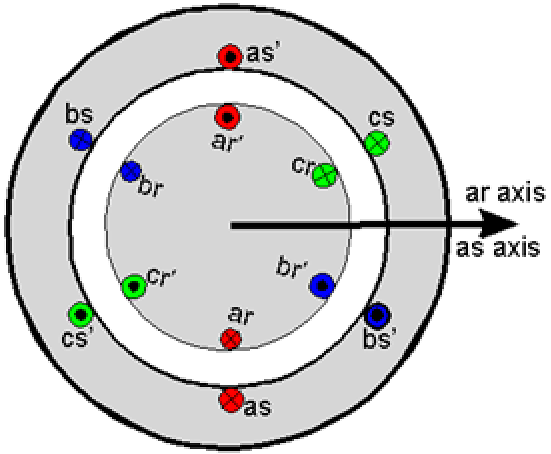
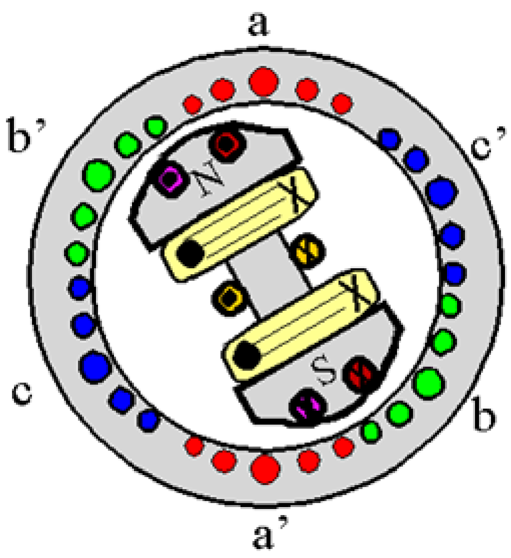
EE373-Electrical Machines

Topic 5: Synchronous Motors

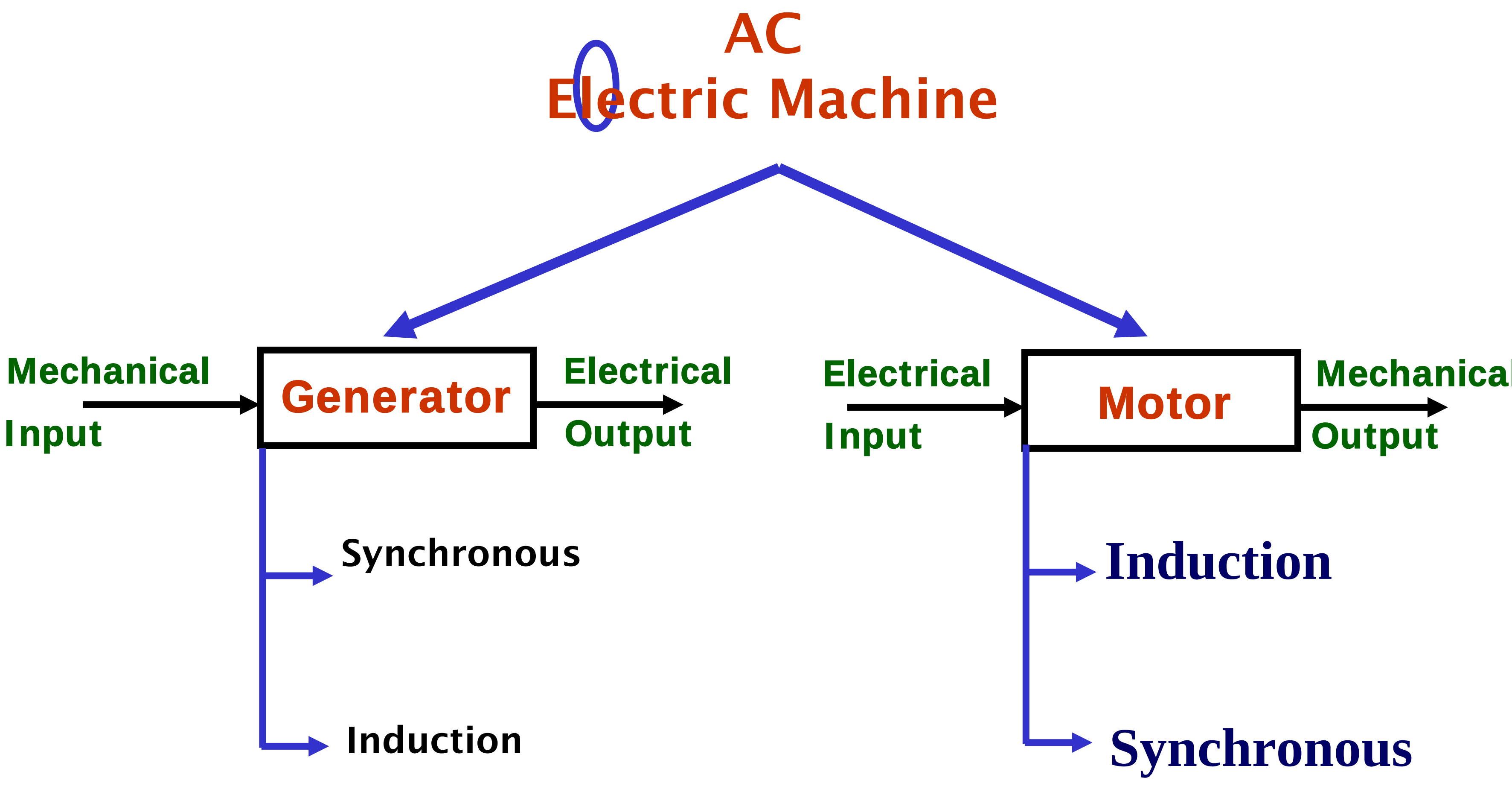




LEARNING GOALS

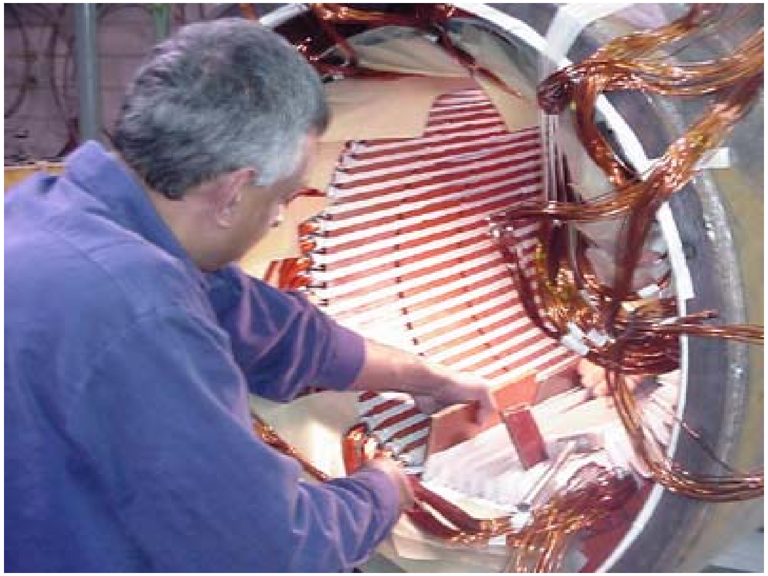
- **Introduction**
- **Motor Equivalent Circuit**
- **Power-angle and other Performance Characteristics (Motor)**
- **Starting of Synchronous Motor**

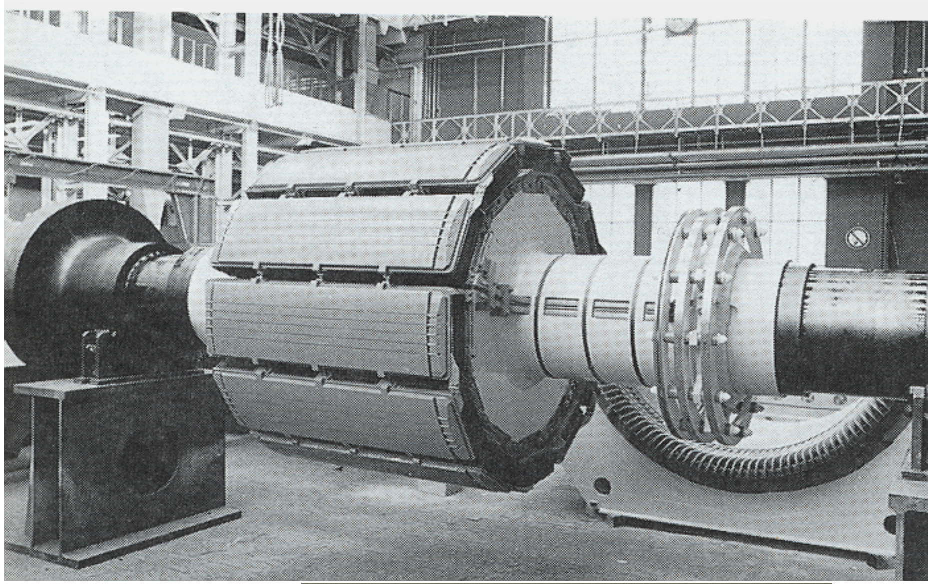
Introduction

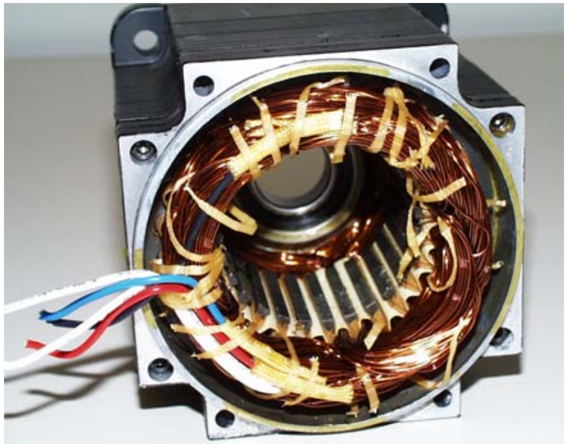


Construction of Synchronous Machine

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





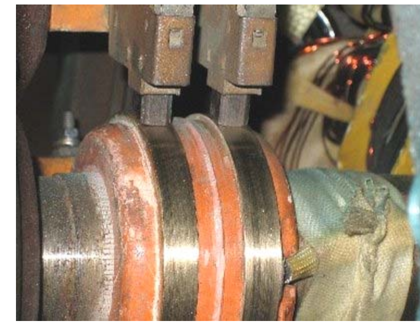


Stator

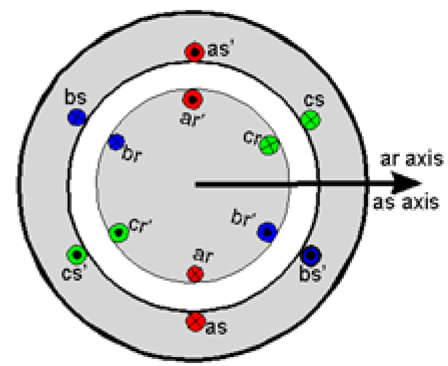
Rotor

Construction of synchronous machines

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



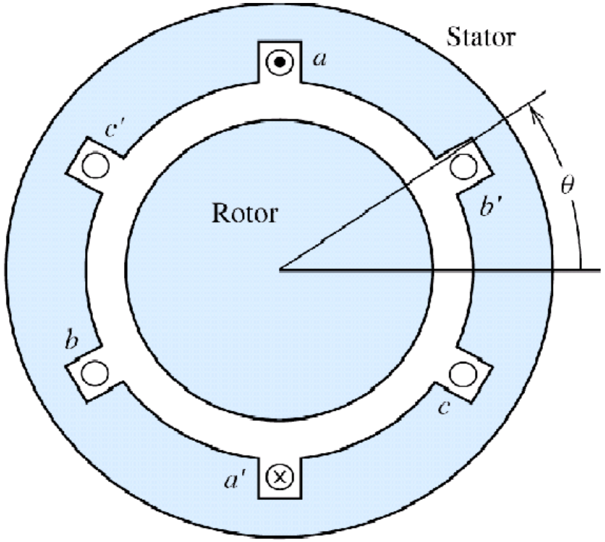
In a synchronous motor, a 3-phase set of stator currents produces a rotating magnetic field causing the rotor magnetic field to align with it. The rotor magnetic field is produced by a DC current applied to the rotor winding.



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

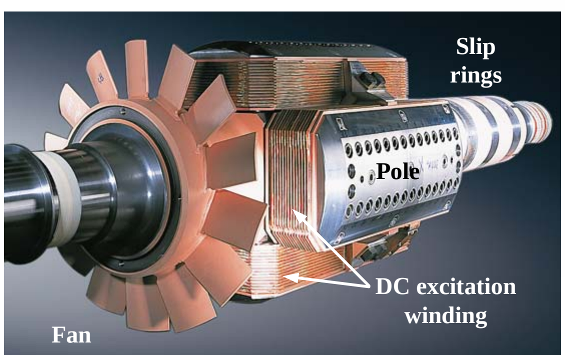
A three-phase windings is placed in slots cut on the inner surface of the stationary part. The ends of these windings can be connected in star or delta to form a three phase connection. These windings are fed from a three-phase ac supply (Motor) or connected to a three-phase ac load (Gen) .

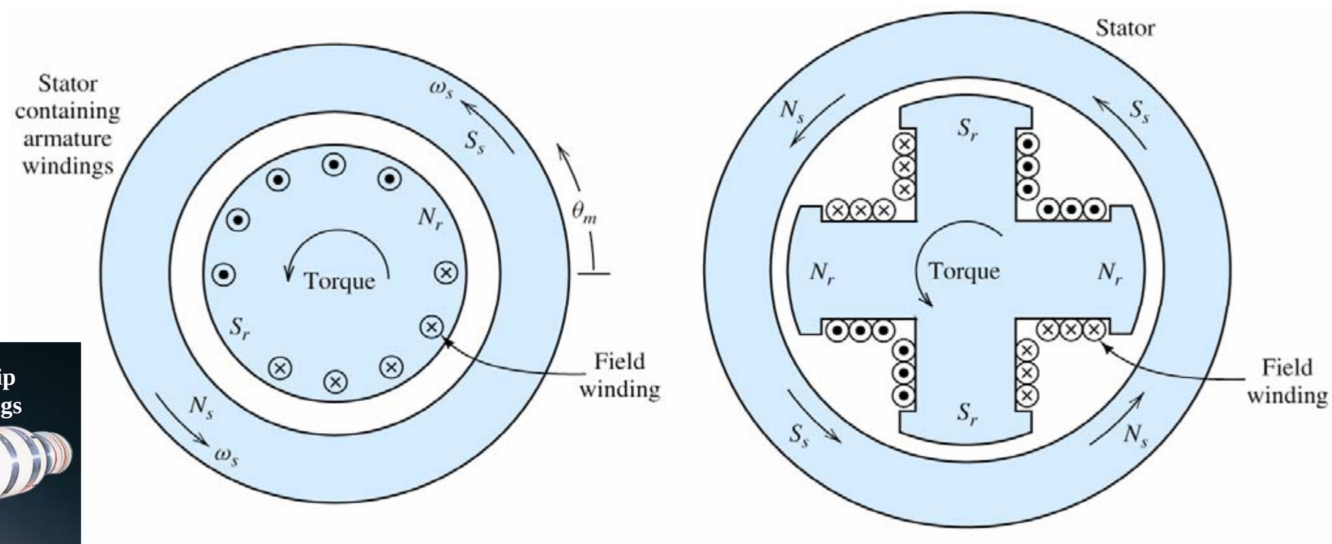


Synchronous Machine: Rotor

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



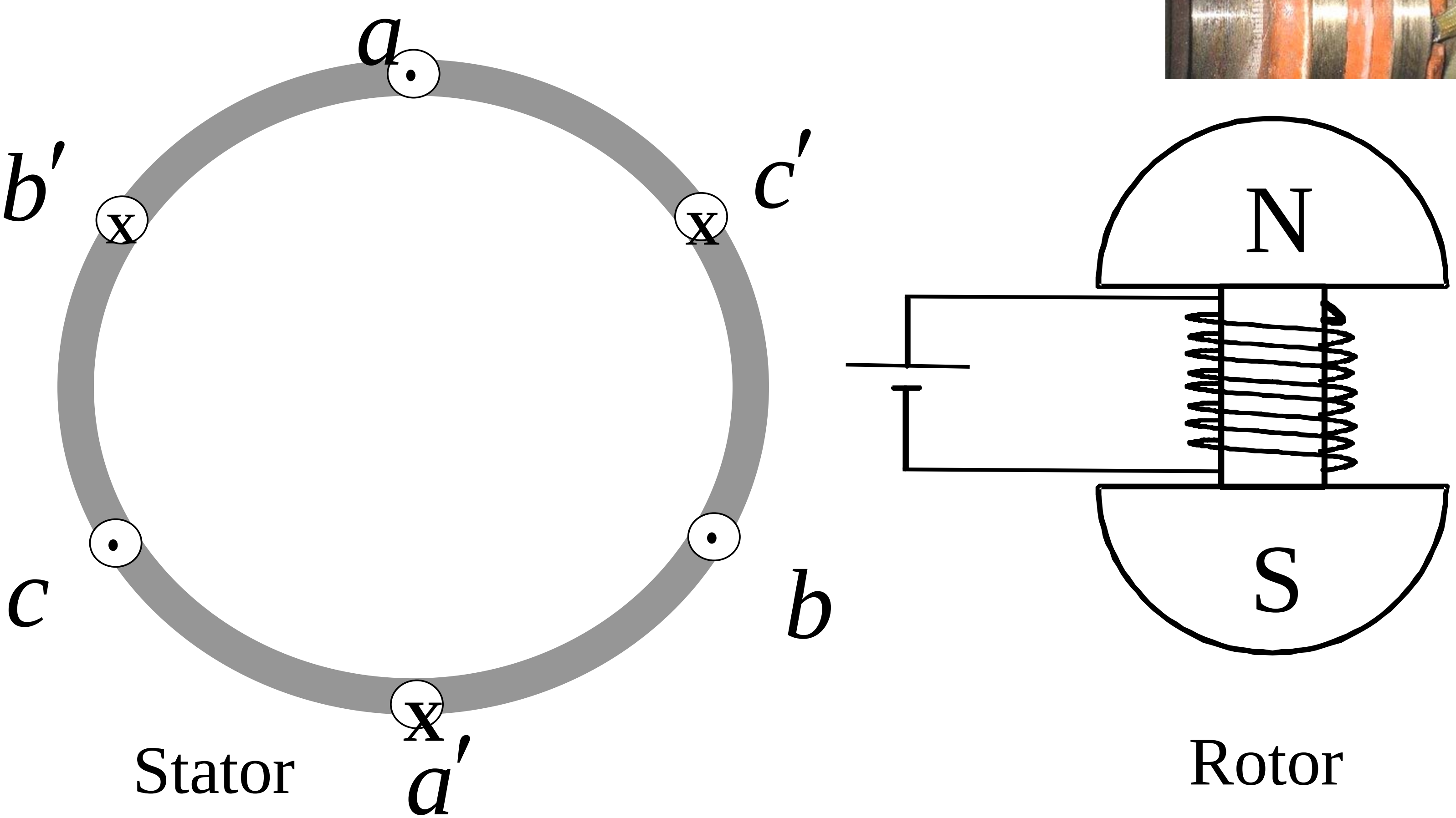


(a) Two-pole cylindrical rotor machine

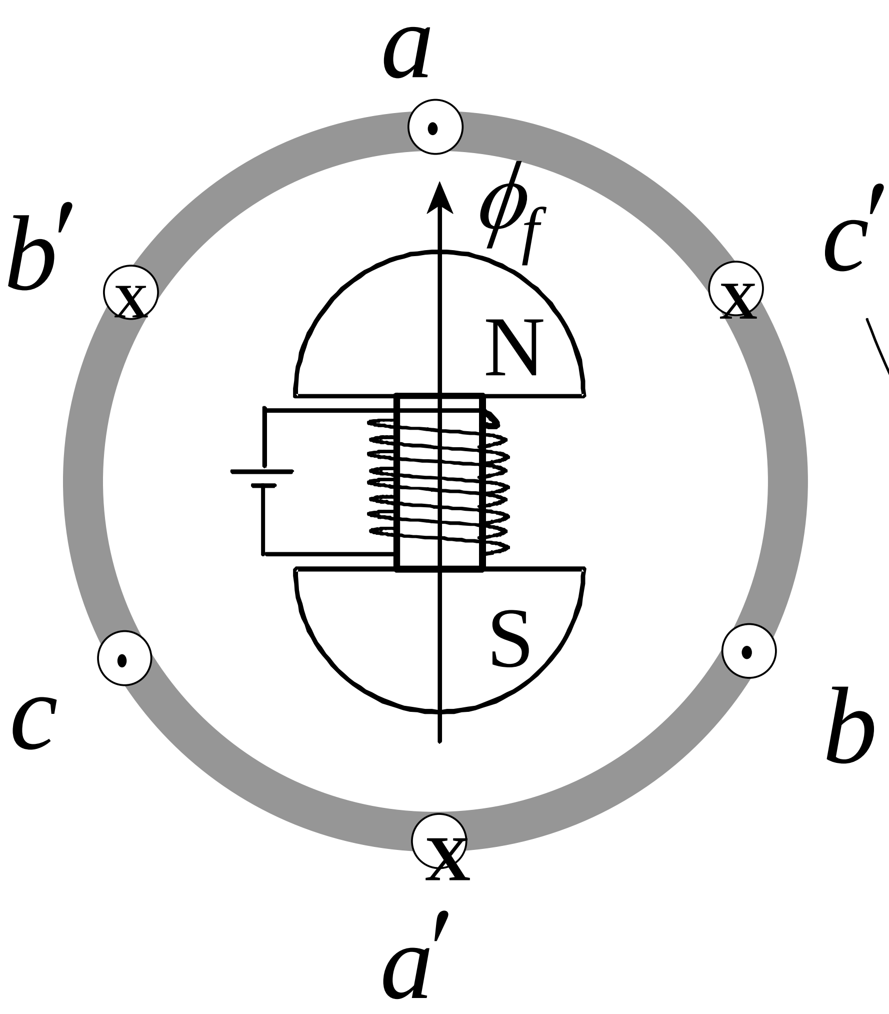
(b) Four-pole salient rotor machine

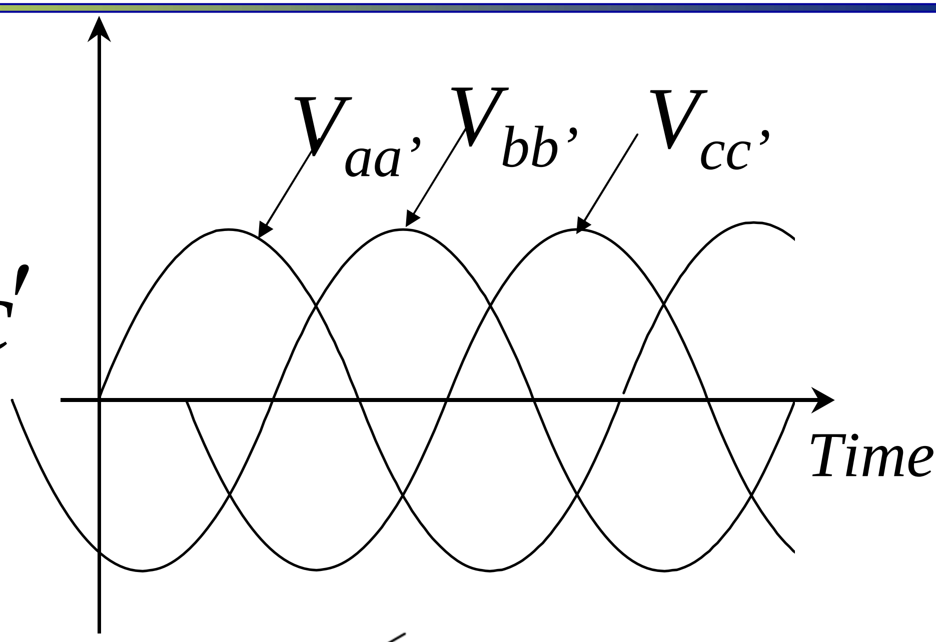
Synchronous Machine: Rotor

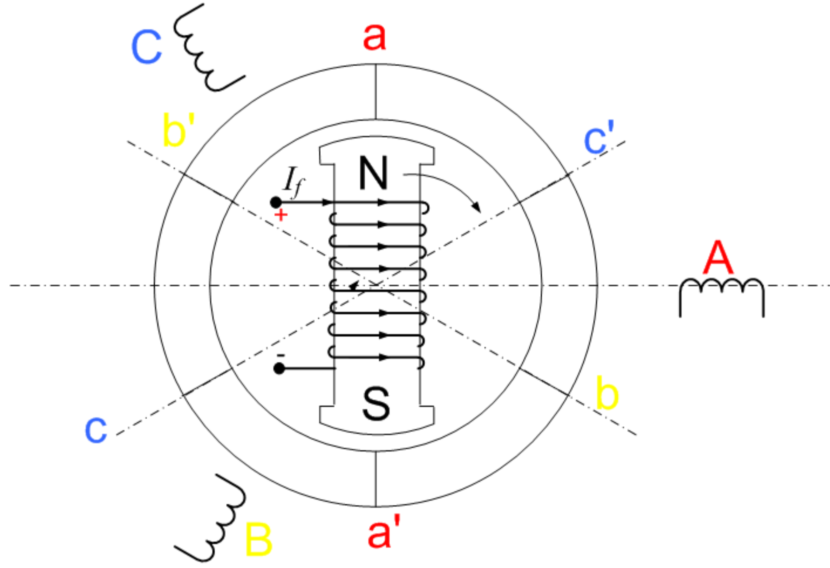
The Rotor winding is known as the field winding or excitation winding



Synchronous Machine: Rotor







Principle of Operation: Generator

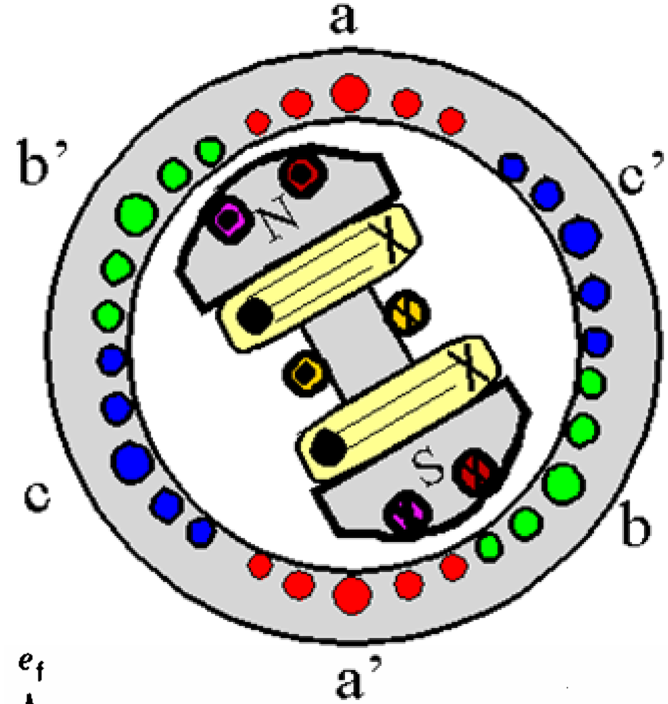
When a dc field current flows through the rotor field winding it establishes a flux in the air-gap.

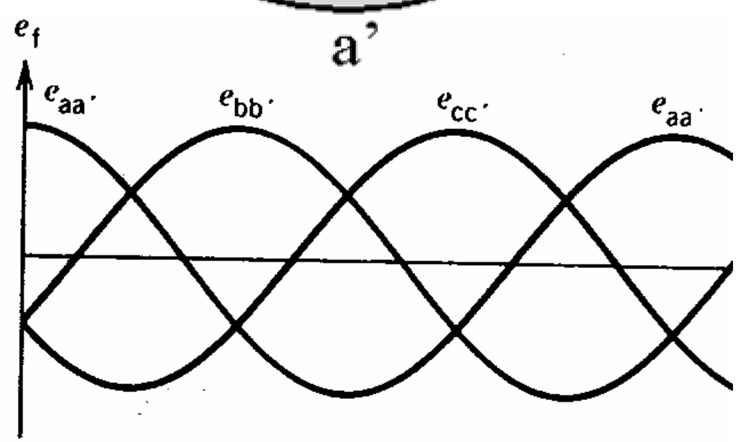
If the rotor is now rotating, a revolving field is produced in the air-gap.

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:

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

$$\text{Let}\quad \phi = \phi_{\mathrm{m}} \sin(\omega\ \mathrm{t})$$

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

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.

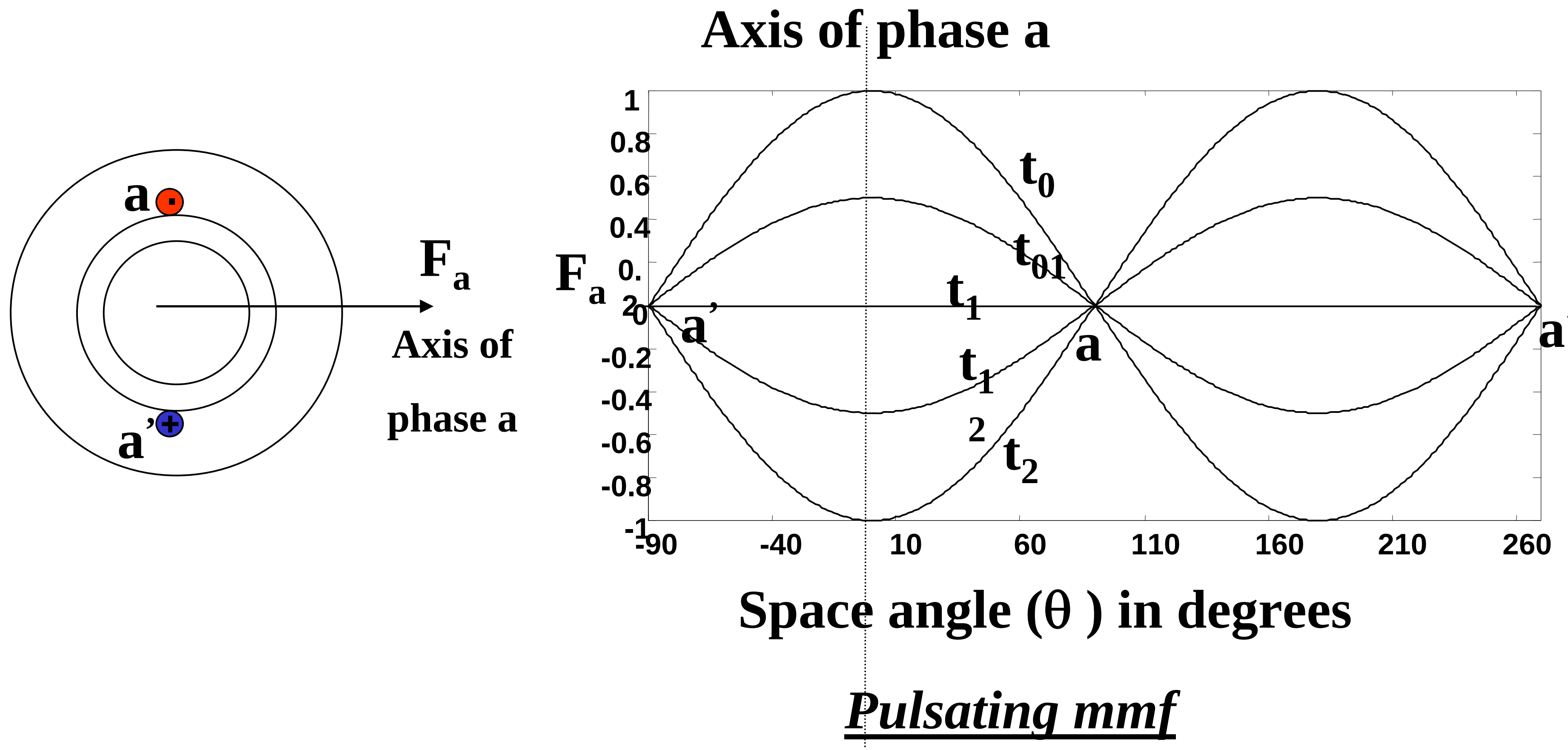
Example 1

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

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

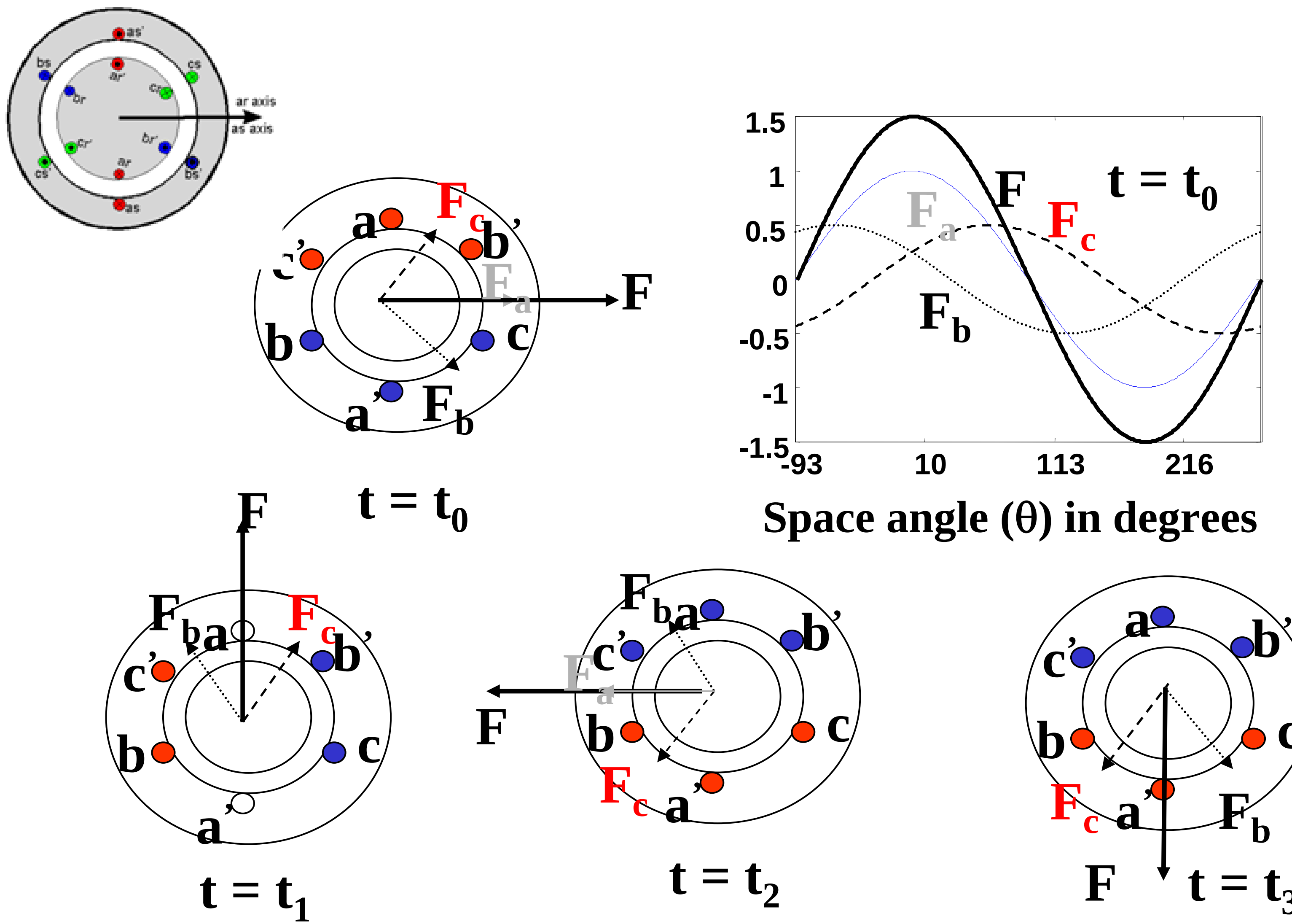
Number of poles (p)	***Speed n_s (rpm)***
2	**3600**
4	**1800**
6	**1200**

MMF due to ac current in phase “a”



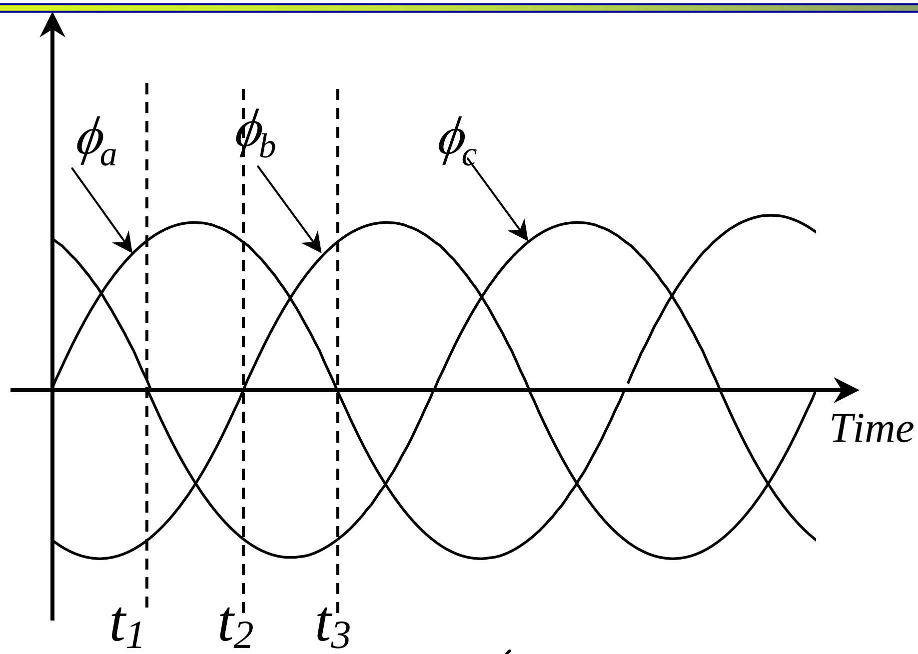
Pulsating mmf

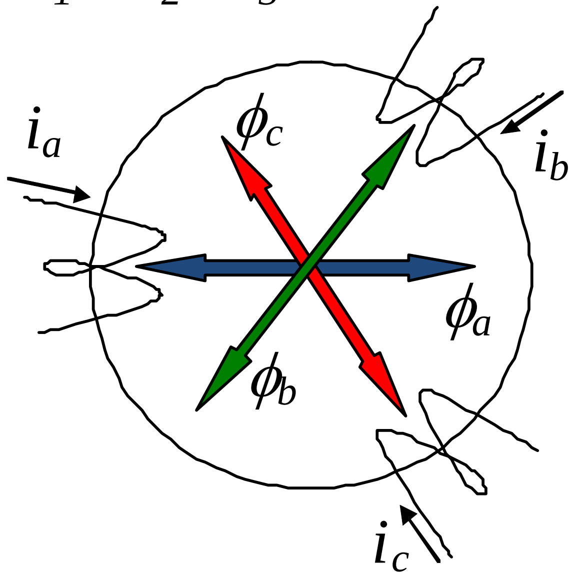
MMF due to three-phase currents in 3-ph winding

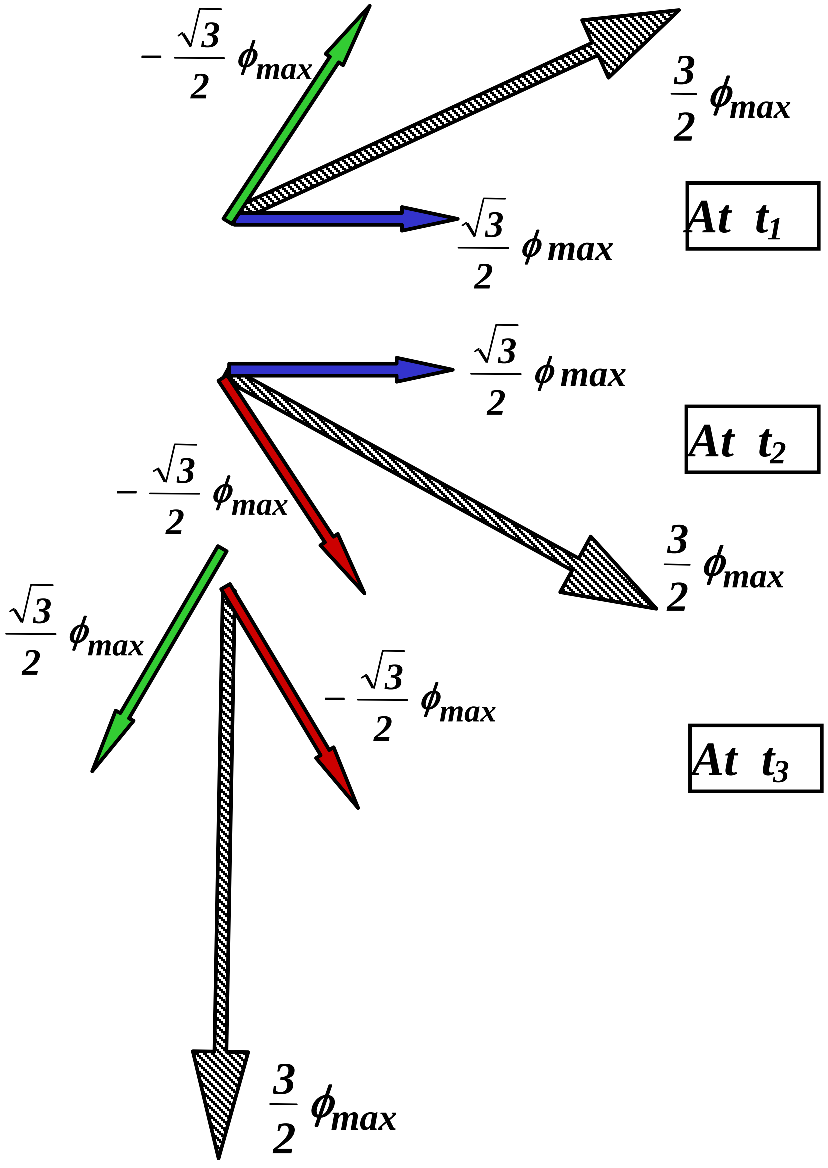


MMF's at various instant (***Rotating mmf***)

Rotating Magnetic Field





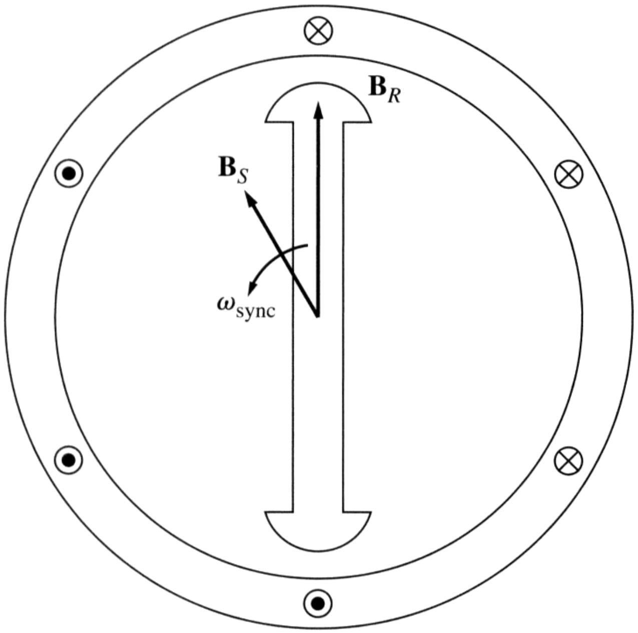


Synchronous motors

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.



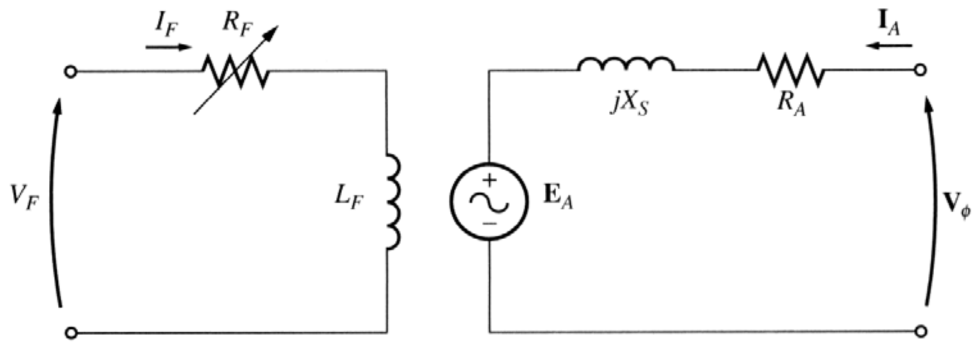
$$\tau_{ind} = k\,\mathbf{B}_R \times \mathbf{B}_S$$
$$= \text{counterclockwise}$$

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:

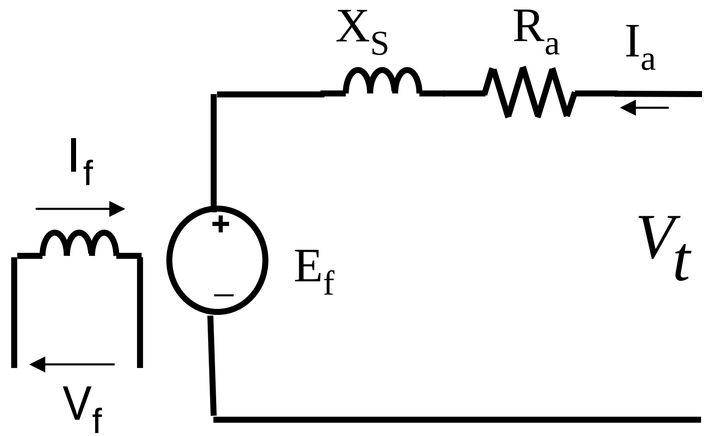
$$V_\phi = E_A + jX_S I_A + R_A I_A$$

Therefore, the internal generated voltage is

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

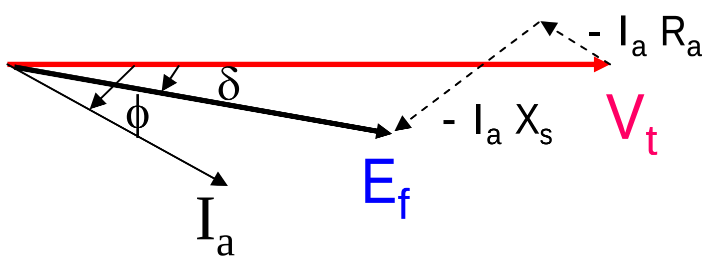
Motor Equivalent Circuit

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

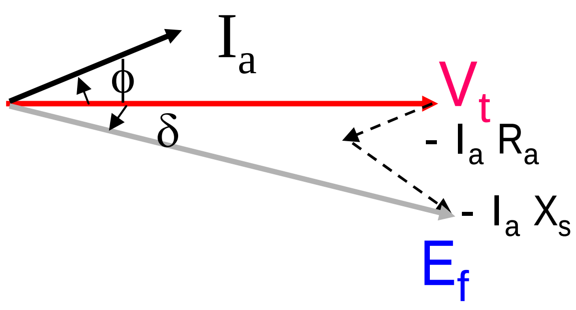


$$E_f \angle \delta^\circ = V_t \angle 0^\circ - I_a R_a \angle \pm \phi^\circ - I_a X_s \angle (\pm \phi + 90)^\circ$$

a-Lagging power factor

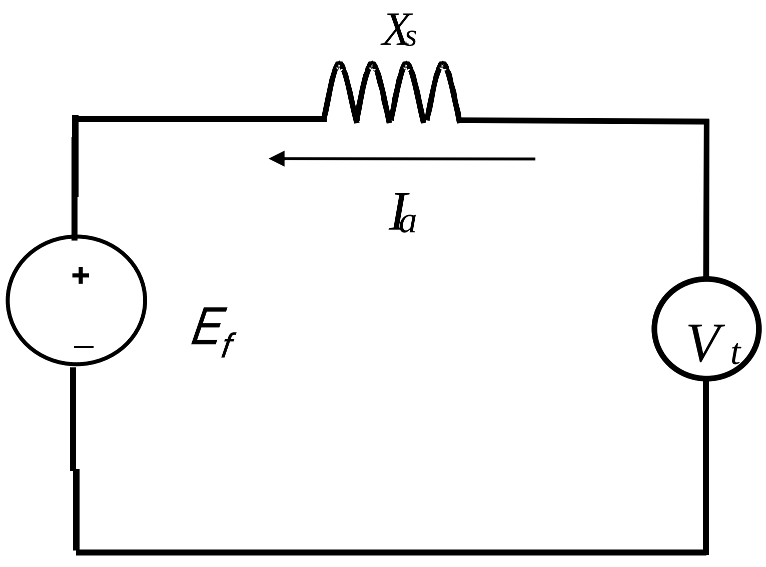


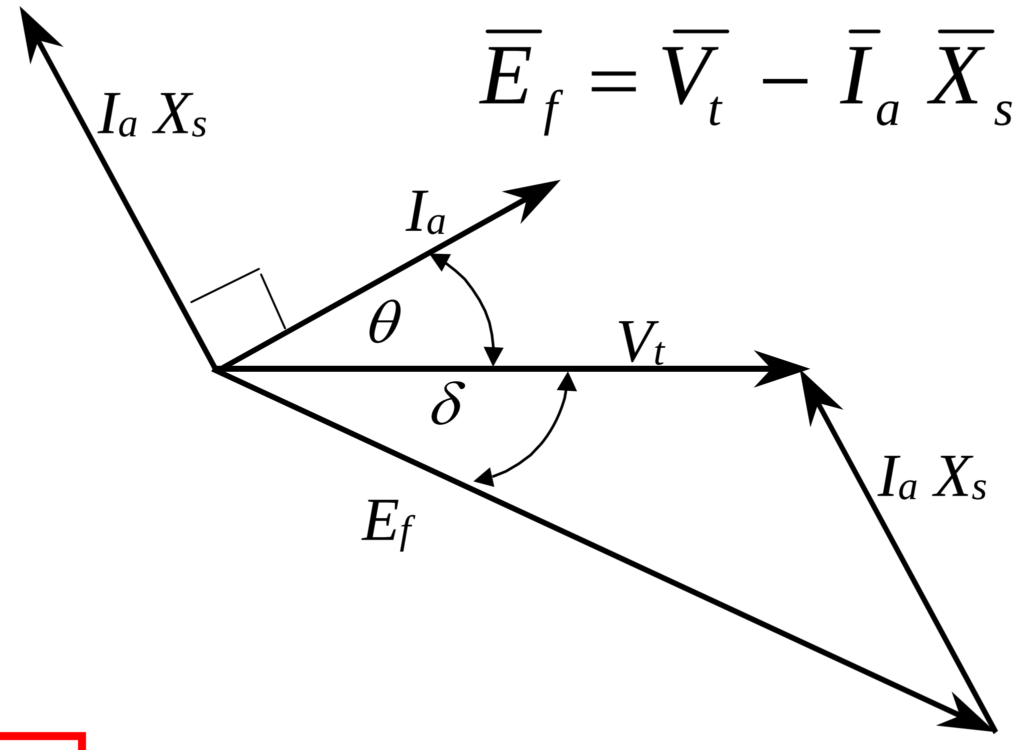
b-Leading power factor



Motor Equivalent Circuit

Leading power factor



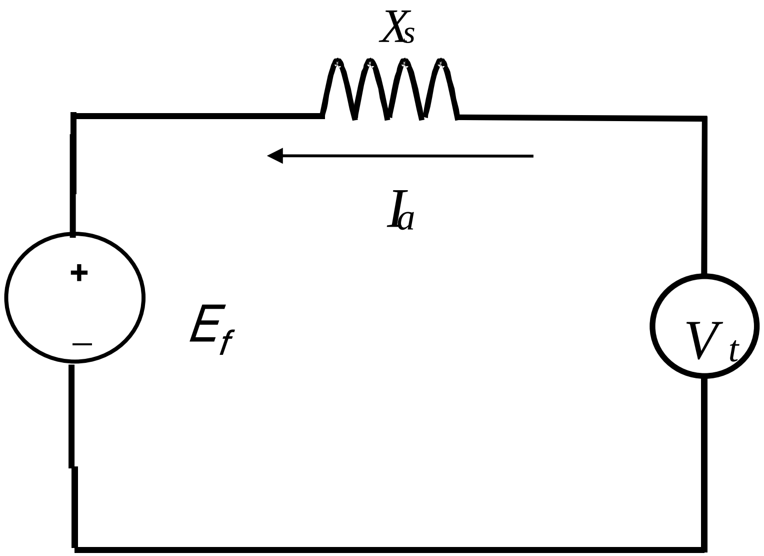


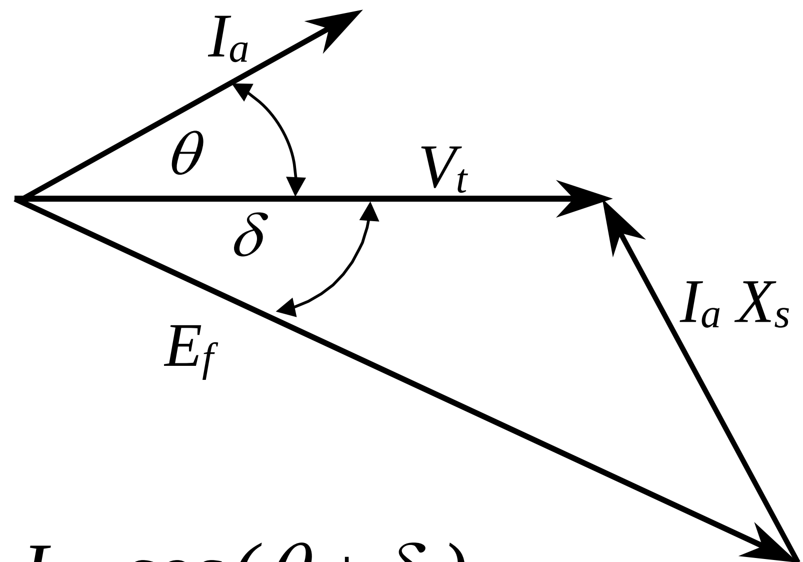
$$\bar{E}_f = \bar{V}_t - \bar{I}_a \bar{X}_s$$

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

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

Power equations





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

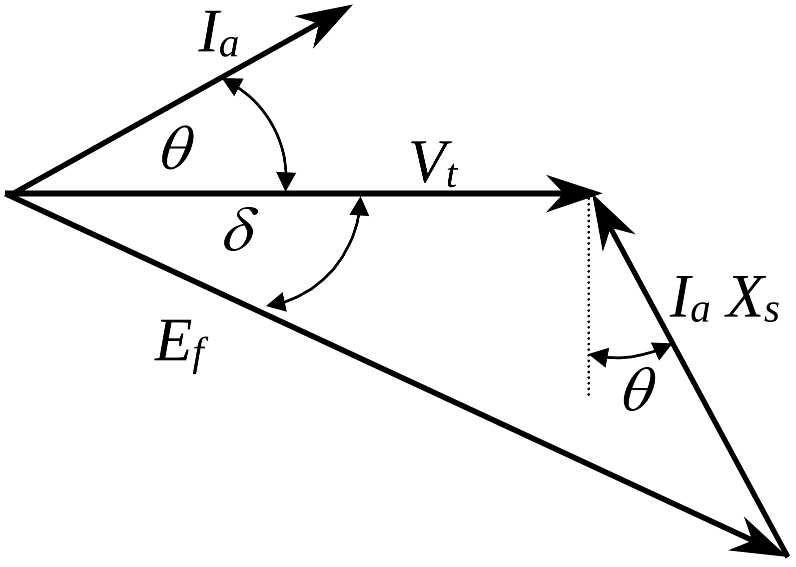
$$Q_t = 3 V_t I_a \sin\theta$$ ← **Reactive power at motor terminal**

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

Power equations

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

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

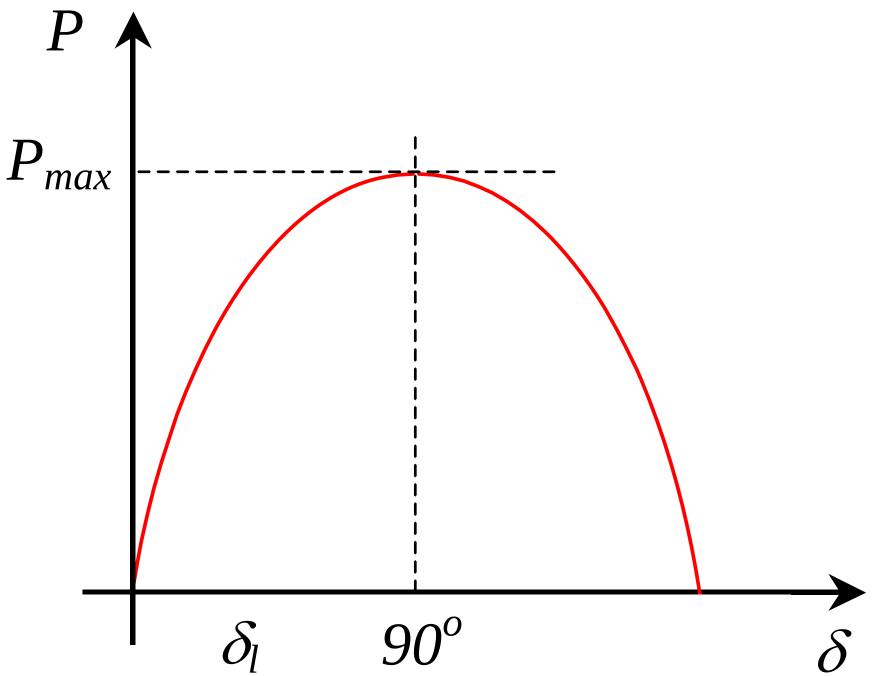


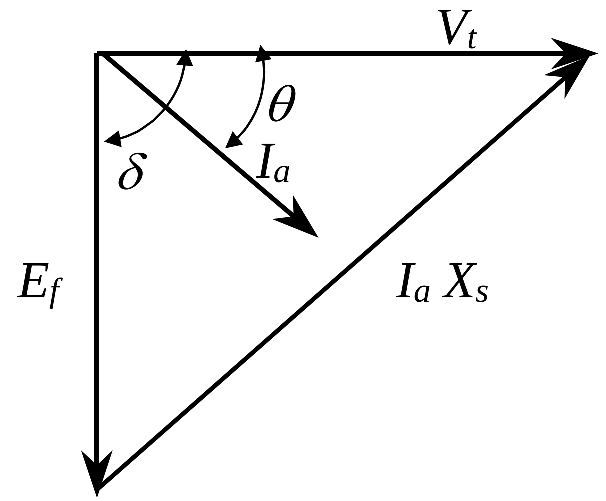
$$P = 3 V_t I_a \cos\theta$$

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

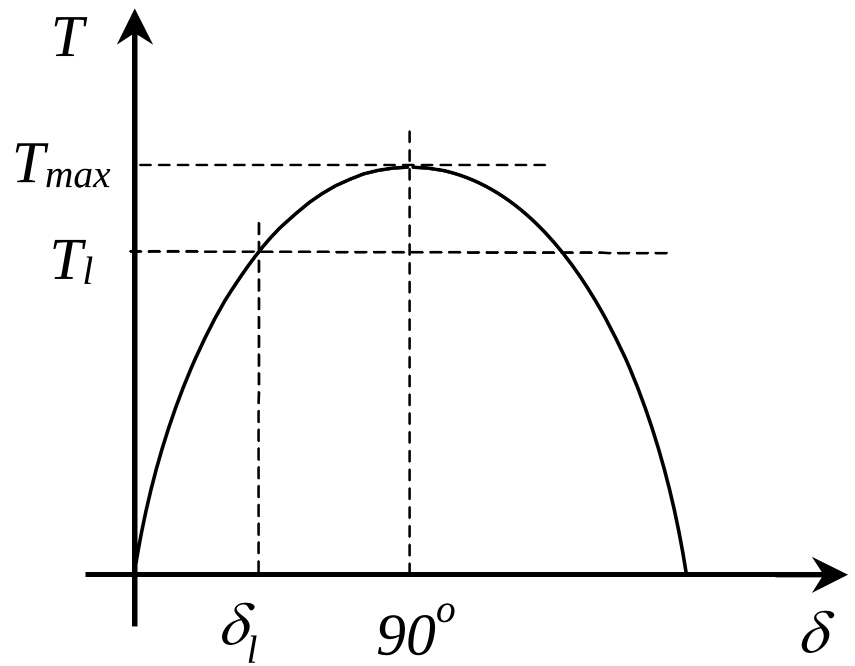
$$P_{max} = \frac{3 V_t E_f}{X_s}$$

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 $\delta = 90^0$:

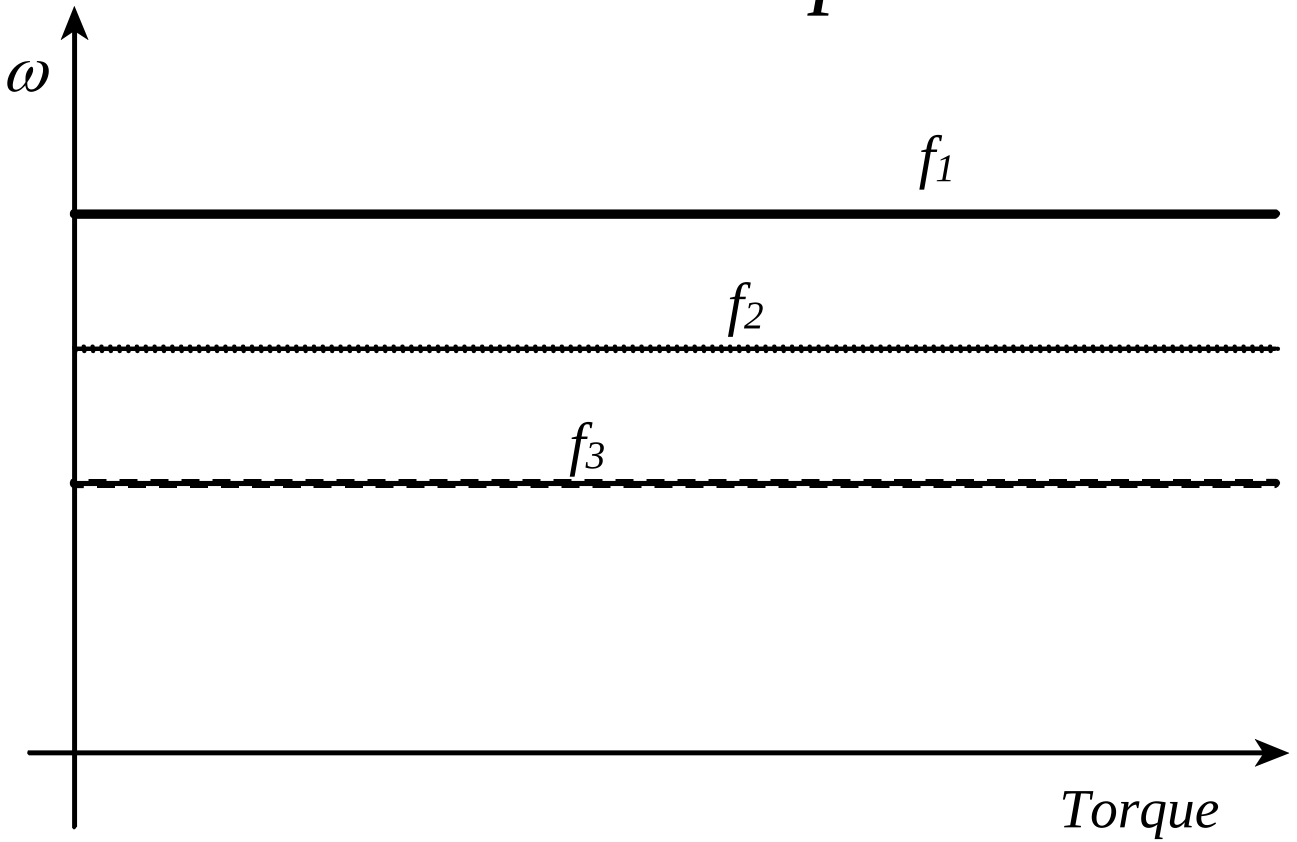
$$T_{\max} = kB_R B_{net} = \frac{3V_t E_f}{\omega_s X_s}$$

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

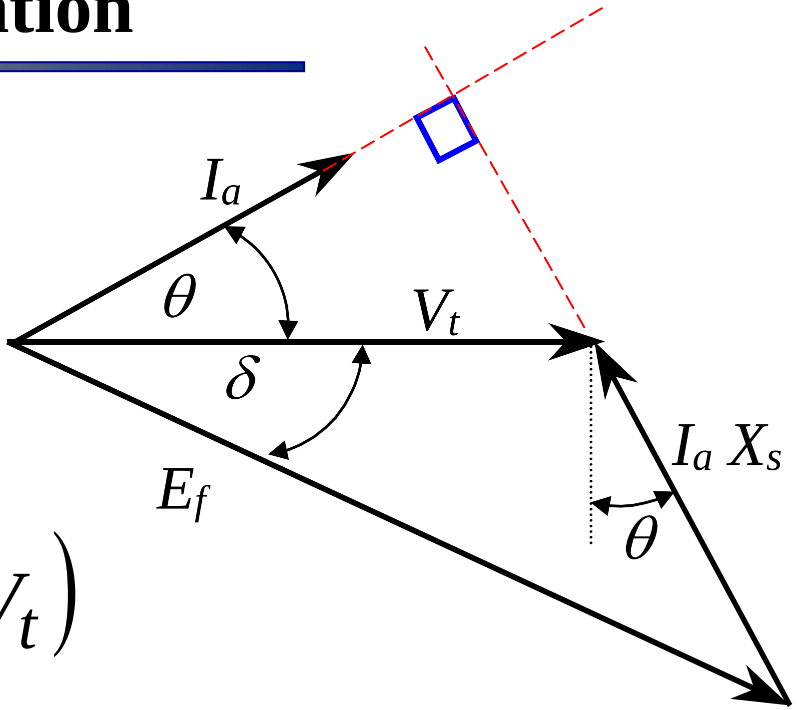
When the torque on the shaft of a synchronous motor exceeds the pullout torque, the rotor can no longer remain locked to the stator and net magnetic fields. It starts to slip behind them. As the motor slows down, the stator magnetic field "laps" it repeatedly, and the direction of the induced torque 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



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

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

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

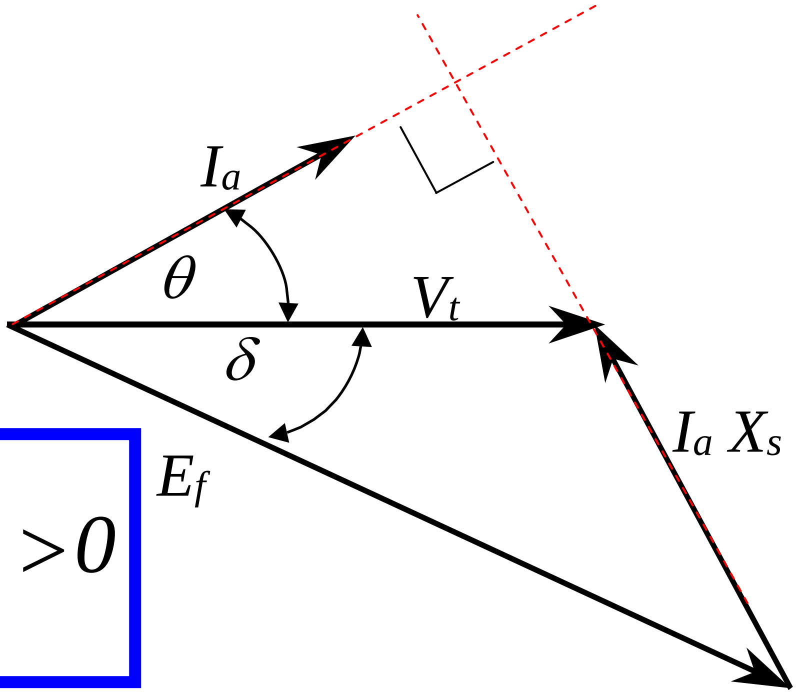
$$Q = \frac{3 V_t}{X_s}\left[E_f \cos\delta - V_t \right]$$

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

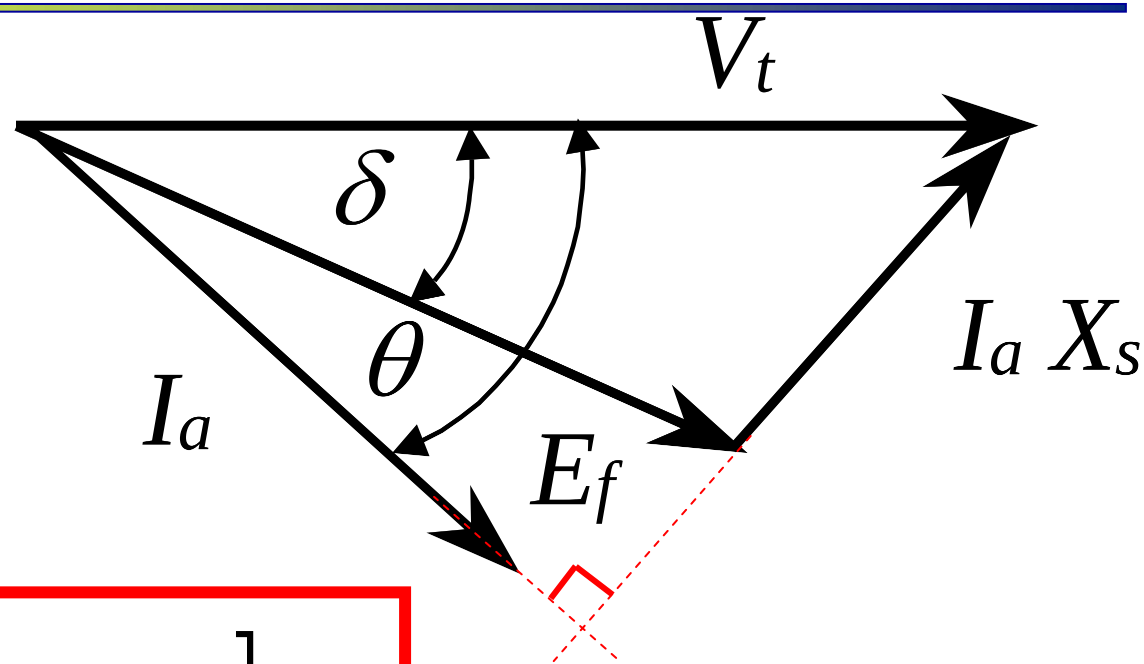
Main conclusions of over excited machines

SM delivers reactive power to source

Under Excited Motor

Adjust I_f until

$$E_f \cos\delta < V_t$$



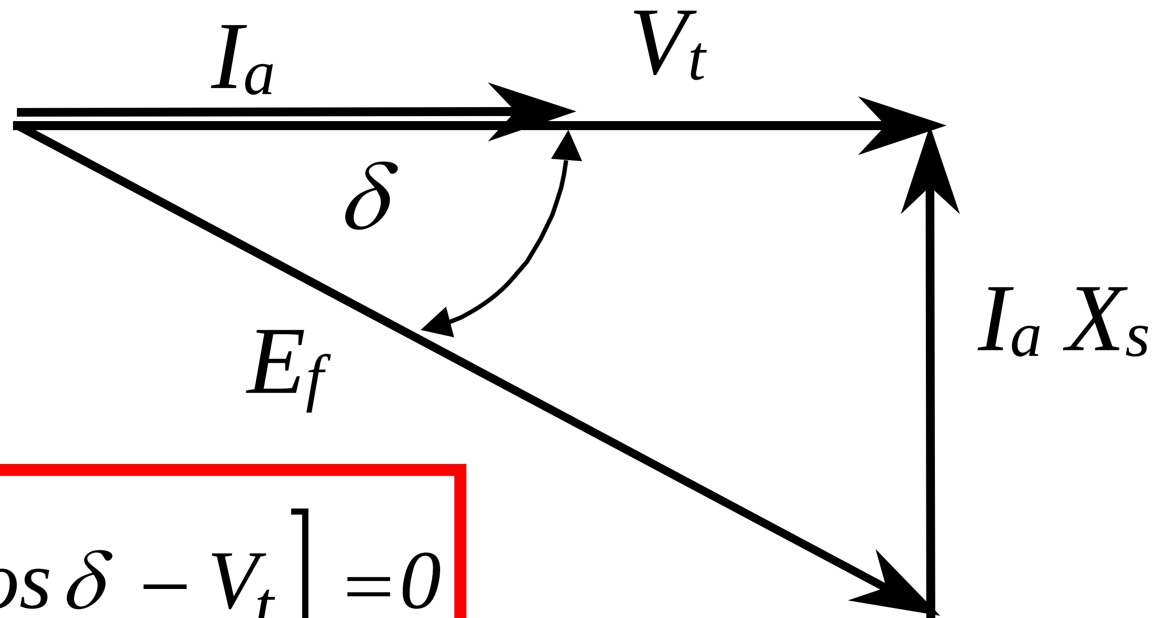
$$Q = \frac{3\,V_t}{X_s}\left[\,E_f\ \cos\delta - V_t\right] < 0$$

I_a Lags V_t

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

Exact Excitation

Adjust I_f until



$$E_f \cos\delta = V_t$$

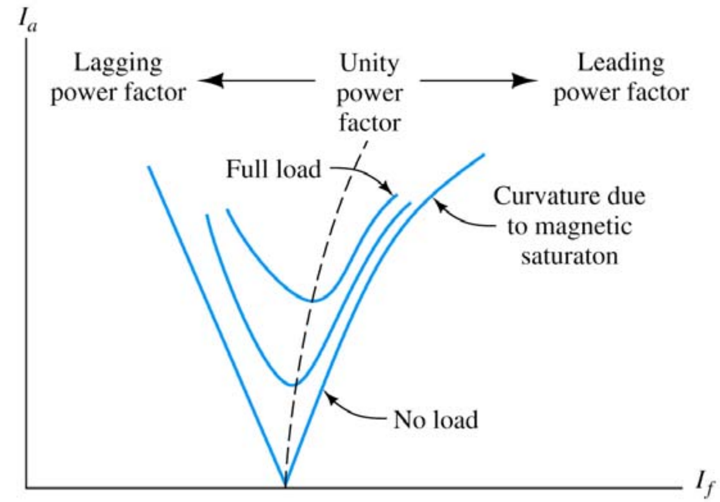
$$Q = \frac{3V_t}{X_s}\left[E_f \cos\delta - V_t\right] = 0$$

I_a in phase with V_t

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

Effect of 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.



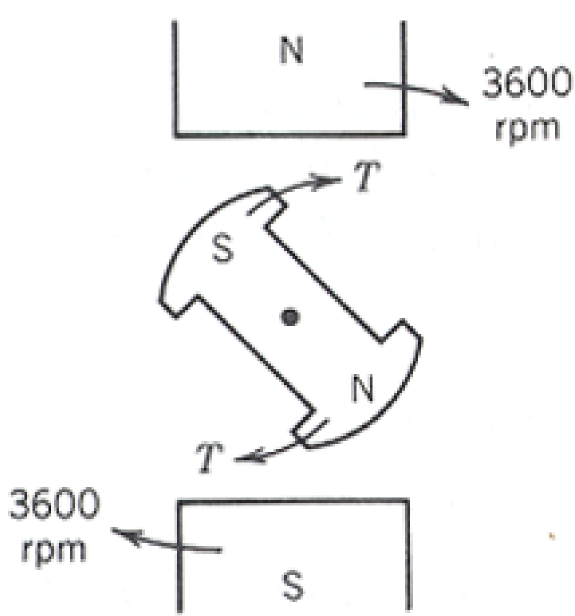
V curves for a synchronous motor with variable excitation.

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

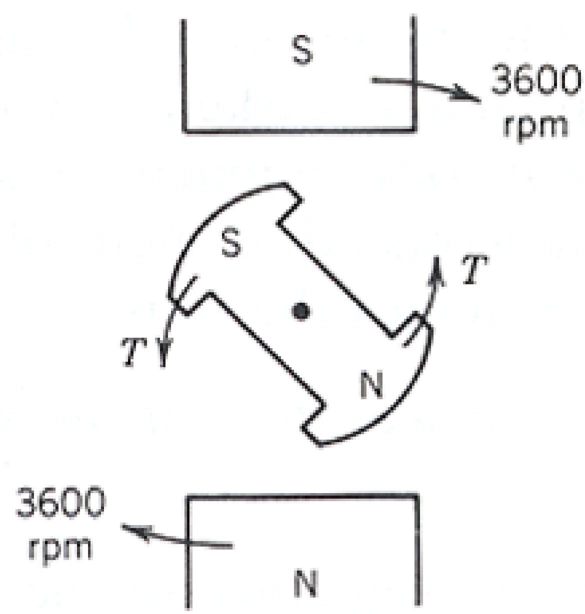
Starting of Synchronous Motors

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 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).

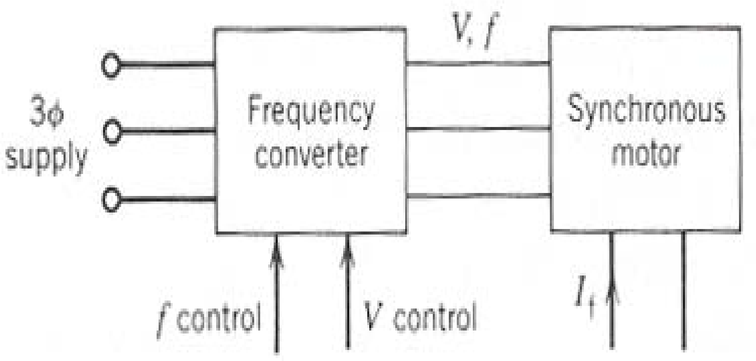
2.Use an external prime mover to accelerate the synchronous motor up to synchronous speed, go through the paralleling procedure, and bring the machine on the line as a generator. Next, turning off the prime mover will make the synchronous machine a motor.

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.

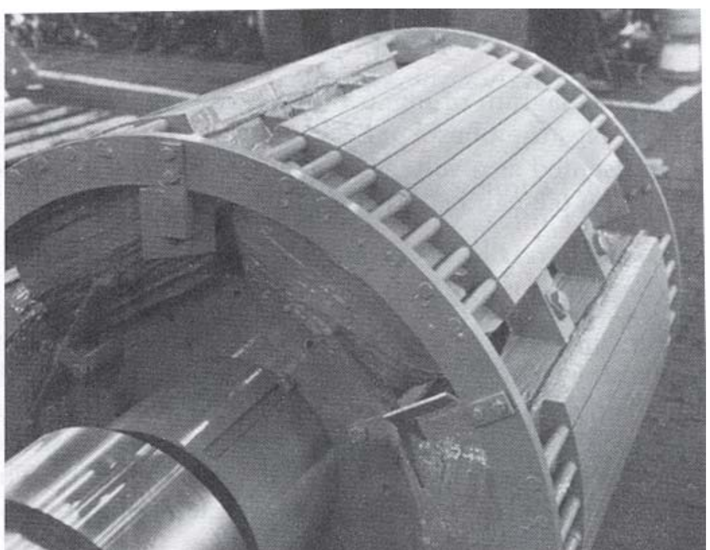


- The motor is started with a low-frequency supply. This will make the stator field rotate slowly so that the rotor poles can follow stator ones. Afterward, the frequency is gradually increased and the motor brought to its desired speed.
- The frequency converter is a costly power conditioning unit,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

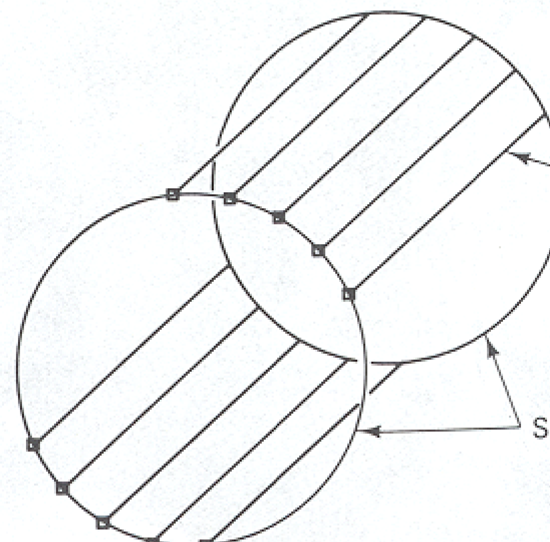
Starting Synchronous Motors

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.