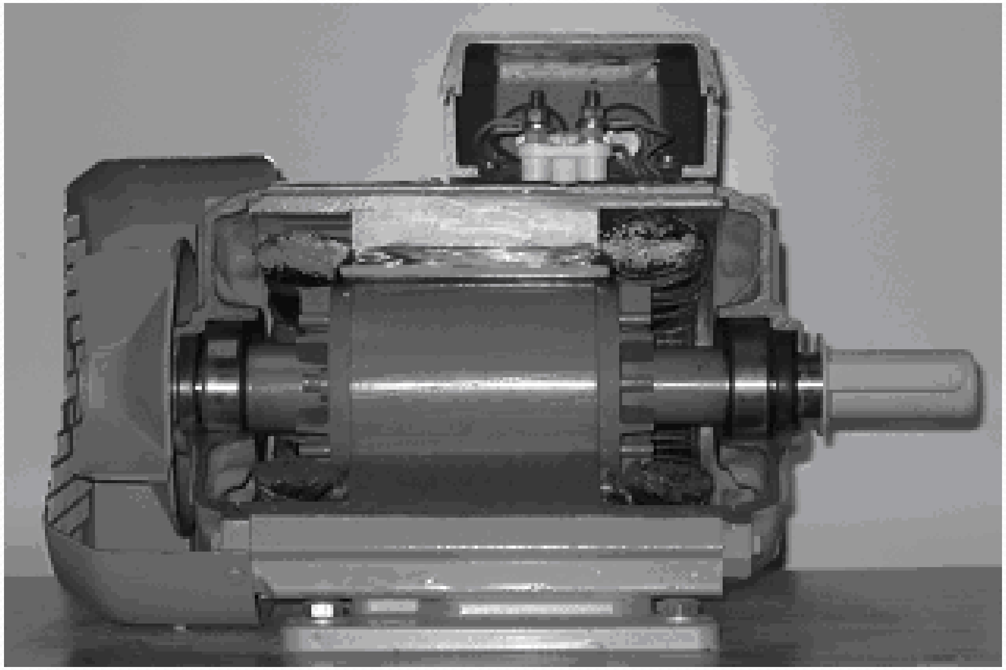
EE 101
Electrical Sciences



Department of Electronics & Electrical Engineering

Indian Institute of Technology Guwahati

Lectures 17-19

3-Phase Induction Motors
Introduction to DC Machines and Synchronous Generators

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Electromechanical Energy Conversion

Two basic electromagnetic processes in electromechanical energy conversion are:

- A moving conductor in a magnetic field induces voltage. This is called **generator action.**
- A current carrying conductor in a magnetic field produces force or torque. This is called **motor action.**
- In all electric machines, both actions/processes take place simultaneously

OPERATING PRINCIPLE – GENERATORS & MOTORS

Generator

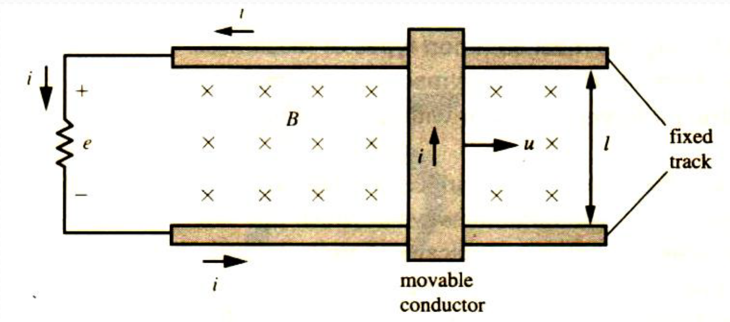
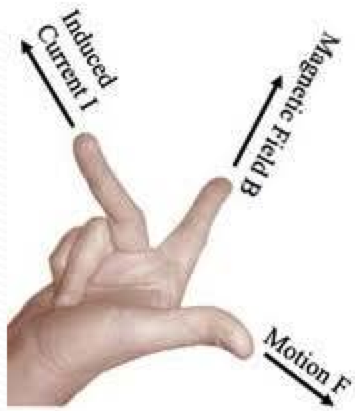


Fig. 15.1 Simple generator.



Input:

Field – B

Movement – u

(Force or Torque)

Output – e

$$e = \frac{d\lambda}{dt} = Blu$$

Motor

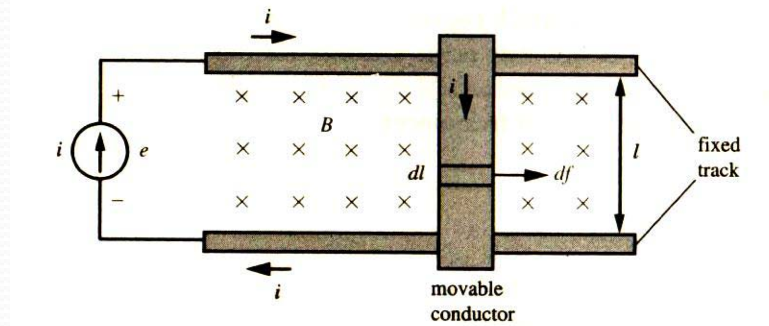
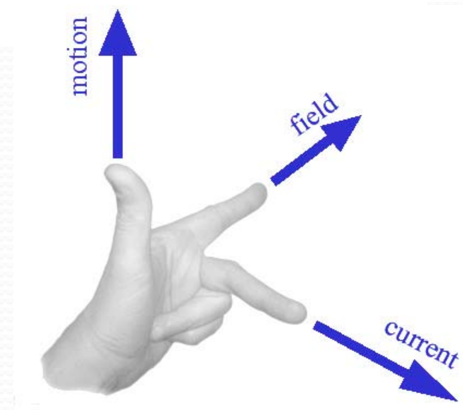


Fig. 15.2 Simple motor.



Input:

Field – B

Current – I

(Voltage)

Output – F or Torque

$$F = \int Bidl = Bil$$

Three-Phase Induction Motors

- An induction motor is a singly-fed motor that converts AC electrical power into mechanical power
- Electrical power is feed to the stator and the mechanical power is obtained from the rotor
- No electrical source is connected to the rotor circuit. The rotor receives power from the stator by induction (**not** by conduction) and that is why it is called induction motor
- The rotor circuit of an induction motor is similar to the secondary circuit of a transformer which also receives power from the primary circuit by induction
- In transformers, both the primary and secondary windings are stationary but in induction motors, the rotor (or secondary) winding is not stationary but rotating
- An induction motor can be considered as a rotating transformer (with stationary primary and rotating secondary) in which the rotor winding receives power by induction while it rotates

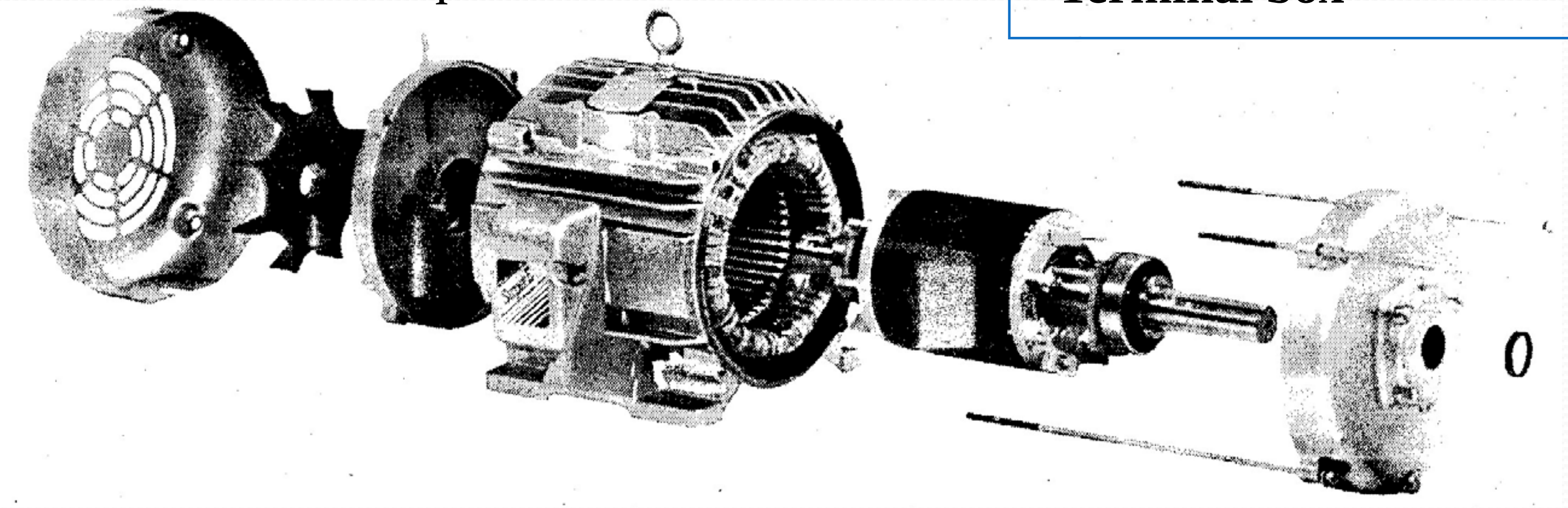
General Features

Two Basic Types of Induction Motors

- Single-phase induction motors
- Three-phase induction motors
    - Most widely used
    - Simple and robust construction
    - Low cost and reasonably good efficiency
    - Reliable and requires less maintenance

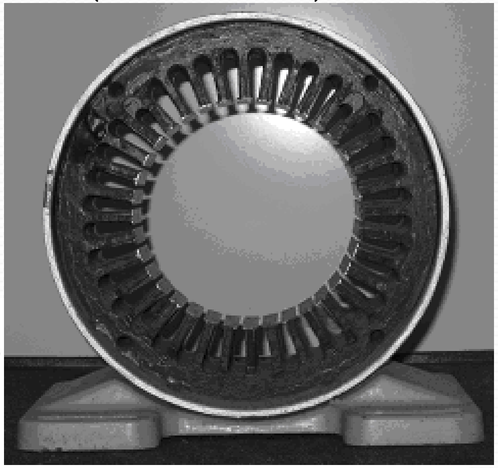
Major Components

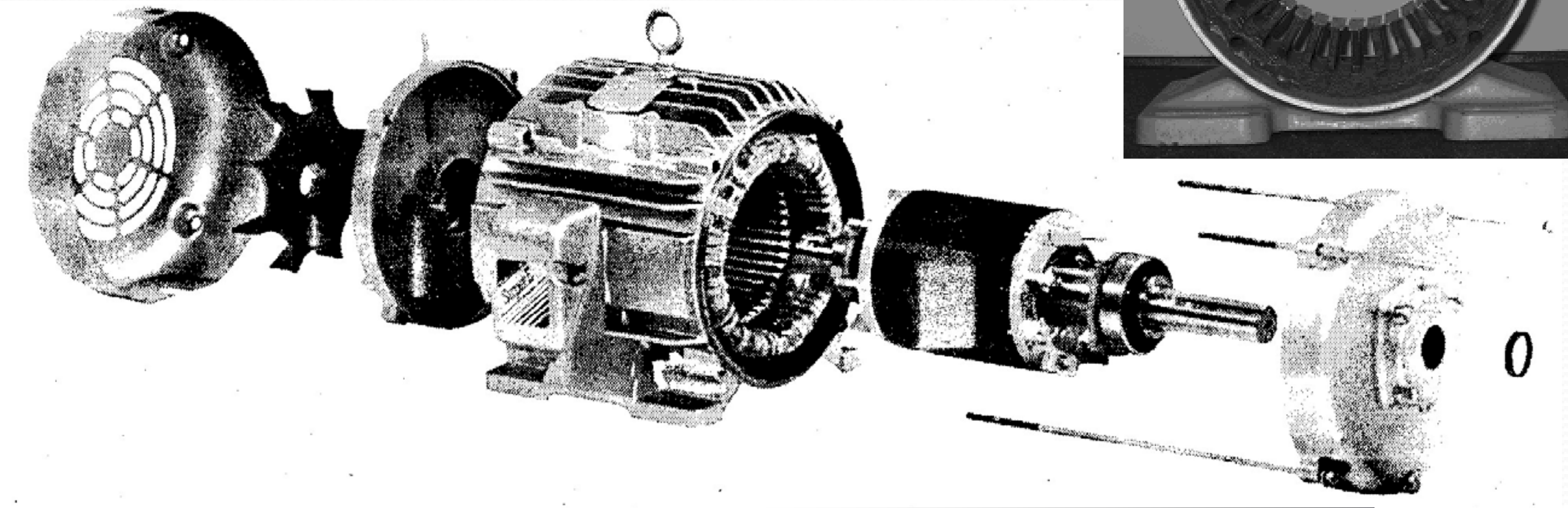
- **Stator (stationary part) or armature**
- **Rotor (rotating part)**
- **Other mechanical fittings (bearing, fan, shaft extension, end-cover, etc.)**
- **Terminal box**



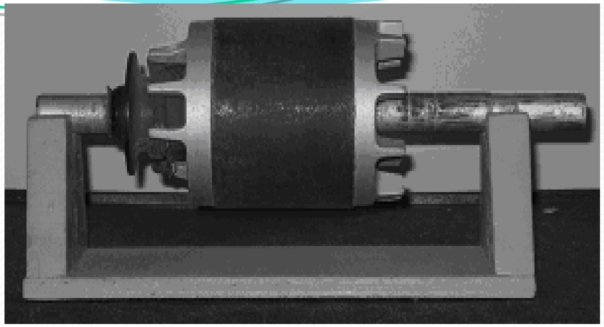
CONSTRUCTION - STATOR

- The outer (or stationary) part of an induction motor is called stator and is composed of laminated high-grade steel sheets
- Three-phase windings are placed in the slots cut on the inner surface of the stator frame. Phase windings are displaced by 120^{o} (electrical) from others
- Winding ends are terminated to the terminal box. Windings can be connected in star (wye) or delta (Δ) configuration





CONSTRUCTION - ROTOR



- Rotor could be solid mild steel core

Two Types of Rotors

(a) Squirrel-cage rotor

- It is very commonly used. Rotor windings or bars are placed in rotor slots. Circular rings called **end-rings** short circuit the rotor bars on both ends of the rotor

(b) Wound rotor

- Three-phase windings (with internal neutral) are placed in rotor slots. Three end terminals are connected to three slip-rings
- With brushes riding on slip-rings, the rotor terminals can be terminated at the terminal box
- Torque-speed characteristic of the motor can be controlled by changing the external rotor resistance

OPERATING PRINCIPLE – ROTATING FIELD

- When the stator windings of a 3-phase induction motor are connected to a 3-phase supply, it draws 3-phase currents and produces three magnetic fields
- The resultant magnetic field is the sum (vector addition) of three magnetic fields. It can be shown that the resultant magnetic field is
  - constant in magnitude, and
  - rotates at a constant speed called **synchronous speed** (N_s)

Under linearity,

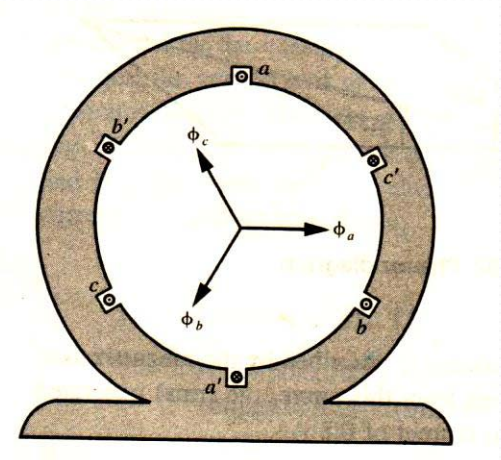
$$\Phi_a = ki_a e^{j0^\circ}, \quad \Phi_b = ki_b e^{-j120^\circ}, \quad \Phi_c = ki_c e^{j120^\circ},$$

and let,

$$i_a = I\cos\omega t, \quad i_b = I\cos(\omega t - 120^\circ), \quad i_c = I\cos(\omega t + 120^\circ)$$

Then it can be derived that,

$$\Phi = \Phi_a + \Phi_b + \Phi_c = \frac{3}{2} kIe^{-j\omega t}$$



SYNCHRONOUS SPEED

- If balanced 3-phase currents of angular frequency ω are applied to the three coiled spaced 120° from each other, the resultant flux is constant and rotates with the same angular speed, called synchronous speed.

  $$\omega_s = f \text{ cycles/s } (= 2\pi f \text{ rad/s}) = f \text{ rps} = 60 f \text{ rpm}$$

  where, f is the frequency of the power supply.

- For a machine with p number of poles, one mechanical rotation will be equivalent to $p/2$ cycles, so that

  $$\omega_s = f \text{ cycles/s } (= 2\pi f \text{ electrical rad/s}) = f/(p/2) \text{ rps} = 120 f/p \text{ rpm}$$

- The rotating magnetic field induces voltage in rotor windings or rotor bars
- The induced voltage causes rotor current (rotor bars or terminals are shorted directly or through resistances)
- The interaction of rotor current and rotating magnetic field produces a torque that tends to rotate the rotor

ROTOR SPEED

- The rotor starts rotating in the direction of rotating magnetic field and ultimately reaches a steady-state speed which is very close to (but less than) synchronous speed
- The rotor can never reach synchronous speed. At synchronous speed, the rotor appears stationary with respect to the rotating magnetic field and thus there will be no rotor induced voltage (and hence no rotor current or torque)
- The rotor speed is also called **motor speed** (N_m in rpm or ω_m in rad/sec)
- The difference between the synchronous speed N_s and motor speed N_m is called **relative speed** N_r

$$N_r = (N_s - N_m) \text{ rpm} \qquad \text{or,} \qquad \omega_r = (\omega_s - \omega_r) \text{ rad/sec}$$

SLIP

- The relative speed N_r is also called **slip-speed**. This is the speed with which the rotor slipping behind the rotating magnetic field which is responsible for the production of torque
- The ratio of slip speed (or relative speed) to synchronous speed is called **slip** (s)

$$\boxed{s = \frac{N_r}{N_s} = \frac{\omega_r}{\omega_s} = \frac{N_s - N_m}{N_s} = \frac{\omega_s - \omega_m}{\omega_s}}$$

At stand still, motor speed $N_m = 0 \Rightarrow$ slip $s = 1$

At synchronous speed, $N_m = N_s \Rightarrow$ slip $s = 0$

In general, $0 \le N_m \le N_s \Rightarrow 1 \ge s \ge 0$

- In terms of the synchronous speed (N_s) and slip (s), the motor speed (N_m) can be written as

$$\boxed{N_m = (1 - s)N_s} \quad \text{or,} \quad \omega_m = (1 - s)\omega_s$$

SLIP

- **At Stand Still (when the motor speed $N_m = 0$)**
  - The slip s becomes unity or 1
  - The rotor appears exactly the same as short-circuited secondary winding of a transformer
  - The frequency of the rotor induced voltage is the same as the stator frequency f

- **When the Rotor Rotates ($0 < N_m < N_s$)**
  - The relative speed N_r (or ω_r) is responsible to induce voltage in the rotor windings. Thus the frequency (f_r) of rotor induced voltage is

$$f_r = \frac{PN_r}{120} = \frac{P(N_s - N_m)}{120} = \left[\frac{N_s - N_m}{N_s}\right]\frac{PN_s}{120} = sf$$

  - The rotor frequency depends on slip (s) of the motor and stator frequency (f)

EXAMPLE

A 240-V, 50-Hz, 4-pole, 3-phase induction motor has a full load speed of 1425 rpm. Calculate (a) the synchronous speed (b) the slip, and (c) the rotor frequency.

Solution

(a) The synchronous speed N_s is

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \quad rpm$$

$$\omega_s = \frac{2\pi N_s}{60} = \frac{4\pi f}{P} = 157\ rad/\sec$$

(b) The slip s is

$$s = \frac{N_s - N_m}{N_s} = \frac{1500 - 1425}{1500} = 0.05\ pu = 5\%$$

(c) The rotor frequency f_r is

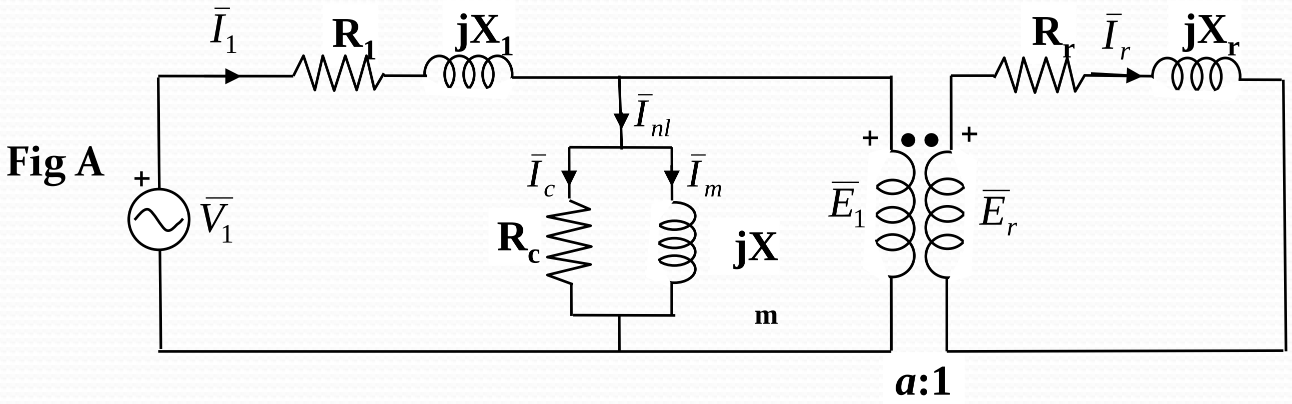
$$f_r = sf = 0.05 \times 50 = 2.5\ Hz$$

DEVELOPMENT OF EQUIVALENT CIRCUIT

- When a 3-phase induction motor is connected to a balanced 3-phase supply, it draws a balanced 3-phase current (stator phase currents are equal in magnitude but shifted by 120^o from others)
- A rotating magnetic field is created as explained earlier.
- At standstill (when N_m = 0, or s = 1), an induction motor can be considered as a transformer with secondary short circuited.
- Balanced 3-phase voltages and therefore balanced 3-phase currents flow in the rotor.
- The rotating magnetic field and the rotor currents produce torque which makes the rotor rotate, but at a speed lower than synchronous speed. At synchronous speed, there is no induced emf, and so no rotor current and therefore no torque developed.
- The stator and rotor windings are coupled inductively and thus a 3-phase induction motor resembles a 3-phase transformer with rotating secondary windings
- The frequency of rotor current f_r is proportional to slip s ($f_r = sf$)

DEVELOPMENT OF EQUIVALENT CIRCUIT

- The per phase equivalent circuit of a 3-phase induction motor is shown in Fig. a and is similar to the equivalent circuit of a transformer with secondary short-circuited



V_1 = per phase stator supply voltage

R_1 = per phase stator winding resistance

X_1 = per phase stator winding leakage reactance

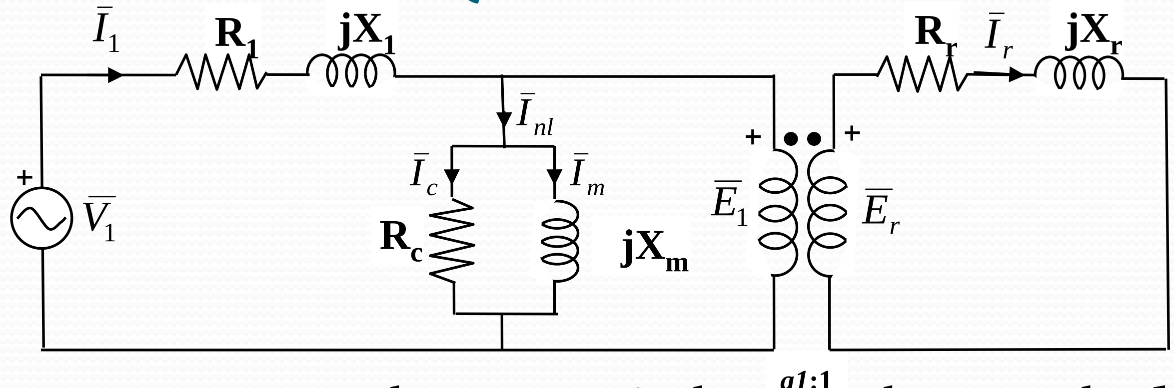
R_c = per phase equivalent core-loss resistance

X_m = per phase magnetizing reactance

$E_1 = 4.44\, fN_1k_{w1}\varphi_m$ = per phase stator induced voltage

DEVELOPMENT OF EQUIVALENT CIRCUIT

Fig A



$E_b = 4.44\, fN_2 k_{w2} \varphi_m$ = per phase rotor induced voltage under **blocked** rotor condition (s =1)

$E_r = s\, E_b$ = per phase rotor induced voltage **at slip s**

R_r = per phase rotor winding resistance

X_b = per phase rotor winding leakage reactance under **blocked** rotor condition (s = 1)

$X_r = sX_b$ = per phase rotor winding leakage reactance **at slip s**

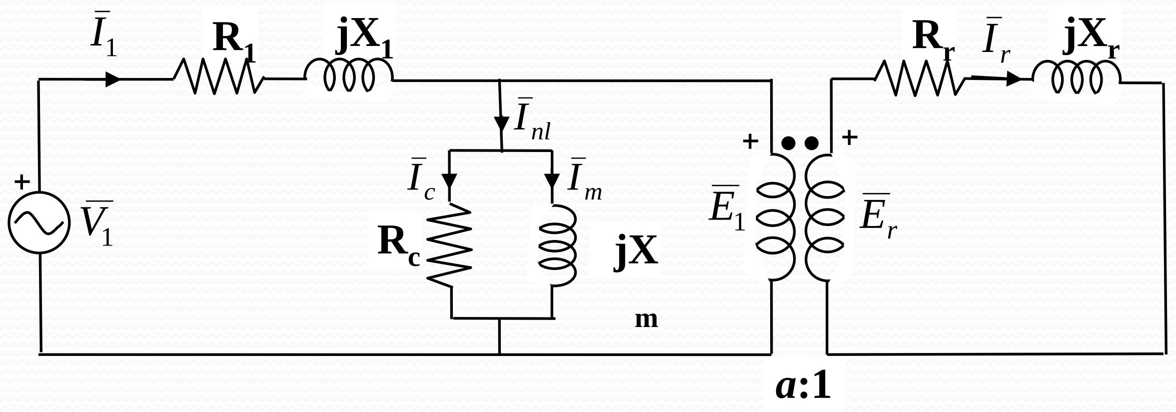
N_1 and N_2 are the number of turns in the stator and rotor windings

k_{w1} and k_{w2} are the stator and rotor winding factors

Note that E_r and X_r depend on frequency and hence slip s

DEVELOPMENT OF EQUIVALENT CIRCUIT

Fig A



- The rotor current in in the circuit is given by $\boxed{\bar{I}_r = \dfrac{\bar{E}_r}{R_r + jX_r}}$

- Noting that $\bar{E}_r = s\bar{E}_b$ and $X_r = sX_b$, the expression can be written as

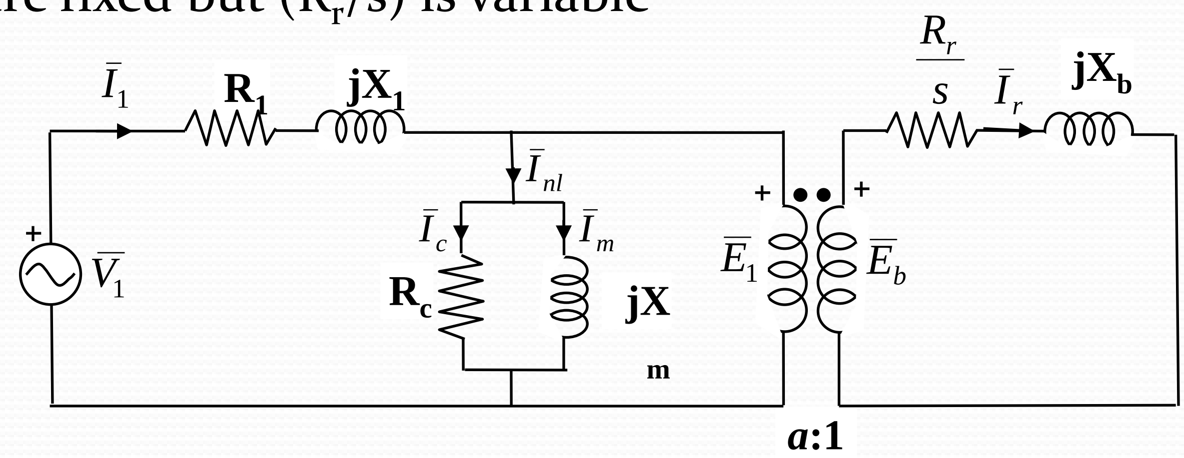
$$\bar{I}_r = \frac{s\bar{E}_b}{R_r + jsX_b} = \frac{\bar{E}_b}{\frac{R_r}{s} + jX_b}$$

- Based on the above equation, a modified equivalent circuit (as shown in the Fig. B in the next page) of the motor can be developed

DEVELOPMENT OF EQUIVALENT CIRCUIT

- In the first Fig. A, E_r and X_r are variable (depends on slip s). In Fig. B, E_r and X_b are fixed but (R_r/s) is variable

Fig B



- The hypothetical resistance $\frac{R_r}{s}$ in the rotor circuit is called **effective rotor resistance**
- At stand still (or blocked rotor condition), s = 1 and thus the effective rotor resistance is the same as the actual rotor resistance R_r
- At no load, the slip s approaches to zero and thus the effective rotor resistance approaches to infinity (very high)

DEVELOPMENT OF EQUIVALENT CIRCUIT

- Transfer the rotor quantities to the stator (similar to transformer) by using the effective turn ratio 'a'
- Let, $R_2 = a^2 R_r$ and, $X_2 = a^2 X_b$

  Then, the per phase equivalent circuit of the motor referred to the stator becomes

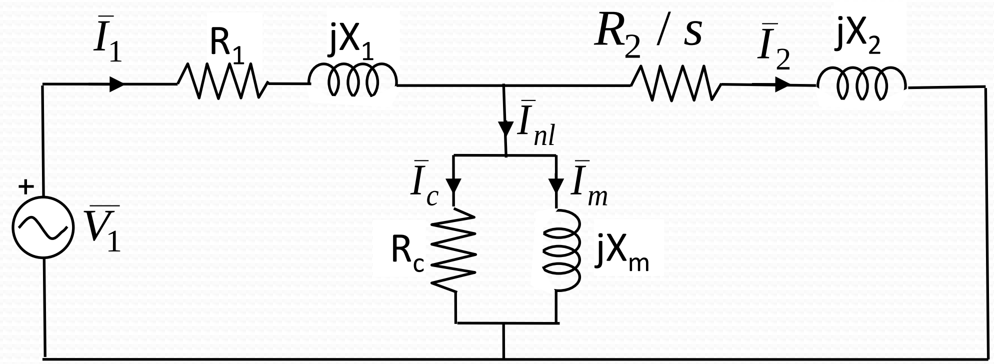


Fig C1

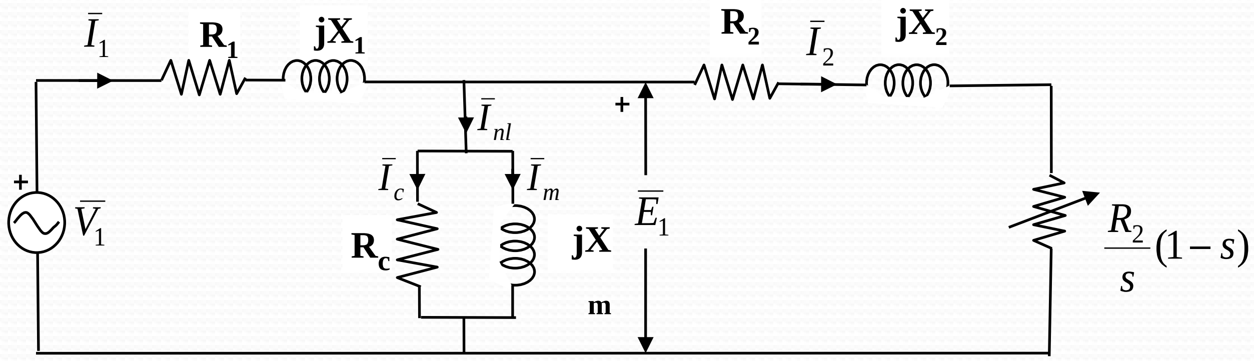
- The above circuit shown in Fig C1 is called the **exact equivalent circuit** of an induction motor
- The effective rotor resistance R_2/s (referred to the stator) in the above figure can be split into two components:

$$R_2 / s = R_2 + (1-s)R_2 / s$$

DEVELOPMENT OF EQUIVALENT CIRCUIT

- The equivalent circuit of the motor showing two components of resistance is shown in Fig. C2

Fig C2



- Where:

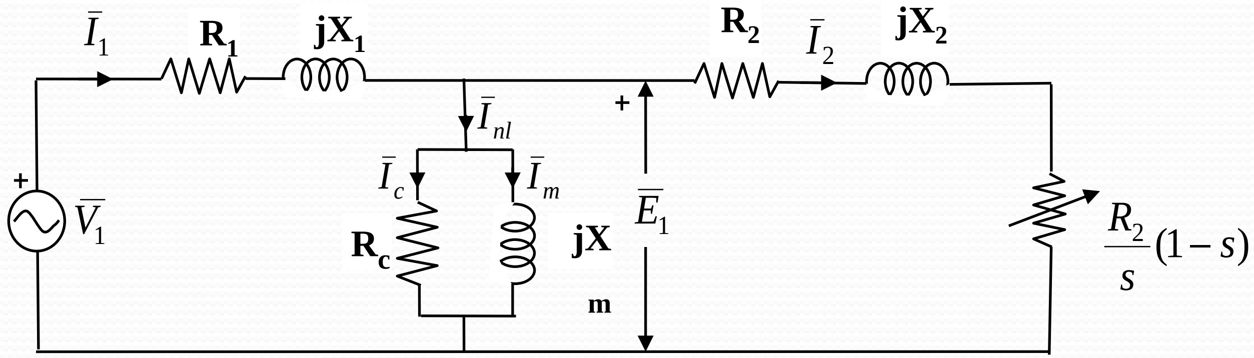
R_2 is the actual rotor resistance of the rotor, and

$\frac{R_2}{s}(1-s)$ is the 'Fictitious' load resistance:

- Note that the sum of above two resistances is always R_2/s
- The value of fictitious load resistance depends on slip (or motor speed) but the actual rotor resistance is independent of slip s

DEVELOPMENT OF EQUIVALENT CIRCUIT

Fig C2



- The fictitious load resistance in Fig. C emulates the **mechanical load** of the motor in electrical equivalent circuit
- The power absorbed by the load resistance represents the **mechanical power developed** (P_d) by the motor. It is the power which is converted from electrical to mechanical

$$\boxed{\therefore \quad P_d = I_2^2 \frac{R_2}{s}(1-s) \ \text{W}}$$

- The above figure (Fig. C) is exactly the same as the exact equivalent circuit of a transformer delivering power to a load resistance of

$$\frac{R_2}{s}(1-s)\ \Omega$$

Example

A 440-V, 50-Hz, Y-connected, 4-pole, 3-phase IM has = (0.02+j0.06) Ω/phase at stand still. The effective turn ratio '*a*' is 5. Determine (a) the rotor resistance R_2 referred to the stator, (b) the fictitious load resistance when the motor runs at 1450 rpm, at starting, and at synchronous speed.

Solution

Here R_r = 0.02 Ω/phase, and X_b = 0.06 Ω/phase

Synchronous speed $N_s = \dfrac{120f}{P} = \dfrac{120 \times 50}{4} = 1500$ rpm

(a) The rotor resistance (R_2) referred to the stator is

$$R_2 = a^2 R_r = 5^2 \times 0.02 = 0.50 \ \Omega/\text{phase}$$

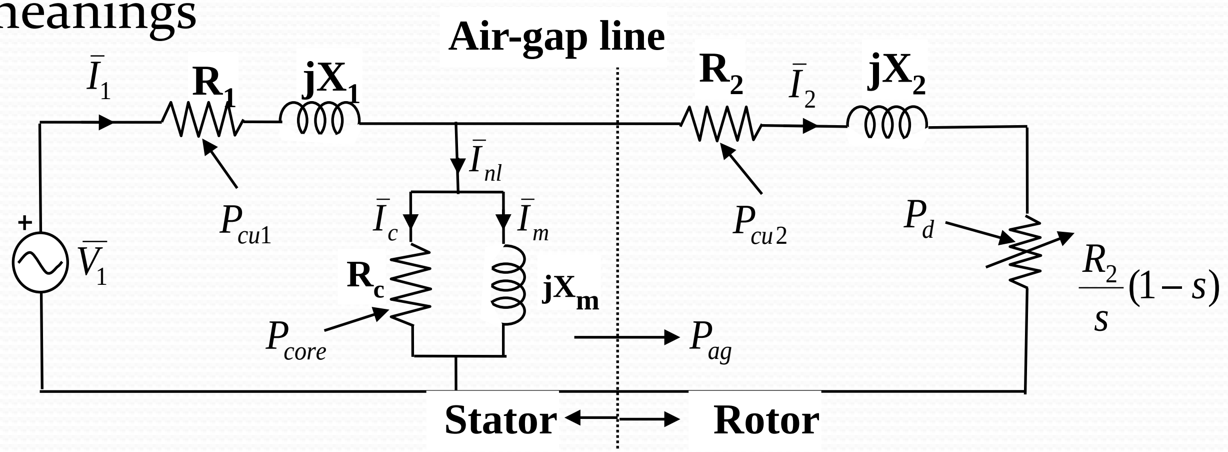
(b) Slip $s = \dfrac{N_s - N_m}{N_s}$ pu

Fictitious load resistance $R_{Load} = \dfrac{R_2}{s}(1-s)\ \Omega$

N_m (rpm)	1450	0 (Starting)	1500 (syn speed)
Slip s (pu)	0.033333	1	0
R_{Load} (Ω)	14.5	0	∞

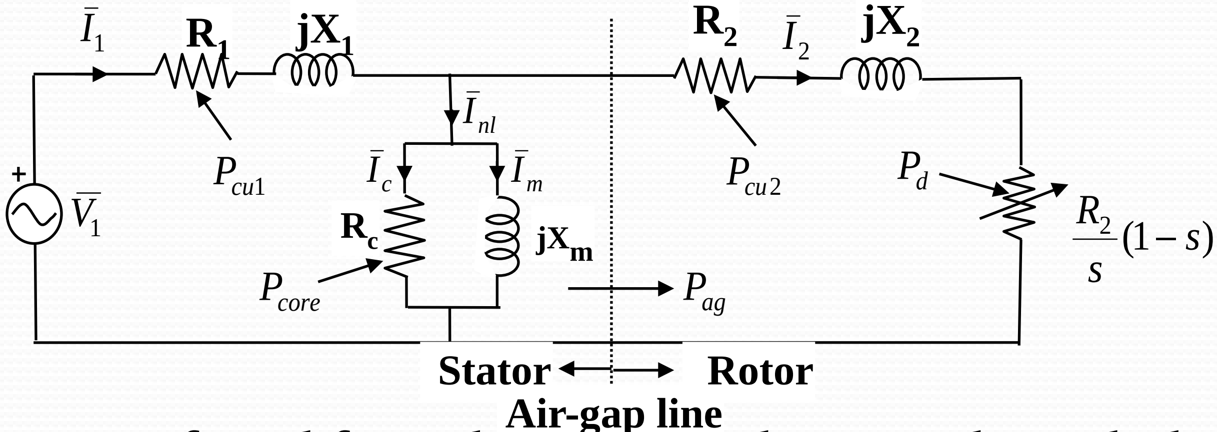
Power Associated with Various Resistances

- There are four resistances in the final equivalent circuit (Fig. C) of an induction motor and the power absorbed by these resistances has some special meanings



$I_1^2 R_1$	: Per phase stator cu-loss (P_{cu1})
$I_c^2 R_c = E_1^2 / R_c$	: Per phase core loss (P_{core})
$I_2^2 R_2$	: Per phase rotor cu-loss (P_{cu2})
$I_2^2 \frac{R_2}{s}(1-s)$	: Per phase mechanical developed power (P_d)

Power Associated with Various Resistances



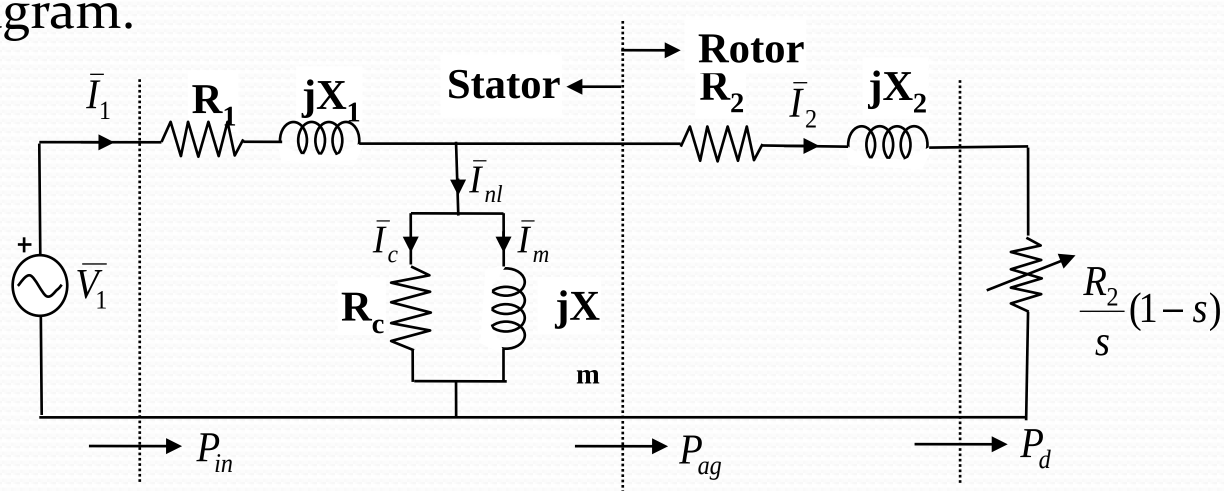
- The power transferred from the stator to the rotor through the air-gap is called the 'Air-gap power'. So the air-gap power consists of the sum of rotor cu-loss (P_{cu2}) and developed power (P_d). Thus,

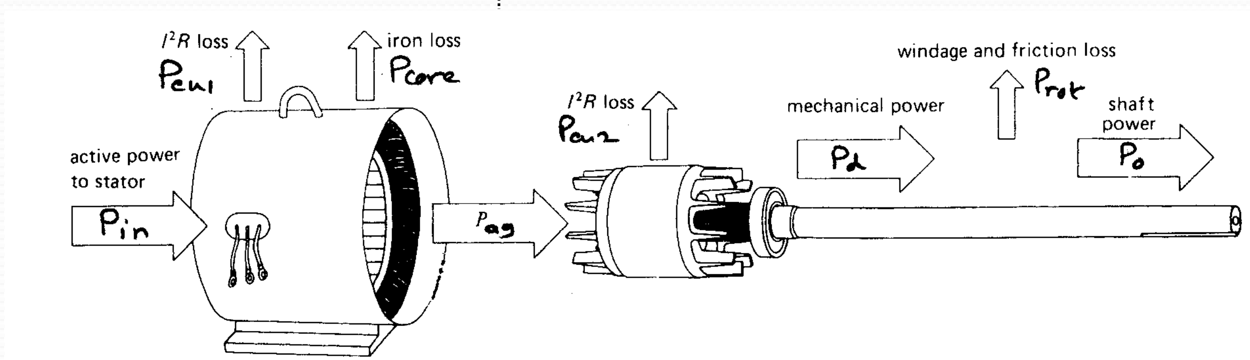
$I_2^2 R_2$	: Per phase rotor cu-loss (P_{cu2})
$I_2^2 \frac{R_2}{s}(1-s)$	: Per phase developed mechanical power (P_d)
$I_2^2 \frac{R_2}{s}$	: Per phase air gap power (P_{ag})

- Note that the above equivalent circuit is on per phase basis and proper relationships should be used to get the total power and line quantities.

Power Flow Diagram

- The equivalent circuit enables us to understand the detailed behavior of an induction motor. However, it is easier to see how electrical energy (or power) is converted into mechanical energy (or power) in the power flow diagram.





Example

A 10-hp, 4-pole, 440-V, 50-Hz, Y-connected, 3-phase induction motor runs at 1440 rpm on full load (P_{out} = 10 hp). The core loss is 200 W and rotational loss is 340 W. The stator copper loss at full load is 215 W. Determine the following quantities at full load: (a) developed power, (b) air-gap power, (c) rotor copper loss, (d) input power, (e) efficiency, and (f) shaft torque.

Solution: Output power P_{out} = 10 hp = 7,460 W

Synchronous speed N_s = 120f/P = 1500 rpm; rad/sec

Slip $$s = \frac{N_s - N_m}{N_s} = \frac{1500-1440}{1500} = 0.04\,pu = 4\%$$

P_{core} = 200 W, P_{rot} = 340 W, and P_{cu1} = 215 W

(a) Developed power: $P_d = P_{out} + P_{rot}$ = 7,460 + 340 = 7,800 W

(b) Air-gap power: $P_{ag} = P_d /(1-s)$ = 7800/0.96 = 8,125 W

(c) Rotor copper loss: $P_{cu2} = sP_{ag}$ = 0.04×8,125 = 325 W

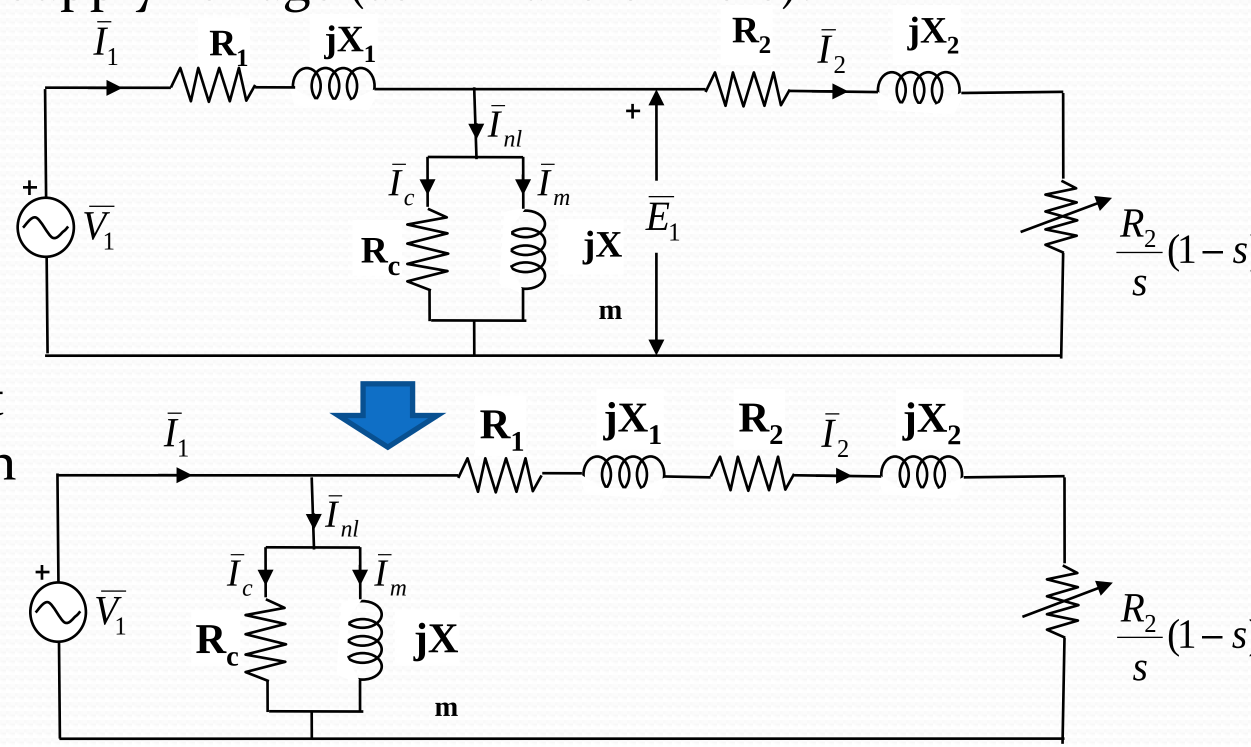
(d) Input power: $P_{in} = (P_{ag} + P_{cu1} + P_{core})$ = (8,125 + 215 + 200) = 8,540 W

(e) Efficiency $$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{7{,}460}{8{,}540} \times 100\% = 87.35\%$$

(f) Shaft torque = output torque $$= T_s = T_{out} = \frac{P_{out}}{\omega_m} = \frac{7{,}460}{2\pi \times 1440/60} = 49.47 \text{ Nm}$$

Approximate Equivalent Circuit

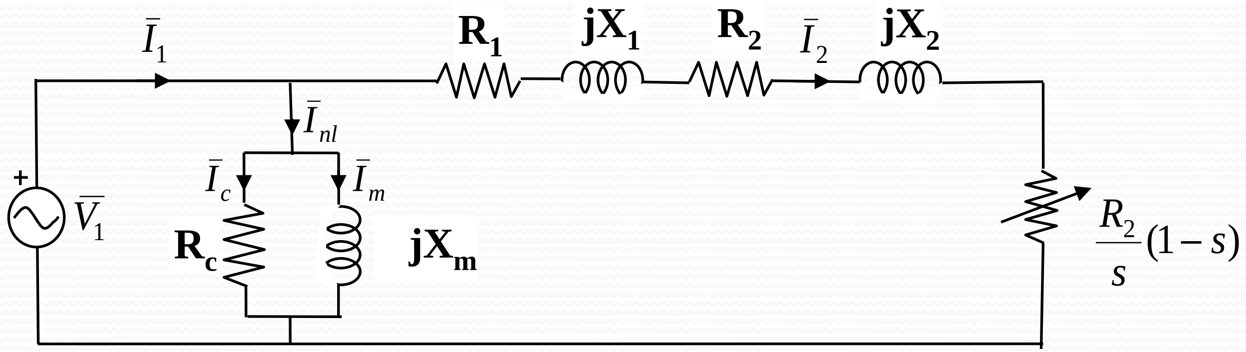
- The performance of an induction motor can be determined from its equivalent circuit – almost exactly the same way as for transformers.
- The approximate equivalent circuit is obtained by removing the shunt impedance (R_c in parallel with jX_m) from middle of the exact circuit and placing it across the supply voltage (as in transformers).
- Determination of motor behaviors/ characteristics from approximate eq. circuit becomes much simpler and it provides results with reasonably small errors for well designed motors.



Example

A 8-pole, 440-V, 50-Hz, Y-connected, 3-phase induction motor has the following parameters on a per phase basis: R_1 = 0.4 Ω, R_2 = 0.5 Ω, X_1 = 1.1 Ω, X_2 = 1.1 Ω, R_c = 350 Ω, and X_m = 60 Ω. The rotational loss is 250 W. Using the approximate equivalent circuit, determine the (a) input current, (b) power factor, (c) air-gap power, (d) developed torque, and (e) efficiency of the motor when it runs at a slip of 5%.

Solution:



Here

$Z_1 = (R_1+jX_1)$

$= (0.4+j1.1)$ Ω,

$Z_2 = (R_2/s+jX_2)$

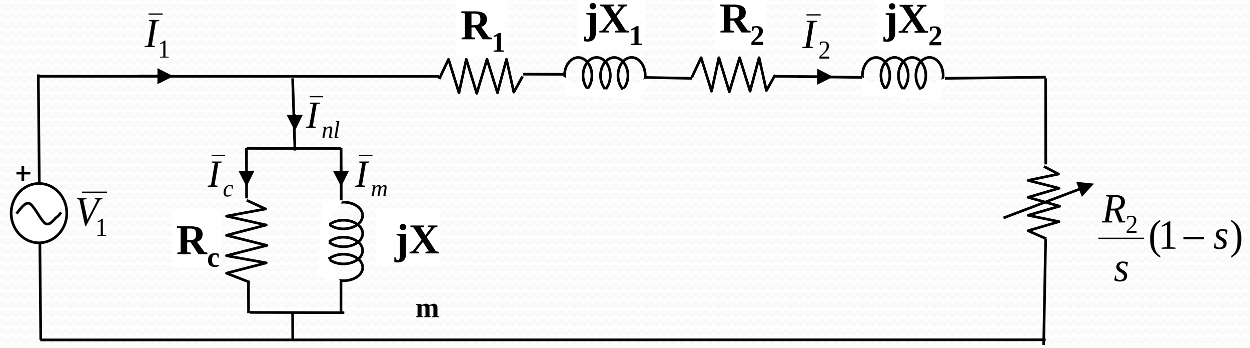
$= (0.5/0.05+j1.1) = (10+j1.1)$ Ω

$$\bar{I}_2 = \frac{\bar{V}_1}{(\bar{Z}_1+\bar{Z}_2)} = \frac{254\angle 0^0}{(10.4+j2.2)} = 23.89\angle -11.944^0\ A$$

$$\bar{I}_{nl} = \left(\frac{\bar{V}_1}{R_c} + \frac{\bar{V}_1}{jX_m}\right) = (0.7257 - j4.233)\ A$$

Example

Solution:



(a) Input current: $\bar{I}_1 = (\bar{I}_{nl} + \bar{I}_2) = 25.786\angle -20.85°$ A

(b) Power factor: pf = cos(-20.85°) = 0.934 (lagging)

(c) Air-gap power: $P_{ag} = 3I_2^2 \frac{R_2}{s} = 3 \times 23.89^2 \times \frac{0.5}{0.05} = 17.122$ W

(d) Developed torque: $T_d = \frac{P_{ag}}{\omega_s} = \frac{17{,}122}{78.54} = 218$ Nm

(e) Developed power: $P_d = (1 - s)P_{ag} = 16.266$ kW

(f) Output power: $P_{out} = (P_d - P_{rot}) = (16.266 - 0.25) = 16.02$ kW

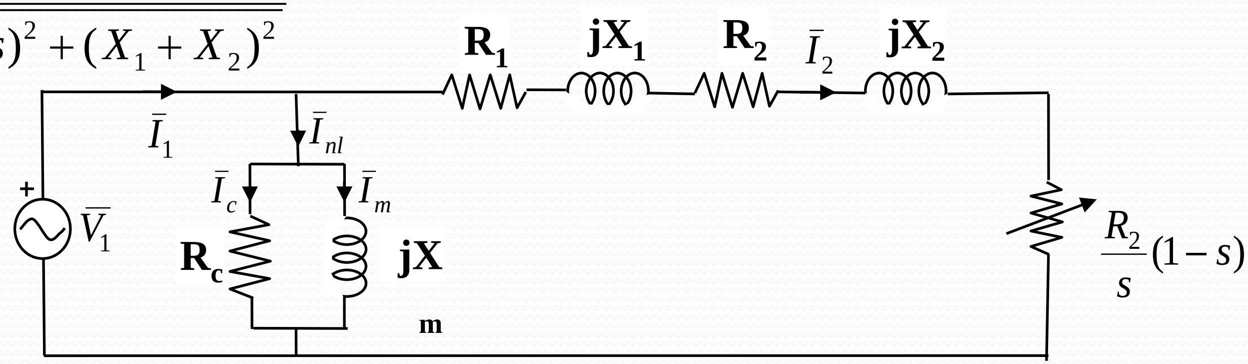
(g) Input power: $P_{in} = 3V_1 I_1 \cos\theta_1 = 3 \times 254 \times 25.786 \times \cos(-20.85) = 18.36$ kW

(h) Efficiency: $\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{16.02}{18.362} \times 100\% = 87.24\%$

Torque-Speed Characteristic

- Torque-speed characteristics showing the variation of torque with the speed of the motor is the most important characteristics of motors.
- Approximate equivalent can be used to for this purpose:

1. $I_2 = \dfrac{V_1}{\sqrt{(R_1 + R_2/s)^2 + (X_1 + X_2)^2}}$
2. $P_{ag} = 3I_2^2 \dfrac{R_2}{s}$
3. $T_d = \dfrac{P_{ag}}{\omega_s}$



Thus the developed torque can be expressed as:

$$T_d = \frac{3}{\omega_s} \times \frac{V_1^2}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2} \times \frac{R_2}{s} \ \text{Nm}$$

which shows very non linear relationship between torque T_d and speed reflected in slip s.

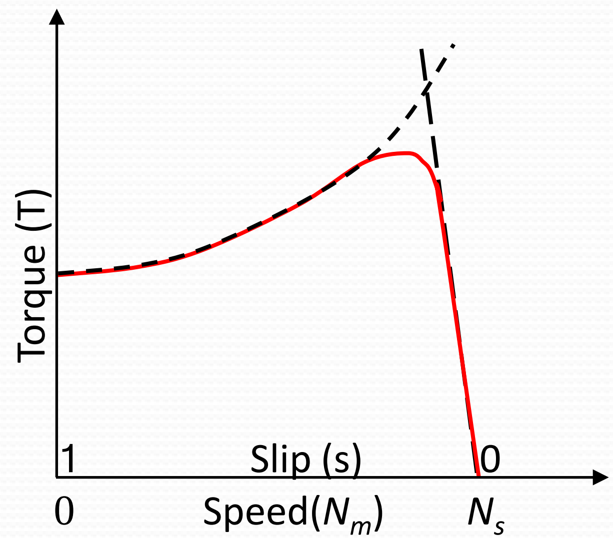
Torque-Speed Characteristic

- For small values s,

$$T_d = \frac{3}{\omega_s} \times \frac{V_1^2}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2} \times \frac{R_2}{s} \ \text{Nm}$$

$$\approx \frac{3V_1^2}{\omega_s} \times \frac{1}{(R_2/s)^2 + (X_1 + X_2)^2} \times \frac{R_2}{s}$$

$$\approx \frac{3V_1^2}{\omega_s} \times \frac{1}{(R_2/s)^2} \times \frac{R_2}{s} = \frac{3V_1^2}{\omega_s} \times \frac{s}{R_2} \propto s$$



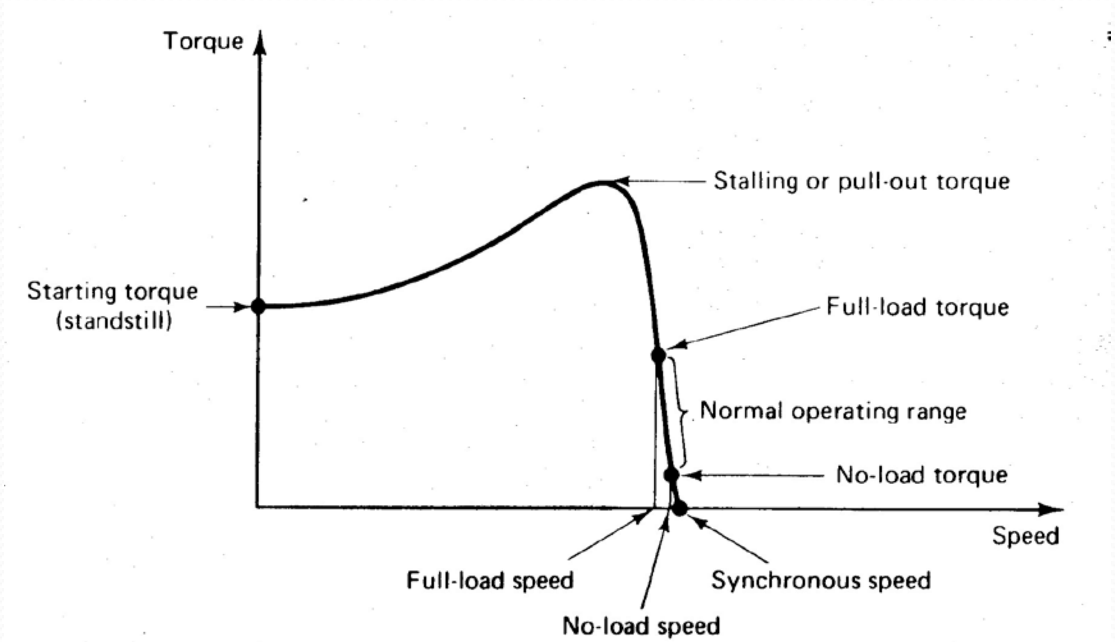
- For large values of s,

$$T_d = \frac{3}{\omega_s} \times \frac{V_1^2}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2} \times \frac{R_2}{s} \ \text{Nm}$$

$$\approx \frac{3}{\omega_s} \times \frac{V_1^2}{(X_1 + X_2)^2} \times \frac{R_2}{s} \propto \frac{1}{s}$$

Torque-Speed Characteristic

- A typical torque-speed characteristic of an IM is shown below. Note that motor speed $N_m = (1 - s)N_s$



- The important features of the characteristics are shown in the diagram.
- Starting Torque: at $N_m = 0$ or s =1

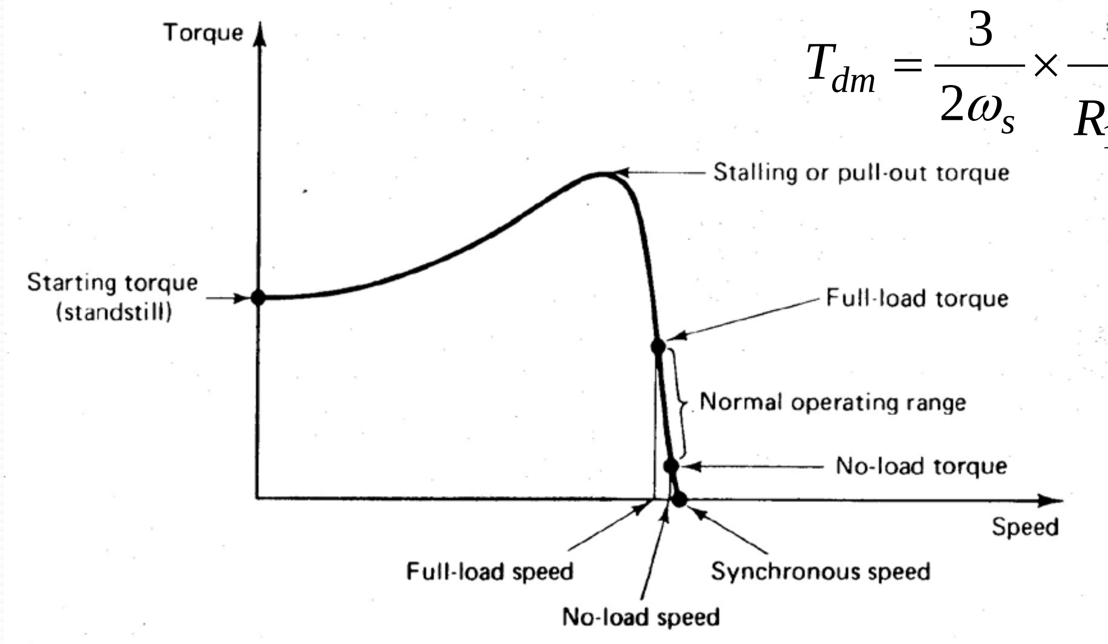
$$T_d = \frac{3}{\omega_s} \times \frac{V_1^2}{(R_1 + R_2)^2 + (X_1 + X_2)^2} \times R_2 \text{ Nm}$$

Important for motors which need to start under load.

Important Features of T-Speed Characteristic

- Maximum Torque: (or pull out torque) can be shown to be:

$$T_{dm} = \frac{3}{2\omega_s} \times \frac{V_1^2}{R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2}}$$



- The motor will not operate beyond this load torque.
- The operating range of induction motors is very narrow. The speed can vary over a limited range. Constant speed motors.
- Methods of speed control is very important for induction motors.

Determination of Equivalent Circuit Parameters

- The procedure of determining the equivalent circuit parameters of an induction motor is very similar to that of a transformer
- For an induction motor, usually the parameters of the exact equivalent circuit (instead of approximate equivalent circuit) are determined
- Two tests are conducted:
  - **Blocked-rotor Test**

    It is also called **locked-rotor test** and is very similar to the short circuit test of a transformer.
  - **No-load Test**

    Conducted at rated voltage without any load (disconnecting the load from the motor shaft) and is very similar to open circuit test of a transformer.
- Some extra measurements such as the stator resistance are also conducted.
- The calculation methods are very similar to that of transformer tests.

Speed Control

- Motor speed N_m is given by

$$N_m = (1-s)N_s = (1-s)\times\frac{120f}{P} \quad \Rightarrow \quad N_m = \frac{120(1-s)f}{P}$$

- Possible Methods of Speed Control are:
  - By changing supply frequency (f)
  - By changing number of poles (P)
  - By changing slip (s)

  Changing the supply frequency is most commonly used

- Advantages
  - Suitable for both squirrel-cage and wound-rotor motors
  - Wide range of speed control is possible

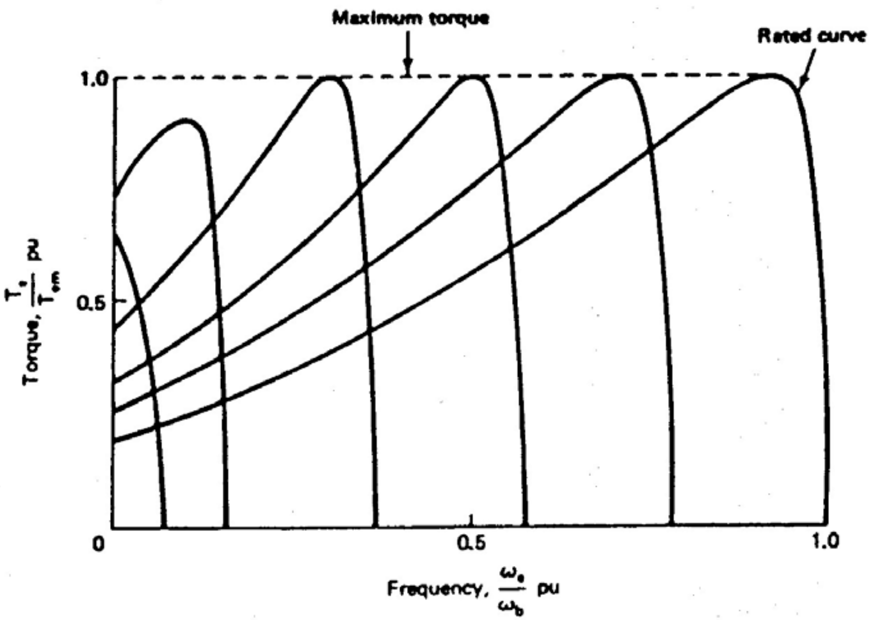
- Disadvantages

  Requires additional equipment (called inverter) to convert DC power into AC power of variable frequency. DC power can be obtained from normal AC supply by using a rectifier.

Speed Control: Modes of operation

(a) Keeping V/f ratio constant

- Since and $V_1 \approx E_1$ (neglect stator leakage impedance voltage drop)
- When V_1/f ratio is kept constant, flux φ_m also remains constant and it provides constant maximum torque capability. This technique is used when $f < f_{rated}$



Motor torque-speed characteristics for constant V/f ratio

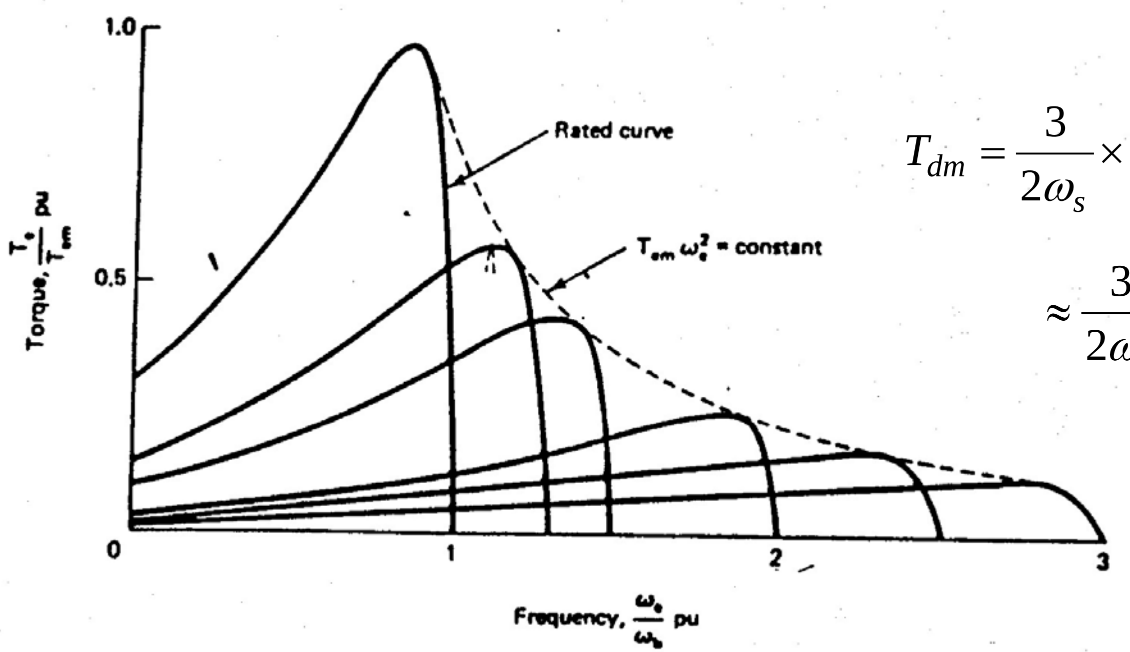
$$T_{dm} = \frac{3}{2\omega_s} \times \frac{V_1^2}{R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2}}$$

$$\approx \frac{3}{2\omega_s} \times \frac{V_1^2}{(X_1 + X_2)}$$

Speed Control: Modes of operation

(a) Keeping V constant

- It is used when $f > f_{rated}$
- At higher frequency ($> f_{rated}$), φ_m reduces for constant V_1
- The maximum torque is also reduced



$$T_{dm} = \frac{3}{2\omega_s} \times \frac{V_1^2}{R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2}}$$

$$\approx \frac{3}{2\omega_s} \times \frac{V_1^2}{(X_1 + X_2)}$$

Example

A 440-V, 50-Hz, 4-pole, Y-connected, 3-phase induction motor has the following parameters on a per phase basis: $R_1 = 0.3\ \Omega$, $R_2 = 0.6\ \Omega$, $X_1 = 0.9\ \Omega$, $X_2 = 0.9\ \Omega$, $R_c = 150\ \Omega$, and $X_m = 60\ \Omega$. Using the approximate equivalent circuit, determine

(a) the developed torque when the motor runs at 1450 rpm.

(b) the starting torque of the motor, and

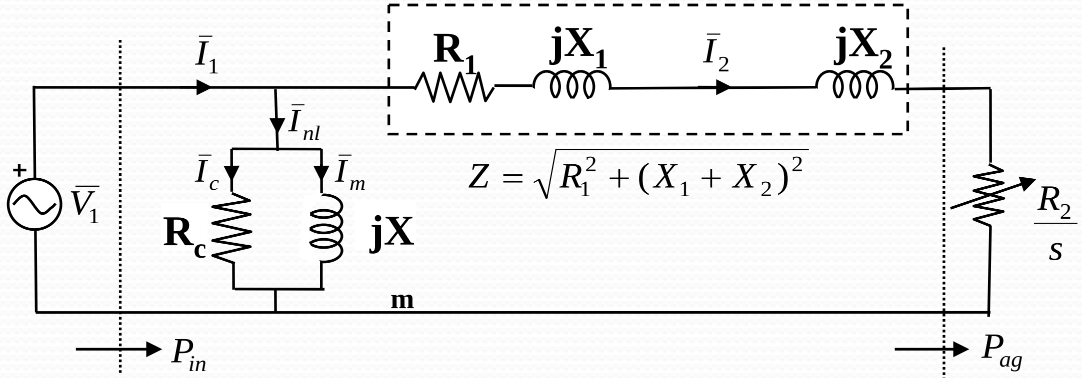
(c) the slip and speed at which the motor develops the maximum torque, and therefore the value of maximum torque.

Solution:

Synchronous speed

$N_s = 120f/P = 1500$ rpm;

$\omega_s = 2\pi N_s / 60 = 157$ rad/s



Example

(a) When N_m = 1450 rpm, slip: $s = \frac{N_s - N_m}{N_s} = \frac{1500 - 1450}{1500} = 0.0333$

Rotor current: $I_2 = \frac{V_1}{\sqrt{(R_1 + R_2/s)^2 + (X_1 + X_2)^2}} = 13.82 \text{ A}$

Air-gap power: $P_{ag} = 3I_2^2 \frac{R_2}{s} = 3 \times 12.82^2 \times \frac{0.6}{0.03333} = 10.31 \text{ kW}$

Developed torque: $T_d = \frac{P_{ag}}{\omega_s} = \frac{10.31}{157} = 65.67 \text{ Nm}$

(b) At starting, N_m = 0 and hence s = 1

Rotor current: $I_2 = \frac{V_1}{\sqrt{(R_1 + R_2/s)^2 + (X_1 + X_2)^2}} = 126.24 \text{ A}$

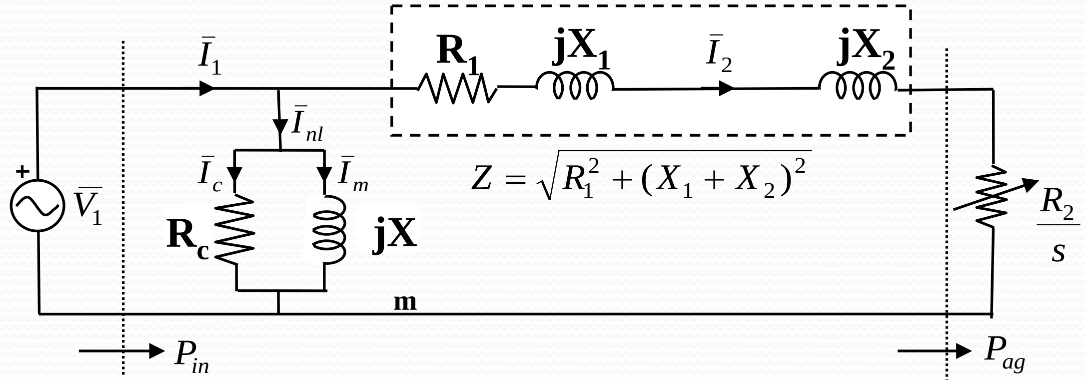
Air-gap power: $P_{ag} = 3I_2^2 \frac{R_2}{s} = 3 \times 218.64^2 \times \frac{0.6}{1} = 28.68 \text{ kW}$

Developed torque: $T_d = \frac{P_{ag}}{\omega_s} = \frac{28.68}{157} = 21.89 \text{ Nm}$

Example:

(c) For maximum torque, it can be shown that:

$$\frac{R_2}{s_m} = \sqrt{R_1^2 + (X_1 + X_2)^2} \Rightarrow \frac{0.6}{s_m} = \sqrt{0.3^2 + (0.9+0.9)^2} \Rightarrow s_m = 0.3288\ pu$$



Corresponding motor speed $N_m = (1 - s_m)N_s = 1006.8$ rpm

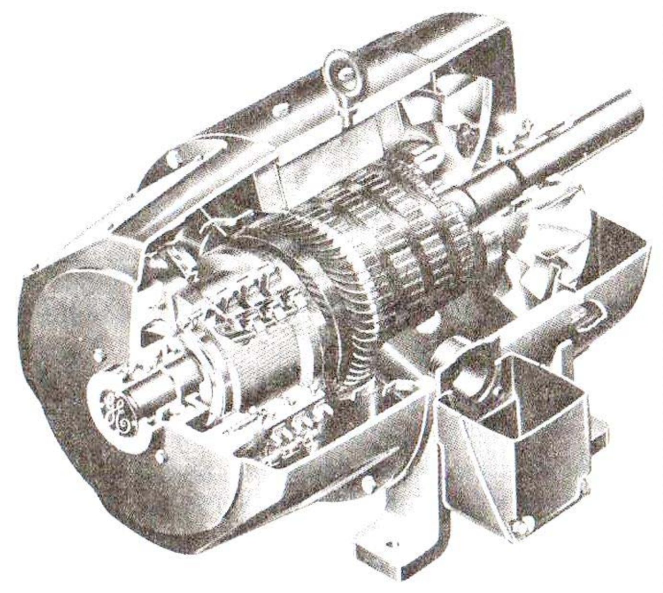
When $s = s_m = 0.3288$

Rotor current: $$I_2 = \frac{V_1}{\sqrt{(R_1 + R_2/s)^2 + (X_1 + X_2)^2}} = 91.22\ \text{A}$$

Air-gap power: $$P_{ag} = 3I_2^2 \frac{R_2}{s} = 3 \times 91.22^2 \times \frac{0.6}{0.3288} = 45.55\ \text{kW}$$

Developed torque: $$T_d = \frac{P_{ag}}{\omega_s} = \frac{45554}{157} = 290.17\ \text{Nm} = T_{dm}$$

Introduction to Synchronous Generators and DC Machines



Dr. Govinda Bol Shrestha

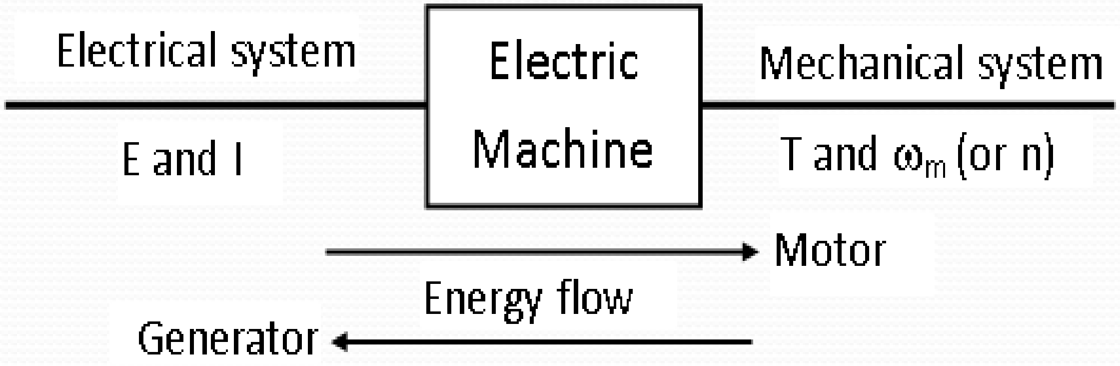
Visiting Professor

Department of Electronics and Electrical Engineering

Electric Machines

Generator: Converts mechanical energy into electrical energy

Motor: Converts electrical energy into mechanical energy



- AC Machines: Electrical system is AC
- DC Machines: Electrical system is DC

The coupling medium between the electrical and mechanical systems is magnetic field and is essential in all electromechanical energy conversion processes.

Electromechanical Energy Conversion

Two basic electromagnetic processes in electromechanical energy conversion are:

- A moving conductor in a magnetic field induces voltage. This is called **generator action.**
- A current carrying conductor in a magnetic field produces force or torque. This is called **motor action.**
- In all electric machines, both actions/processes take place simultaneously

OPERATING PRINCIPLE – GENERATORS & MOTORS

Generator

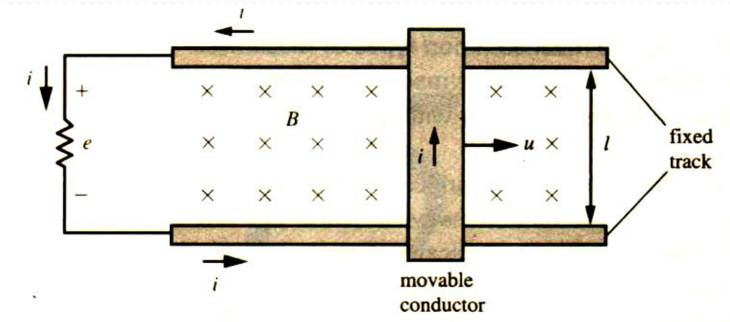
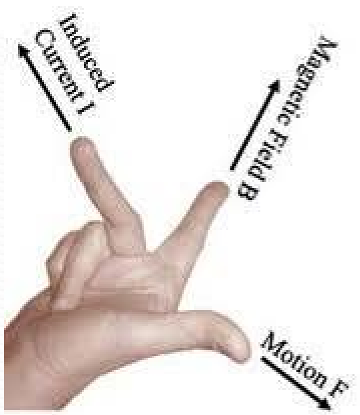


Fig. 15.1 Simple generator.



Input:

Field – B

Movement – u

(Force or Torque)

Output – e

$$e = \frac{d\lambda}{dt} = Blu$$

Motor

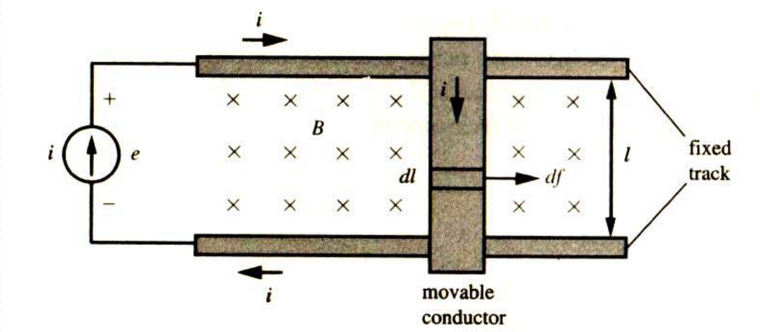
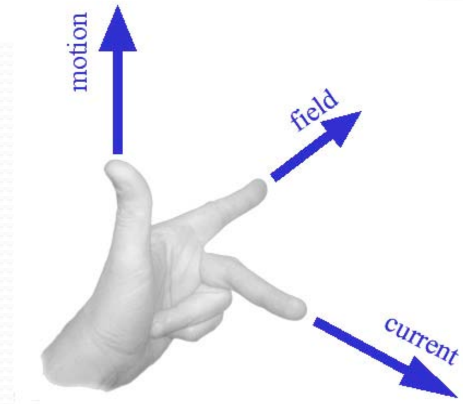


Fig. 15.2 Simple motor.



Input:

Field – B

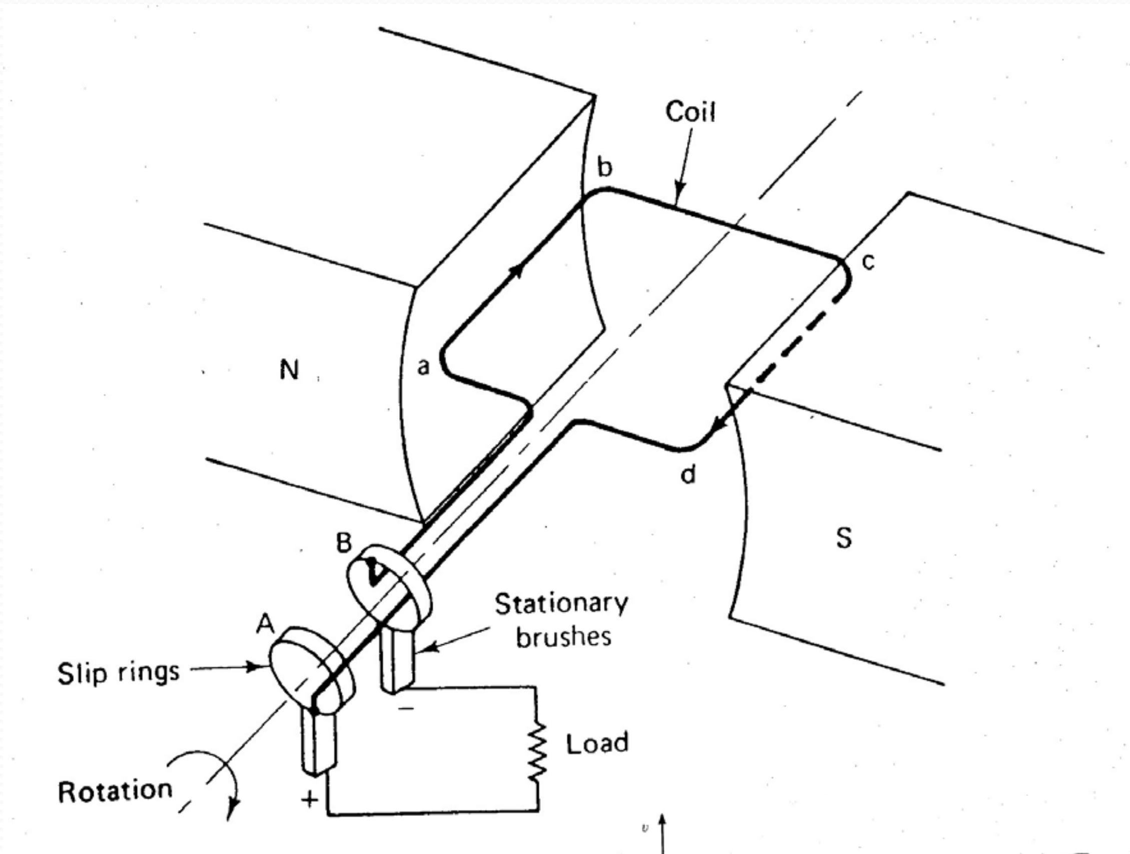
Current – I

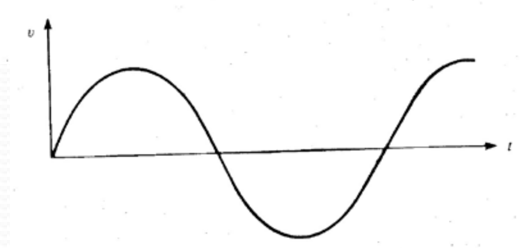
(Voltage)

Output – F *or Torque*

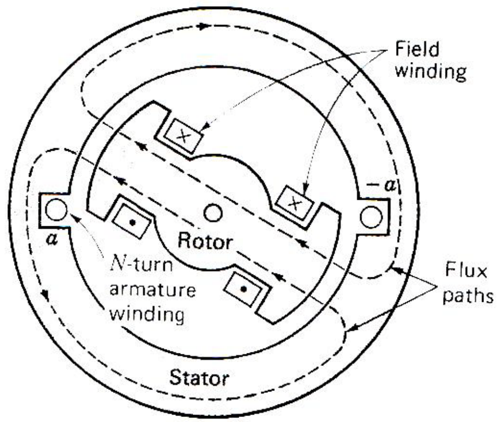
$$F = \int Bidl = Bil$$

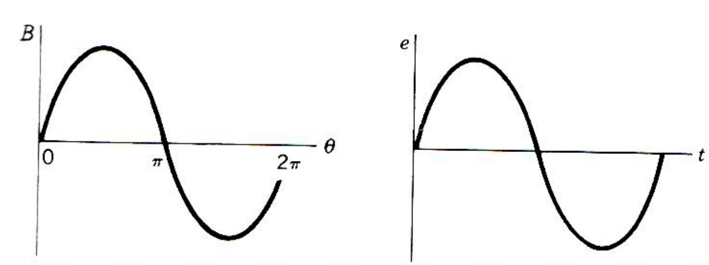
A Simple Generator

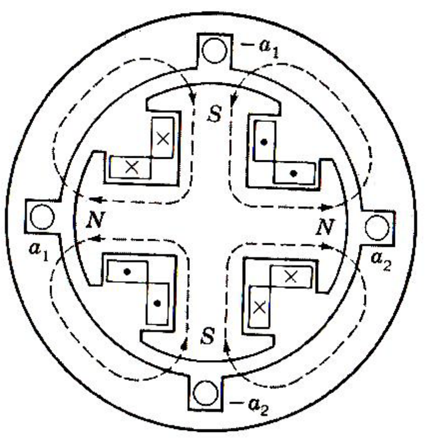


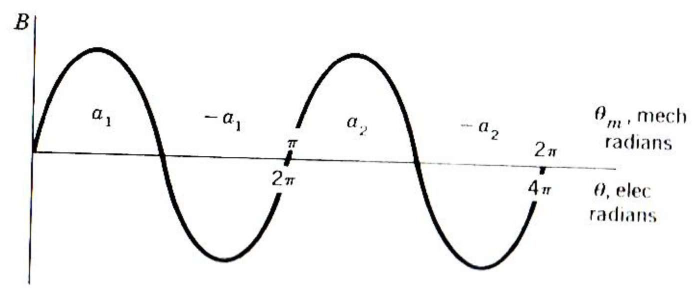


Synchronous Generators

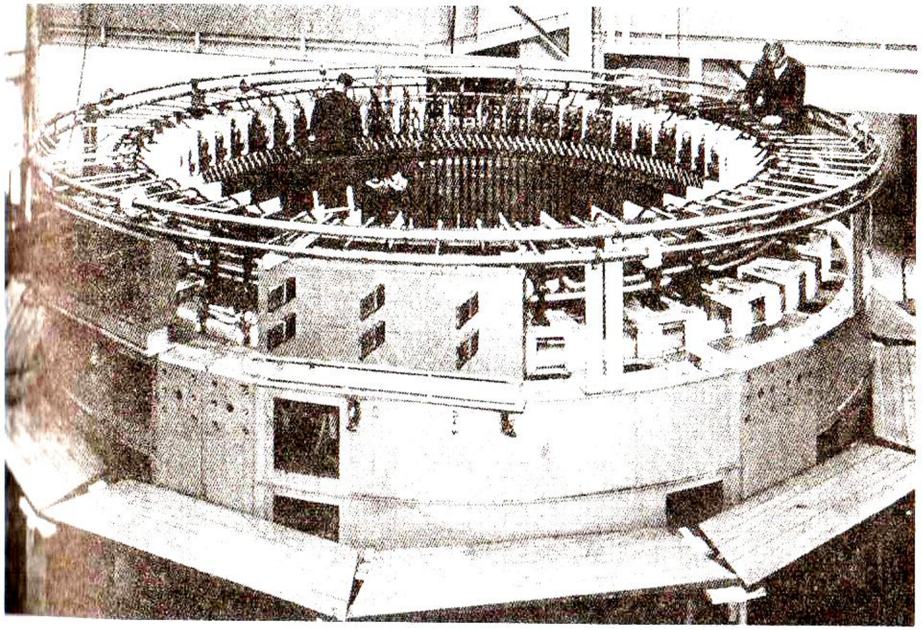


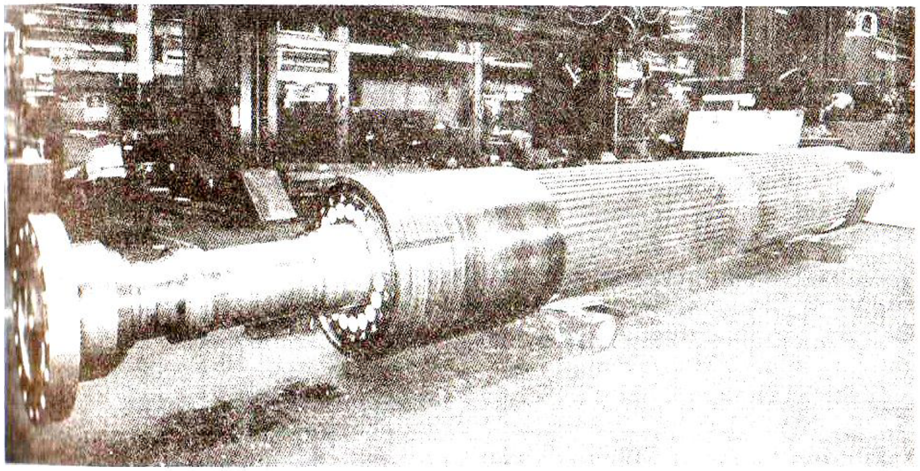


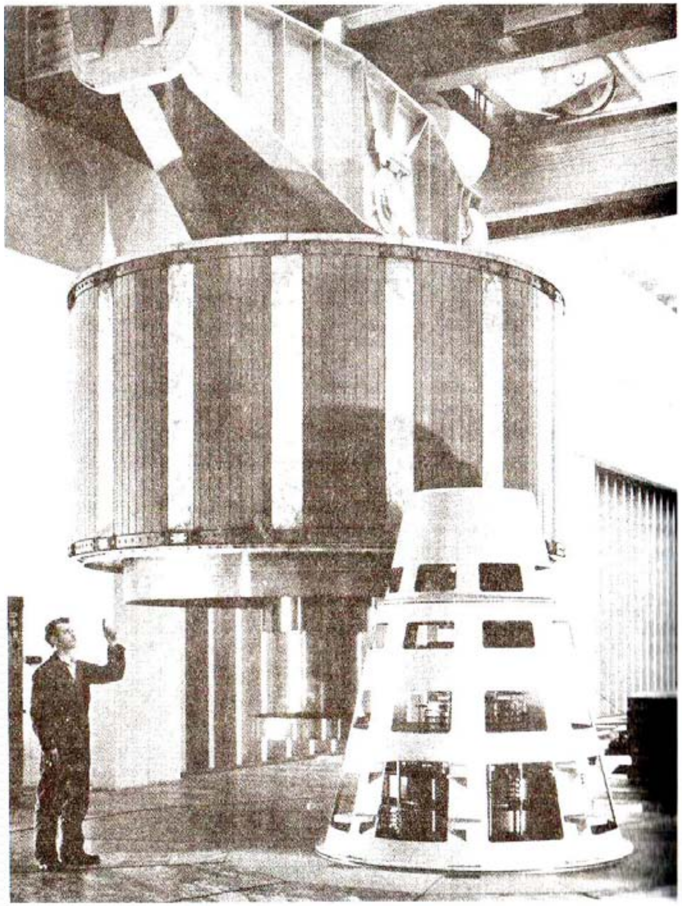




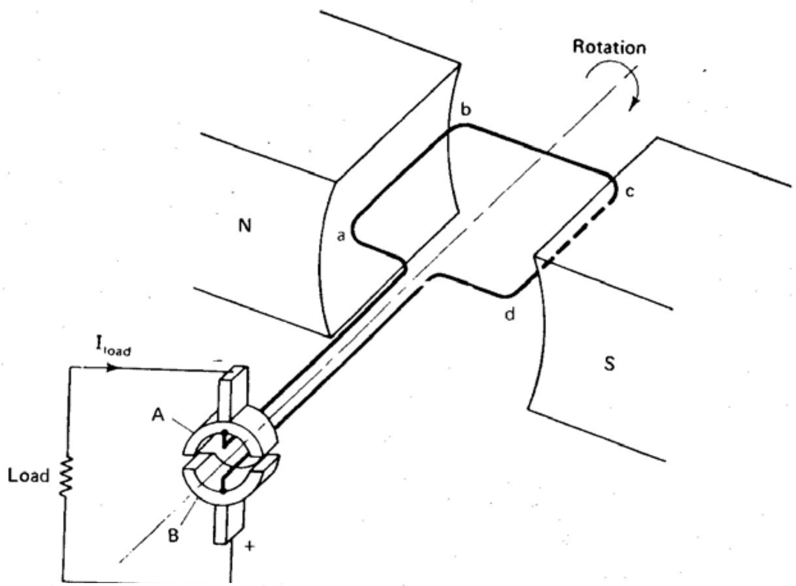
Synchronous Generators

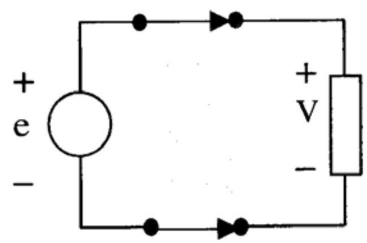


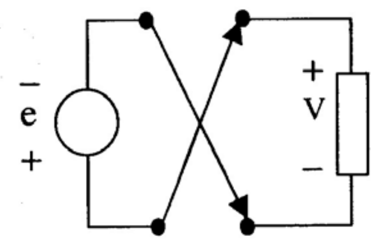


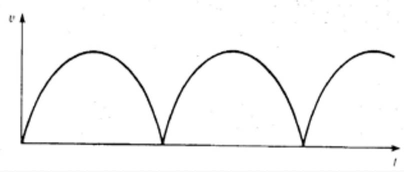


Generation of Unidirectional Voltage

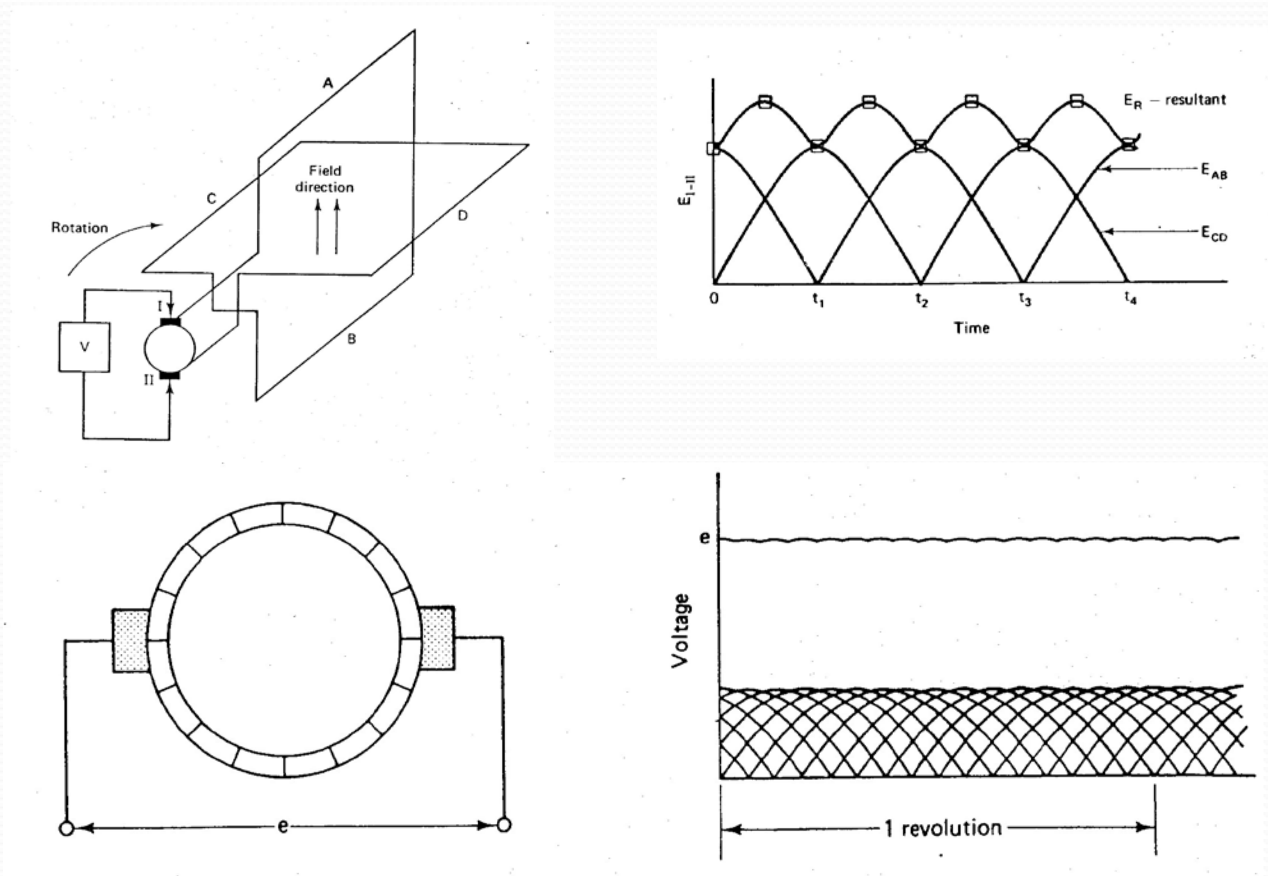








Generation of DC Voltage



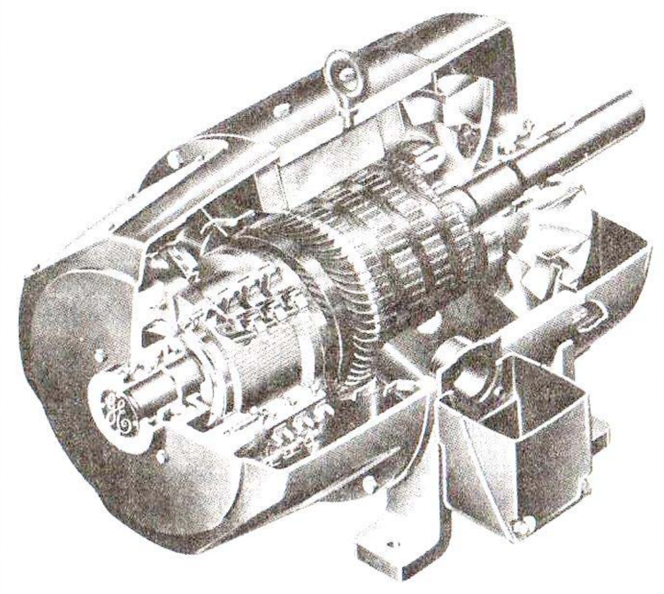
(c)

DC machines

- **Stator:** - Provides the physical support and magnetic poles.

  - The magnetic poles are excited by coils, are commonly called the **Field** or the **Excitation**
- **Rotor:** - The main winding (where the voltage is induced) is placed in the rotor. The rotor is also called the **Armature.**

  Commutator is an important part of the rotor.



BASIC OPERATING PRINCIPLES

- **Types of DC machines:**

  is defined by the arrangement of the excitation or the filed

  - Shunt Machines

  - Series Machines

  - Compound Machines

- **AC Generators:** $E = k\phi\omega_m$ V

  Important Topics: Generation of rated voltage

  Voltage regulation

  Efficiency

- **DC Motors:** $T_d = k\varphi I_a$

  Important Topics: Torque – Speed Characteristics

  Speed control

  Starting arrangements

Thank you!