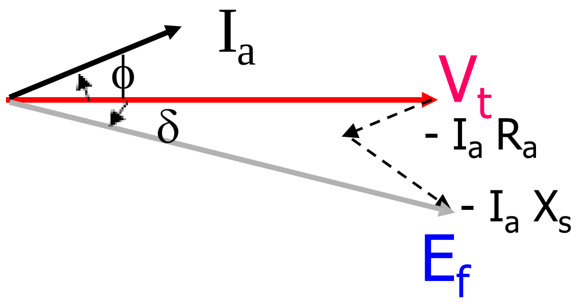


$$E_f \angle \delta^\circ = V_t \angle 0^\circ - I_a R_a \angle \pm\phi^\circ - I_a X_s \angle (\pm\phi + 90)^\circ$$

a-Lagging power factor

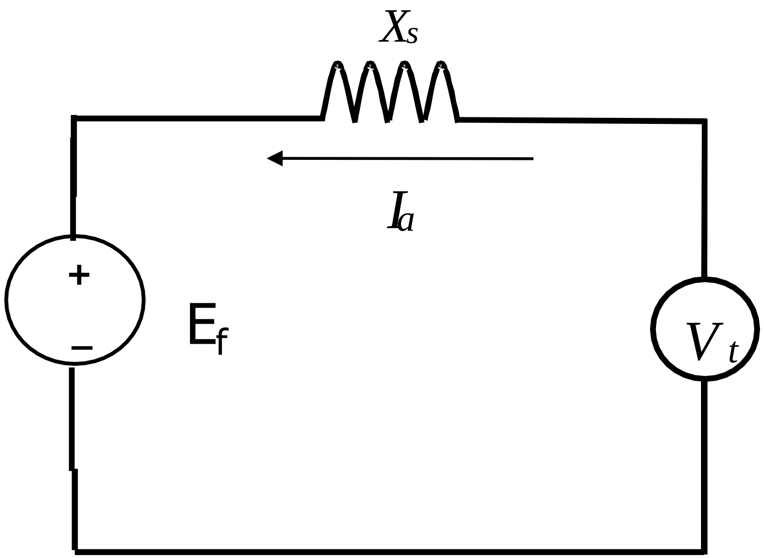


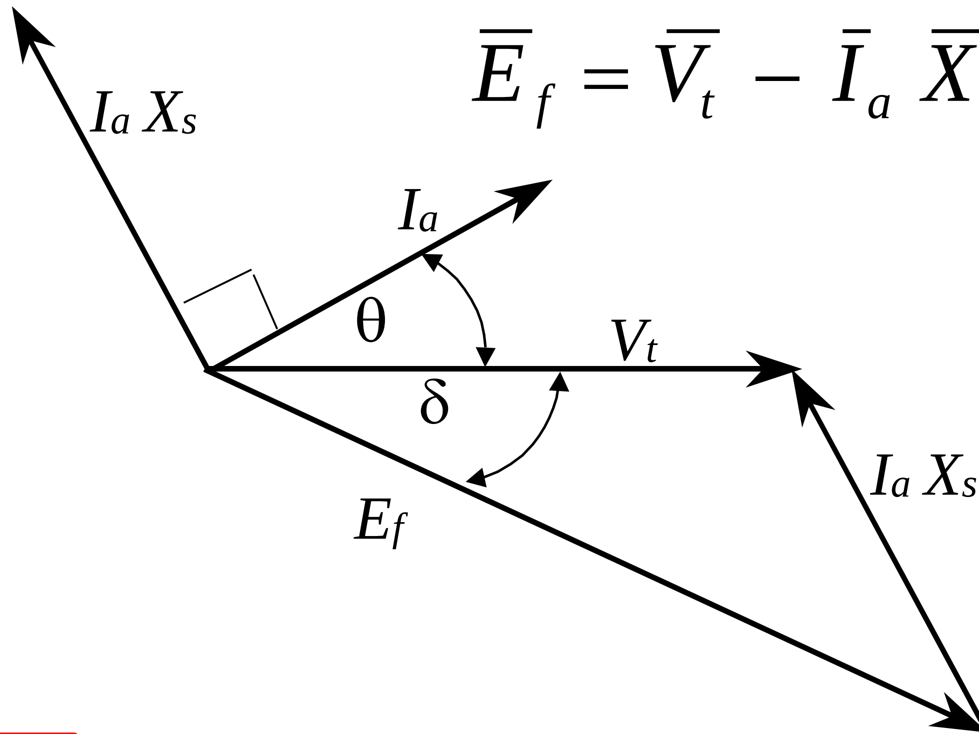
b-Leading power factor



Motor Equivalent Circuit

Leading power factor



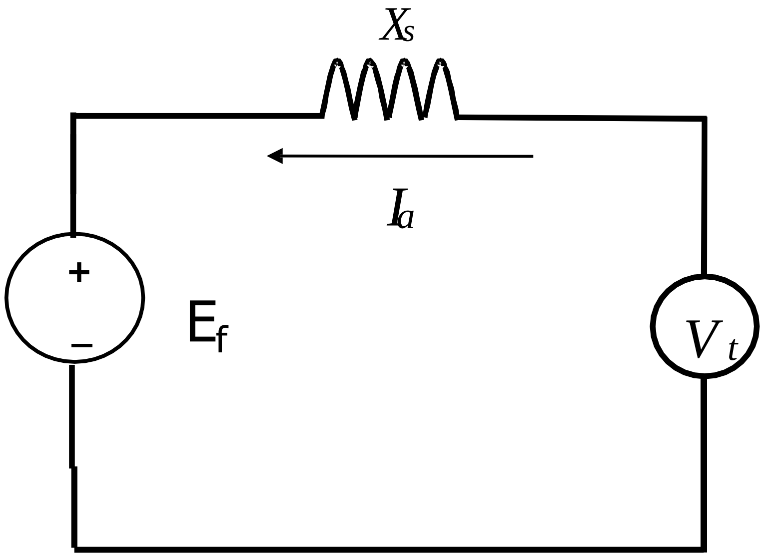


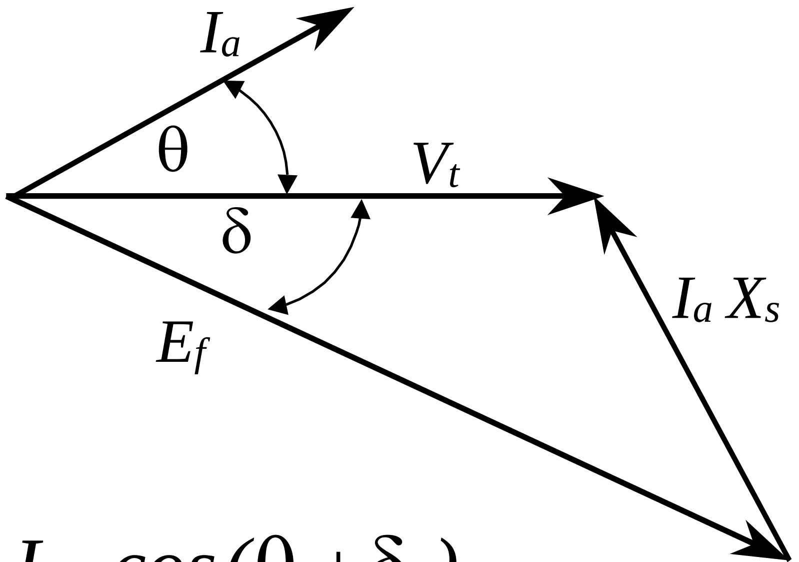
$$\bar{E}_f = \bar{V}_t - \bar{I}_a \bar{X}_s$$

$$\bar{V}_t = \bar{E}_f + \bar{I}_a \bar{X}_s$$

V_t is Fixed (infinite Bus)
E_f is function of I_f
Magnitude and ***phase*** of I_a
are dependant variables

Power equations





$$P = 3\,V_t\ I_a\ \cos\theta\ = 3\,E_f\ I_a\ \cos(\theta+\delta\,)$$

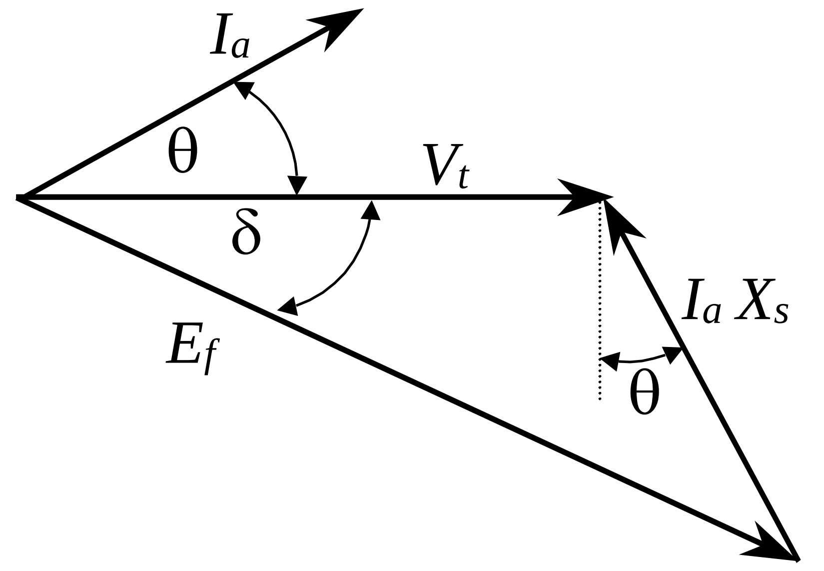
$$Q_t = 3\,V_t\ I_a\ \sin\theta$$ ← **Reactive power at motor terminal**

$$Q_f = 3\,E_f\ I_a\ \sin(\theta+\delta\,)$$

Power equations

$$I_a X_s \cos\theta = E_f \sin\delta$$

$$I_a \cos\theta = \frac{E_f \sin\delta}{X_s}$$

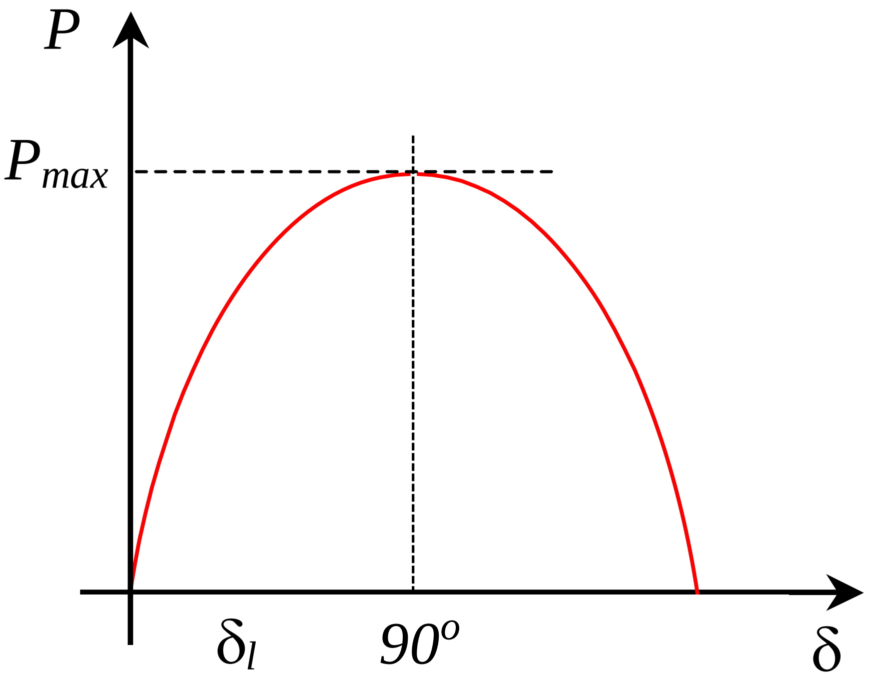


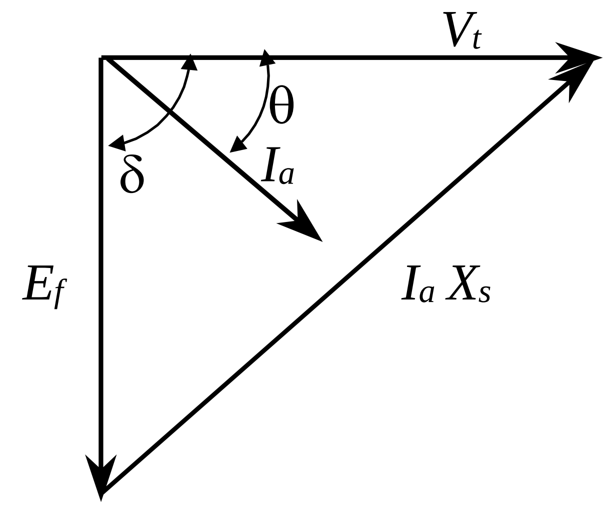
$$P = 3\, V_t\, I_a \cos\theta$$

$$P = \frac{3\, V_t\, E_f}{X_s} \sin\delta$$

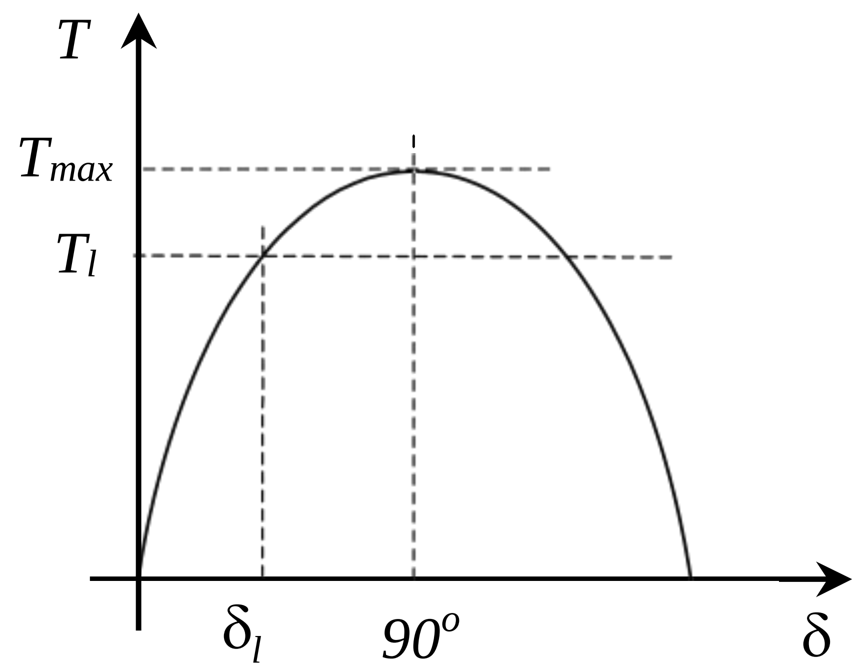
$$P_{max} = \frac{3\, V_t\, E_f}{X_s}$$

Torque Characteristics





Phasor Diagram at P_{max}



$$T = \frac{P}{\omega_s} = \frac{3}{\omega_s}\frac{V_t E_f}{X_s}\sin\delta$$

$$T_{\max} = \frac{3V_t E_f}{\omega_s X_s}$$

Torque-speed curve

The maximum pullout torque occurs when $\delta = 90^0$:

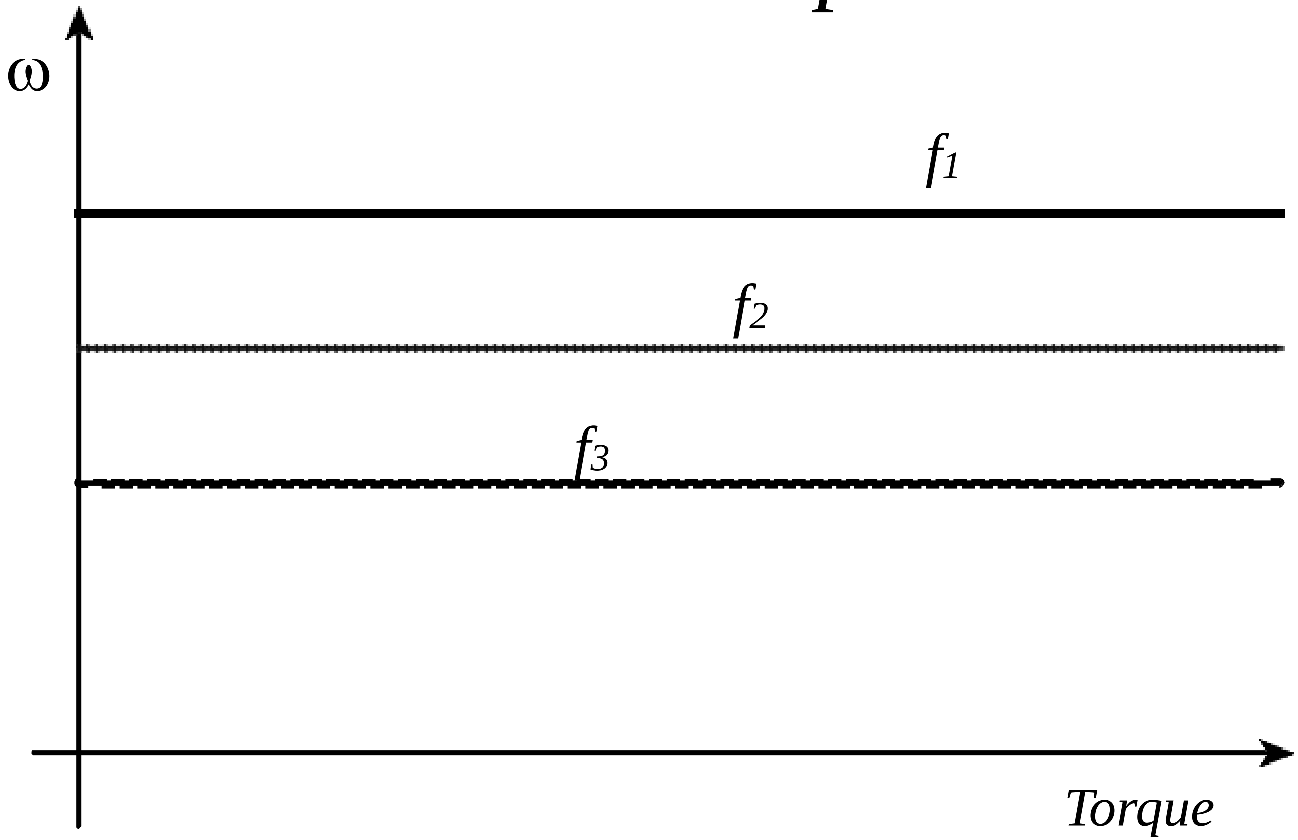
$$T_{\max} = kB_R B_{net} = \frac{3V_t E_f}{\omega_s X_s}$$

Normal full-load torques are much less than that (usually, about 3 times smaller).

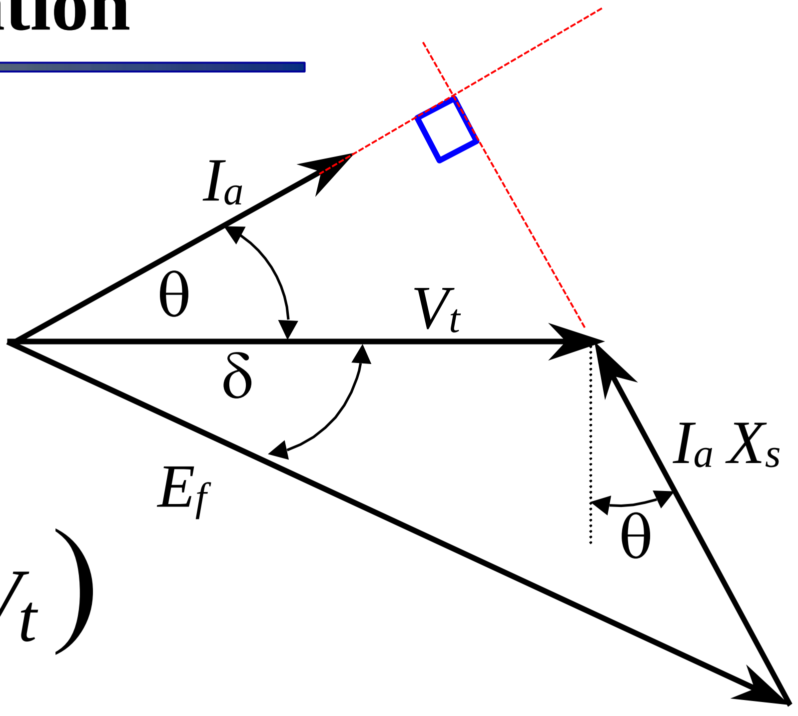
When the torque on the shaft of a synchronous motor exceeds the pullout torque, the rotor can no longer remain locked to the stator and net magnetic fields. It starts to slip behind them. As the motor slows down, the stator magnetic field "laps" it repeatedly, and the direction of the induced torque in the rotor reverses with each pass. As a result, huge torque surges of alternating direction cause the motor vibrate severely. The loss of synchronization after the pullout torque is exceeded is known as slipping poles.

Torque-Speed Characteristics

$$n_s = 120\frac{f}{p}$$



Reactive Power equation



$$I_a X_s \sin\theta = E_f \cos\delta - V_t$$

$$I_a \sin\theta = \frac{1}{X_s}\left(E_f \cos\delta - V_t\right)$$

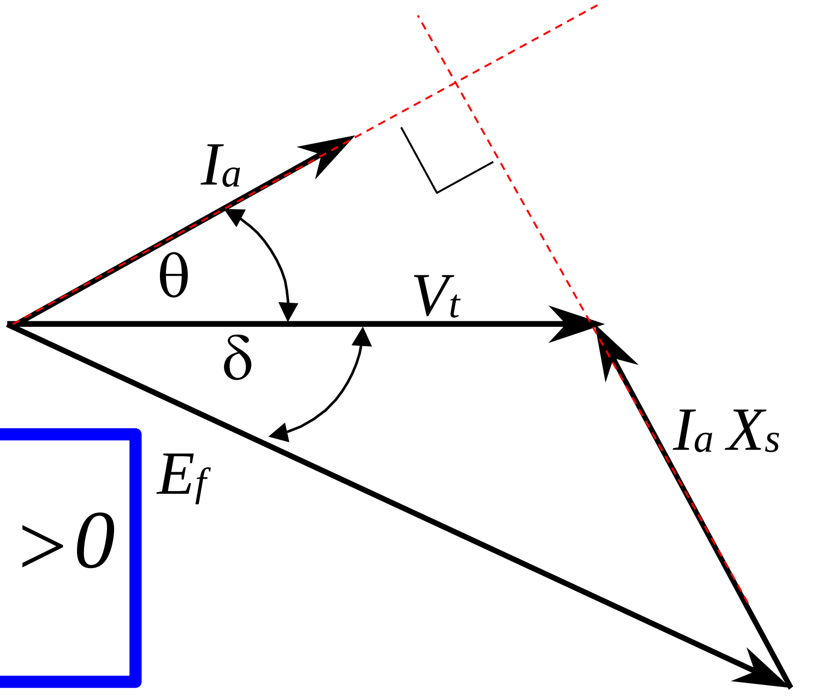
$$Q_t = 3\, V_t\, I_a \sin\theta$$

$$Q = \frac{3\, V_t}{X_s}\left[E_f \cos\delta - V_t\right]$$

Over Excited Motor

Adjust I_f until

$$E_f \cos\delta > V_t$$



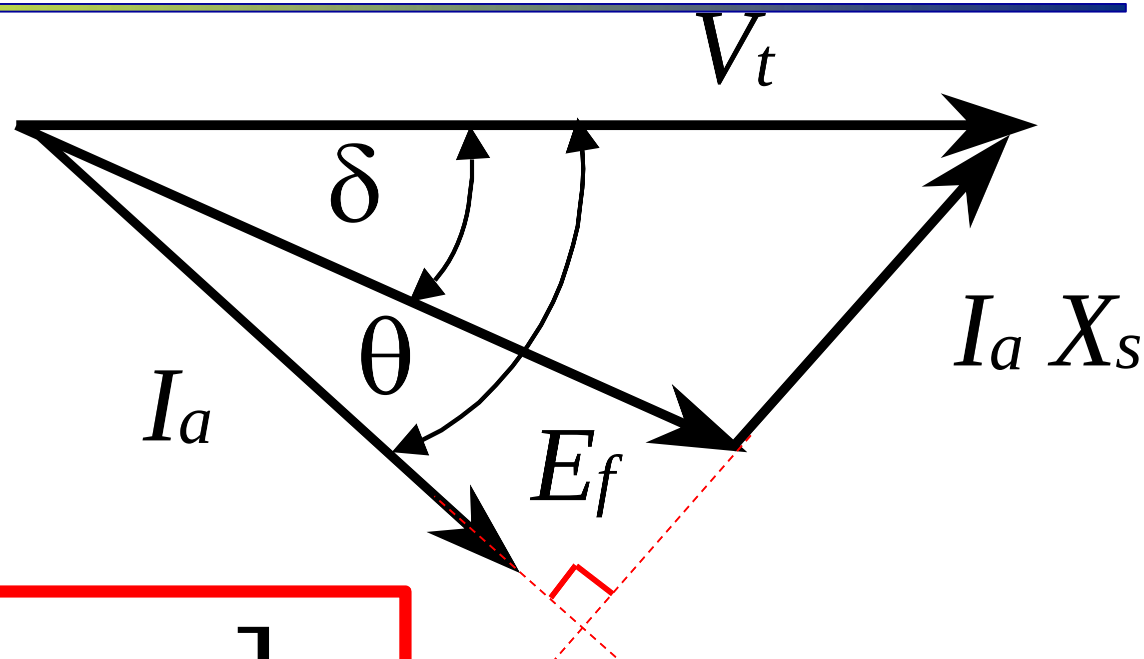
$$Q = \frac{3V_t}{X_s}\left[E_f \cos\delta - V_t\right] > 0$$

I_a Leads V_t

Main conclusions of over excited machines

SM delivers reactive power to source

Under Excited Motor



Adjust I_f until

$$E_f \cos\delta < V_t$$

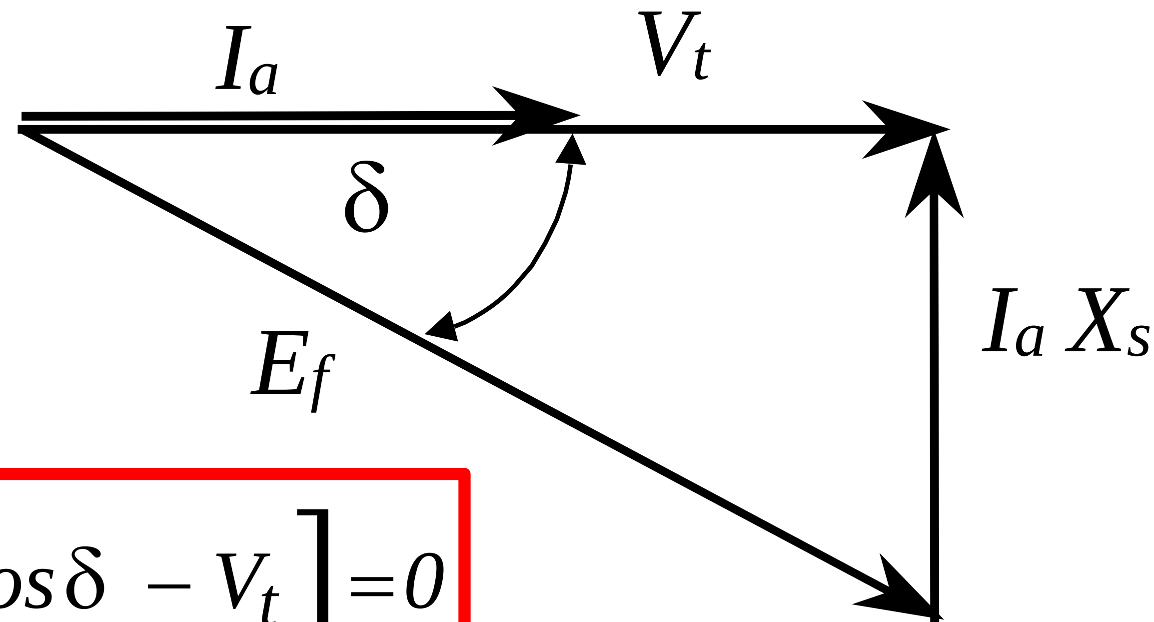
$$Q = \frac{3V_t}{X_s}\left[E_f \cos\delta - V_t\right] < 0$$

I_a Lags V_t

Main conclusions of under excited machines
SM receives reactive power from source

Exact Excitation

Adjust I_f until



$$E_f \cos\delta = V_t$$

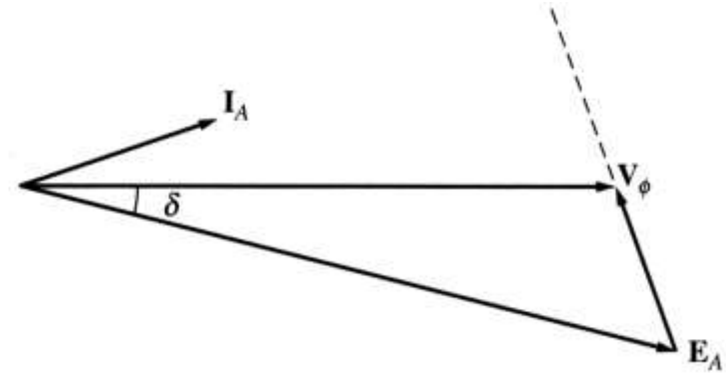
$$Q = \frac{3V_t}{X_s}\left[E_f \cos\delta - V_t\right] = 0$$

I_a in phase with V_t

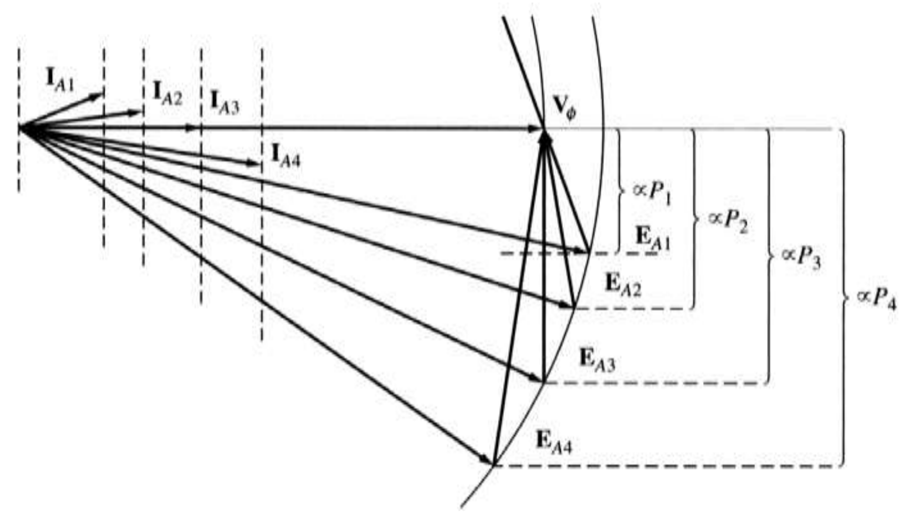
Main conclusions of exact excitation machines
NO reactive power at the motor's terminals

Effect of torque changes

Assuming that a synchronous motor operates initially with a leading PF. If the load on the motor increases, the rotor initially slows down increasing the torque angle δ. As a result, the induced torque increases speeding up the rotor up to the synchronous speed with a larger torque angle δ.

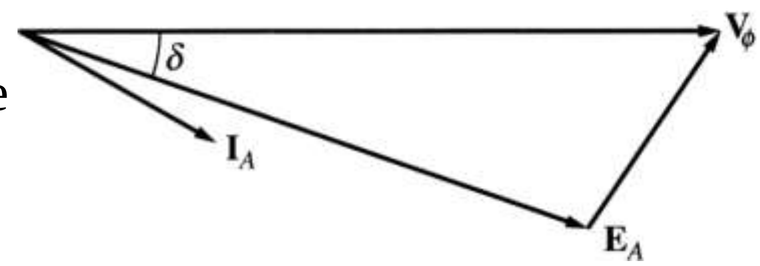


Since the terminal voltage and frequency supplied to the motor are constant, the magnitude of internal generated voltage must be constant at the load changes ($E_A = K\phi\omega$ and field current is constant).

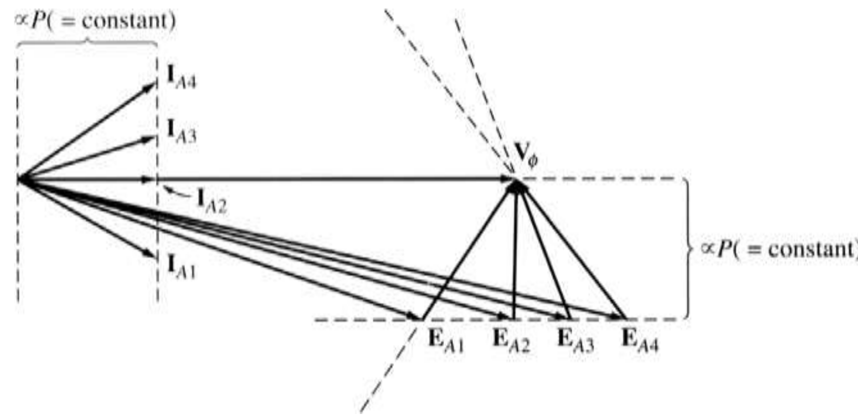


Effect of field current changes

Assuming that a synchronous motor operates initially with a lagging PF.
If, for the constant load, the field current on the motor increases, the magnitude of the internal generated voltage E_A increases.



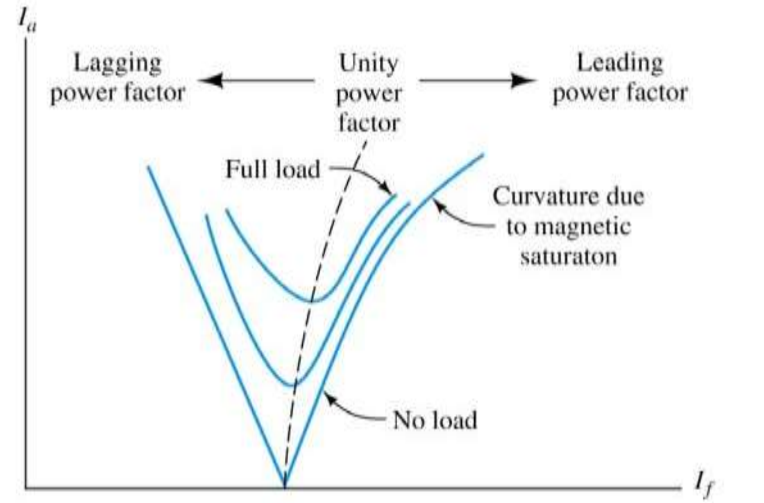
Since changes in I_A do not affect the shaft speed and the motor load is constant, the real power supplied by the motor is unchanged. Therefore, the distances proportional to power on the phasor diagram ($E_A sin\delta$ and $I_A cos\theta$) must be constant.



Notice that as E_A increases, the magnitude of the armature current I_A first decreases and then increases again. At low E_A, the armature current is lagging and the motor is an inductive load that consumes reactive power Q. As the field current increases , I_A eventually lines up with V_ϕ, and the motor is purely resistive. As the field current further increases, I_A becomes leading and the motor is a capacitive load that supplies reactive power Q to the system (consumes $-Q$).

Effect of field current changes

A plot of armature current vs. field current is called a synchronous motor V curve. V curves for different levels of real power have their minimum at unity PF, when only real power is supplied to the motor. For field currents less than the one giving the minimum I_A, the armature current is lagging and the motor consumes reactive power. For field currents greater than the one giving the minimum I_A, the armature current is leading and the motor supplies reactive power to the system.

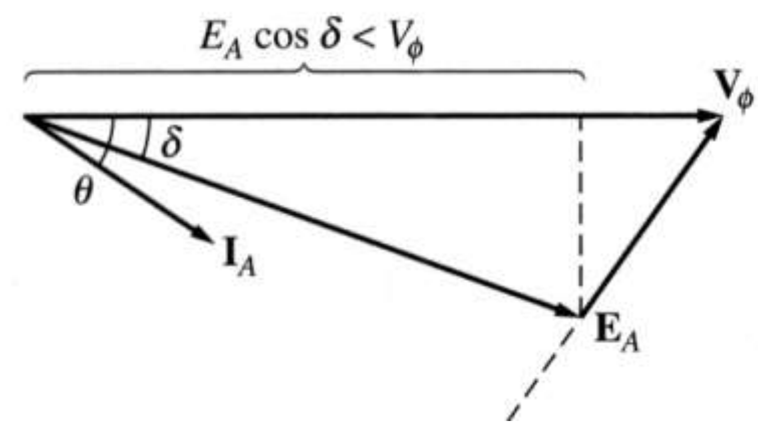


V curves for a synchronous motor with variable excitation.

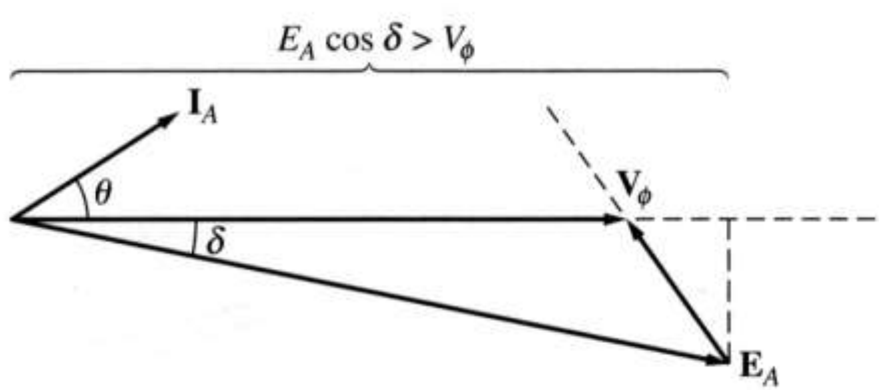
Therefore, by controlling the field current of a synchronous motor, the reactive power consumed or supplied to the power system can be controlled.

Effect of field current changes

When the projection of the phasor E_A onto V_ϕ ($E_A\cos\delta$) is shorter than V_ϕ, a synchronous motor has a lagging current and consumes Q. Since the field current is small in this situation, the motor is sais to be under-excited.

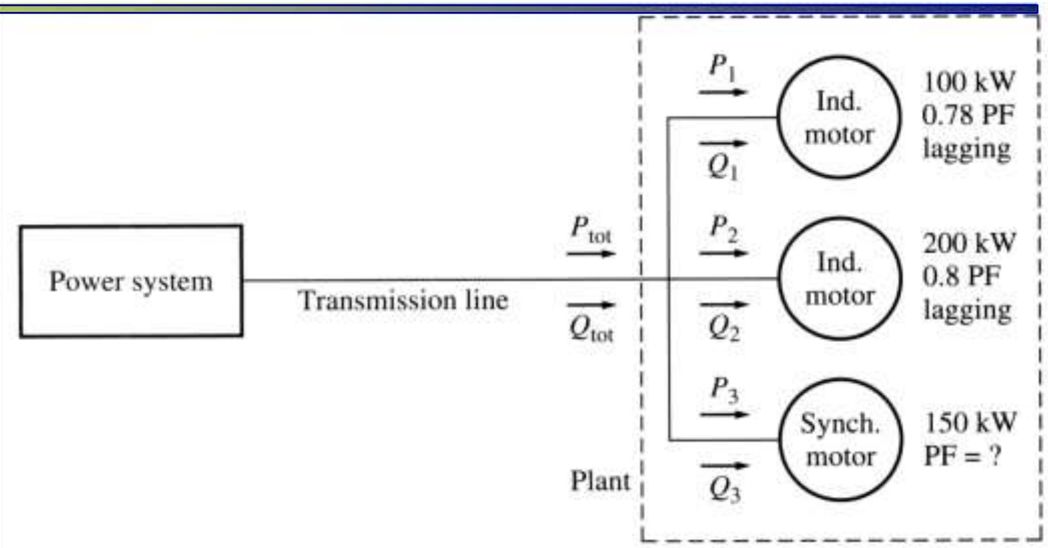


When the projection of the phasor E_A onto V_ϕ ($E_A\cos\delta$) is longer than V_ϕ, a synchronous motor has a leading current and supplies Q to the system. Since the field current is large in this situation, the motor is said to be over-excited.



Power Factor Correction

Assuming that a load contains a synchronous motor (whose PF can be adjusted) in addition to motors of other types. What does the ability to set the PF of one of the loads do for the power system?



Let us consider a large power system operating 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 0.85 PF lagging, what is the line current?

b.If the synchronous motor is adjusted to 0.85 PF leading, what is the line current?

c.Assuming that the line losses are $P_{LL} = 3I_L^2R_L$, how do these losses compare in the two cases?

Power Factor Correction

a. The real power of load 1 is 100 kW, and the reactive power of load 1 is

$$Q_1 = P_1 \tan\theta = 100 \tan\left(\cos^{-1} 0.78\right) = 80.2\ kVAR$$

The real power of load 2 is 200 kW, and the reactive power of load 2 is

$$Q_2 = P_2 \tan\theta = 200 \tan\left(\cos^{-1} 0.8\right) = 150\ kVAR$$

The real power of load 3 is 150 kW, and the reactive power of load 3 is

$$Q_3 = P_3 \tan\theta = 150 \tan\left(\cos^{-1} 0.85\right) = 93\ kVAR$$

The total real load is

$$P_{tot} = P_1 + P_2 + P_3 = 100 + 200 + 150 = 450\ kW$$

The total reactive load is

$$Q_{tot} = Q_1 + Q_2 + Q_3 = 80.2 + 150 + 93 = 323.2\ kVAR$$

The equivalent system PF is

$$PF = \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{323.2}{450}\right) = 0.812\ \ lagging$$

The line current is

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L\cos\theta} = \frac{450\,000}{\sqrt{3}\cdot 480 \cdot 0.812} = 667\ A$$

Power Factor Correction

b. The real and reactive powers of loads 1 and 2 are the same. The reactive power of load 3 is

$$Q_3 = P_3 \tan\theta = 150 \tan\left(-\cos^{-1} 0.85\right) = -93\, kVAR$$

The total real load is

$$P_{tot} = P_1 + P_2 + P_3 = 100 + 200 + 150 = 450\, kW$$

The total reactive load is

$$Q_{tot} = Q_1 + Q_2 + Q_3 = 80.2 + 150 - 93 = 137.2\, kVAR$$

The equivalent system PF is

$$PF = \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{137.2}{450}\right) = 0.957\ \ lagging$$

The line current is

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L \cos\theta} = \frac{450\,000}{\sqrt{3}\cdot 480 \cdot 0.957} = 566\ A$$

Power Factor Correction

c. The transmission line losses in the first case are

$$P_{LL} = 3I_L^2 R_L = 1344\,700\, R_L$$

The transmission line losses in the second case are

$$P_{LL} = 3I_L^2 R_L = 961\,070\, R_L$$

We notice that the transmission power losses are 28% less in the second case, while the real power supplied to the loads is the same.

Power Factor Correction

The ability to adjust the power factor of one or more loads in a power system can significantly affect the efficiency of the power system: the lower the PF, the greater the losses in the power lines. Since most loads in a typical power system are induction motors, having one or more over-excided synchronous motors (leading loads) in the system is useful for the following reasons:

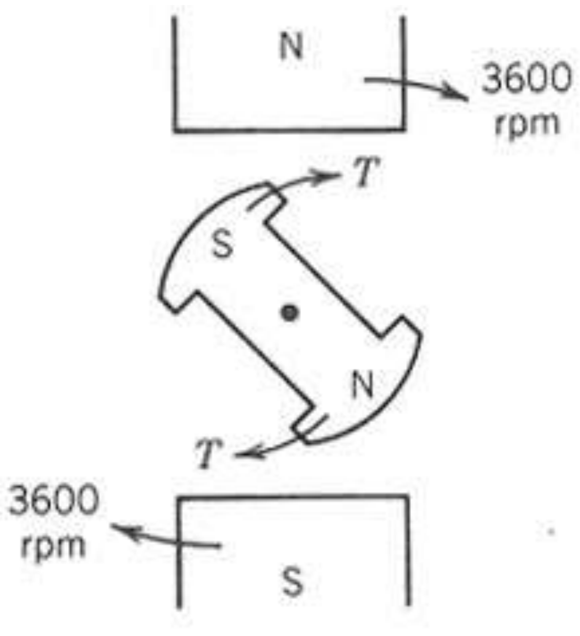
1. A leading load supplies some reactive power to lagging loads in the system. Since this reactive power does not travel along the transmission line, transmission line current is reduced reducing power losses.
2. Since the transmission line carries less current, the line can be smaller for a given power flow reducing system cost.
3. The over-excited mode of synchronous motor increases the motor's maximum torque.

Usage of synchronous motors or other equipment increasing the overall system's PF is called power-factor correction. Since a synchronous motor can provide PF correction, many loads that can accept constant speed are driven by over-excited synchronous motors.

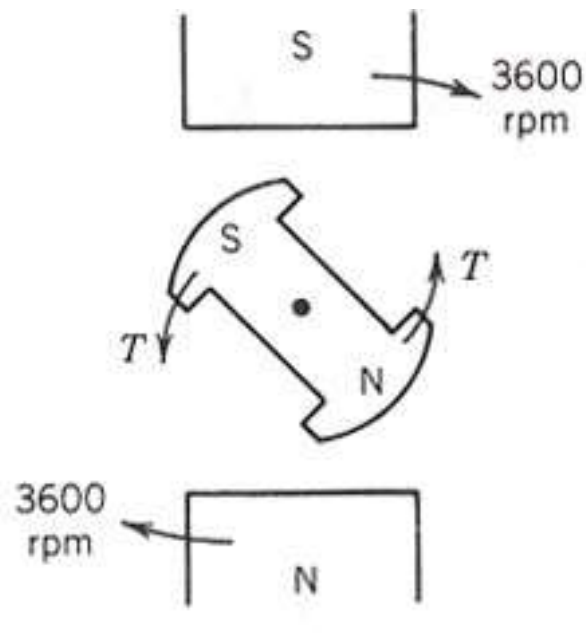
Starting of Synchronous Motors

Why the three phase synchronous motor has zero starting torque?

If the rotor field poles are excited by the field current and the stator terminals are connected to the a.c. supply, the motor will not start; instead, it will vibrates. The stator field is rotating so fast that the rotor poles cannot catch up or lock onto it (see Figure) because of the high inertia of the rotor.



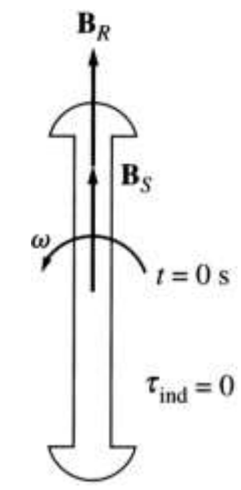
(a) $t = 0$



(b) $t = t_1$

Starting of Synchronous Motors

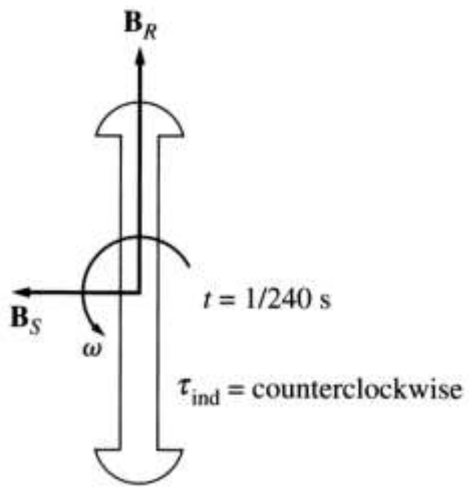
Consider a 60 Hz synchronous motor.
When the power is applied to the stator windings, the rotor (and, therefore its magnetic field B_R) is stationary. The stator magnetic field B_S starts sweeping around the motor at synchronous speed.
Note that the induced torque on the shaft



$$\tau_{ind} = kB_R \times B_S$$

is zero at t = 0 since both magnetic fields are aligned.

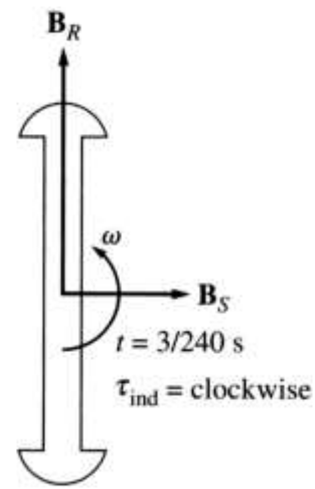
At t = 1/240 s the rotor has barely moved but the stator magnetic field B_S has rotated by 90^0. Therefore, the torque on the shaft is non-zero and counter-clockwise.

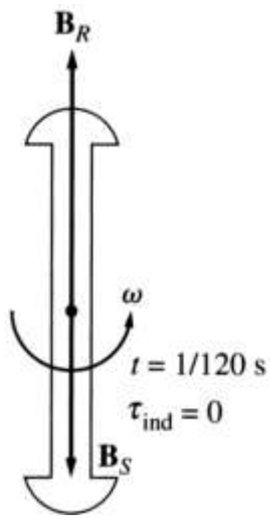


Starting of Synchronous Motors

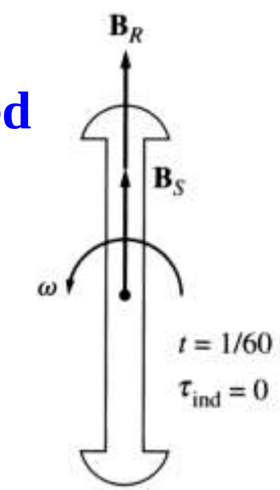
At t = 1/120 s the rotor and stator magnetic fields point in opposite directions, and the induced torque on the shaft is zero again.

At t = 3/240 s the stator magnetic fields point to the right, and the induced torque on the shaft is non-zero but clockwise.





Finally, at t = 1/60 s the rotor and stator magnetic fields are aligned again, and the induced torque on the shaft is zero.



During one electrical cycle, the torque was counter-clockwise and then clockwise, and the average torque is zero. The motor will vibrate heavily and finally overheats!

Starting Synchronous Motors

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 two magnetic fields lock in during one half-cycle of field rotation. This can be achieved by reducing the frequency of the applied electric power (which used to be difficult but can be done now).

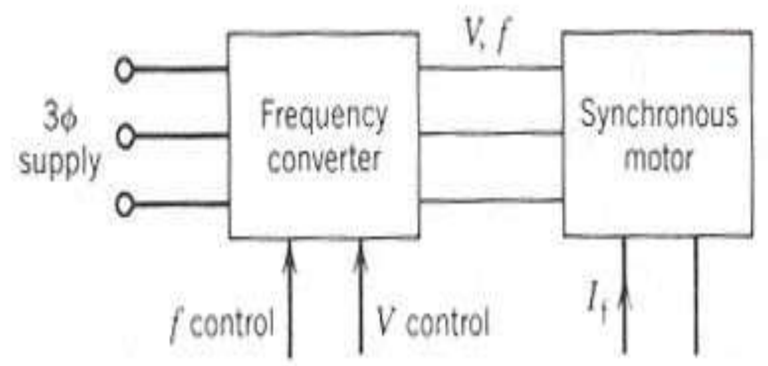
2.Use an external prime mover to accelerate the synchronous motor up to synchronous speed, go through the paralleling procedure, and bring the machine on the line as a generator. Next, turning off the prime mover will make the synchronous machine a motor.

3.Use damper windings or amortisseur windings – the most popular.

Starting Synchronous Motors

Use a variable-frequency supply

- By using a frequency converter, a synchronous motor can be brought from standstill to its desired speed.

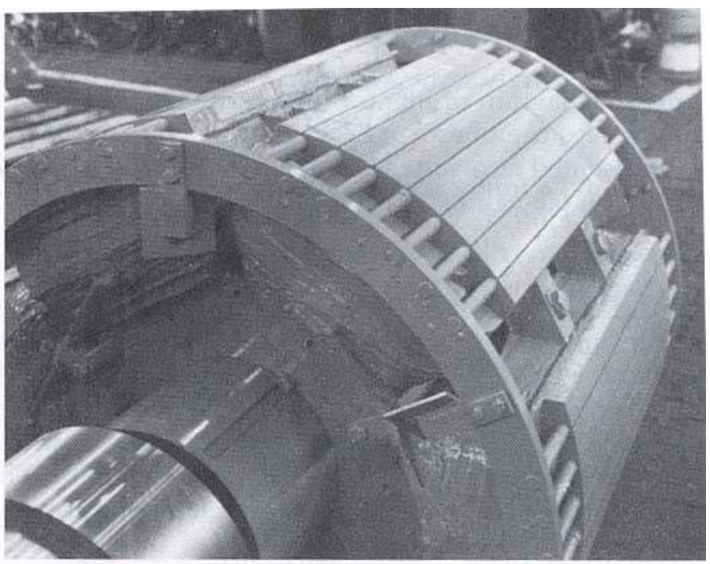


- The motor is started with a low-frequency supply. This will make the stator field rotate slowly so that the rotor poles can follow stator ones. Afterward, the frequency is gradually increased and the motor brought to its desired speed.
- The frequency converter is a costly power conditioning unit, and this method is expensive. However, if the synchronous motor has to run at variable speeds, this method may be used.

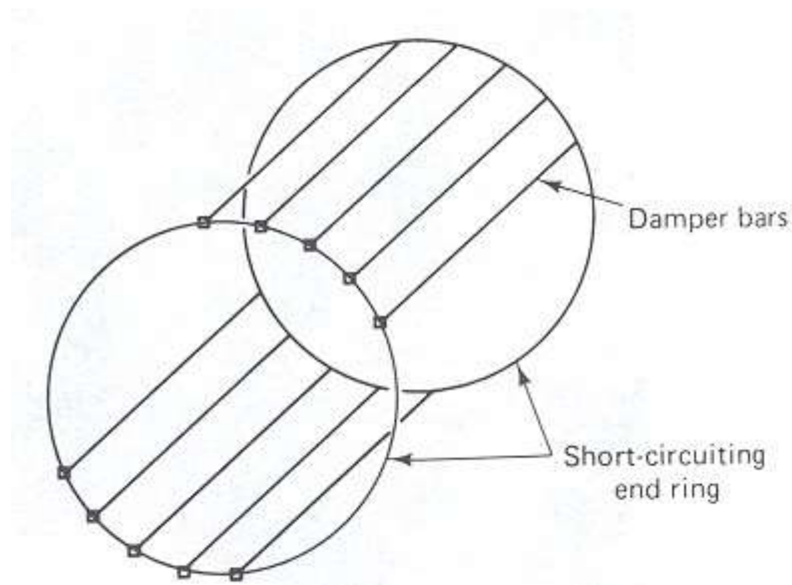
Starting Synchronous Motors

Start as an induction motor

- To start the synchronous motor as an induction motor an additional winding, which resembles the cage of an induction motor, is mounted on the rotor. This cage-type winding is known as a **damper winding**. This winding is placed in slots located in the pole faces and parallel to the shaft as shown in the following Figures.

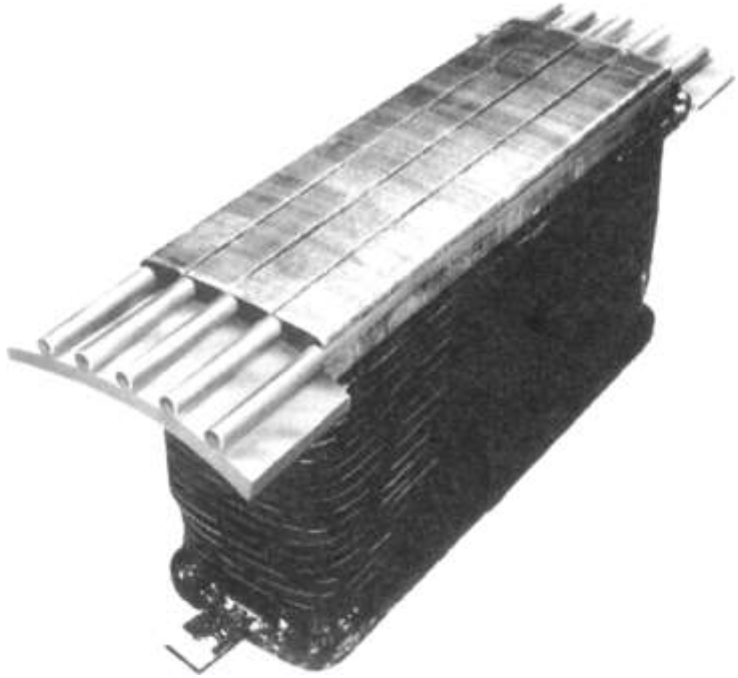


Cage-type damper (or amortisseur) winding in a synchronous machine. (Courtesy of General Electric Canada Inc.)



Motor starting by Amortisseur or Damper windings

Amortisseur (damper) windings are special bars laid into notches carved in the rotor face and then shorted out on each end by a large shorting ring.



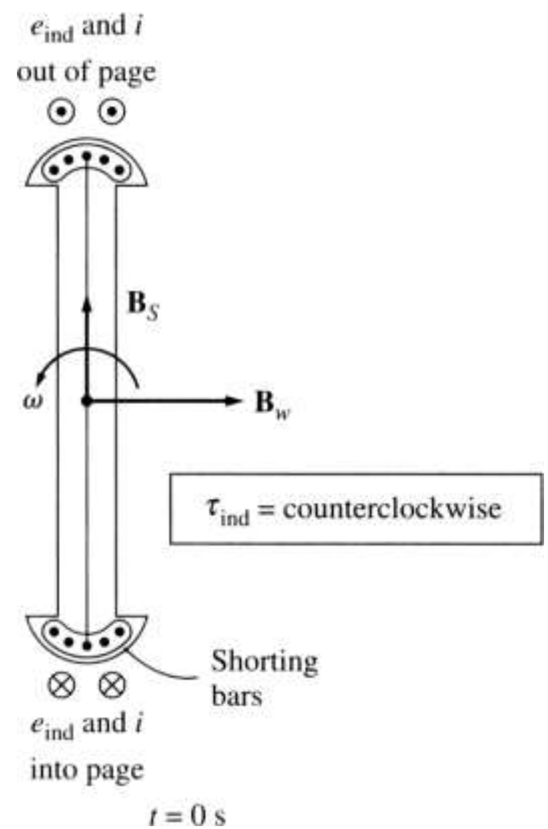
Motor starting by Amortisseur or Damper windings

Here v **– the velocity of the bar relative to the magnetic field;**

B **– magnetic flux density vector;**

l **– length of conductor in the magnetic field.**

The bars at the top of the rotor are moving to the right relative to the magnetic field: a voltage, with direction out of page, will be induced. Similarly, the induced voltage is into the page in the bottom bars. These voltages produce a current flow out of the top bars and into the bottom bars generating a winding magnetic field B_w **to the right. Two magnetic fields will create a torque**

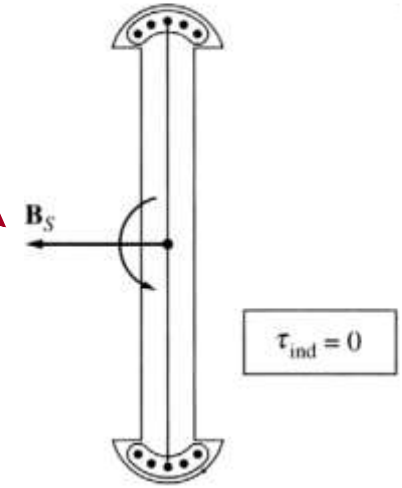


$$\tau_{ind} = kB_W \times B_S$$

The resulting induced torque will be counter-clockwise.

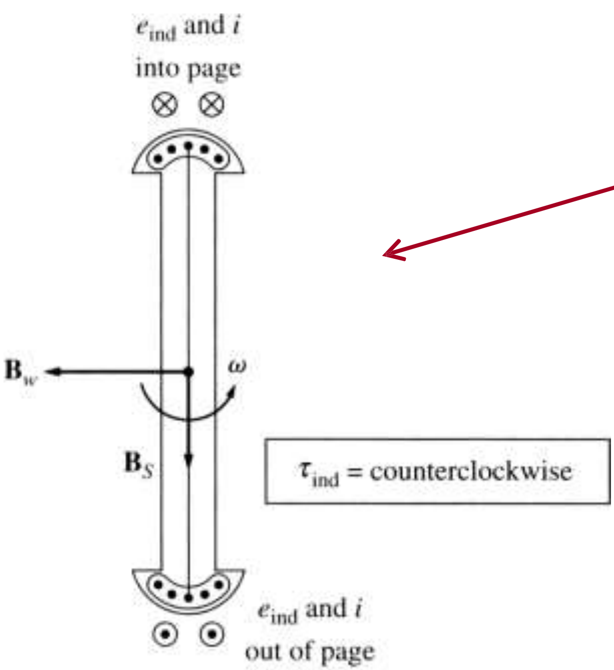
Motor starting by Amortisseur or Damper windings

At t = 1/240 s, B_S has rotated 90⁰ while the rotor has barely moved. Since v is parallel to B_S, the voltage induced in the amortisseur windings is zero, therefore, no current in wires create a zero-torque.



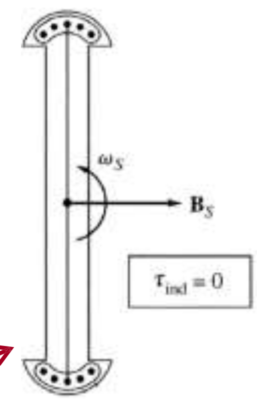
t = 1/240 s

At t = 1/120 s, B_S has rotated another 90⁰ and the rotor is still. The voltages induced in the bars create a current inducing a magnetic field pointing to the left. The torque is counter-clockwise.



t = 1/120 s

Finally, at t = 3/240 s, no voltage is induced in the amortisseur windings and, therefore, the torque will be zero.



t = 3/240 s

Motor starting by Amortisseur or Damper windings

We observe that the torque is either counter-clockwise or zero, but it is always unidirectional. Since the net torque is nonzero, the motor will speed up.

However, the rotor will never reach the synchronous speed! If a rotor was running at the synchronous speed, the speed of stator magnetic field B_S would be the same as the speed of the rotor and, therefore, no relative motion between the rotor and the stator magnetic field. If there is no relative motion, no voltage is induced and, therefore, the torque will be zero.

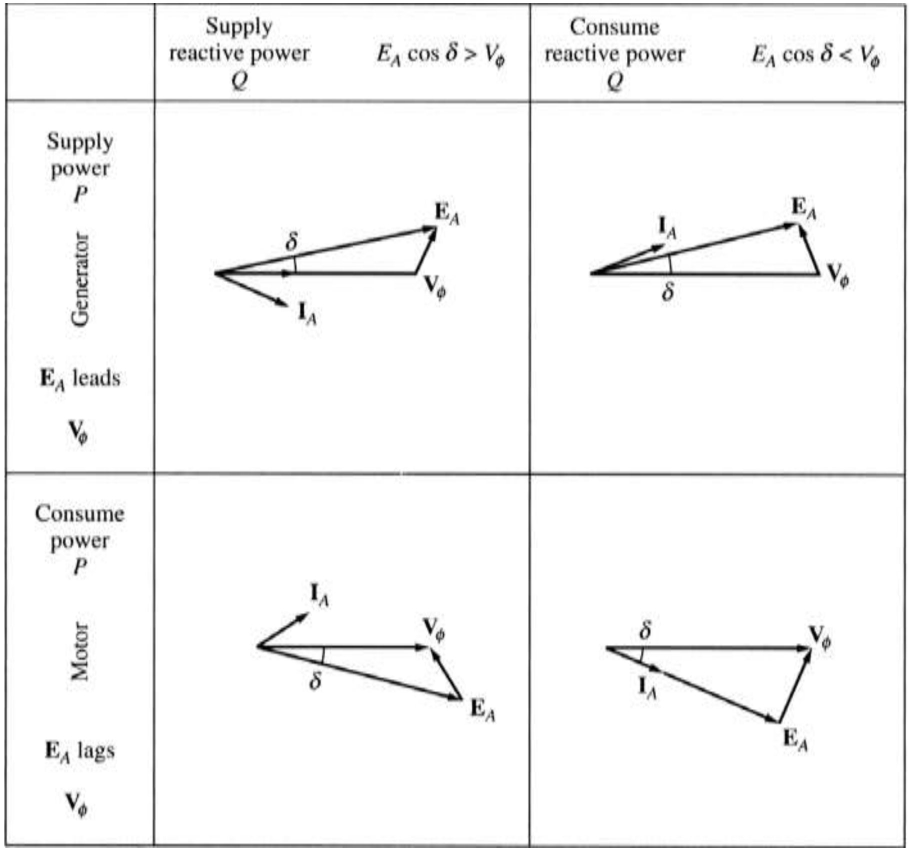
Instead, when the rotor's speed is close to synchronous, the regular field current can be turned on and the motor will operate normally. In real machines, field circuit are shorted during starting. Therefore, if a machine has damper winding:

1. **Disconnect the field windings from their DC power source and short them out;**
2. **Apply a 3-phase voltage to the stator and let the rotor to accelerate up to near-synchronous speed. The motor should have no load on its shaft to enable motor speed to approach the synchronous speed as closely as possible;**
3. **Connect the DC field circuit to its power source: the motor will lock at synchronous speed and loads may be added to the shaft.**

Relationship between synchronous generators and synchronous motors

Synchronous generator and synchronous motor are physically the same machines! A synchronous machine can supply real power to (generator) or consume real power (motor) from a power system. It can also either consume or supply reactive power to the system.

1. **The distinguishing characteristic of a synchronous generator (supplying *P*) is that E_A lies ahead of V_ϕ while for a motor E_A lies behind V_ϕ.**
2. **The distinguishing characteristic of a machine supplying reactive power *Q* is that $E_a \cos\delta > V_\phi$ (regardless whether it is a motor or generator). The machine consuming reactive power *Q* has $E_a \cos\delta < V_\phi$.**



Synchronous machine ratings

The speed and power that can be obtained from a synchronous motor or generator are limited. These limited values are called ratings of the machine. The purpose of ratings is to protect the machine from damage. Typical ratings of synchronous machines are voltage, speed, apparent power (kVA), power factor, field current and service factor.

1. Voltage, Speed, and Frequency

The rated frequency of a synchronous machine depends on the power system to which it is connected. The commonly used frequencies are 50 Hz (Europe, Asia), 60 Hz (Americas), and 400 Hz (special applications: aircraft, spacecraft, etc.). Once the operation frequency is determined, only one rotational speed in possible for the given number of poles:

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

Synchronous machine ratings

- **A generator's voltage depends on the flux, the rotational speed, and the mechanical construction of the machine. For a given design and speed, the higher the desired voltage, the higher the flux should be. However, the flux is limited by the field current.**

- **The rated voltage is also limited by the windings insulation breakdown limit, which should not be approached closely.**

- **Is it possible to operate a synchronous machine at a frequency other than the machine is rated for? For instance, can a 60 Hz generator operate at 50 Hz?**

- **The change in frequency would change the speed. Since $E_A = K\phi\omega$, the maximum allowed armature voltage changes when frequency changes.**
- **Specifically, if a 60 Hz generator will be operating at 50 Hz, its operating voltage must be derated to 50/60 or 83.3 %.**

Synchronous machine ratings

2. Apparent power and Power factor

Two factors limiting the power of electric machines are
1)Mechanical torque on its shaft (usually, shaft can handle much more torque)
2)Heating of the machine's winding

The practical steady-state limits are set by heating in the windings.
The maximum acceptable armature current sets the apparent power rating for a generator:

$$S = 3V_{\phi} I_A$$

If the rated voltage is known, the maximum accepted armature current determines the apparent power rating of the generator:

$$S = 3V_{\phi,rated} I_{A,\max} = \sqrt{3} V_{L,rated} I_{L,\max}$$

The power factor of the armature current is irrelevant for heating the armature windings.

Synchronous machine ratings

The stator cupper losses also do not depend on the current angle:

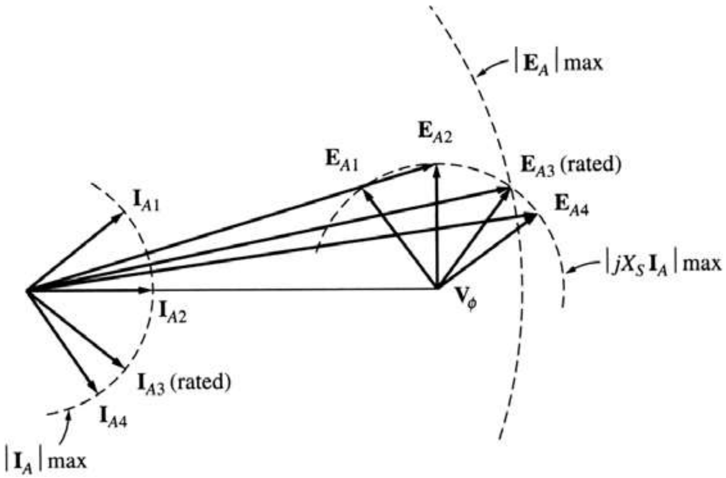
$$P_{SCL} = 3I_A^2 R_A$$

Since the current angle is irrelevant to the armature heating, synchronous generators are rated in kVA rather than in KW.

The rotor (field winding) cupper losses are:

$$P_{RCL} = I_F^2 R_F$$

Allowable heating sets the maximum field current, which determines the maximum acceptable armature voltage E_A. These translate to restrictions on the lowest acceptable power factor:
The current I_A can have different angles (that depends on PF). E_A is a sum of V_ϕ and jX_SI_A. We see that, (for a constant V_ϕ) for some angles the required E_A exceeds its maximum value.



Synchronous machine ratings

If the armature voltage exceeds its maximum allowed value, the windings could be damaged. The angle of I_A that requires maximum possible E_A specifies the rated power factor of the generator. It is possible to operate the generator at a lower (more lagging) PF than the rated value, but only by decreasing the apparent power supplied by the generator.

Synchronous motors are usually rated in terms of real output power and the lowest PF at full-load conditions.

3. Short-time operation and service factor

A typical synchronous machine is often able to supply up to 300% of its rated power for a while (until its windings burn up). This ability to supply power above the rated values is used to supply momentary power surges during motor starts.

It is also possible to use synchronous machine at powers exceeding the rated values for longer periods of time, as long as windings do not have time to hit up too much before the excess load is removed. For instance, a generator that could supply 1 MW indefinitely, would be able to supply 1.5 MW for 1 minute without serious harm and for longer periods at lower power levels.

Synchronous machine ratings

The maximum temperature rise that a machine can stand depends on the insulation class of its windings. The four standard insulation classes with they temperature ratings are:

A – 60^{0}C above the ambient temperature
B – 80^{0}C above the ambient temperature
F – 105^{0}C above the ambient temperature
H – 125^{0}C above the ambient temperature

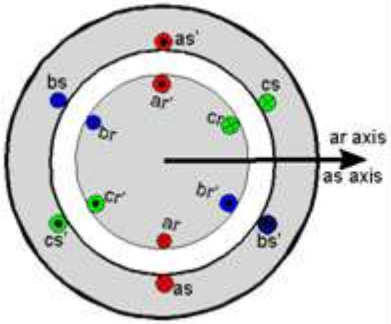
The higher the insulation class of a given machine, the greater the power that can be drawn out of it without overheating its windings.

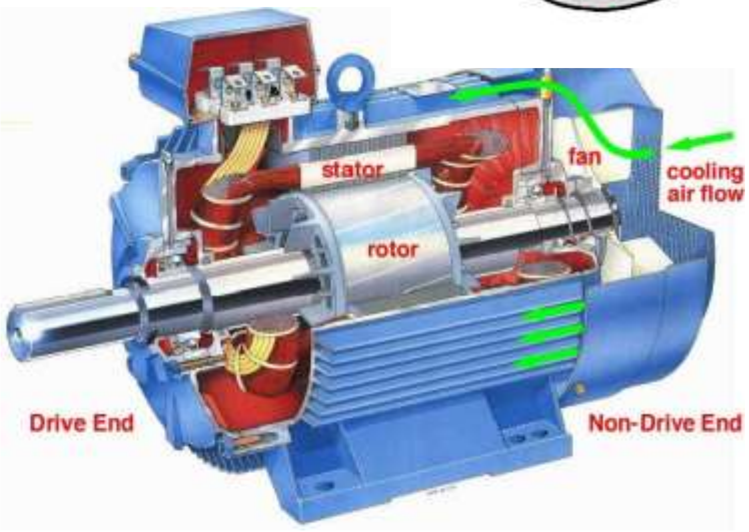
The overheating is a serious problem and synchronous machines should not be overheated unless absolutely necessary. However, power requirements of the machine not always known exactly prior its installation. Because of this, general-purpose machines usually have their service factor defined as the ratio of the actual maximum power of the machine to the rating on its plate. For instance, a machine with a service factor of 1.15 can actually be operated at 115% of the rated load indefinitely without harm.

EE471-Electrical Machines II

Topic 2: Three-Phase Induction Motor

(Asynchronous motor)





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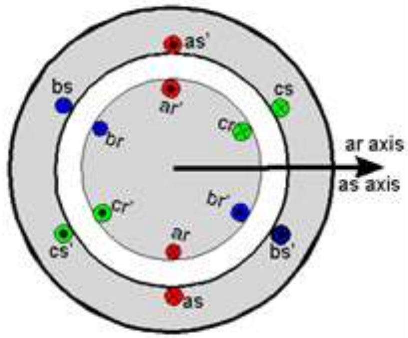
- Construction and Principle of Operation
- Equivalent Circuit
- Performance Characteristics
- Starting Methods
- Speed Control



Type Of Asynchrounous Motor

- Asynchronous motor
  - 3-phase
    - Squirrel cage
      - Double poles
        - 2 separate winding
        - Dahl ender
    - Slip-ring
  - Single phase
    - Resistor start
    - Capacitor start
    - Capacitor start-run
    - Permanent capacitor
    - Commutator
      - Universal
      - Repulsion

Introduction: Induction Motors

- An induction motor is a singly-fed motor. Therefore, it does not require a commutator, slip-rings, or brushes. In fact, there are no moving contacts between the stator and the rotor. This results in a motor that is rugged, reliable, and almost maintenance free (Squirrel Cage type).
- The absence of brushes eliminates the electrical loss due to the brush voltage drop and the mechanical loss due to friction between the brushes and commutator or the slip-rings (Squirrel Cage type).. Thus, an induction motor has a relatively high efficiency.
- An induction motor carries alternating current in both the stator and the rotor windings.
- An induction motor is a rotating transformer in which the secondary winding receives energy by induction while it rotates.

Application

In the industrial sector alone, about 75% is consumed by motors and over 90% of them are induction machines.

- **Small single-phase induction motors are used in many household appliances, such as blenders, juice mixtures, washing machines, refrigerators, etc.**
- **Large three-phase induction motors are used in pumps, fans, compressors, paper mills, and so forth**

Simple construction, Robust, Cheap

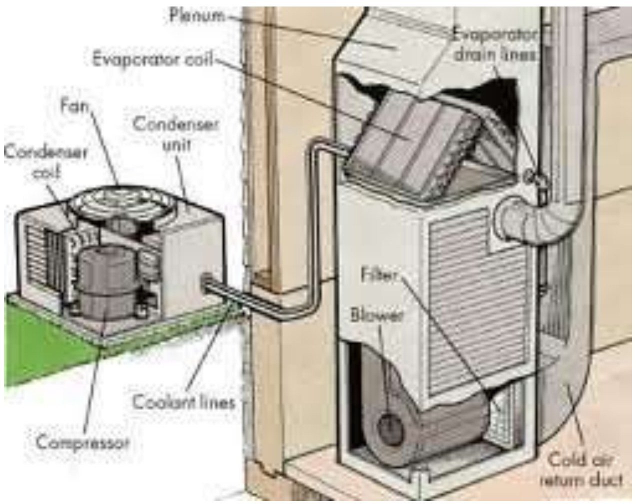
Induction Motor

Transportation Prime-mover

Induction Motor

Application Of Slip Ring Motor

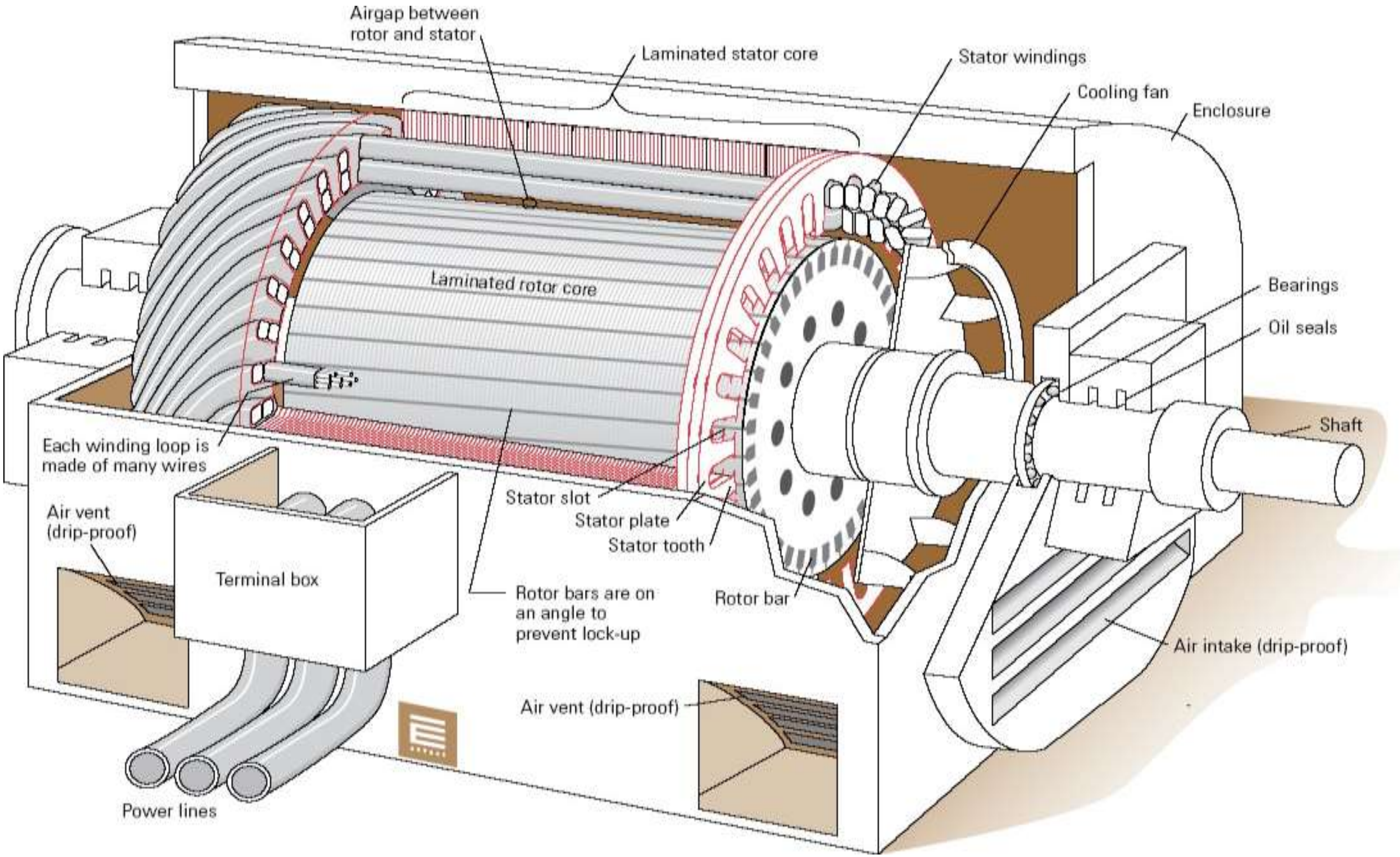
Wound rotr



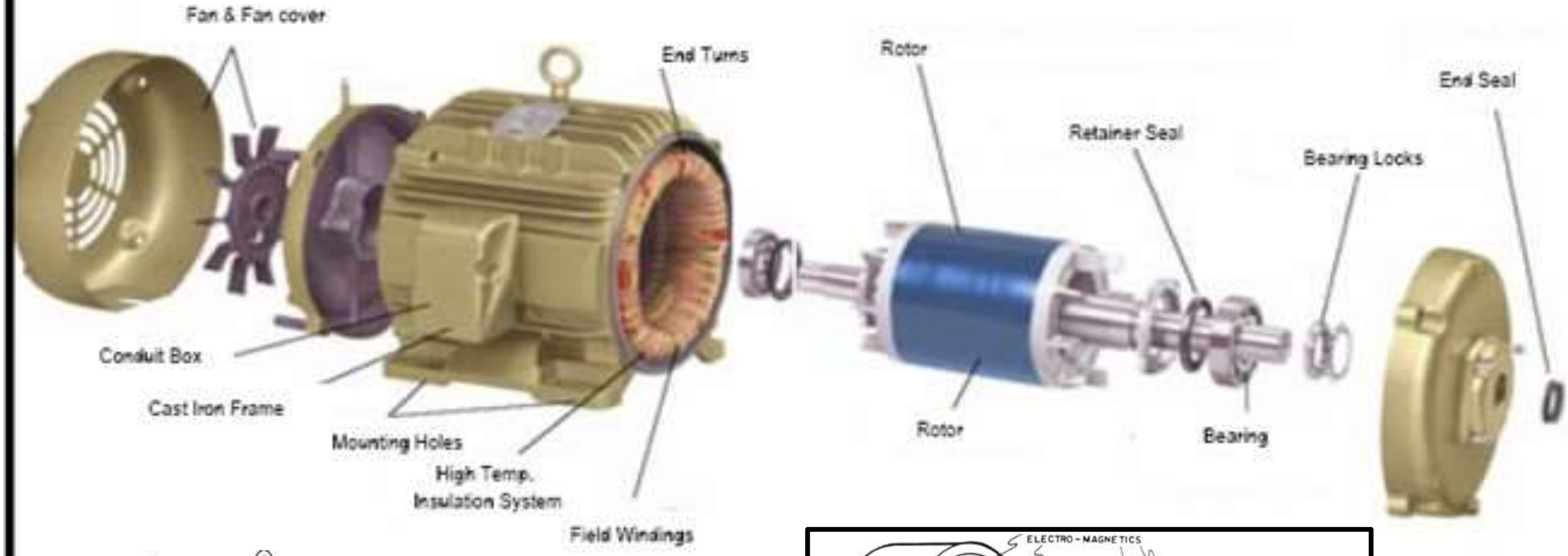
Central air conditoining

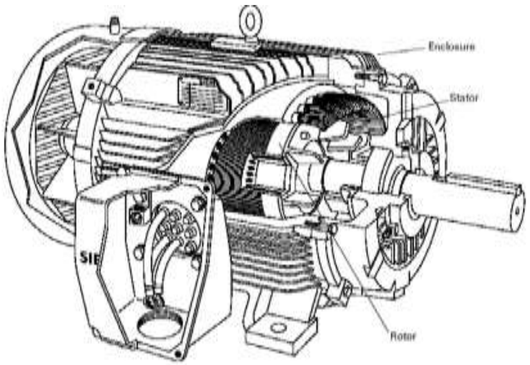
compressor

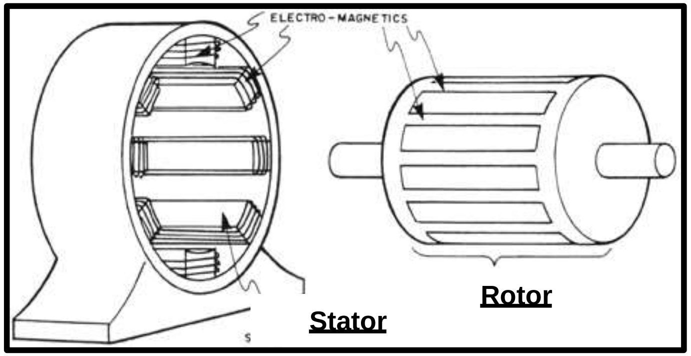
Inside View of An Induction Motor



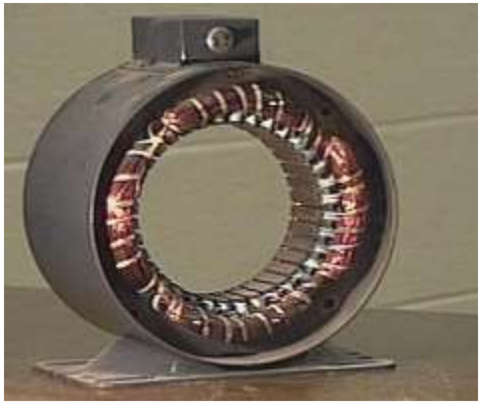
Parts of AC Motor





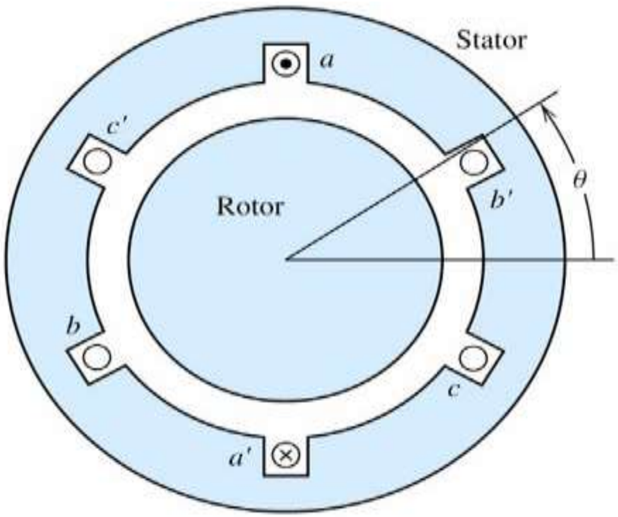


Construction

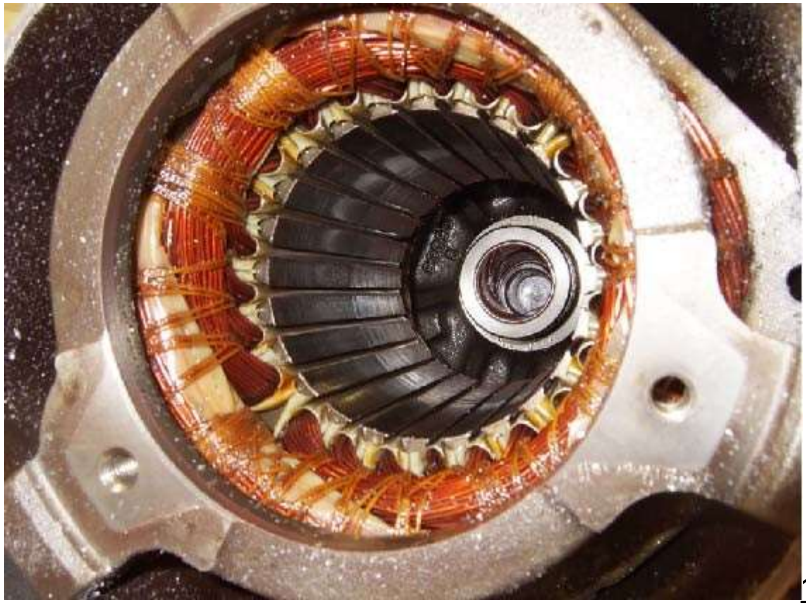


1- STATOR

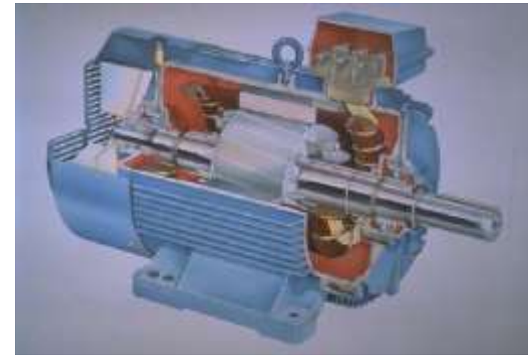
A three-phase windings is put in slots cut on the inner surface of the stationary part. The ends of these windings can be connected in star or delta to form a three phase connection. These windings are fed from a three-phase ac supply.



The stator of a two-pole machine contains three identical windings spaced 120° apart.



Construction

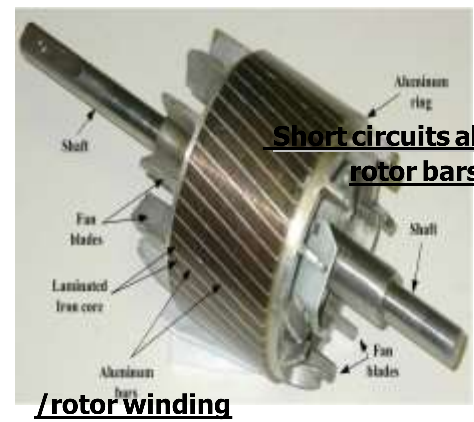


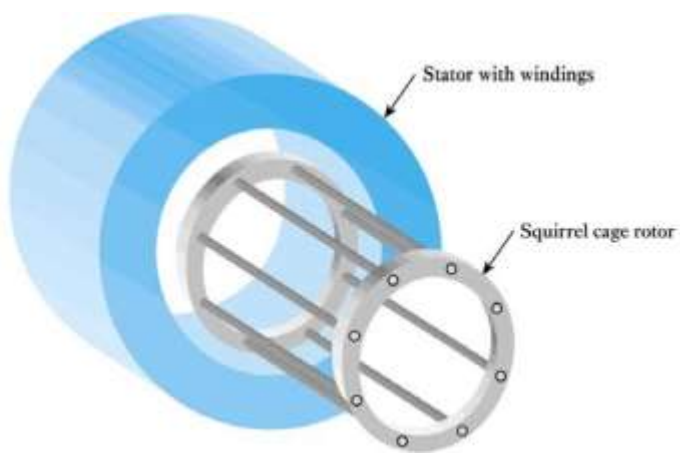
2- Rotor

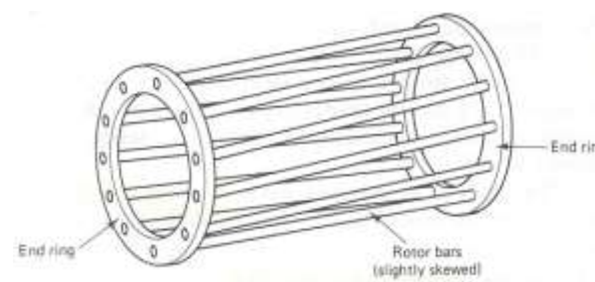
it can be either:

a- Squirrel-cage (brushless) (SCIM)

- The squirrel-cage winding consists of bars embedded in the rotor slots and shorted at both ends by end rings.
- The squirrel-cage rotor is the most common type because it is more rugged, more economical, and simpler.



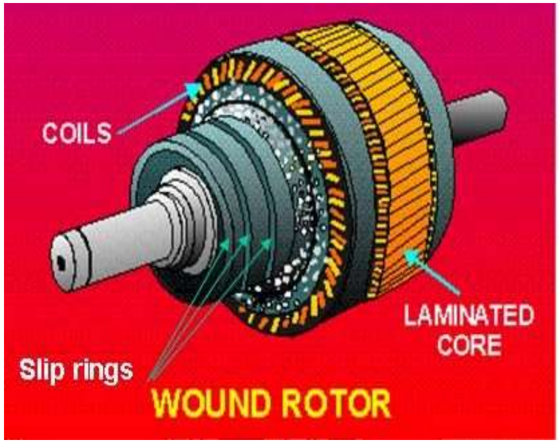




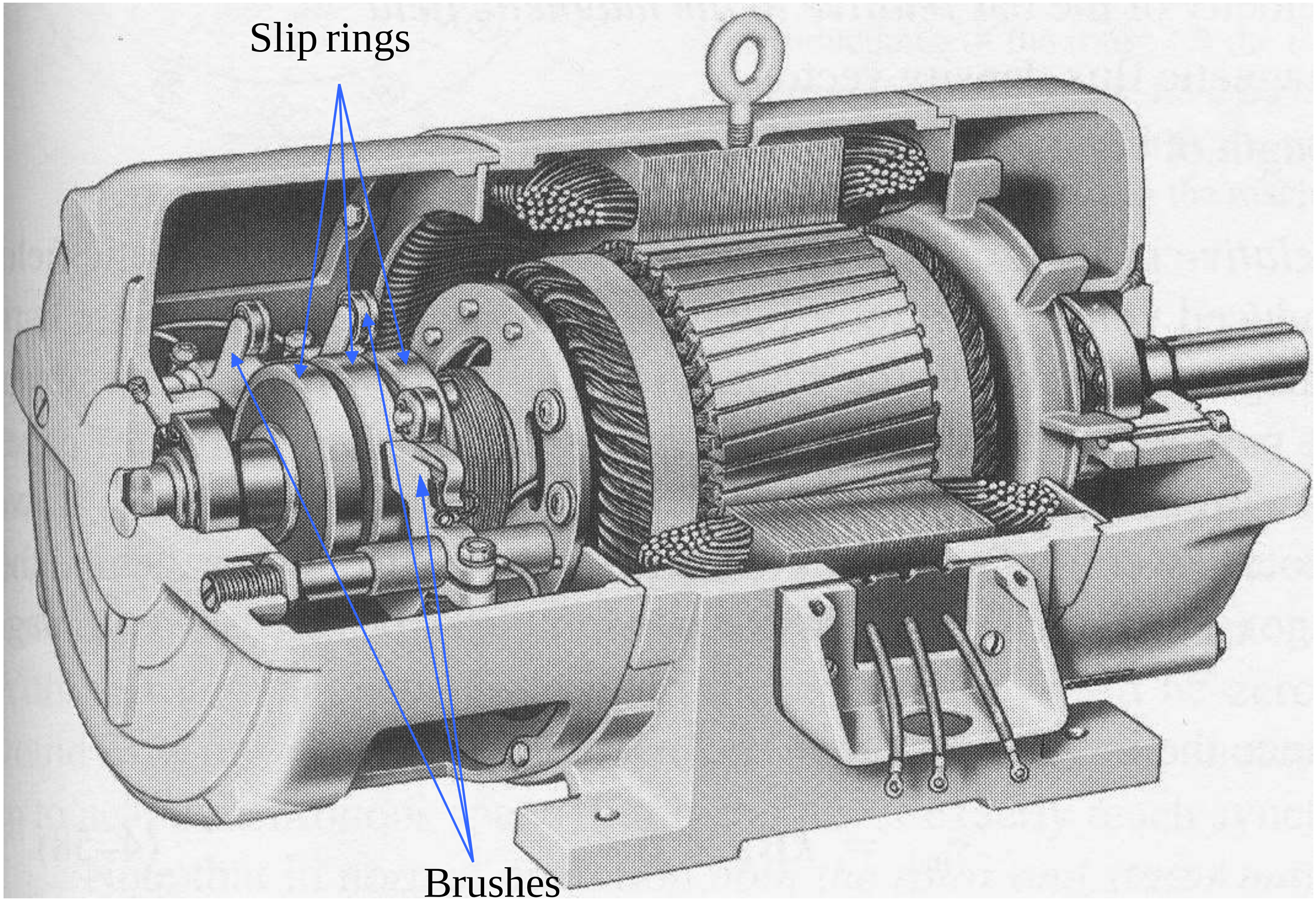
Construction

b- Slip ring (wound-rotor) (WRIM)

The wound-rotor winding has the same form as the stator winding. The windings are connected in star. The terminals of the rotor windings are connected to three slip rings. Using stationary brushes pressing against the slip rings, the rotor terminals can be connected to an external circuit.

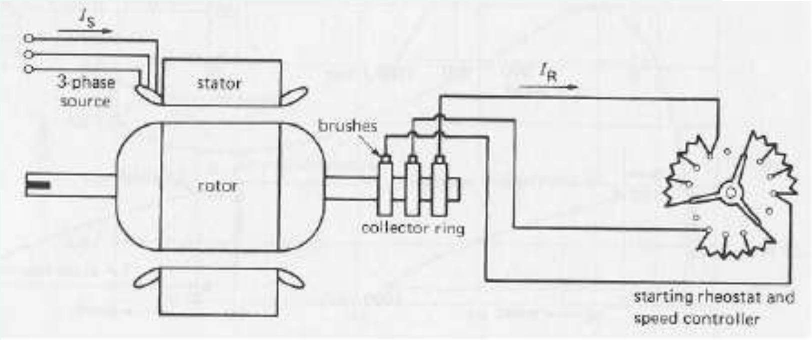


Construction-Wound Rotor Induction Motor (WRIM)

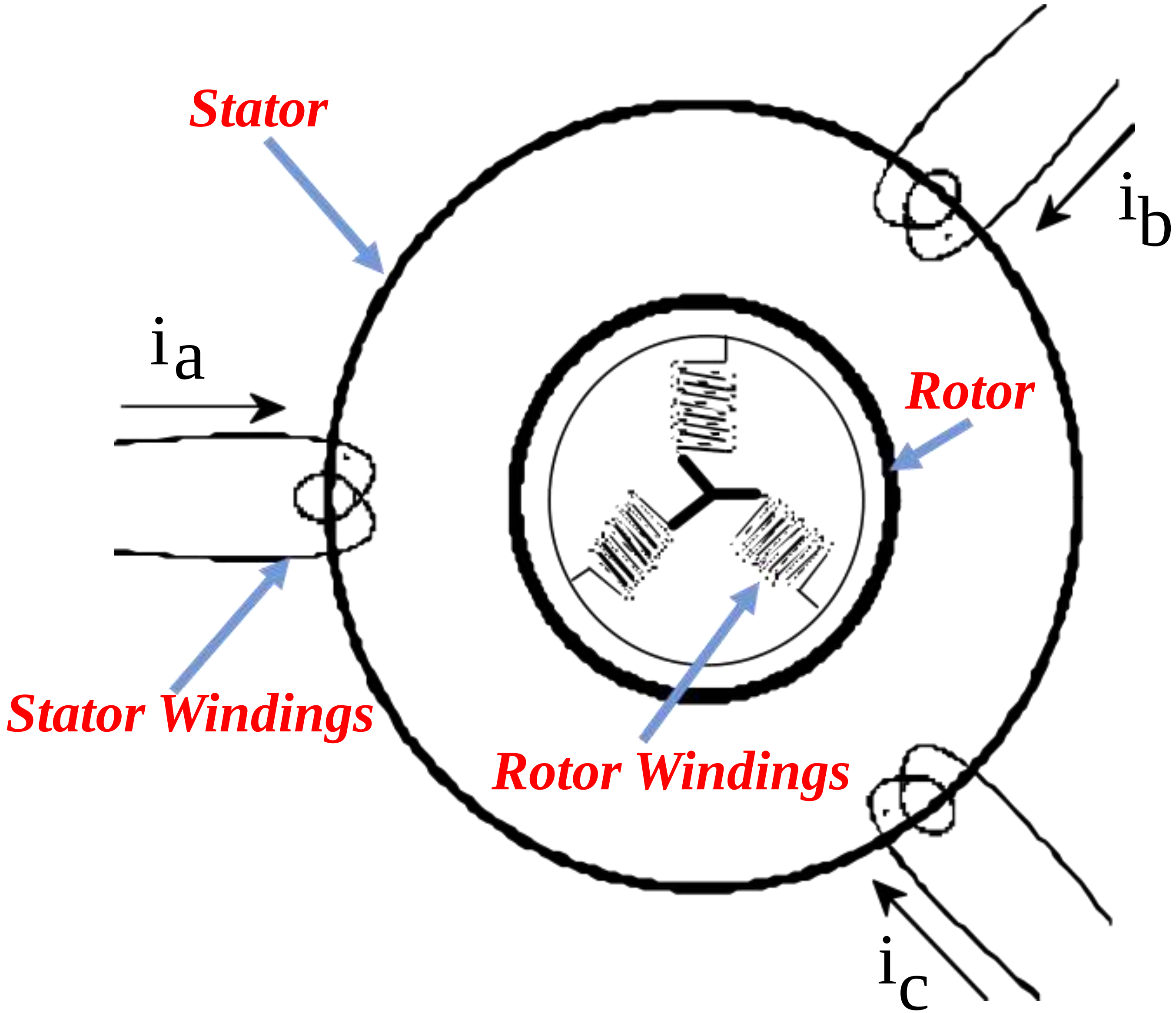


Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings

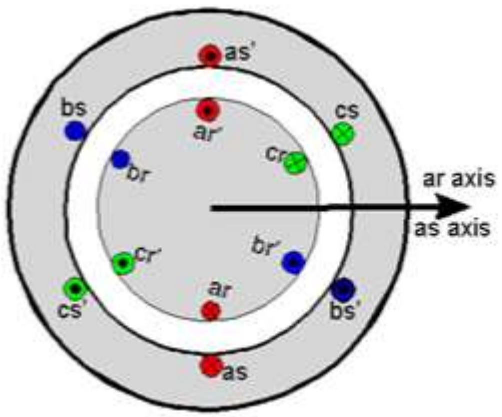
Advantages of Slip Ring and Squirrel Cage Motor

SQUIRREL CAGE	SLIP RING
cheaper and more robust slightly	the starting torque is much higher and the starting current much lower
higher efficiency and power factor	the speed can be varied by means of external rotor resistors
explosion proof, since the absence of slip-rings and brushes eliminates risk of sparking.	

Three-Phase Induction Motor



Principle of Operation



- If the stator windings are connected to a three-phase supply; a rotating field will be produced in the air-gap. This field rotates at synchronous speed n_s. This rotating field induces voltages in the rotor windings. Since 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 will eventually reach a steady-state speed n_m that is less than the synchronous speed n_s.

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

- The difference between the rotor speed and the synchronous speed is called the slip, s ,

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

$$S = \frac{\omega_s - \omega}{\omega_s}$$

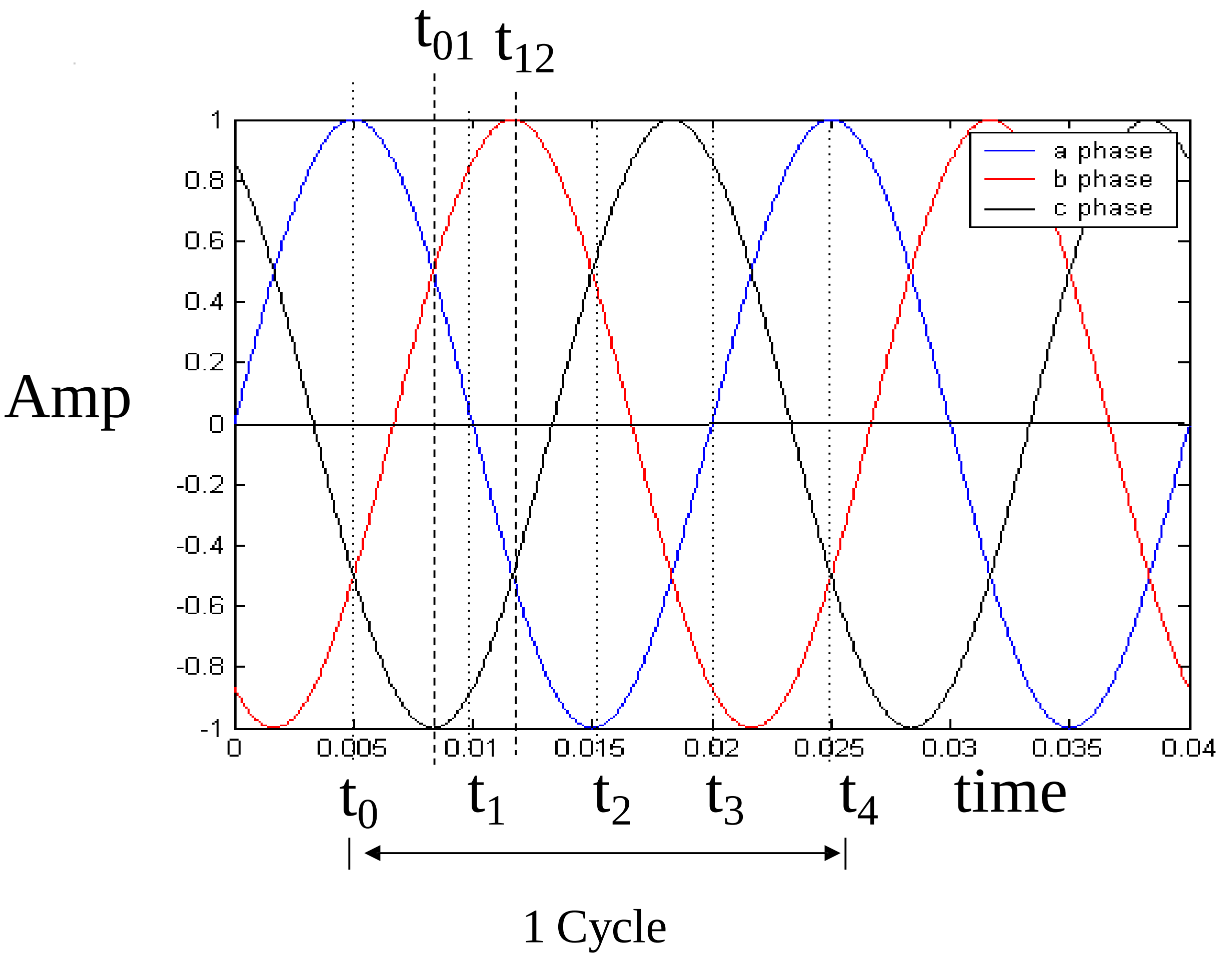
fs is the supply frequency
P is the total number of poles.

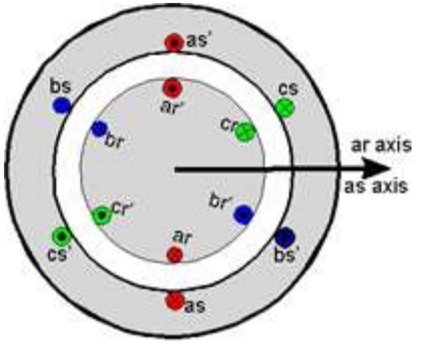
$$\omega = \frac{2\pi n}{60}$$

n in rpm
ω in rad/s

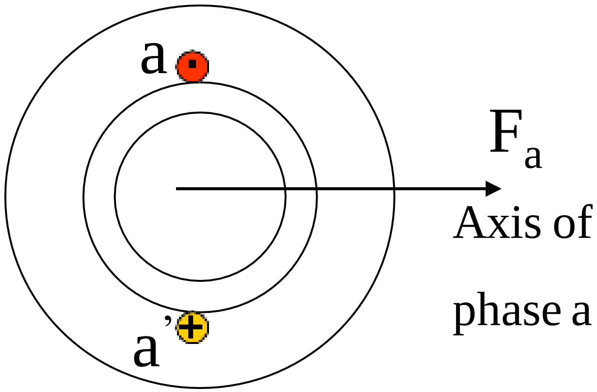
Rotating Magnetic Field

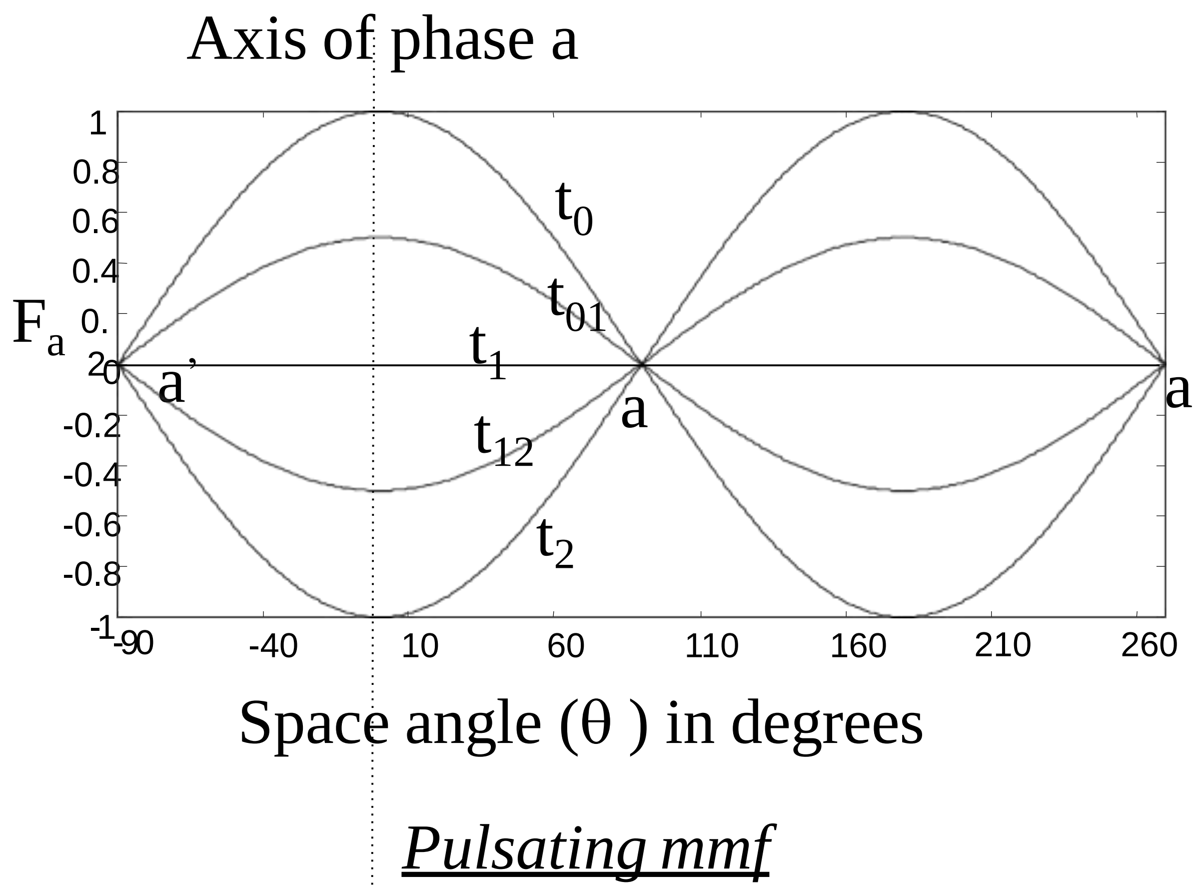
- Currents in different phases of AC Machine





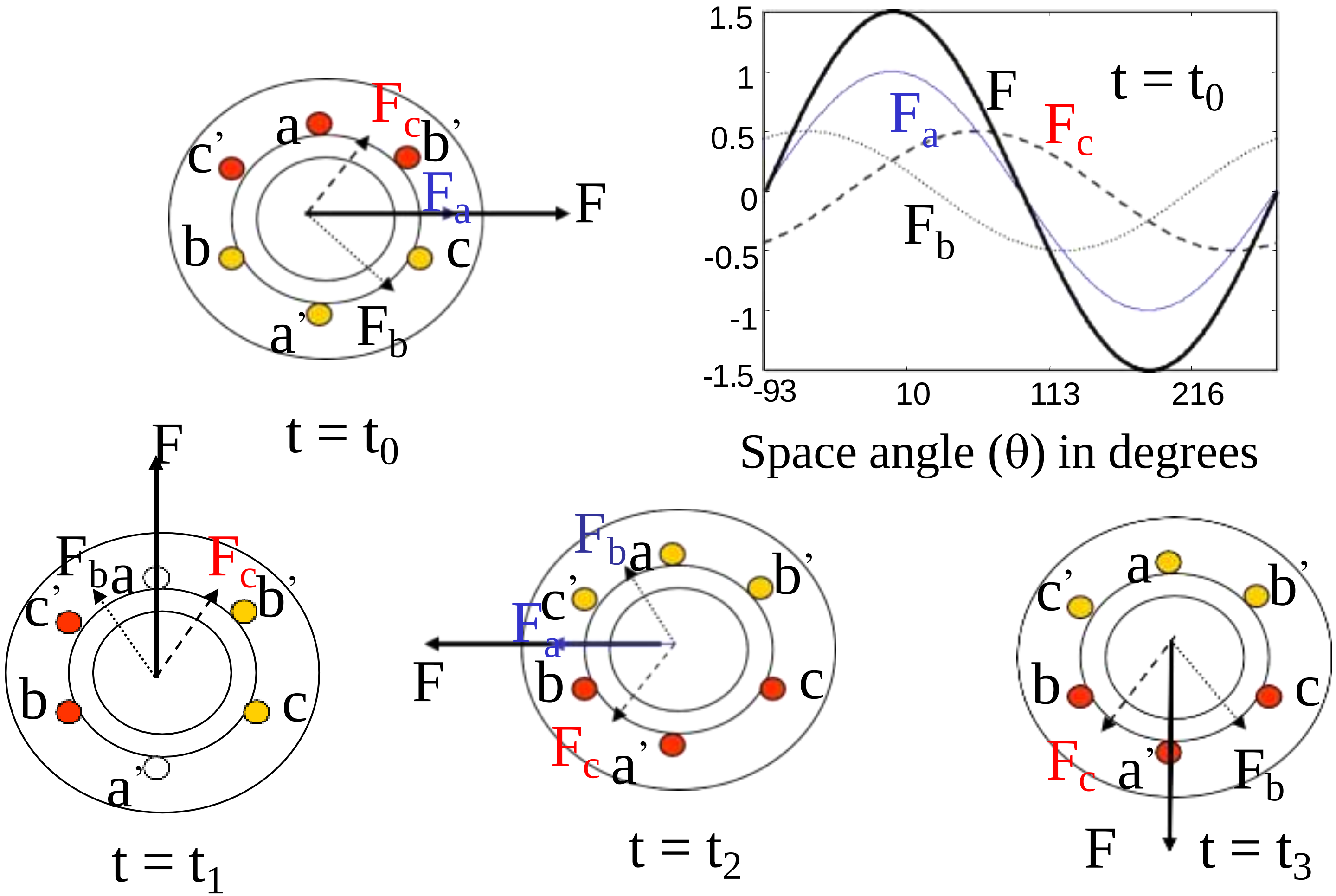
MMF due to ac current in phase "a"





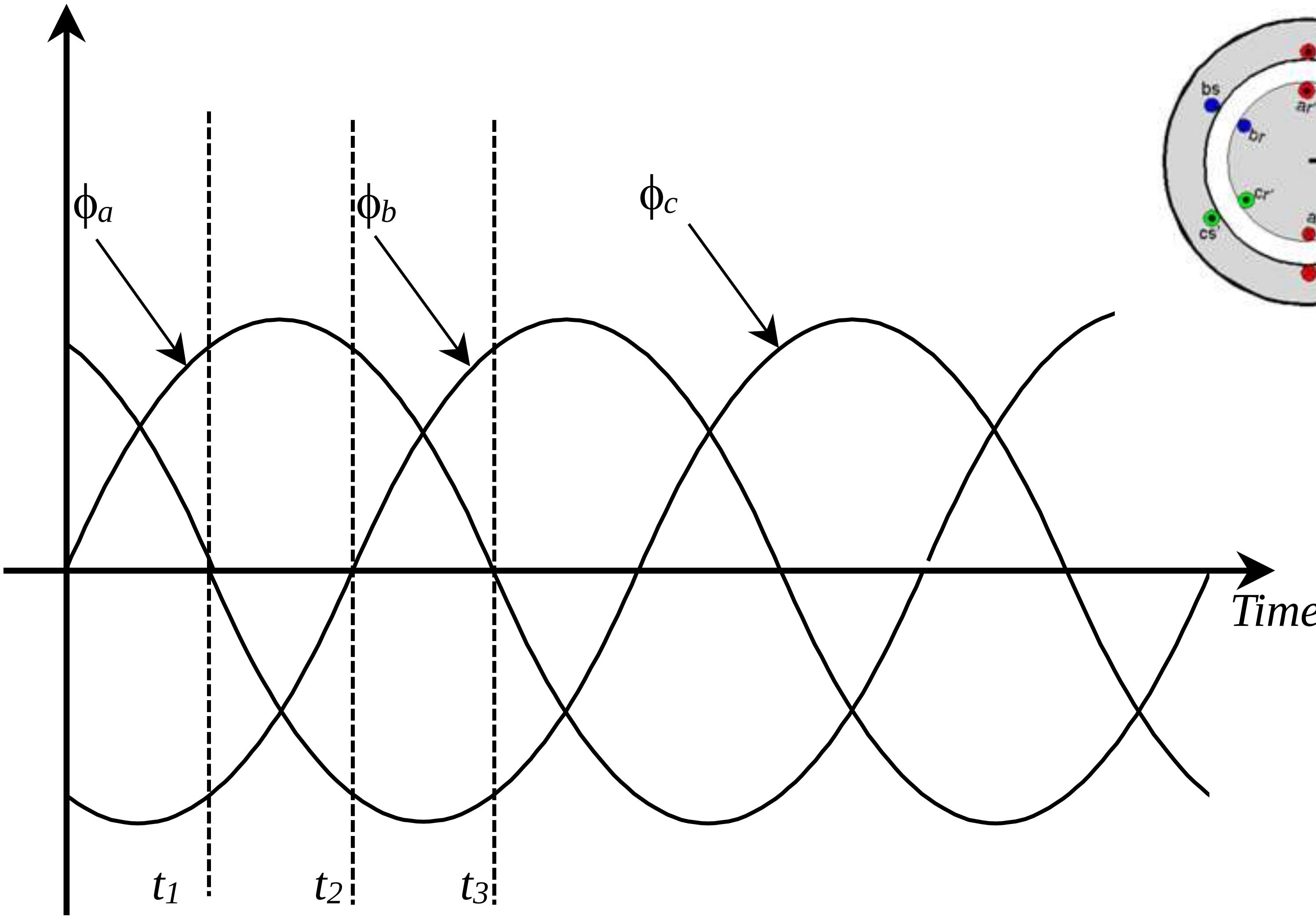
Pulsating mmf

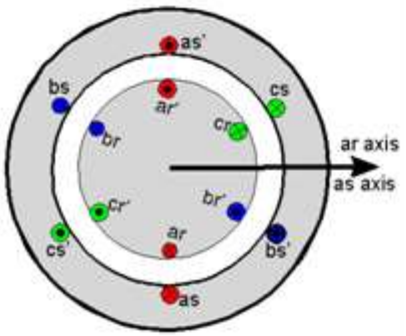
MMF due to three-phase currents in 3-ph winding



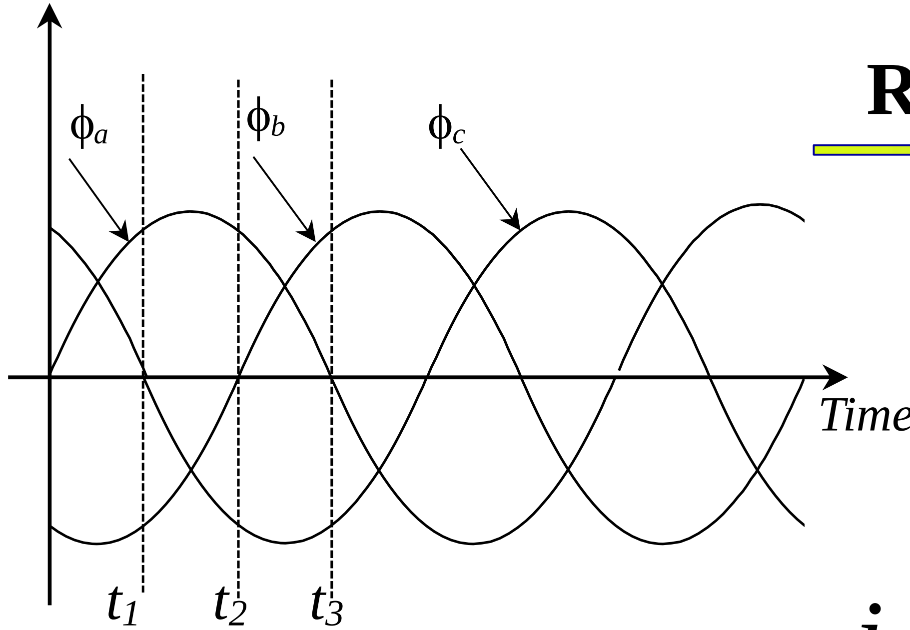
MMF’s at various instant (*Rotating mmf*)

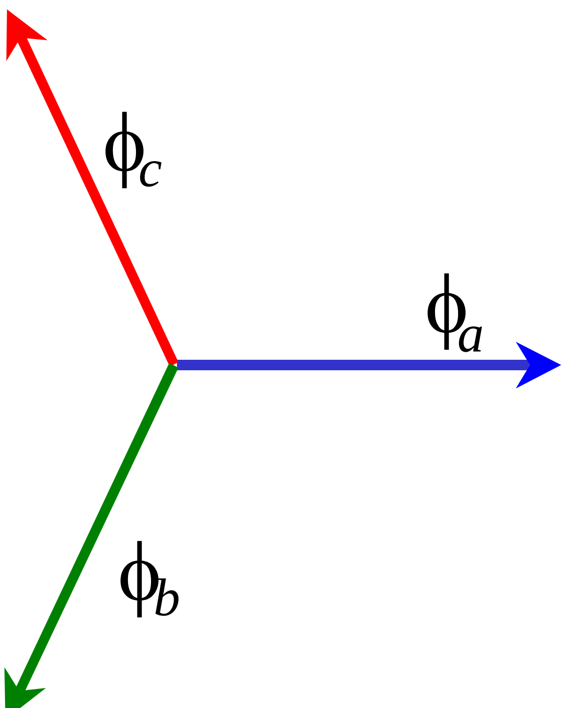
Rotating Magnetic Field

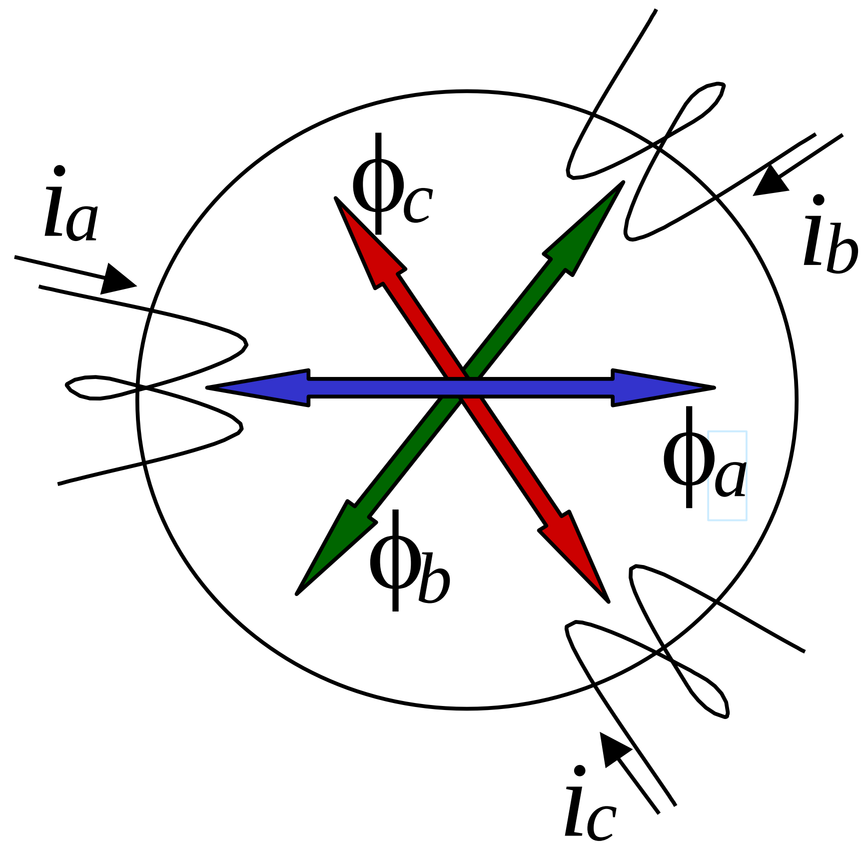




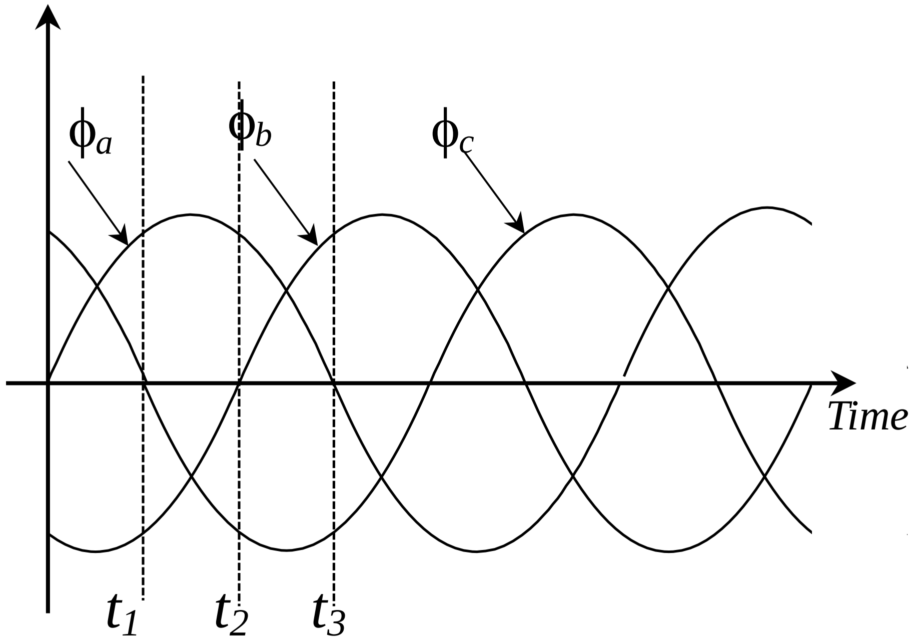
Rotating Magnetic Field

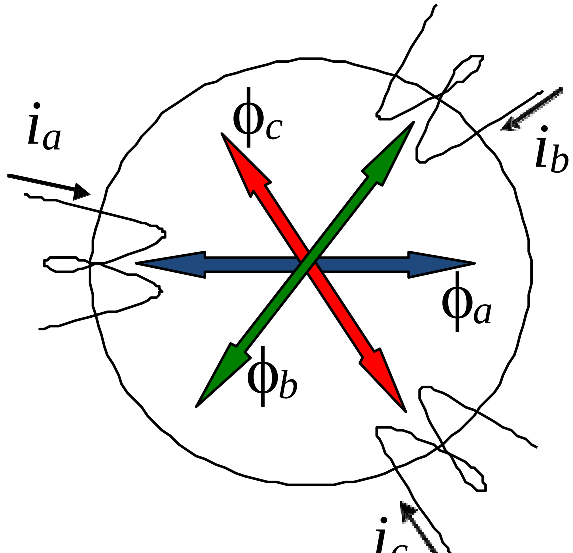


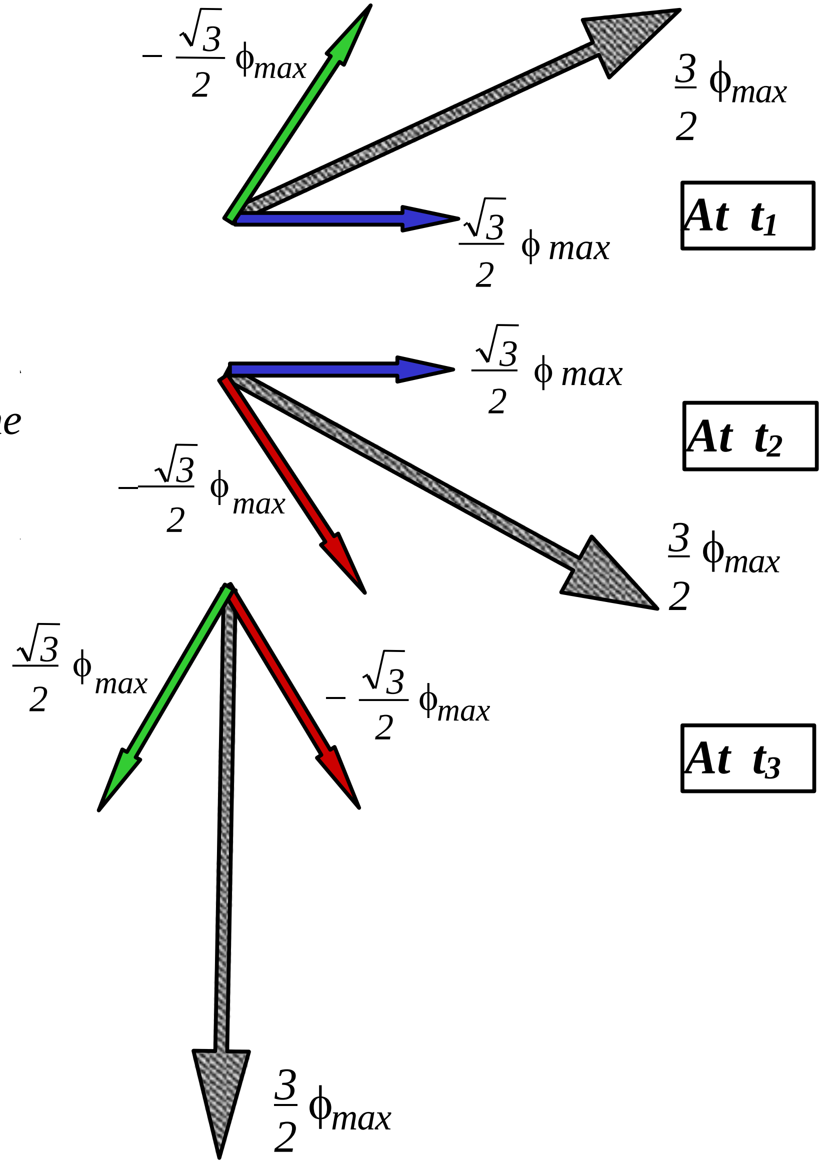




Rotating Magnetic Field







Principle of Operation: Definitions

- n_m = the rotor speed (the motor speed) w.r.t. **stator**
- n_s = the speed of stator field w.r.t. **stator** or the synch. speed
- n_r = the speed of rotor field w.r.t **rotor**
- S = the slip
- f_s = the frequency of the induced voltage in the stator (stator
- or supply frequency)
- f_r = the rotor circuit frequency or the slip frequency

$$n_r = n_S - n_m = sn_S$$ → Slip rpm

$$f_r = \frac{p}{120}(n_r) = \frac{p}{120}(n_S - n_m) = \frac{p}{120}(S\ n_S) = S\ f_S$$

Induced EMF

The instantaneous value of the induced voltage in N turns coil is given by:

$$e = -N \frac{d\phi}{dt}$$

$$Let \;\; \phi = \phi_m \sin(\omega t)$$

$$\therefore \quad e = -N \, \omega \, \phi_m \cos(\omega t) = N \; 2\pi f \; \phi_m \sin(\omega t - 90°)$$

The r.m.s. value of the induced voltage per phase is

$$E_{rms} = 4.44 \; f \; N_{ph} \, \Phi_p \, K_w$$

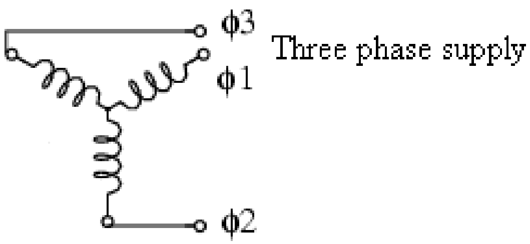
where

N_{ph} is the number of turns in series per phase

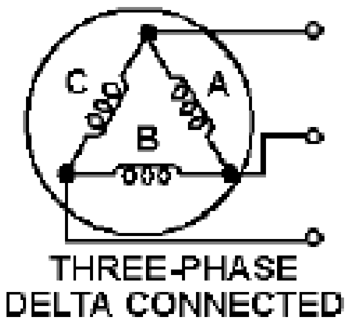
f is the frequency

ϕ_p is the flux per pole

K_w is the winding factor



phase voltage is 1/√3 of the normal voltage

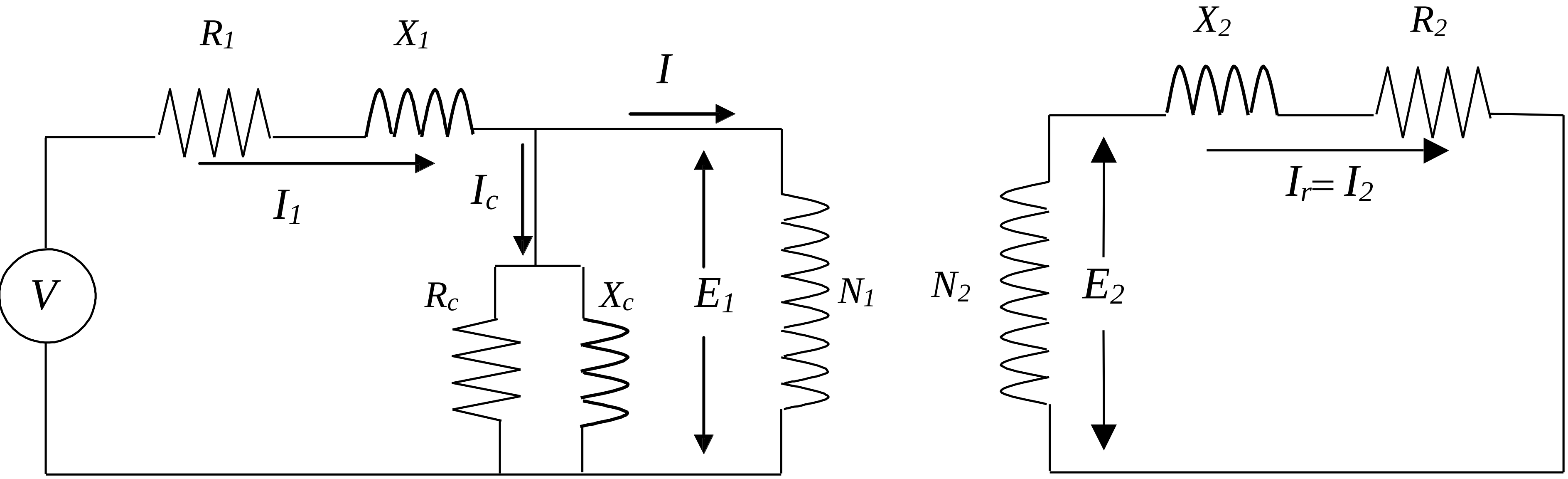


phase voltage is equal to the line voltage.

Equivalent Circuit Per Phase

- <u>At standstill</u> $(n_m = 0 \, , S = 1)$

The equivalent circuit of an induction motor at standstill is the same as that of a transformer with secondary short circuited.



$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \qquad \frac{I_2}{I} = \frac{N_1}{N_2} \cong \frac{I_2}{I_1}$$

Equivalent Circuit Per Phase (cont.)

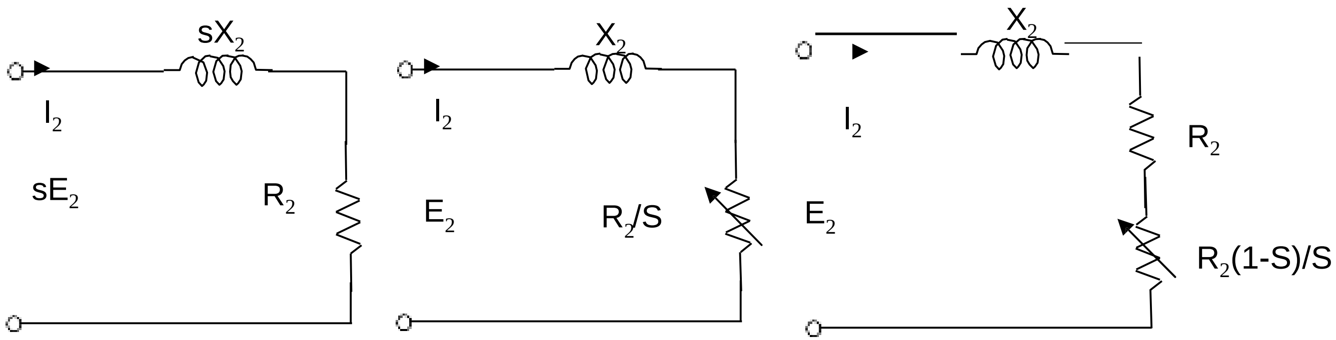
- **At any slip S**

When the rotor rotates with speed n_m the rotor circuit frequency will be:

$$f_r = S\ f_s$$

Therefore induced voltage in the rotor at any slip S will be $E_{2S} = S\,E_2$, similarly $X_{2S} = SX_2$

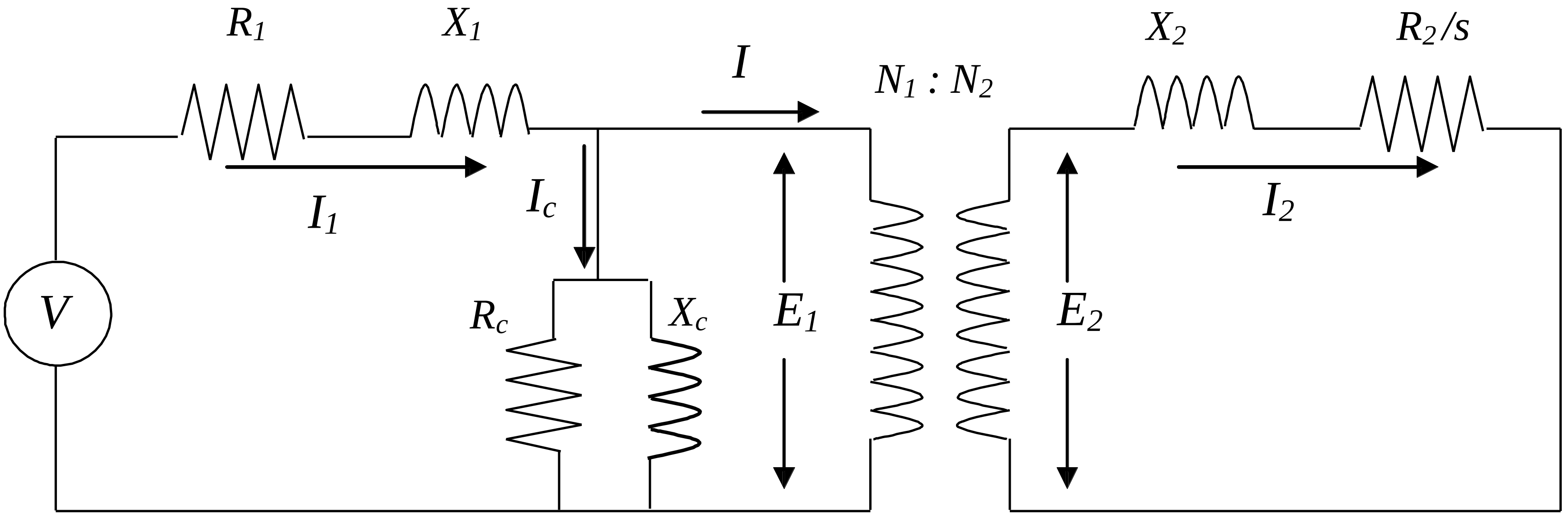
and the rotor equivalent circuit per-phase will be:



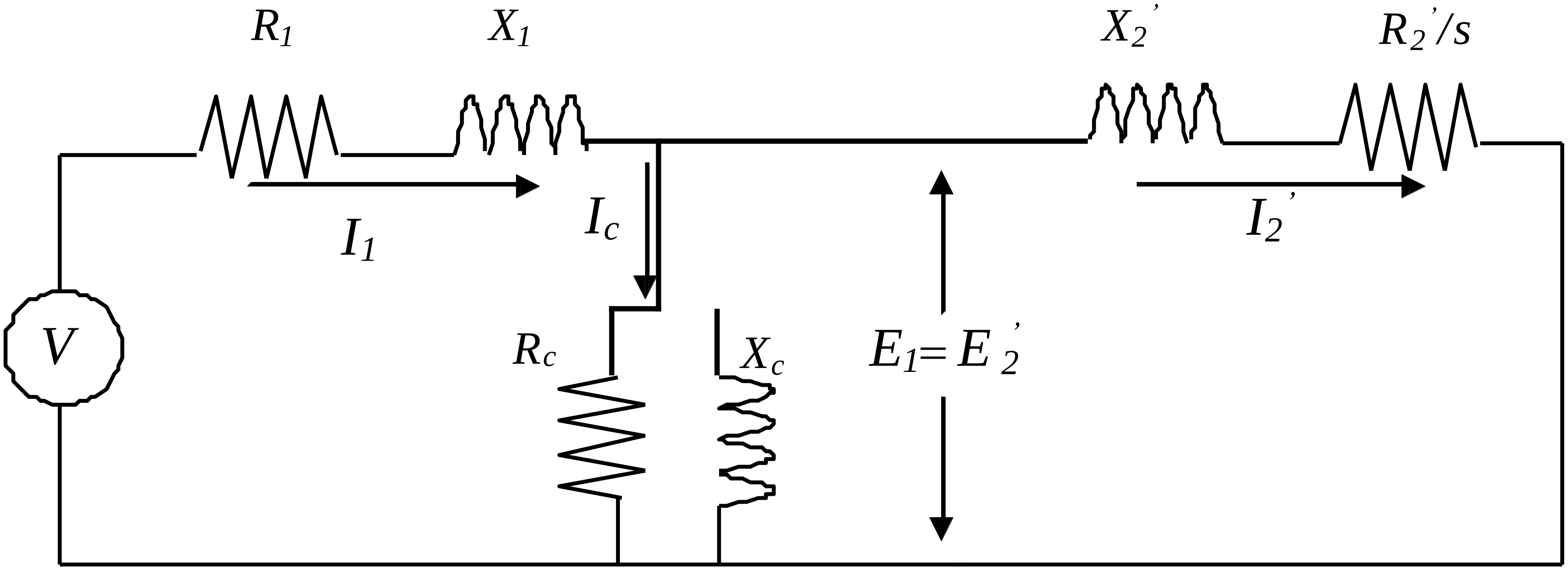
Where $$I_2 = \frac{SE_2}{R_2 + jSX_2} = \frac{E_2}{(R_2/s) + jX_2}$$

Combined Equivalent Circuit

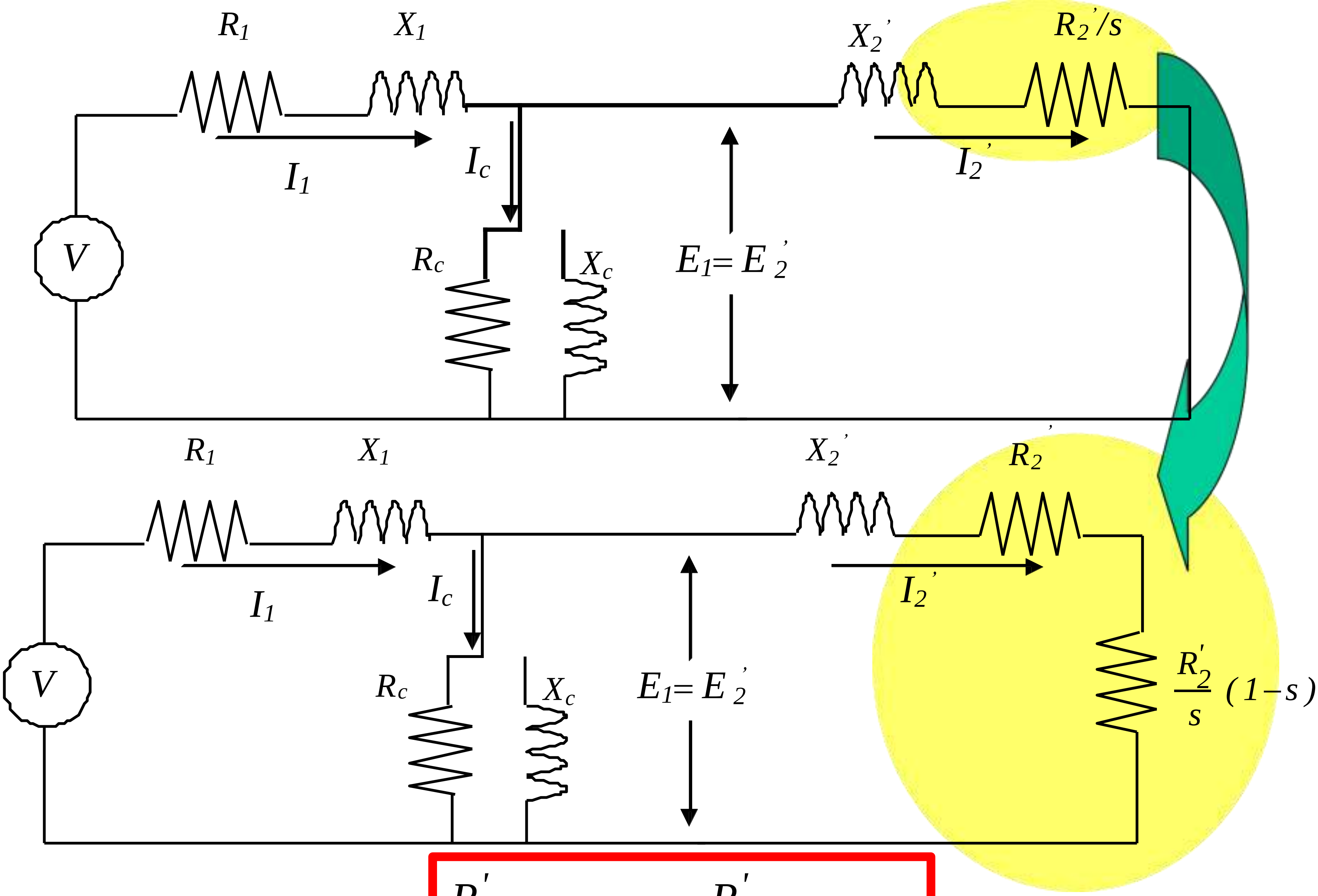
At any slip *S*



Combined Equivalent Circuit

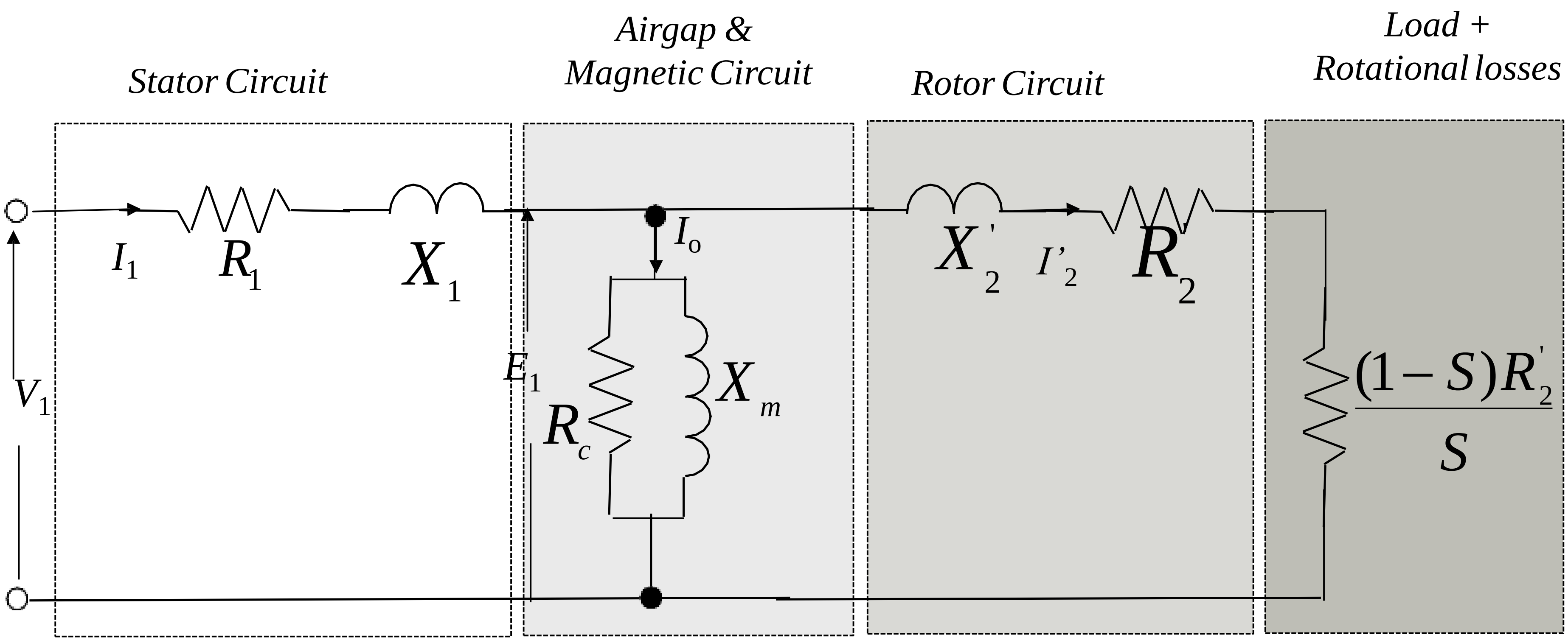


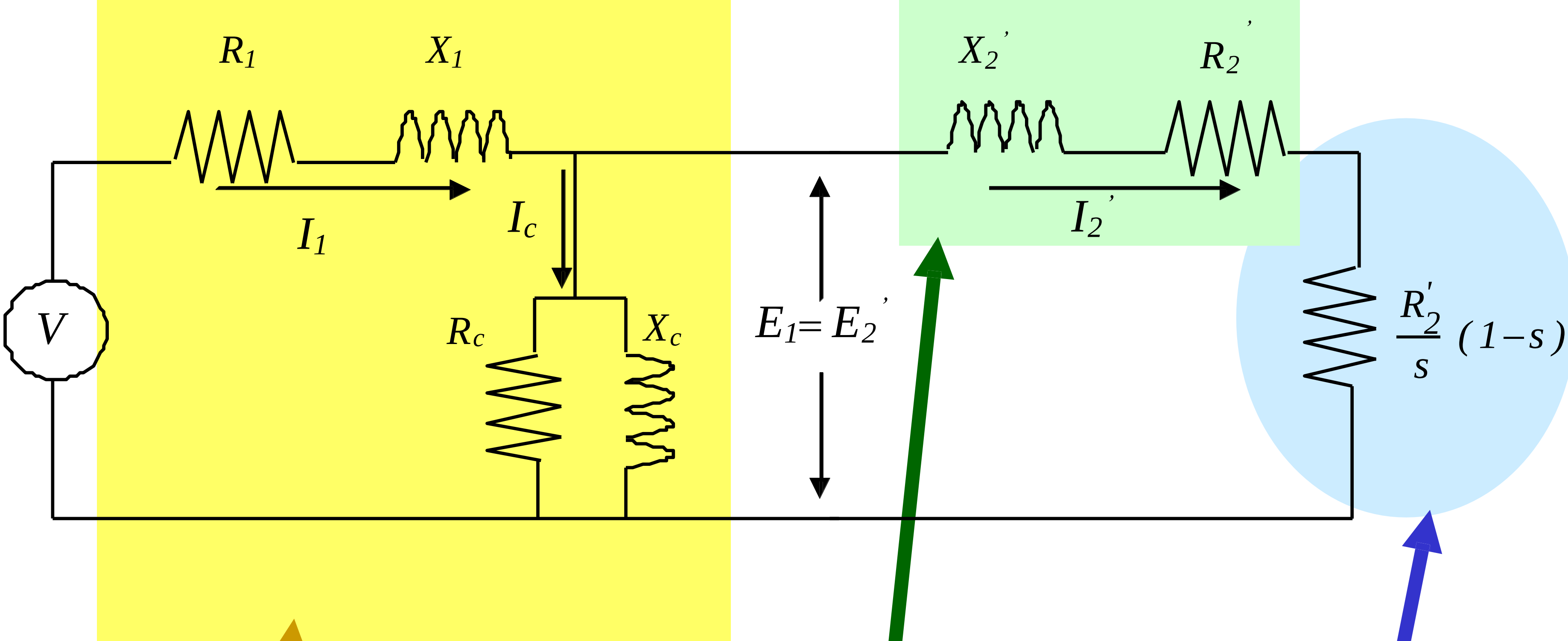
$$R_2' = R_2\left(\frac{N_1}{N_2}\right)^2 \qquad I_2' = I_2\left(\frac{N_2}{N_1}\right) \qquad X_2' = X_2\left(\frac{N_1}{N_2}\right)^2$$



$$\frac{R_2'}{s} = R_2' + \frac{R_2'}{s}(1-s)$$

Combined Equivalent Circuit

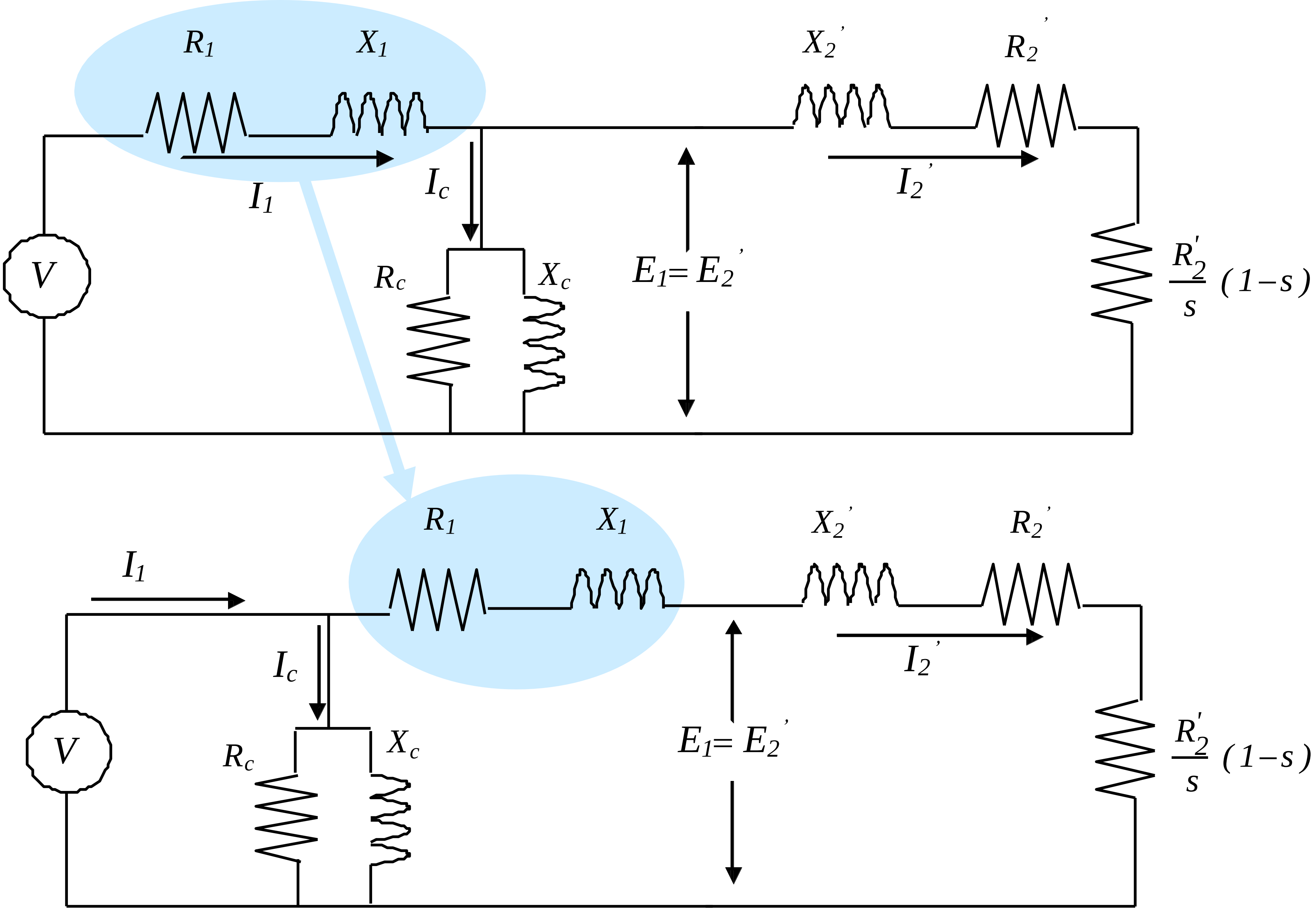




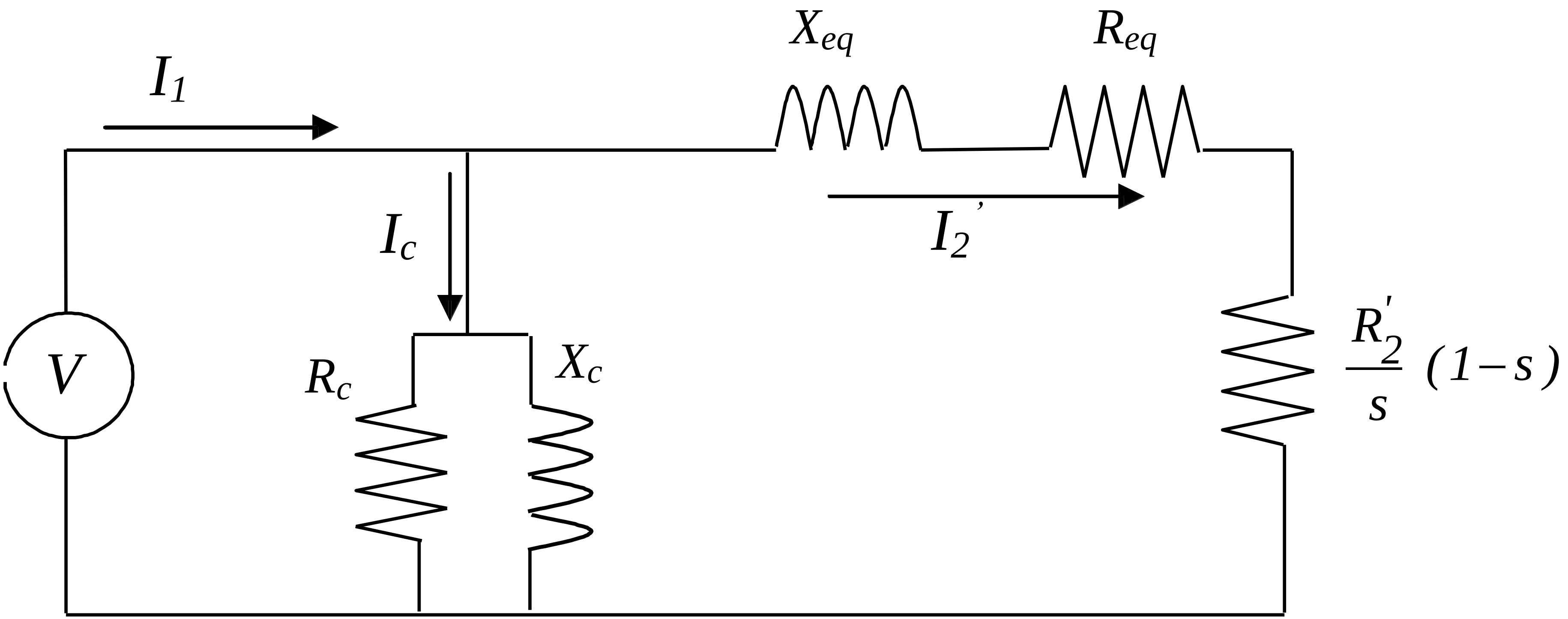
Equivalent to transformer's secondary windings

Equivalent to transformer's primary windings

Equivalent to transformer's load


R1
X1
X2'
R2'
I1
Ic
I2'
V
Rc
Xc
E1= E2'
R'2/s (1−s)
R1
X1
X2'
R2'
I1
Ic
I2'
V
Rc
Xc
E1= E2'
R'2/s (1−s)

Approximate Equivalent Circuit



$$R_{eq} = R_1 + R_2'$$

$$X_{eq} = X_1 + X_2'$$

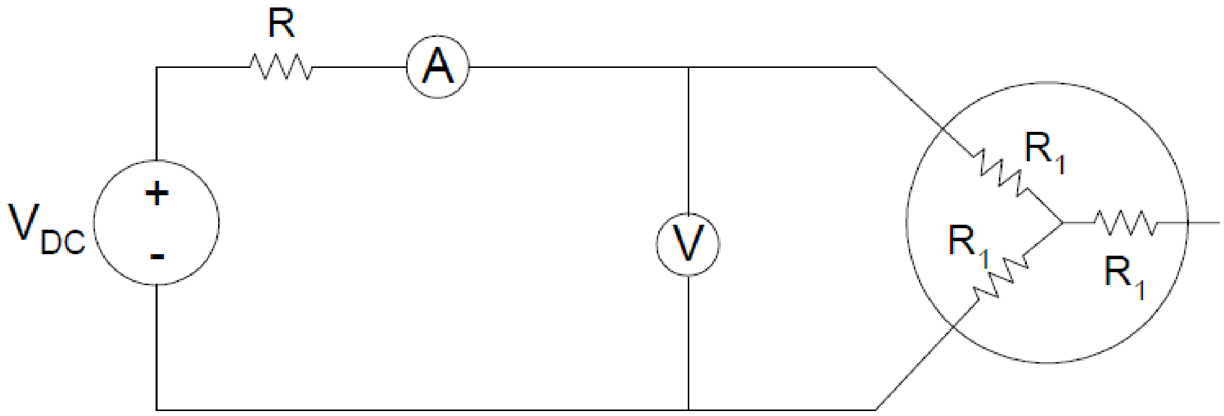
Determination of the Equivalent Circuit Parameters

1. Resistance Determination

The winding's resistance can be approximated by applying a DC voltage to a stationary machine's winding and measuring the current. However, AC resistance is slightly larger than DC resistance (skin effect).

For Y-Connection

$$\frac{V_{dc}}{I_{dc}} = 2R_{dc} \Rightarrow R_{dc} = \frac{1}{2}\frac{V_{dc}}{I_{dc}}$$

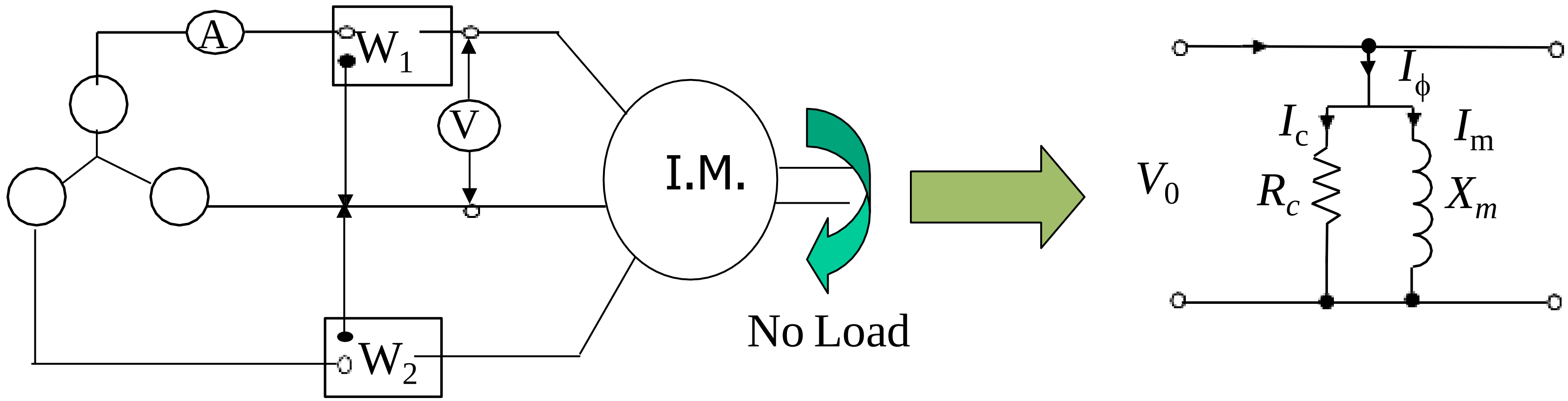


For Δ-Connection

$$\frac{V_{dc}}{I_{dc}} = \frac{2}{3}R_{dc} \Rightarrow R_{dc} = \frac{3}{2}\frac{V_{dc}}{I_{dc}}$$

Determination of the Equivalent Circuit Parameters

2. No-Load Test ($S = 0$)



Measured values $V_{oL} = V_{1L}$, $I_{\phi L}$, and $P_{ot} = W_1 \pm W_2$

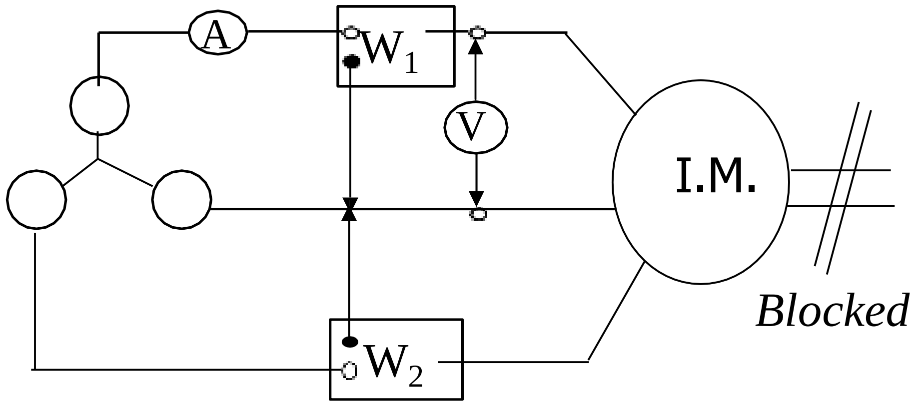
Calculate the per phase values V_0 , I_ϕ and $P_0 = P_{ot}/3$

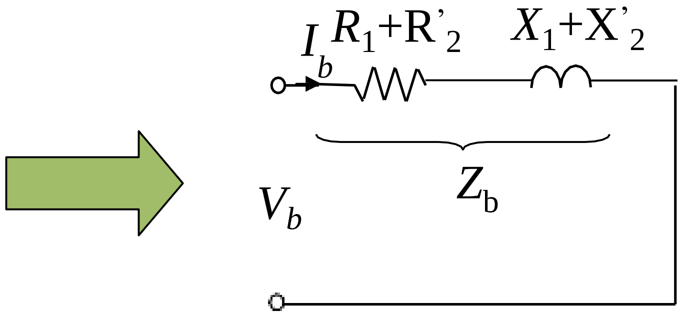
$$\cos(\Phi_o) = \frac{P_o}{V_0 I_\phi} \qquad I_c = I_\phi \cos(\Phi_o) \qquad I_m = I_\phi \sin(\Phi_o)$$

$$R_c = \frac{V_0}{I_c} \qquad X_m = \frac{V_0}{I_m}$$

Determination of the Equivalent Circuit Parameters

<u>3. Blocked rotor Test</u> (*S =1*)





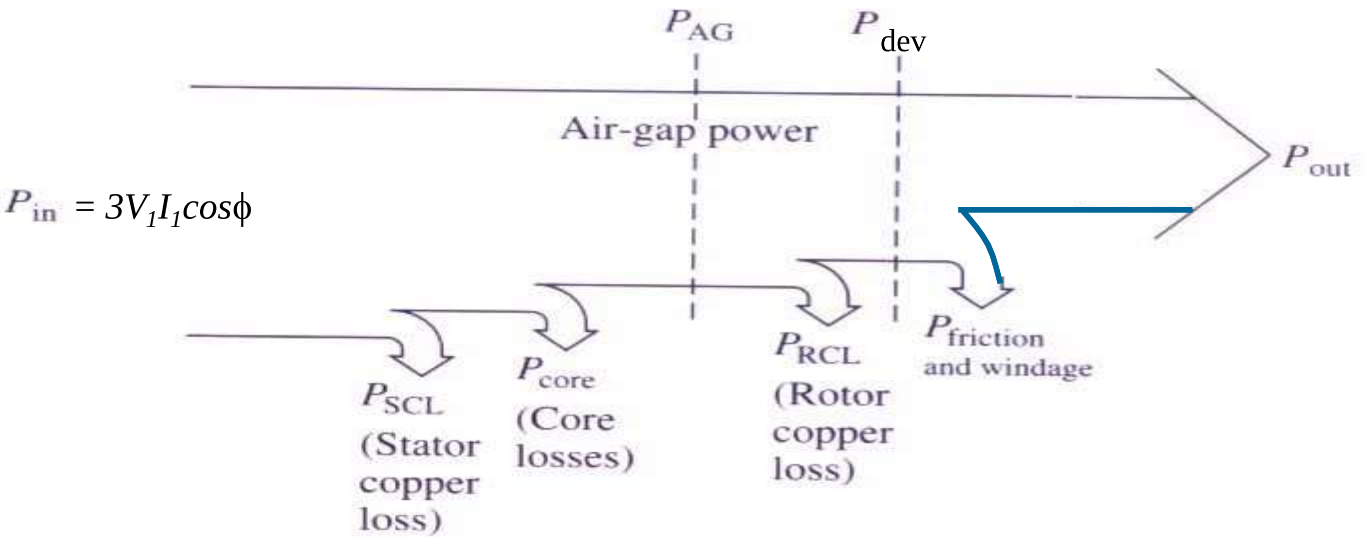
Measured values $V_{bL} < V_{1L}$, I_{bL}, and $P_{bt} = W_1 \pm W_2$

Calculate the per phase values V_b, I_b and $P_b = P_{ot}/3$

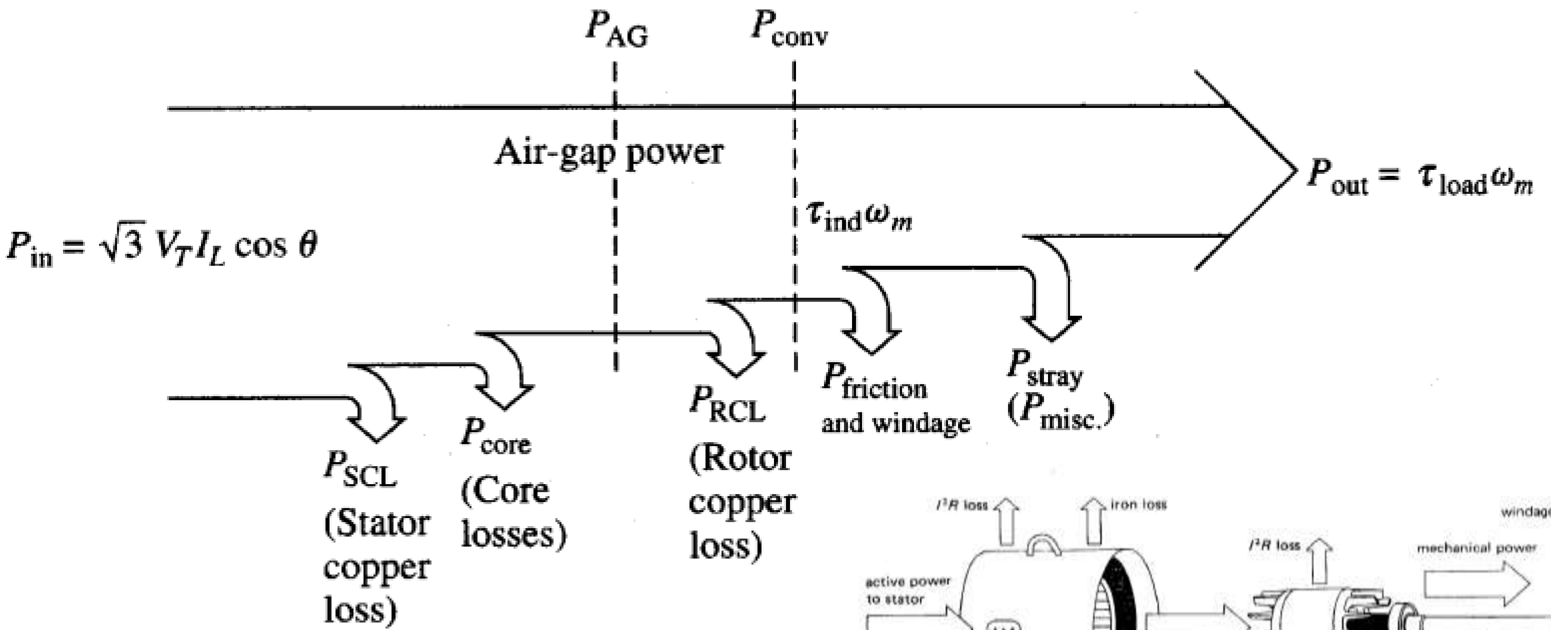
$$R_b = R_1 + R_2' = \frac{P_b}{I_b^{\,2}}, \qquad Z_b = \frac{V_b}{I_b}, \qquad X_b = X_1 + X_2' = \sqrt{Z_b^2 - R_b^2}$$

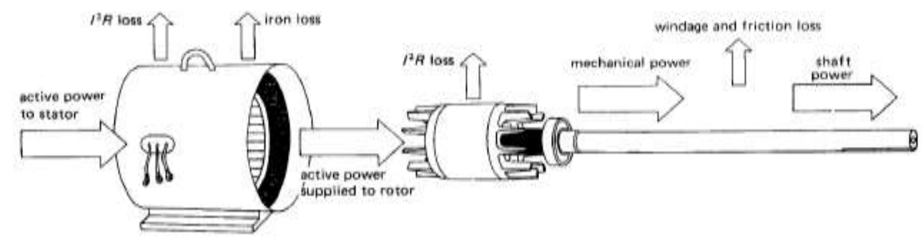
$$\therefore R_2' = R_b - R_1 \qquad \& \qquad X_1 = X_2' = \frac{X_b}{2}$$

Power Flow In Induction Motors



Power Flow In Induction Motors



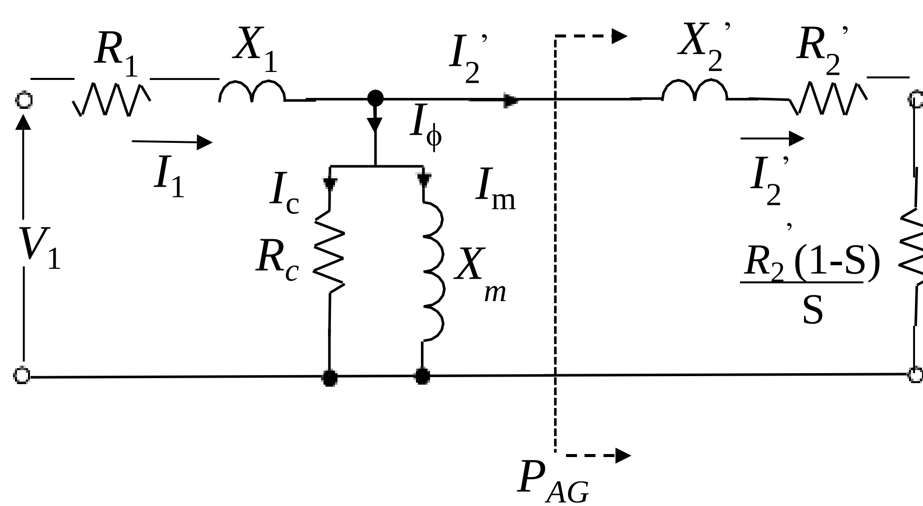


$$P_{AG} = 3(I_2')^2 \frac{R_2'}{S}$$

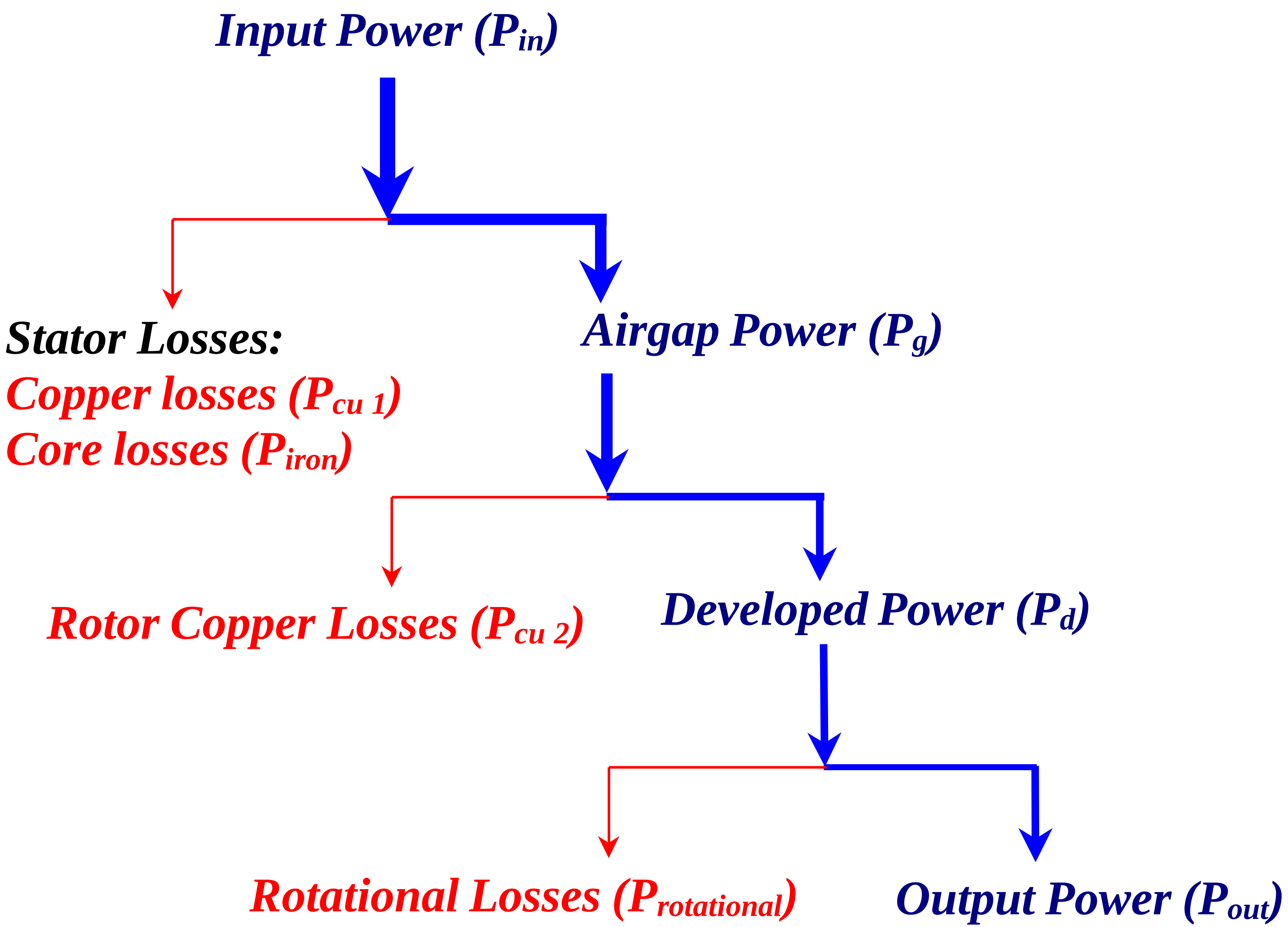
$$P_{RCL} = 3(I_2')^2 R_2'$$

$$P_{dev} = 3(I_2')^2 \frac{R_2'(1-S)}{S}$$

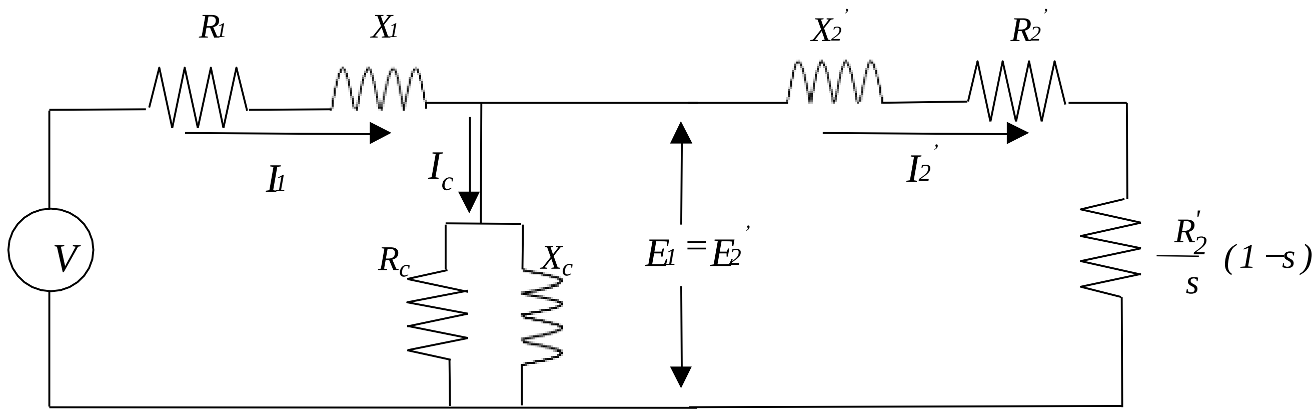
$$\therefore P_{GA} : P_{RCL} : P_{dev} = 1 : S : (1-S)$$



Power Flow In Induction Motor



Power Flow In Induction Motor



$$P_{in} = 3 V I_1 \cos\theta_1$$

$$P_{cu1} = 3\ I_1^2 R_1$$

$$P_{iron} \cong 3 \frac{V^2}{R_m}$$

$$P_g = 3\ (I_2')^2 \frac{R_2'}{s} = T_d\ \omega_s$$

$$P_g : P_{cu2} : P_d = 1 : s : (1-s)$$

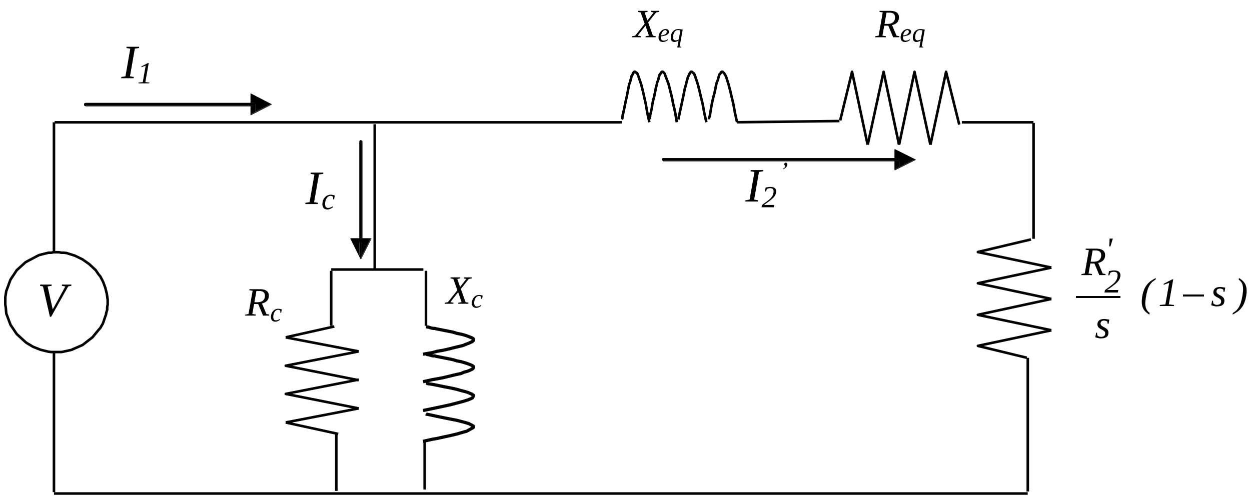
$$P_{cu2} = 3\left(I_2'\right)^2 R_2' = s\ P_g$$

$$P_d = 3\left(I_2'\right)^2 \frac{R_2'}{s}(1-s) = P_g\ (1-s)\ = T_d\ \omega$$

$$P_{rotational}$$

$$P_{out} = T\ \omega$$

Torque Characteristics

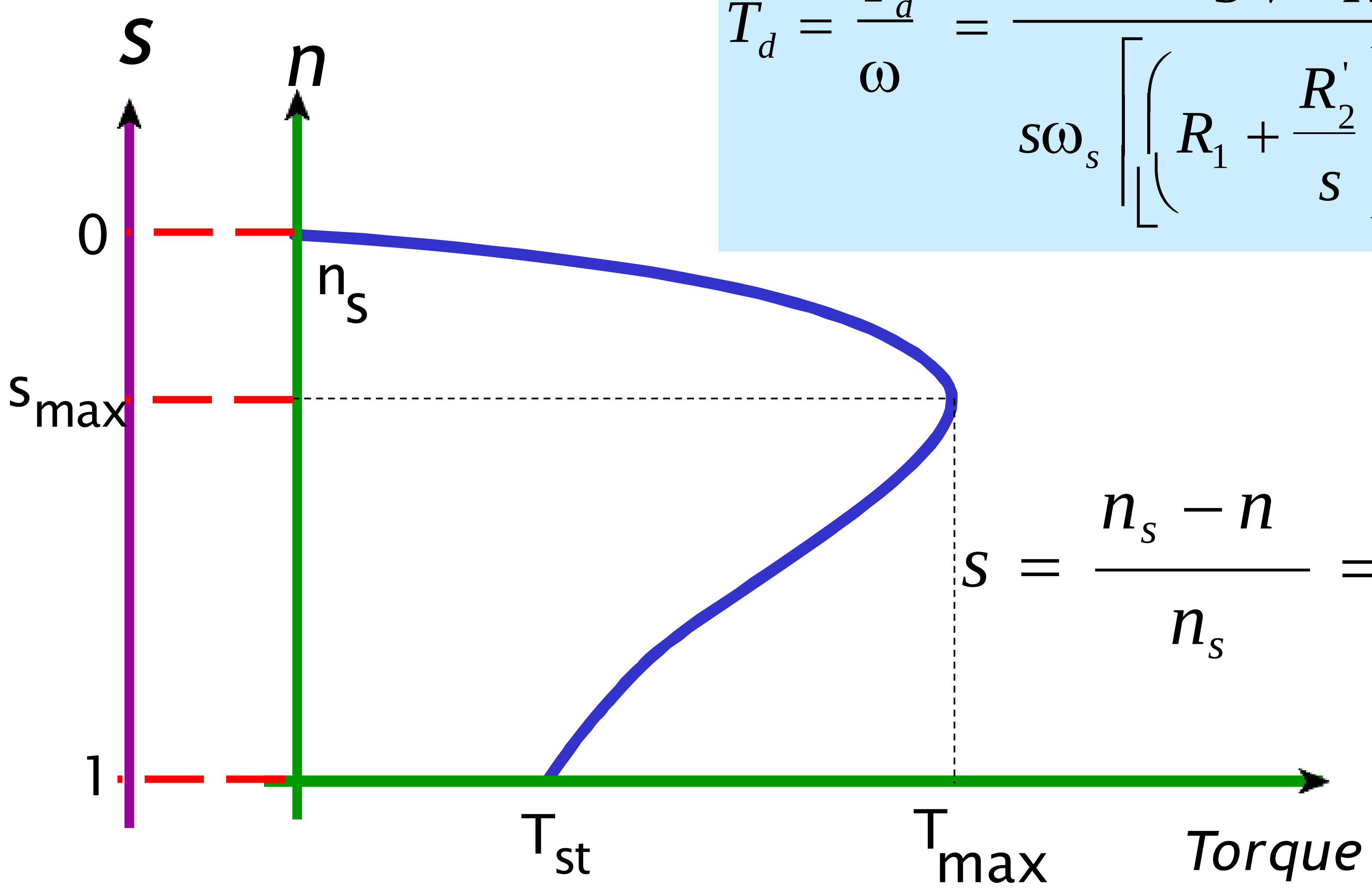


$$I_2' = \frac{V}{\sqrt{\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2}}$$

$$T_d = \frac{P_d}{\omega} = \frac{3}{\omega}(I_2')^2 \frac{R_2'}{s}(1-s) = \frac{3V^2 R_2'(1-s)}{s\omega\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

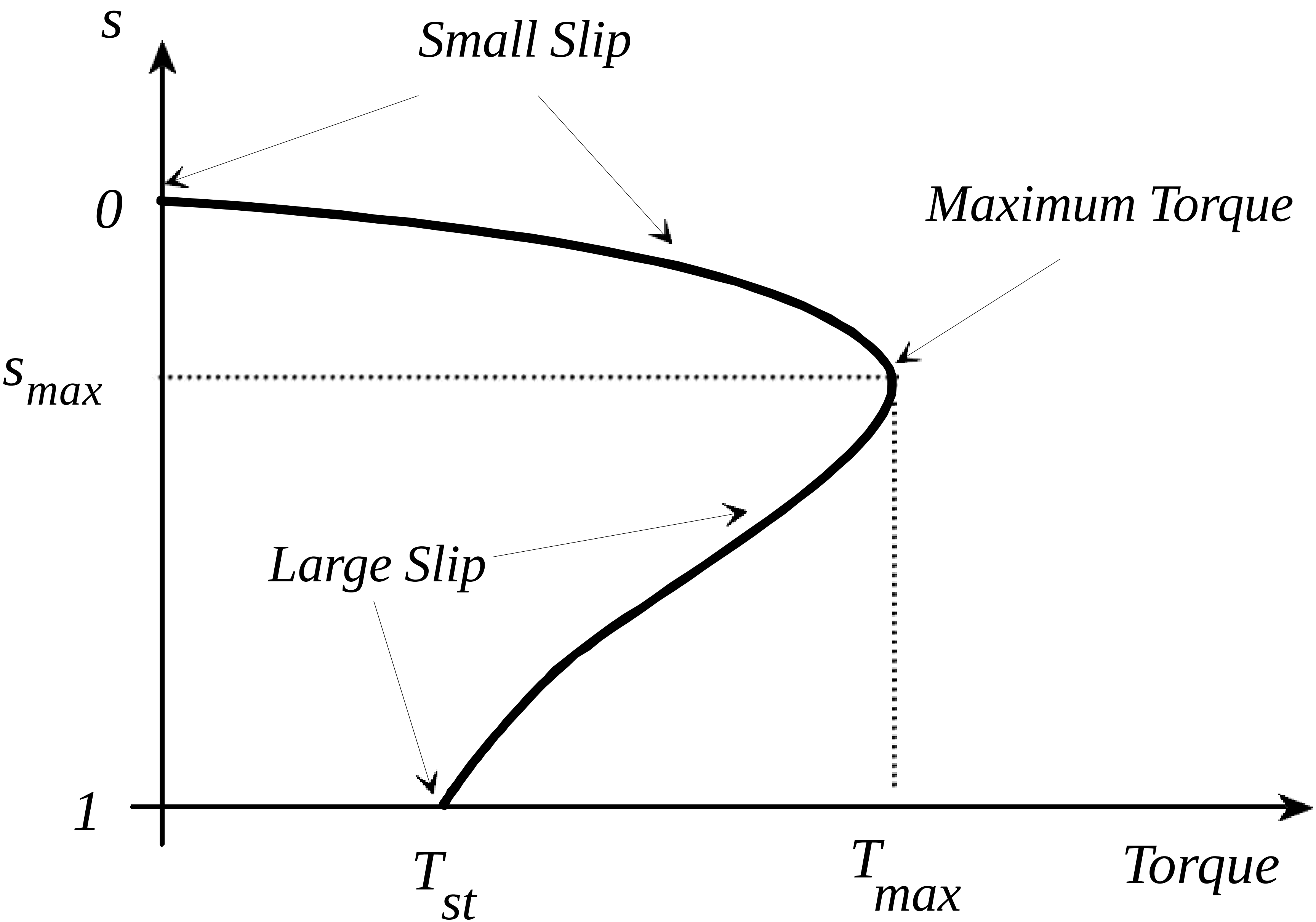
Torque Characteristics

$$T_d = \frac{P_d}{\omega} = \frac{3V^2 R_2'}{s\omega_s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

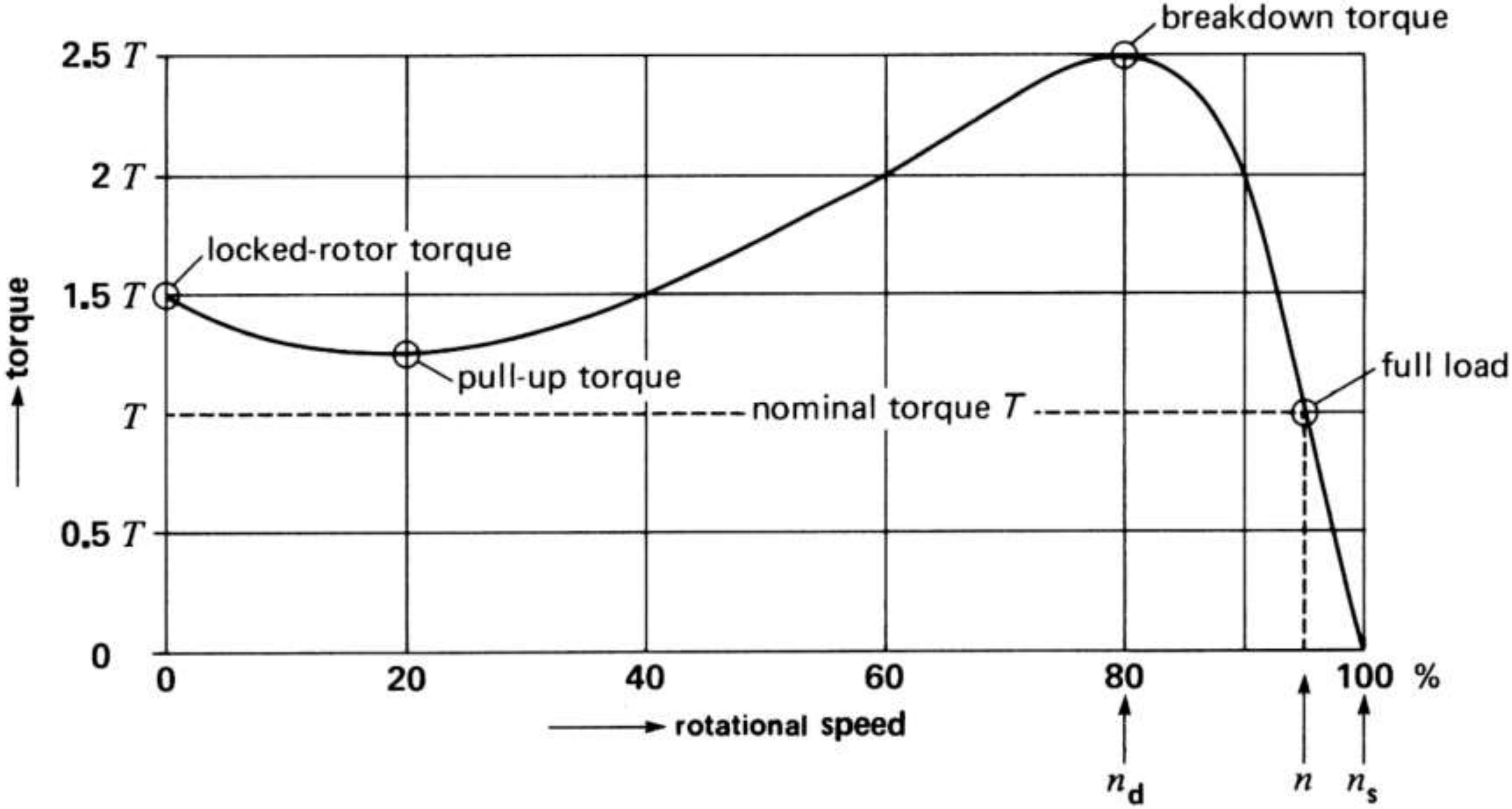


$$s = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega_s}$$

Torque Characteristics



Torque Characteristics



Maximum Torque

$$T_d = \frac{P_d}{\omega} = \frac{3V^2 R_2'}{s\omega_s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

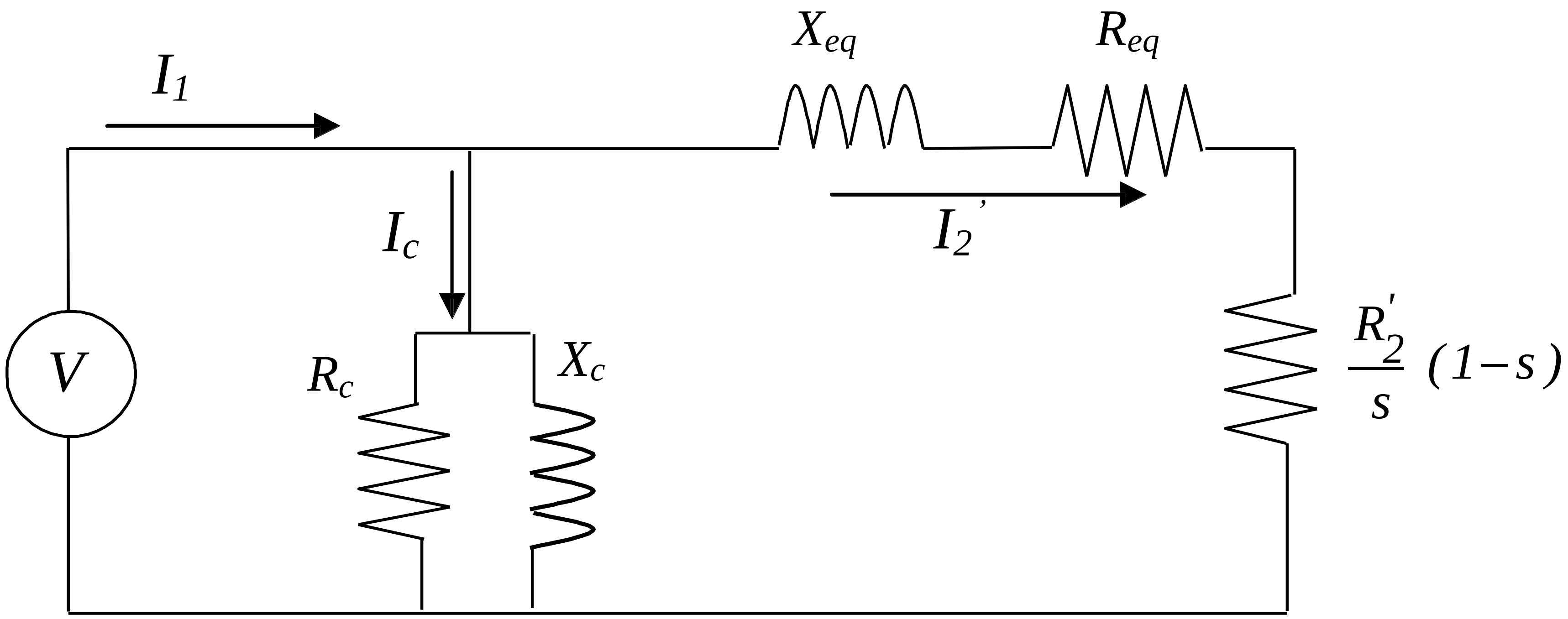
Set

$$\frac{\partial T_d}{\partial s} = 0$$

$$s_{max} = \frac{R_2'}{\sqrt{R_1^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

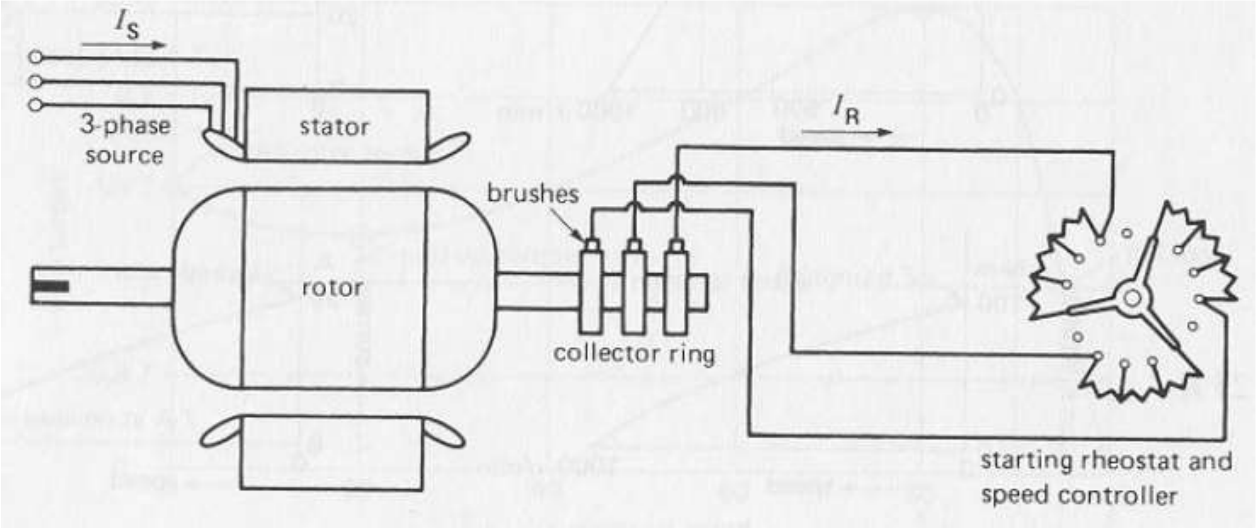
Starting of Induction Motor



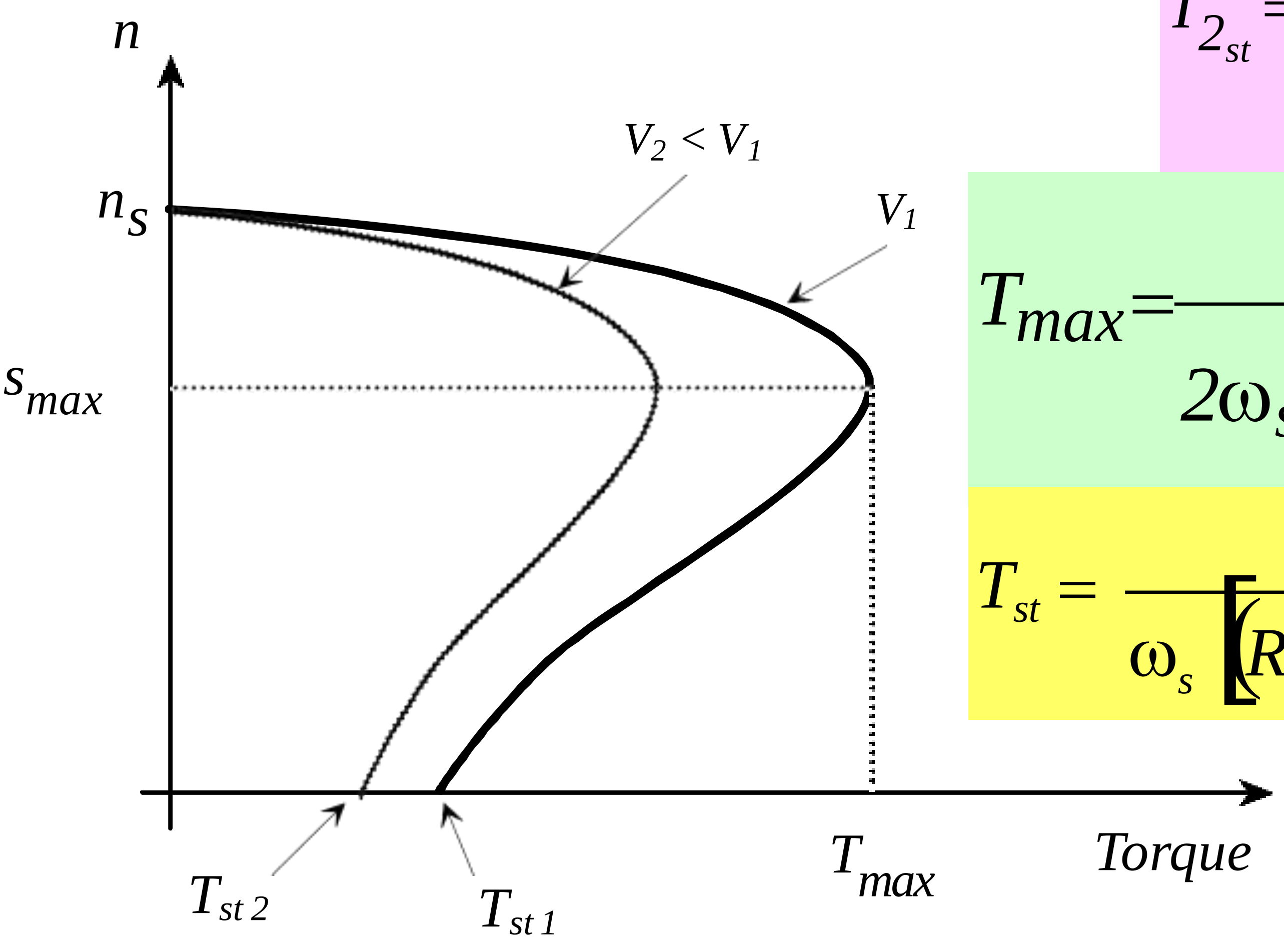
$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R'_2\right)^2 + X_{eq}^2}}$$

Starting by Reducing Voltage

- Starting current is reduced (good)
- Starting torque is reduced (cannot start heavy loads)
- Maximum torque is reduced (Motor acceleration is low)
- Speed at maximum torque is unchanged



Starting by Reducing Voltage



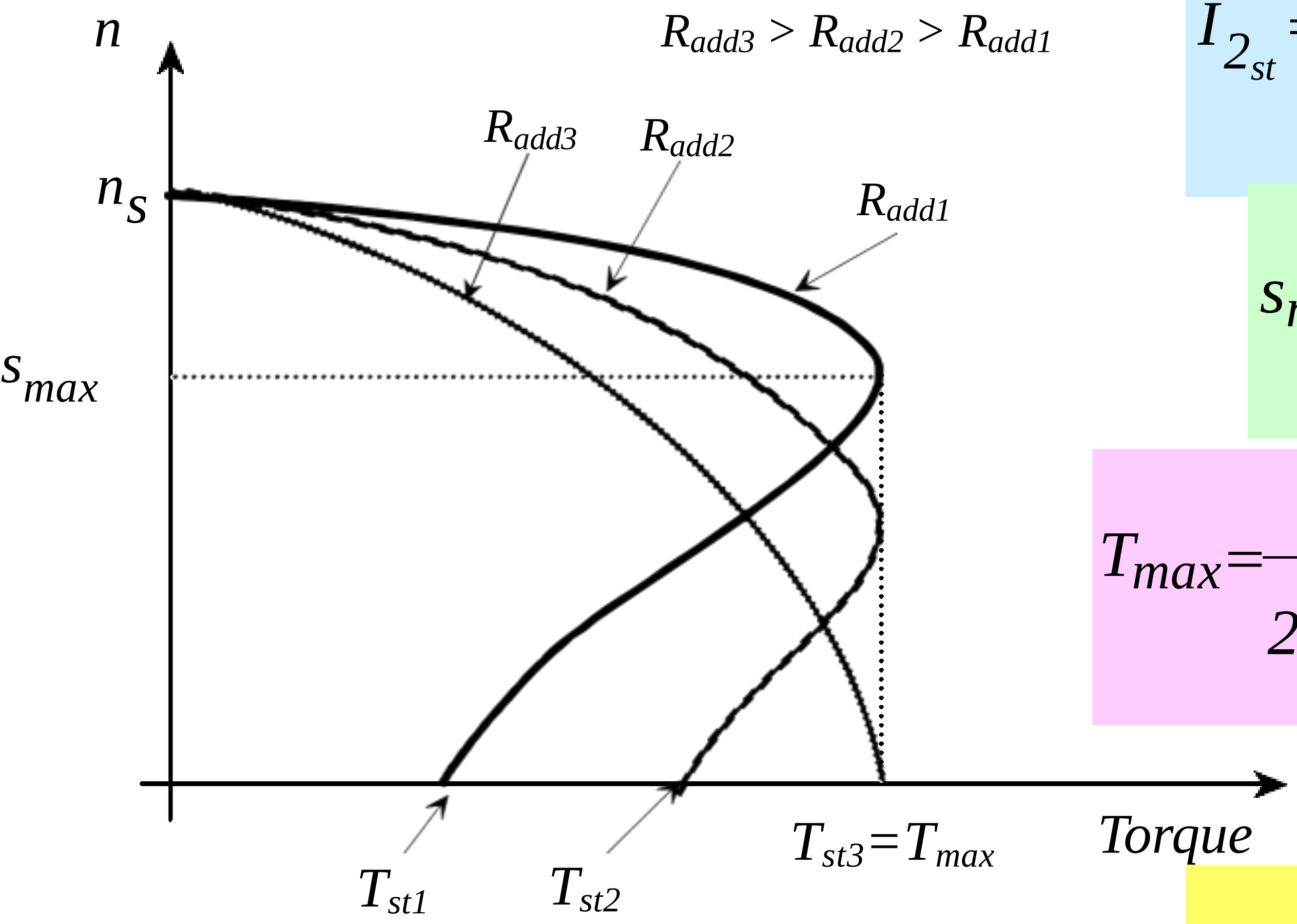
$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R'_2\right)^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3\,V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

$$T_{st} = \frac{3\,V^2\,R'_2}{\omega_s\left[\left(R_1 + R'_2\right)^2 + X_{eq}^2\right]}$$

$$s_{max} = \frac{R'_2}{\sqrt{R_1^2 + X_{eq}^2}}$$

Starting by Adding Rotor Resistance



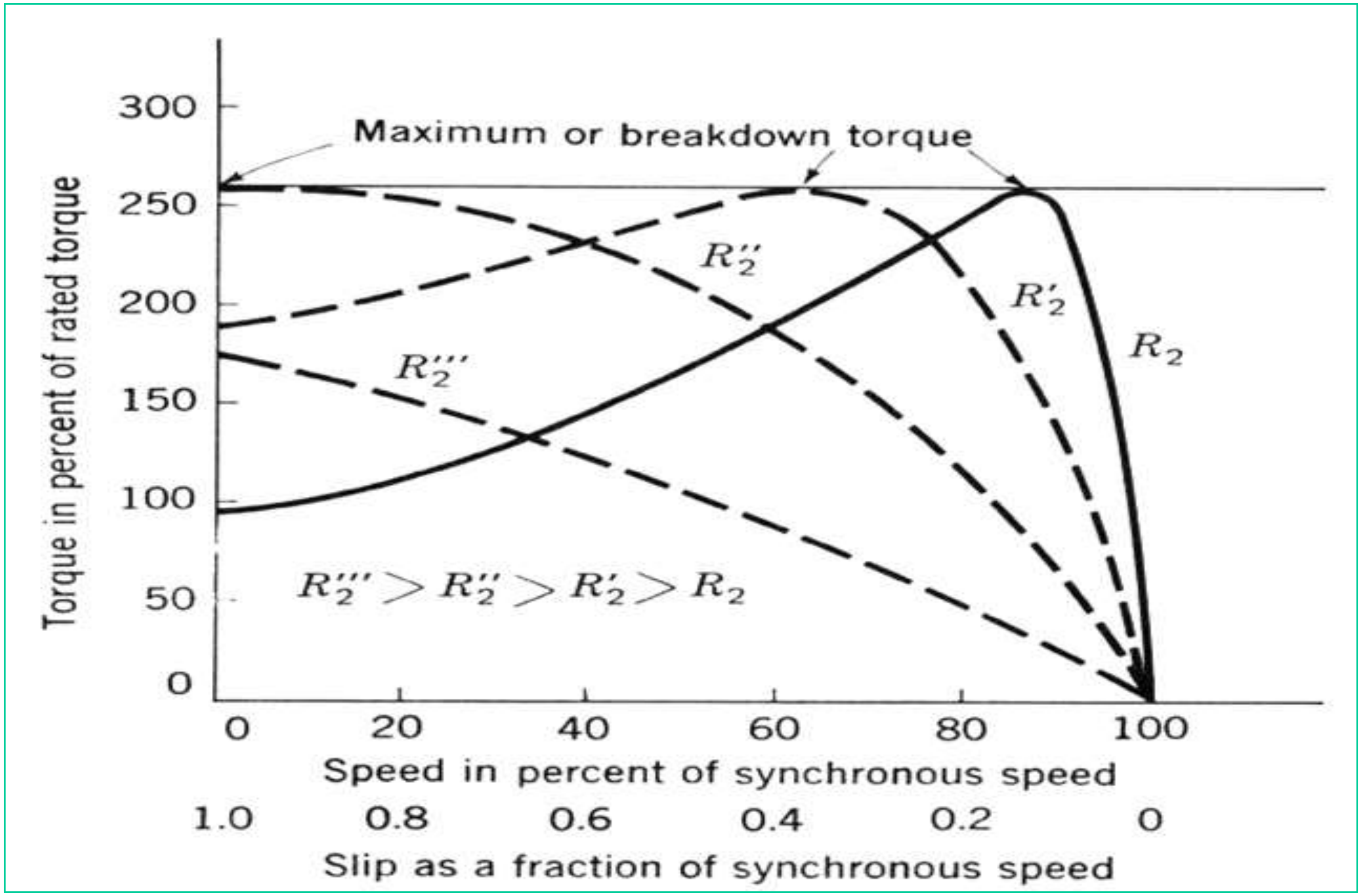
$$I'_{2_{st}} = \frac{V}{\sqrt{\left(R_1 + R'_2\right)^2 + X_{eq}^2}}$$

$$s_{max} = \frac{R'_2}{\sqrt{R_1^2 + X_{eq}^2}}$$

$$T_{max} = \frac{3\,V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$

$$T_{st} = \frac{3\,V^2\,R'_2}{\omega_s\left[\left(R_1 + R'_2\right)^2 + X_{eq}^2\right]}$$

Starting by Adding Rotor Resistance

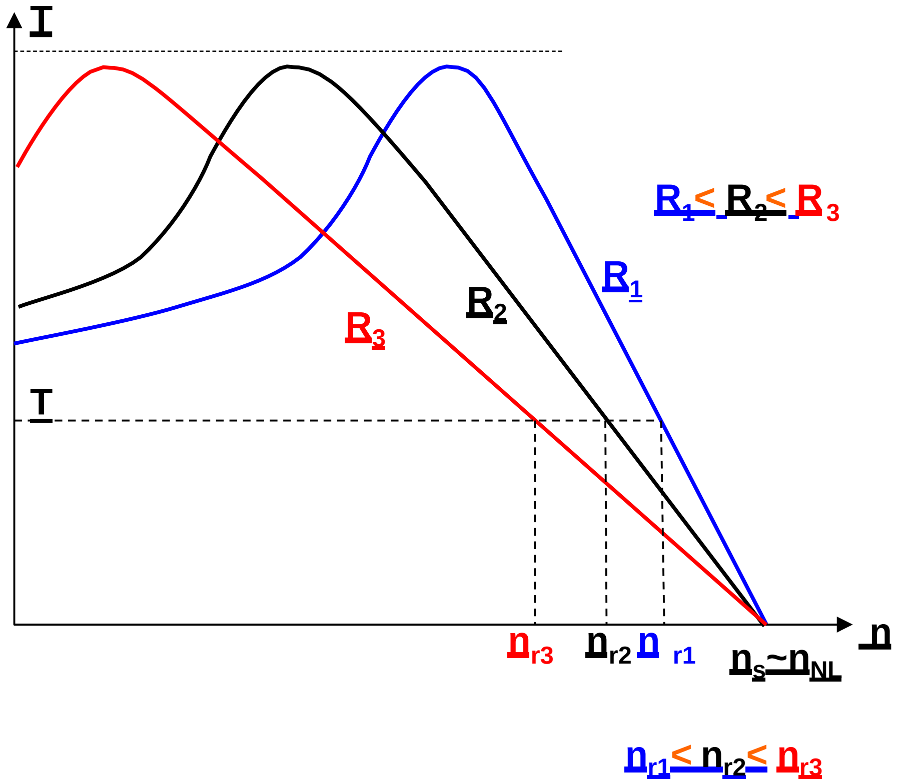


Effect of rotor resistance on torque-speed characteristic

Torque/Speed Curve for varying R_2

$$T_{\max} \approx \frac{3}{2\omega_s} \frac{V_{th}^2}{(X_{th} + X_2')}$$

$$S_{T\max} \approx \frac{R_2'}{(X_{th} + X_2')}$$



- The maximum torque is independent of the rotor resistance. However, the value of the rotor resistance determines the slip at which the maximum torque will occur. The torque-slip characteristics for various values of are shown.
- To get maximum torque at starting::

$$S_{T\max} = 1 \qquad i.e.\ R_2' = (X_{th} + X_2')$$

Starting by Adding Rotor Resistance

- Starting current is reduced (good)
- Starting torque is increased (good)
- Maximum torque is unchanged (Motor acceleration is high)
- Speed at maximum torque is reduced

Speed Control of IM by Changing Frequency

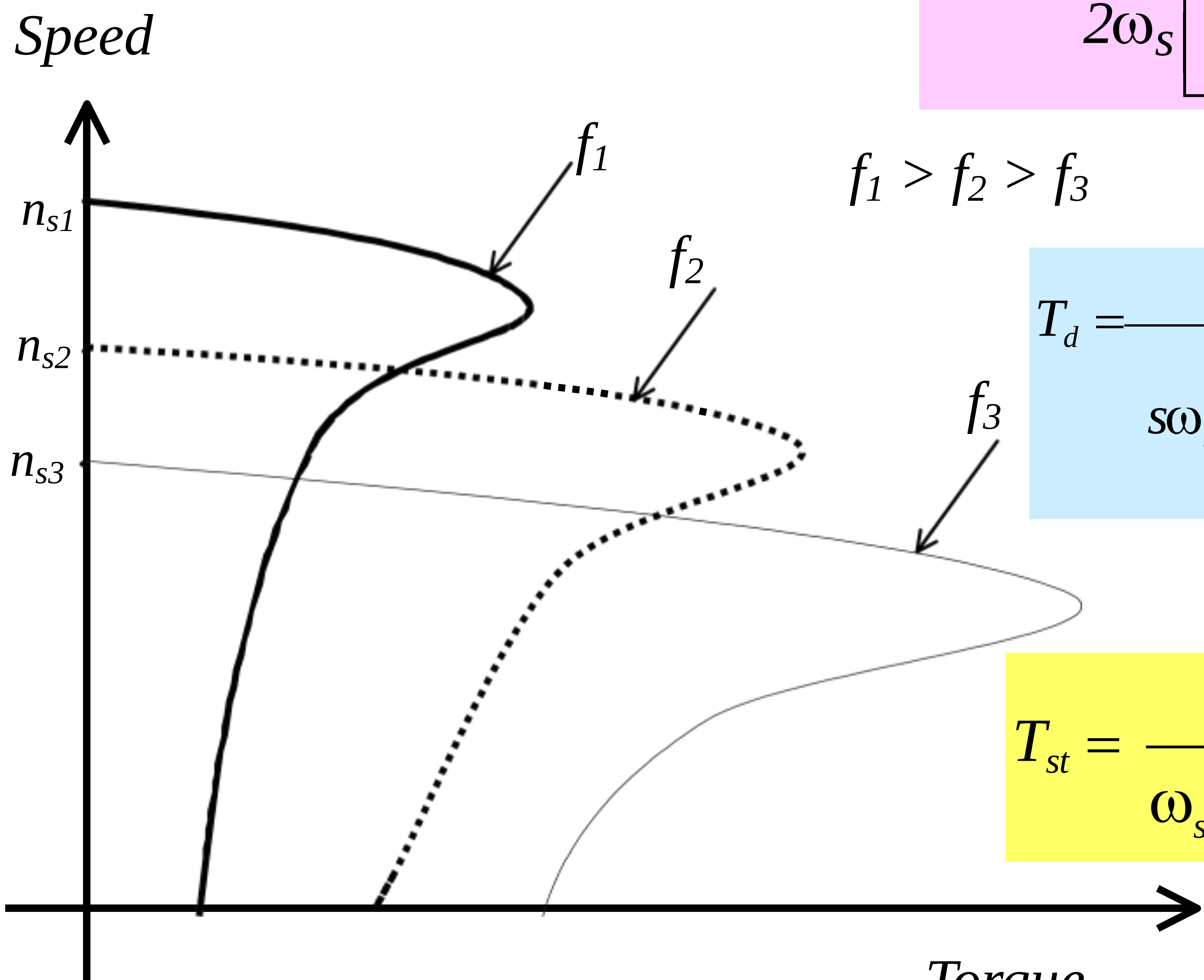
$$n_s = 120\frac{f}{p}$$

Changing $n_s = \dfrac{120\ f}{p}$

- Change f → Continuous variation
- Change p → Step variation

Speed Control of IM by Changing Frequency

$$T_{max} = \frac{3V^2}{2\omega_s\left[R_1 + \sqrt{R_1^2 + X_{eq}^2}\right]}$$



$f_1 > f_2 > f_3$

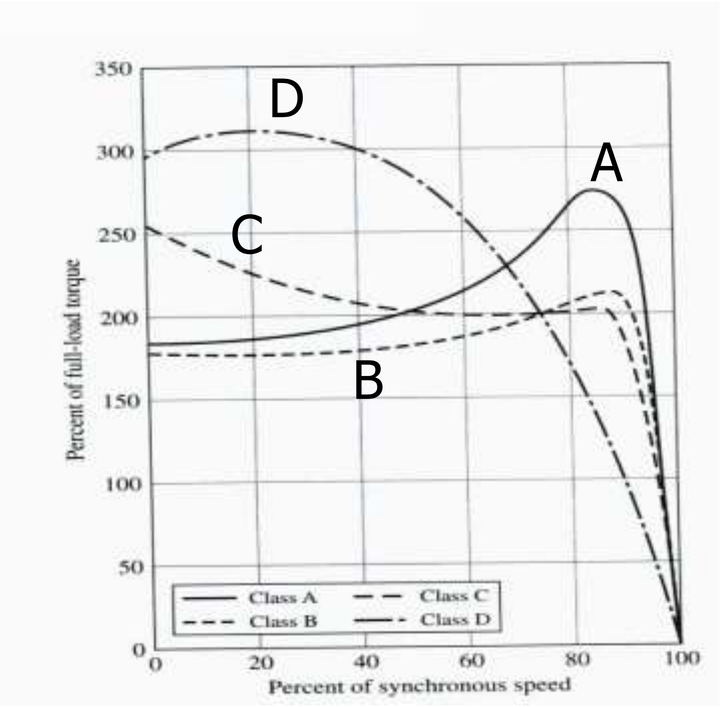
$$T_d = \frac{3V^2 R_2'}{s\omega_s\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2\right]}$$

$$T_{st} = \frac{3V^2 R_2'}{\omega_s\left[\left(R_1 + R_2'\right)^2 + X_{eq}^2\right]}$$

Classes of squirrel-cage motors

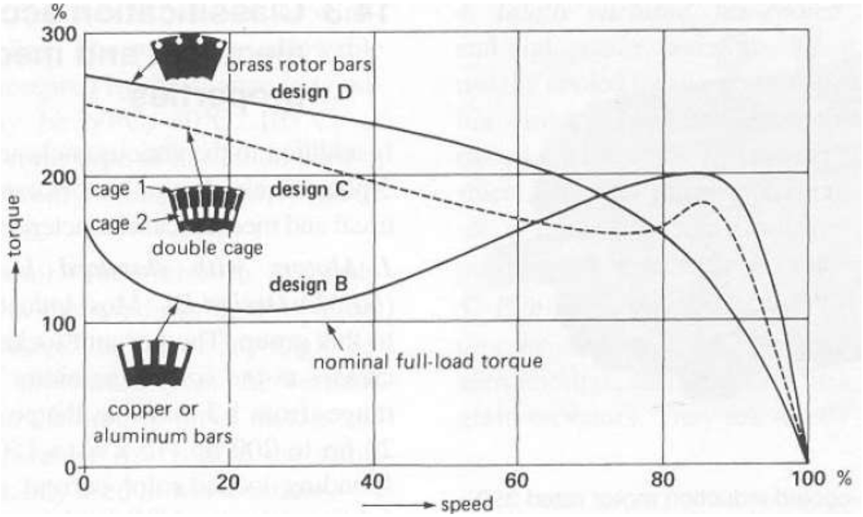
- According to the National Electrical Manufacturing Association (NEMA) criteria, squirrel-cage motors are classified into class A, B, C or D. The torque-speed curves and the design characteristics for these classes are :

Class	Starting Current	Starting Torque	Rated Load Slip
A	Normal	Normal	< 5%
B	Low	Normal	< 5%
C	Low	High	< 5%
D	Low	Very High	8-13 %



Classes of squirrel-cage motors

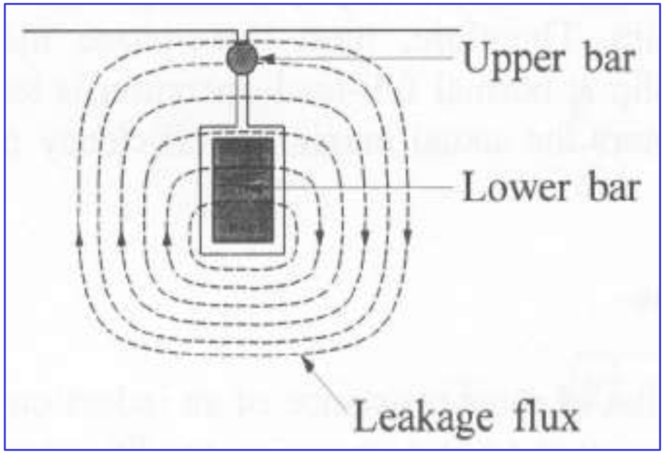
1. Motors with standard locked-rotor torque (NEMA B)
   - **Good for fans, centrifugal pumps, machine tools…**
2. High-starting torque motors (NEMA C)
   - **Good for starting under load – hydraulic pumps and piston-type compressors**
3. High-slip motors (NEMA D)
   - **Good for starting high-inertia loads**



Double Squirrel-Cage Rotor Construction

- Following double squirrel-cage arrangements can also be used to obtained a high value of effective resistance at starting and a low value of the resistance at full-load operation.
- It consists of two layers of bars, both short-circuited by end rings.
- The upper bars are small in cross-section and have a high resistance.
- They are placed near the rotor surface so that the leakage flux sees a path of high reluctance; consequently, they have a low leakage inductance.
- The lower bars have a large cross-section, a lower resistance and a high leakage inductance.

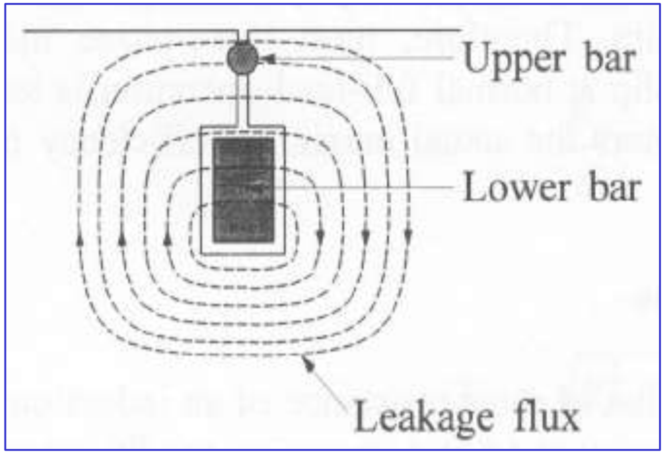
Double squirrel-cage rotor bars



Double Squirrel-Cage Rotor Construction

- At starting, rotor frequency is high and very little current flows through the lower bars; the effective resistance of the rotor is then the high resistance upper bars.
- At normal low slip operation, leakage reactances are negligible, and the rotor current flows largely through the low resistance lower bars; the effective rotor resistance is equal to that of the two sets of bars in parallel..

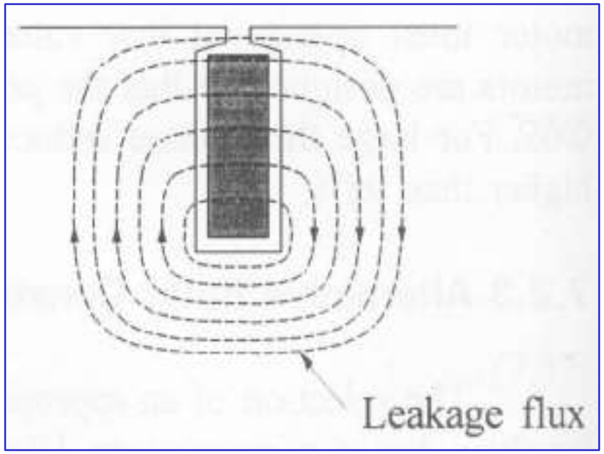
Double squirrel-cage rotor bars



Deep-Bar Rotor Construction

- The use of deep, narrow rotor bars produces torque-slip characteristics similar to those of a double-cage rotor.
- Leakage inductance of the top cross-section of the rotor bar is relatively low; the lower sections have progressively higher leakage inductance.
- At starting, due to the high rotor frequency, the current is concentrated towards the top layers of the rotor bar.
- At full-load operation, the current distribution becomes uniform and the effective resistance is low.

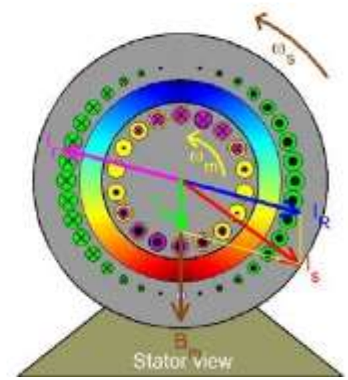
Deep-bar rotor construction

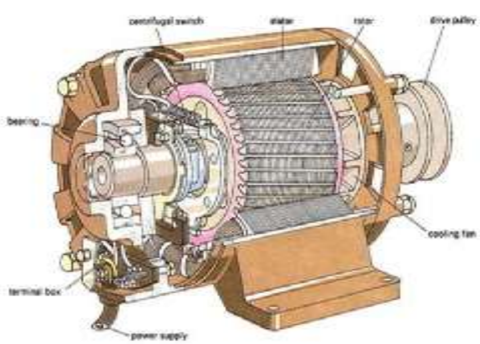


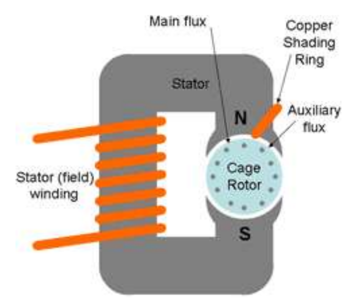
EE471-Electrical Machines II

Topic 3: Single-Phase Induction Motor

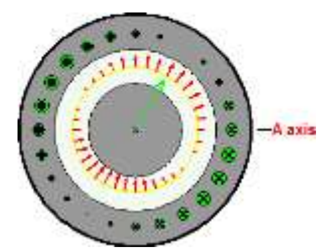
Contents:





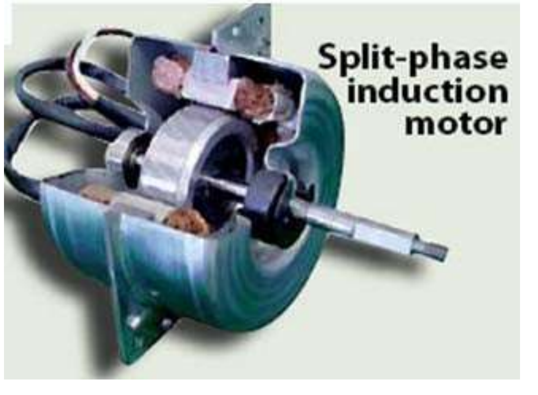


Shaded Pole Induction Motor



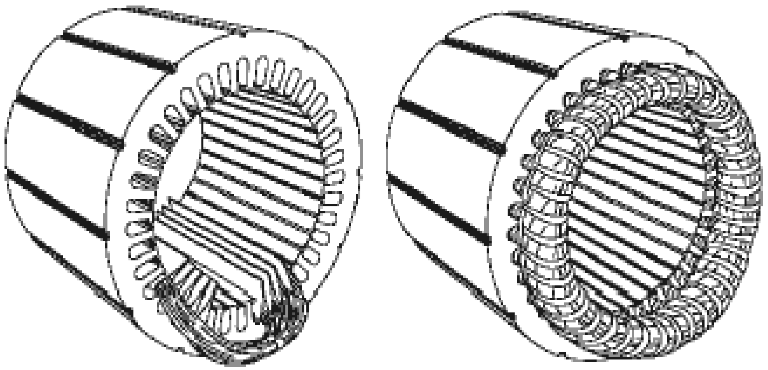
Introduction

- Three-phase a.c supply is not always available, so we need motors directly supplied from the main which is a single phase a.c supply.
- The majority of single-phase induction motors are built in the fractional horsepower range.
- Single-phase induction motors are used mainly in domestic application e.g., in vacuum cleaners, washing machines, fans, pumps, photocopy machines, ….etc.

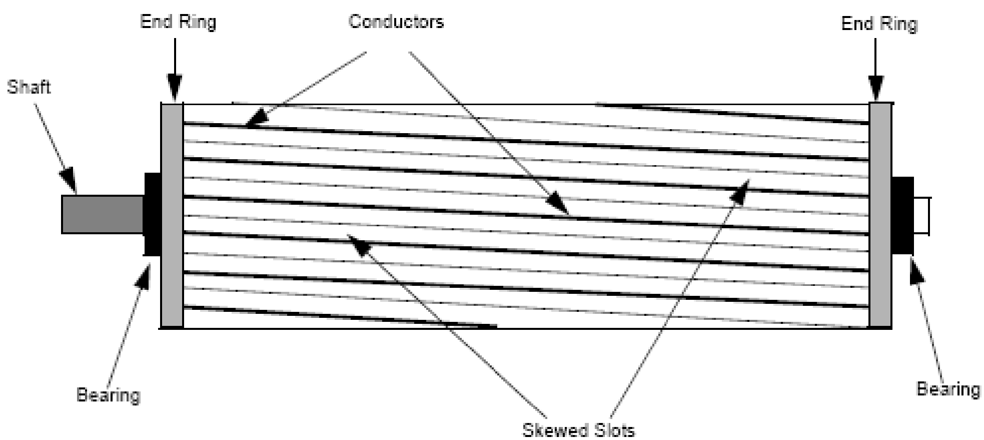


Construction

- Single phase induction motor have a cage rotor and a single-phase distributed stator winding.

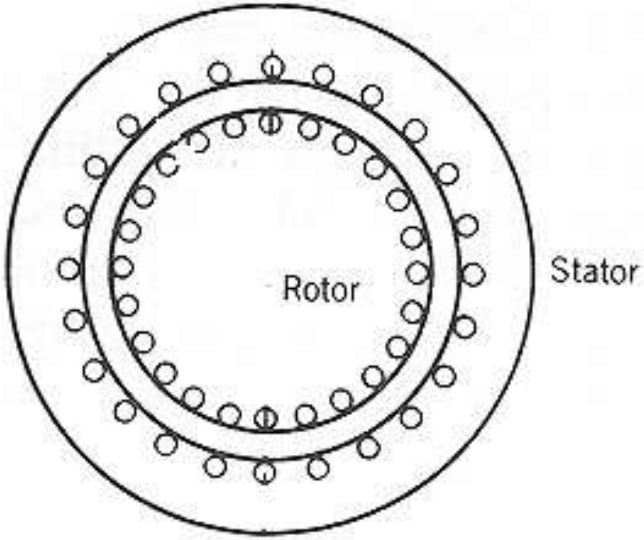


Stator

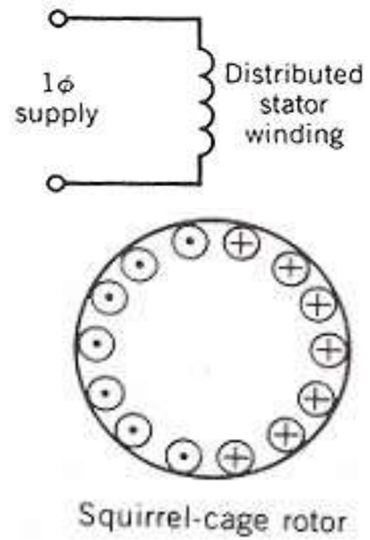


Rotor

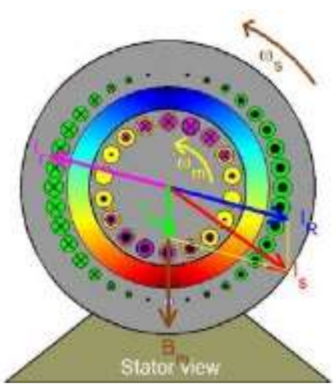
Construction

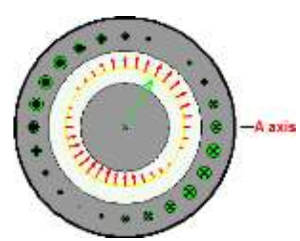


Single-phase induction motor



Schematic diagram of single-phase induction motor



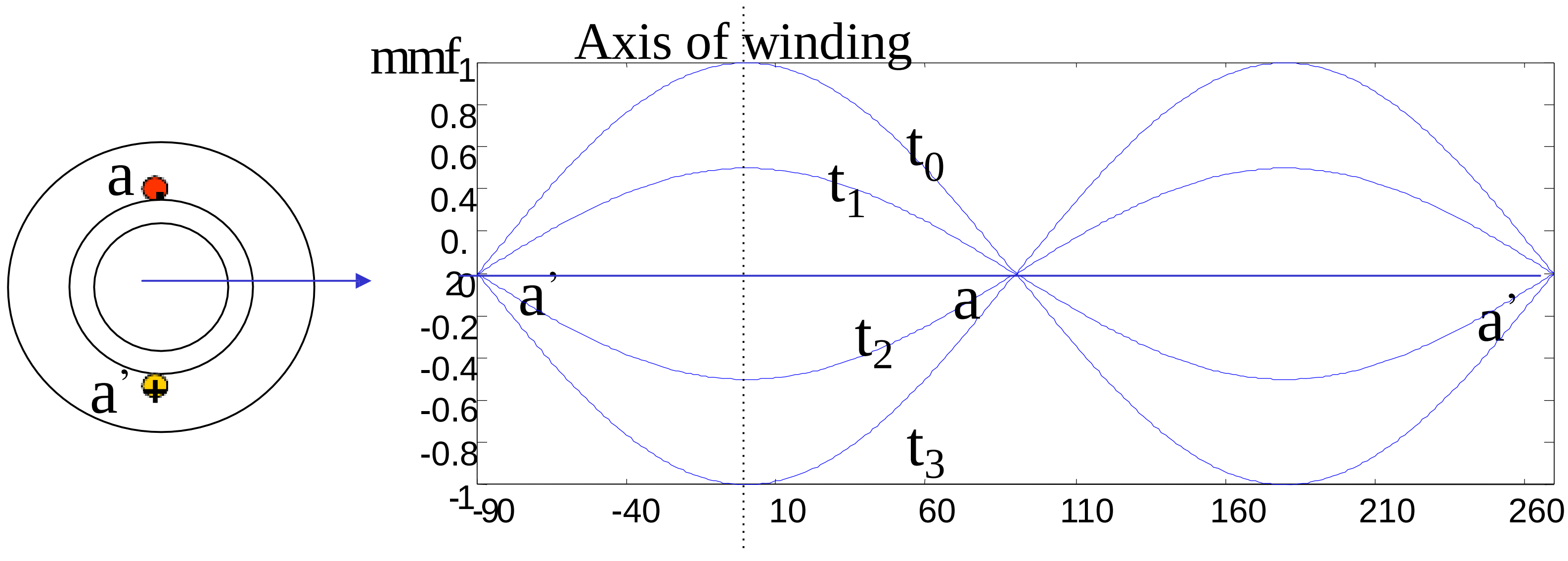


Principle of Operation

- **<u>Pulsating magnetic field</u>**

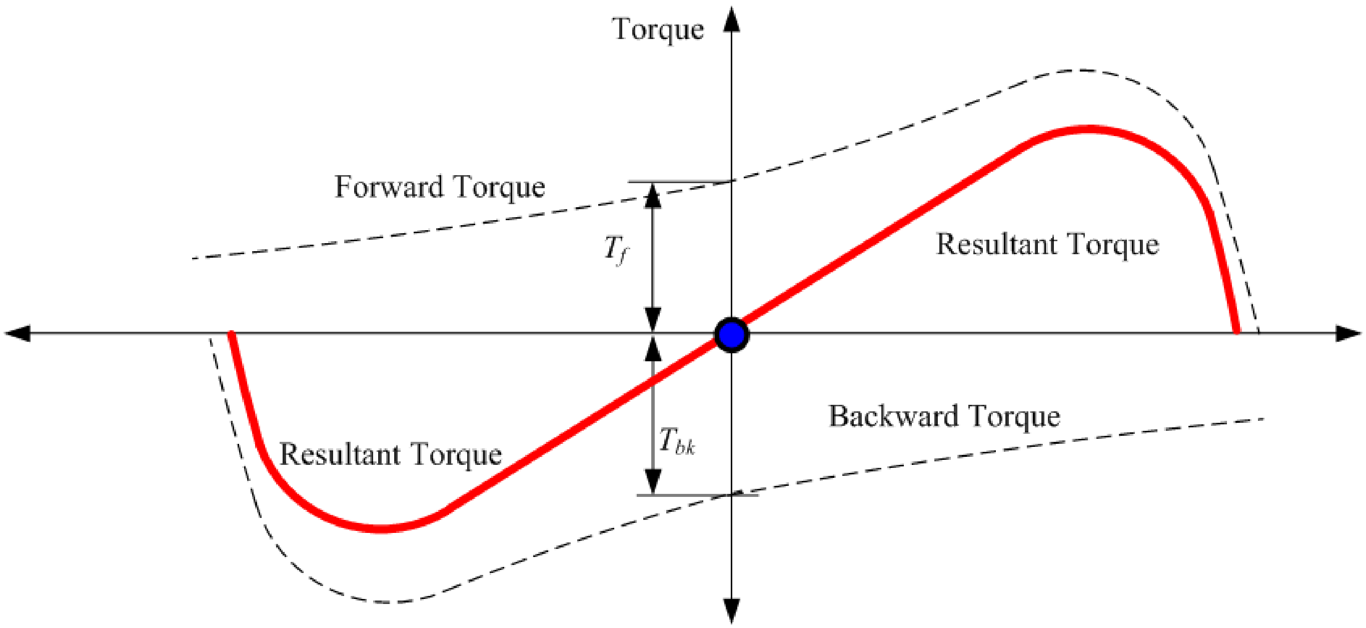
When a single-phase winding carries an alternating current, a flux-density distribution whose axis is fixed along the axis of the winding and pulsates sinusoidally in magnitude will be produced.

$$\text{mmf} = N\, i \cos\theta = N\, I_m \cos\omega t \cos\theta$$



Principle of Operation

- In three-phase induction motor, the rotor emf is induced by one rotating field, while in single-phase induction motor the rotor emf will be induced by two rotating field and the influence of each field on the rotor has to be considered separately.
- The wave rotating in the same direction as the rotor is known as forward field, while the wave rotating in the opposite direction is known as backward field.



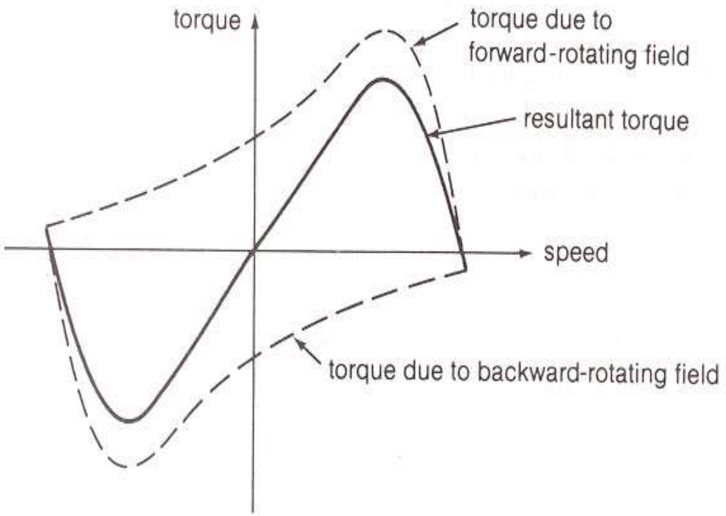
Principle of Operation

- The slip, S_f, of the machine with respect to the forward field is:

- The rotor rotates opposite to the rotation of the backward field. Therefore, the slip, S_b, of the machine with respect to the backward field is:

$$S_f = \frac{n_s - n_m}{n_s} = S$$

$$S_b = \frac{-n_s - n_m}{-n_s} = \frac{n_s + n_m}{n_s} = 2 - S$$



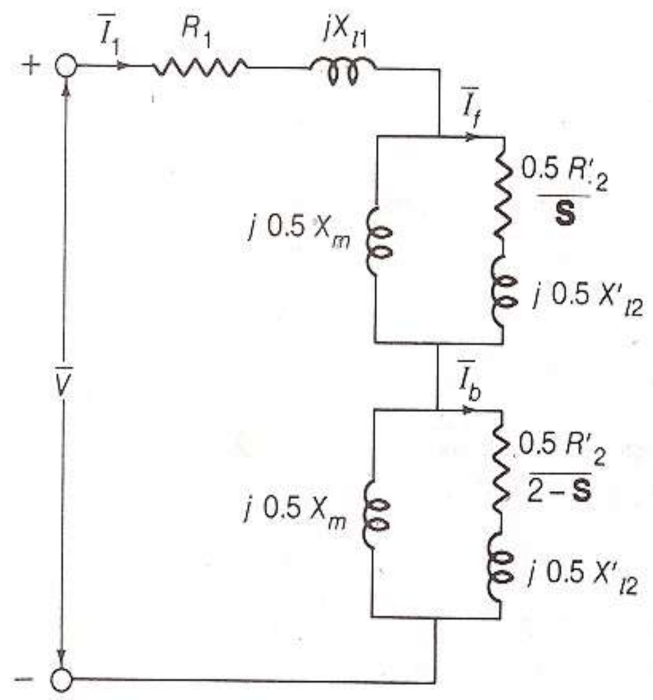
Equivalent Circuit

- The equivalent circuit of a single phase induction motor consists of series connection of a forward field equivalent circuit and a backward field equivalent circuit. Each circuit is similar to that of the three phase induction motor but in the backward rotating field circuit the parameter *S* is replaced by *2-S*.

- Since the forward and the backward revolving fields have amplitudes that are one-half the value of the alternating field, it is necessary to apply a factor of 0.5 to the parameters.

Equivalent Circuit

Therefore the equivalent circuit of a single phase induction motor will be as shown,



where

V = supply voltage

R_1 = resistance of the stator main winding.

X_{l1} = Leakage reactance of the stator main winding

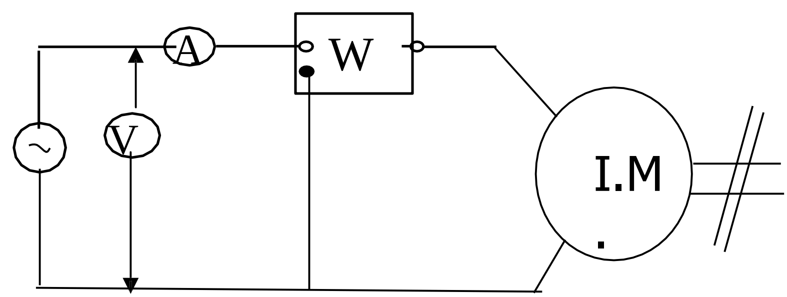
X_m = magnetizing reactance

$$R_2' = \text{resistance of the rotor referred to the stator}$$

$$X_{l2}' = \text{leakage reactance of the rotor referred to stator}$$

Determination of the Equivalent Circuit Parameters

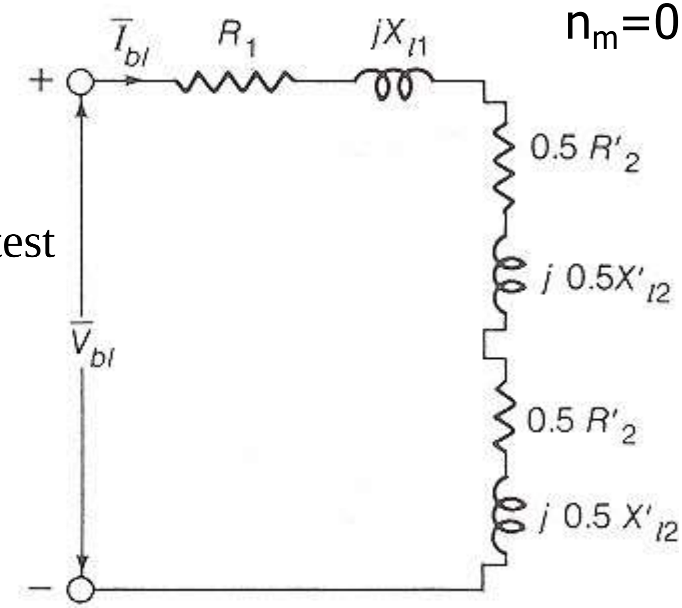
- The parameters of the equivalent circuit may be determined from no-load and blocked-rotor tests.



1- Blocked rotor test (at reduced voltage)

For the blocked-rotor-test $n_m=0$,i.e. (S=1), neglecting the magnetizing reactance, the equivalent circuit will be as shown

$n_m=0$



$P_{bl} = I_{bl}^2(R_1 + R_2')$, R_1 can be determined using the dc test

$$Z_{bl} = \frac{V_{bl}}{I_{bl}}$$

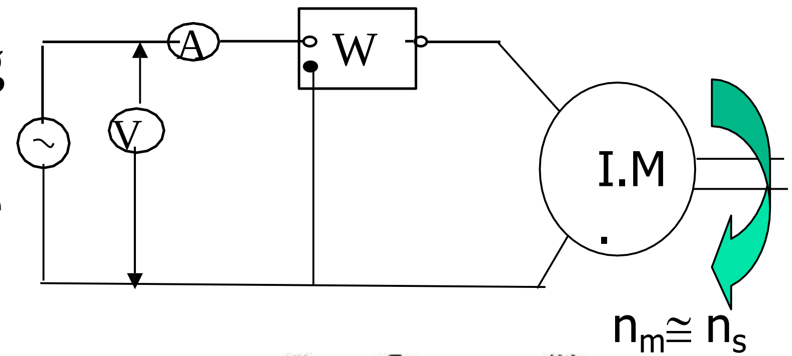
$$X_{bl} = \sqrt{Z_{bl}^2 - (R_1 + R_2')^2}$$

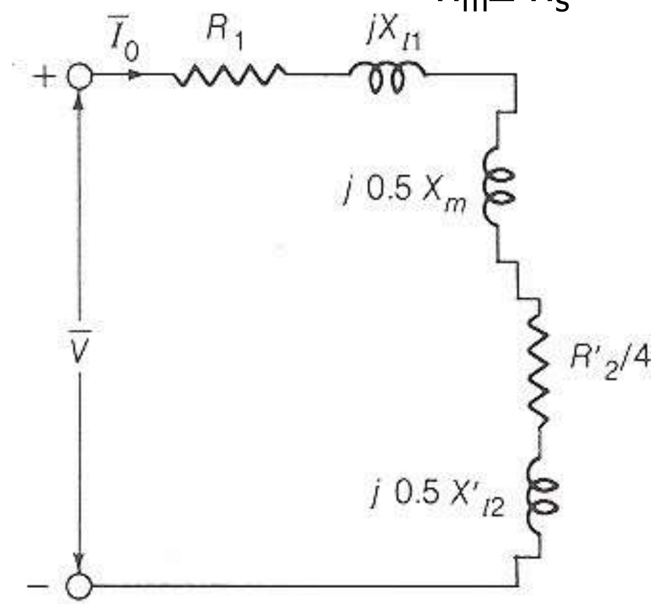
$$X_{l1} = X_{l2}' = \frac{X_{bl}}{2}$$

Determination of the Equivalent Circuit Parameters

2- No load test

The no-load test is conducted by running the motor without load at rated voltage. Since the no-load slip is small, S ≅ 0, the equivalent circuit can be considered as shown.





$$Z_{nl} = V_{nl} / I_{nl}$$

$$\phi_{nl} = \cos^{-1}\left(\frac{P_{nl}}{V_{nl} I_{nl}}\right)$$

$$X_{nl} = Z_{nl} \sin(\phi_{nl})$$

$$X_m = 2\,(X_{nl} - X_{l1} - 0.5X'_{l2})$$

The rotational losses can be calculated from the equation :

$$P_{nl} = P_{rot} + I_{oc}^2 (R_1 + \frac{R'_2}{4})$$

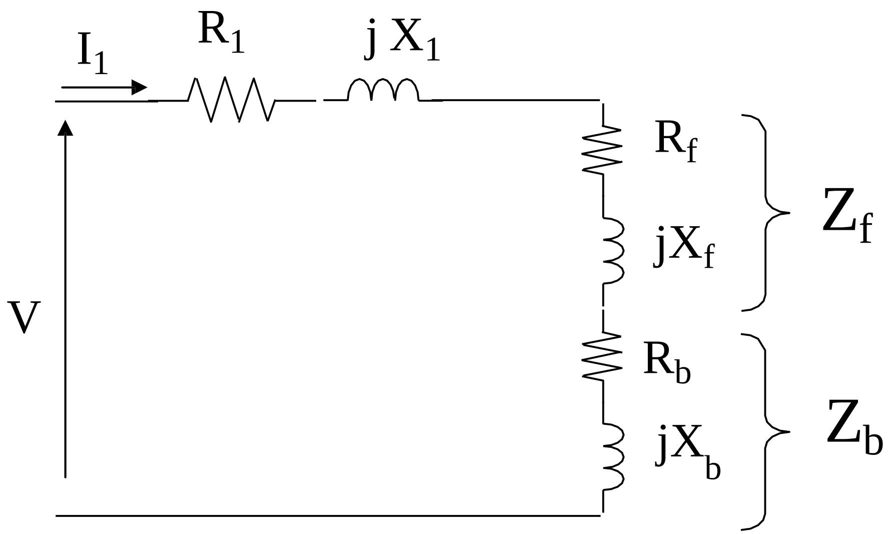
Simplified Equivalent Circuit

From the previous equivalent circuit:

$$Z_f = R_f + jX_f = j0.5X_m // (j0.5X'_{l2} + 0.5R'_2 / S)$$

$$Z_b = R_b + jX_b = j0.5X_m // (j0.5X'_{l2} + 0.5R'_2 /(2 - S))$$

$\therefore$ The simplified equivalent circuit can be used to represent the motor.



Performance Characteristics

From the simplified equivalent circuit, the air gap powers due to the forward and backward fields are:

$P_{gf} = I_1^2 R_f$ and $P_{gb} = I_1^2 R_b$

The corresponding torques are :

$T_f = \dfrac{P_{gf}}{\omega_s}$ and $T_b = \dfrac{P_{gb}}{\omega_s}$

and the resultant torque will be: $T = T_f - T_b = \dfrac{I_1^2}{\omega_s}(R_f - R_b)$

The mechanical power developed is:

$$P_{dev} = T\omega_m = T\omega_s(1-S) = (P_{gf} - P_{gb})(1-S)$$

and the output power is:

$$P_{out} = P_{dev} - P_{rot}$$

Performance Characteristics

The two air gap fields produce currents in the rotor circuit at different frequencies. Therefore the rotor copper loss is the numerical sum of the losses produced by each field.

The rotor copper loss produced by the forward field is: $P_{2f} = S\,P_{gf}$

and that produced by the backward field is: $P_{2b} = (2 - S)\,P_{gb}$

The total rotor copper loss is: $P_{RCL} = S\,P_{gf} + (2 - S)\,P_{gb}$

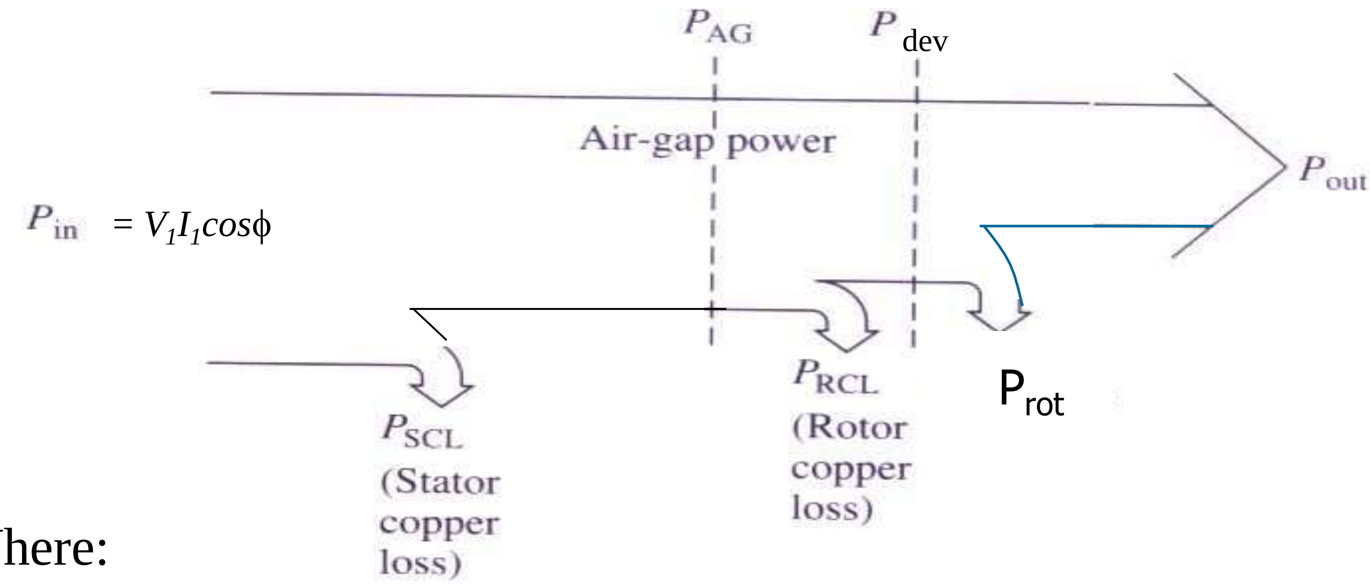
The total air gap power is the numerical sum of the air gap powers absorbed from the stator by the two component air gap fields. Thus :

$$P_g = P_{gf} + P_{gb}$$

The motor input power is: $P_{in} = VI\cos(\phi) = P_g + I_1^2 R_1$

and the motor efficiency is: $Efficiency = P_{out} / P_{in}$

Power flow diagram



Where:

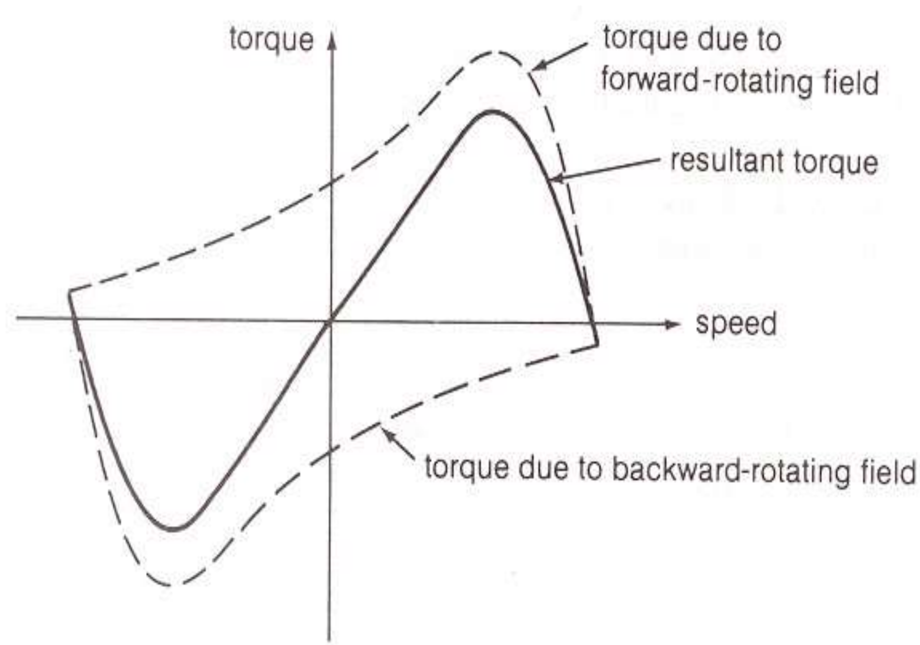
$$P_g = P_{gf} + P_{gb}$$

$$P_{dev} = (P_{gf} - P_{gb})(1 - S)$$

$$P_{RCL} = S\,P_{gf} + (2 - S)\,P_{gb}$$

Torque Speed Characteristics

When the rotor rotates, $Z_f > Z_b$ and consequently $E_f > E_b$. Therefore, as the speed increases, the resultant forward air gap field increases while the resultant backward air gap field decreases. Hence, the forward torque increases and the backward torque decreases. The torque speed characteristics is shown:



Example:

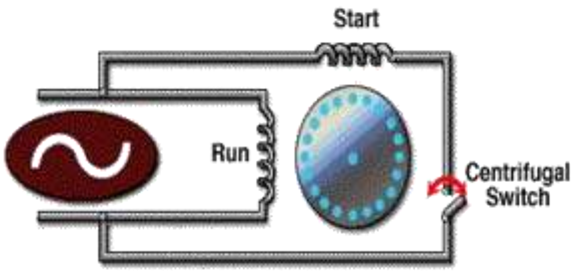
The following test data were obtained for a 1/2 hp, 110V, 950 rpm, 50 Hz, 6 pole,
single-phase induction motor**:**

Stator winding resistance = 1.8

Blocked rotor test : V = 36 V, I = 5 A, P = 100 W

No load test : V = 110 V, I = 4 A, P = 90 W

- Obtain an equivalent circuit for the motor for running conditions.
- Determine the no load rotational loss.
- Determine the input power, the power factor, the developed torque and the motor efficiency at rated speed.



Example: Cont'd

$$110\ V,\ 50\ Hz,\ 950\ rpm,\ 6\ pole$$

$$n_s = \frac{120\ .f_s}{p} = 1000\ rpm$$

$$S_{rated} = \frac{n_s - n_m}{n_s} = 0.05$$

$$From\ the\ bloked\ rotor\ test:$$

$$R_1 + R_2^{'} = \frac{P_{bl}}{I_{bl}^2} = \frac{100}{25} = 4\Omega$$

$$R_1 = 1.8\Omega \quad \therefore\ R_2^{'} = 2.2\Omega$$

$$Z_{bl} = \frac{V_{bl}}{I_{bl}} = \frac{36}{5} = 7.2$$

Example: Cont'd

$$X_{bl} = \sqrt{Z_{bl}^2 - (R_1 + R_2^{'})^2} = 6$$

$$X_1 = X_2^{'} = 3\,\Omega$$

From the no load test

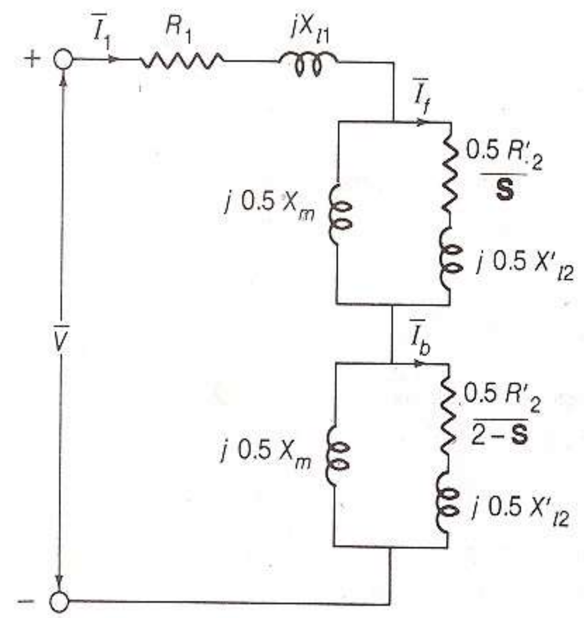
$$Z_{nl} = \frac{V_{nl}}{I_{nl}} = \frac{110}{4} = 27.5$$

$$\phi_{nl} = \cos^{-1}\frac{P_{nl}}{V_{nl} I_{nl}} = 78.2^{\circ}$$

$$X_{nl} = Z_{nl} \sin\phi_{nl} = 26.92$$

$$X_m = 2(X_0 - X_1 - \frac{X_2^{'}}{2}) = 44.84\,\Omega$$

$$ii - \quad Rotational\ losses = P_{nl} - I_{nl}^2 (R_1 + \frac{R_2^{'}}{4}) = 52.4\,W$$



Example: Cont'd

$$iii - \quad at\ rated\ \ speed\ \Rightarrow S = 0.05$$

$$\bar{Z}_f = \frac{(22 + j1.5)(j22.42)}{22 + j1.5 + j22.42} = 15.212\angle 46.5^\circ = 10.47 + j11.03$$

$$\bar{Z}_b = \frac{(0.564 + j1.5)(j22.42)}{0.564 + j1.5 + j22.42} = 1.5\angle 70.75 = 0.49 + j1.42$$

$$\bar{I} = \frac{\bar{V}}{\bar{Z}_1 + \bar{Z}_f + \bar{Z}_b} = \frac{110}{12.76 + j15.45} = 5.49\angle 50.45$$

$$* \quad P_{in} = V.I.\cos\phi = 110 * 5.49 * \cos(50.45) = 384.5\ W$$

$$* \quad P.F. = \cos(50.45) = 0.637\ \ lag$$

$$* \quad T = \frac{I^2(R_f - R_b)}{\omega_s} = \frac{(5.49)^2(10.47 - 0.49)}{2 * \pi * 1000 / 60} = 2.872\ \ Nm$$

$$P_{dev} = T * \omega_s * (1 - S) = 285.8$$

$$P_{0ut} = P_{dev} - Rotational\ \ \ Losses\ = 285.8 - 52.4 = 233.4\ W$$

$$* \quad Efficiency\ = \frac{P_{out}}{P_{in}} = \frac{233.4}{384.5} = 0.607$$

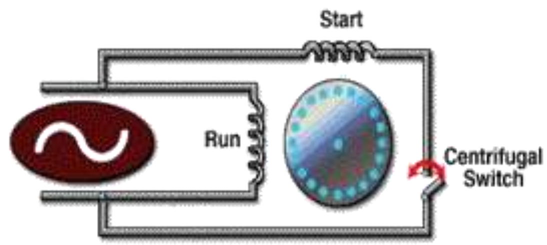
Starting Methods

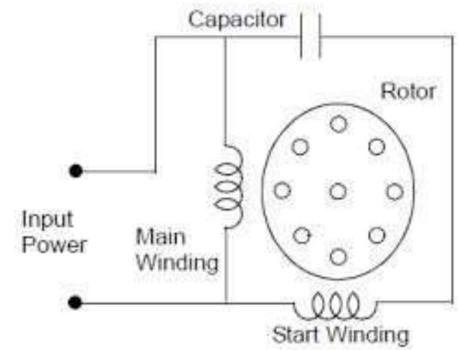
- A single-phase induction motor with one stator winding does not produce any starting torque. In order to make the motor start rotating, some arrangements is required so that the motor produces a starting torque.
- The simplest method of starting a single phase induction motor is to provide an auxiliary winding on the stator in addition to the main winding and start the motor as a two-phase machine. The two windings are displaced 90 elec° in space. The impedances of the two circuits are such that the current in the two windings are phase-shifted from each other. The motor will start as an unbalanced two-phase induction motor.
- In the running condition, motor will produce torque with only one stator winding. Therefore the auxiliary winding can be taken out of the circuit. In most motors this is done by connecting a centrifugal switch in series with the auxiliary windings.

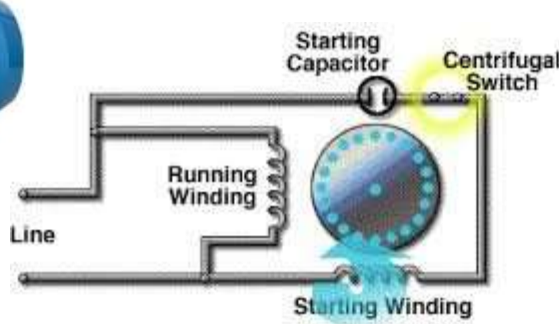
Classification of Single-phase Induction Motors

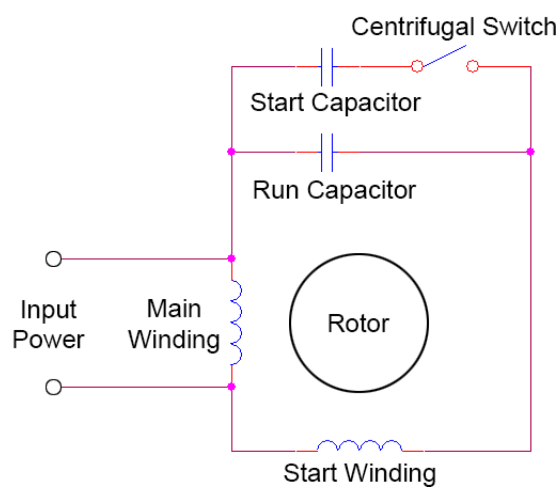
- Single-phase induction motors are known by various names. The names are descriptive of the methods used to produce the phase difference between the currents in the main and auxiliary windings. Some of the commonly used types of single-phase induction motors are:

1. **Split-Phase IM**
2. **Capacitor Start**
3. **Capacitor Run IM**
4. **Capacitor Start-Capacitor Run**







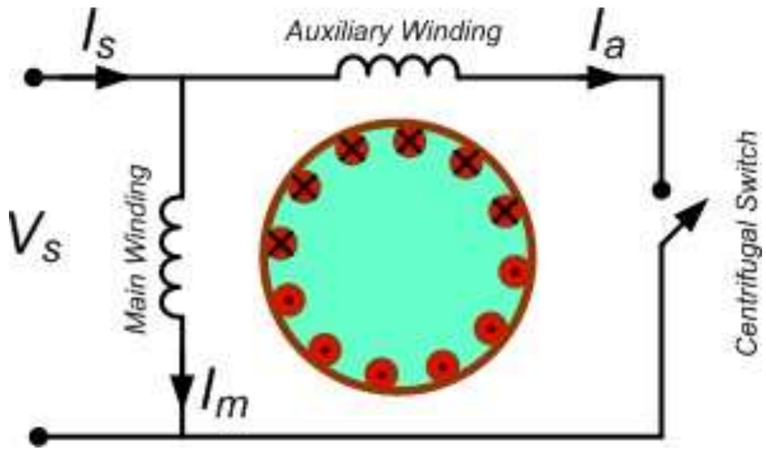


Classification of Single-phase Induction Motors

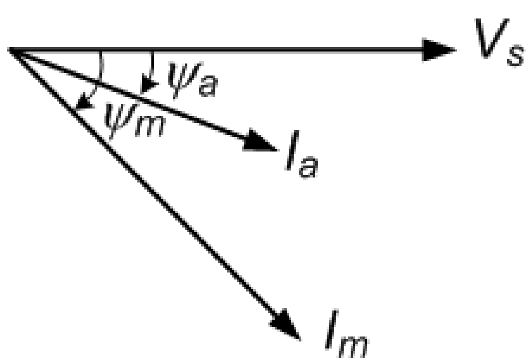
1 Split-Phase Induction Motor

A schematic diagram of the split-phase induction motor is shown in Fig. a

- The auxiliary winding has a higher resistance-to-reactance ratio than the main winding, so the two currents are out of phase, as shown in Fig. b.
- The high resistance to reactance ratio is usually obtained by using finer wire for the auxiliary winding. This is permissible because the auxiliary winding is in the circuit only during the starting period.
- Both winding are connected in parallel across the supply.



(a)



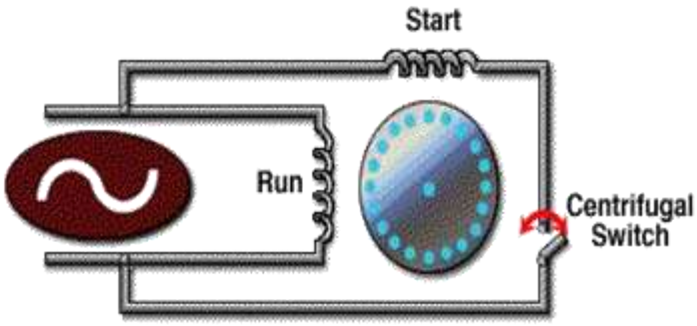
(b)

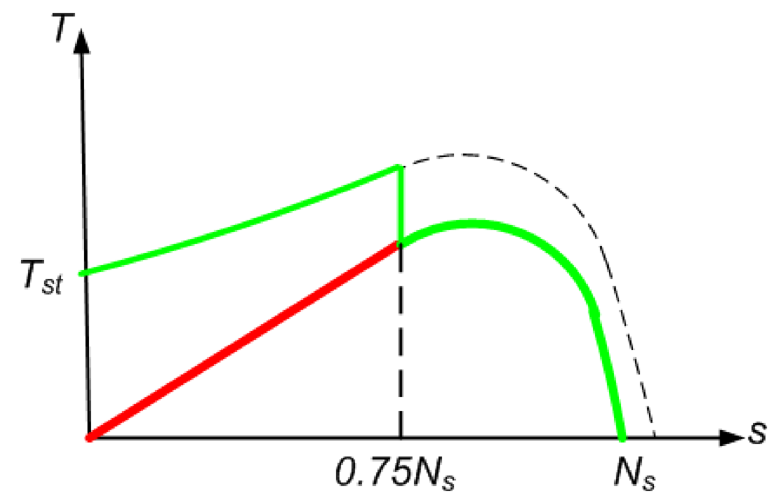
1- Split-Phase Induction Motor (cont.)

- During starting period up to 75 % of synchronous speed then starting winding is disconnected using centrifugal switch which is connected in series with the auxiliary winding.

- Starting torque will depend on the magnitude and phase shift between main and auxiliary winding currents at starting. The starting torque is moderate in this case and motor drive loads requires moderate starting torque such as fans and blowers.

- The typical torque-speed characteristics is shown. This motor has low to moderate starting torque.





Performance Evaluation of Split-phase IM

- The power range is 1/20 – 1 hp.
- Power factor in range of 0.5 to 0.65.
- Efficiency in range of 55 to 65 %.
- Starting torque is 100 % - 250 % of rated torque.
- Maximum torque or break down torque is 300 % rated torque.
- Cost is 1 pu

- **Applications:**
  - Fans,
  - blowers,
  - centrifugal pumps,
  - washing machines,
  - loads with low or medium starting torque

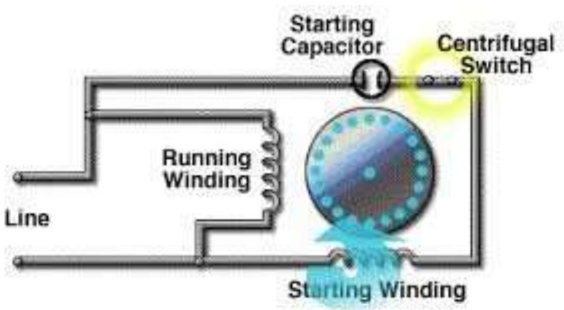
2-Capacitor Motors

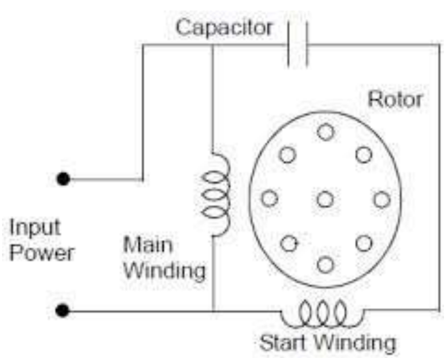
They have a capacitor in series with the auxiliary winding and come in three varieties:

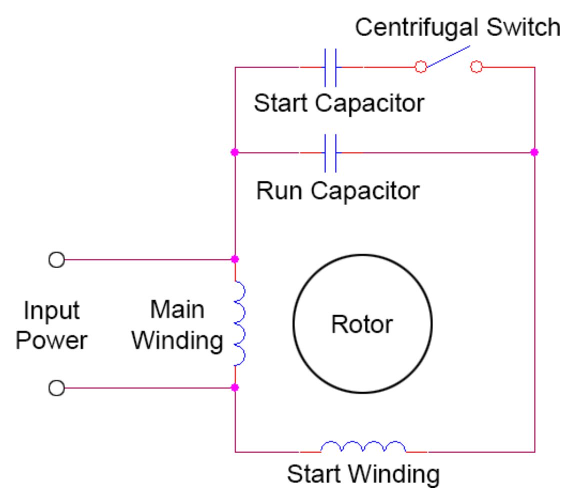
a- Capacitor-Start Motors

b - Capacitor-Run Motors (permanent-split capacitor)

C. Capacitor-Start Capacitor-Run Motors (two-value-capacitor)

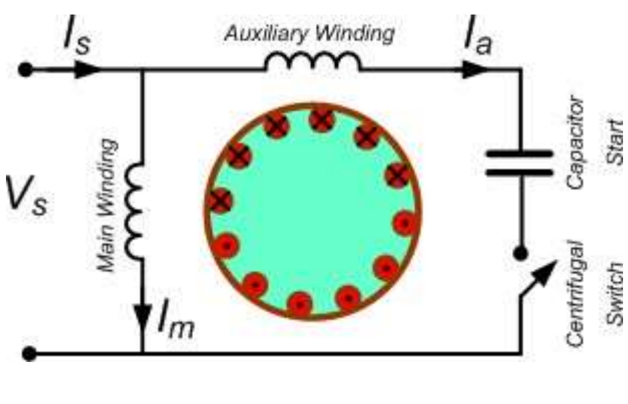




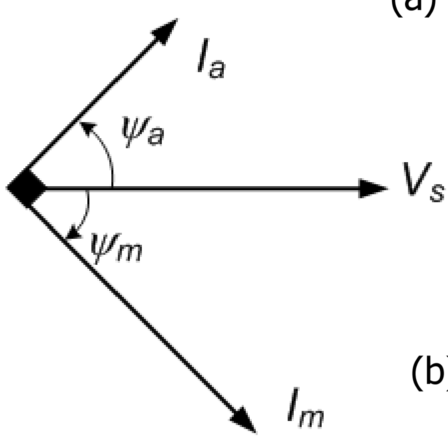


2-a: Capacitor Start IM

- A schematic diagram of the capacitor-start motor is shown in Fig. a. The phasor diagram at starting is shown in Fig. b. High starting torque is the outstanding feature of this arrangement, as shown in Fig c.



(a)



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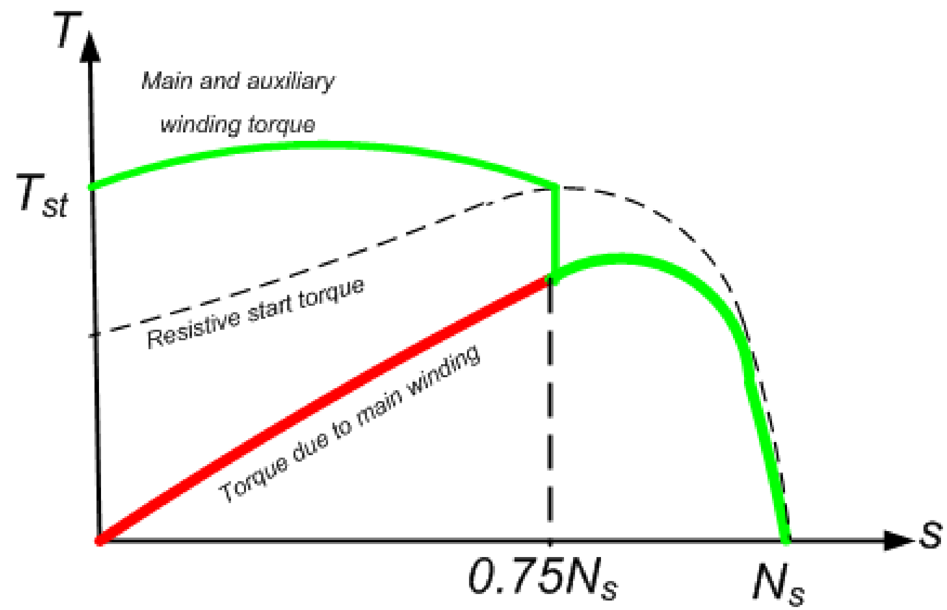


(c)

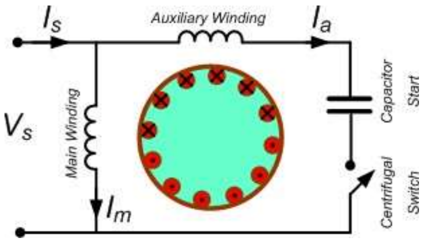
Torque-speed characteristic of capacitor –start single-phase IM

2-a: Capacitor Start IM

- Split phase IM suffers from its moderate value of starting torque which is attributed to the relatively small phase shift between main and auxiliary winding currents.

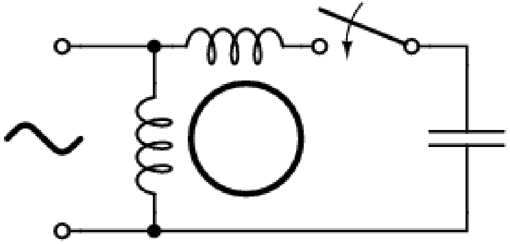
- The phase shift is increased by inserting a chosen **Electrolytic** capacitor in series with the auxiliary winding. Because the capacitor is in the circuit only during starting period, it can be an **inexpensive** ac **Electrolytic** capacitor.

- This capacitor is designed to eliminate backward field component at starting. It is compact and cheap with accepted voltage range. This capacitor and auxiliary winding are to be switched out of the circuit using centrifugal switch at a speed almost 75 % of synchronous speed.



Performance Evaluation of Capacitor Start IM

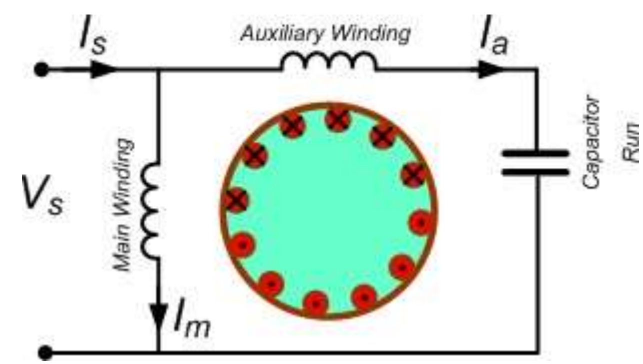
- The power range is 1/8 – 1 hp.
- Power factor in range of 0.5 to 0.65.
- Efficiency in range of 55 to 65 %.
- Starting torque is 250 % - 400 % of rated torque.
- Maximum torque or break down torque is 350 % rated torque.
- A typical capacitor value is 300 μF for ½ hp motor.
- Cost is 1.25 pu



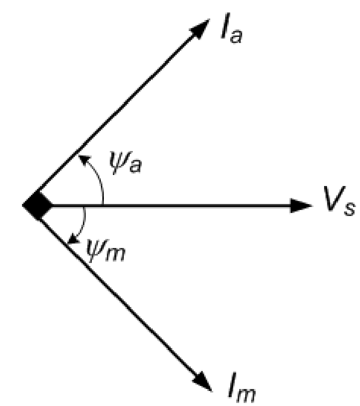
- **Applications:**
  - Compressors, pumps,
  - air conditioning,
  - electric refrigerators,
  - and loads require heavy starting torque

2-b: Capacitor-Run IM

- In this motor, as shown in Fig. a, the capacitor that is connected in series with the auxiliary winding is not cut out after starting and is left in the circuit all the time, as a result the backward field would then be reduced. Therefore, the power factor, torque pulsation, and efficiency are improved because the motor runs as a two-phase motor.
- The construction and the cost are simplified because the centrifugal switch is not needed. The motor runs more quietly. The capacitor is a compromise between the best starting and running values and therefore the starting torque is sacrificed, as shown in Fig.c.



(a)



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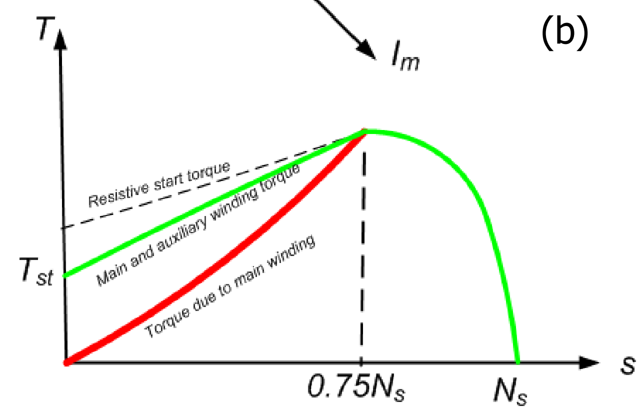
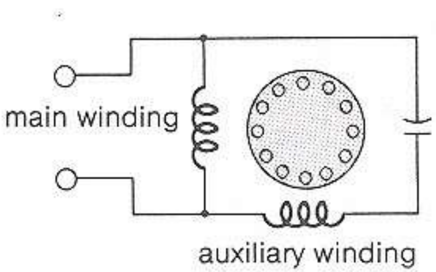


(c)

Performance Evaluation of Capacitor RUN IM

- The power range is 1/8 – 1 hp.
- Power factor in range of 0.75 to 0.9.
- Efficiency in range of 60 to 70 %.
- Starting torque is 100 % - 250 % of rated torque.
- Maximum torque or break down torque is 250 % rated torque.
- Capacitors are in range 20 – 50 μF.
- Cost is 1.4 pu

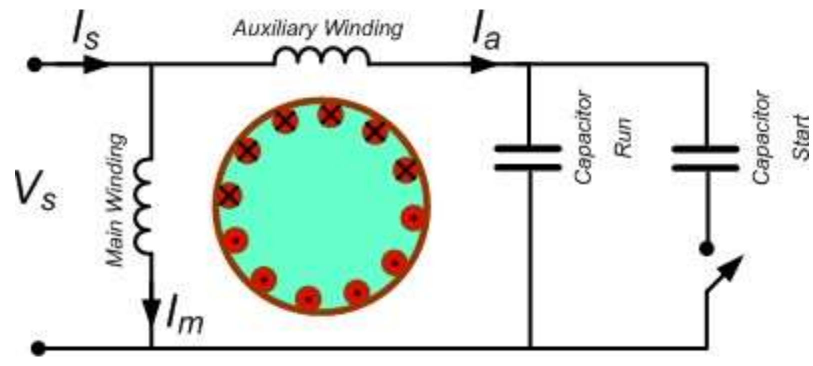


(a)

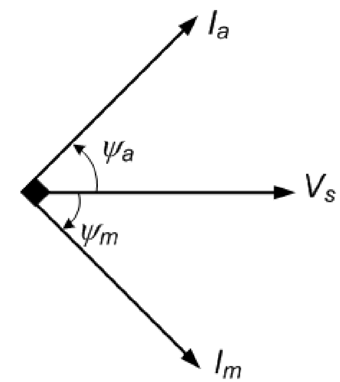
- **Applications:**
  - Fans
  - Blowers
  - Low noise applications,

2-c: Capacitor-Start Capacitor-Run IM

- Two capacitors, one for starting and one for running, can be used, as shown in Fig. a.
- Theoretically optimum starting and running performance can be obtained by having two capacitors.
- The typical torque-speed characteristics is shown in Fig. c.
- The motor is, of course, expensive compared to others; however, it provides the best performance.



(a)



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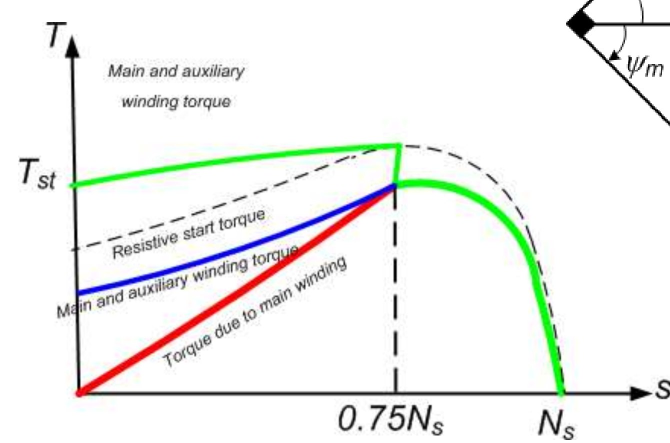
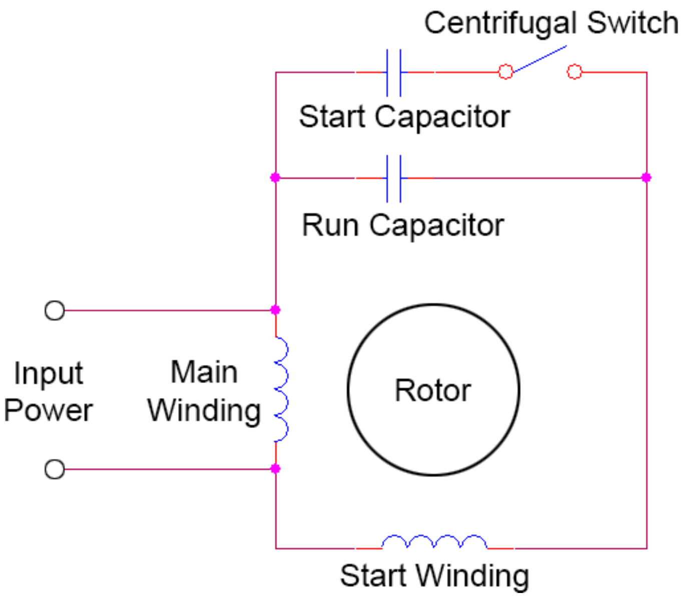


(c)

Performance Evaluation of Capacitor Start Capacitor Run IM

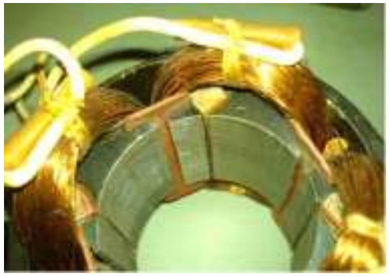
- The power range is 1/8 – 1 hp.
- Power factor in range of 0.75 to 0.9.
- Efficiency in range of 60 to 70 %.
- Starting torque is 200 % - 300 % of rated torque.
- Maximum torque or break down torque is 250 % rated torque.
- Capacitors are in range 20 – 50 µF.
- Cost is 1.8 pu.

- **Applications:**
  - Fans,
  - blowers,
  - Low noise and high starting torque applications

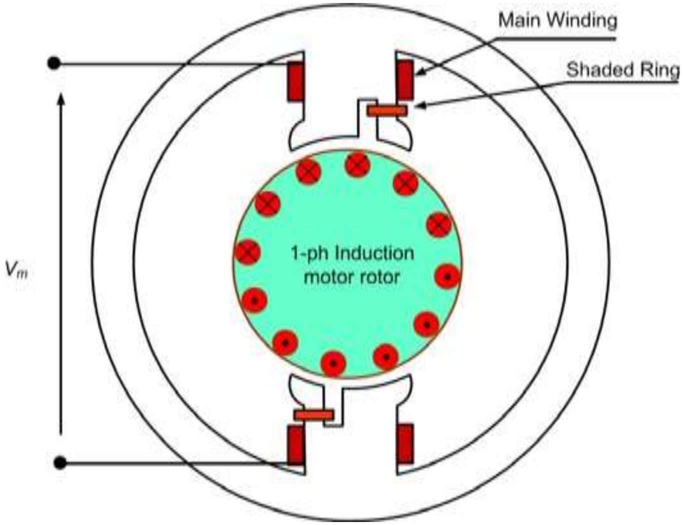


Classification Of single-phase Induction Motors (cont.)

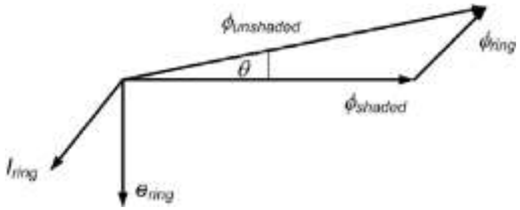
3- Shaded-Pole Motors



- These motors have a salient pole construction.
- A shaded band consisting of a short-circuited copper ring, called the shading coil, is used on one portion of each pole, as shown in Fig. a.
- The main single-phase winding is wound on the salient poles. The result is that the current induced in the shading band causes the flux in the shaded portion of the pole to lag the flux in the unshaded portion of the pole.

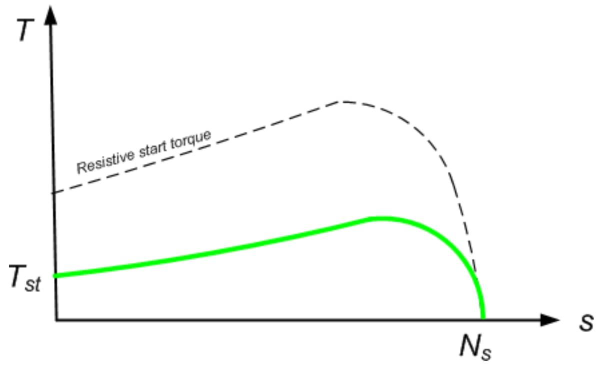


(a)



3- Shaded-Pole Motors

- The result is then like a rotating field moving in the direction from the unshaded to the shaded portion of the pole. A low starting torque is produced; a typical torque-speed characteristic is shown in Fig. b.

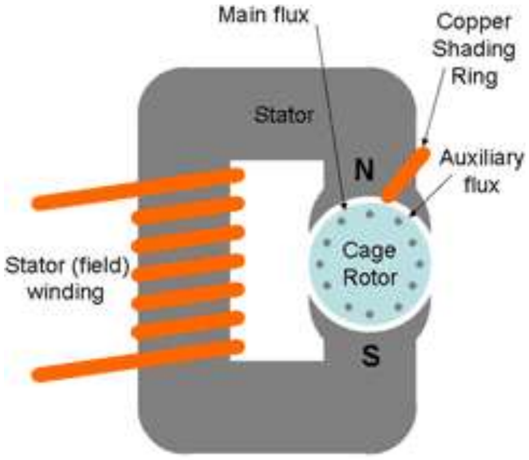


(b)

Performance Evaluation of Shaded-Pole IM

- The power range is 1/200 – 1/20 hp.
- Power factor in range of 0.25 to 0.4.
- Efficiency in range of 25 to 40 %.
- Starting torque is 40 % - 60 % of rated torque.
- Maximum torque or break down torque is 140 % rated torque.
- Cost is 0.6 pu

- **Applications:**
  - Fans,
  - toys,
  - hair driers, and
  - loads require low starting torque,



Shaded Pole Induction Motor

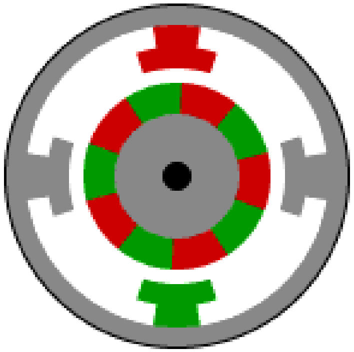
Characteristics and applications of single-phase induction motors

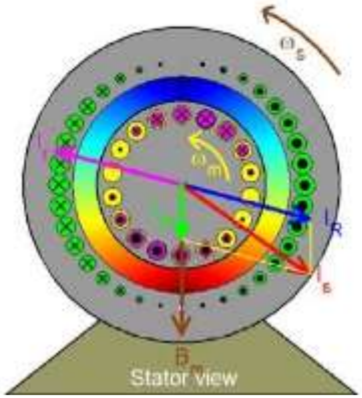
TABLE 1.1 Single-Phase Induction Motors: Characteristics and Applications

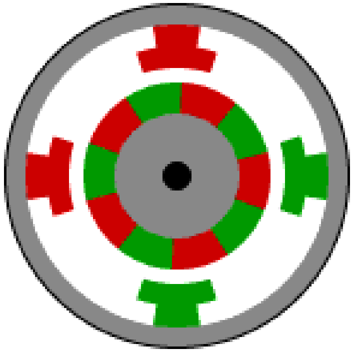
Type of Motor	Torque as % of Rated Torque		Rated Load		Horsepower Range	Approx. Comparative Price (%)	Applications
	Starting	Breakdown	Power Factor	Efficiency			
Split-phase (resistance-start)	100–250	Up to 300	50–65	55–65	1/20–1	100	Fans, blowers, centrifugal pumps, washing machines, etc. Loads requiring low or medium starting torque
Capacitor-start	250–400	Up to 350	50–65	55–65	1/8–1	125	Compressors, pumps, conveyors, refrigerators, air-conditioning equipment, washing machines, and other hard-to-start loads
Capacitor-run	100–200	Up to 250	75–90	60–70	1/8–1	140	Fans, blowers, centrifugal pumps, etc. Low noise applications
Capacitor-start, capacitor-run	200–300	Up to 250	75–90	60–70	1/8–1	180	Compressors, pumps, conveyors, refrigerators etc. Low noise and high starting torque applications
Shaded-pole	40–60	140	25–40	25–40	1/200–1/20	60	Fans, hair driers, toys, etc. Loads requiring low starting torque

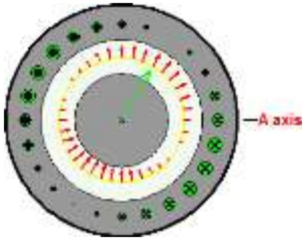
EE471-Electrical Machines II

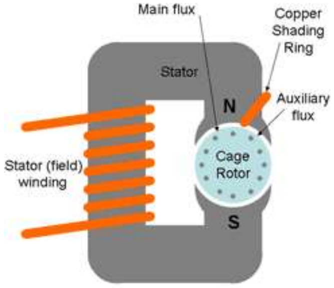
Topic 4: Special Motors







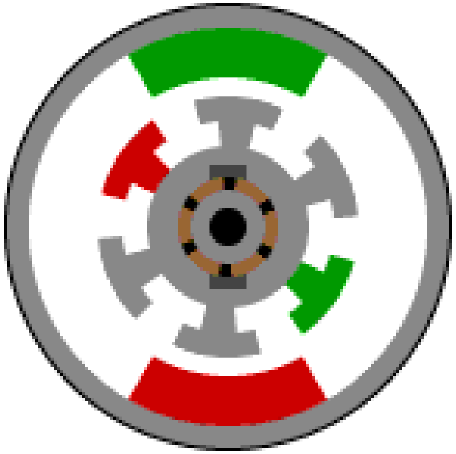




Shaded Pole Induction Motor

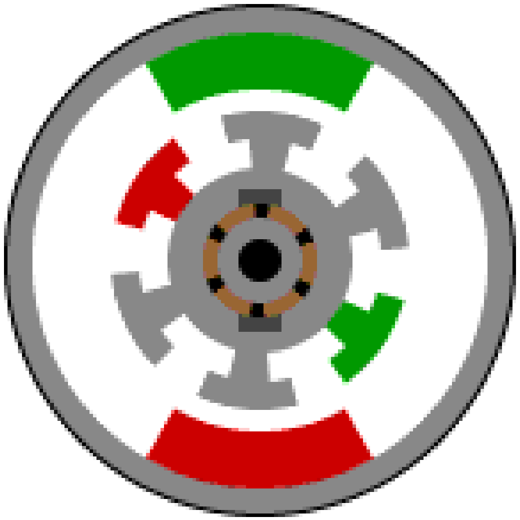
1. DC Motors

- The stator is the stationary outside part of a motor. The rotor is the inner part which rotates.
- In the motor animations, red represents a magnet or winding with a north polarization, while green represents a magnet or winding with a south polarization.
- Opposite, red and green, polarities attract.



DC Motors

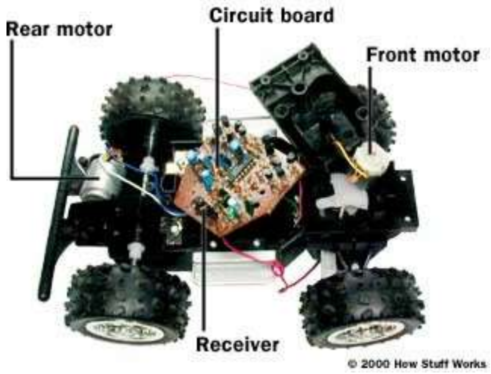
- Just as the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding.
- In the animation the commutator contacts are brown and the brushes are dark grey.
- A yellow spark shows when the brushes switch to the next winding.



DC Motor Applications

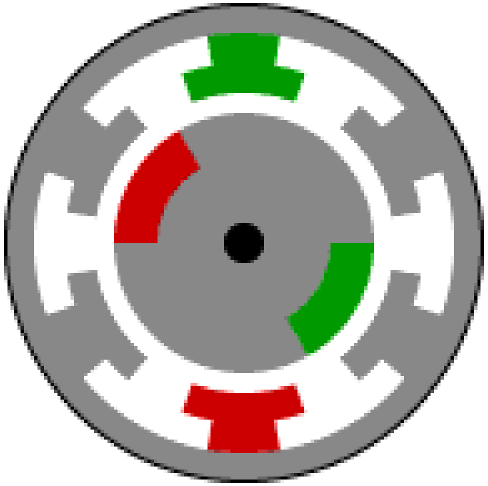
- Automobiles
  - Windshield Wipers
  - Door locks
  - Window lifts
  - Antenna retractor
  - Seat adjust
  - Mirror adjust
  - Anti-lock Braking System

- Cordless hand drill
- Electric lawnmower
- Fans
- Toys
- Electric toothbrush
- Servo Motor



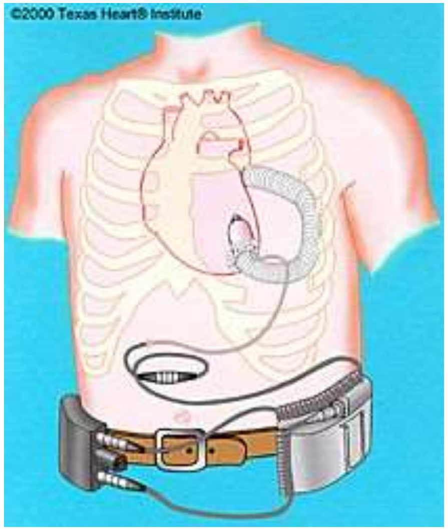
2. Brushless DC Motors

- A brushless dc motor has a rotor with permanent magnets and a stator with windings.
- It is essentially a dc motor turned inside out. The control electronics replace the function of the commutator and energize the proper winding.



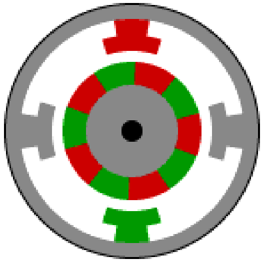
Brushless DC Motor Applictions

- Medical: centrifuges, orthoscopic surgical tools, respirators, dental surgical tools, and organ transport pump systems
- Model airplanes, cars, boats, helicopters
- Microscopes
- Tape drives and winders
- Artificial heart

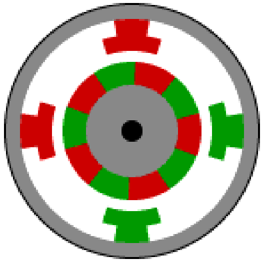


3. Stepper Motors

- The rotor of a real stepper motor usually has many poles.
- The animation has only ten poles, however a real stepper motor might have a hundred.
- These are formed using a single magnet mounted inline with the rotor axis and two pole pieces with many teeth. The teeth are staggered to produce many poles.



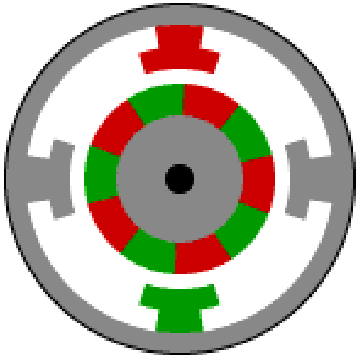
- The stator poles of a real stepper motor also has many teeth. The teeth are arranged so that the two phases are still 90° out of phase.
- This stepper motor uses permanent magnets.



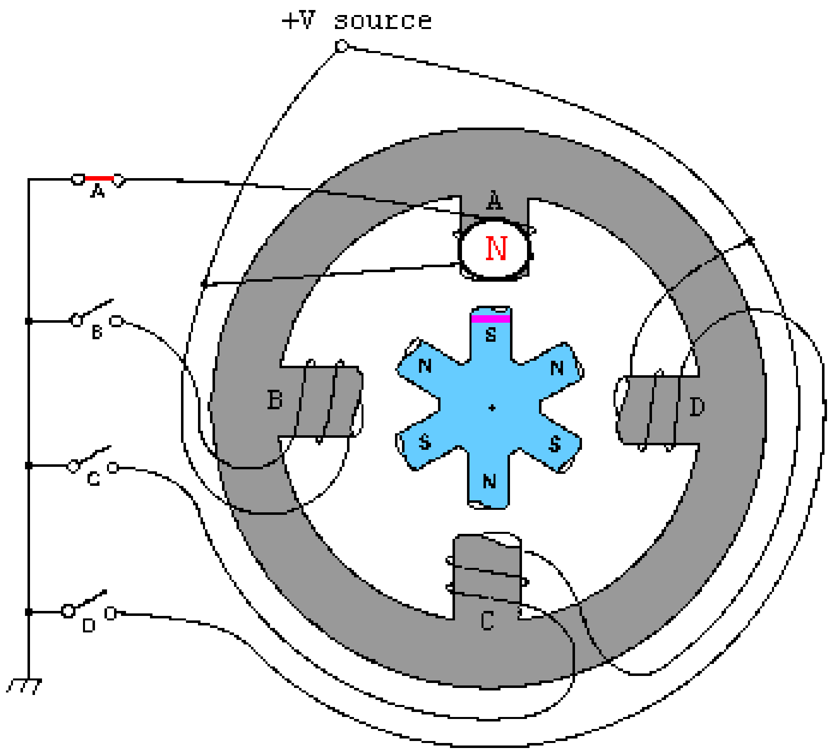
- Some stepper motors do not have magnets and instead use the basic principles of a switched reluctance motor.
- The stator is similar but the rotor is composed of a iron laminates.

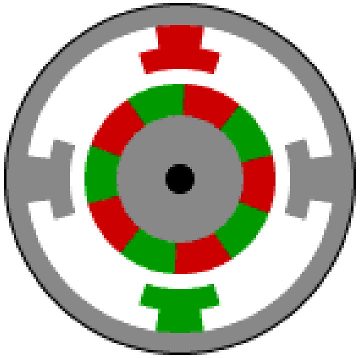
Full Stepper Motor

- This animation demonstrates the principle for a stepper motor using full step commutation.
- The rotor of a permanent magnet stepper motor consists of permanent magnets and the stator has two pairs of windings.
- Just as the rotor aligns with one of the stator poles, the second phase is energized.
- The two phases alternate on and off and also reverse polarity.
- There are four steps. One phase lags the other phase by one step. This is equivalent to one forth of an electrical cycle or 90°.



More on Stepper Motors

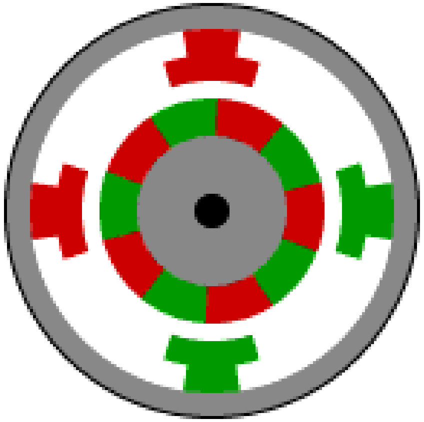




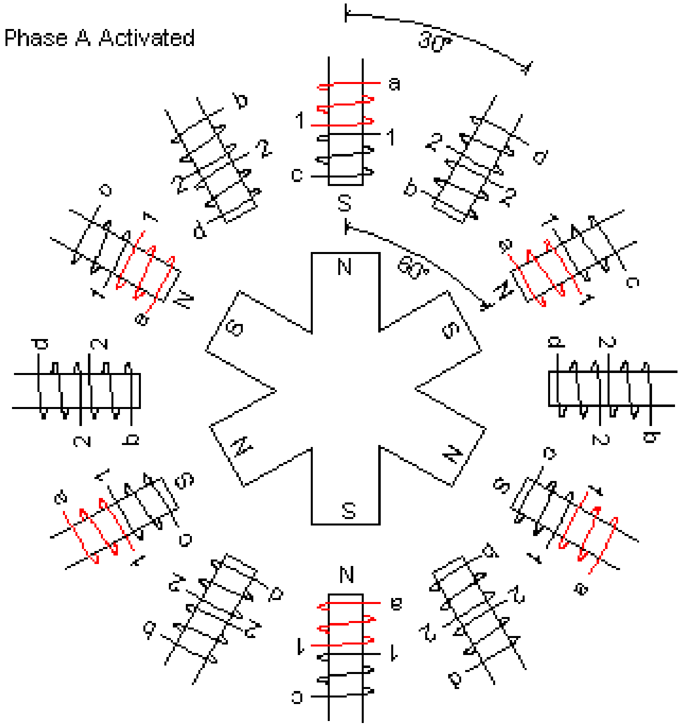
- Animation shows how coils are energized for full steps

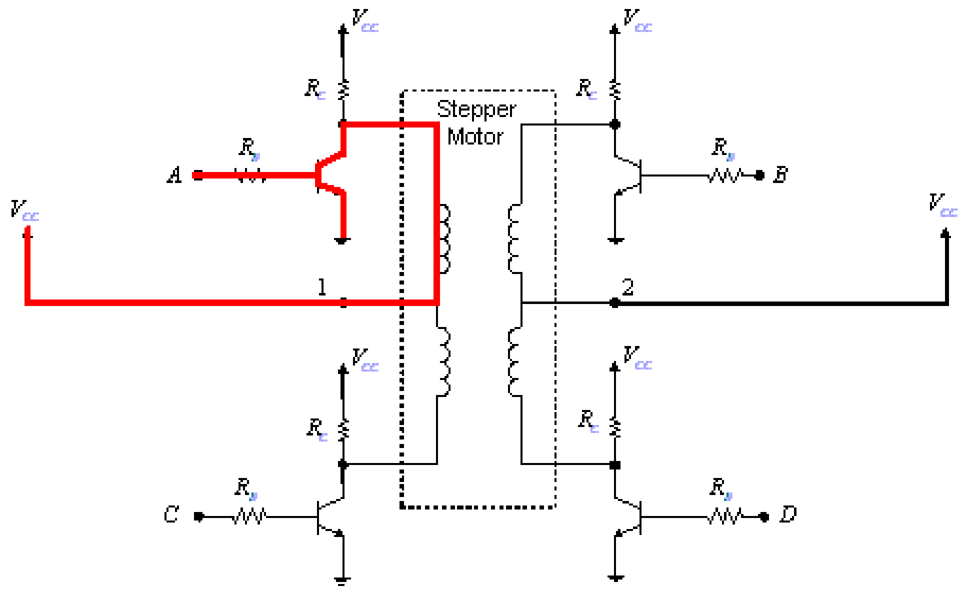
Half Stepper Motor

- This animation shows the stepping pattern for a half-step stepper motor.
- The commutation sequence for a half-step stepper motor has eight steps instead of four.
- The main difference is that the second phase is turned on before the first phase is turned off.
- Thus, sometimes both phases are energized at the same time.
- During the half-steps the rotor is held in between the two full-step positions.
- A half-step motor has twice the resolution of a full step motor. It is very popular for this reason.



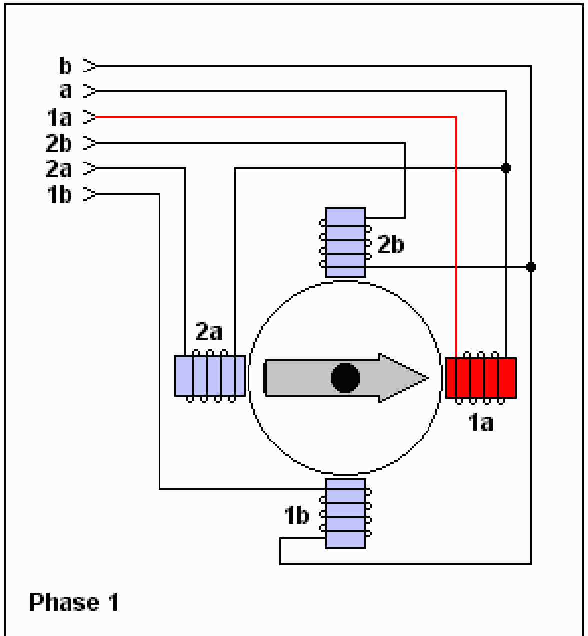
More on Stepper Motors





- **Note how the phases are driven so that the rotor takes half steps**

More on Stepper Motors



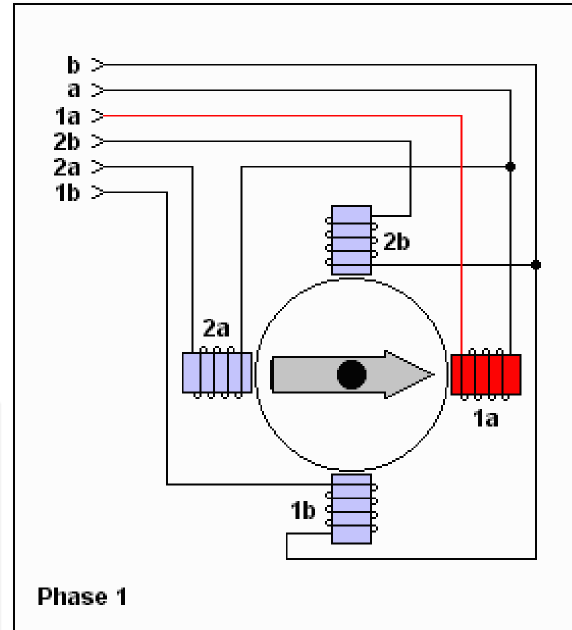
Stepper Motor Operation (Unipolar, Full step)

Clockwise Rotation

Index	1a	1b	2a	2b
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1
5	1	0	0	0
6	0	1	0	0
7	0	0	1	0
8	0	0	0	1

Clockwise Rotation

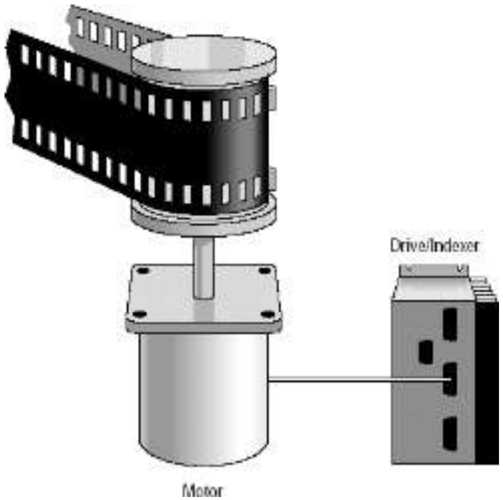
Index	1a	1b	2a	2b
1	1	0	0	0
2	1	1	0	0
3	0	1	0	0
4	0	1	1	0
5	0	0	1	0
6	0	0	1	1
7	0	0	0	1
8	1	0	0	1
9	1	0	0	0
10	1	1	0	0
11	0	1	0	0
12	0	1	1	0
13	0	0	1	0
14	0	0	1	1
15	0	0	0	1
16	1	0	0	1



Stepper Motor Operation (Unipolar, Half step)

- Full step sequence showing how binary numbers can control the motor
- Half step sequence of binary control numbers

Stepper Motor Applications

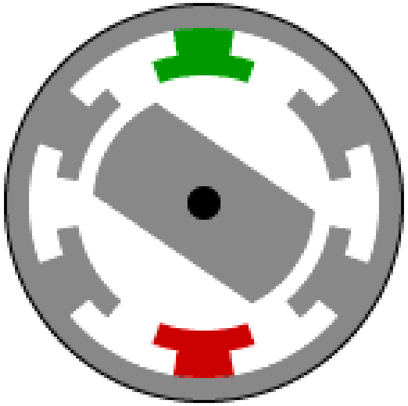


- Film Drive
- Optical Scanner
- Printers
- ATM Machines

- I. V. Pump
- Blood Analyzer
- FAX Machines
- Thermostats

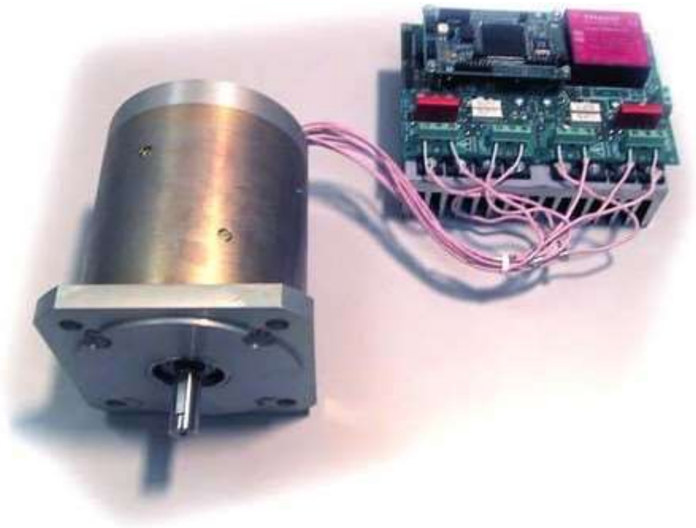
4. Switched Reluctance Motor

- A switched reluctance or variable reluctance motor does not contain any permanent magnets.
- The stator is similar to a brushless dc motor. However, the rotor consists only of iron laminates. The iron rotor is attracted to the energized stator pole.
- The polarity of the stator pole does not matter. Torque is produced as a result of the attraction between the electromagnet and the iron rotor in the same way a magnet is attracted to a refrigerator door.
- An electrically quiet motor since it has no brushes.



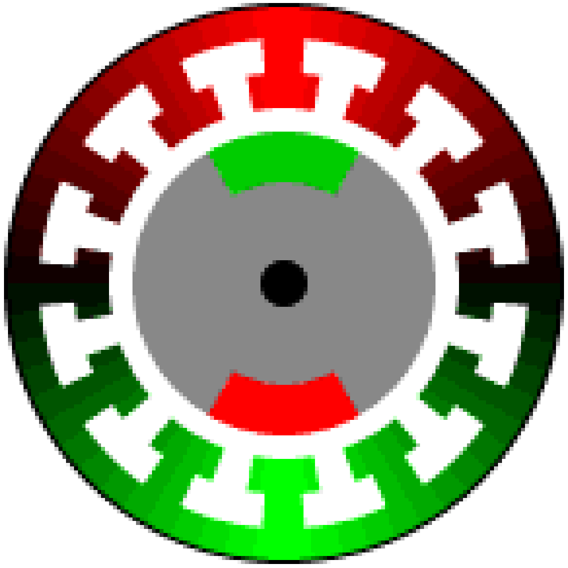
Switched Reluctance Motor Applications

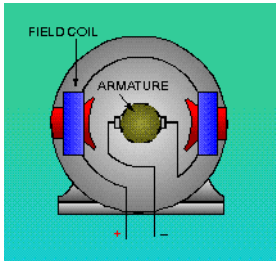
- Motor scooters and other electric and hybrid vehicles
- Industrial fans, blowers, pumps, mixers, centrifuges, machine tools
- Domestic appliances



5. Brushless AC Motor

- A brushless ac motor is driven with ac sine wave voltages.
- The permanent magnet rotor rotates synchronous to the rotating magnetic field.
- The rotating magnetic field is illustrated using a red and green gradient.
- An actual simulation of the magnetic field would show a far more complex magnetic field.

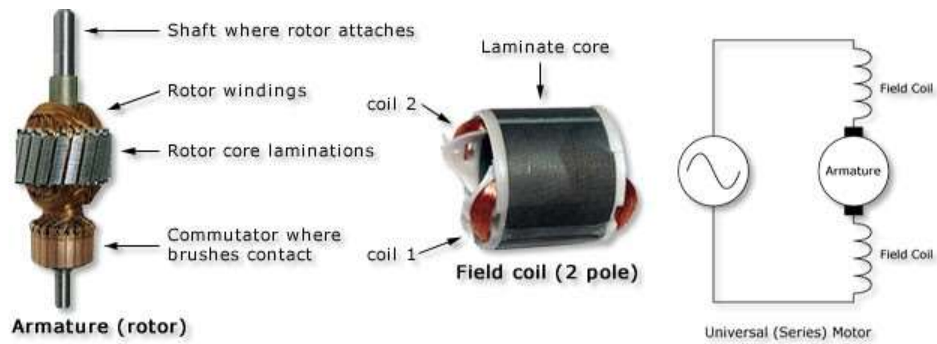


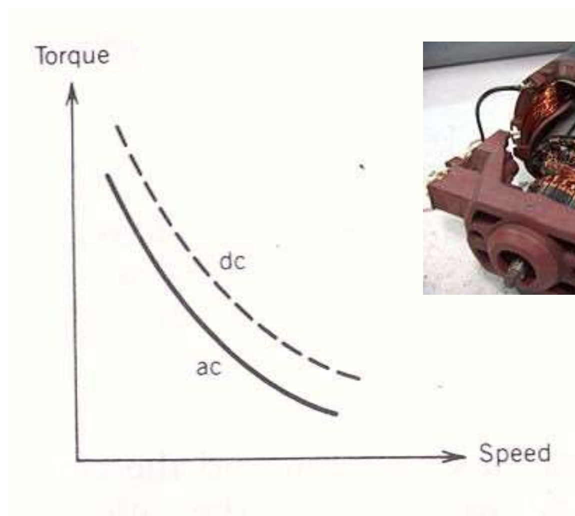


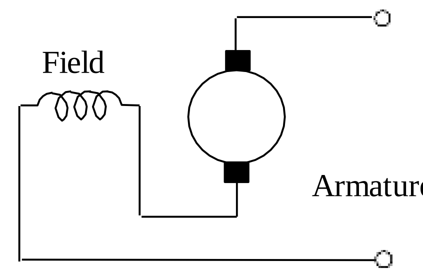
6. Universal Motor

A universal motor is a series motor that may be operated either on d.c. or on single phase a.c . Its speed is usually high (1500-15000 rpm) and widely used in fractional horsepower ratings. It is identical to a series d.c. motor except that stator core and poles are laminated to limit the iron losses when operated from a.c. supply

- Runs on AC or DC
- Commutator and brushes
- Generally found in portable power tools.
- Lower Hp sizes
- Very high starting torque.
- Higher torque on DC than AC (battery operated tools)
- The higher the rpm, the lower the torque.







Universal Motor