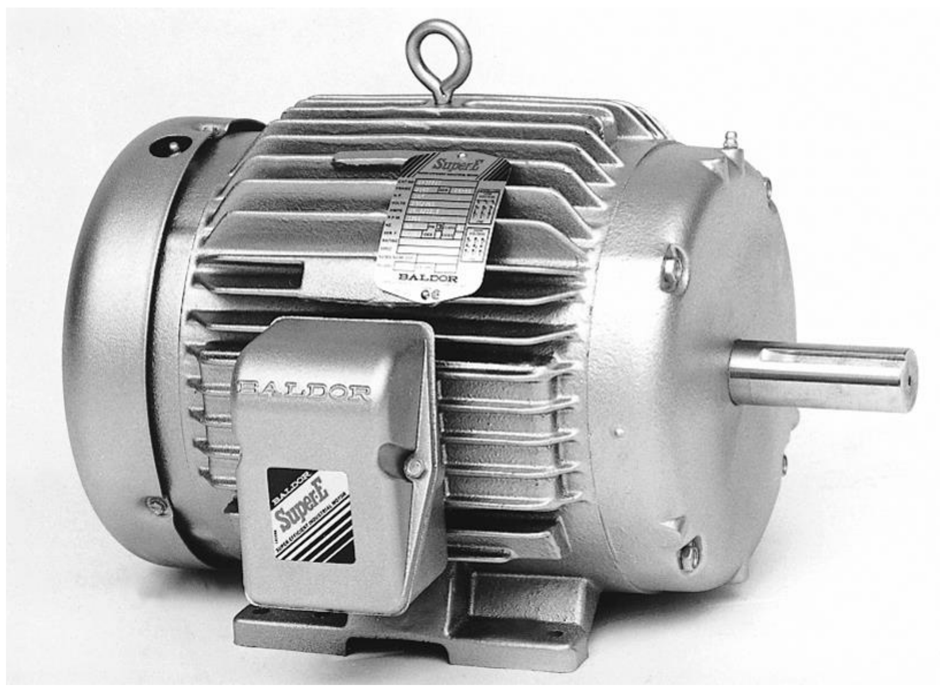
3-Phase Induction Motor



Induction Motor

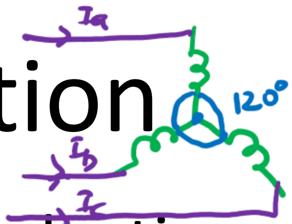
- Induction machines can operate both as a motor and as a generator
- However, it is seldom used as a generator, the Induction machine is extensively used as a motor in many applications
- The induction motor is used in various sizes. Small 1-phase induction motors (fractional horsepower rating) are used in many household appliances, such as blenders, lawn mowers, juice mixers, washing machines, and refrigerators.
- Large 3-phase induction motors (hundreds of horsepower) are used in pumps, fans, compressors, paper mills, and textile mills.
- The linear version of the Induction machine has been developed primarily for use in transportation systems
- Induction motor is rugged, reliable and almost maintenance free and has relatively high efficiency
- Induction motor speed is frequency dependent, variable frequency drives (VFD) are used to control the speed of commercial induction motors

Induction Motor

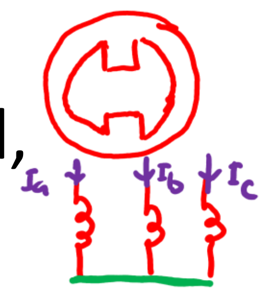
(is equivalent to secondary winding of a transformer)

- Induction motor's rotor voltage (which produces the rotor current and the rotor magnetic field) is induced in the rotor windings instead of being physically connected by wires and is therefore called INDUCTION MOTOR
- No DC field current is required to run the machine
- An induction motor carries alternating current in both the stator and the rotor windings
- A winding that receives its power exclusively by induction constitutes a transformer
- An induction motor is a transformer with a rotating secondary winding

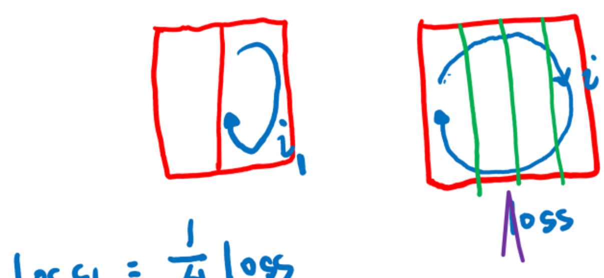
3 Phase Induction Motor - Construction



- Stator – stationary part: the outer member of an induction motor is called a stator and is formed by stacking thin-slotted, highly permeable steel laminations inside a steel or cast-iron frame. The frame provides mechanical support to the motor. Identical coil are placed into the slots and then connected to form a balanced three-phase winding



- Rotor – revolving part: it is composed of thin-slotted, highly permeable steel laminations that are pressed together onto a shaft.
- The rotor is separated from the stator by a small air gap (0.4 mm to 4 mm, depending on the power of the motor)

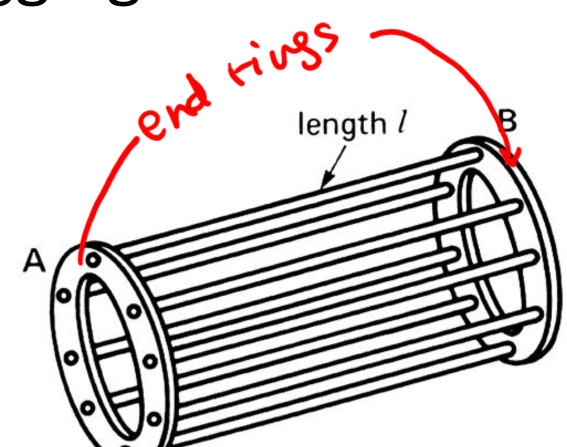


hysteresis loss

- eddy current loss

3 Phase Induction Motor - Construction

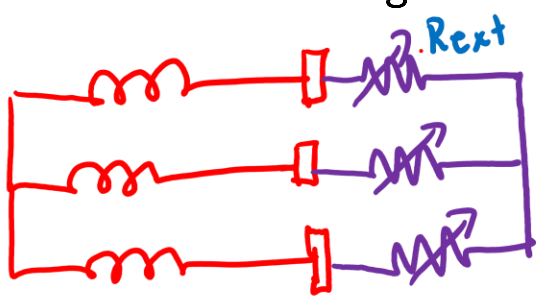
- Two types for Rotor: squirrel-cage rotor and a wound rotor
- Squirrel cage rotor: it is commonly used when the load requires low starting torque. Squirrel cage winding is formed by inserting heavy conducting bars into the slots and then welding or bolting them to the end-rings
- Squirrel cage rotor: each pair of poles has as many rotor phases as there are bars because each bar behaves independently of the other. It is common practice to skew the rotor laminations to reduce cogging and electrical noise in the motor



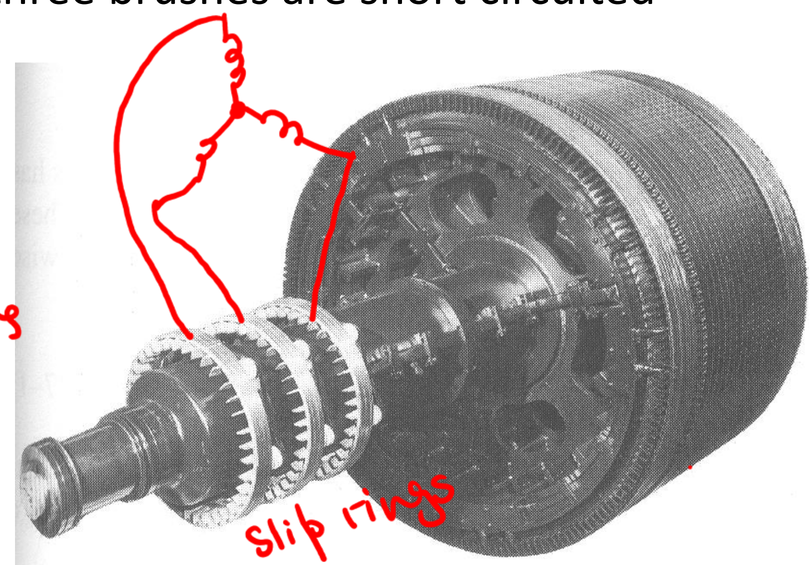
3 Phase Induction Motor - Construction

Y/Δ

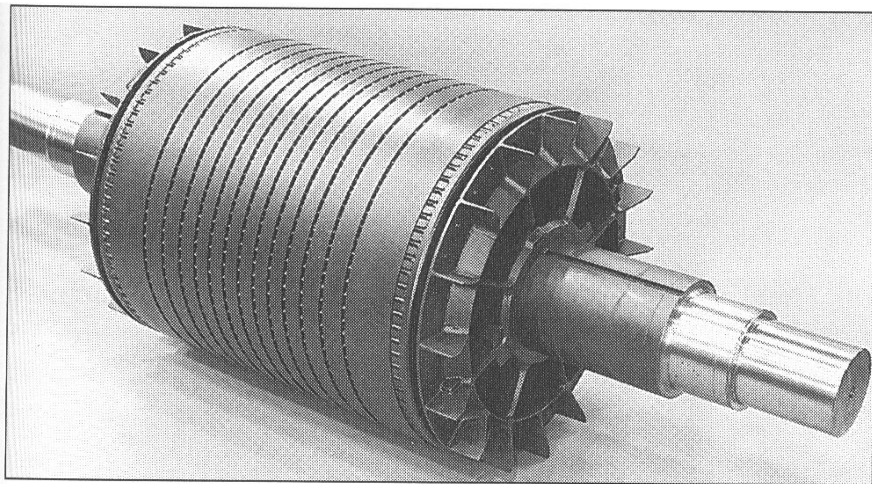
- Wound rotor:
  - it is used when load requires a high starting torque.
  - A wound rotor must have as many poles and phases as the stator. The placement of the coils in a wound rotor is same as in the stator.
  - The 3-phase windings on the rotor are internally connected to form an internal connection, usually a Y connection. The other three ends are connected to the slip rings on the rotor shaft
  - The rotor windings are shorted through brushes riding on the slip rings
  - WRIM have their rotor currents accessible at the stator brushes, and therefore can be controlled using external rotor resistance
  - The external resistors connected in series with the rotor winding are mainly used during the starting
  - Under normal running conditions, the three brushes are short circuited



Rotor resistance ⇐ Starting Torque

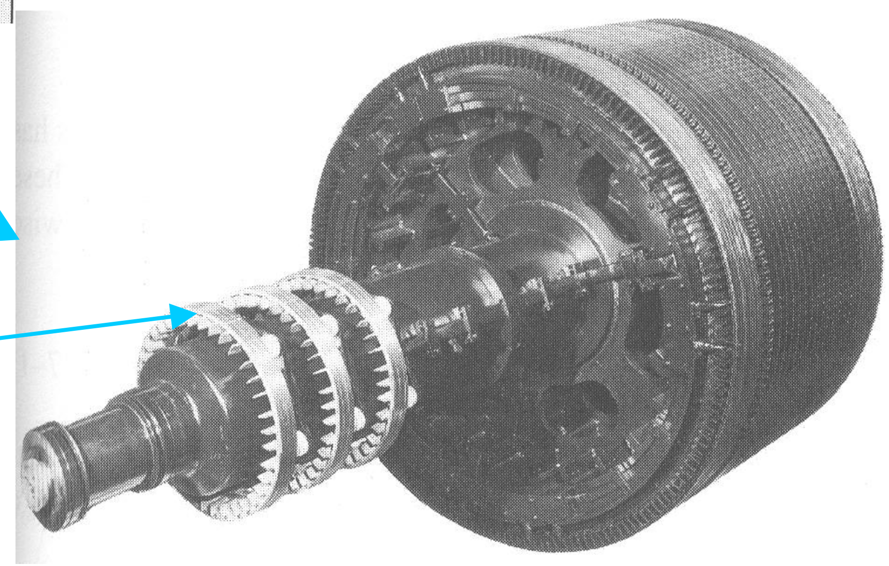


3 Phase Induction Motor - Construction



Squirrel cage rotor

Wound rotor



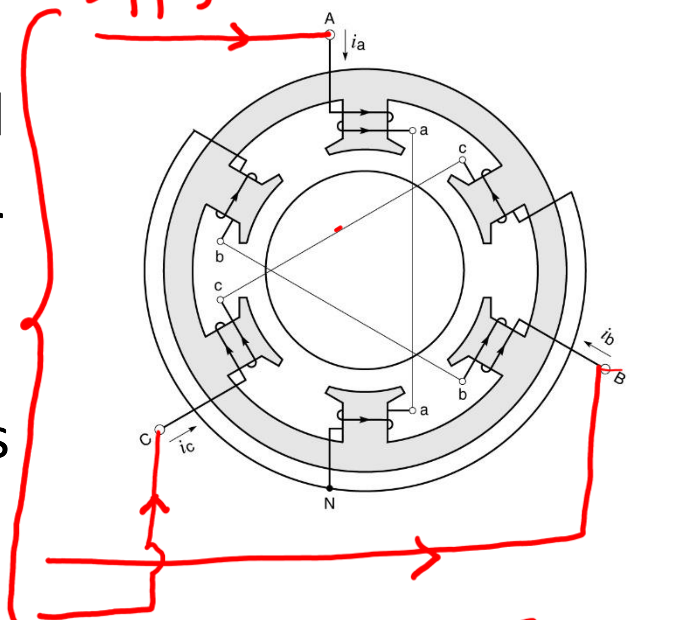
Notice the slip rings

3 Phase Induction Motor - Operation

3-phase AC supply

$i_a = I_m \sin(\omega t - \phi)$

- When the stator windings of a 3-phase induction motor is connected to a 3-phase power source, it produces a magnetic field that (a) is constant in magnitude and (b) revolves around the periphery of the rotor at synchronous speed

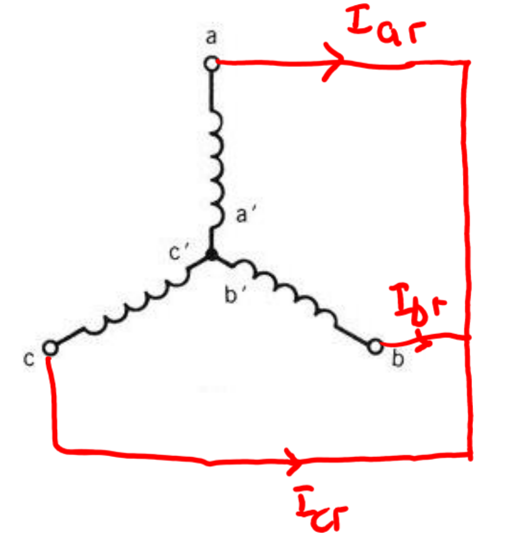


- Synchronous speed of the revolving field is given by

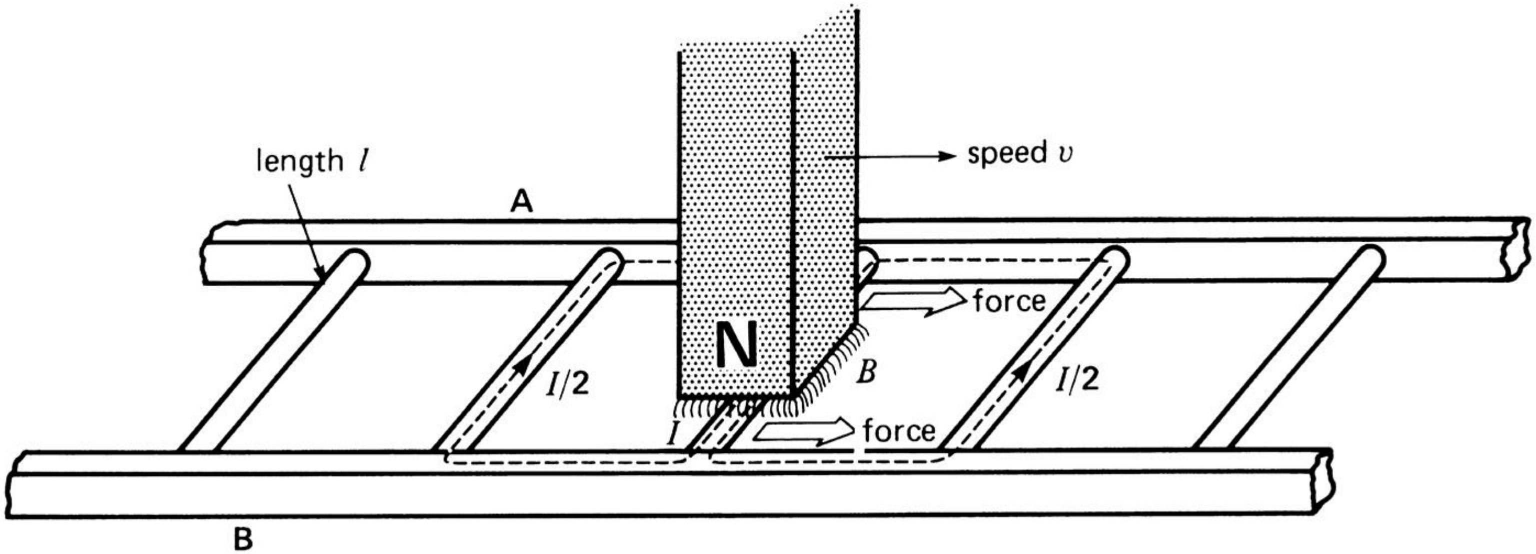
$$\underset{\text{rpm}}{N_s} = \frac{120f}{P}$$

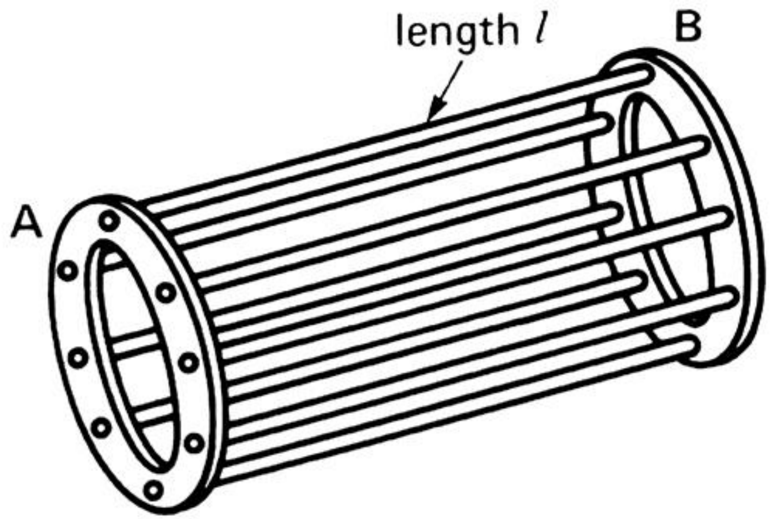
(Hz) ↳ frequency of the supply

- The revolving field induces voltage in the rotor winding. As the rotor winding forms a closed loop, the induced voltage in each coil gives rise to an induced current in that coil. When a current carrying coil is placed in a magnetic field, it experiences a force that tends to rotate it. The force (torque) thus developed is called starting torque.



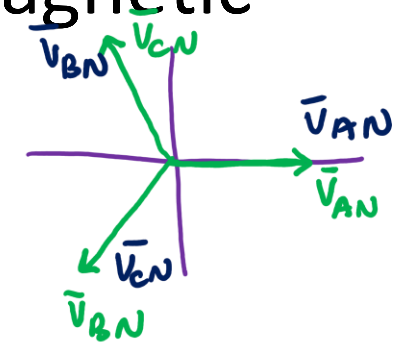
3 Phase Induction Motor - Operation

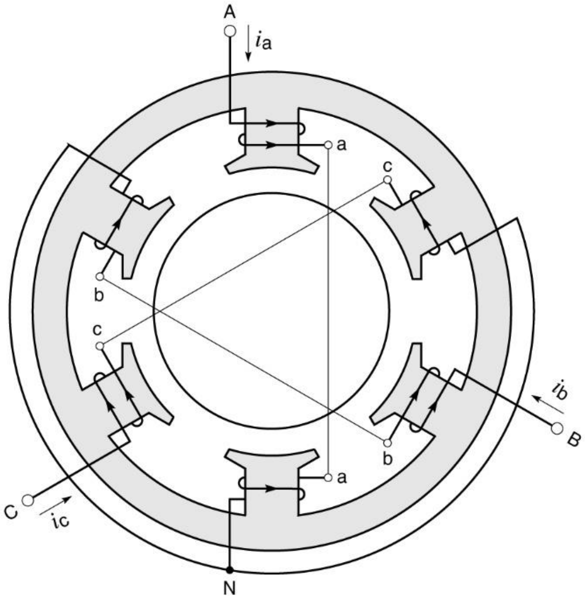


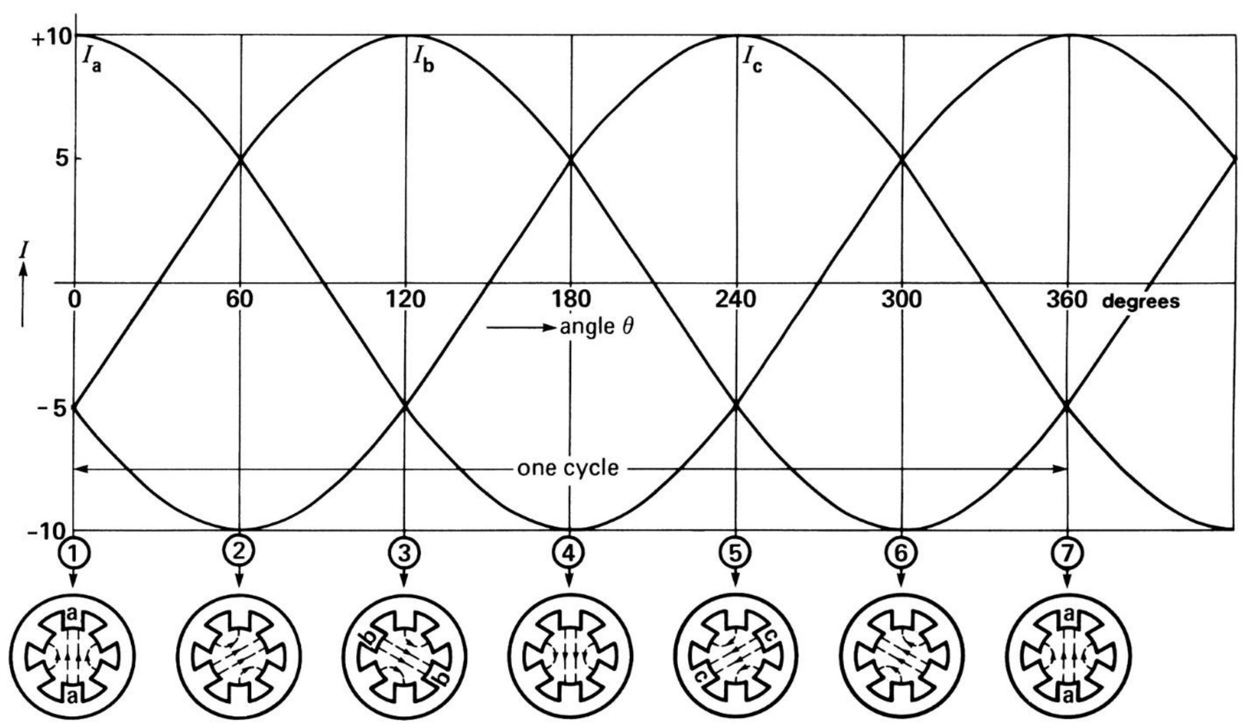


3 Phase Induction Motor – The rotating Magnetic Field (RMF)

3-phase AC supply
- magnitude
- frequency
- phase angle
- phase sequence
  [+ve ABC   -ve ACB]



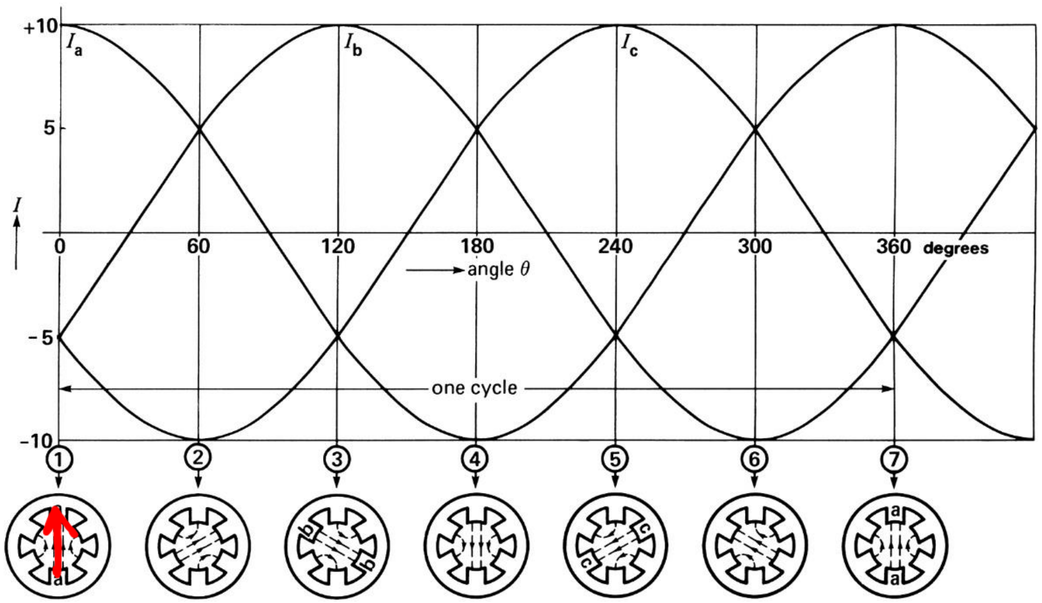


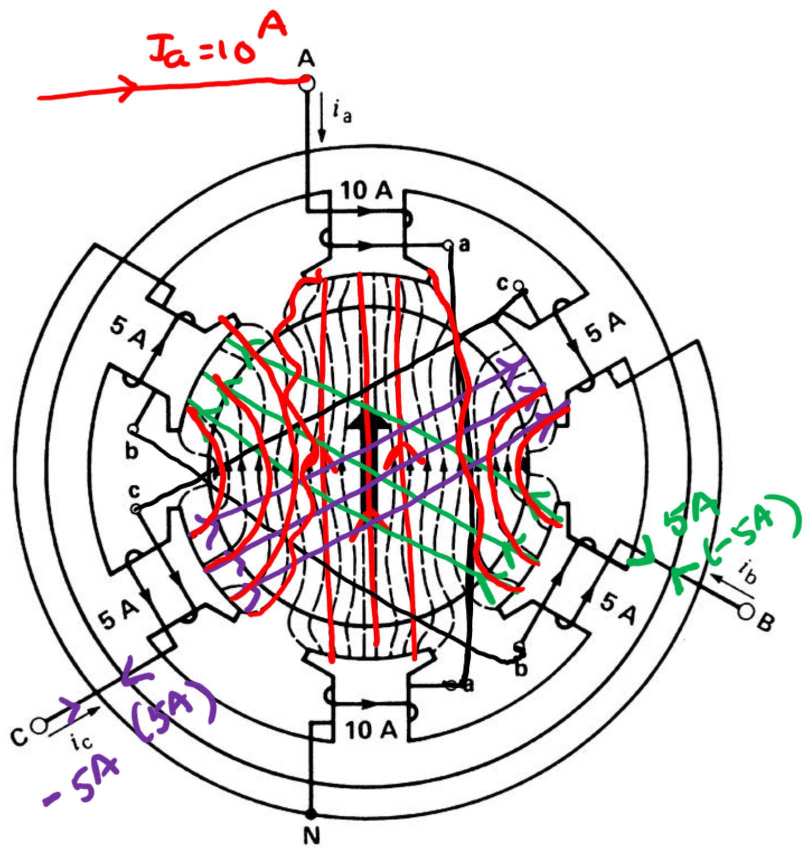


3 Phase Induction Motor – RMF

- Flux pattern at Instant 1

$I_a = 10^A$ $I_b = -5^A$ $I_c = -5^A$

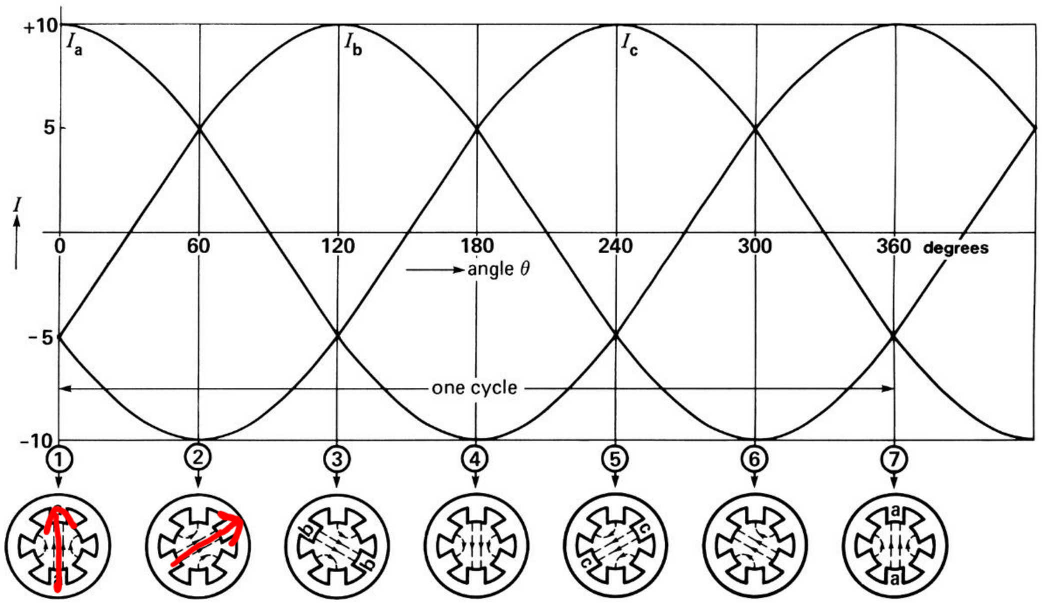


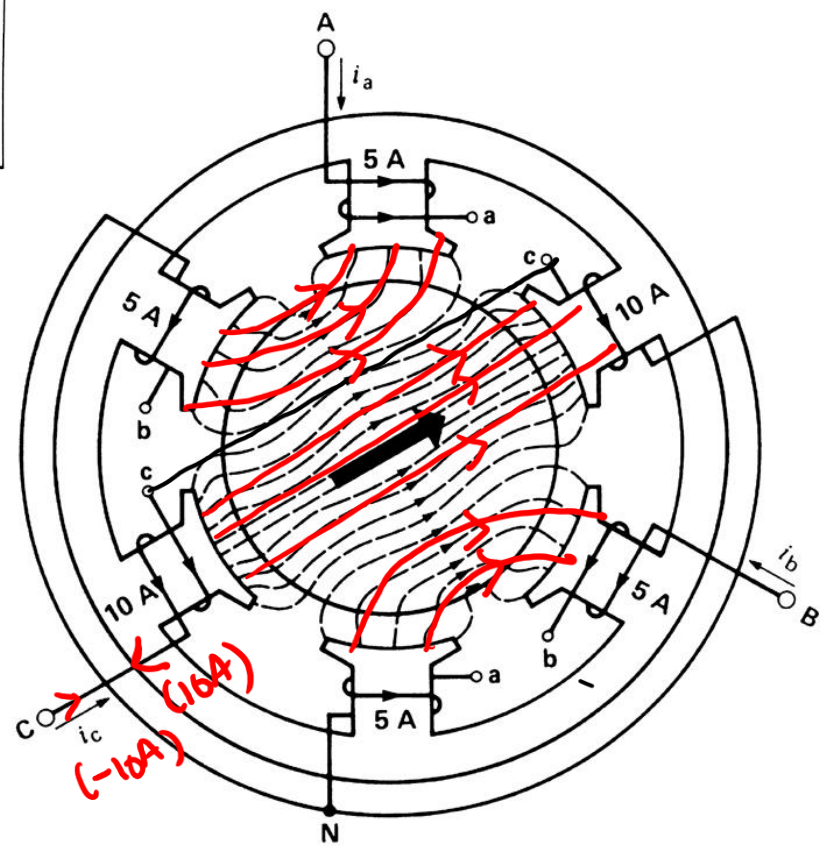


3 Phase Induction Motor – RMF

$I_a = 5^A \quad I_b = 5^A \quad I_c = -10^A$

- Flux pattern at Instant 2

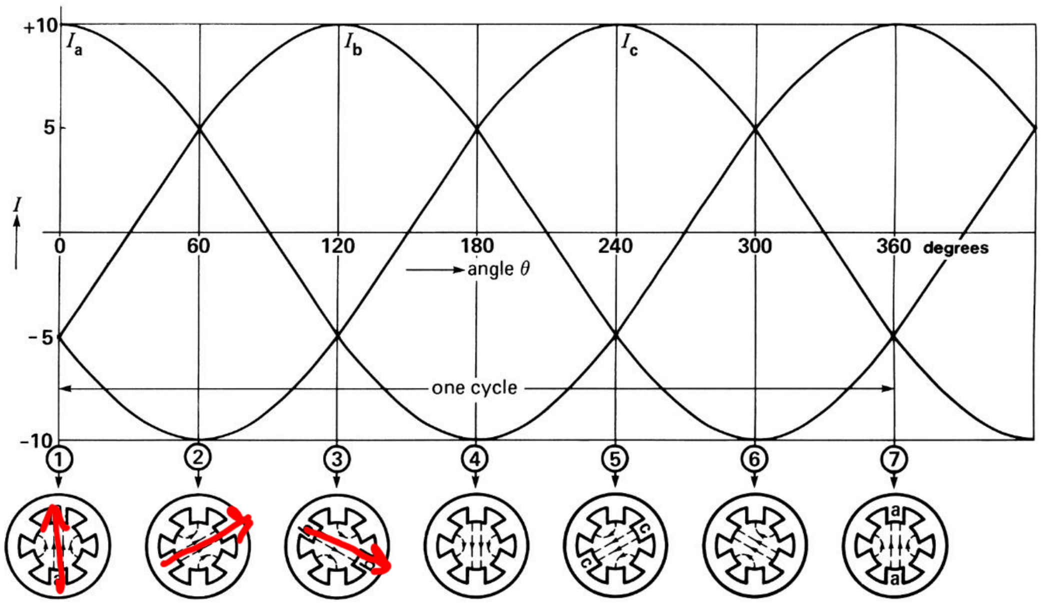


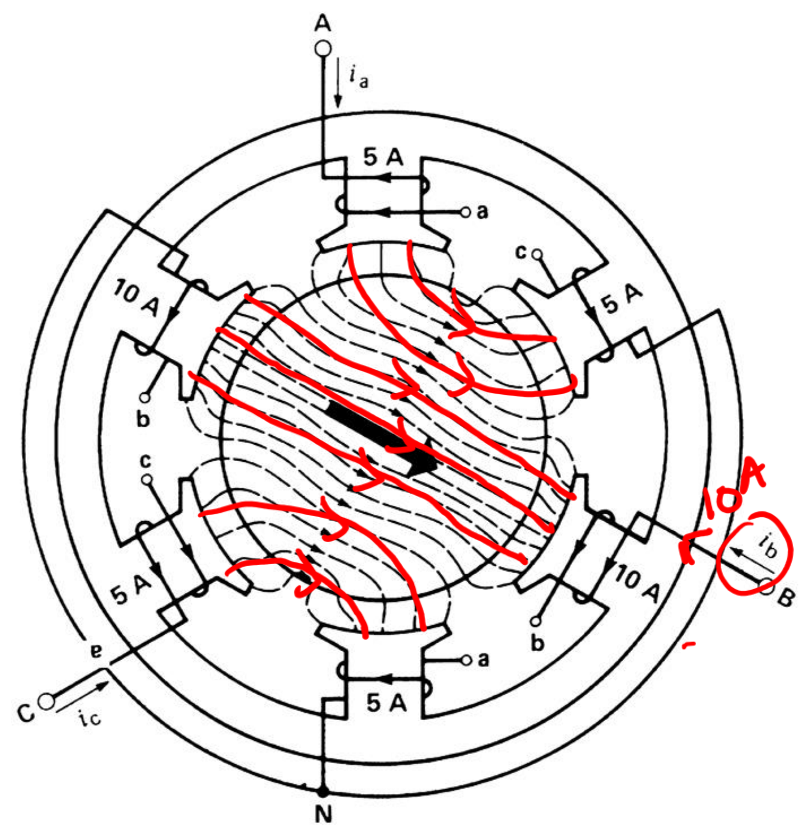


3 Phase Induction Motor – RMF

- Flux pattern at Instant 3

$I_a = -5^A$ $I_b = +10^A$ $I_c = 5^A$

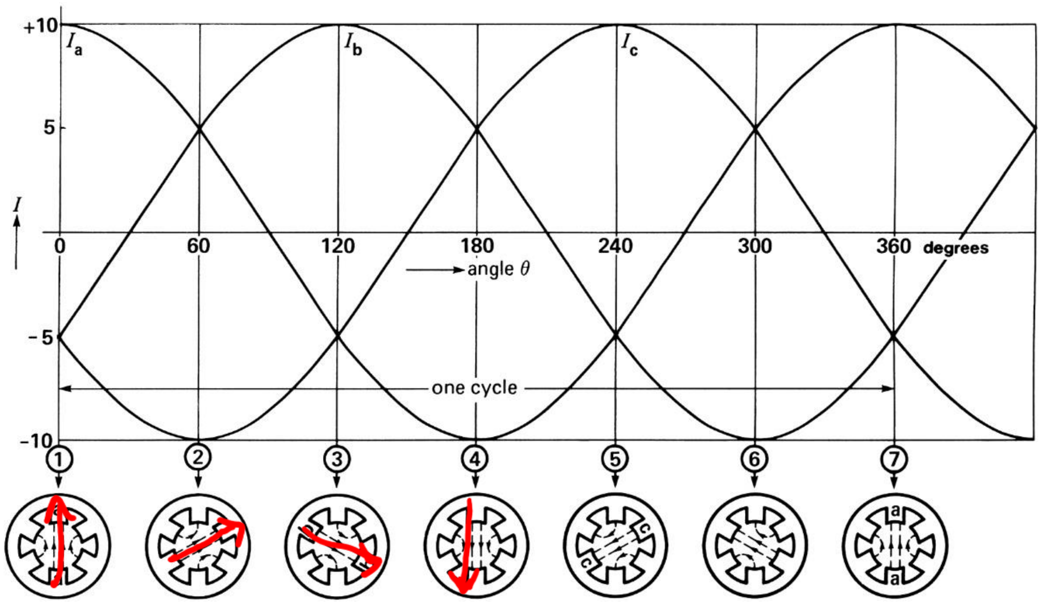


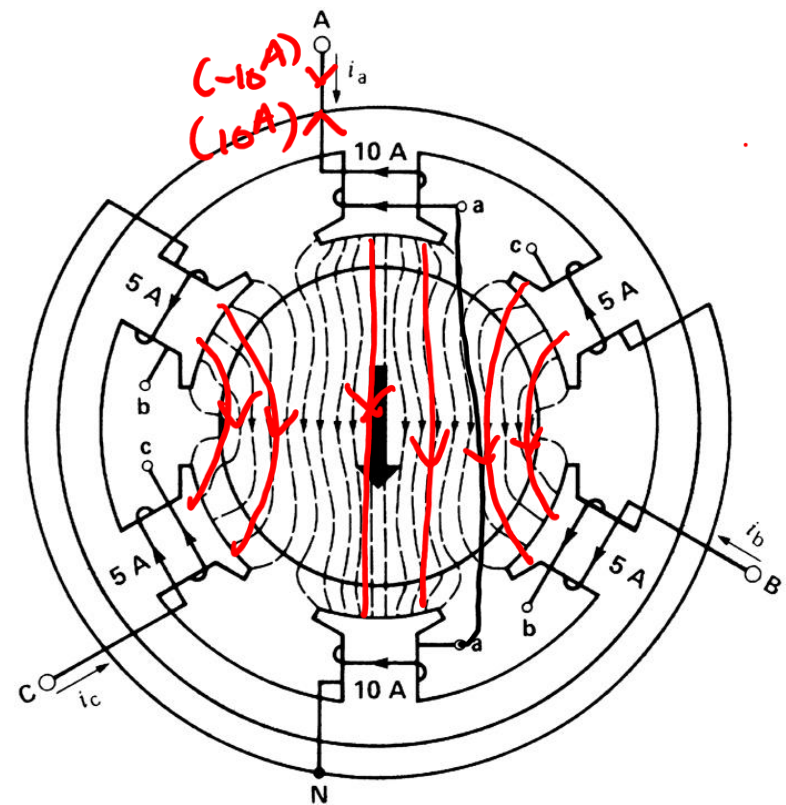


3 Phase Induction Motor – RMF

- Flux pattern at Instant 4

$$I_a = -10\,A \quad I_b = 5\,A \quad I_c = 5\,A$$

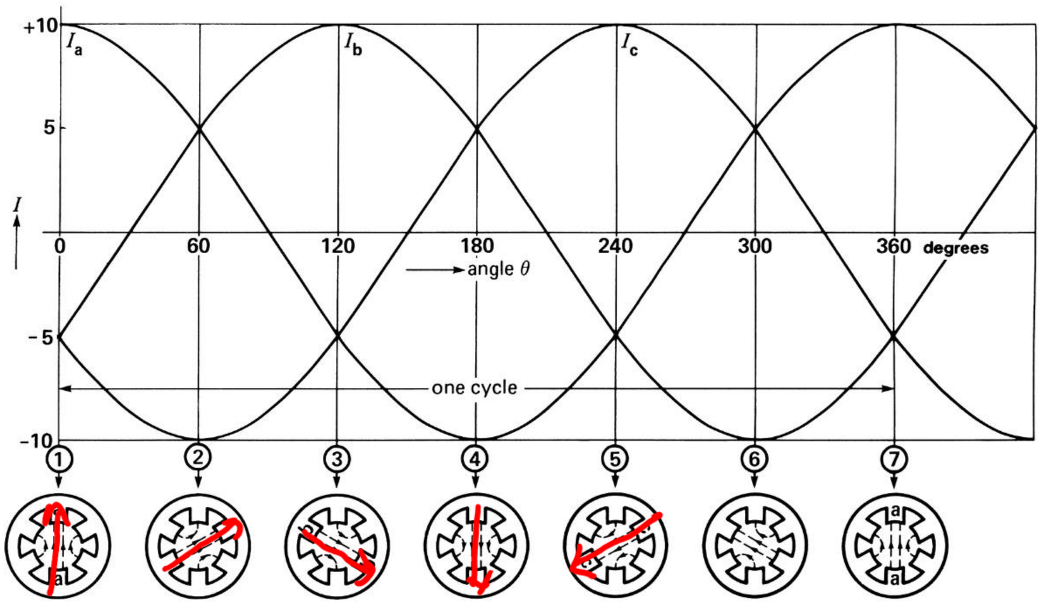


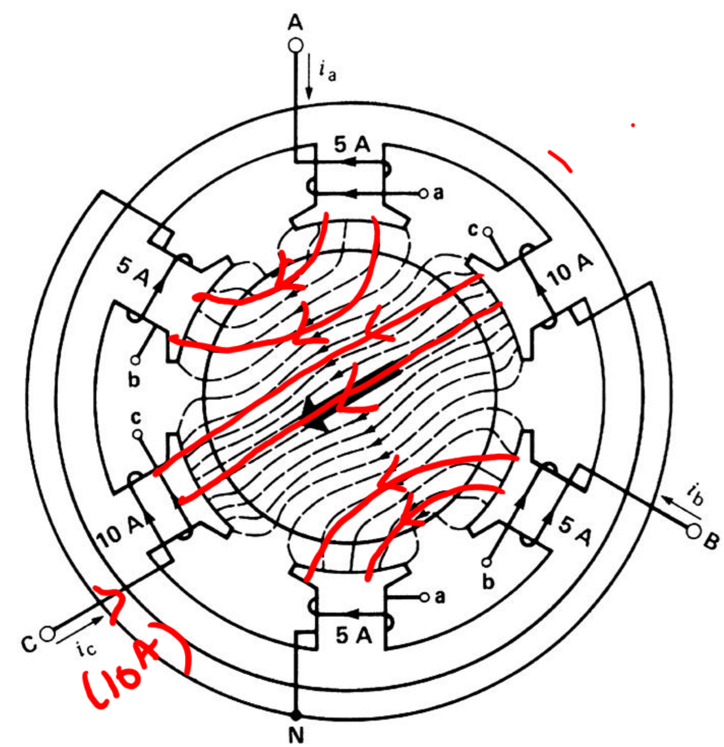


3 Phase Induction Motor – RMF

- Flux pattern at Instant 5

$I_a = -5^A$ $I_b = -5^A$ $I_c = 10^A$



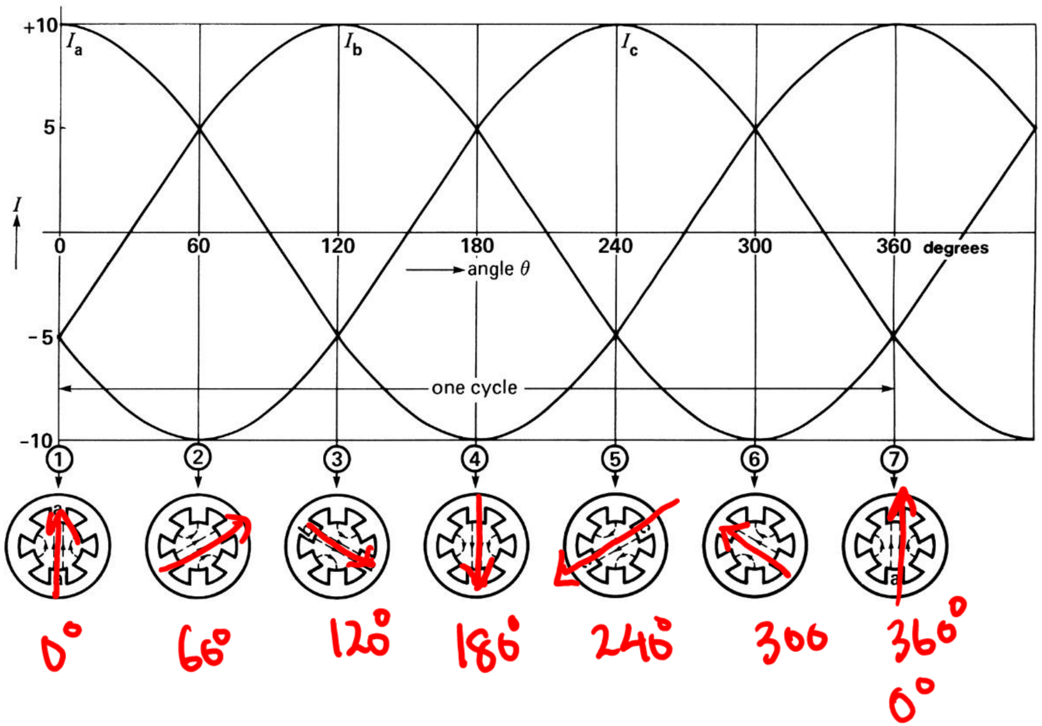


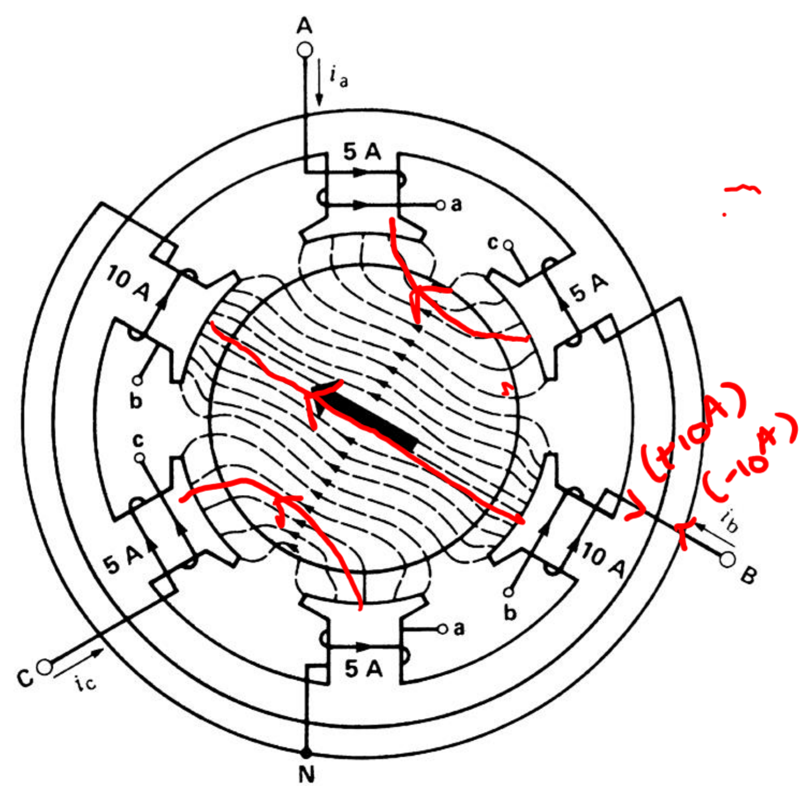
3 Phase Induction Motor – RMF

- Flux pattern at Instant 6

$I_a = +5A$ $I_b = -10^A$ $I_c = 5A$

When stator of an IM is supplied from balanced 3-phase AC with +ve (ABC) phase sequence, the RMF rotates in CW direction.



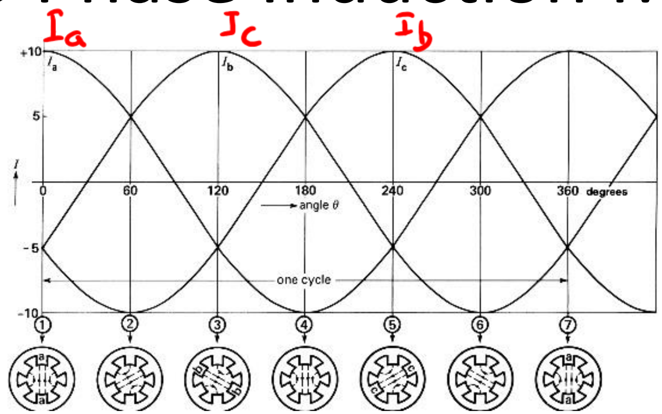


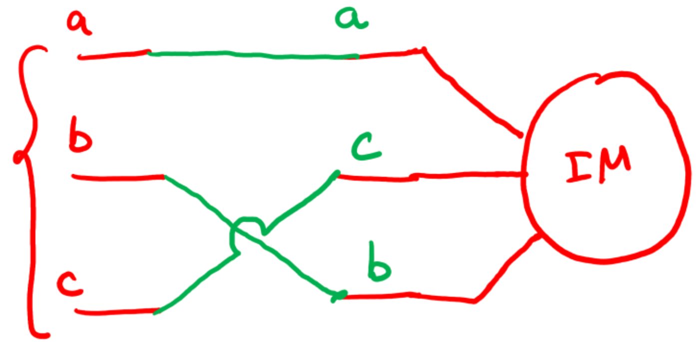
3 Phase Induction Motor - Operation

- If the load torque is less than the starting torque, the rotor starts rotating. The force developed and thereby the rotation of the rotor are in the same direction as the revolving field.
- Under no load, the rotor achieves a speed nearly equal to synchronous speed. However, the rotor can never rotate at synchronous speed because the rotor coils would appear stationary with respect to the revolving field and there would be no induced emf in them. In the absence of an induced emf in the rotor coils, there would be no current in the rotor conductors and consequently no force would be experienced by them. In the absence of a force, the rotor would tend to slow down. As soon as the rotor slows down, the induction process takes over again.

$N < N_S$ $N \neq N_S$

3 Phase Induction Motor – Direction of Rotation





- Positive (ABC) phase sequence supply to the stator
- Produced field rotates CW
- Motor rotates CW
- If any two leads of the supply are interchanged, the new phase sequence will be negative (ACB)
- The field now will rotate at synchronous speed but in opposite or CCW direction and the motor will rotate in CCW direction
- Interchanging any two lines of the supply of a 3-phase IM will reverse its direction of rotation

3 Phase Induction Motor - Slip

$N_s = \frac{120f}{P}$

- The voltage induced in the rotor conductors of an IM depends on the speed of the rotor RELATIVE TO THE MAGNTIC FIELD.
- The difference between synchronous speed and the rotor (motor) speed – Slip Speed

speed of revolving magnetic field

$$N_{slip} = N_s - N$$

speed of rotor (motor)

- The rotor rotates at a speed lower than the synchronous speed of the revolving field, an induction motor is also called an Asynchronous motor
- The difference between actual rotor speed and synchronous speed expressed on a pu basis is called slip and is normally expressed as %

$$s = \frac{N_s - N}{N_s} \quad \begin{matrix} \text{rpm} \\ \text{rpm} \end{matrix}$$

no units

$$\%S = \frac{N_s - N}{N_s} \times 100\%$$

$$sN_s = N_s - N$$

$$N = N_s - sN_s$$

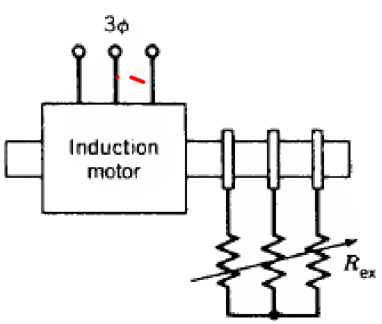
$$N = (1-s)N_s$$

- where N is the rotor speed at a certain load

$$N = (1\text{-s})N_s$$

3 Phase Induction Motor - Slip

- Squirrel Cage:
  1% 6%
  - Slip is small (typically between .01 and 0.06). It means that the shaft spins at a speed very close to that of the rotational field (N_s) speed.
  - Squirrel cage machines are inherently constant speed machines [their speed remains almost constant with load changes]
- Wound Rotor:
  - The shaft speed can be significantly varied by connecting external resistors to their slip rings



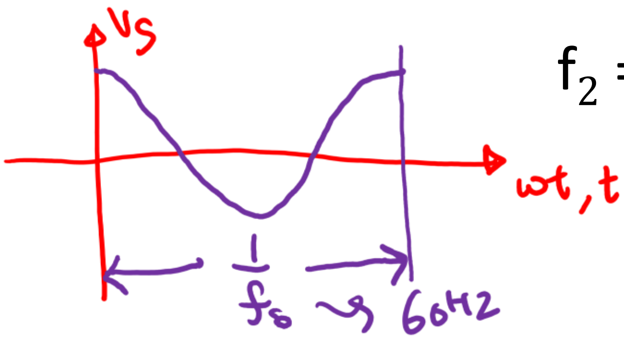
3 Phase Induction Motor – Rotor Frequency

$N=0$ $s = \frac{N_s - 0}{N_s} = 1$ $N_s = \frac{120f}{P}$

- When rotor is stationary, the per unit slip is 1 and the rotor appears exactly like a short circuited secondary winding of a transformer. The frequency of the induced emf in the rotor winding is the same as that of the revolving field. However, when the rotor rotates, it is the relative speed of the rotor (N_{slip}) that is responsible for the induced voltage in its windings. Thus, the frequency of the induced voltage and the voltage is given as

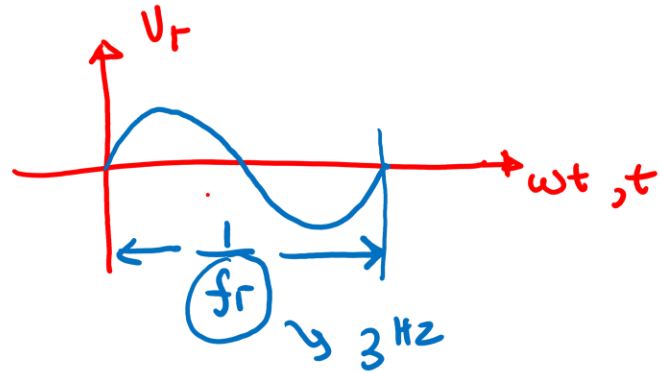
rotor voltage $f_r = f_s$ N

$N_{slip} = \frac{120 f_r}{P}$



$$f_2 = f_r = \frac{PN_{slip}}{120} = sf$$

$$E_2 = sE_{oc}$$



- E_{oc} – open circuit voltage induced in the rotor when stationary (Volts)
- the rotor frequency and voltage depends on the slip of the motor

$$f_2 = \frac{P(N_s - N)}{120} = \frac{P(sN_s)}{120} = s\frac{\cancel{P}}{\cancel{120}}\frac{\cancel{120}f}{\cancel{P}} = sf$$

(rotor frequency)

slip stator freq.

Example

Pout

A 208-V, 10hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip of 5 percent

$s = \frac{N_s - N}{N_s}$

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

① $N_s = \frac{120f}{P} = \frac{120 \times 60}{4} = 1800^{rpm}$

② $N = (1-s)N_s = (1-0.05) \times 1800 = 1710^{rpm}$

③ $f_r = sf = 0.05 \times 60 = 3^{Hz}$

④ $\tau_{shaft} = \frac{P_{out}}{\omega} = \frac{10 \times 746}{(1710/9.55)}$

$= 41.66^{N\text{-}m}$

$P = \tau\omega$ ↳ speed of the shaft in rad/sec

↑ Watts ↑ N-m

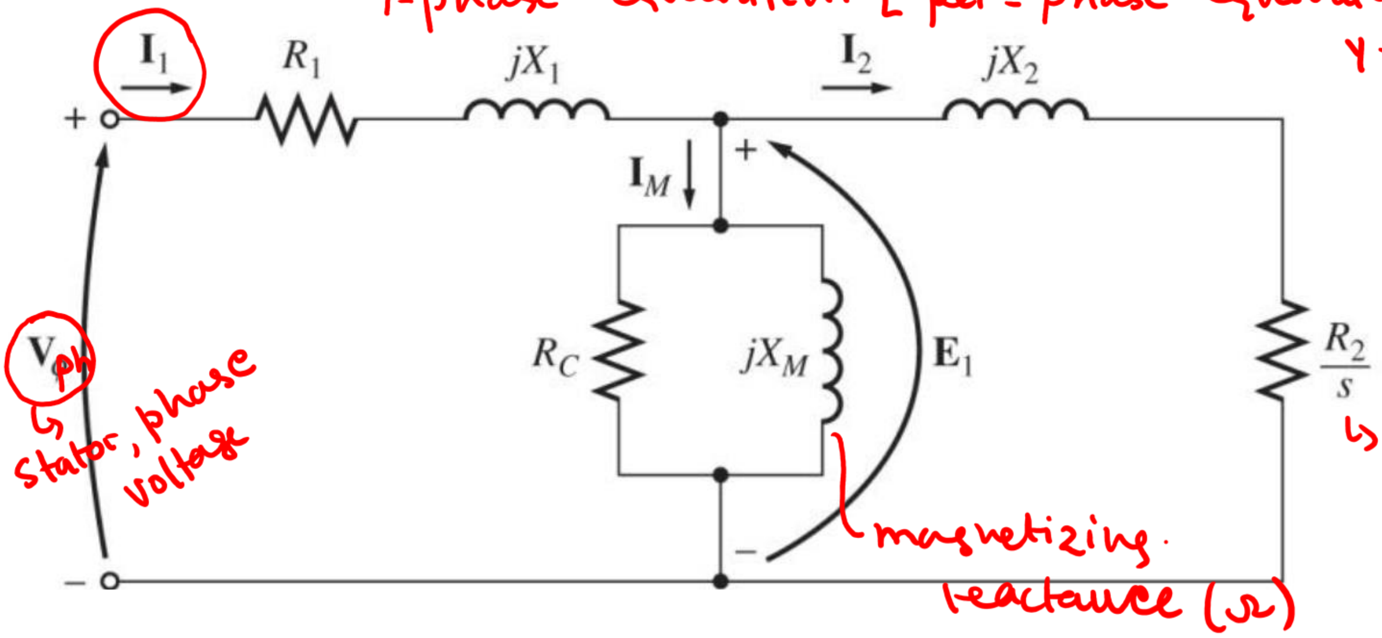
Exercises

Wednesday
Nov 13

- Problem 1: A 208 V, 60Hz, 4-pole, three-phase induction motor has a full load speed of 1755rpm. Calculate (a) its synchronous speed, (b) the slip, and (c) the rotor frequency
- Problem 2: The rotor speed of a 440 V, 50Hz, 8-pole, three-phase induction motor is 720rpm. Calculate (a) the synchronous speed, (b) the slip, and (c) the rotor frequency
- Problem 3: If the rotor frequency of a 6-pole, 50Hz, three-phase Induction motor is 3Hz, determine (a) the slip, and (b) the rotor speed
- Problem 4: The magnetic field produced by a three-phase induction motor revolves at a speed of 900 rpm. If the frequency of the applied voltage is 60Hz, determine the number of poles in the motor. When the motor turns at a speed of 800 rpm, what is the percent slip of the motor?

Induction Motor – Equivalent Circuit

1-phase equivalent [per-phase equivalent circuit)



Y-connection

$V_{ph} = \frac{V_L}{\sqrt{3}}$

$I_1 \rightarrow$ line current

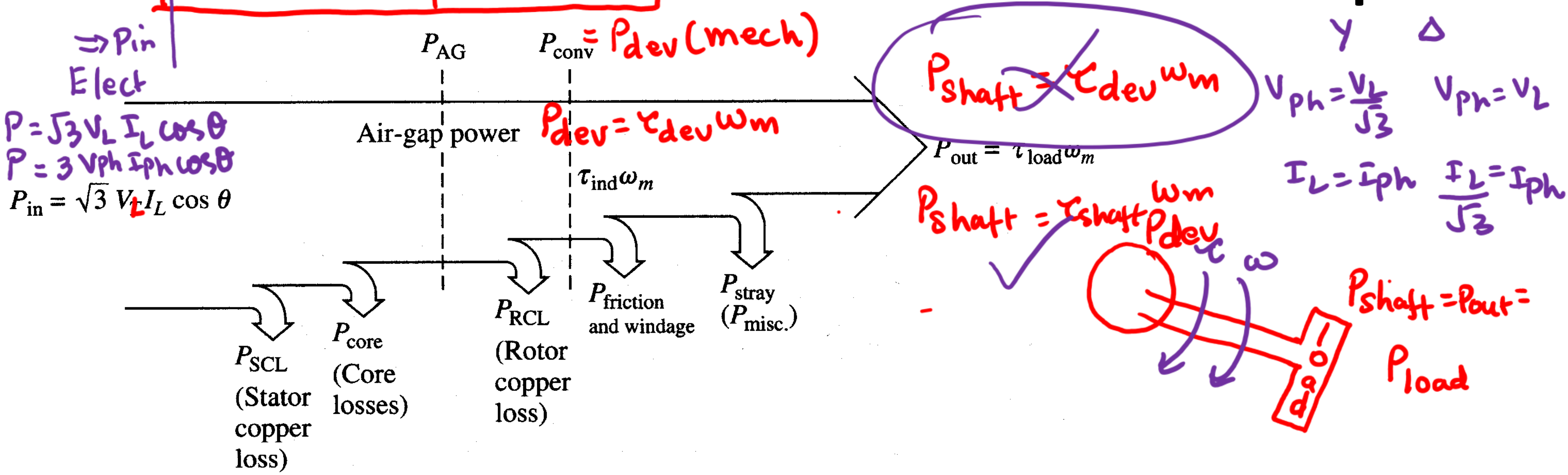
$I_L = I_{ph}$

slip $= \frac{N_s - N}{N_s}$

- R_1 stator resistance, per phase
- X_1 stator leakage reactance, per phase $X_1 = 2\pi f L_1$
- R_2 rotor resistance referred to stator, per phase
- X_2 rotor leakage reactance referred to stator, per phase

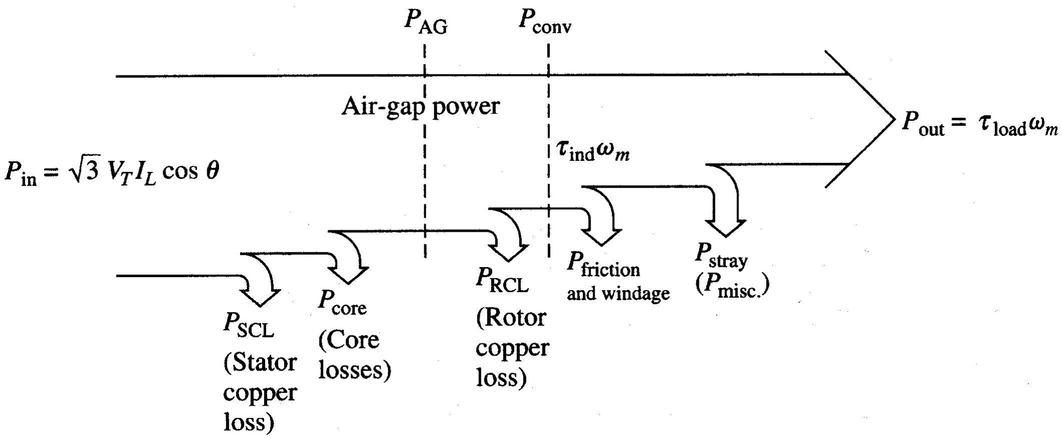
$X_2 = 2\pi (sf) L_2$

Induction motor – Power and Torque



- Active power P_{in} flows from the line into the 3-phase stator
- A portion of P_{in} is dissipated as heat in the stator winding and is represented by the Stator copper losses $= 3 I_1^2 R_1$
- Another portion of P_{in} is dissipated as heat in the stator core and is represented by the core losses
- Remaining active power is carried across the air gap and is transferred to rotor through electromagnetic induction, called air gap power P_{AG} $= P_{in} - P_{SCL} - P_{core}$
- Another portion is dissipated as heat in the rotor and is represented by rotor copper loss $= 3 I_2^2 R_2$
- Rest is converted to mechanical power, P_{conv} $= P_{AG} - P_{RCL}$
- Then Friction and Windage and Stray losses are subtracted, the remaining power is the output of the motor P_{out} $= P_{conv} - P_{FW} - P_{stray}$

Induction motor – Power and Torque



- From the total power input to the rotor (P_{AG}), a fraction **s** is dissipated in the resistance of the rotor as RCL and a fraction **(1-s)** is converted into mechanical power (P_{conv})

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

$$\frac{R_2}{S} = R_2 - R_2 + \frac{R_2}{S} = R_2 + R_2\left[\frac{1}{S} - 1\right] = R_2 + R_2\left[\frac{1-S}{S}\right]$$

Loss

O/P

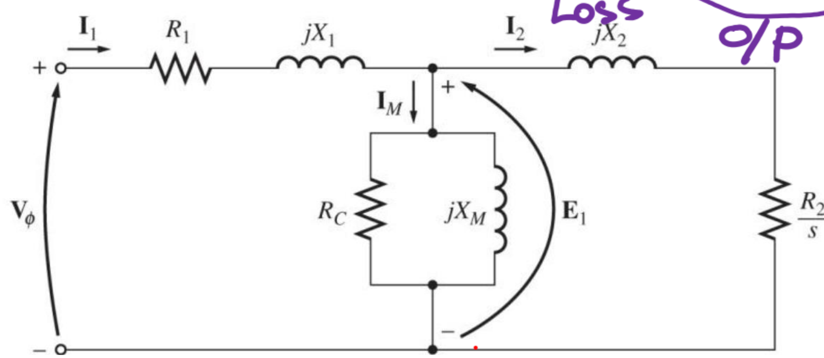
$$P_{SCL} = 3 I_1^2 R_1$$

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

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

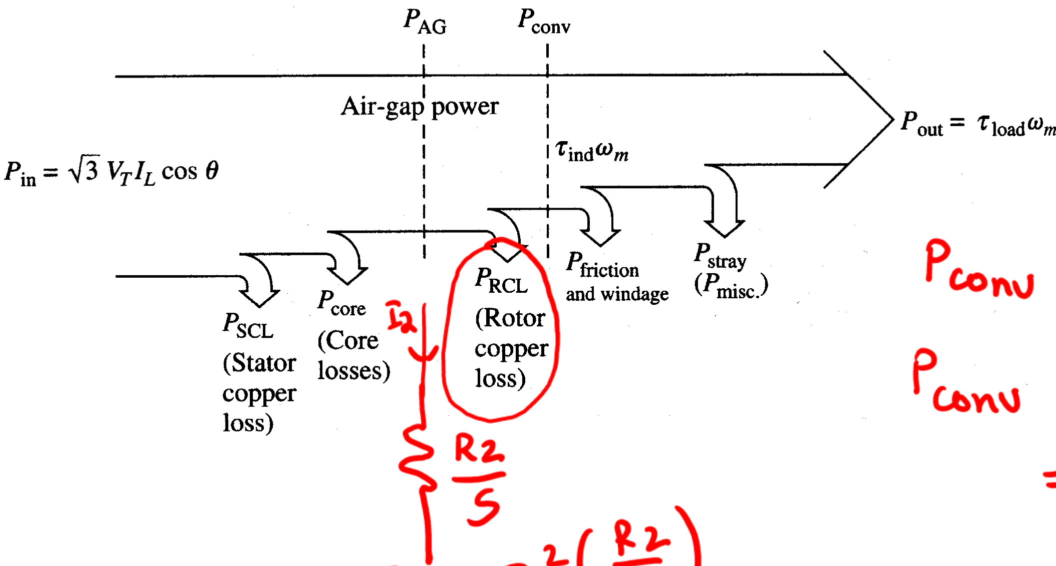
$$P_{conv} = P_{AG} - P_{RCL}$$

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



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

Induction motor – Power and Torque



$$N = (1-s) N_s$$

$$\omega = (1-s)\omega_s$$

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

$$P_{conv} = P_{dev} = I_2^2 R_2 \left(\frac{1-s}{s}\right) = \left[\frac{I_2^2 R_2}{s}\right](1-s) = (1-s) P_{AG}$$

$$P_{AG} = I_2^2 \left(\frac{R_2}{s}\right)$$

- Induced torque is the torque generated by the internal electric to mechanical power conversion, τ_{ind}
- This torque is different than the actual torque available at the terminals of the motor by an amount equal to friction and windage torques in the motor
- The induced torque, also called developed torque, is given by

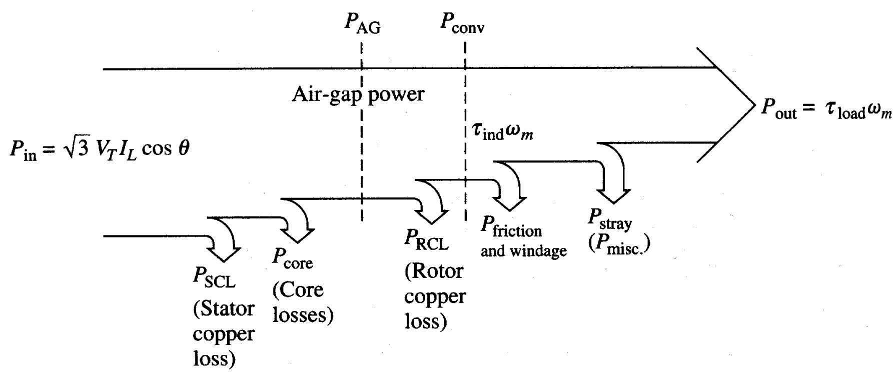
$$\tau_{ind} = \frac{P_{conv}}{\omega} = \frac{(1-s)P_{AG}}{(1-s)\omega_s} = \frac{P_{AG}}{\omega_s}$$

Induction motor – Power and Torque - Example

A 50 kw, 440 V, 50 Hz, six pole induction motor has a slip of 6% when operating at full load conditions. At full load conditions, the friction and windage losses are 300 W, and the core losses are 600 W. Calculate the following values for full load conditions:

Pout

1. The shaft speed, N
2. The output power in W
3. The load torque in Nm
4. The induced torque in Nm
5. The rotor frequency in Hz



① $N = (1-s)N_s$

$N_s = \frac{120 \times 50}{6} = 1000\ \text{rpm}$

$N = (1-0.06) \times 1000 = 940\ \text{rpm}$

② $P_{out} = 50000\ \text{W}$

③ $\tau_{load} = \frac{P_{out}}{\omega} = \frac{50000}{(940/9.55)}$

$= 508\ \text{N-m}$

Induction motor – Power and Torque - Example

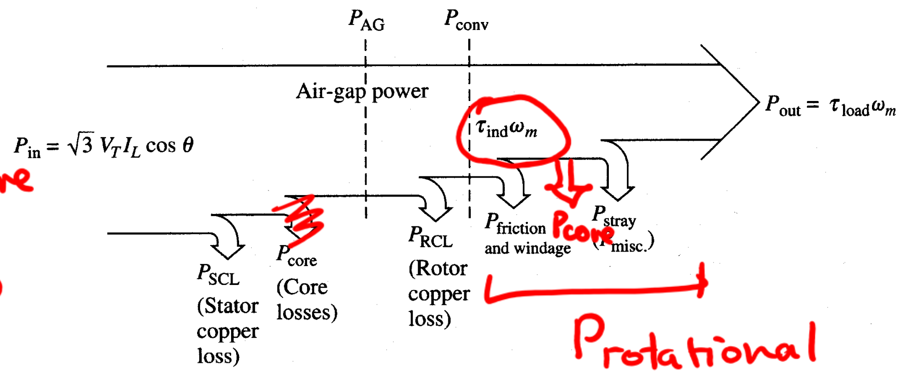
④ $P_{conv} = \tau_{ind}\,\omega$

$P_{conv} = P_{out} + P_{stray} + P_{FW} + P_{core}$

$P_{conv} = 50000 + 0 + 300 + 600$

$P_{conv} = 50900^{W}$

$\tau_{ind} = \dfrac{50900}{(940/9.55)} = 517^{N\text{-}m}$



$P_{rotational}$

core losses makes a part of the rotational losses

⑤ $f_2 = sf = 0.06 \times 50 = 3^{Hz}$

Induction motor – Equivalent circuit and Power and Torque - Example

A 460 V, 60 Hz, 25 hp, 3-phase, 4-pole, Y connected IM has the following parameters in ohms per phase referred to the stator circuit.

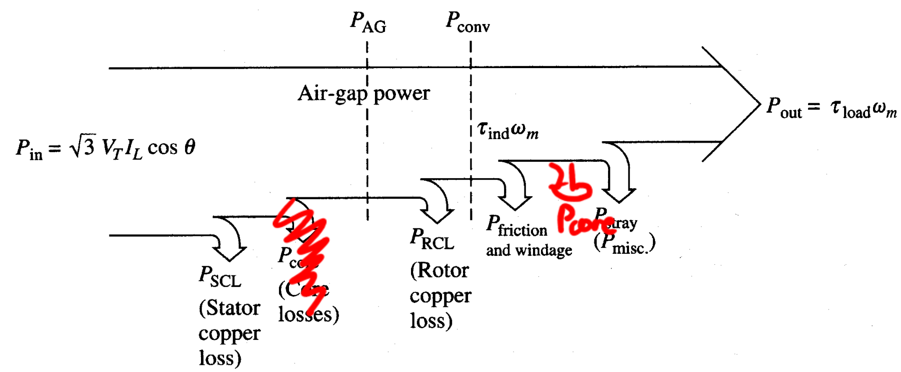
$R_1 = 0.641\ \Omega$; $R_2 = 0.332\ \Omega$; $X_1 = 1.106\ \Omega$; $X_2 = 0.464\ \Omega$; $X_m = 26.3\ \Omega$

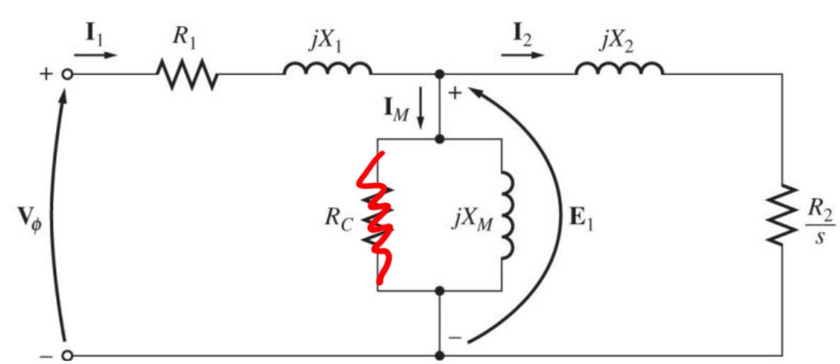
The total rotational losses are 1100 W and are assumed to be constant. The core losses are lumped in with the rotational losses. For a rotor slip of 2.2% at the rated voltage and rated frequency,

0.022

Calculate the following:

1. The motor speed
2. The stator current
3. The power factor
4. P_{conv} and P_{out}
5. τ_{ind} and τ_{load}
6. The efficiency of the motor





① $N = (1-s)\,N_s$

$N_s = \dfrac{120 \times 60}{4} = 1800$ rpm

$N = (1-0.022) \times 1800 = 1760$ rpm

Induction motor – Equivalent circuit and Power and Torque - Example

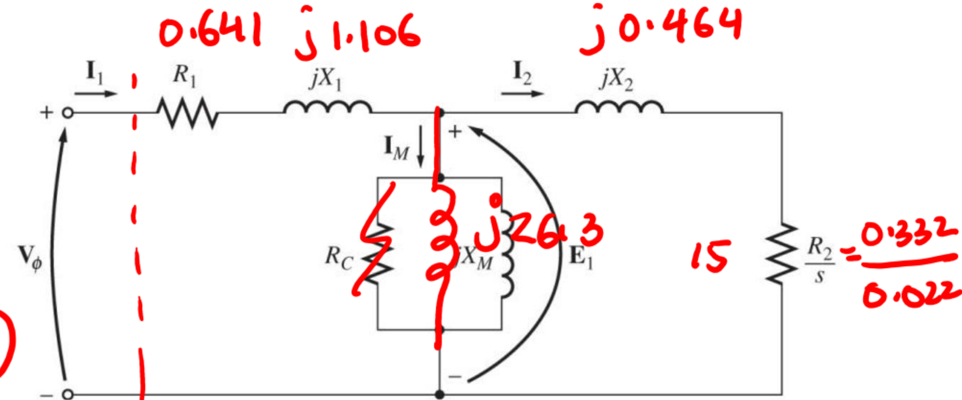
(2) $I_1 = \dfrac{V_{ph}}{Z_T}$

$$Z_T = \left[(15+j0.464) \,//\, (j26.3)\right] + [0.641+j1.106]$$

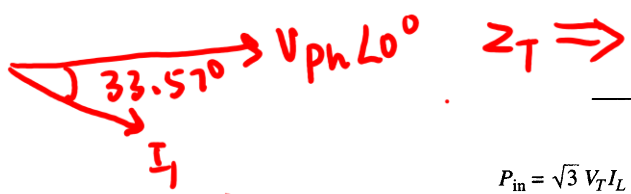
$$Z_T = \frac{(15+j0.464)(j26.3)}{(15+j26.764)} + [0.641+j1.106] = 14\angle 33.57^\circ\,\Omega$$

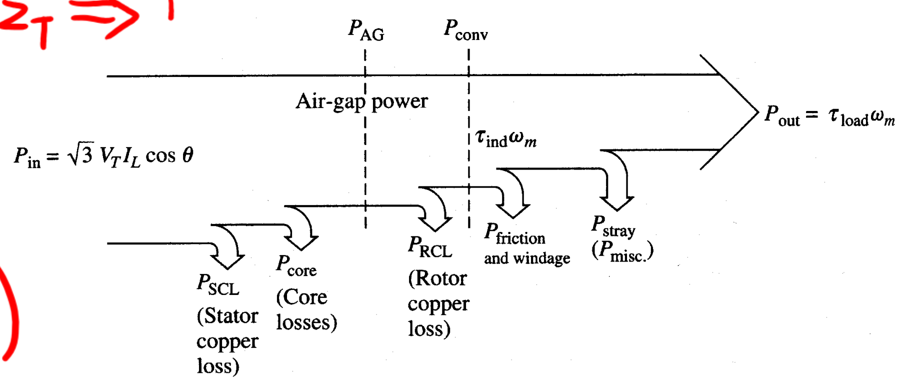
$$I_1 = \frac{(460/\sqrt{3}\angle 0^\circ)}{14\angle 33.57^\circ}$$

$$I_1 = 18.97\angle -33.57^\circ \text{ A}$$



(3) p.f. = cos(angle b/w V_{ph} and I_1)





$$\text{p.f.} = \cos(33.57^\circ)$$

$$= 0.83 \quad \text{(lagging)}$$

Induction motor – Equivalent circuit and Power and Torque - Example

(4) $P_{conv} = P_{in} - P_{SCL} - P_{RCL}$

$P_{in} = \sqrt{3} \times 460 \times 18.97 \times 0.83$

$= 12544\ W$

$P_{SCL} = 3 I_1^2 R_1 = 3(18.97^2) \times 0.641 = 692\ W$

$P_{RCL} = 3 I_2^2 R_2 = 3(16.26^2) \times 0.464$

$= 368\ W$

current division [2 branches only]

$I_2 = \frac{j26.3}{[15 + j26.764]} I_1$

$= \frac{j26.3}{(15 + j26.764)} (18.97 \angle -33.57°)$

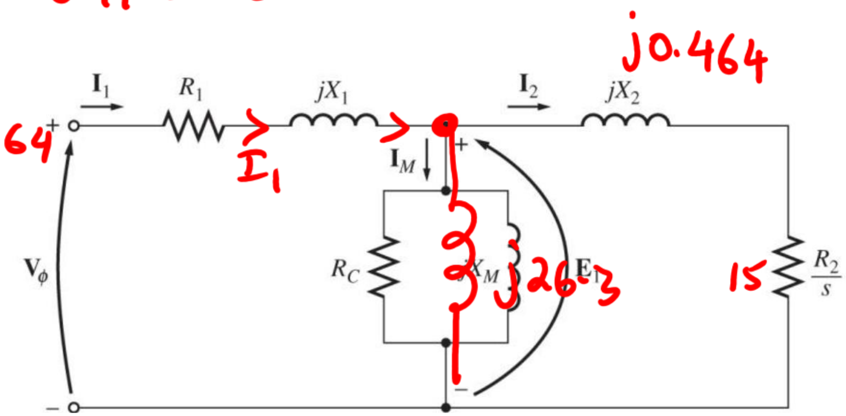
$= 16.26 \angle -4°\ A$

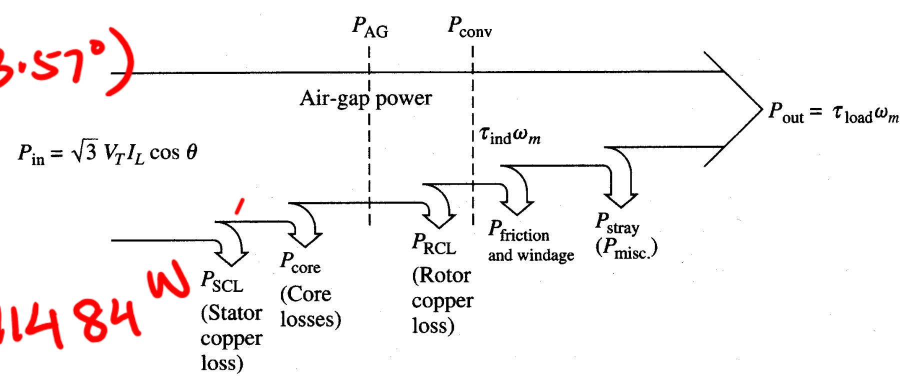
$P_{conv} = 12544 - 692 - 368 = 11484\ W$

$P_{out} = P_{conv} - P_{rotational}$

$P_{out} = 11484 - 1100$

$= 10384\ W$





Induction motor – Equivalent circuit and Power and Torque - Example

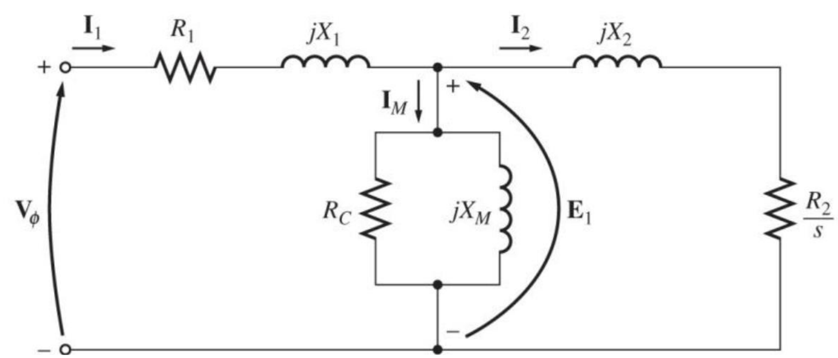
(5) $$\tau_{ind} = \frac{P_{conv}}{\omega} = \frac{11484}{(1760/9.55)} = 62.3 \text{ N-m}$$

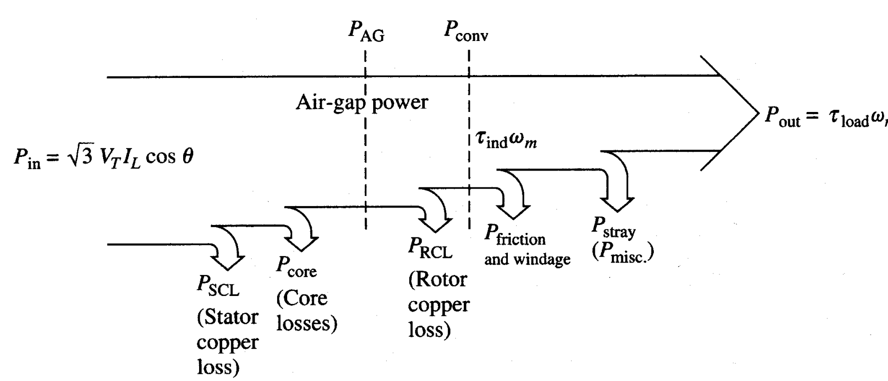
$$\tau_{load} = \frac{P_{out}}{\omega} = \frac{10384}{(1760/9.55)} = 56.3 \text{ N-m}$$

(6) $$\eta = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{10384}{12544} \times 100\,\%$$

$$= 82.8\%$$





Induction motor – Power and Torque - Example

A 480 V, 60 Hz, 50 hp, 3-phase IM is drawing 60 A (I_1) at 0.85 pf (lagging). The stator copper losses are 2 kW (P_{SCL}) and the rotor copper losses are 700 W (P_{RCL}). The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible. Calculate the following:

1. The air gap power, P_{AG}
2. The power converted P_{conv}
3. The output power P_{out}
4. The efficiency of the motor

$P_{AG} = P_{in} - P_{SCL}$

$P_{in} = \sqrt{3} \times 480 \times 60 \times 0.85 = 42^{kW}$

$P_{AG} = 42 - 2 = 40^{kW}$

2 $P_{conv} = P_{AG} - P_{RCL} = 40 - 0.7$

$= 39.3 \quad W$

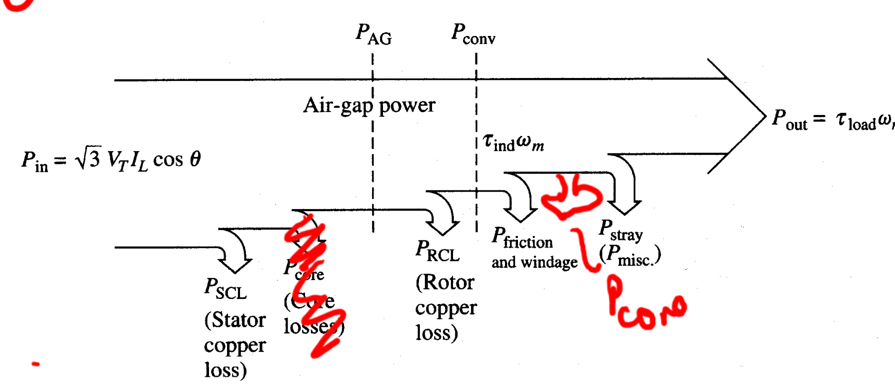
3 $P_{out} = P_{conv} - P_{rotational}$

$= 39.3 - 0.6 - 1.8 - 0$

$= 36.9 \quad kW$

4 $\eta = \frac{36.9}{42} \times 100\%$

$\eta = 88\%$



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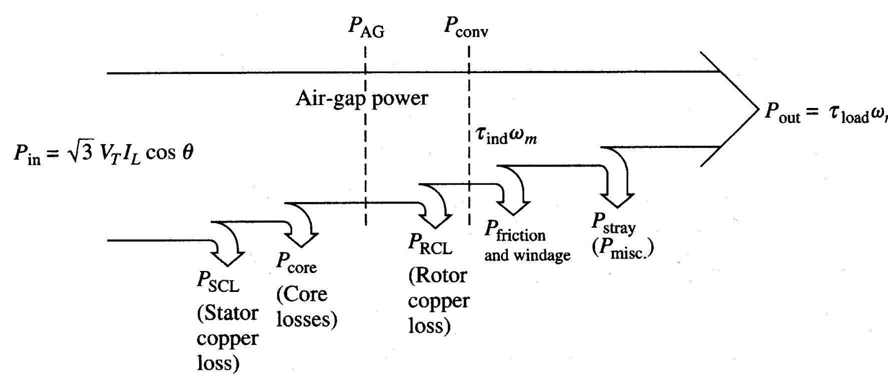


Induction motor – Torque-Speed Characteristics

T – rated full load or nominal torque

Pull – up torque is the minimum torque developed by the motor while it is accelerating from rest to the breakdown torque

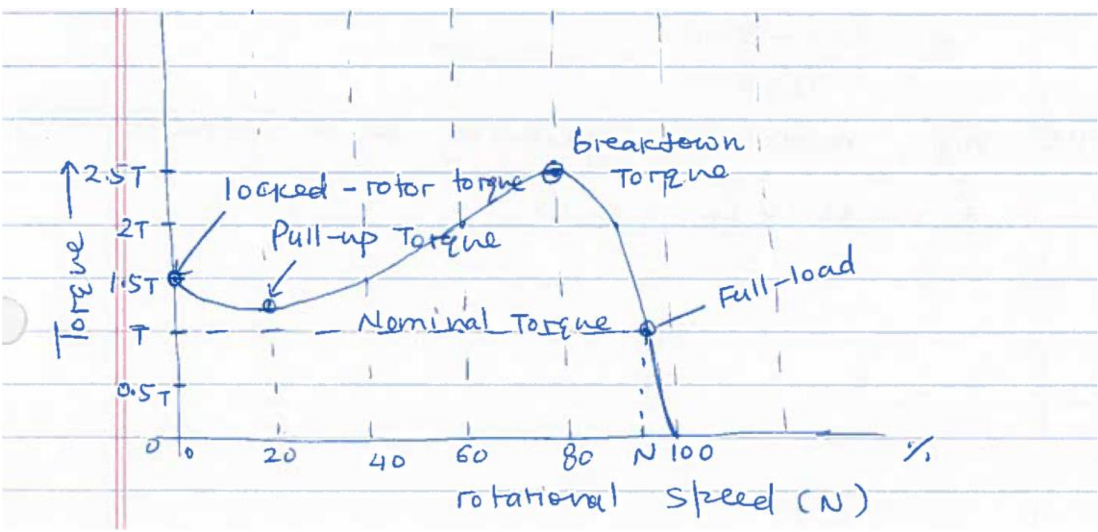
Starting torque is slightly larger than its full-load torque, motor will start carrying any load that it can supply at full power

At full load the motor runs at a speed N, the torque is proportional to the square of the stator supply voltage.

If load increases slightly, the speed will drop until the motor torque is again equal to the load torque

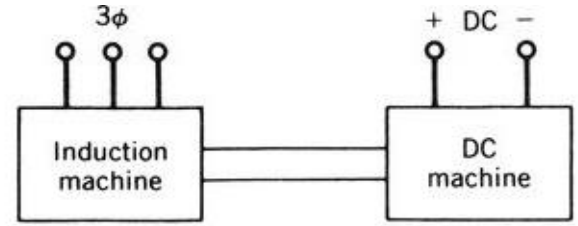
As torque generated by the motor becomes equal to the load torque, motor will rotate at a constant but slightly lower speed

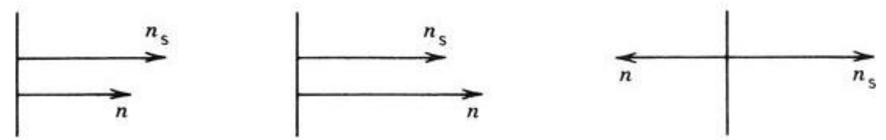
If the load torque exceeds 2.5T, the motor will quickly stop



Induction motor – Torque-Speed Characteristics

- 3 Modes of Operation
- Motor:
  - If the stator terminals are connected to a 3-phase supply, the rotor will rotate in the direction of the stator rotating magnetic field. The steady state speed N is less than the synchronous speed, N_s
- Generator:
  - The DC motor can be adjusted so that the speed of the system is higher than the synchronous speed and the system rotates in the same direction as the stator rotating magnetic field. It is used in Regenerative braking.
- Plugging:
  - The DC motor can be adjusted so that the system rotates in a direction opposite to the stator rotating magnetic field. The torque will be in the direction of the rotating field but will oppose the motion of the rotor. This torque is braking torque. This mode of operation is utilized in drive applications where the drive system is required to stop very quickly.

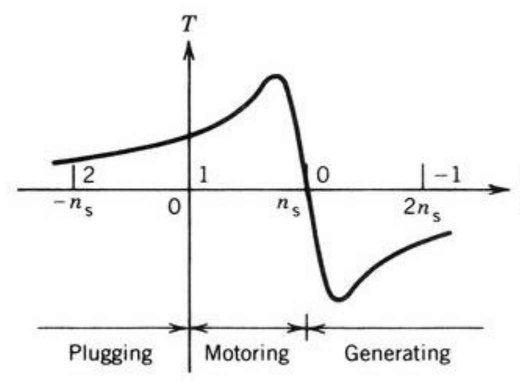




(b) Motoring $0 \leqslant n \leqslant n_s$ $1 \geqslant s \geqslant 0$

(c) Generating $n > n_s$ $s < 0$

(d) Plugging $n < 0$ $s > 1$



(e)

3 Phase Induction Motor – Speed Control

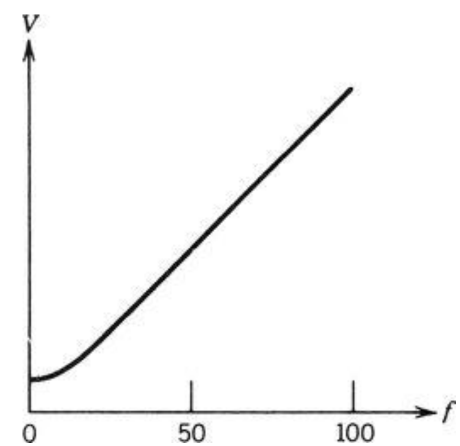
- An induction motor is essentially a constant speed motor when connected to a constant voltage and constant frequency power supply
- If the load torque increases, the speed drops by a very small amount, the induction motor is suitable for constant speed drive systems
- Many industrial applications require several speeds or a continuously adjustable range of speeds
- The availability of solid state controllers has made it possible to use induction motors in variable speed drive systems

3 Phase Induction Motor – Speed Control

- Speed control by changing the Supply frequency: Frequency of power supply determines the synchronous speed. Changing the frequency changes the speed
- Speed control by changing the supply voltage: Voltage changes affect the torque. By reducing voltage, the torque is reduced and thus slip increases
- Speed control by changing the rotor resistance: applicable to wound rotor induction motors only. The resistance change in the rotor circuit can be accomplished . This changes the shape of the characteristic speed versus torque curve, and thus will reduce the speed of a loaded wound rotor Induction Motor

3 Phase Induction Motor – Speed Control: frequency change

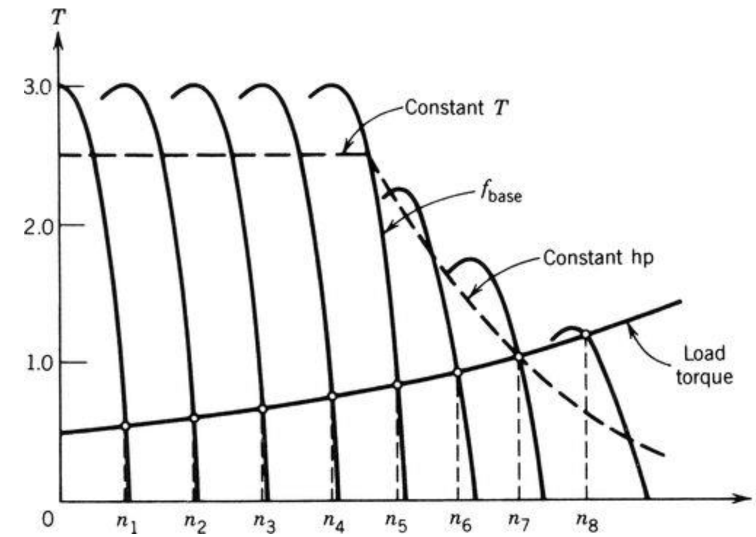
- A 4-pole motor has synchronous speed of 1800 rpm at 60 Hz. If the frequency were raised to 90 Hz, the synchronous speed would then be 2700 rpm.
- To avoid magnetic saturation, the terminal voltage of the motor must be varied in proportion to the frequency.
- Constant Volts per Hertz control



Voltage and frequency vary proportionally to maintain constant air gap flux

3 Phase Induction Motor – Speed Control: frequency change

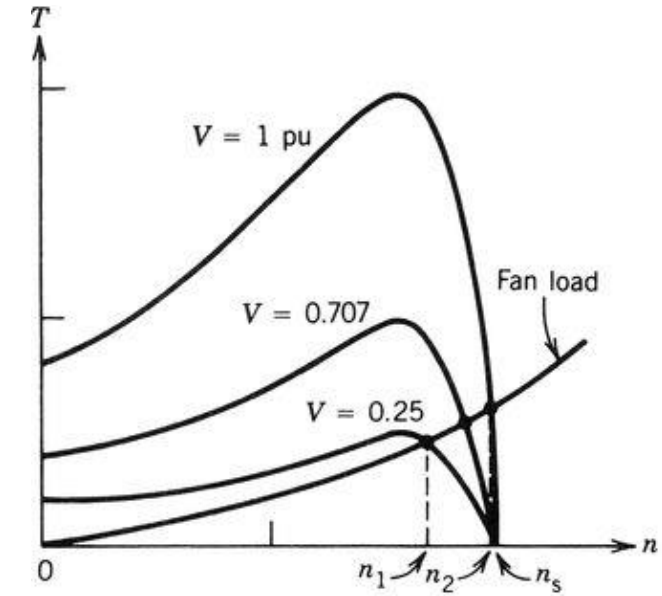
- At the base frequency f_{base} the machine terminal voltage is maximum that can be obtained from the inverter
- Below f_{base}, the air gap flux is maintained constant by changing V_1 with f_1, hence same maximum torque
- Beyond f_{base}, since V_1 cannot be further increased, the air gap flux decreases, and so does the maximum torque
- As the speeds n_1 to n_5 are close to synchronous speed, slip is low and the efficiency is high



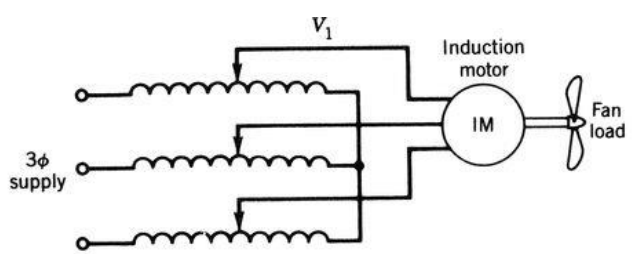
T-n characteristics of an IM with variable voltage, variable frequency control

3 Phase Induction Motor – Speed Control: Voltage Change

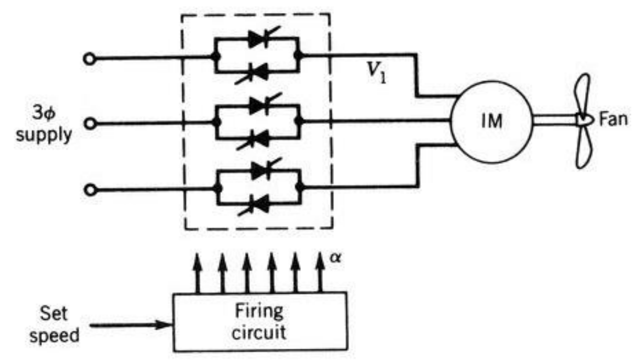
- Squirrel cage or wound rotor induction motor speed can be controlled by changing the voltage.
- Torque is proportional to the square of the applied voltage, a reduction of voltage reduces the torque and causes increased slip.
- If the rotor drives a fan load, the speed can be varied over the range n_1 to n_2 by changing the line voltage
- The terminal voltage V_1 can be varied by:



Using a 3-phase autotransformer – provides a sinusoidal voltage

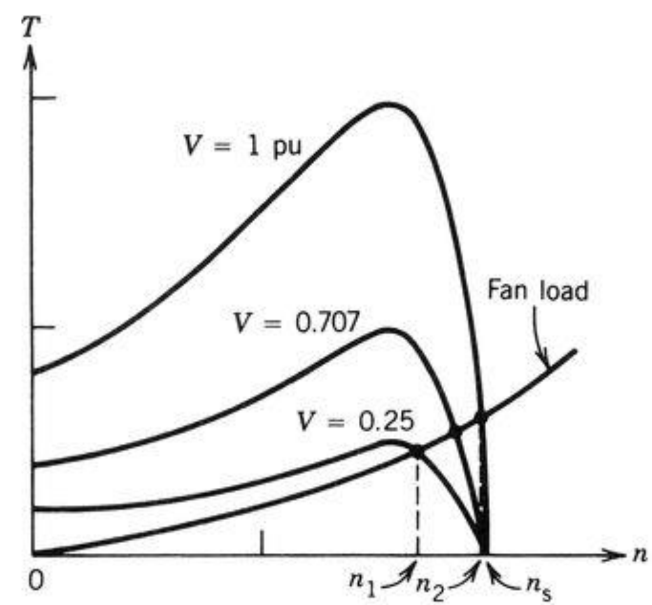


Solid state voltage controller – non sinusoidal (filter is required)



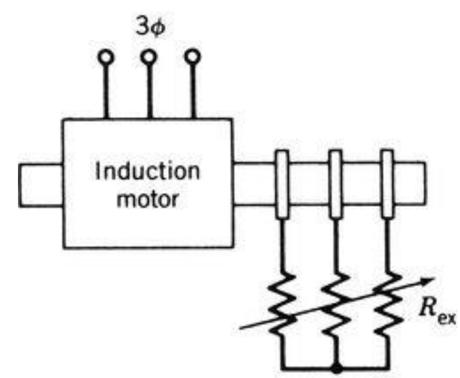
3 Phase Induction Motor – Speed Control: Voltage Change

- In this method, the slip increases at lower speeds, making the operation inefficient
- For fans, pumps, or other centrifugal drives, where the torque varies approximately as the square of the speed, the power decreases significantly with decrease in speed. All the power loss in the rotor circuit (sP_{AG}) may be a significant portion of the air gap power but the air gap power by itself is small, therefore the rotor will not overheat



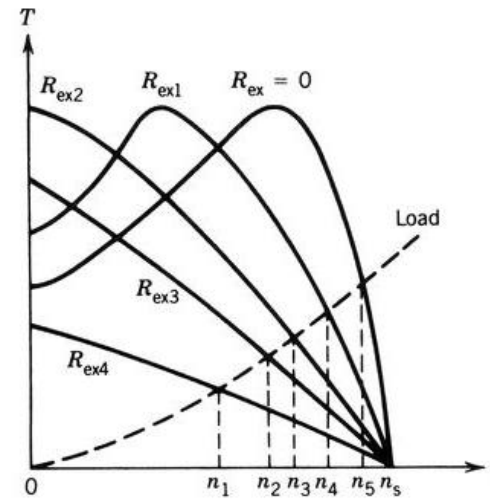
3 Phase Induction Motor – Speed Control: Rotor Resistance Change

- In a wound rotor induction motor it is possible to change the shape of Torque-speed characteristics by inserting extra resistance into the rotor circuit
- When loaded at rated torque, the operating speed can be continuously raised or lowered by changing the external rotor circuit resistance
- Leads to lowering the efficiency of the machine, that is why used only for short periods.



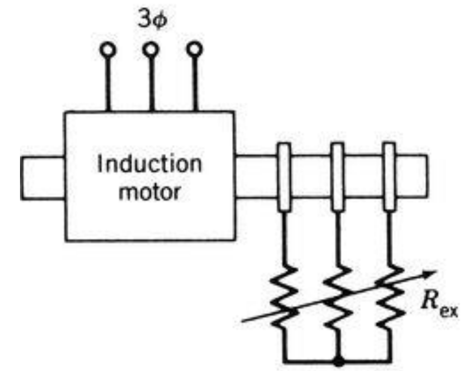
3 Phase Induction Motor – Speed Control: Rotor Resistance Change

- The T-n characteristics for 4 different external resistances are shown.
- The load T-n is shown by the dotted line
- By varying the external resistance $0 < R_{ex} < R_{ex4}$, the speed of the motor can be controlled in the range $n_1 < n < n_5$
- By adjusting the external resistance ($R_{ex} = R_{ex2}$), maximum starting torque can be obtained



3 Phase Induction Motor – Speed Control: Rotor Resistance Change

- Solid state control of external resistance



- The effective value R_{ex}* of the external resistance R_{ex} can be controlled by varying the on time (duty ratio, α) of the chopper connected across R_{ex}

$$R_{ex}^{*} = (1 - \alpha) R_{ex}$$