POWER POINT PRESENTATION
ON
AC MACHINES

IV Semester (IARE-R16)

Prepared

By

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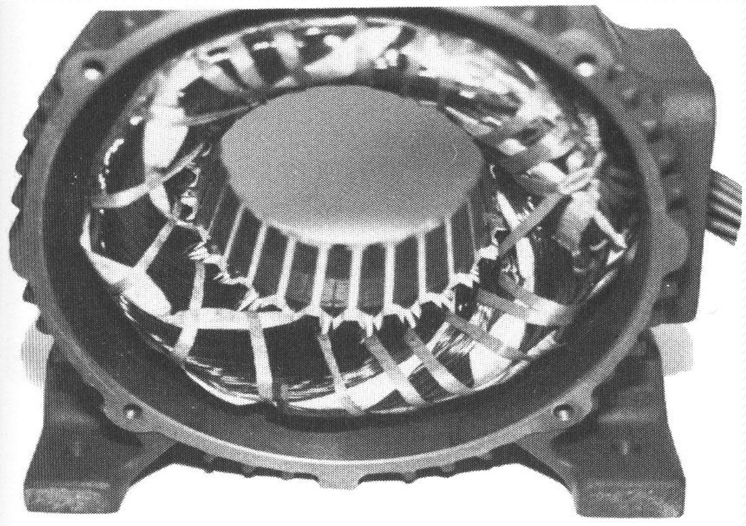
UNIT -I
Poly phase Induction motors

Construction

- An induction motor has two main parts
  - a stationary stator
    - consisting of a steel frame that supports a hollow, cylindrical core
    - core, constructed from stacked laminations (why?), having a number of evenly spaced slots, providing the space for the stator winding



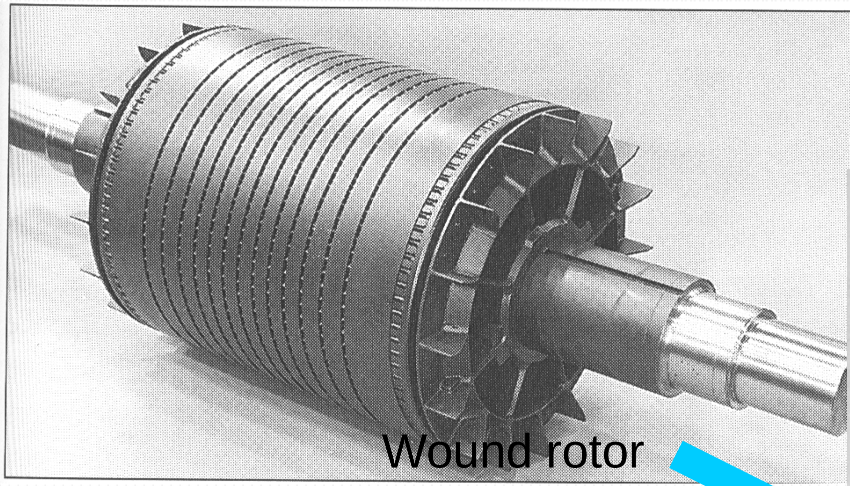
Stator of IM

Construction

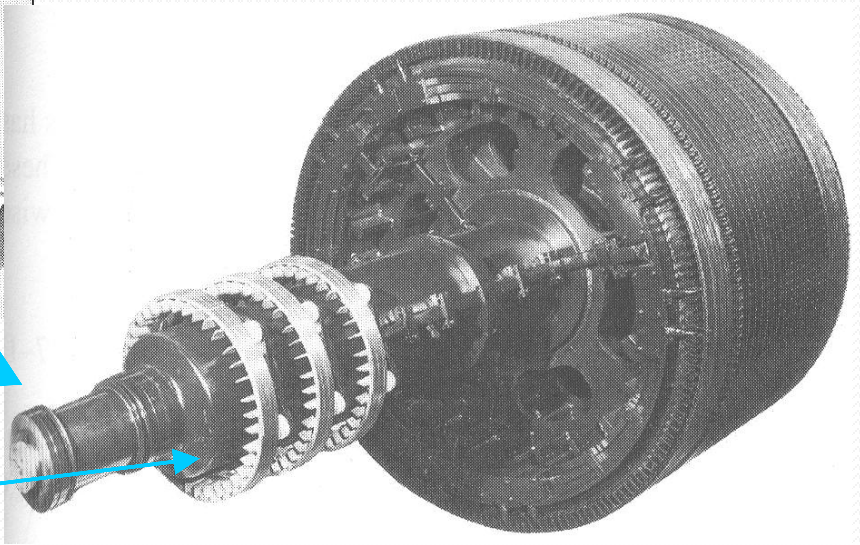
  - a revolving rotor
    - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
    - one of two types of rotor windings
    - conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
    - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)
- Two basic design types depending on the rotor design
  - squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.
  - wound-rotor: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.

Construction

Squirrel cage rotor



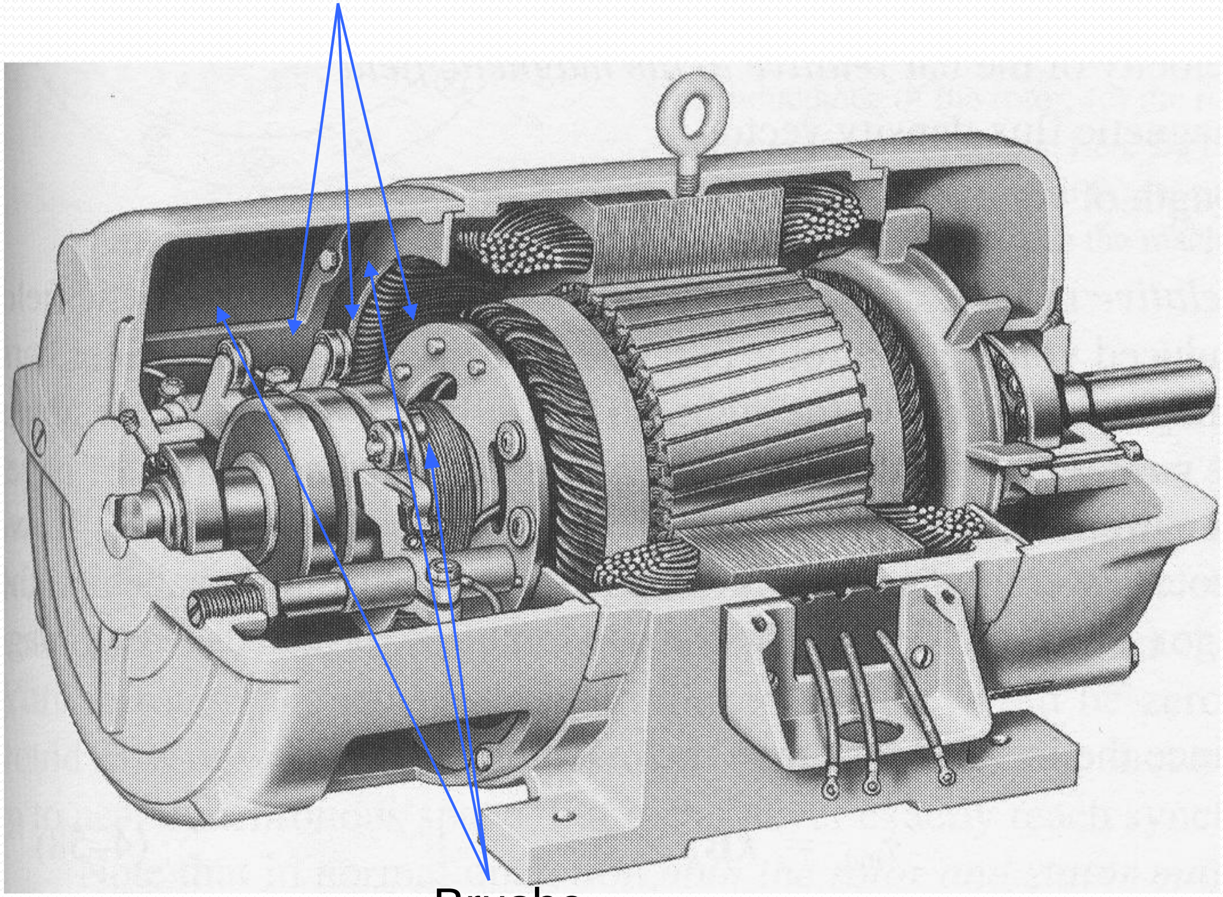
Wound rotor



Notice the
slip rings

Construction

Slip rings



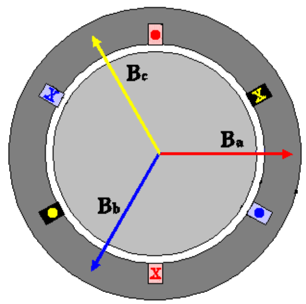
Brushes

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

Rotating Magnetic Field

- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$\boxed{n_{sync} = \frac{120 f_e}{P} \quad rpm}$$



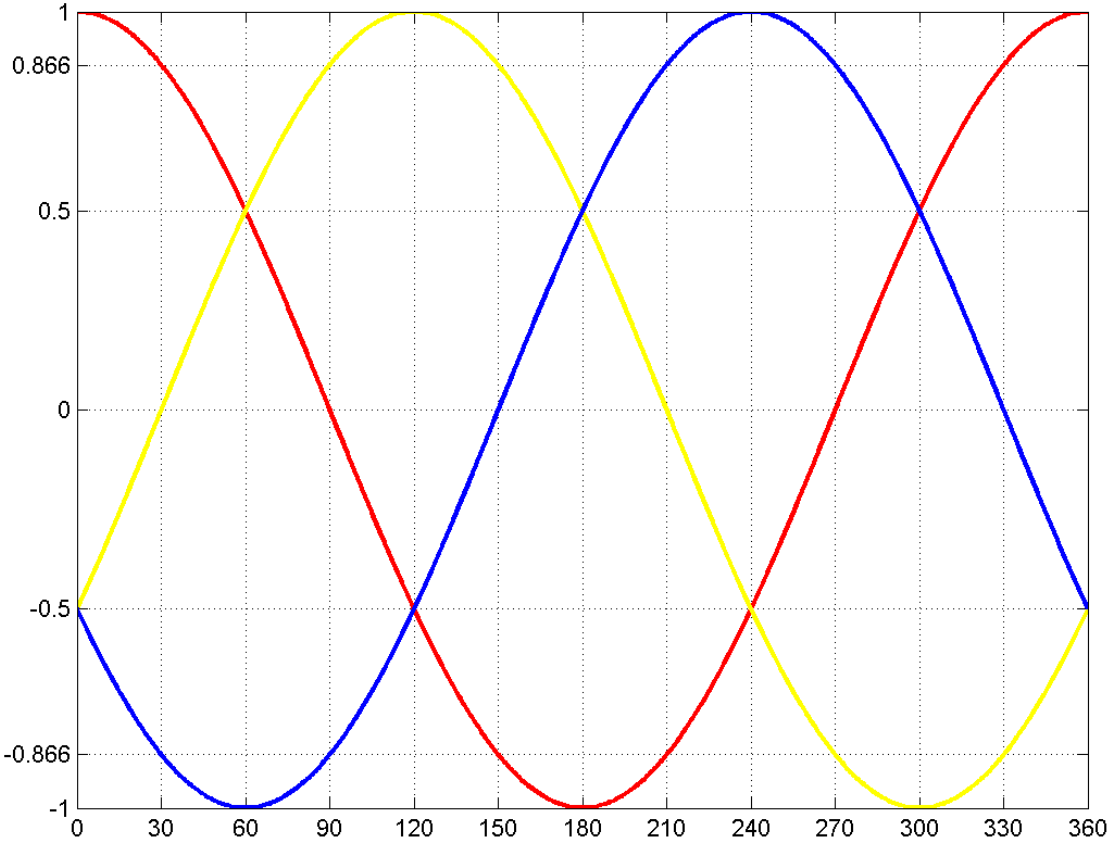
Where f_e is the supply frequency and

P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)

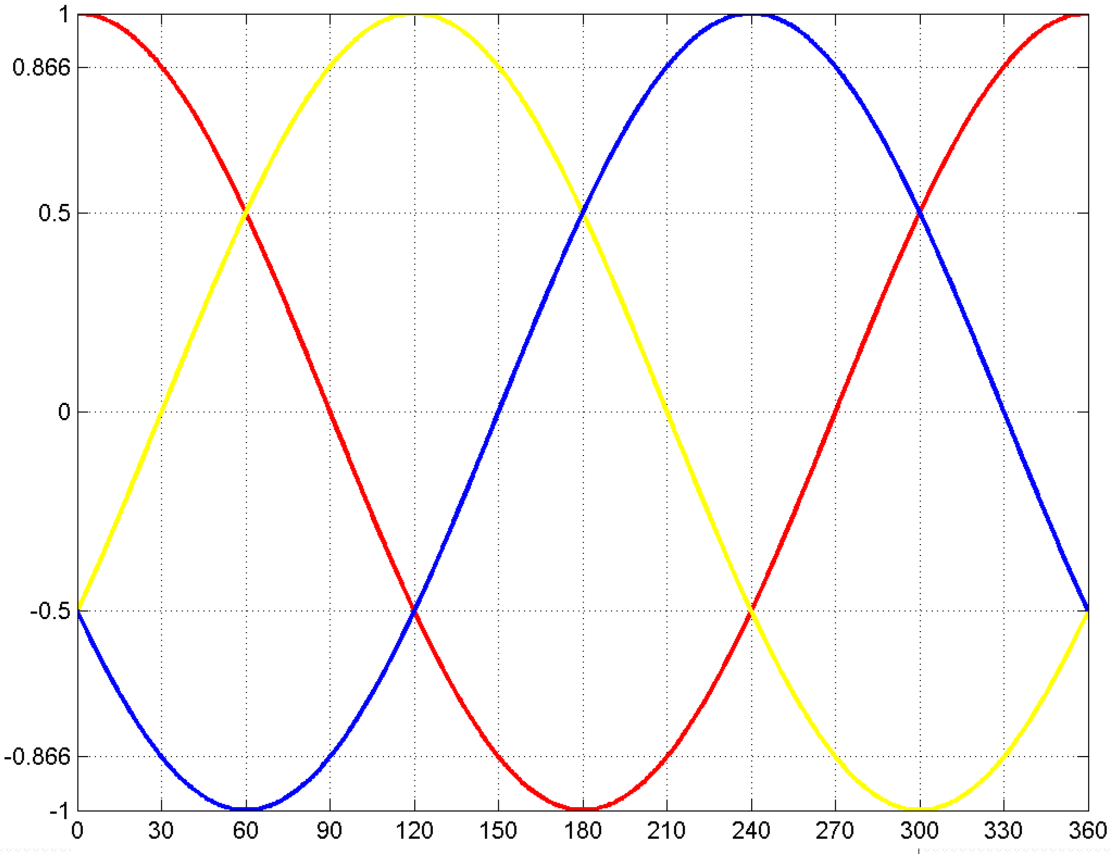
Synchronous speed

P	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

Rotating Magnetic Field



Rotating Magnetic Field



Rotating Magnetic Field

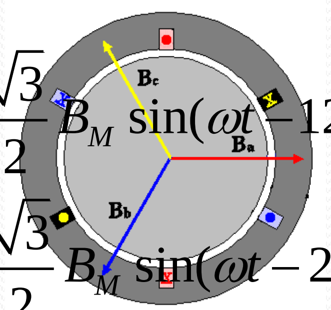
$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

$$= B_M \sin(\omega t)\angle 0^\circ + B_M \sin(\omega t - 120^\circ)\angle 120^\circ + B_M \sin(\omega t - 240)\angle 240^\circ$$

$$= B_M \sin(\omega t)\hat{\mathbf{x}}$$

$$-[0.5B_M \sin(\omega t - 120^\circ)]\hat{\mathbf{x}} - [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 120^\circ)]\hat{\mathbf{y}}$$

$$-[0.5B_M \sin(\omega t - 240^\circ)]\hat{\mathbf{x}} + [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240^\circ)]\hat{\mathbf{y}}$$



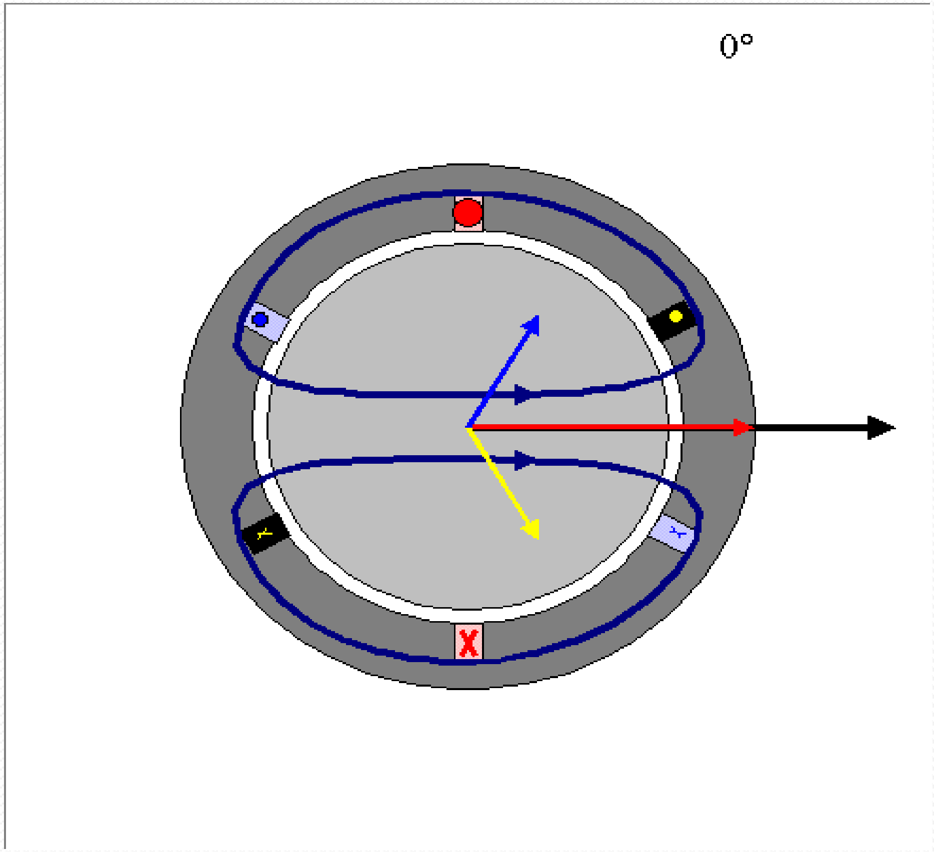
Rotating Magnetic Field

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

$$+[-\frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t) + \frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t)]\hat{\mathbf{y}}$$

$$= [1.5 B_M \sin(\omega t)]\hat{\mathbf{x}} - [1.5 B_M \cos(\omega t)]\hat{\mathbf{y}}$$

Rotating Magnetic Field



Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

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

Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction motor speed

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

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

Where n_{slip}= slip speed

n_{sync}= speed of the magnetic field

n_m = mechanical shaft speed of the motor

The Slip

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Where *s* is the *slip*

Notice that : if the rotor runs at synchronous speed

$s = 0$

if the rotor is stationary

$s = 1$

Slip may be expressed as a percentage by multiplying the above eq. by 100, notice that the slip is a ratio and doesn't have units

Frequency

- The frequency of the voltage induced in the rotor is given by

$$f_r = \frac{P \times n}{120}$$

Where f_r = the rotor frequency (Hz)

P = number of stator poles

n = slip speed (rpm)

$$f_r = \frac{P \times (n_s - n_m)}{120}$$

$$= \frac{P \times sn_s}{120} = sf_e$$

Frequency

- What would be the frequency of the rotor's induced voltage at any speed n_m?

$$\boxed{f_r = s\, f_e}$$

- When the rotor is blocked (s=1) , the frequency of the induced voltage is equal to the supply frequency
- On the other hand, if the rotor runs at synchronous speed (s = 0), the frequency will be zero

Torque

- While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power
- Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed

$$\boxed{\tau_{load} = \frac{P_{out}}{\omega_m} \quad N.m}$$

and

$$\boxed{\omega_m = \frac{2\pi n_m}{60} \quad rad/s}$$

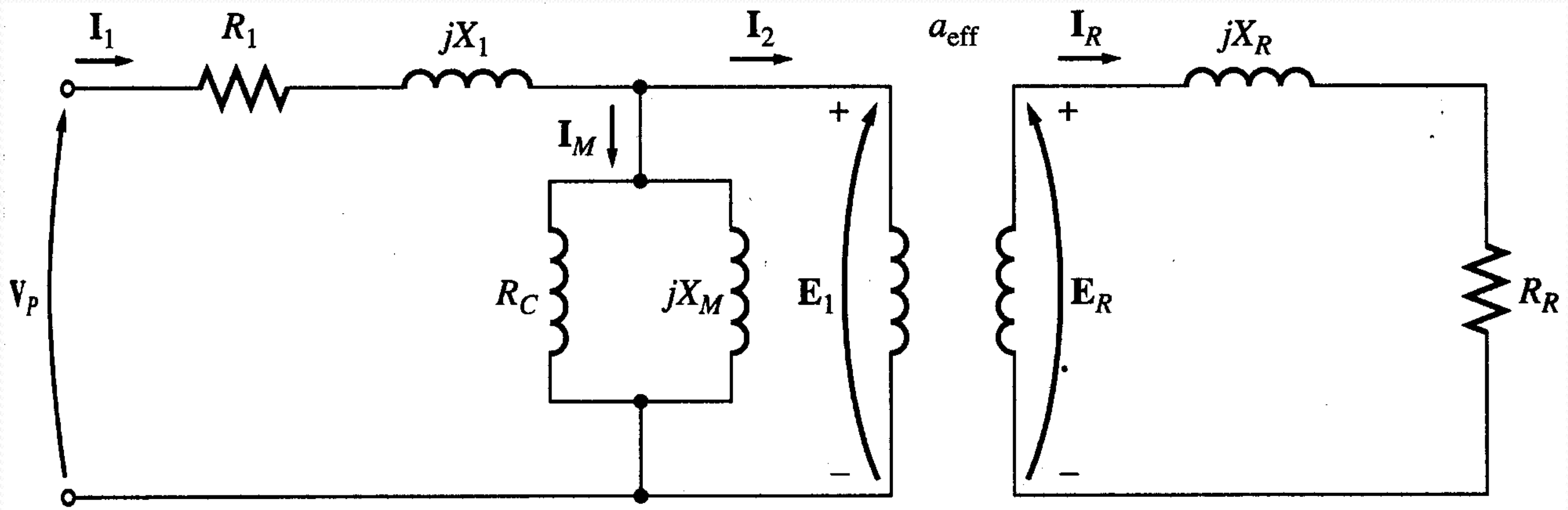
Horse power

- Another unit used to measure mechanical power is the horse power
- It is used to refer to the mechanical output power of the motor
- Since we, as an electrical engineers, deal with watts as a unit to measure electrical power, there is a relation between horse power and watts

$$\boxed{hp = 746\ watts}$$

Equivalent Circuit

- The induction motor is similar to the transformer with the exception that its secondary windings are free to rotate



combine these two circuits in one circuit but there are some difficulties

Equivalent Circuit

- When the rotor is locked (or blocked), i.e. s =1, the largest voltage and rotor frequency are induced in the rotor, Why?
- On the other side, if the rotor rotates at synchronous speed, i.e. s = 0, the induced voltage and frequency in the rotor will be equal to zero, Why?

$$\boxed{E_R = sE_{R0}}$$

Where E_{Ro} is the largest value of the rotor's induced voltage obtained at s = 1(loacked rotor)

Equivalent Circuit

- The same is true for the frequency, i.e.

$$\boxed{f_r = s\ f_e}$$

- It is known that

$$\boxed{X = \omega L = 2\pi f\ L}$$

- So, as the frequency of the induced voltage in the rotor changes, the reactance of the rotor circuit also changes

Where X_{ro} is the rotor reactance

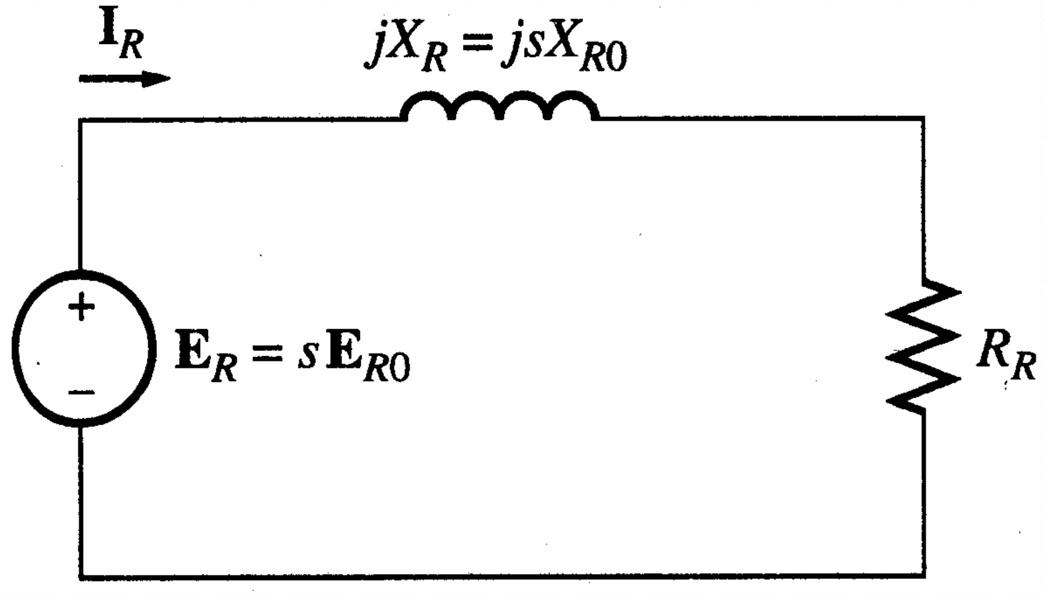
at the supply frequency

(at blocked rotor)

$$\boxed{\begin{aligned} X_r &= \omega_r L_r = 2\pi f_r\ L_r \\ &= 2\pi s f_e L_r \\ &= s X_{r0} \end{aligned}}$$

Equivalent Circuit

- Then, we can draw the rotor equivalent circuit as follows



Where E_R is the induced voltage in the rotor and R_R is the rotor resistance

Equivalent Circuit

- Now we can calculate the rotor current as

$$I_R = \frac{E_R}{(R_R + jX_R)}$$

$$= \frac{sE_{R0}}{(R_R + jsX_{R0})}$$

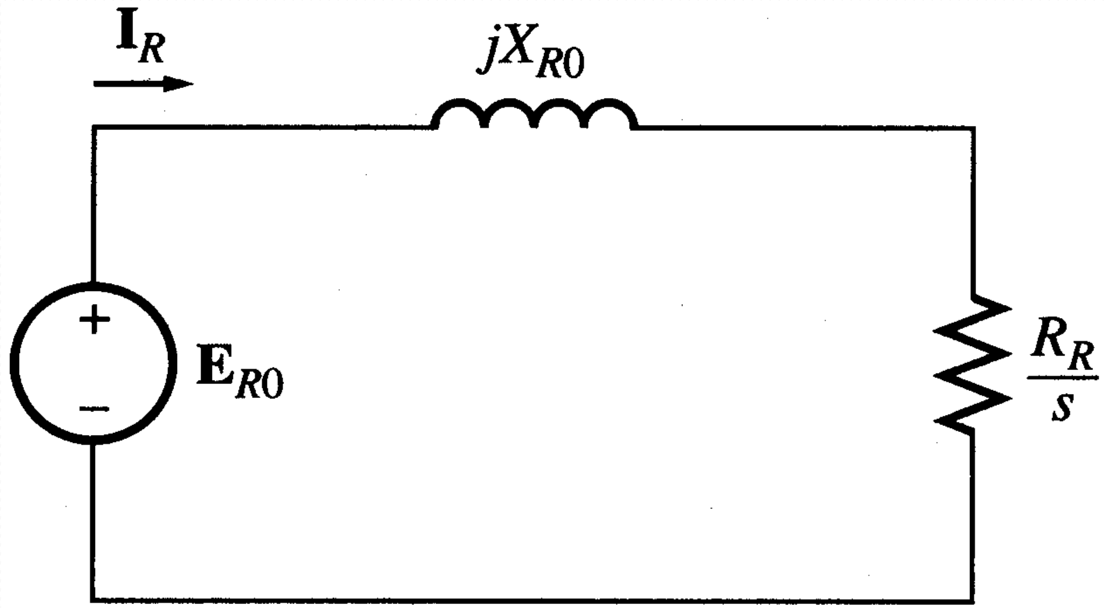
- Dividing both the numerator and denominator by *s* so nothing changes we get

$$\boxed{I_R = \frac{E_{R0}}{(\frac{R_R}{s} + jX_{R0})}}$$

Where E_{Ro} is the induced voltage and X_{Ro} is the rotor reactance at blocked rotor condition ($s = 1$)

Equivalent Circuit

- Now we can have the rotor equivalent circuit



Equivalent Circuit

- Now as we managed to solve the induced voltage and different frequency problems, we can combine the stator and rotor circuits in one equivalent circuit

Where

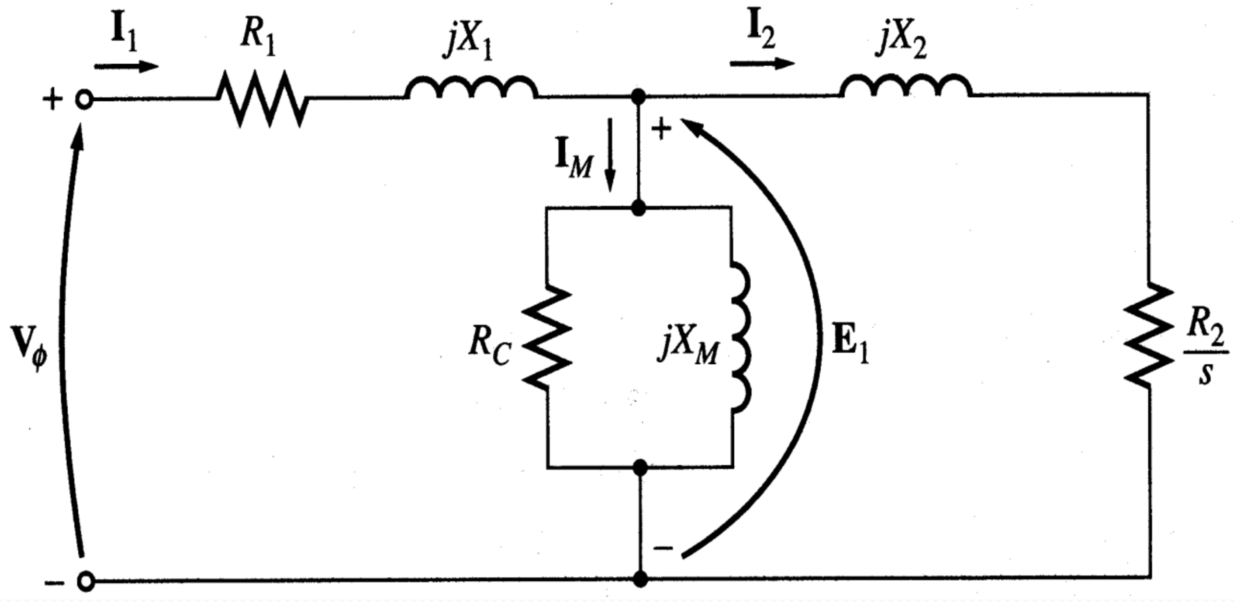
$$X_2 = a_{eff}^2 X_{R0}$$

$$R_2 = a_{eff}^2 R_R$$

$$I_2 = \frac{I_R}{a_{eff}}$$

$$E_1 = a_{eff} E_{R0}$$

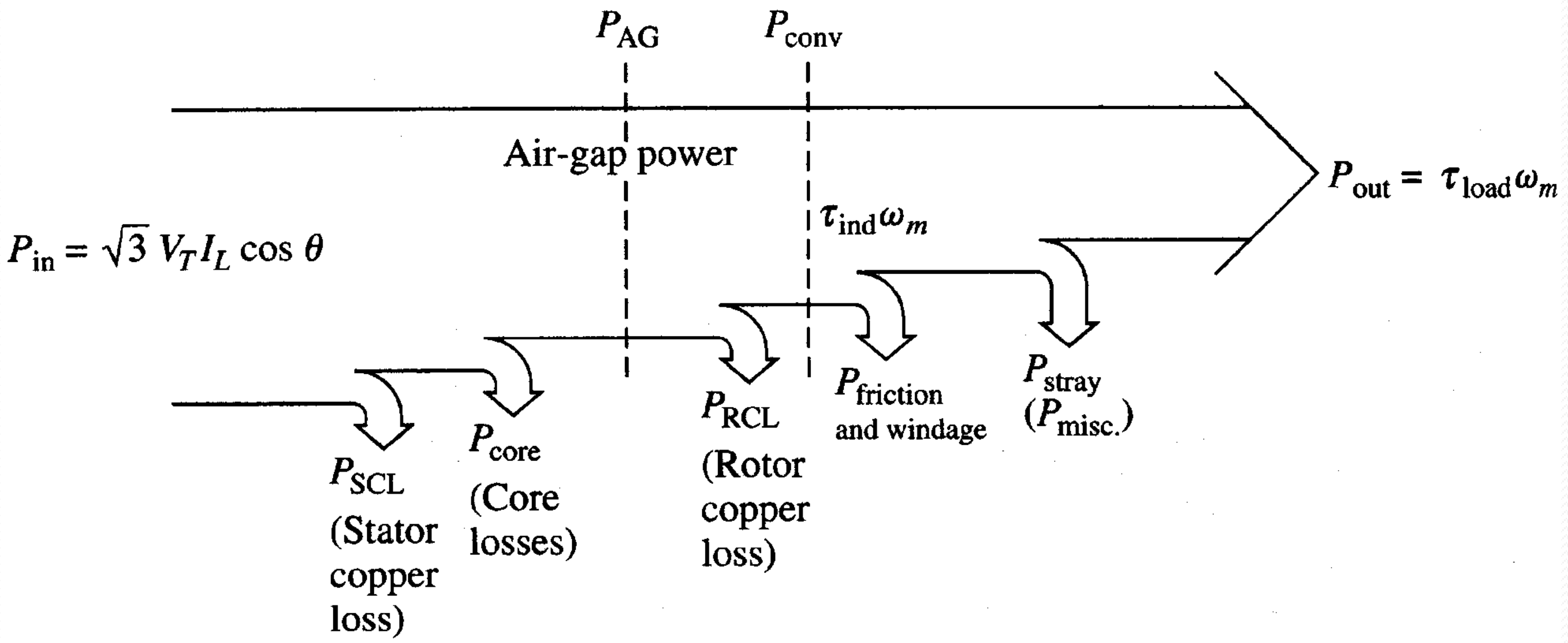
$$a_{eff} = \frac{N_S}{N_R}$$



Power losses in Induction machines

- Copper losses
  - Copper loss in the stator (P_{SCL}) = $I_1^2 R_1$
  - Copper loss in the rotor (P_{RCL}) = $I_2^2 R_2$
- Core loss (P_{core})
- Mechanical power loss due to friction and windage
- How this power flow in the motor?

Power flow in induction motor



Power relations

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3 V_{ph} I_{ph} \cos\theta$$

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

$$P_{AG} = P_{in} - (P_{SCL} + P_{core})$$

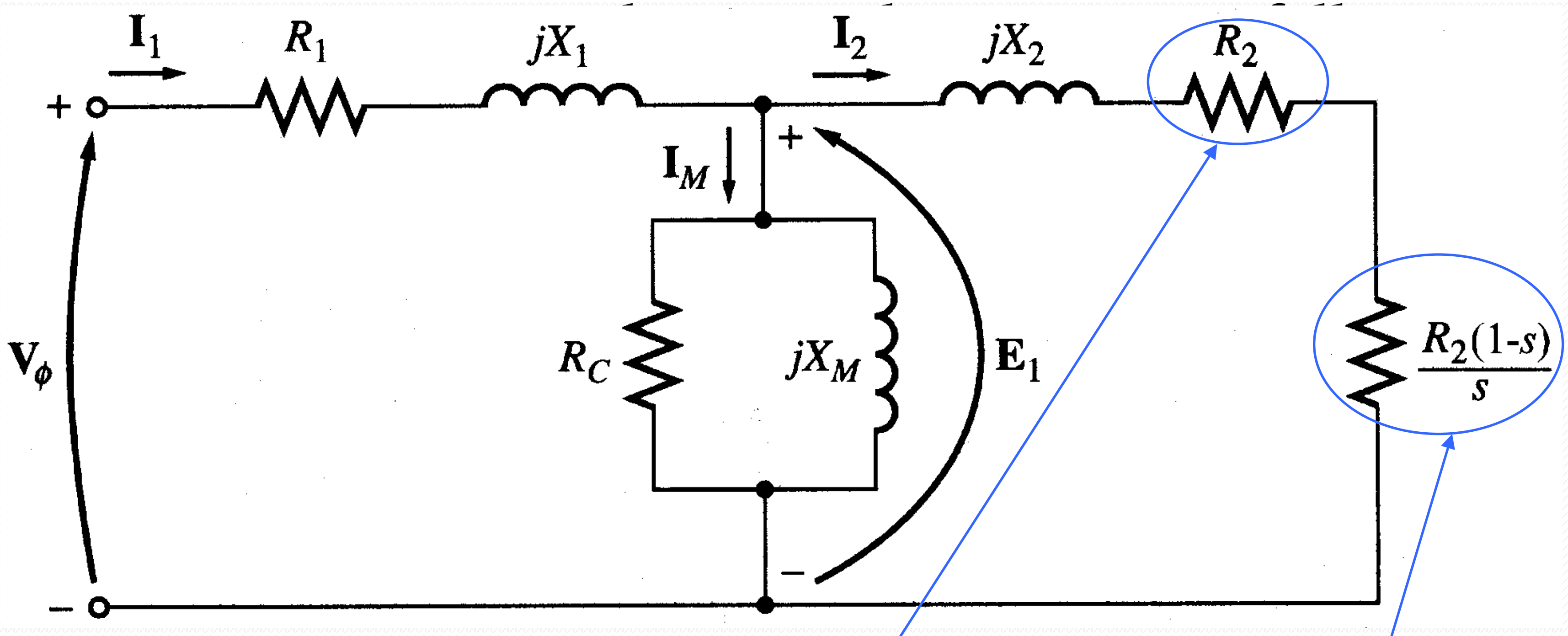
$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

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

Equivalent Circuit



Actual rotor resistance

Resistance equivalent to mechanical load

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3\, V_{ph} I_{ph} \cos\theta$$

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

$$P_{AG} = P_{in} - (P_{SCL} + P_{core}) \quad = P_{conv} + P_{RCL} \quad = 3I_2^2 \frac{R_2}{s} \quad = \frac{P_{RCL}}{s}$$

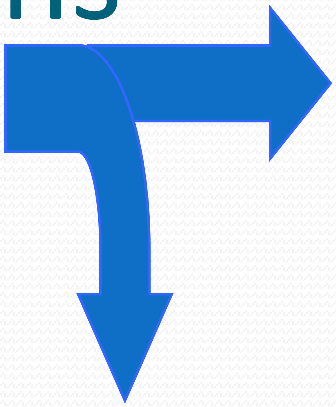
$$P_{RCL} = 3I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL} \quad = 3I_2^2 \frac{R_2(1-s)}{s} \quad = \frac{P_{RCL}(1-s)}{s}$$

$$P_{conv} = (1-s)P_{AG}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \qquad \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s)P_{AG}}{(1-s)\omega_s}$$

Power relations



P_{AG}

1

P_{conv}

1-s

P_{RCL}

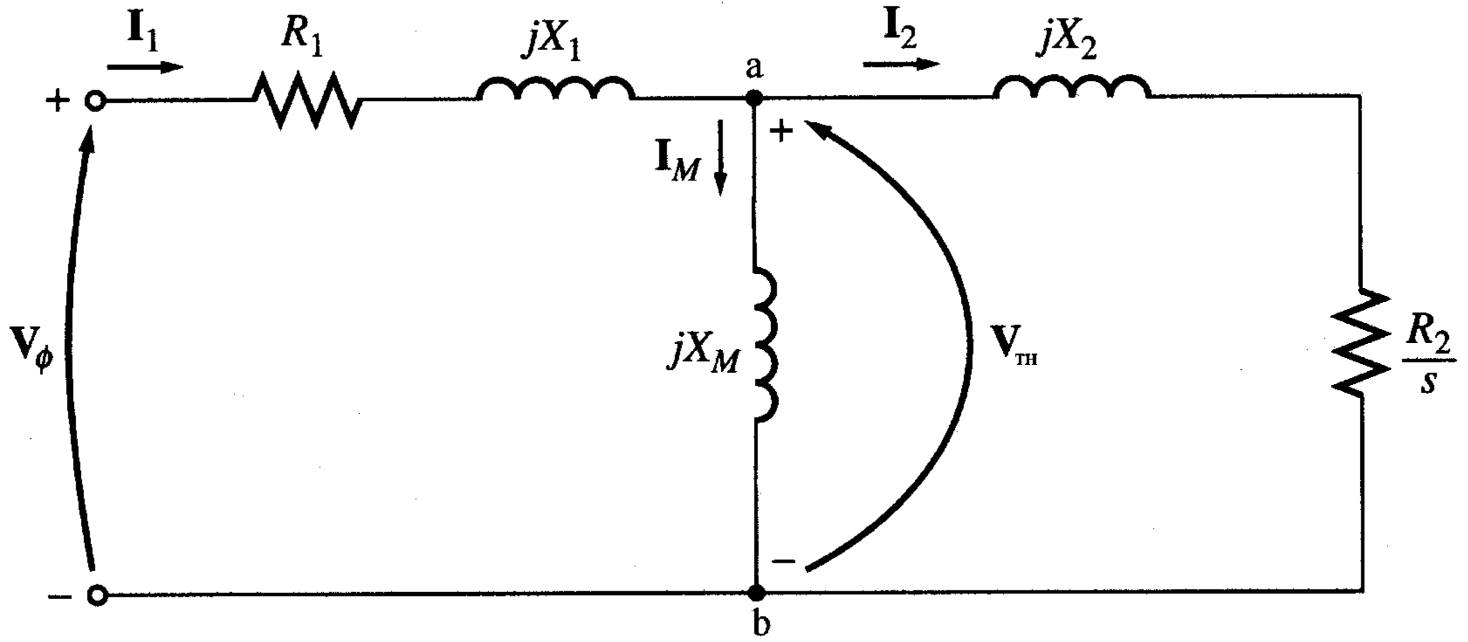
s

$$P_{AG} : P_{RCL} : P_{conv}$$

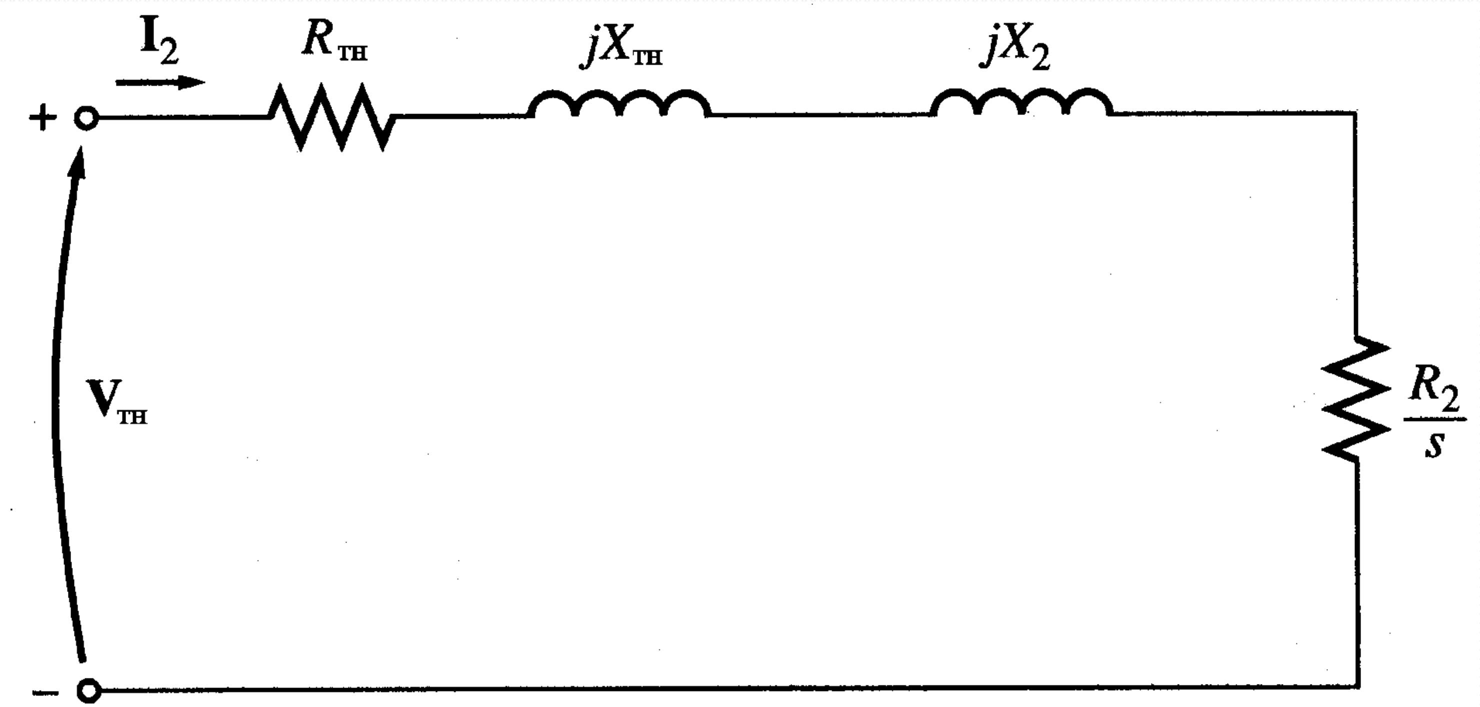
$$1 : s : 1\text{-}s$$

Torque, power and Thevenin’s Theorem

- Thevenin’s theorem can be used to transform the network to the left of points ‘a’ and ‘b’ into an equivalent voltage source V_{TH} in series with equivalent im



Torq



$$V_{TH} = V_{\phi} \frac{jX_M}{R_1 + j(X_1 + X_M)} \qquad |V_{TH}| = |V_{\phi}| \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}}$$

$$R_{TH} + jX_{TH} = (R_1 + jX_1) // jX_M$$

Torque, power and Thevenin’s Theorem

- Since $X_M >> X_1$ and $X_M >> R_1$

$$\boxed{V_{TH} \approx V_\phi \frac{X_M}{X_1 + X_M}}$$

- Because $X_M >> X_1$ and $X_M + X_1 >> R_1$

$$R_{TH} \approx R_1 \left(\frac{X_M}{X_1 + X_M} \right)^2$$

$$X_{TH} \approx X_1$$

Torque, power and Thevenin’s Theorem

$$I_2 = \frac{V_{TH}}{Z_T} = \frac{V_{TH}}{\sqrt{\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2}}$$

Then the power converted to mechanical (P_{conv})

$$P_{conv} = 3I_2^2 \frac{R_2(1-s)}{s}$$

And the internal mechanical torque (T_{conv})

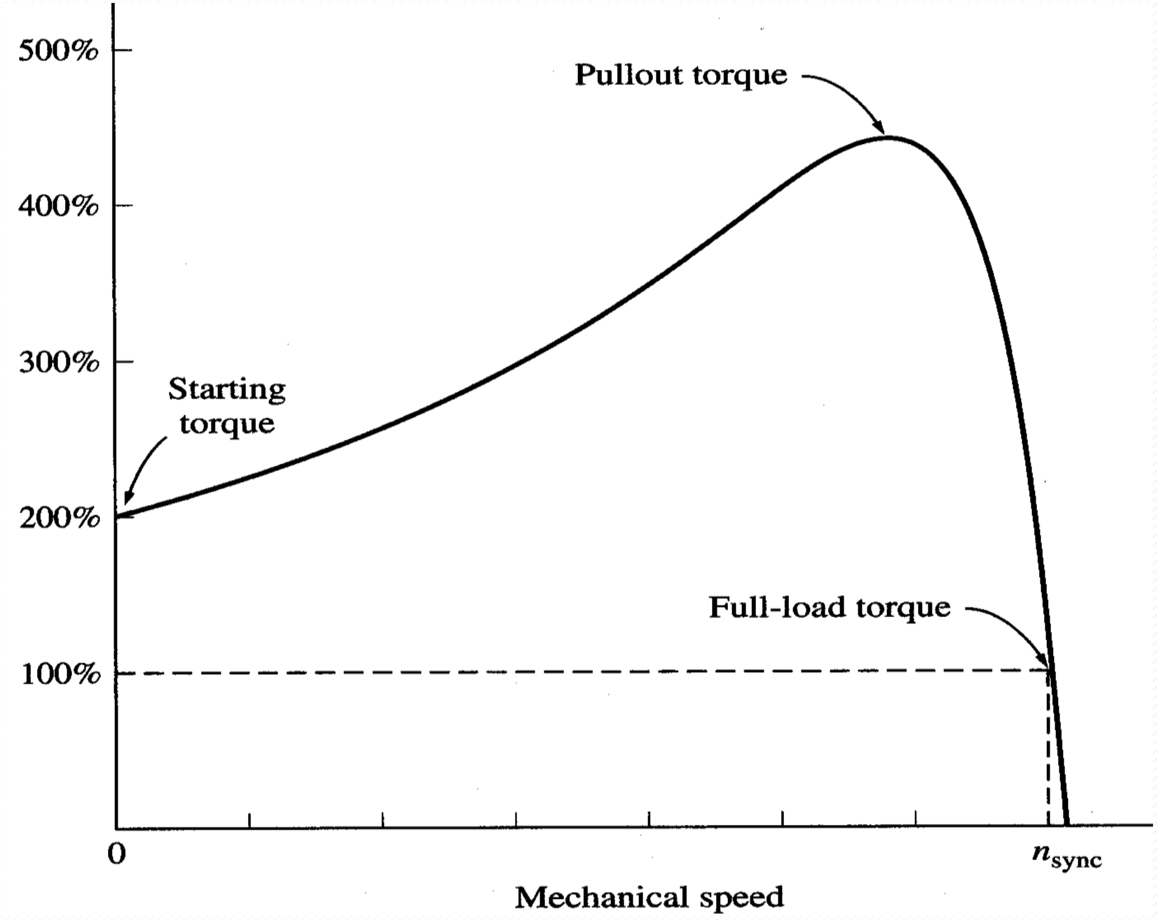
$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{conv}}{(1-s)\omega_s} = \frac{3I_2^2 \frac{R_2}{s}}{\omega_s} = \frac{P_{AG}}{\omega_s}$$

Torque, power and Thevenin's Theorem

$$\tau_{ind} = \frac{3}{\omega_s}\left(\frac{V_{TH}}{\sqrt{\left(R_{TH}+\frac{R_2}{s}\right)^2+(X_{TH}+X_2)^2}}\right)^2\left(\frac{R_2}{s}\right)$$

$$\boxed{\tau_{ind} = \frac{1}{\omega_s}\frac{3V_{TH}^2\left(\frac{R_2}{s}\right)}{\left(R_{TH}+\frac{R_2}{s}\right)^2+(X_{TH}+X_2)^2}}$$

Torque-speed characteristics



Typical torque-speed characteristics of induction motor

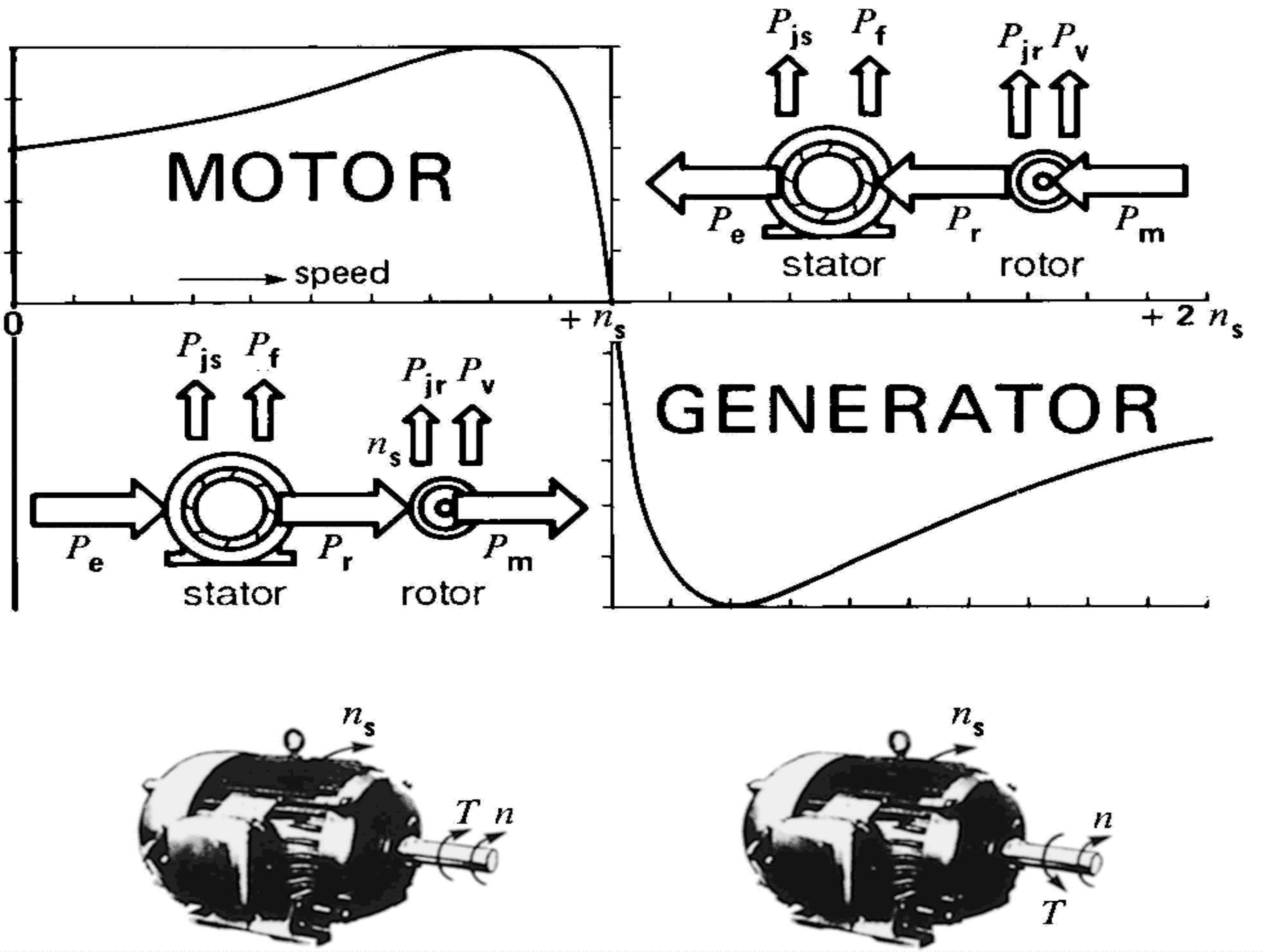
Comments

1. The induced torque is zero at synchronous speed. Discussed earlier.
2. The curve is nearly linear between no-load and full load. In this range, the rotor resistance is much greater than the reactance, so the rotor current, torque increase linearly with the slip.
3. There is a maximum possible torque that can’t be exceeded. This torque is called *pullout torque* and is 2 to 3 times the rated full-load torque.

Comments

4. The starting torque of the motor is slightly higher than its full-load torque, so the motor will start carrying any load it can supply at full load.
5. The torque of the motor for a given slip varies as the square of the applied voltage.
6. If the rotor is driven faster than synchronous speed it will run as a generator, converting mechanical power to electric power.

Complete Speed-torque c/c



Maximum torque

- Maximum torque occurs when the power transferred to R_2/s is maximum.
- This condition occurs when R_2/s equals the magnitude of the impedance $R_{TH} + j\,(X_{TH} + X_2)$

$$\frac{R_2}{s_{T_{\max}}} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}$$

$$\boxed{s_{T_{\max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}}$$

Maximum torque

- The corresponding maximum torque of an induction motor equals

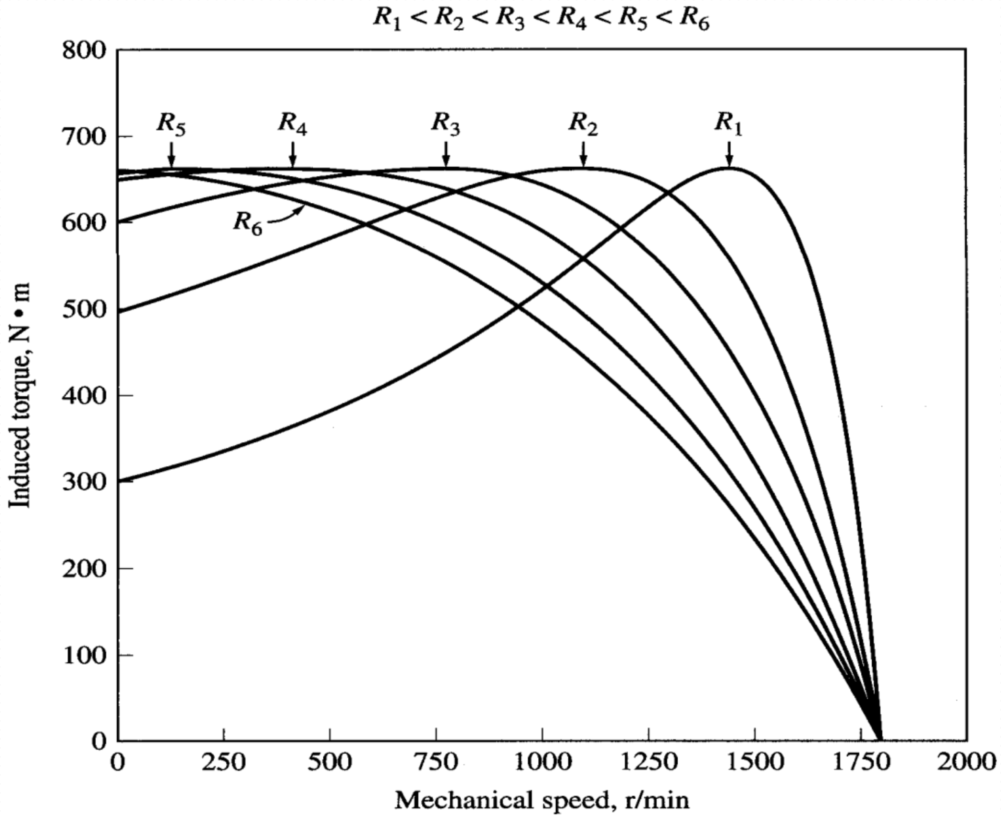
$$\boxed{\tau_{\max} = \frac{1}{2\omega_s}\left(\frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}\right)}$$

The slip at maximum torque is directly proportional to the rotor resistance R_2

The maximum torque is independent of R_2

Maximum torque

- Rotor resistance can be increased by inserting external resistance in the rotor of a wound-rotor induction motor. The value of the maximum torque remains unaffected but the speed at which it occurs can be controlled.



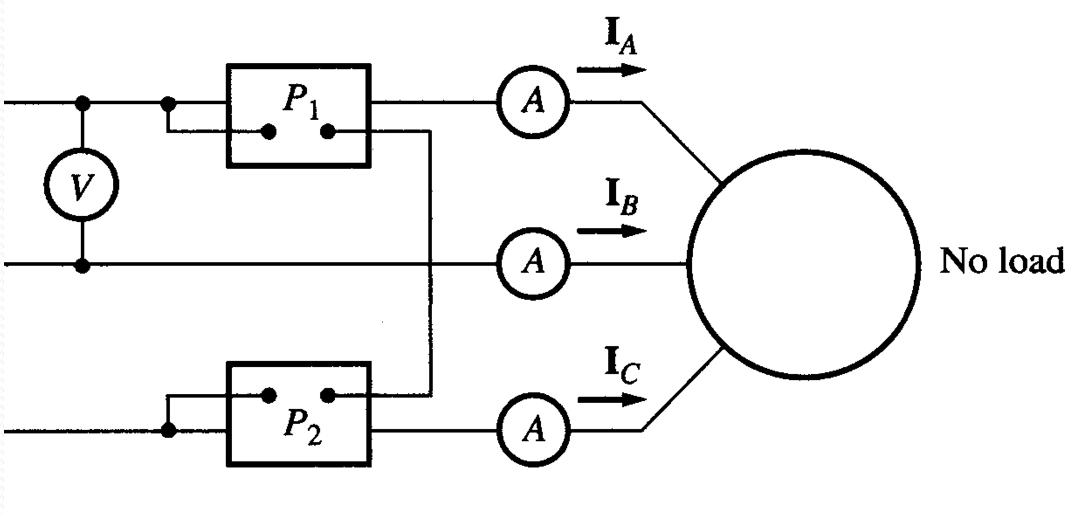
Determination of motor parameters

- Due to the similarity between the induction motor equivalent circuit and the transformer equivalent circuit, same tests are used to determine the values of the motor parameters.
  - No-load test: determine the rotational losses and magnetization current (similar to no-load test in Transformers).
  - Locked-rotor test: determine the rotor and stator impedances (similar to short-circuit test in Transformers).

UNIT-II

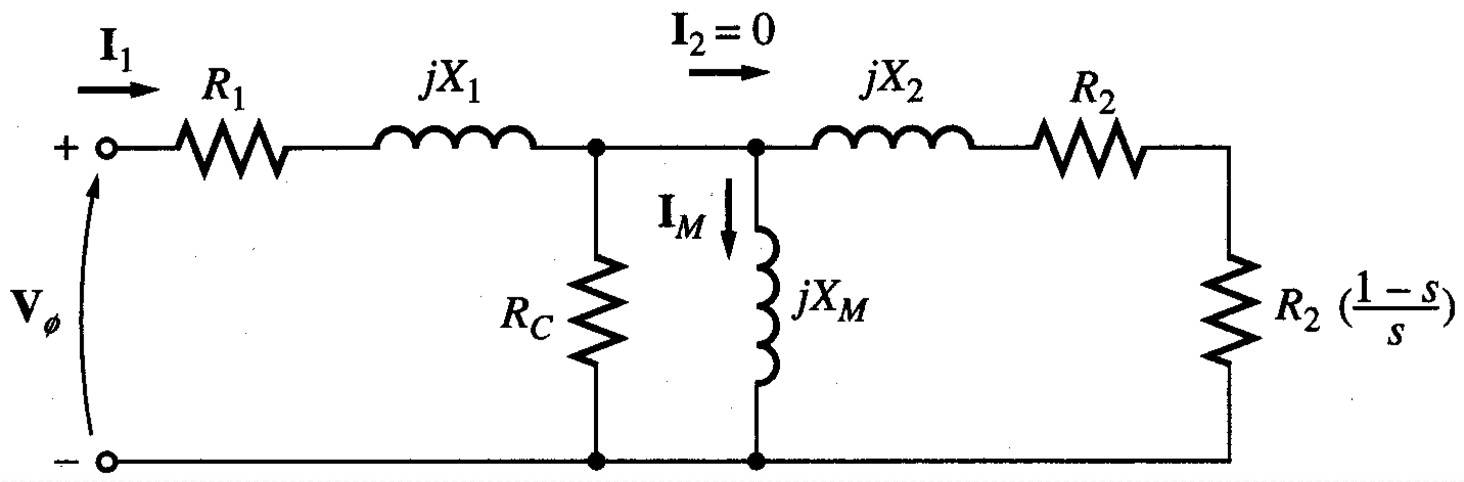
CIRCLE DIAGRAM AND SPEED CONTROL OF INDUCTION MOTORS

No-load test



1. The motor is allowed to spin freely
2. The only load on the motor is the friction and windage losses, so all P_{conv} is consumed by mechanical losses
3. The slip is very small

No-load test

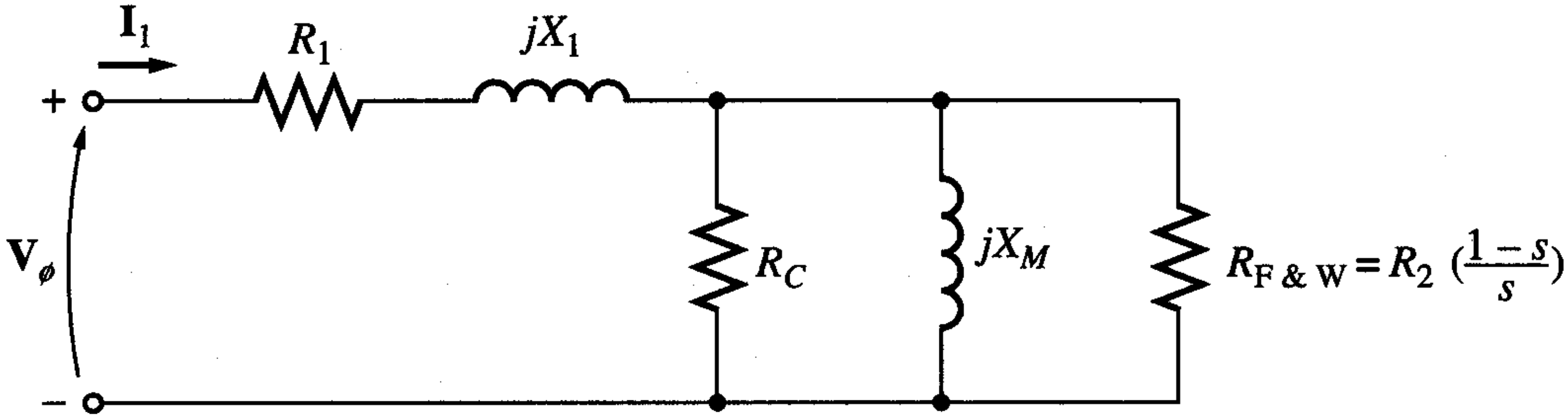


4. At this small slip

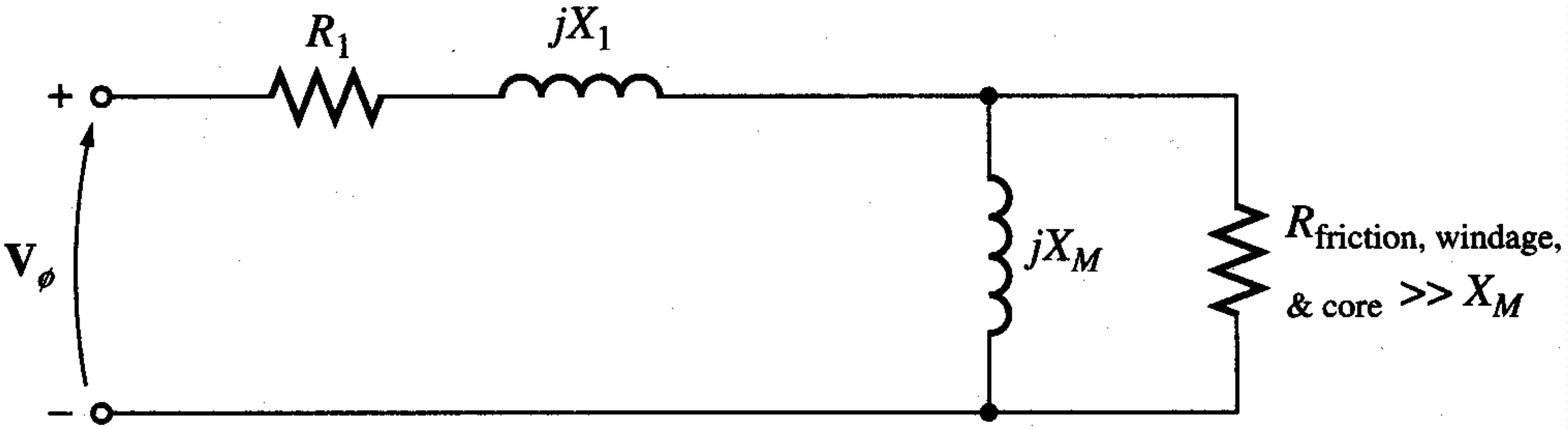
$$\frac{R_2(1-s)}{s} \gg R_2 \qquad \& \qquad \frac{\mathrm{R}_2(1-s)}{s} \gg X_2$$

The equivalent circuit reduces to…

No-load test



5. Combining R_c & R_{F+W} we get……



No-load test

6. At the no-load conditions, the input power measured by meters must equal the losses in the motor.
7. The P_{RCL} is negligible because I_2 is extremely small because $R_2(1\text{-}s)/s$ is very large.
8. The input power equals

$$\boxed{\begin{aligned} P_{in} &= P_{SCL} + P_{core} + P_{F\&W} \\ &= 3I_1^2 R_1 + P_{rot} \end{aligned}}$$

Where

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

No-load test

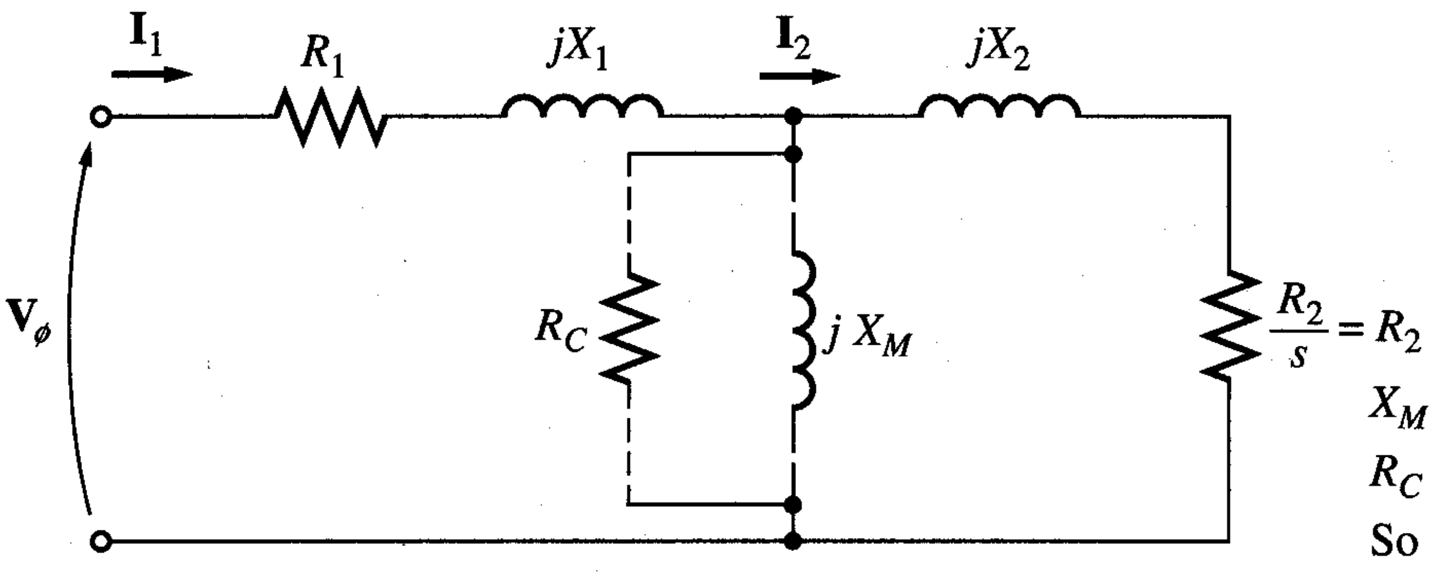
9. The equivalent input impedance is thus approximately

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

If X_1 can be found, in some other fashion, the magnetizing impedance X_M will be known

Blocked-rotor test

- In this test, the rotor is locked or blocked so that it cannot move, a voltage is applied to the motor, and the resulting voltage, current and power are measured.



$X_M >> |R_2 + jX_2|$

$R_C >> |R_2 + jX_2|$

So neglect R_C and X_M

Blocked-rotor test

- The AC voltage applied to the stator is adjusted so that the current flow is approximately full-load value.
- The locked-rotor power factor can be found as

$$\boxed{PF = \cos\theta = \frac{P_{in}}{\sqrt{3}V_l I_l}}$$

- The magnitude of the total impedance

$$\boxed{\left|Z_{LR}\right| = \frac{V_\phi}{I}}$$

Blocked-rotor test

$$\left|Z_{LR}\right| = R_{LR} + jX'_{LR}$$

$$= \left|Z_{LR}\right| \cos\theta + j\left|Z_{LR}\right| \sin\theta$$

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

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

Where X'_1 and X'_2 are the stator and rotor reactances at the test frequency respectively

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

$$X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = X_1 + X_2$$

Blocked-rotor test

	X_1 and X_2 as function of X_{LR}	
Rotor Design	X_1	X_2
Wound rotor	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Design A	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Design B	$0.4\ X_{LR}$	$0.6\ X_{LR}$
Design C	$0.3\ X_{LR}$	$0.7\ X_{LR}$
Design D	$0.5\ X_{LR}$	$0.5\ X_{LR}$

Speed Control of Induction Motor

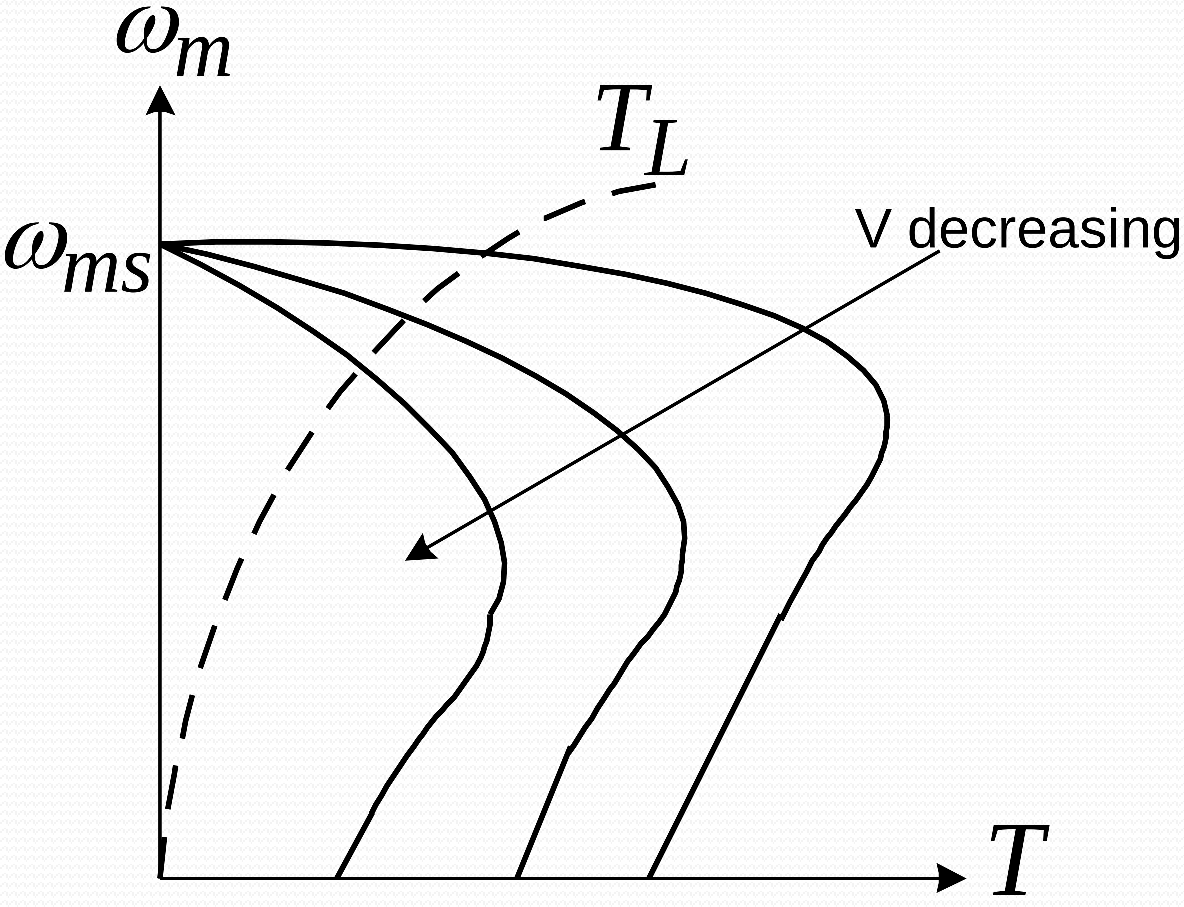
1- Variable Terminal Voltage Control

2- Variable Frequency Control

3- Rotor Resistance Control

4- Injecting Voltage in Rotor Circuit

1- Variable Terminal Voltage Control



variable terminal voltage control	variable frequency control
Low speed range	Wide speed range
Lower rated speed	Lower & higher rated speed

2- Variable Frequency Control

$$a = f \,/\, f_{rated}$$

Per-Unit Frequency

1- Operation Below the Rated Frequency $a < 1$

$$I_m = \frac{E_{rated}}{X_m} = \frac{E_{rated}}{f_{rated}} * \frac{1}{2\pi L_m} \longleftarrow$$

At rated frequency

$$I_m = \frac{E}{aX_m} = \frac{E}{a * f_{rated}} * \frac{1}{2\pi L_m} \longleftarrow$$

At any frequency, f

Comparing of the above equations, I_m will stay constant at a value equal to its rated value if

$$E = a\,E_{rated} = \frac{f}{f_{rated}} E_{rated} \longrightarrow \frac{E}{f} = \frac{E_{rated}}{f_{rated}}$$

The above equation suggests that the flux will remain constant if the back emf changes in the same ratio as the frequency, in other ward, when E/f ratio is maintained constant.

The rotor current at any frequency *f can be obtained from the following equation:*

$$I'_r = \frac{aE_{rated}}{\sqrt{\left(\frac{R'_r}{s}\right)^2 + (aX'_r)^2}} = \frac{E_{rated}}{\sqrt{\left(\frac{R'_r}{as}\right)^2 + (X'_r)^2}}$$

$$s = \frac{a\omega_{ms} - \omega_m}{a\omega_{ms}} = \frac{\omega_{sl}}{a\omega_{ms}}$$

ω_{ms} Synchronous Speed at rated frequency f_{rated}

ω_m Angular Speed at frequency f

$$sa = \frac{a\omega_{ms} - \omega_m}{\omega_{ms}} = \frac{\omega_{sl}}{\omega_{ms}}$$

$$\omega_{sl} = a\omega_{ms} - \omega_m$$

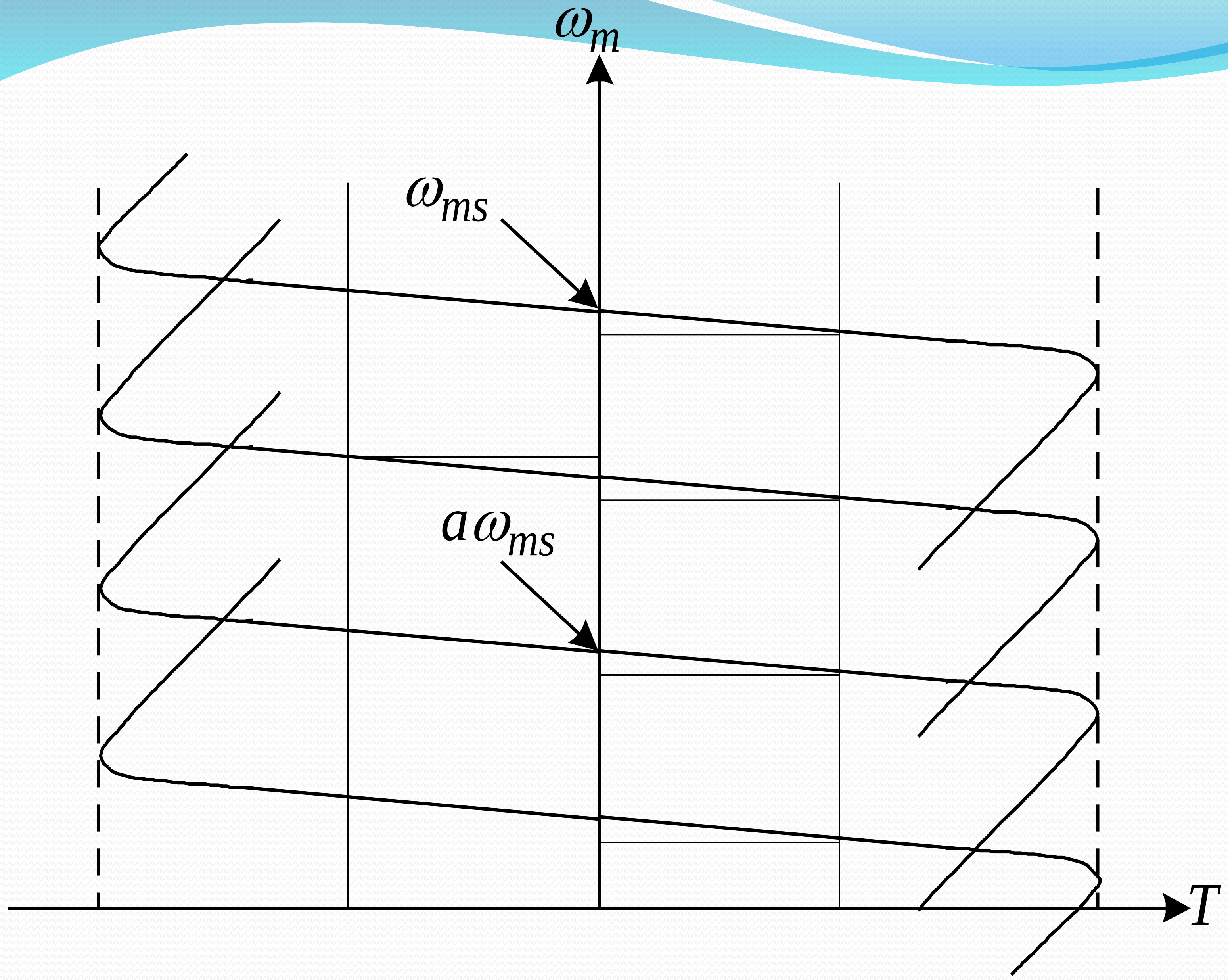
$$T = \frac{3}{a\omega_{ms}} I'^2_r \left(\frac{R'_r}{s}\right) = \frac{3}{\omega_{ms}} \left[\frac{E^2_{rated} * R'_r \;/\, as}{\left(\frac{R'_r}{as}\right)^2 + (X'_r)^2} \right]$$

→ Torque at frequency f

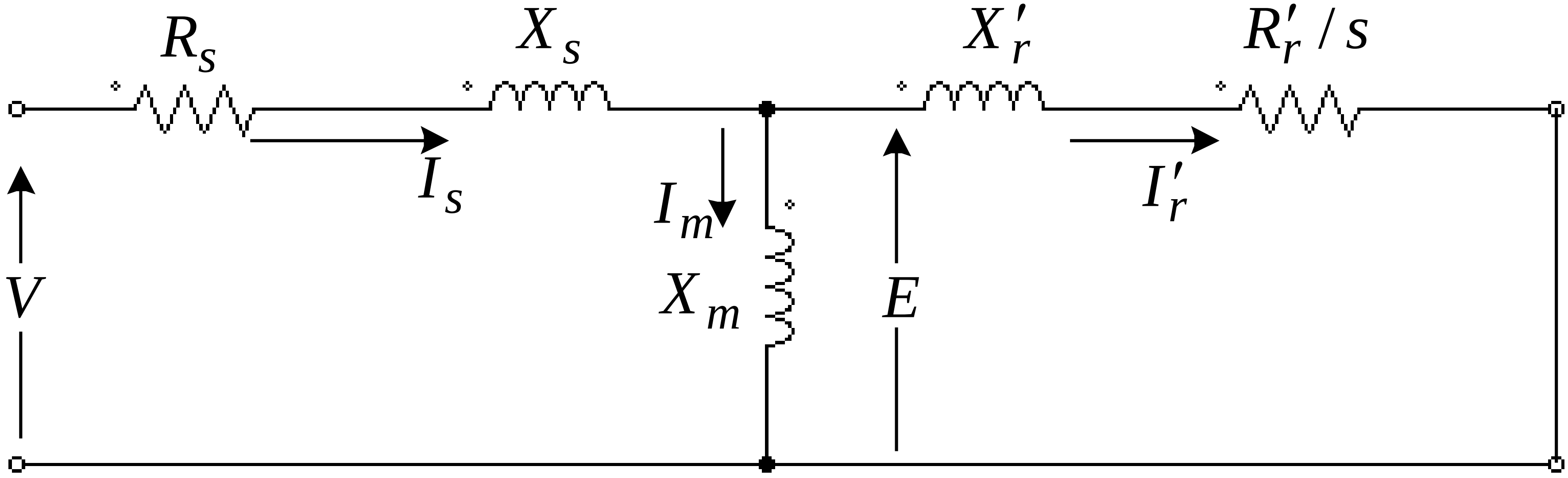
At a given *f* and *E* $\quad s_m \cong \pm \frac{R'_r}{aX'_r} \longrightarrow T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{E^2_{rated}}{X'_r} \right]$

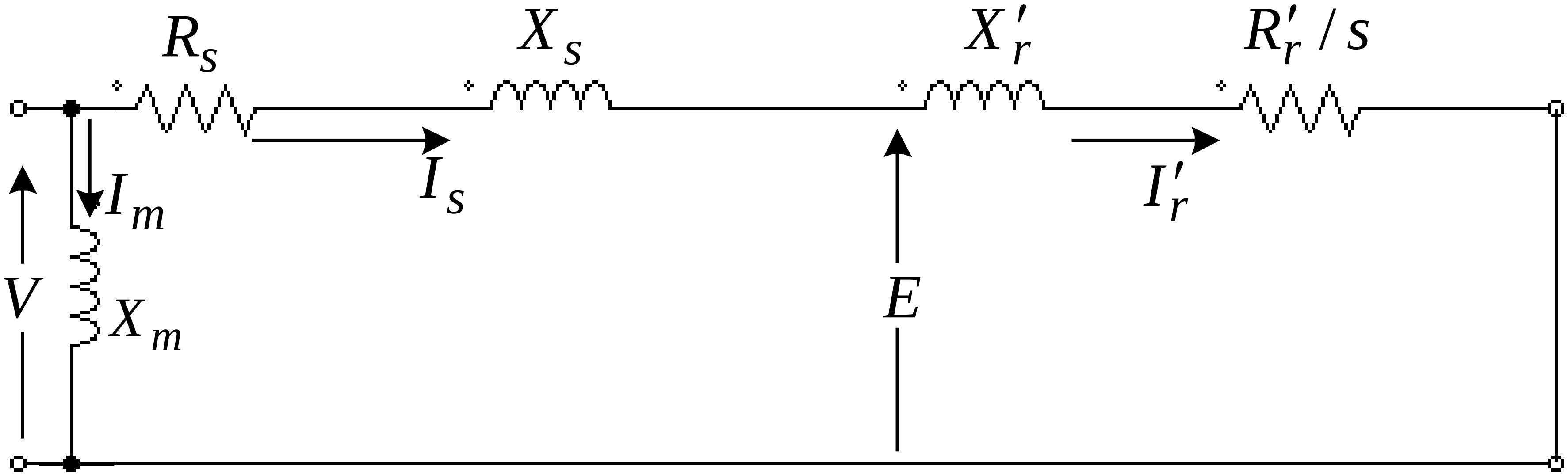
$$T = \frac{3}{a\omega_{ms}} I_r'^2 \left(\frac{R_r'}{s}\right) \underbrace{= \frac{3}{\omega_{ms}} \left[\frac{E_{rated}^2 * R_r' / as}{\left(\frac{R_r'}{as}\right)^2 + \left(X_r'\right)^2} \right] \qquad \because \frac{R_r'}{as} \gg X_r'}$$

$$T = \frac{3E_{rated}^2}{\omega_{ms} R_r'} (as) = constant\,(\omega_{sl}) \tag{6-51}$$


ω_m
ω_{ms}
$a\omega_{ms}$
T
Braking
Motoring

V/f Control





V/f Control

At rated frequency

$$T = \frac{3}{\omega_{ms}} I_r'^2 \left(\frac{R_r'}{s} \right) = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^2 * R_r' \ / s}{(R_s + R_r' / s)^2 + (X_s + X_r')^2} \right]$$

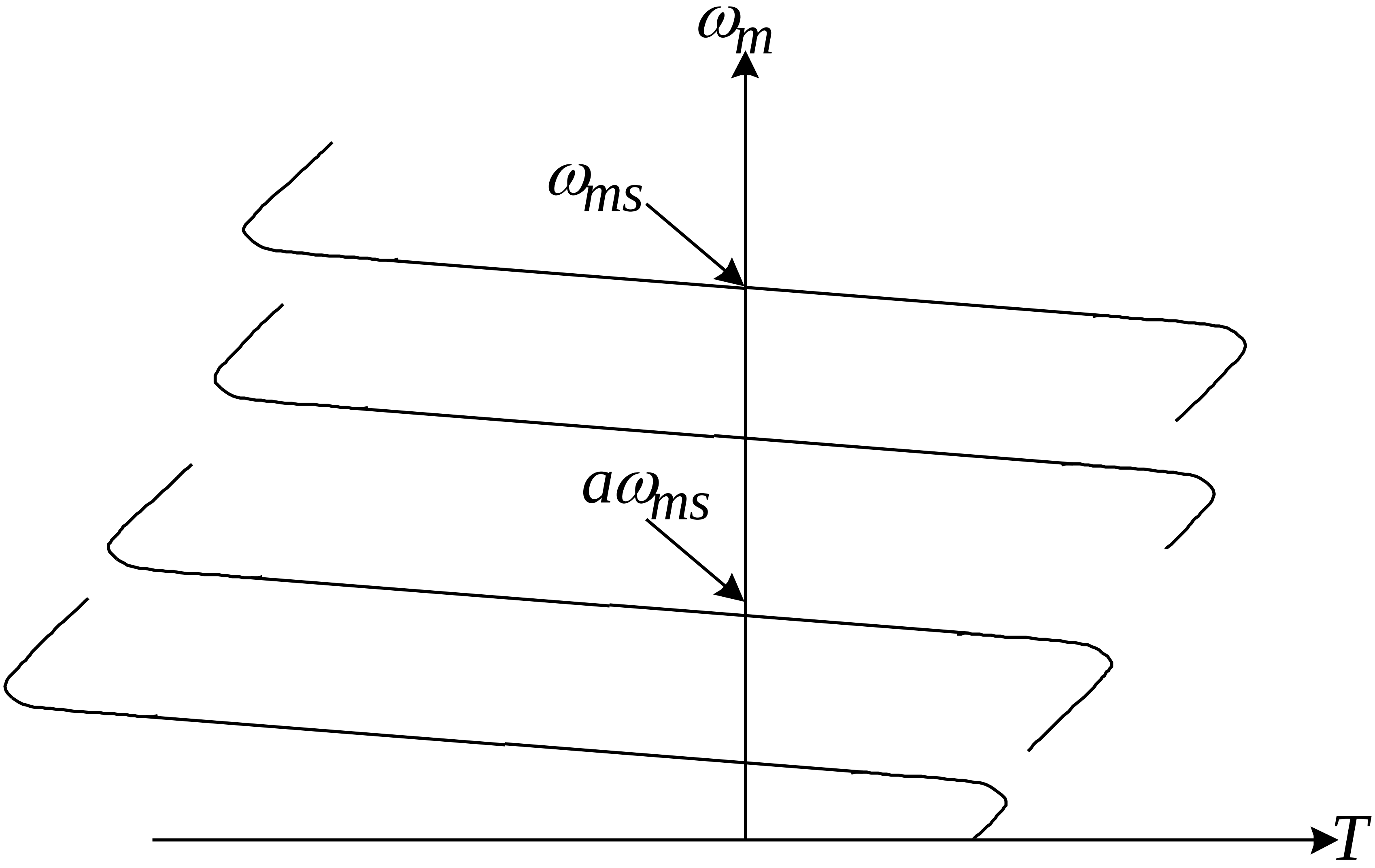
$$T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{V_{rated}^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}} \right]$$

At any frequency, *f*, $a < 1$

$$T = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^2 * R_r' \ / as}{(R_s / a + R_r' / as)^2 + (X_s + X_r')^2} \right]$$

$$T_{\max} = \frac{3}{2\omega_{ms}} \left[\frac{V_{rated}^2}{R_s / a \pm \sqrt{(R_s / a)^2 + (X_s + X_r')^2}} \right]$$

V/f Control



Operation above the rated frequency *a*>1

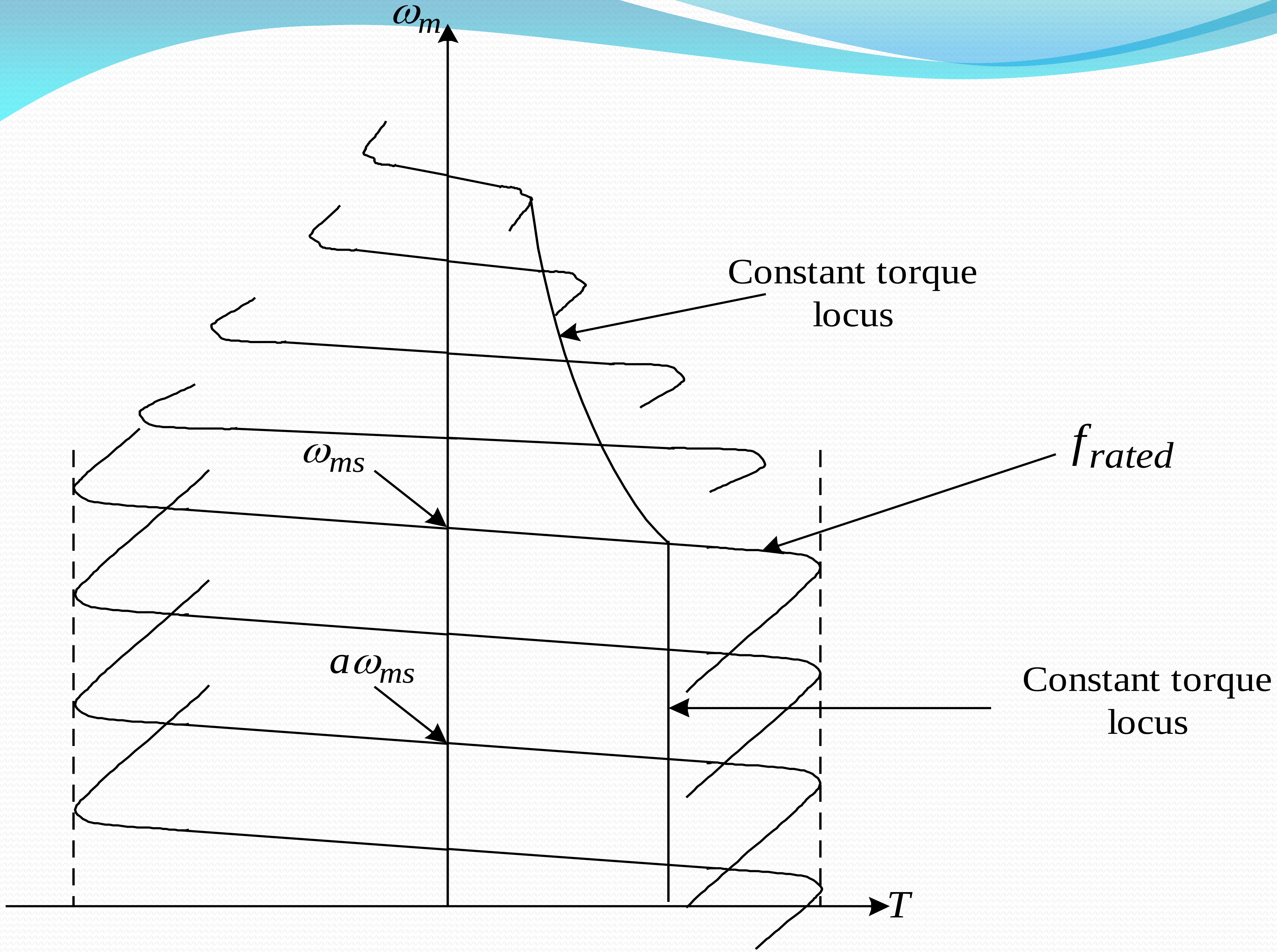
The terminal voltage has to be constant = Rated Volatge= V_{rated}

$$\because V = constant \longrightarrow \because Flux \downarrow \;\; when\ a \uparrow$$

At any frequency, *f*, $a > 1$

$$T = \frac{3}{\omega_{ms}} \left[\frac{V_{rated}^{2} * R_r' \;/ as}{\left(R_s + R_r'/s\right)^2 + a^2\left(X_s + X_r'\right)^2} \right]$$

$$T_{\max} = \frac{3}{2\omega_{ms} a} \left[\frac{V_{rated}^{2}}{R_s \pm \sqrt{(R_s)^2 + a^2(X_s + X_r')^2}} \right]$$


ω_m
Constant torque locus
f_{rated}
ω_{ms}
$a\omega_{ms}$
Constant torque locus
T

UNIT-III

Synchronous generators

Synchronous Machines

- Synchronous generators or alternators are used to convert mechanical power derived from steam, gas, or hydraulic-turbine to ac electric power
- Synchronous generators are the primary source of electrical energy we consume today
- Large ac power networks rely almost exclusively on synchronous generators
- Synchronous motors are built in large units compare to induction motors (Induction motors are cheaper for smaller ratings) and used for constant speed industrial drives

Construction

- Basic parts of a synchronous generator:
- Rotor - dc excited winding
- Stator - 3-phase winding in which the ac EMF is generated

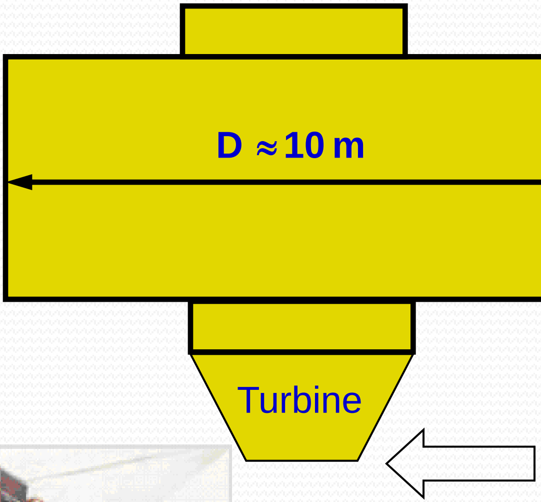
- The manner in which the active parts of a synchronous machine are cooled determines its overall physical size and structure

Various Types

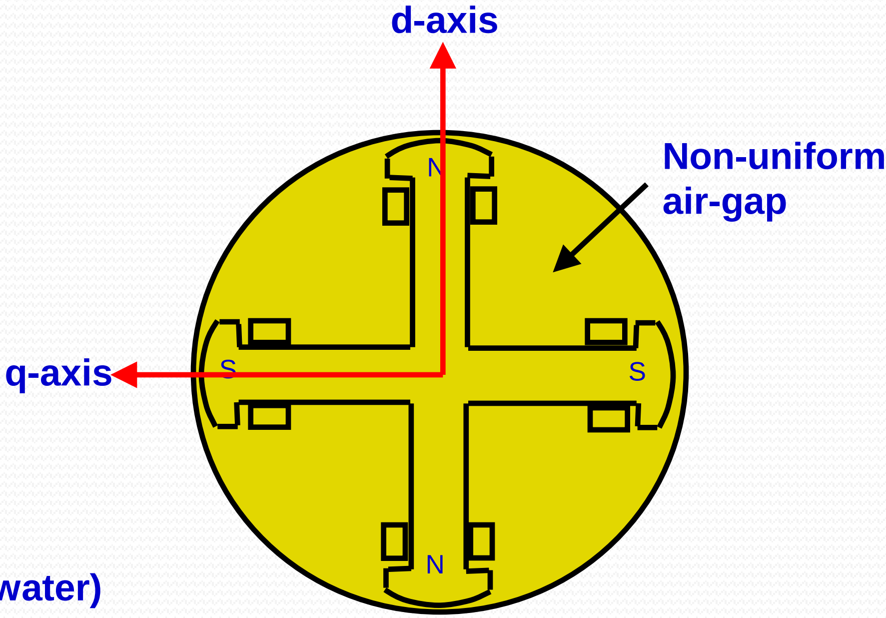
- Salient-pole synchronous machine
- Cylindrical or round-rotor synchronous machine

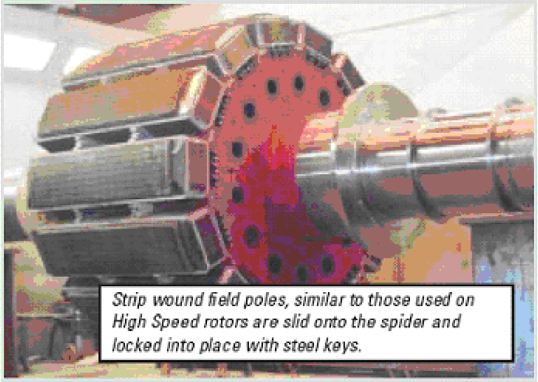
Salient-Pole Synchronous Generator

1. **Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min)**
2. **A large number of poles are required on the rotor**



Hydro (water)

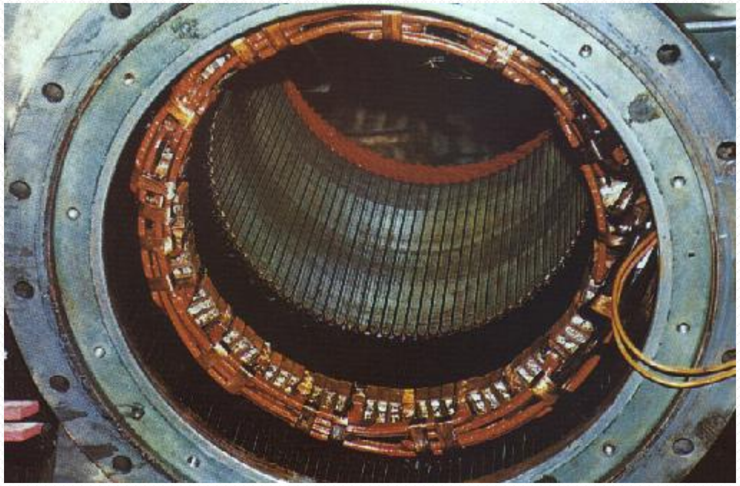




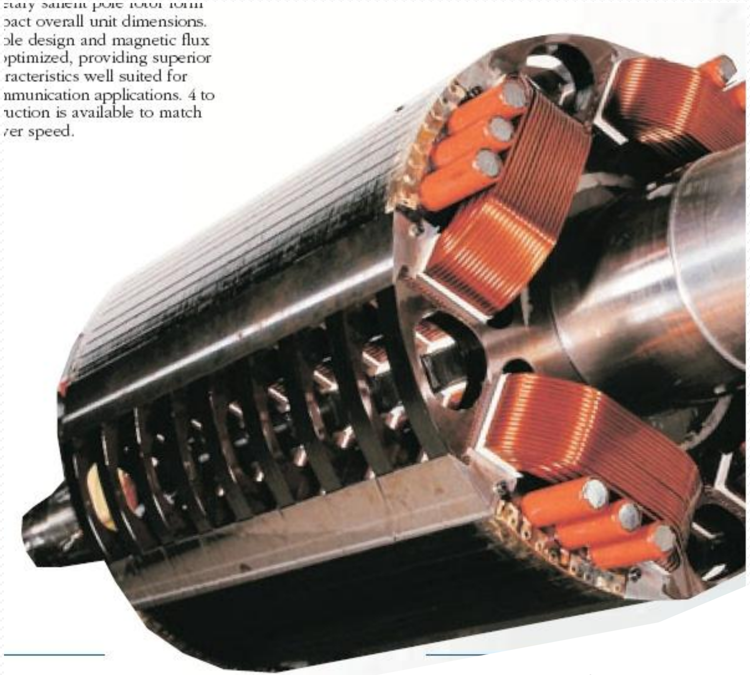
Strip wound field poles, similar to those used on High Speed rotors are slid onto the spider and locked into place with steel keys.

Hydrogenerator

Salient-Pole Synchronous Generator

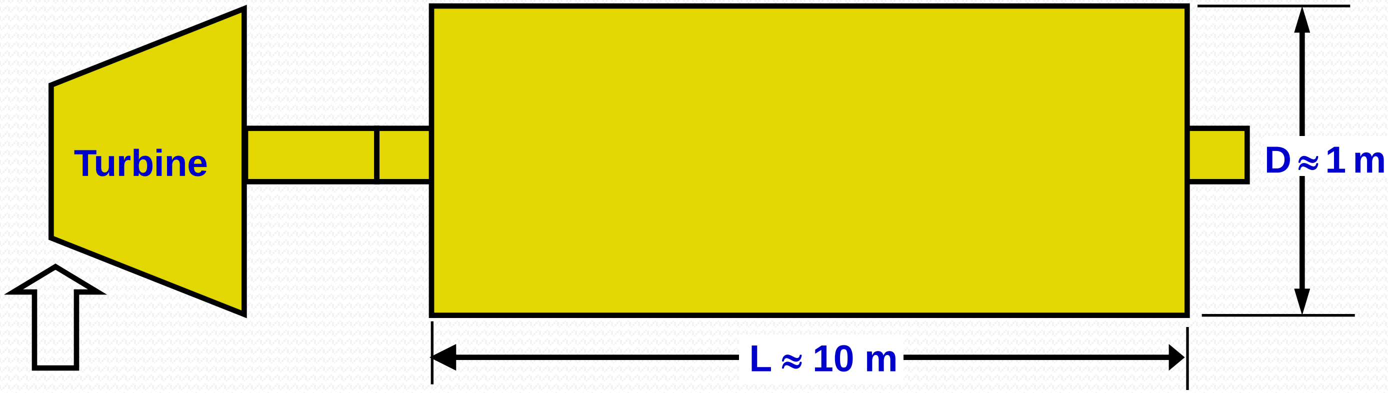


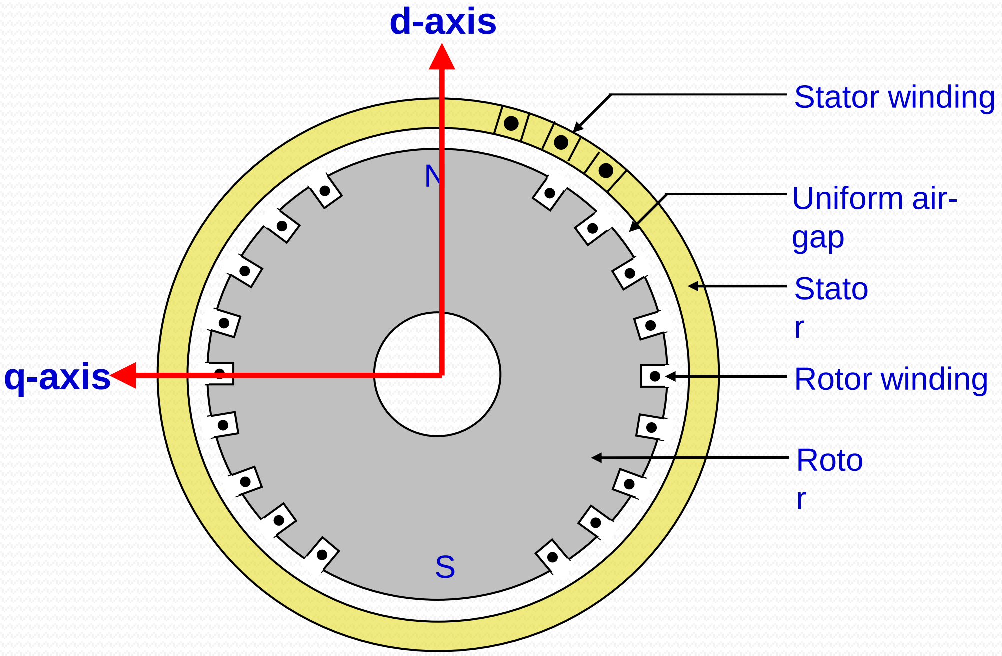
Stator



Salient-pole rotor

Cylindrical-Rotor Synchronous Generator

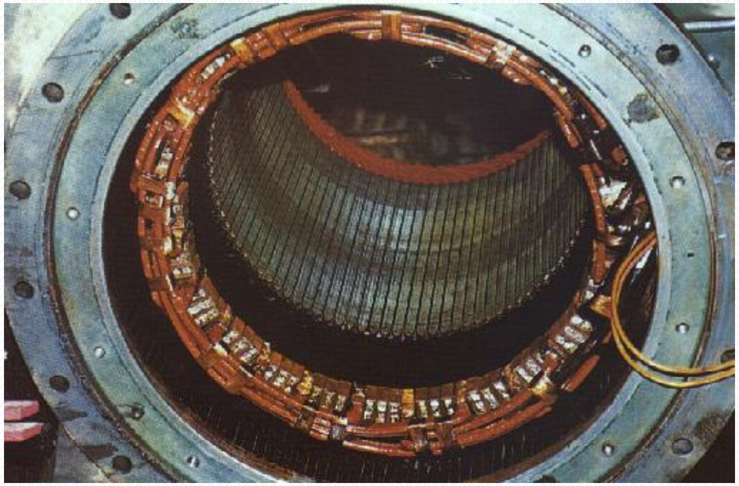




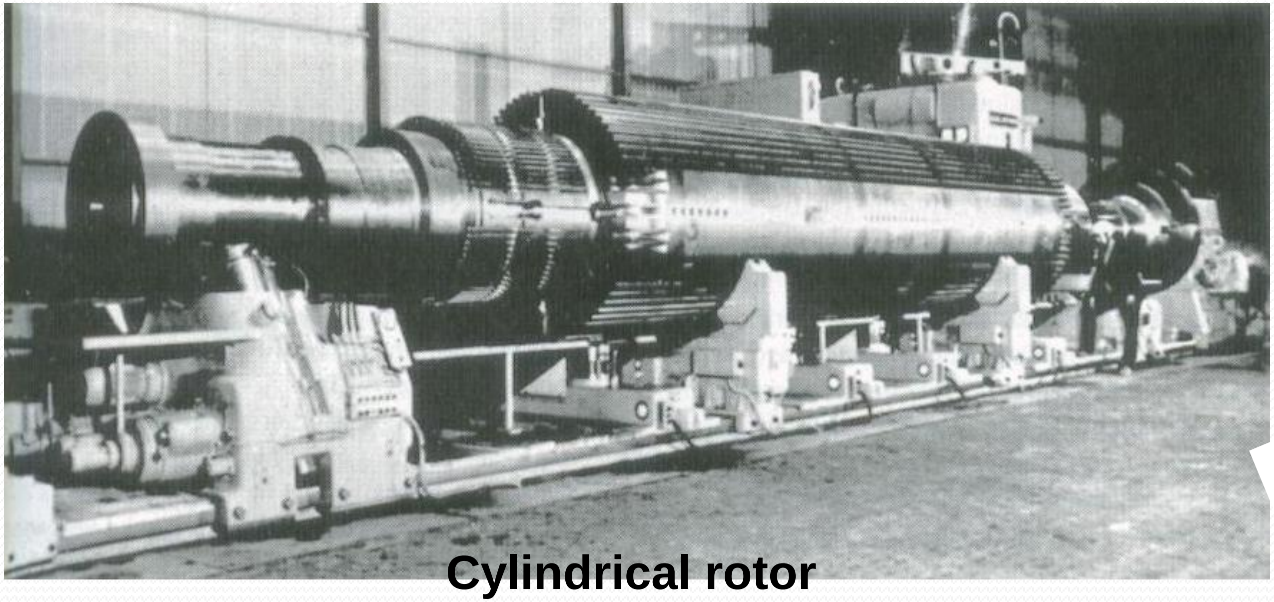
- High speed
- 3600 r/min ⇒ 2-pole
- 1800 r/min ⇒ 4-pole
- Direct-conductor cooling (using hydrogen or water as coolant)
- Rating up to 2000 MVA

Turbogenerator

Cylindrical-Rotor Synchronous Generator



Stator



Cylindrical rotor

Operation Principle

The rotor of the generator is driven by a prime-mover

↓

A dc current is flowing in the rotor winding which produces a rotating magnetic field within the machine

↓

The rotating magnetic field induces a three-phase voltage in the stator winding of the generator

Electrical Frequency

Electrical frequency produced is locked or synchronized to the mechanical speed of rotation of a synchronous generator:

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

where f_e = electrical frequency in Hz

P = number of poles

n_m = mechanical speed of the rotor, in r/min

Generated Voltage

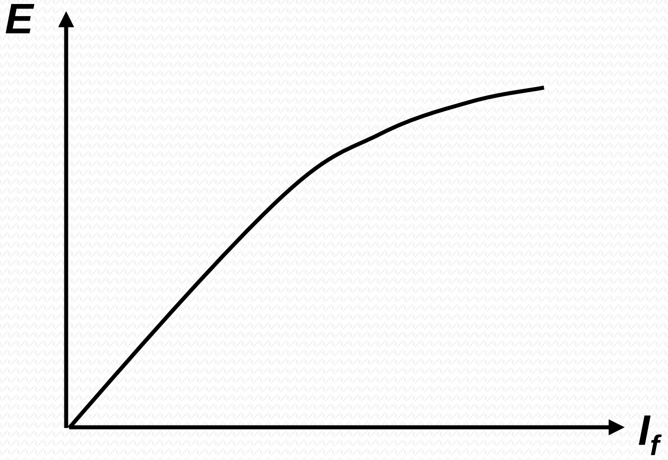
The generated voltage of a synchronous generator is given by

$$E = K_c \phi f_e$$

where ϕ = flux in the machine (function of I_f)

f_e = electrical frequency

K_c= synchronous machine constant



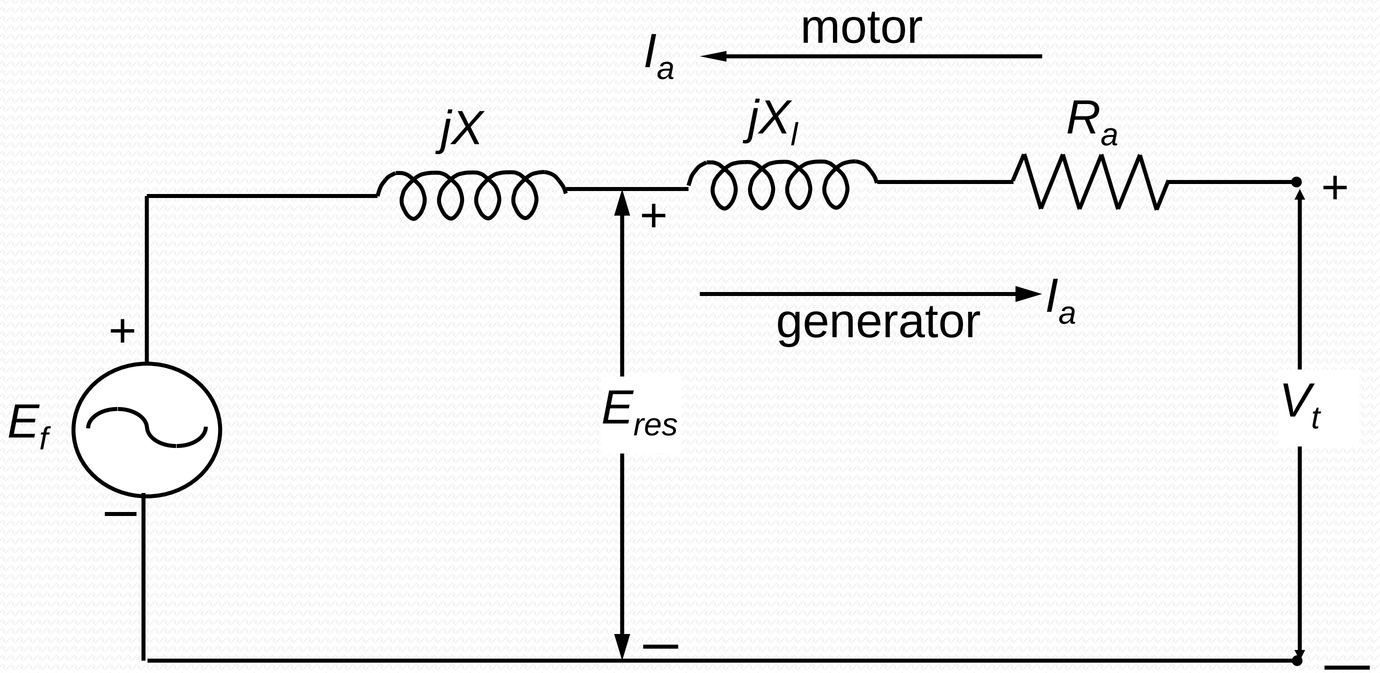
Saturation characteristic of a synchronous generator.

Equivalent Circuit_1

- The internal voltage E_f produced in a machine is not usually the voltage that appears at the terminals of the generator.
- The only time E_f is same as the output voltage of a phase is when there is no armature current flowing in the machine.
- There are a number of factors that cause the difference between E_f and V_t:

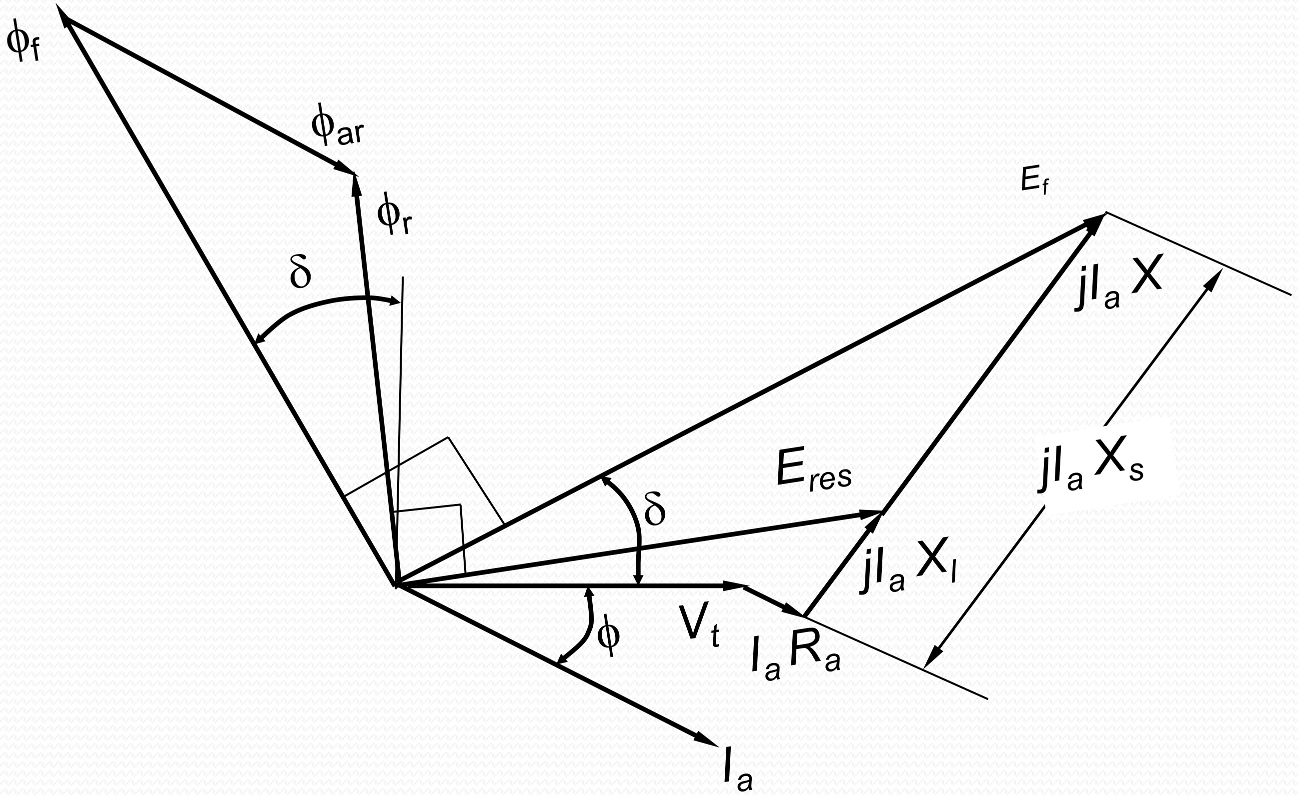
  - The distortion of the air-gap magnetic field by the current flowing in the stator, called the armature reaction
  - The self-inductance of the armature coils.
  - The resistance of the armature coils
  - The effect of salient-pole rotor shapes.

Equivalent Circuit_2



Equivalent circuit of a cylindrical-rotor synchronous machine

Phasor Diagram

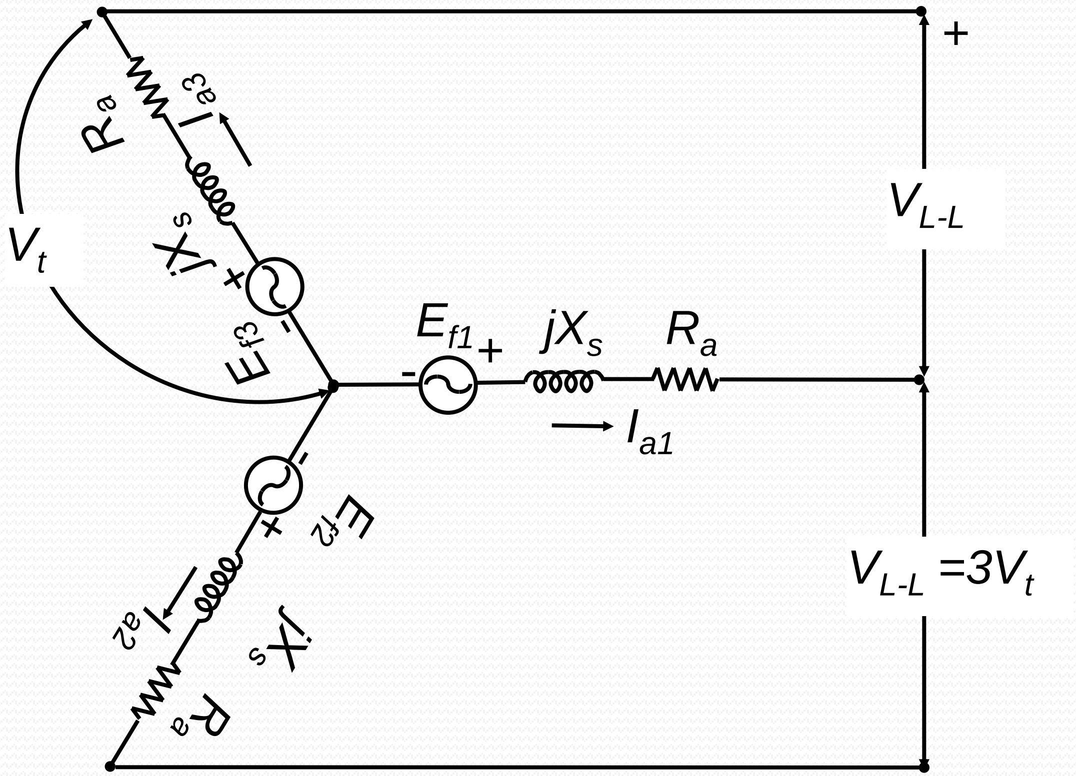


Phasor diagram of a cylindrical-rotor synchronous generator, for the case of lagging power factor

Lagging PF: $|V_t|<|E_f|$ for overexcited condition
Leading PF: $|V_t|>|E_f|$ for under excited condition

Three-phase equivalent circuit of a cylindrical-rotor synchronous machine

The voltages and currents of the three phases are 120° apart in angle, but otherwise the three phases are identical.



Determination of the parameters of the equivalent circuit from test data

- The equivalent circuit of a synchronous generator that has been derived contains three quantities that must be determined in order to completely describe the behaviour of a real synchronous generator:
    - The saturation characteristic: relationship between I_f and ϕ (and therefore between I_f and E_f)
    - The synchronous reactance, X_s
    - The armature resistance, R_a
- The above three quantities could be determined by performing the following three tests:
    - Open-circuit test
    - Short-circuit test
    - DC test

Voltage Regulation

A convenient way to compare the voltage behaviour of two generators is by their *voltage regulation* (*VR*). The *VR* of a synchronous generator at a given load, power factor, and at rated speed is defined as

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

Where V_{fl} is the full-load terminal voltage, and E_{nl} (equal to E_f) is the no-load terminal voltage (internal voltage) at rated speed when the load is removed without changing the field current. For lagging power factor (*PF*), *VR* is fairly positive, for unity *PF*, *VR* is small positive and for leading *PF*, *VR* is negative.

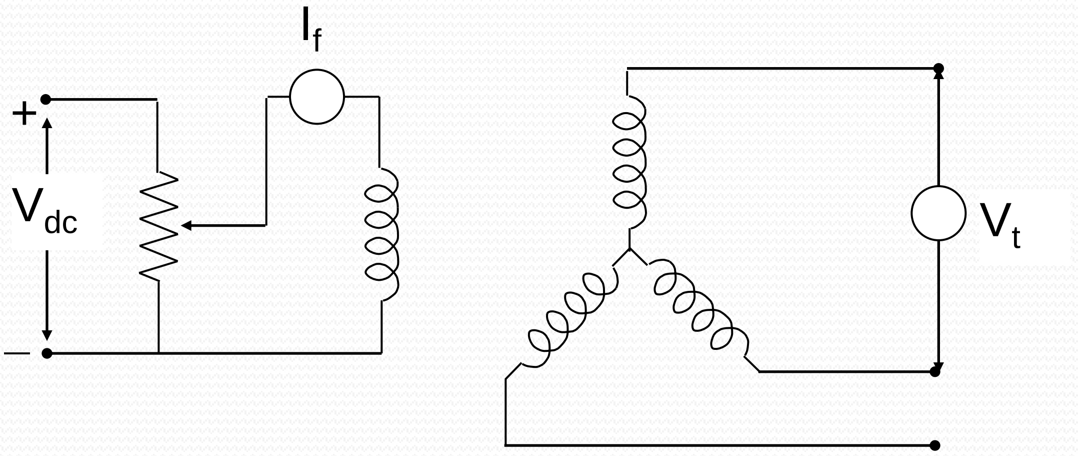
EMFmethod

This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent EMF, and hence called EMF method.

To predetermine the regulation by this method the following information's are to be determined. Armature resistance/phase of the alternator, open circuit and short circuit characteristics of the alternator.

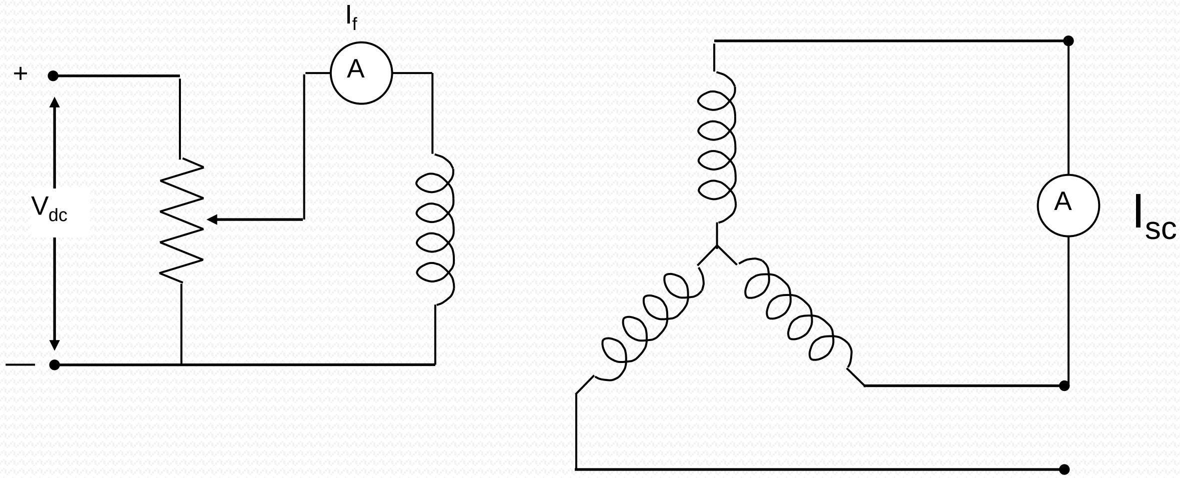
Open-circuit test

- The generator is turned at the rated speed
- The terminals are disconnected from all loads, and the field current is set to zero.
- Then the field current is gradually increased in steps, and the terminal voltage is measured at each step along the way.
- It is thus possible to obtain an open-circuit characteristic of a generator (E_f or V_t versus I_f) from this information



Short-circuit test

- Adjust the field current to zero and short-circuit the terminals of the generator through a set of ammeters.
- Record the armature current I_{sc} as the field current is increased.
- Such a plot is called short-circuit characteristic.



DC Test

- The purpose of the DC test is to determine R_a. A variable DC voltage source is connected between two stator terminals.
- The DC source is adjusted to provide approximately rated stator current, and the resistance between the two stator leads is determined from the voltmeter and ammeter readings

– then $$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

– If the stator is Y-connected, the per phase stator resistance is

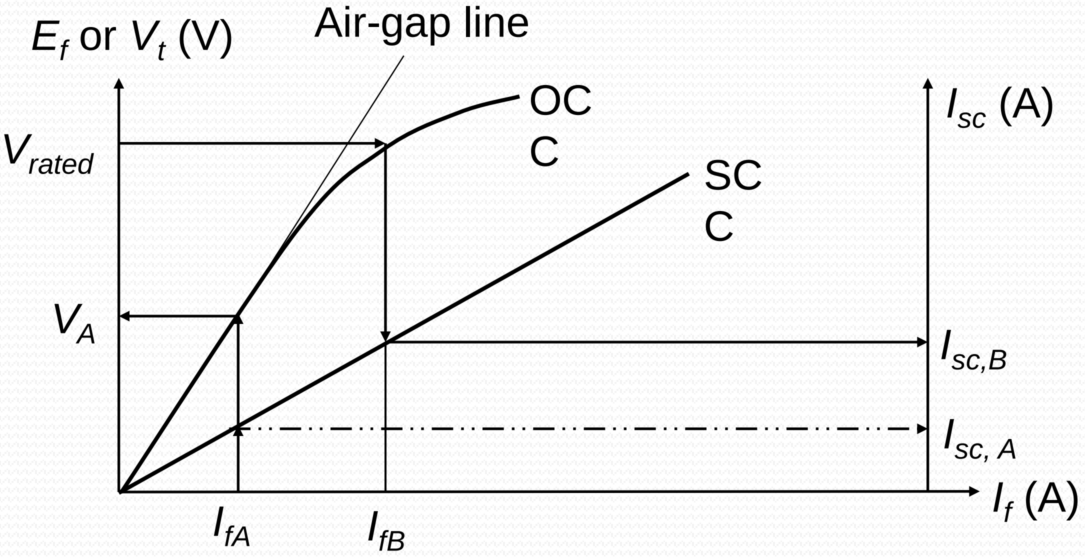
$$\boldsymbol{R_a = \frac{R_{DC}}{2}}$$

– If the stator is delta-connected, the per phase stator resistance is

$$\boldsymbol{R_a = \frac{3}{2} R_{DC}}$$

Determination of X_s

- For a particular field current I_{fA}, the internal voltage E_f (=V_A) could be found from the occ and the short-circuit current flow $I_{sc,A}$ could be found from the scc.
- Then the synchronous reactance X_s could be obtained using



$$Z_{s,unsat} = \sqrt{R_a^2 + X_{s,unsat}^2} = \frac{V_A(= E_f)}{|I_{scA}|}$$

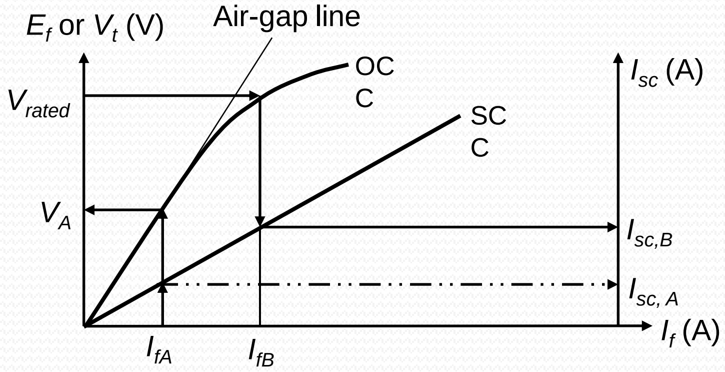
$$X_{s,unsat} = \sqrt{Z_{s,unsat}^2 - R_a^2}$$

: R_a is known from the DC test.

Since $X_{s,unsat} >> R_a$,

$$X_{s,unsat} \approx \frac{E_f}{I_{scA}} = \frac{V_{t,oc}}{I_{scA}}$$

X_s under saturated condition

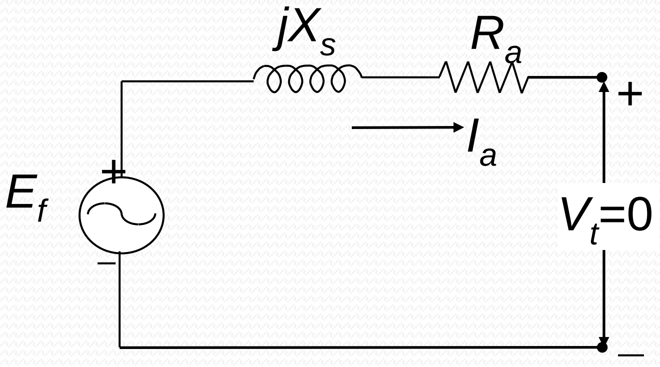


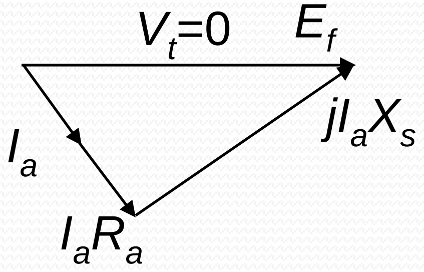
At $V = V_{rated}$,

$$Z_{s,sat} = \sqrt{R_a^2 + X_{s,sat}^2} = \frac{V_{rated}\left(= E_f\right)}{\left|I_{scB}\right|}$$

$$X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_a^2}$$ R_a is known from the DC test.

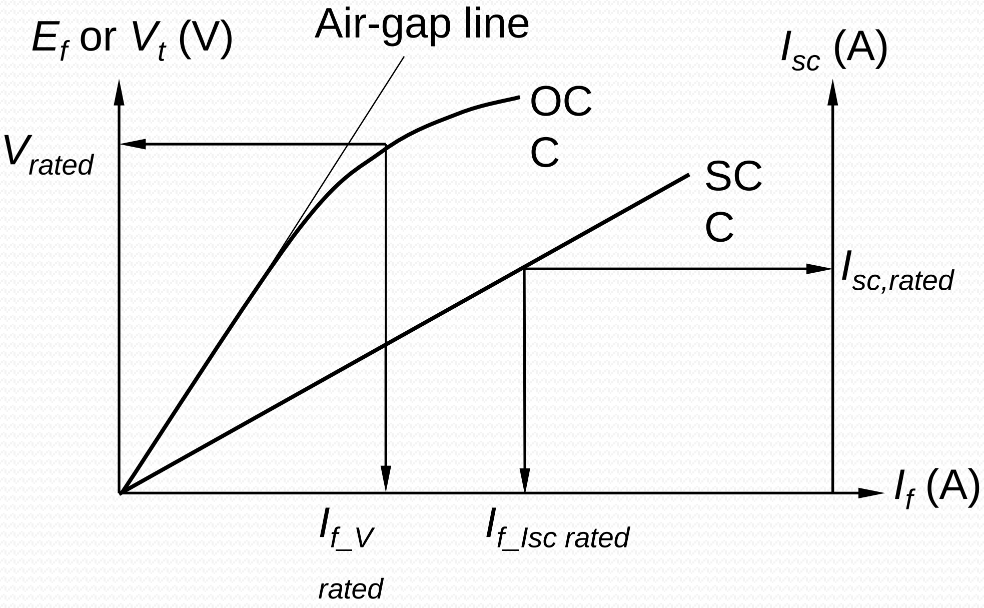
Equivalent circuit and phasor diagram under condition





Short-circuit Ratio

Another parameter used to describe synchronous generators is the short-circuit ratio (*SCR*). The SCR of a generator defined as the ratio of the *field current required for the rated voltage at open circuit* to the *field current required for the rated armature current at short circuit*. *SCR* is just the reciprocal of the per unit value of the saturated synchronous reactance calculated by



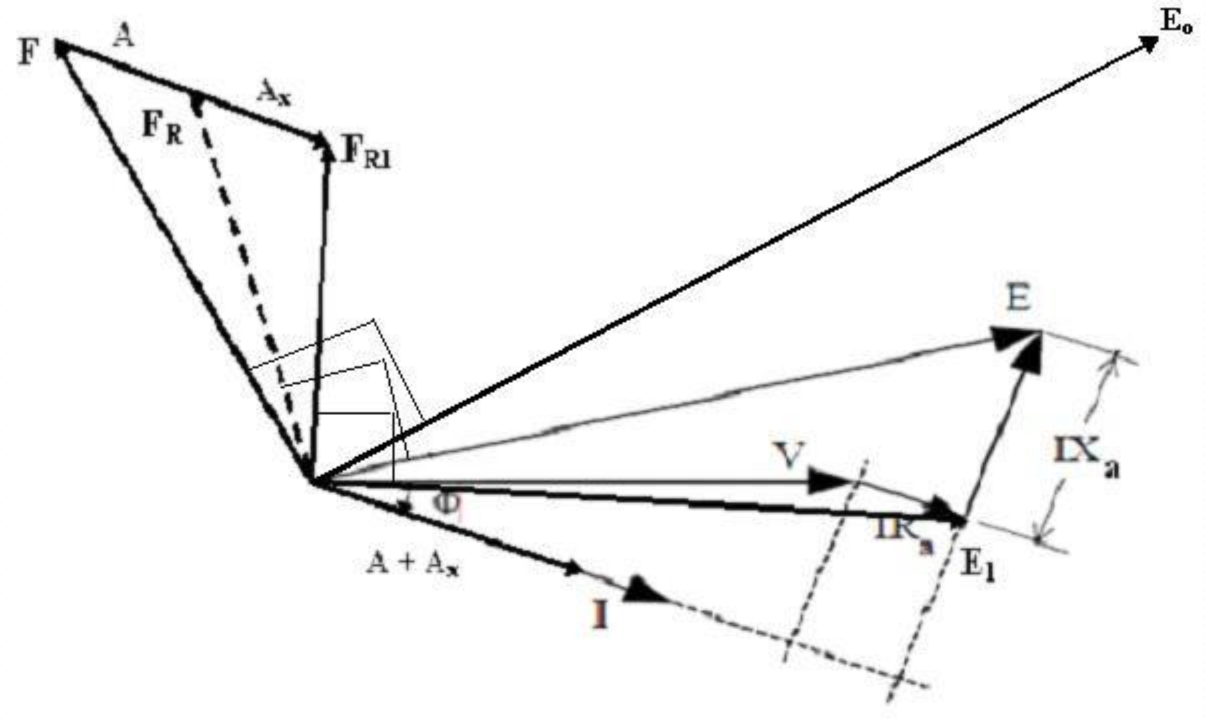
$$SCR = \frac{I_{f\_Vrated}}{I_{f\_Iscrated}}$$

$$= \frac{1}{X_{s\_sat}\ [in\ p.u.]}$$

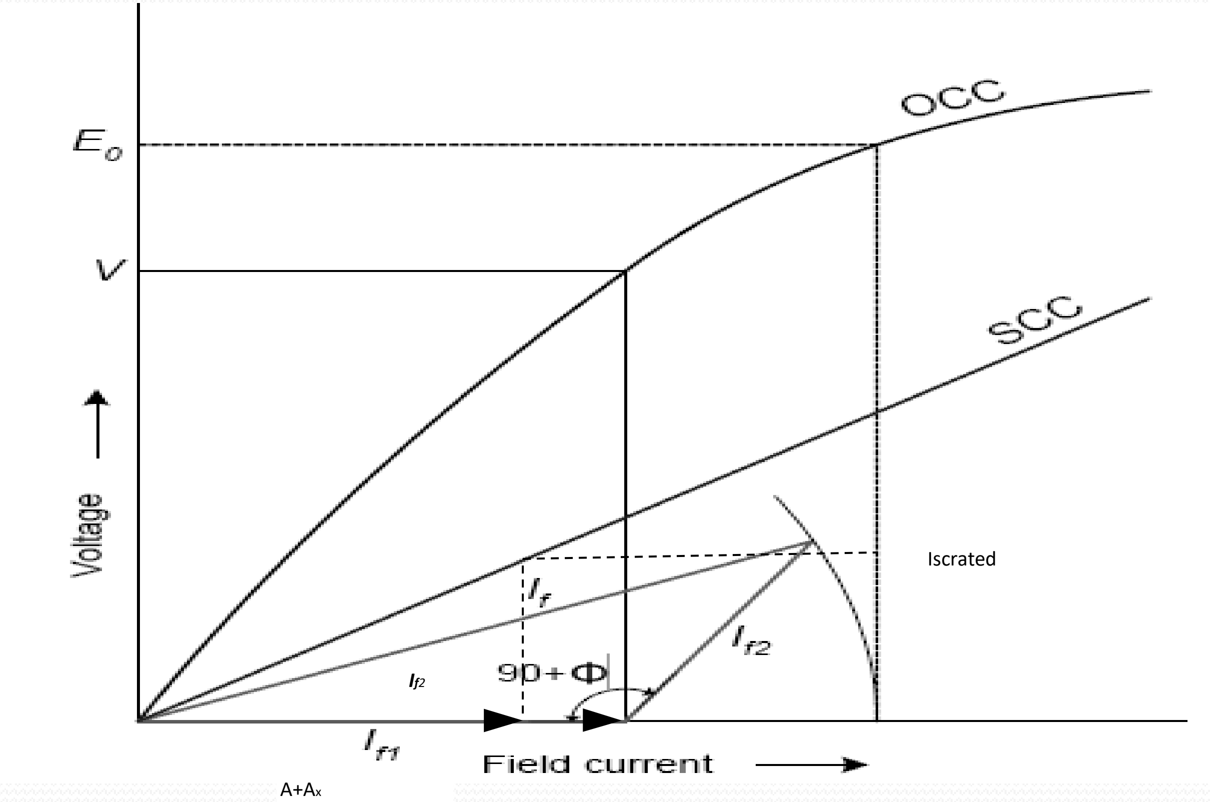
MMFmethod

This method is also known as amp-turns method. In this method the all the EMF s produced by rotor and stator are replaced by their equivalent MMFs(fluxes), and hence called MMF method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent MMF s. Similar to EMF method OC and SC characteristics are used for the determination of regulation by MMF method. Using the details it is possible determine the regulation at different power factors.

Phasor diagram



Open circuit and short circuit characteristics



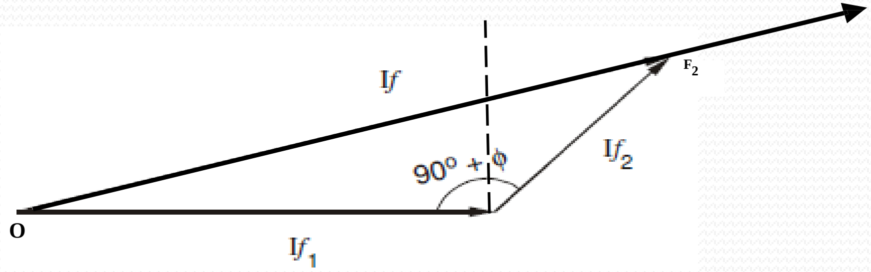
Following procedure can be used for determination of regulation by mmf method.

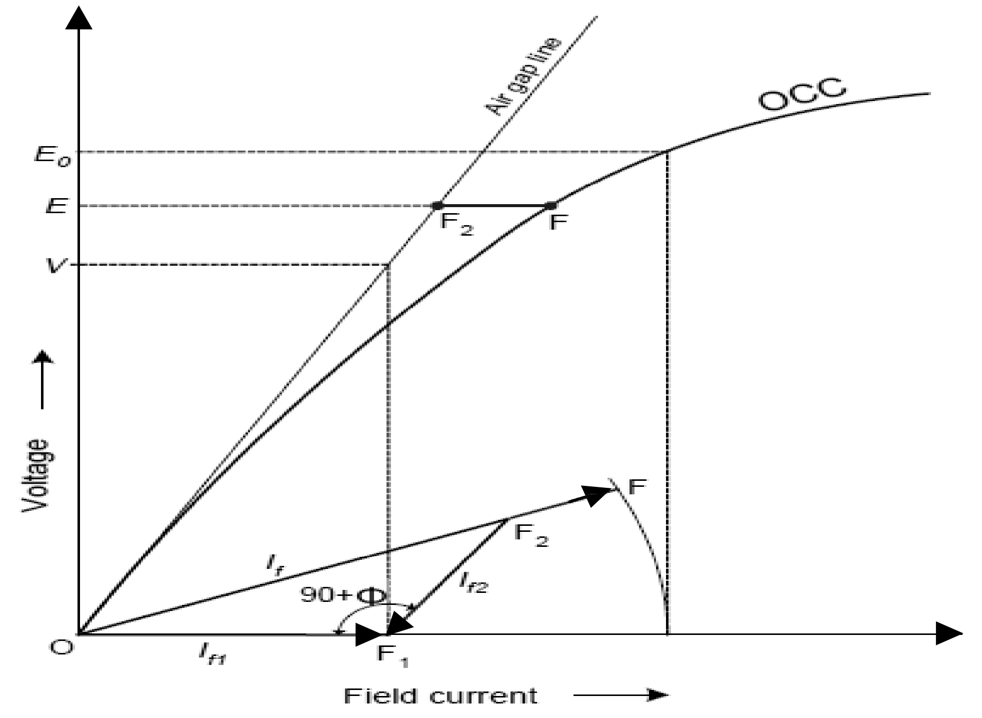
- By conducting OC and SC test plot OCC and SCC as shown.
- From the OCC find the field current $If1$ required to produce the voltage,

  $E1=(V+IRa)$.
- From SCC find the magnitude of field current $If2$ (A+Ax) to produce the required armature current. A+Ax can also found from ZPF characteristics.
- Draw $If2$ at angle (90+) from $If1$, where is the phase angle of current w.r.t voltage. If current is leading, take the angle of $If2$ as (90-) as shown
- Determine the resultant field current, If and mark its magnitude on the field current axis.
- From OCC. Find the voltage corresponding to If, which will be Eo and hence find the regulation.

ASA Modified MMF Method

- Because of the un realistic assumption of unsaturated magnetic circuit neither the EMF method nor the MMF method are giving the realistic value of regulation. Inspite of these short comings these methods are being used because of their simplicity. Hence ASA has modified MMF method for calculation of regulation. With reference to the phasor diagram of MMF method it can be seen that $F=FR_1-(A+Ax)$. In the MMF method the total MMF F computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount FF_2 which can be computed from OCC, SCC and air gap lines

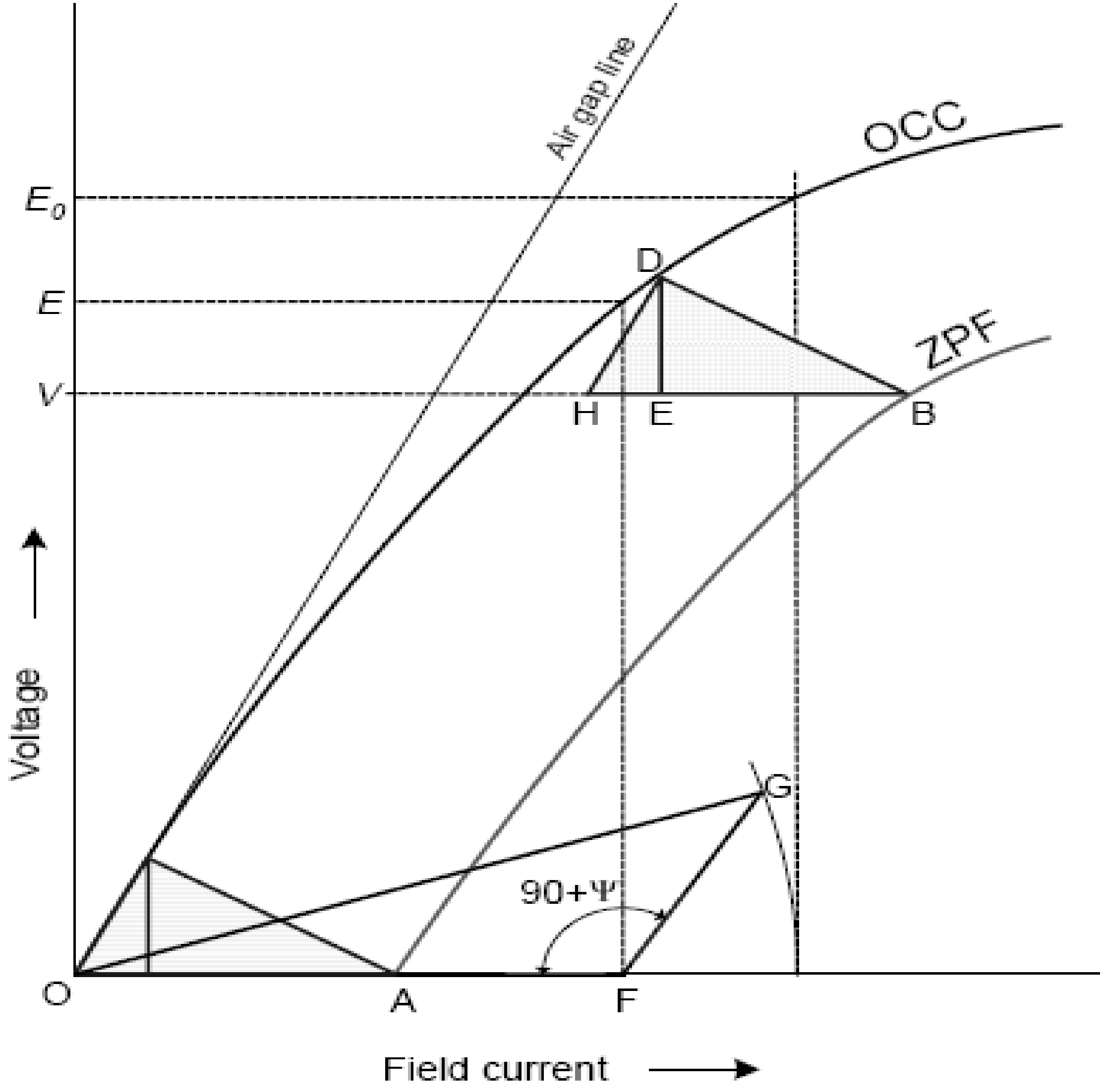

If
F2
90° + φ
If2
O
If1


Air gap line
OCC
Eo
E
F2
F
V
Voltage
F
F2
If
If2
90+Φ
O
If1
F1
Field current

Zero Power Factor (ZPF) method : Potier Triangle Method

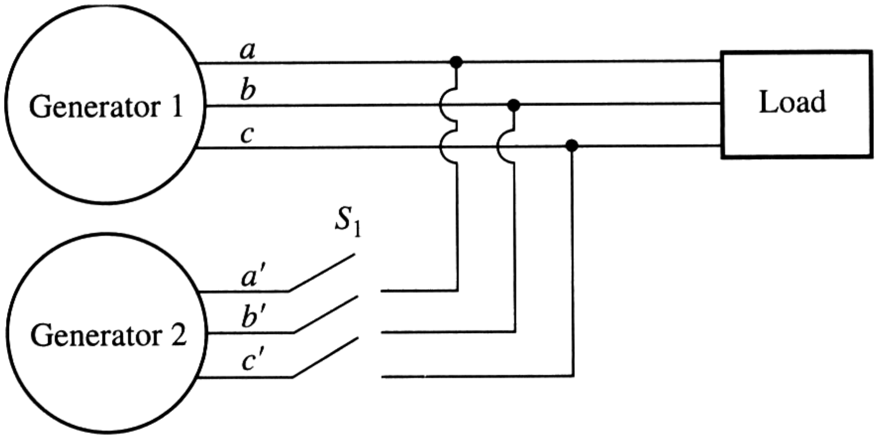
During the operation of the alternator, resistance voltage drop IaRa and armature leakage reactance drop IaXL are actually EMF quantities and the armature reaction reactance is a MMF quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. AS explained earlier OC and d SC tests are conducted and OCC and SCC are drawn.

ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from SCC and the other at rated voltage and rated current under ZPF load. This zero power factor curve appears like *OCC* but shifted by a factor *IXL* vertically and horizontally by armature reaction MMF as shown.


Air gap line
OCC
ZPF
E_0
E
V
D
H
E
B
G
$90+\Psi$
O
A
F
Voltage
Field current

Conditions required for paralleling

A diagram shows that Generator 2 (oncoming generator) will be connected in parallel when the switch S_1 is closed. However, closing the switch **at an arbitrary moment** can severely damage both generators!

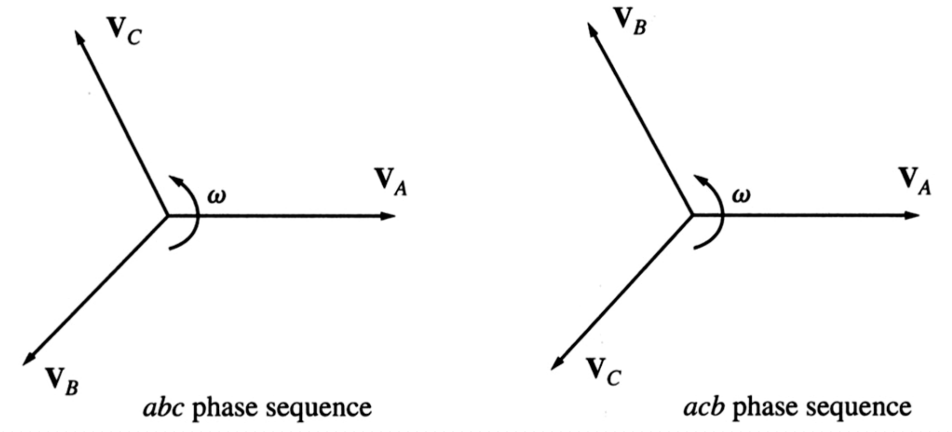


If voltages are not exactly the same in both lines (i.e. in *a* and *a'*, *b* and *b'* etc.), a very large current will flow when the switch is closed. Therefore, to avoid this, voltages coming from both generators must be exactly the same. Therefore, the following conditions must be met:

1. The rms line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of two *a* phases must be equal.
4. The frequency of the oncoming generator must be slightly higher than the frequency of the running system.

Conditions required for paralleling

If the phase sequences are different, then even if one pair of voltages (phases *a*) are in phase, the other two pairs will be 120^0 out of phase creating huge currents in these phases.

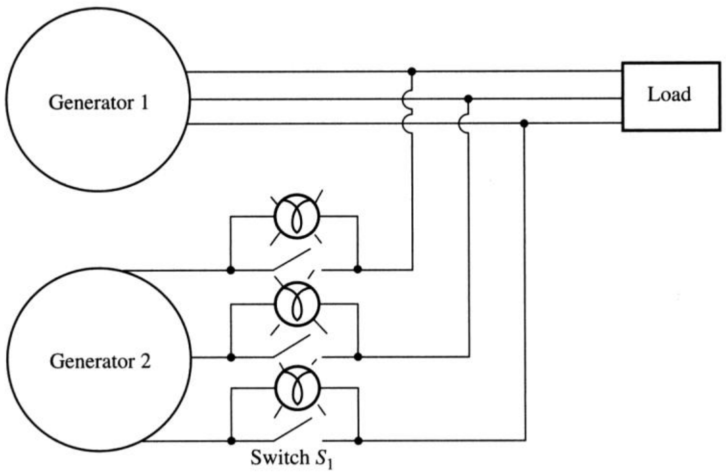


If the frequencies of the generators are different, a large power transient may occur until the generators stabilize at a common frequency. The frequencies of two machines must be very close to each other but not exactly equal. If frequencies differ by a small amount, the phase angles of the oncoming generator will change slowly with respect to the phase angles of the running system.
If the angles between the voltages can be observed, it is possible to close the switch S_1 when the machines are in phase.

General procedure for paralleling generators

When connecting the generator G_2 to the running system, the following steps should be taken:

1. Adjust the field current of the oncoming generator to make its terminal voltage equal to the line voltage of the system (use a voltmeter).
2. Compare the phase sequences of the oncoming generator and the running system. This can be done by different ways:
   1) Connect a small induction motor to the terminals of the oncoming generator and then to the terminals of the running system. If the motor rotates in the same direction, the phase sequence is the same;
   2) Connect three light bulbs across the open terminals of the switch. As the phase changes between the two generators, light bulbs get brighter (large phase difference) or dimmer (small phase difference). If all three



General procedure for paralleling generators

If phase sequences are different, two of the conductors on the oncoming generator must be reversed.

3. The frequency of the oncoming generator is adjusted to be slightly higher than the system's frequency.
4. Turn on the switch connecting G_2 to the system when phase angles are equal.

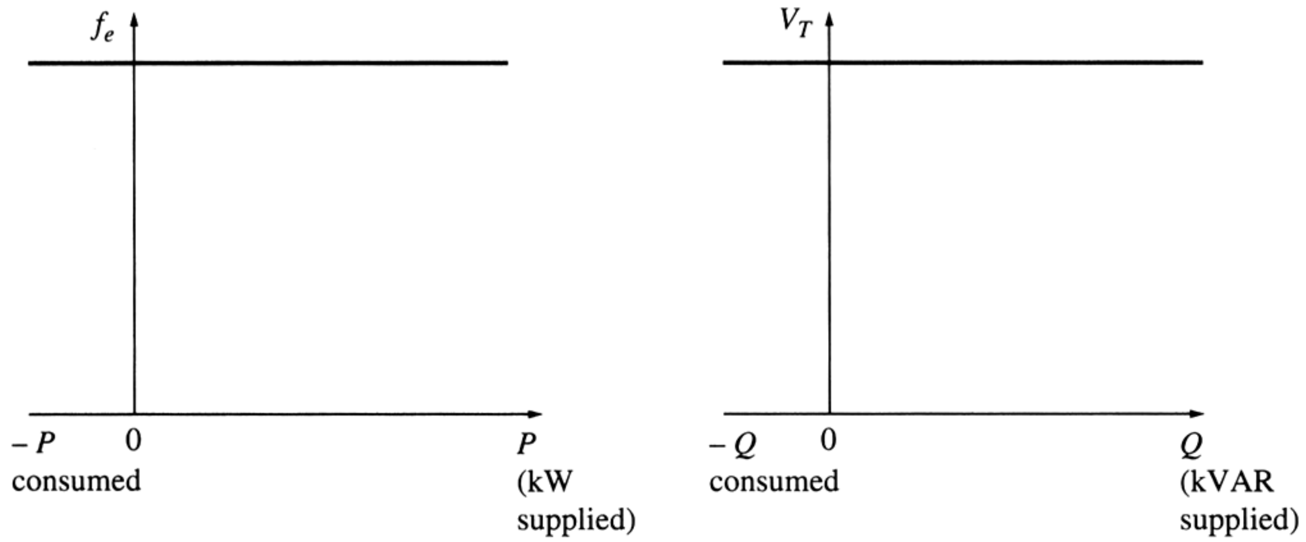
The simplest way to determine the moment when two generators are in phase is by observing the same three light bulbs. When all three lights go out, the voltage across them is zero and, therefore, machines are in phase.

A more accurate way is to use a synchroscope – a meter measuring the difference in phase angles between two *a* phases. However, a synchroscope does not check the phase sequence since it only measures the phase difference in one phase.

The whole process is usually automated…

Operation of generators in parallel with large power systems

Often, when a synchronous generator is added to a power system, that system is so large that one additional generator does not cause observable changes to the system. A concept of an infinite bus is used to characterize such power systems. An infinite bus is a power system that is so large that its voltage and frequency do not vary regardless of how much real and reactive power is drawn from or supplied to it. The power-frequency and reactive power-voltage characteristics are:

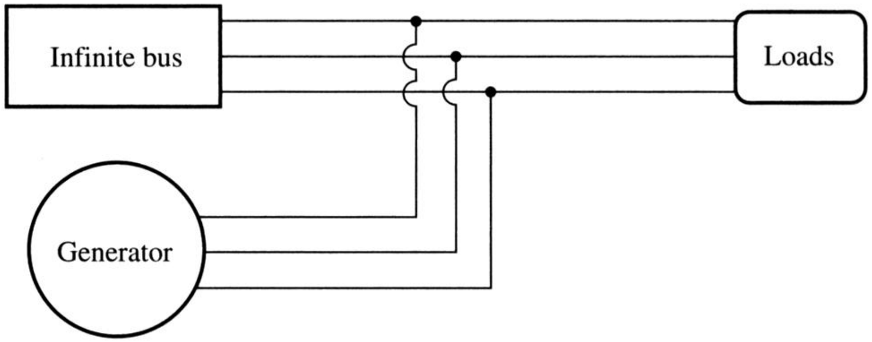


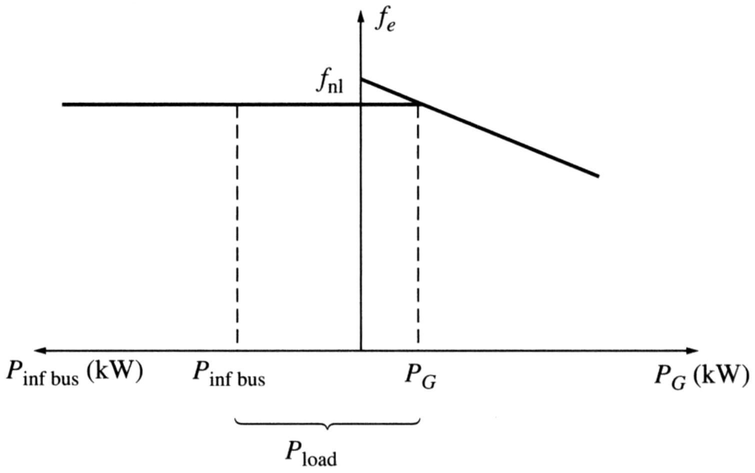
Operation of generators in parallel with large power systems

Consider adding a generator to an infinite bus supplying a load.

The frequency and terminal voltage of all machines must be the same. Therefore, their power-frequency and reactive power-voltage characteristics can be plotted with a common vertical axis.

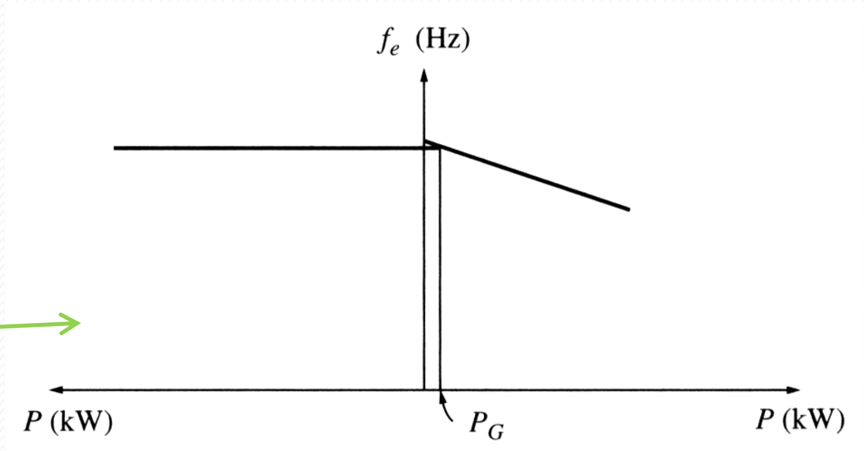
Such plots are called sometimes as house





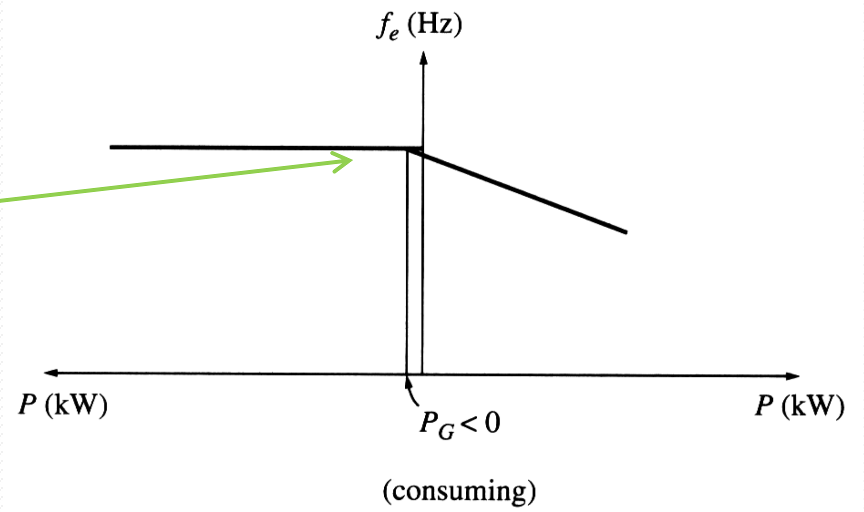
Operation of generators in parallel with large power systems

If the no-load frequency of the oncoming generator is slightly higher than the system’s frequency, the generator will be “floating” on the line supplying a small amount of real power and little or no reactive power.



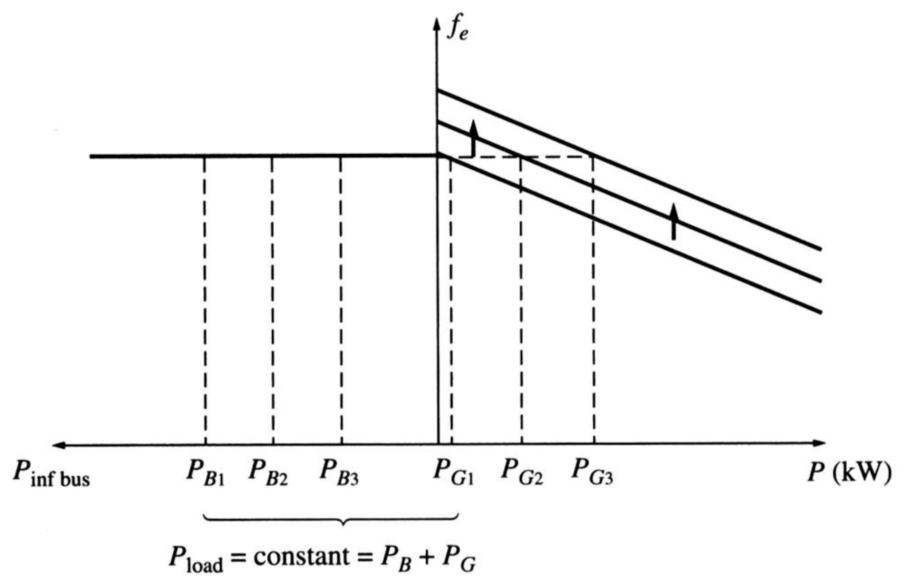
If the no-load frequency of the oncoming generator is slightly lower than the system’s frequency, the generator will supply a negative power to the system: the generator actually consumes energy acting as a motor!

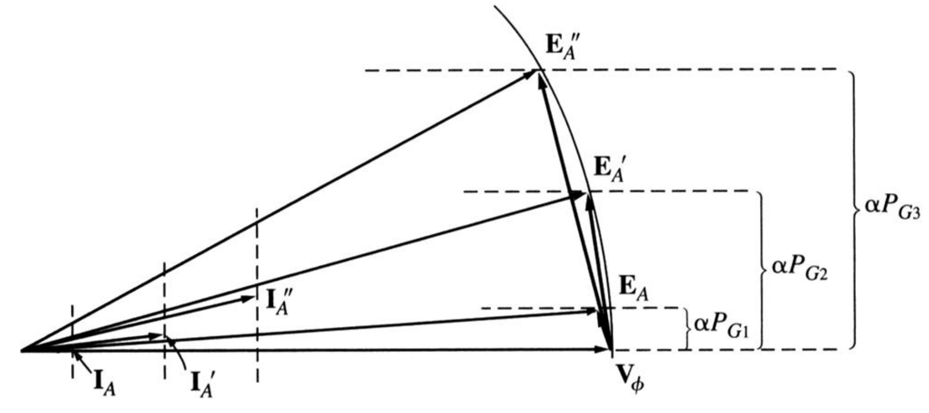
Many generators have circuitry automatically disconnecting them from the line when they start consuming energy.



Operation of generators in parallel with large power systems

If the frequency of the generator is increased after it is connected to the infinite bus, the system frequency cannot change and the power supplied by the generator increases.





Notice that when E_A stays constant (field current and speed are the same), $E_A\sin\delta$ (which is proportional to the output power if V_T is constant) increases.

If the frequency of the generator is further increased, power output from the generator will be increased and at some point it may exceed the power consumed by the load. This extra power will be consumed by the load.

Operation of generators in parallel with large power systems

After the real power of the generator is adjusted to the desired value, the generator will be operating at a slightly leading PF acting as a capacitor that consumes reactive power. Adjusting the field current of the machine, it is possible to make it to supply reactive power *Q* to the system.

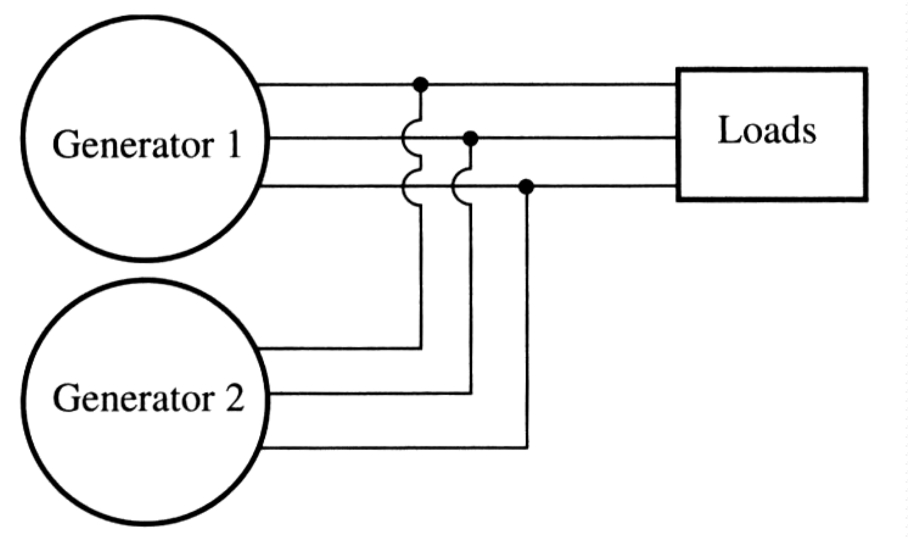
Summarizing, when the generator is operating in parallel to an infinite bus:

1. The frequency and terminal voltage of the generator are controlled by the system to which it is connected.
2. The governor set points of the generator control the real power supplied by the generator to the system.
3. The generator’s field current controls the reactive power supplied by the generator to the system.

Generators in parallel with other generators of the same size

When a generator is working alone, its real and reactive power are fixed and determined by the load.
When a generator is connected to an infinite bus, its frequency and the terminal voltage are constant and determined by a bus.

When two generators of the same size are connected to the same load, the sum of the real and reactive powers supplied by the two generators must equal the real and reactive powers demanded by the load:

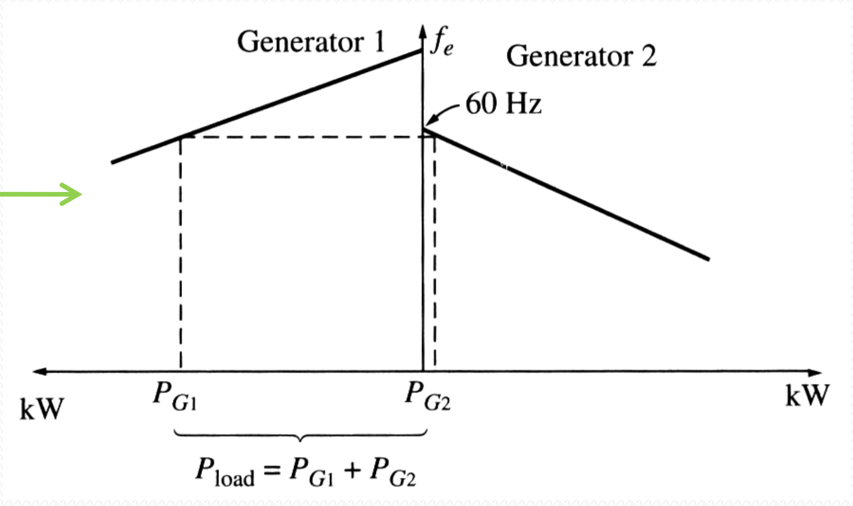


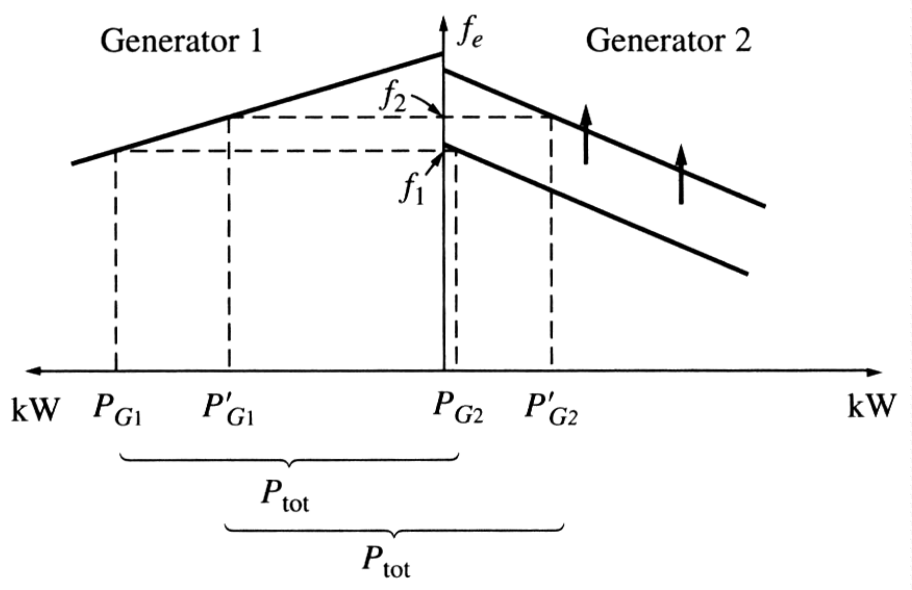
$$P_{tot} = P_{load} = P_{G1} + P_{G2}$$

$$Q_{tot} = Q_{load} = Q_{G1} + Q_{G2}$$

Generators in parallel with other generators of the same size

Since the frequency of G_2 must be slightly higher than the system's frequency, the power-frequency diagram right after G_2 is connected to the system is shown.





If the frequency of G_2 is next increased, its power-frequency diagram shifts upwards. Since the total power supplied to the load is constant, G_2 starts supplying more power and G_1 starts supplying less power and the system's frequency increases.

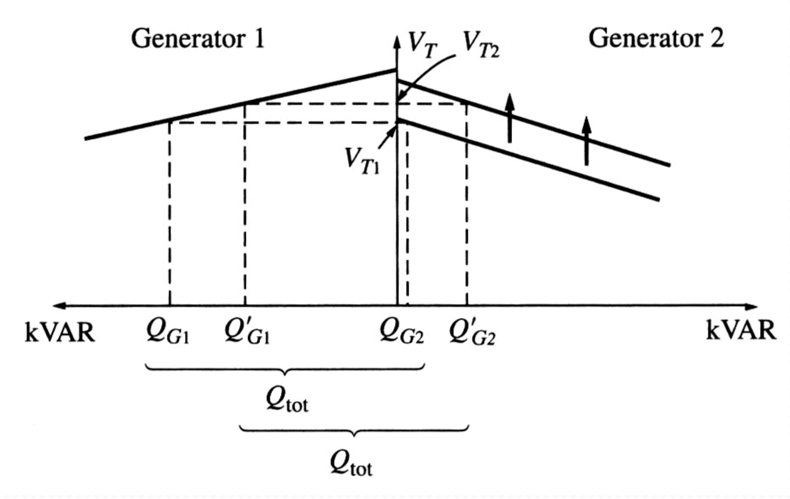
Generators in parallel with other generators of the same size

Therefore, when two generators are operating together, an increase in frequency (governor set point) on one of them:

1. Increases the system frequency.
2. Increases the real power supplied by that generator, while reducing the real power supplied by the other one.

When two generators are operating together, an increase in the field current on one of them:

1. Increases the system terminal voltage.
2. Increases the reactive power supplied by that generator, while reducing the reactive power supplied by the other.

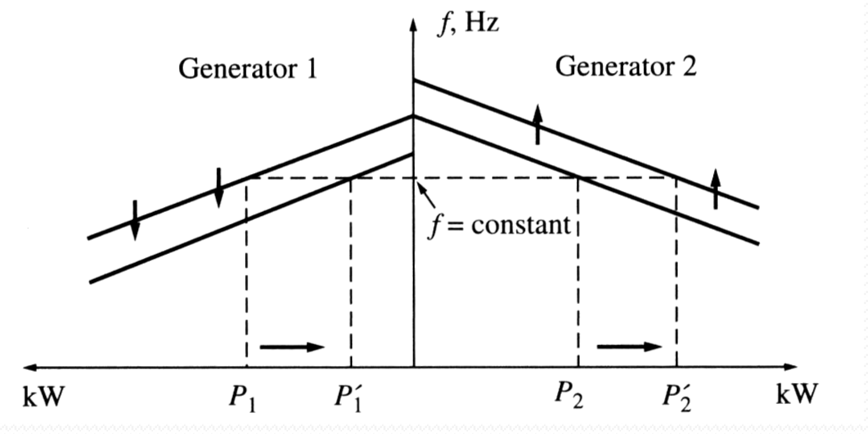


If the frequency-power curves of both generators are known, the powers supplied by each generator and the resulting system frequency can be determined.

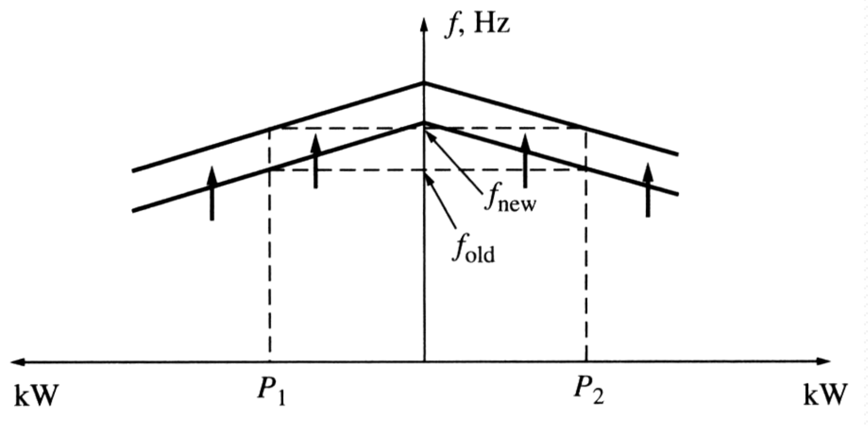
Generators in parallel with other generators of the same size

When two generators of the same size are working in parallel, a change in frequency (governor set points) of one of them changes both the system frequency and power supplied by each generator.

To adjust power sharing without changing the system frequency, we need to increase the frequency (governor set points) of one generator and simultaneously decrease the frequency of the other generator.

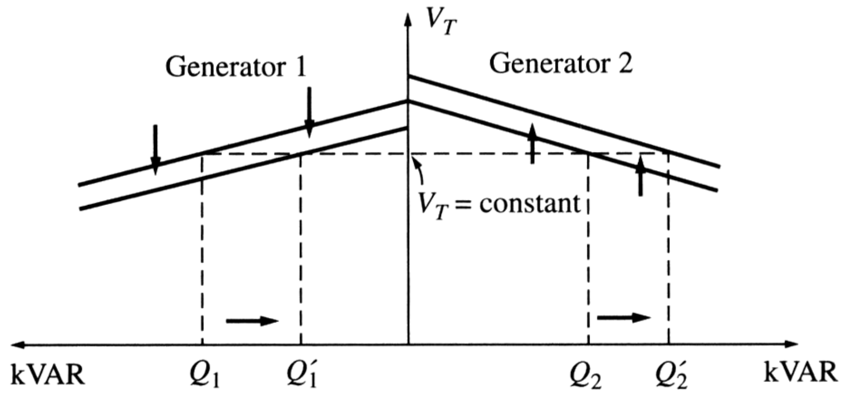


To adjust the system frequency without changing power sharing, we need to simultaneously increase or decrease the frequency (governor set points) of both generators.

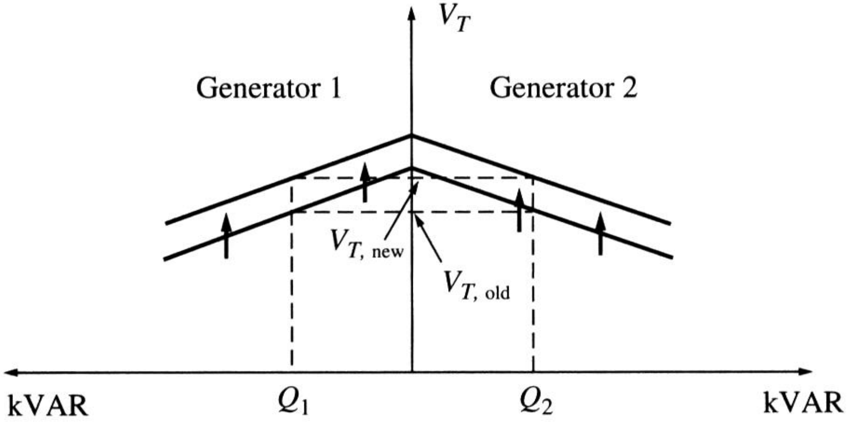


Generators in parallel with other generators of the same size

Similarly, to adjust the reactive power sharing without changing the terminal voltage, we need to increase simultaneously the field current of one generator and decrease the field current of the other generator.



To adjust the terminal voltage without changing the reactive power sharing, we need to simultaneously increase or decrease the field currents of both generators.



Parallel operation of synchronous generators

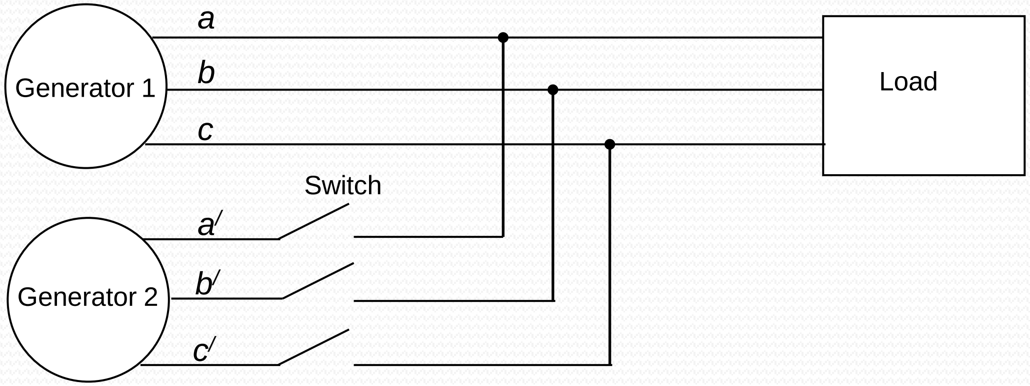
There are several major advantages to operate generators in parallel:

- Several generators can supply a bigger load than one machine by itself.
- Having many generators increases the reliability of the power system.
- It allows one or more generators to be removed for shutdown or preventive maintenance.

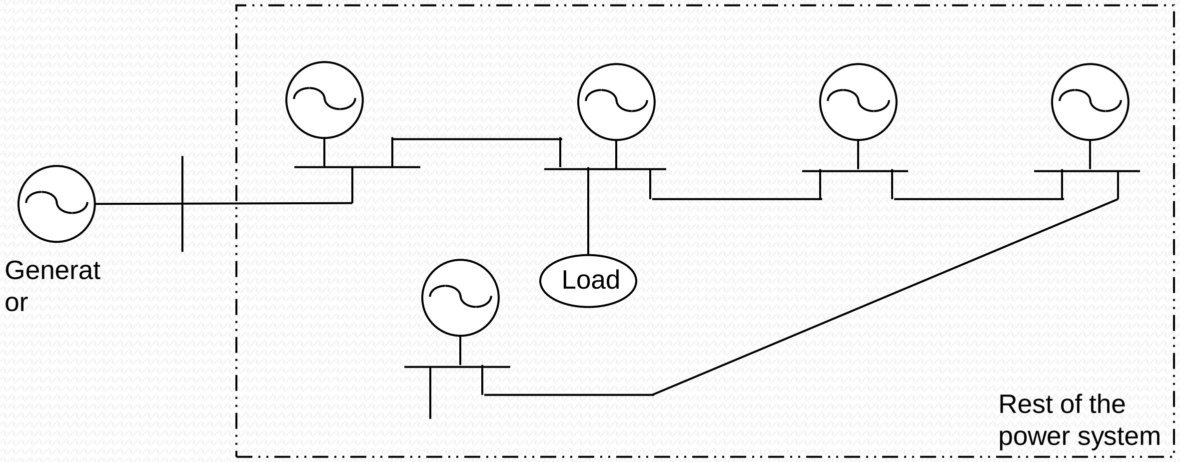
Synchronization

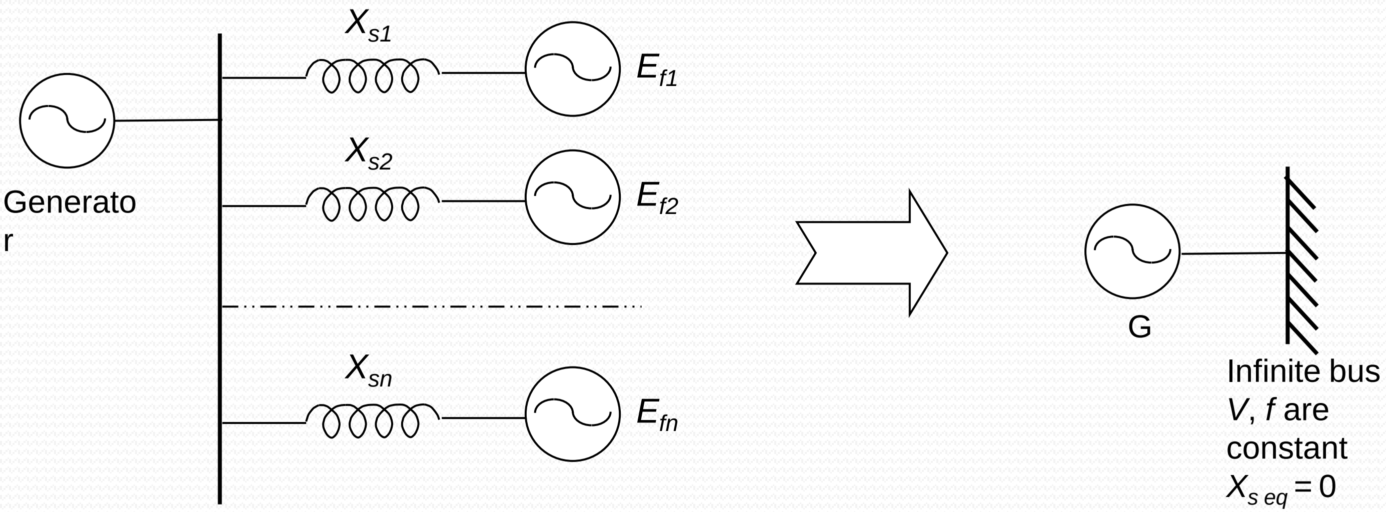
Before connecting a generator in parallel with another generator, it must be synchronized. A generator is said to be synchronized when it meets all the following conditions:

- The *rms line voltages* of the two generators must be equal.
- The two generators must have the same *phase sequence*.
- The *phase angles* of the two *a* phases must be equal.
- The *oncoming generator frequency* is equal to the running system frequency.



Synchronization





Concept of the infinite bus

When a synchronous generator is connected to a power system, the power system is often so large that nothing the operator of the generator does will have much of an effect on the power system. An example of this situation is the connection of a single generator to the Canadian power grid. Our Canadian power grid is so large that no reasonable action on the part of one generator can cause an observable change in overall grid frequency. This idea is idealized in the concept of an infinite bus. *An infinite bus is a power system so large that its voltage and frequency do not vary regardless of how much real or reactive power is drawn from or supplied to it.*

Active and reactive power-angle characteristics

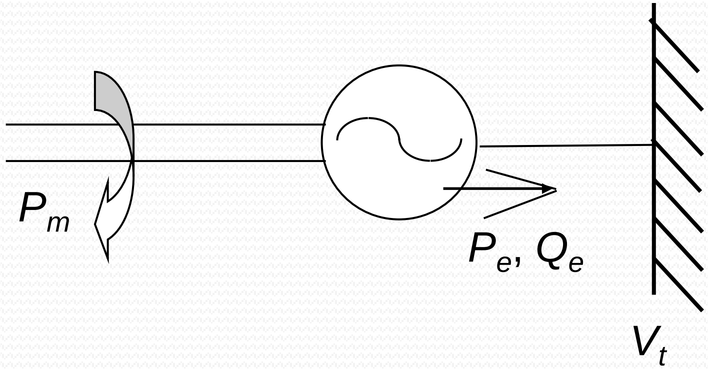
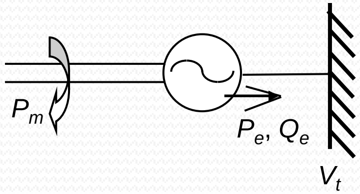


Fig. Synchronous generator connected to an infinite bus.

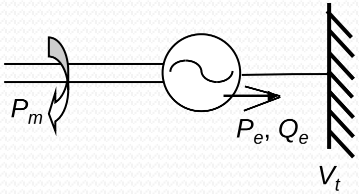
- $P>0$: generator operation
- $P<0$: motor operation
- Positive Q: delivering inductive vars for a generator action or receiving inductive vars for a motor action
- Negaive Q: delivering capacitive vars for a generator action or receiving capacitive vars for a motor action

Active and reactive power-angle characteristics



- The real and reactive power delivered by a synchronous generator or consumed by a synchronous motor can be expressed in terms of the terminal voltage V_t, generated voltage E_f, synchronous impedance Z_s, and the power angle or torque angle δ.
- Referring to Fig. 8, it is convenient to adopt a convention that makes positive real power P and positive reactive power Q delivered by an *overexcited generator*.
- The generator action corresponds to positive value of δ, while the motor action corresponds to negative value of δ.

Active and reactive power-angle characteristics



The complex power output of the generator in volt-amperes per phase is given by

$$S = P + jQ = \bar{V}_t\, I_a^*$$

where:

V_t = terminal voltage per phase

I_a^* = complex conjugate of the armature current per phase

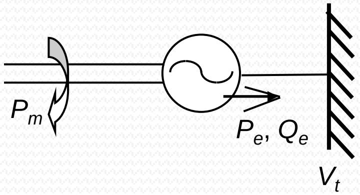
Taking the terminal voltage as reference

$$\bar{V}_t = V_t + j0$$

the excitation or the generated voltage,

$$\bar{E}_f = E_f\left(\cos\delta + j\sin\delta\right)$$

Active and reactive power-angle characteristics



and the armature current,

$$\bar{I}_a = \frac{\bar{E}_f - \bar{V}_t}{jX_s} = \frac{\left(E_f \cos\delta - V_t\right) + jE_f \sin\delta}{jX_s}$$

where X_s is the synchronous reactance per phase.

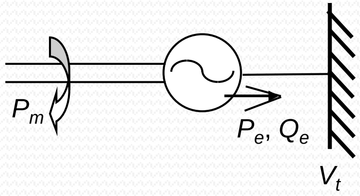
$$S = P + jQ = \bar{V}_t \bar{I}_a^* = V_t \left[\frac{\left(E_f \cos\delta - V_t\right) - jE_f \sin\delta}{-jX_s}\right]$$

$$= \frac{V_t E_f \sin\delta}{X_s} + j\frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

$$\therefore \quad P = \frac{V_t E_f \sin\delta}{X_s} \qquad \&$$

$$Q = \frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

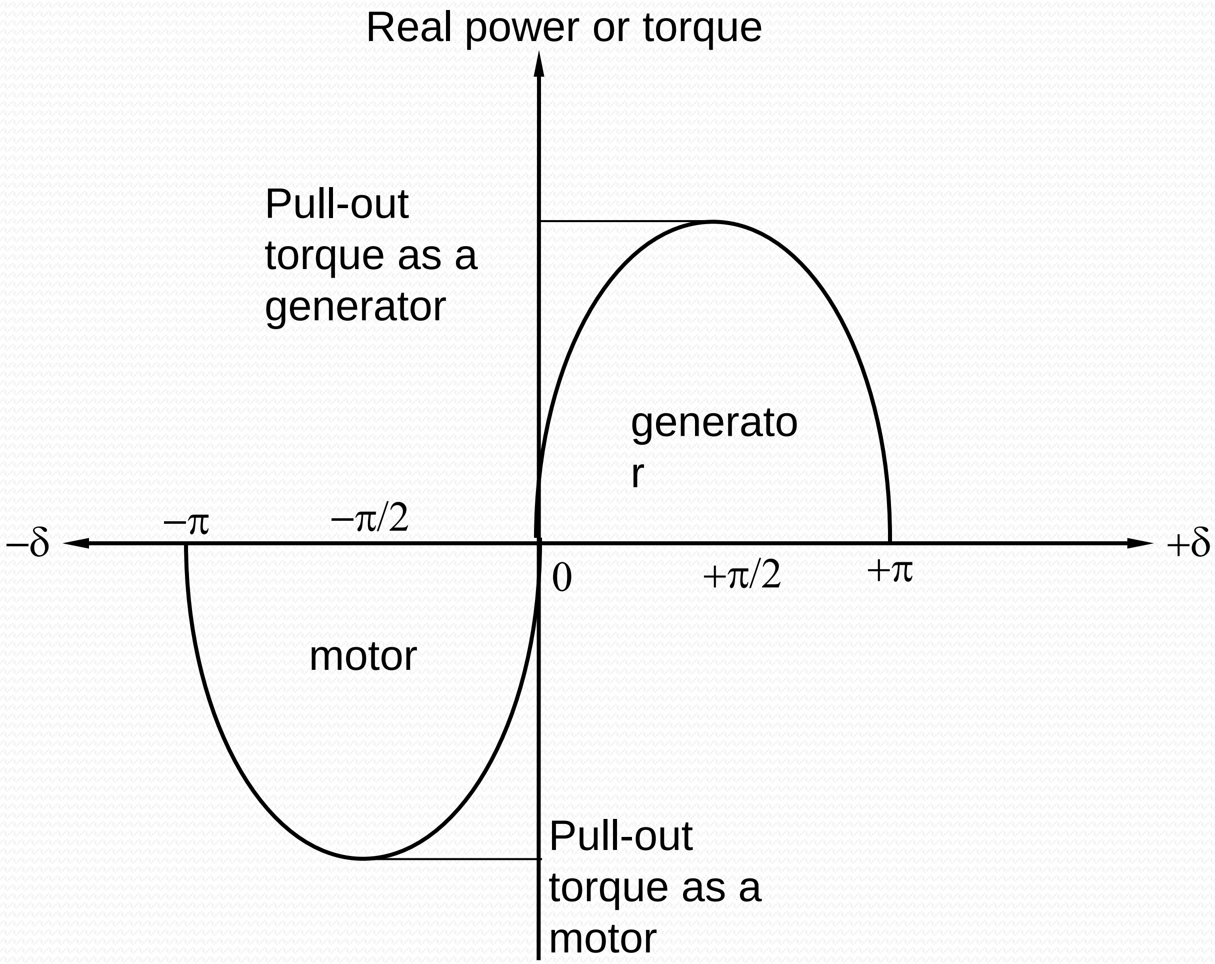
Active and reactive power-angle characteristics



$$\therefore \quad P = \frac{V_t E_f \sin\delta}{X_s} \qquad \& \qquad Q = \frac{V_t E_f \cos\delta - V_t^2}{X_s}$$

- The above two equations for active and reactive powers hold good for cylindrical-rotor synchronous machines for negligible resistance
- To obtain the total power for a three-phase generator, the above equations should be multiplied by 3 when the voltages are line-to-neutral
- If the line-to-line magnitudes are used for the voltages, however, these equations give the total three-phase power

Steady-state power-angle or torque-angle characteristic of a cylindrical-rotor synchronous machine (with negligible armature resistance).



Steady-state stability limit

Total three-phase power: $P = \frac{3V_t E_f}{X_s} \sin\delta$

The above equation shows that the power produced by a synchronous generator depends on the angle δ between the V_t and E_f. The maximum power that the generator can supply occurs when $\delta = 90^o$.

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

The maximum power indicated by this equation is called *steady-state stability limit* of the generator. If we try to exceed this limit (such as by admitting more steam to the turbine), the rotor will accelerate and lose synchronism with the infinite bus. In practice, this condition is never reached because the circuit breakers trip as soon as synchronism is lost. We have to resynchronize the generator before it can again pick up the load. Normally, real generators never even come close to the limit. Full-load torque angle of 15^o to 20^o are more typical of real machines.

Pull-out torque

The maximum torque or *pull-out torque* per phase that a two-pole round-rotor synchronous motor can develop is

$$T_{max} = \frac{P_{max}}{\omega_m} = \frac{P_{max}}{2\pi\left(n_s/60\right)}$$

where n_s is the synchronous speed of the motor in rpm

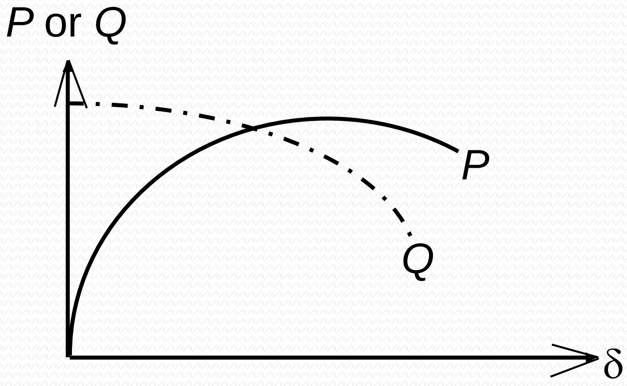
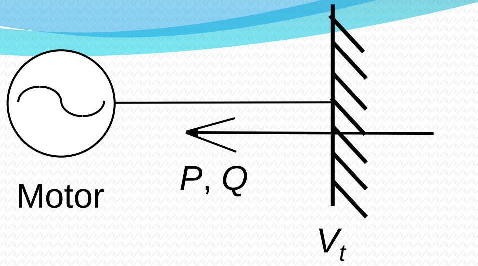


Fig. Active and reactive power as a function of the internal angle

Unit -IV

Synchronous Motor and Power circles

Synchronous Motors



- A synchronous motor is the same physical machine as a generator, except that the direction of real power flow is reversed
- Synchronous motors are used to convert electric power to mechanical power
- Most synchronous motors are rated between 150 kW (200 hp) and 15 MW (20,000 hp) and turn at speed ranging from 150 to 1800 r/min. Consequently, these machines are used in heavy industry
- At the other end of the power spectrum, we find tiny single-phase synchronous motors used in control devices and electric clocks

Operation Principle

- The field current of a synchronous motor produces a steady-state magnetic field B_R
- A three-phase set of voltages is applied to the stator windings of the motor, which produces a three-phase current flow in the windings. This three-phase set of currents in the armature winding produces a uniform rotating magnetic field of B_s
- Therefore, there are two magnetic fields present in the machine, and *the rotor field will tend to line up with the stator field*, just as two bar magnets will tend to line up if placed near each other.
- Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will try to catch up
- The larger the angle between the two magnetic fields (up to certain maximum), the greater the torque on the rotor of the machine

Vector Diagram

- The equivalent circuit of a synchronous motor is exactly same as the equivalent circuit of a synchronous generator, except that the reference direction of I_a is reversed.
- The basic difference between motor and generator operation in synchronous machines can be seen either in the magnetic field diagram or in the phasor diagram.
- In a generator, E_f lies ahead of V_t, and B_R lies ahead of B_{net}. In a motor, E_f lies behind V_t, and B_R lies behind B_{net}.
- In a motor the induced torque is in the direction of motion, and in a generator the induced torque is a countertorque opposing the direction of motion

Vector Diagram

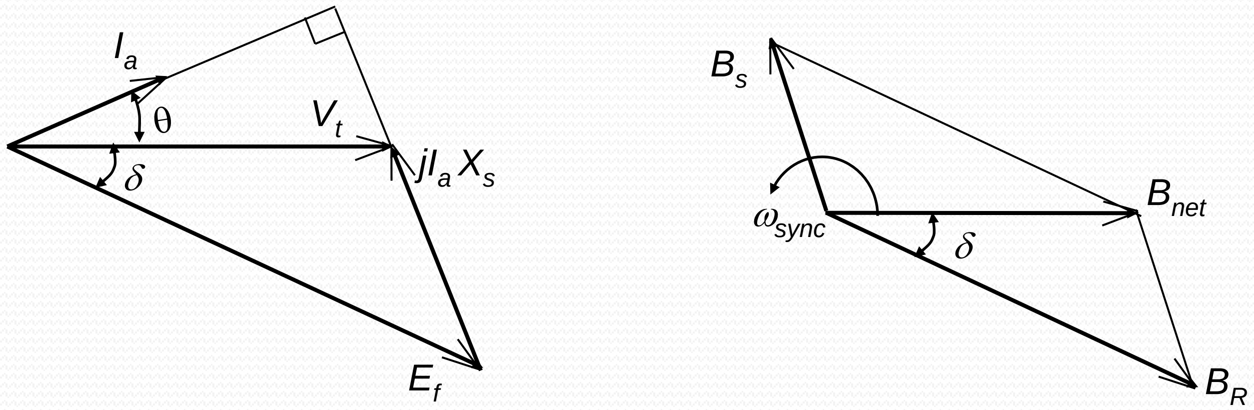


Fig. The phasor diagram (leading PF: overexcited and $|V_t|<|E_f|$) and the corresponding magnetic field diagram of a synchronous motor.

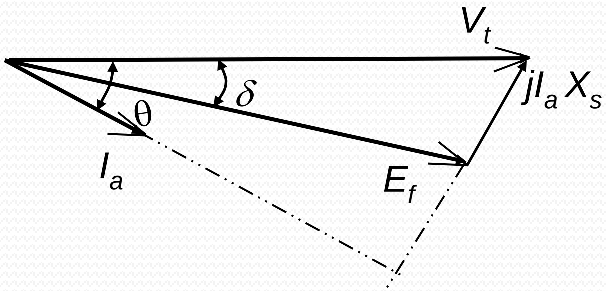


Fig. The phasor diagram of an underexcited synchronous motor (lagging PF and $|V_t|>|E_f|$).

Effect of Field Change (Load constant)

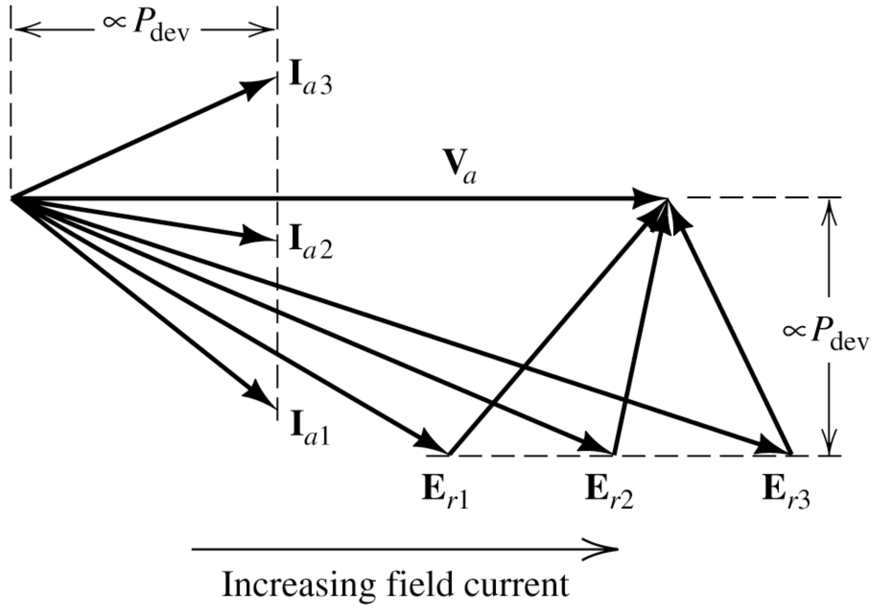


Figure 17.22 Phasor diagram for constant developed power and increasing field current.

Note: E_r same as E_f
V_a same as V_t
R_a has been neglected

Question: 1)Why is the loci of stator current and excitation voltage moves on a straight line?

2) What is happening to power factor as field is changed?

V curves

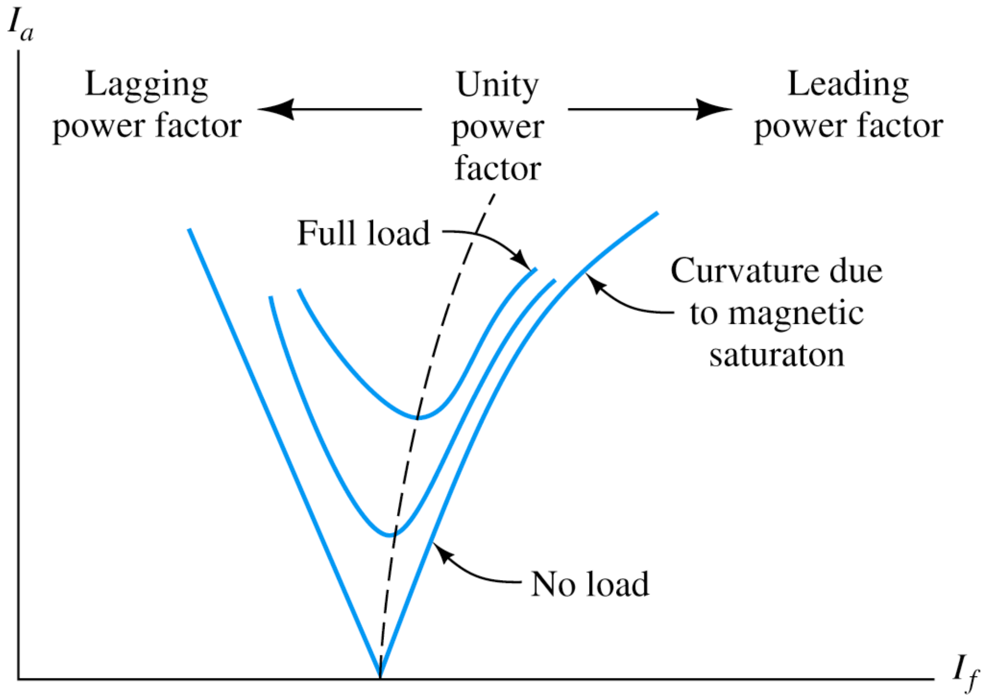
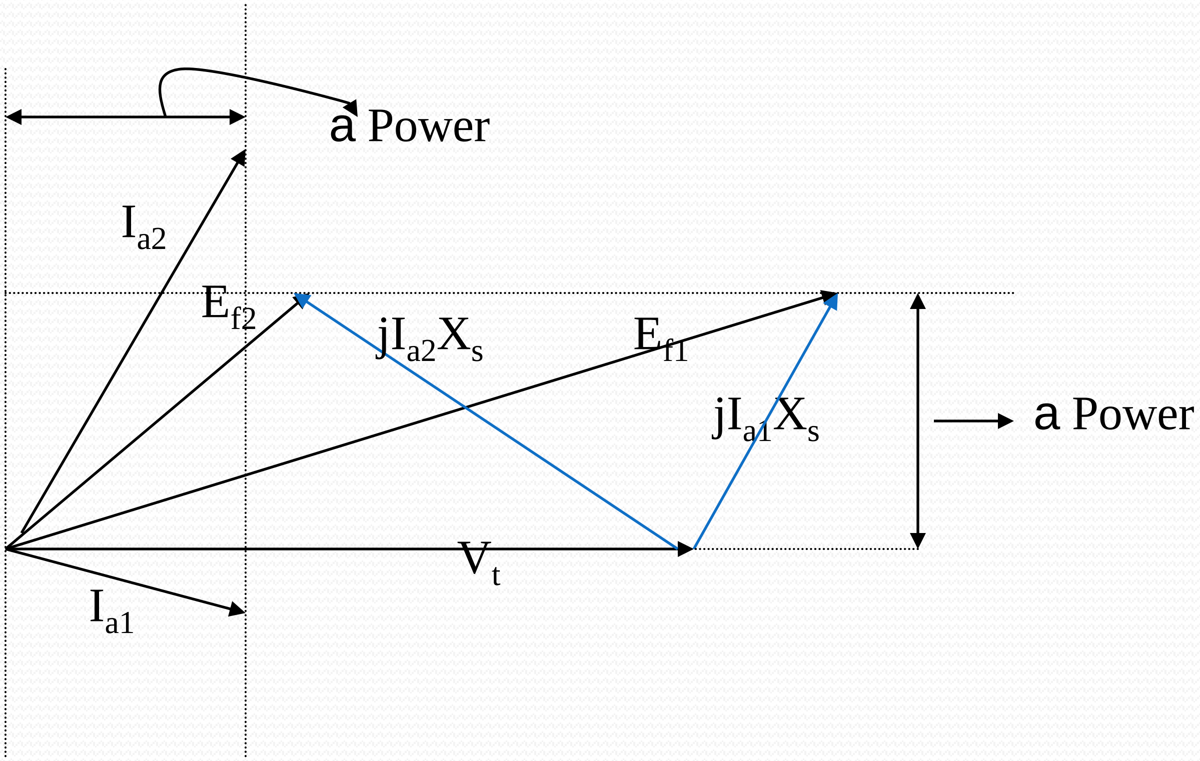


Figure 17.23 V curves for a synchronous motor with variable excitation.

Effect of Field Change (Load constant) for a generator



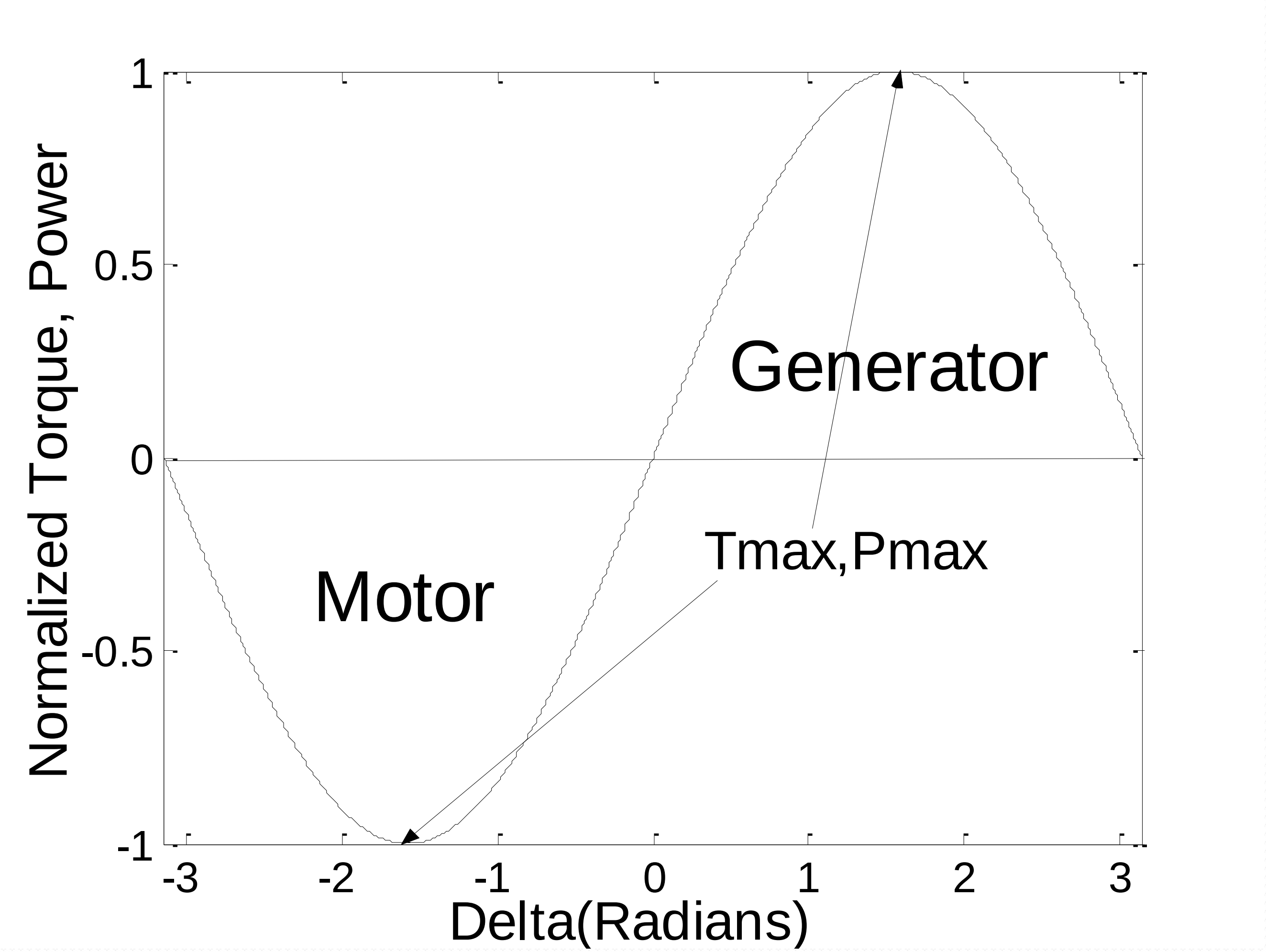
Conclusion for effect for field change with constant load on power factor

- For motor with increased (decreased)excitation power factor becomes leading (lagging)

- For generator with increased (decreased) excitation power factor becomes lagging (leading)

- *Unloaded* overexcited synchronous motors are sometimes used to improve power factor. They are known as *synchronous condensers*

Torque versus Electrical Load Angle



Torque versus Speed

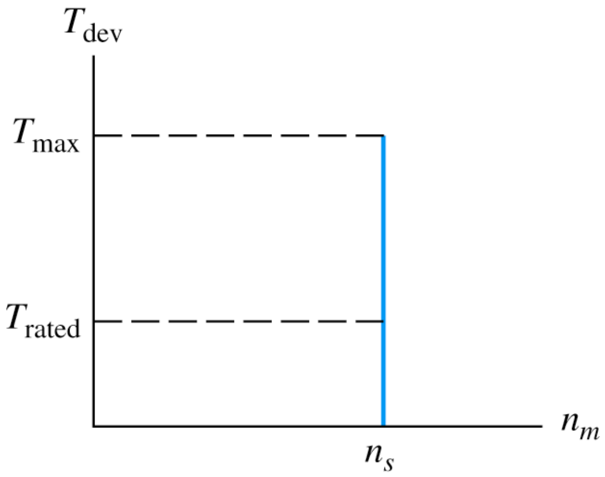
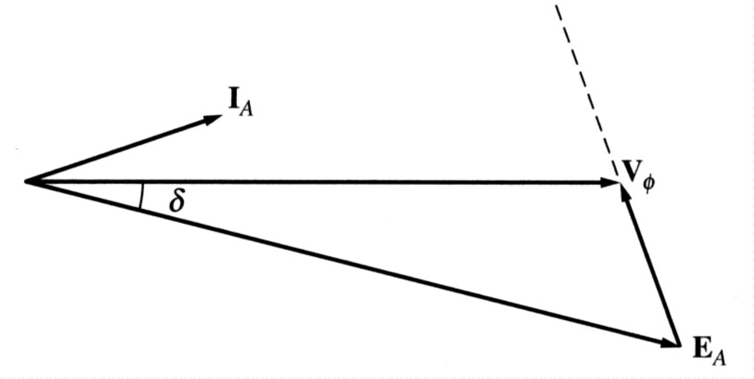


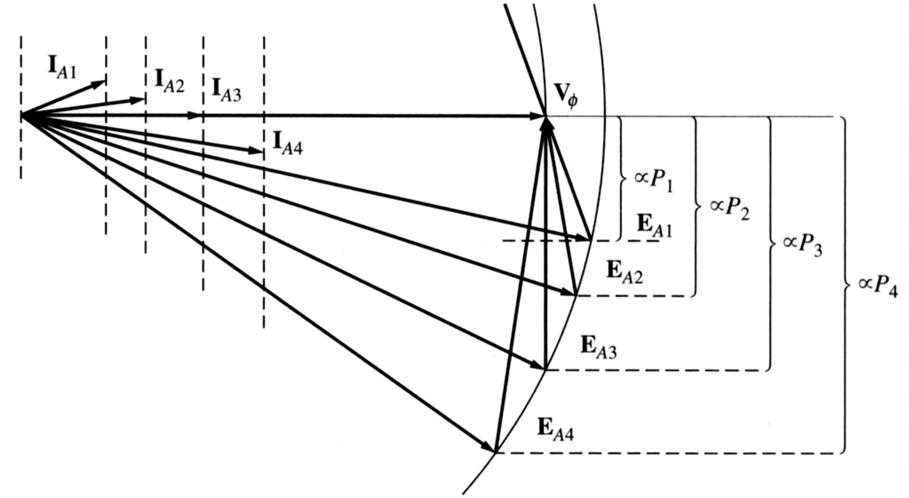
Figure 17.26 Torque–speed characteristic of synchronous motors.

Steady-state operation of motor: 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).

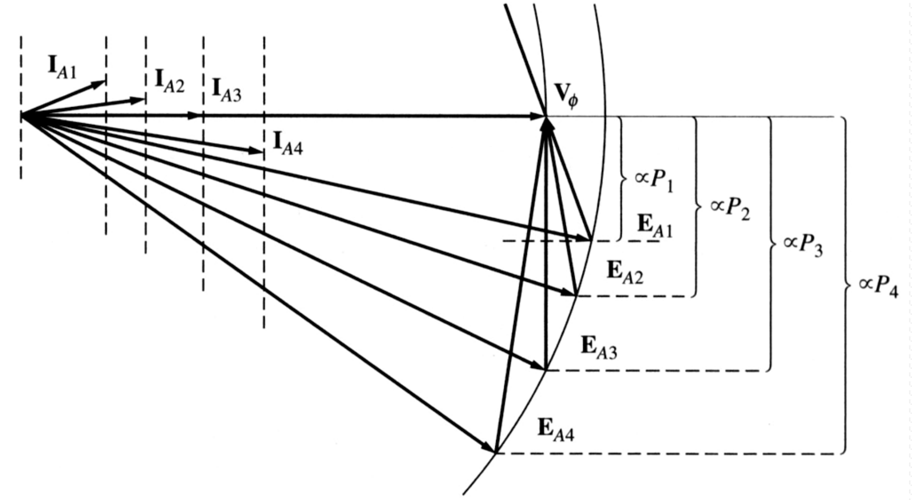


Steady-state operation of motor: Effect of torque changes

Assuming that the armature resistance is negligible, the power converted from electrical to mechanical form in the motor will be the same as its input power:

Since the phase voltage is constant, the quantities $I_A cos\theta$ and $E_A sin\delta$ are directly proportional to the power supplied by (and to) the motor. When the power supplied by the motor increases, the distance proportional to power increases.

Since the internal generated voltage is constant, its phasor “swings down” as load increases. The quantity $jX_S I_A$ has to increase; therefore, the armature current I_A increases too.



Application of Synchronous Motors

Synchronous motors are usually used in large sizes because in small sizes they are costlier as compared with induction machines. The principal advantages of using synchronous machine are as follows:

- Power factor of synchronous machine can be controlled very easily by controlling the field current.
- It has very high operating efficiency and constant speed.
- For operating speed less than about 500 rpm and for high-power requirements (above 600KW) synchronous motor is cheaper than induction motor.

In view of these advantages, synchronous motors are preferred for driving the loads requiring high power at low speed; e.g; reciprocating pumps and compressor, crushers, rolling mills, pulp grinders etc.

Unit-V

Single Phase motors and Special Machines

Introduction

- Although all electric machines have the same basic principle of operation, special-purpose machines have some features that distinguish them from conventional machines.
- It is not our intention to discuss all kinds of special-purpose machines in one chapter; rather, an attempt is made to introduce the basic operating principles of some special-purpose machines that are being used extensively in home, recreational, and industrial applications.
- With the proliferation of power electronic circuits and digital control systems, precise speed and position control can be achieved in conjunction with special-purpose electric machines such as permanent-magnet (PM) motors, step motors, switched-reluctance motors, brushless direct-current (dc) motors, hysteresis motors, and linear motors.

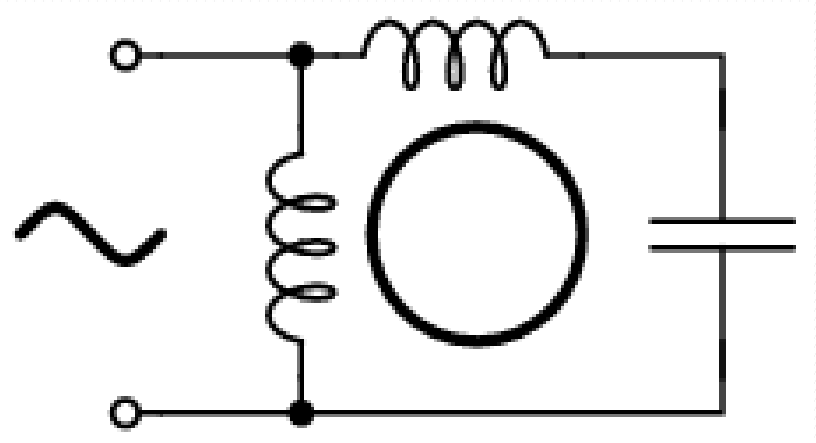
Introduction

- Some of these devices find applications in computer peripheral equipment or in process-control systems whereas others can be used in devices such as home appliances.
- For example, step motors are employed extensively in computers where precise positioning is required, as in the case of a magnetic head for a disk drive.
- For applications that demand constant-speed drives, brushless dc motors offer excellent characteristics.
- Switched-reluctance motors, on the other hand, find applications where we traditionally use dc or induction motors.
- In the following sections we discuss the construction, operating principles, and characteristics of each of the above-mentioned special-purpose electric machines.

Single Phase Induction

Permanent-split capacitor motor

One way to solve the single phase problem is to build a 2-phase motor, deriving 2-phase power from single phase. This requires a motor with two windings spaced apart 90º electrical, fed with two phases of current displaced 90º in time. This is called a permanent-split capacitor motor in Figure



Main and Auxiliary windings

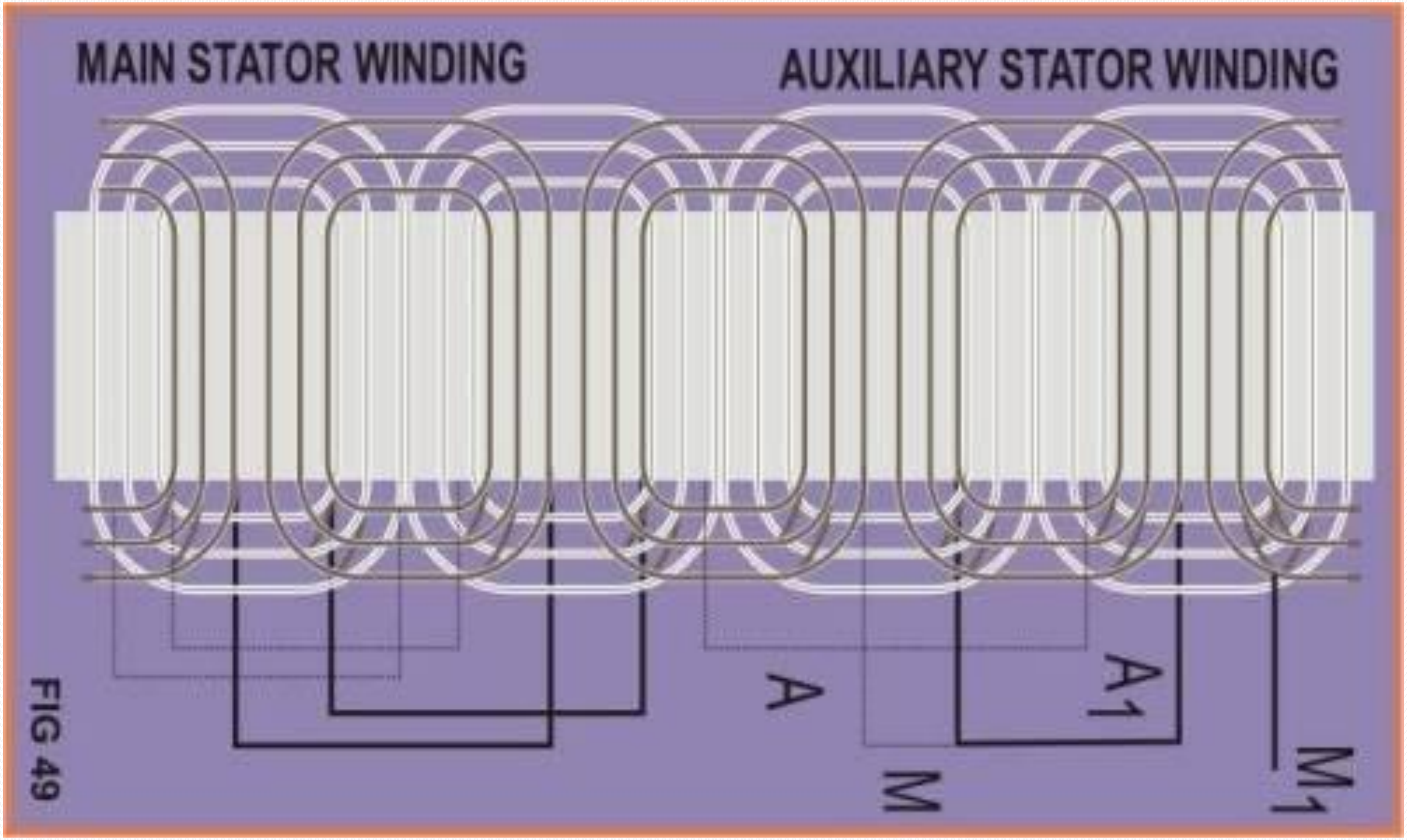


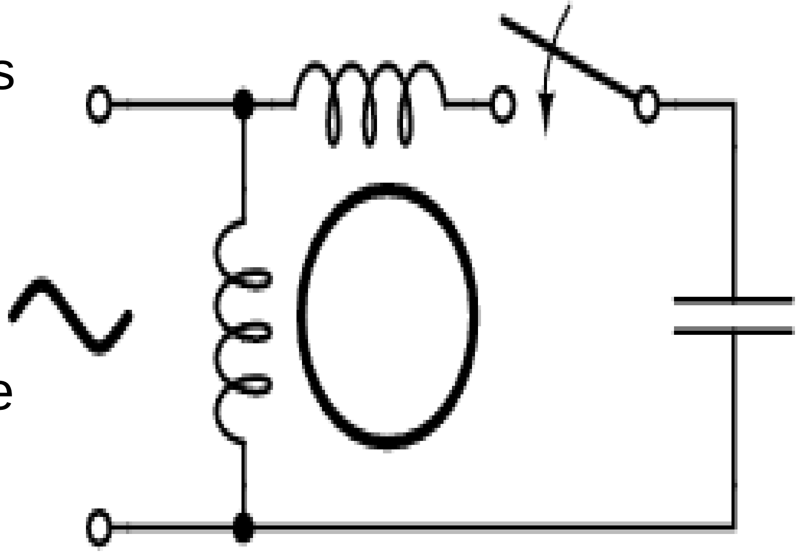
FIG 49

1-Phase Induction Motor

- This type of motor suffers increased current magnitude and backward time shift as the motor comes up to speed, with torque pulsations at full speed. The solution is to keep the capacitor (impedance) small to minimize losses. The losses are less than for a shaded pole motor.
- This motor configuration works well up to 1/4 horsepower (200watt), though, usually applied to smaller motors. The direction of the motor is easily reversed by switching the capacitor in series with the other winding. This type of motor can be adapted for use as a servo motor, described elsewhere is this chapter

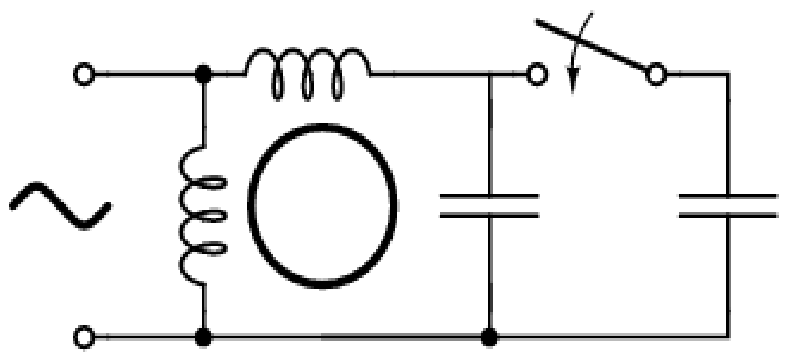
Capacitor-start induction motor

In Figure a larger capacitor may be used to start a single phase induction motor via the auxiliary winding if it is switched out by a centrifugal switch once the motor is up to speed. Moreover, the auxiliary winding may be many more turns of heavier wire than used in a resistance split-phase motor to mitigate excessive temperature rise. The result is that more starting torque is available for heavy loads like air conditioning compressors. This motor configuration works so well that it is available in multi-horsepower (multi-kilowatt) sizes.



Capacitor-run motor induction motor

A variation of the capacitor-start motor Figure is to start the motor with a relatively large capacitor for high starting torque, but leave a smaller value capacitor in place after starting to improve running characteristics while not drawing excessive current. The additional complexity of the capacitor-run motor is justified for larger size motors.



1-phase Capacitor start

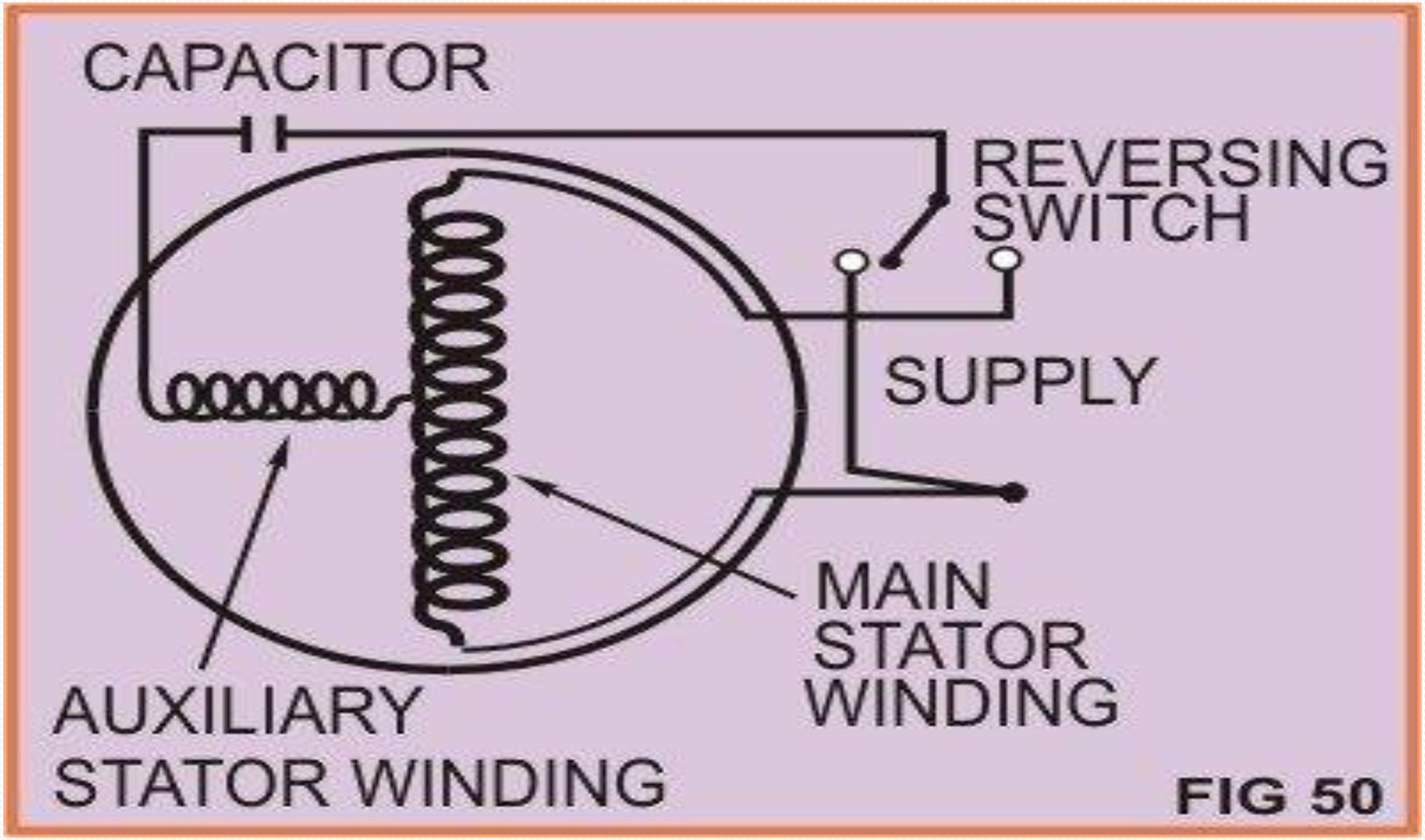


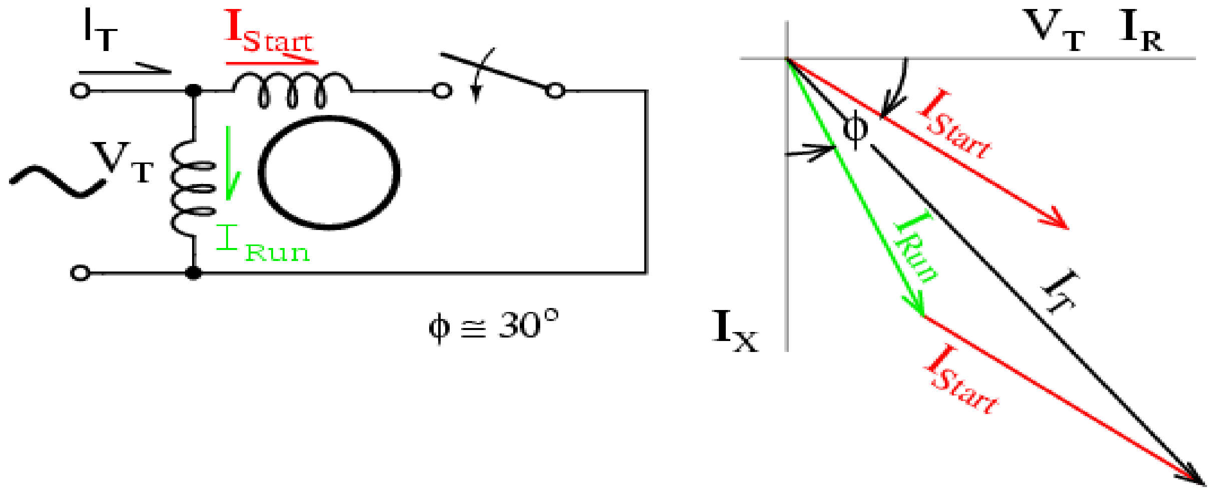
FIG 50

Capacitor Start-Run Induction Motor

- A motor starting capacitor may be a double-anode non-polar electrolytic capacitor which could be two + to + (or - to -) series connected polarized electrolytic capacitors. Such AC rated electrolytic capacitors have such high losses that they can only be used for intermittent duty (1 second on, 60 seconds off) like motor starting. A capacitor for motor running must not be of electrolytic construction, but a lower loss polymer type.

Resistance split-phase motor induction motor

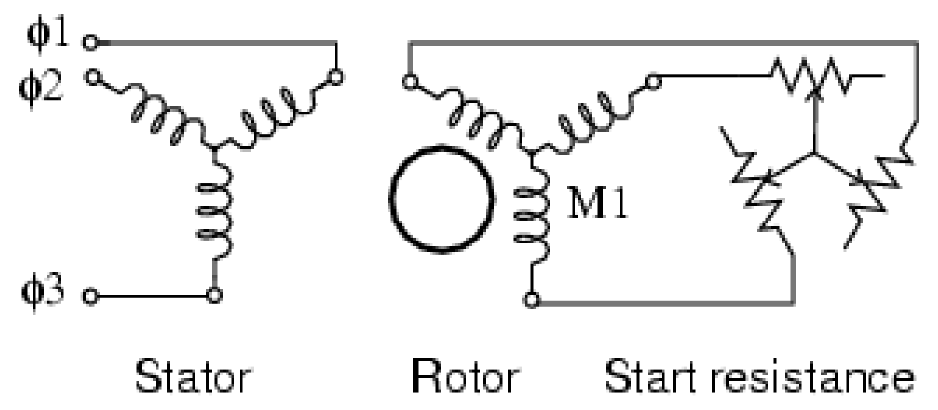
If an auxiliary winding of much fewer turns of smaller wire is placed at 90° electrical to the main winding, it can start a single phase induction motor. With lower inductance and higher resistance, the current will experience less phase shift than the main winding. About 30° of phase difference may be obtained. This coil produces a moderate starting torque, which is disconnected by a centrifugal switch at 3/4 of synchronous speed. This simple (no capacitor) arrangement serves well for motors up to 1/3 horsepower (250 watts) driving easily started loads.



Wound rotor induction motors

A *wound rotor* induction motor has a stator like the squirrel cage induction motor, but a rotor with insulated windings brought out via slip rings and brushes. However, no power is applied to the slip rings. Their sole purpose is to allow resistance to be placed in series with the rotor windings while starting.

This resistance is shorted out once the motor is started to make the rotor look electrically like the squirrel cage counterpart.



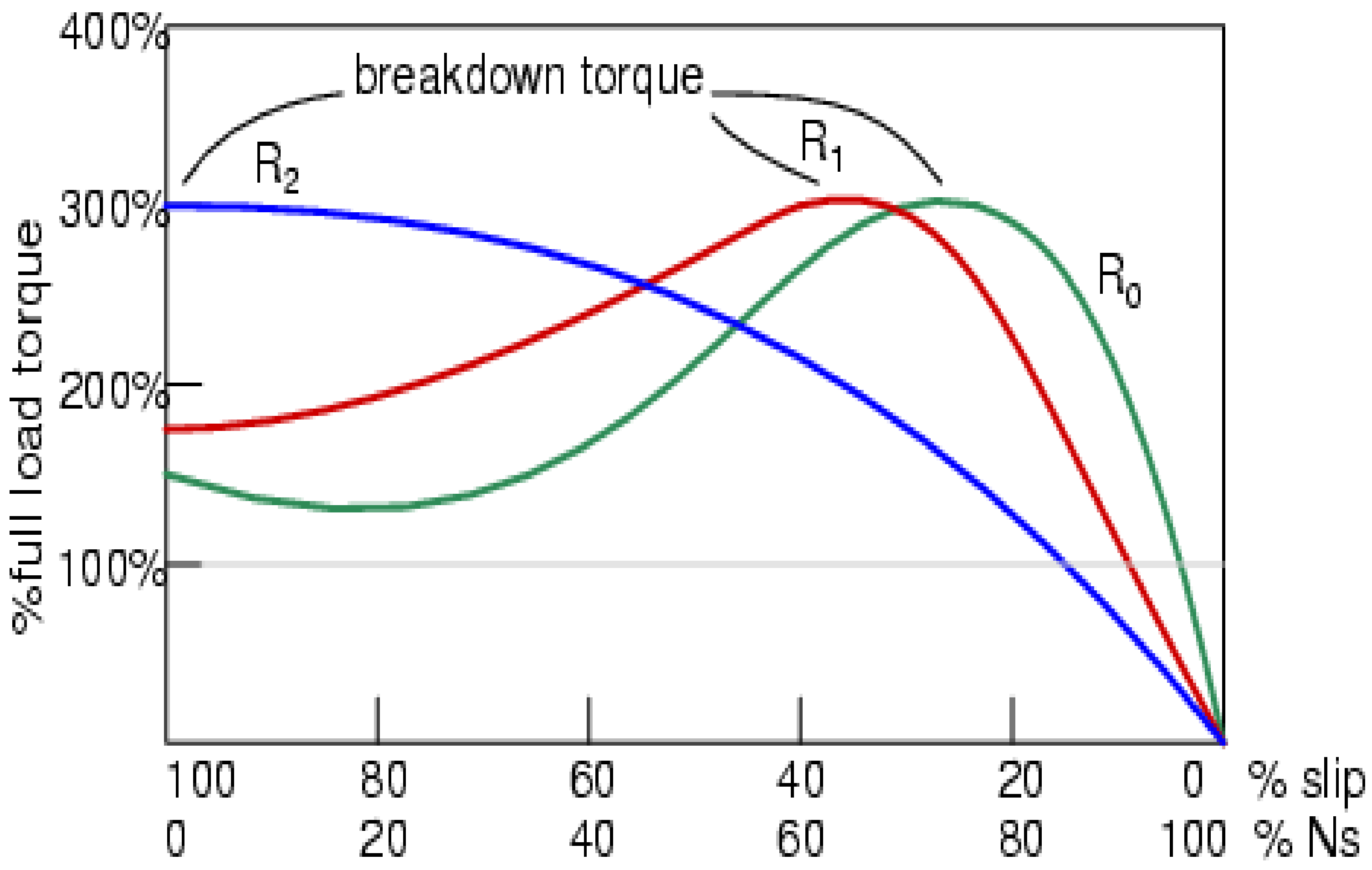
Wound Rotor Induction Motor

- Why put resistance in series with the rotor? Squirrel cage induction motors draw 500% to over 1000% of full load current (FLC) during starting. While this is not a severe problem for small motors, it is for large (10's of kW) motors. Placing resistance in series with the rotor windings not only decreases start current, locked rotor current (LRC), but also increases the starting torque, locked rotor torque (LRT).

Wound Rotor Induction M/C

- Figure shows that by increasing the rotor resistance from R_0 to R_1 to R_2, the breakdown torque peak is shifted left to zero speed. Note that this torque peak is much higher than the starting torque available with no rotor resistance (R_0) Slip is proportional to rotor resistance, and pullout torque is proportional to slip. Thus, high torque is produced while starting.

Wound Rotor Induction Motor



Wound Rotor Induction M/C

- The resistance decreases the torque available at full running speed. But that resistance is shorted out by the time the rotor is started. A shorted rotor operates like a squirrel cage rotor. Heat generated during starting is mostly dissipated external to the motor in the starting resistance. The complication and maintenance associated with brushes and slip rings is a disadvantage of the wound rotor as compared to the simple squirrel cage rotor.

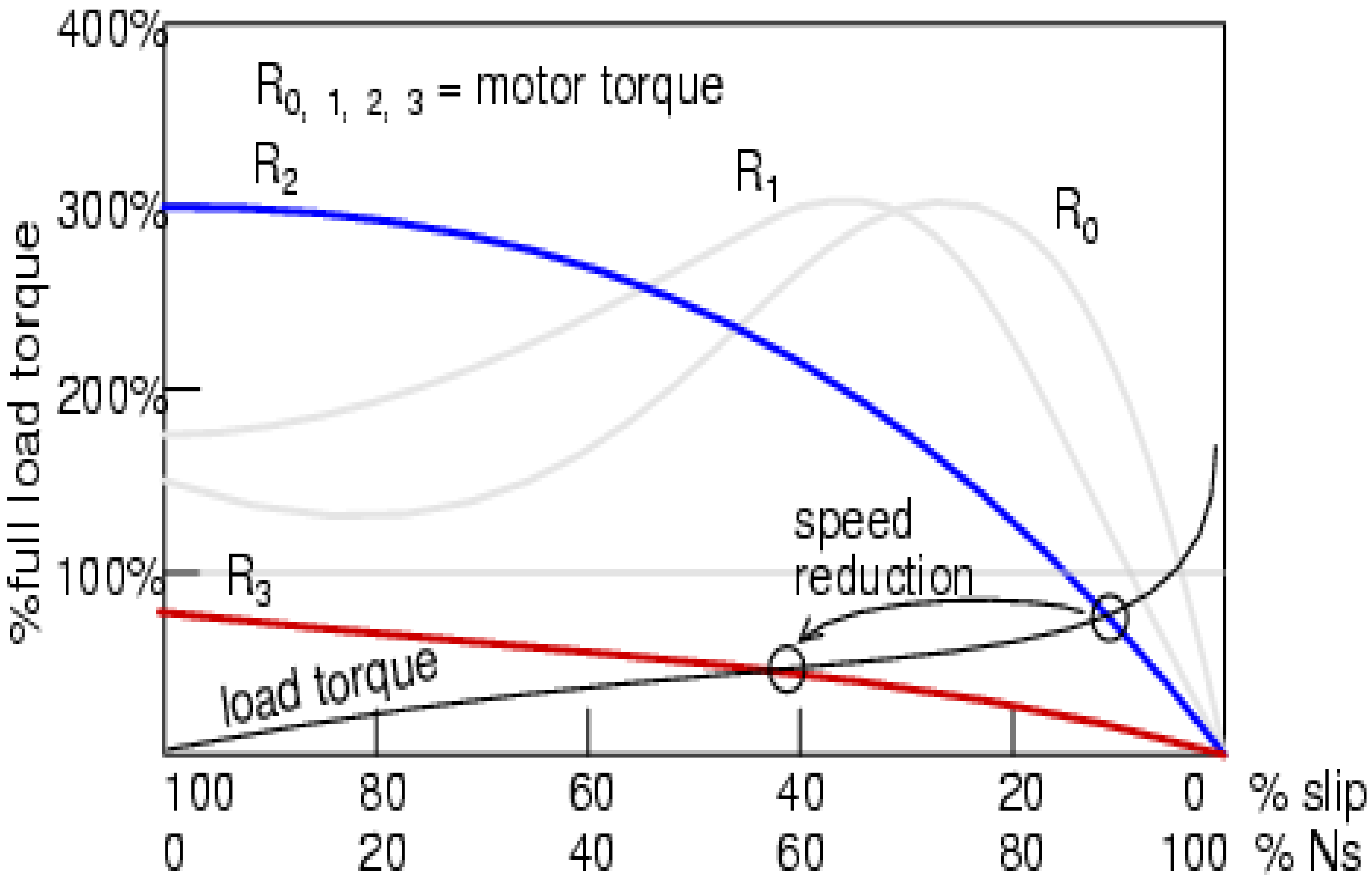
Wound Rotor Induction

- This motor is suited for starting high inertial loads. A high starting resistance makes the high pull out torque available at zero speed. For comparison, a squirrel cage rotor only exhibits pull out (peak) torque at 80% of its' synchronous speed

Speed Control

- Motor speed may be varied by putting variable resistance back into the rotor circuit. This reduces rotor current and speed. The high starting torque available at zero speed, the down shifted break down torque, is not available at high speed. See R_2 curve at 90% Ns, Resistors $R_0R_1R_2R_3$ increase in value from zero. A higher resistance at R_3 reduces the speed further. Speed regulation is poor with respect to changing torque loads. This speed control technique is only useful over a range of 50% to 100% of full speed. Speed control works well with variable speed loads like elevators and printing presses.

Speed Control



Shaded pole induction motor

Main windings and Shaded Pole winding at the Stator, while shaded pole is short circuited.