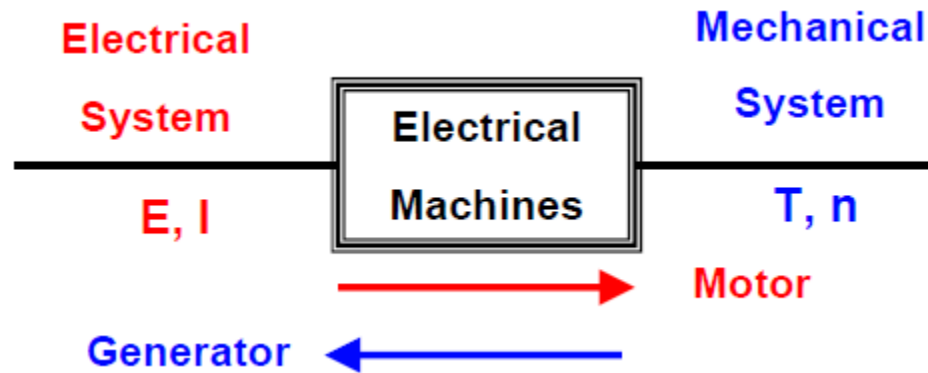


Induction Machines

- Induction machines are rotating electromechanical energy converting devices
- Operating principle of all rotating electrical machines is based on the two electromagnetic laws.
 1. If a conductor is moved in a uniform magnetic field, an emf will be induced in the conductor (Generator action)
 2. If a current carrying conductor is placed in a uniform magnetic field, a conductor experiences force (motor action)

Cont...



- The two systems in the above figure are Electrical and Mechanical and they are different in nature.
- In electrical system the **primary quantities involved are voltage & current** while
- In mechanical system, the analogous quantities are **torque & speed**.
- The **coupling medium** between these different systems is the **magnetic field**.

Cont...

- The induction machine can operate both as a motor and as a generator.
- However, it is seldom used as a generator supplying electrical power to a load.
- The performance characteristics as a generator are not satisfactory for most applications.
- The induction machine is extensively used as a motor in many applications.
- Of all the ac motors the 3-phase induction motor is the most commonly used type of AC₃

Cont...

- ✓ In an IM only the stator winding is supplied from 3-phase supply.
- The rotor winding gets power from the stator winding through **electromagnetic induction** that's why such motors are known as Induction motor.
- Thus, an induction motor is treated as a rotating transformer
- IM run at constant speed from no-load to full-load.
- However, the speed is frequency dependent and as a result these motors are not easily adapted to speed control

Advantages of IM

- It has simple and rugged construction.
- It is relatively cheap and very reliable.
- It requires little maintenance.
- It has high efficiency and reasonably good power factor
- It has self starting torque.
- (It is self starting or no need of starting device)

Disadvantages

- It is essentially a constant speed motor and its speed cannot be varied without sacrificing some of its efficiency
- Just like a dc shunt motor, its speed decreases with increase in load.
- Its starting torque is inferior to d.c shunt motor.

1. Generator action

$$e = BLV, \text{ volts}$$

Where,

e - induced e.m.f , v

B - magnetic field density,
Tesla
L - length
of the conductor, m

V - velocity of the
conductor m/s

B, L, V, are orthogonal to
each other.

2. Motor action

$$F = BLI, \text{ Newtons}$$

For rotating object,
torque is expressed as:-

$$T = F * r = BLI r, \text{ N-m}$$

where,

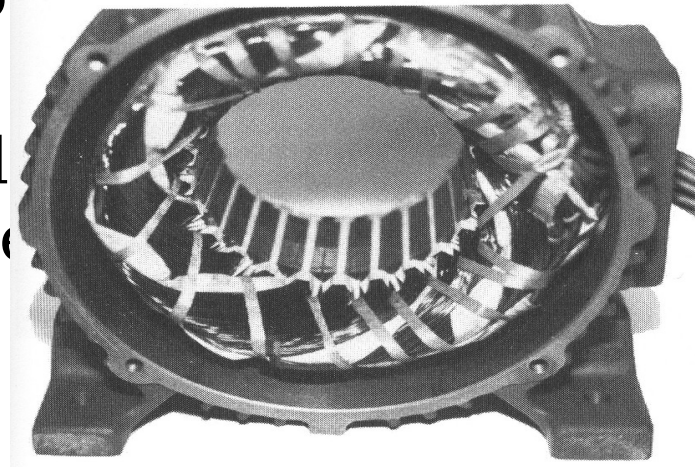
r - radius of the
rotating
object.

Construction of 3-phase induction motor

❖ It has two main parts

i) **Stator:** is the stationary part of the motor, it consists of:

- **a steel frame** which encloses a hollow, cylindrical stator core
- **Stator Core:** which have a number of evenly spaced slots, providing the space for the stator winding
- The stator core is made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses
- Three phase d... two ends covers bearings and to



Cont...

ii. Rotor: is the rotating part of an electrical motor and fits inside the stator with a slight airgap separating it from the stator.

- The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery.
- The **rotor winding placed in these slots** may be one of the following two types of construction:

(a) Squirrel cage type (b) Wound rotor type

a) Squirrel-cage Rotor:

- ❖ One Cu or Al bar is placed in each slot.
- ❖ All bars are shorted at each end by end rings, forming a squirrel-cage shaped circuit and hence the name squirrel-cage.
- ❖ This forms a permanently short-circuited winding which is unbreakable.

Cont...

- Almost 90% of 3-phase IM use cage rotor because this type of rotor has simple and unbreakable construction.
- The rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit during starting.
- Therefore, the squirrel cage IM is suffering from:-
 - Low starting torque
 - High starting current
 - They are not good for speed control

Cont...

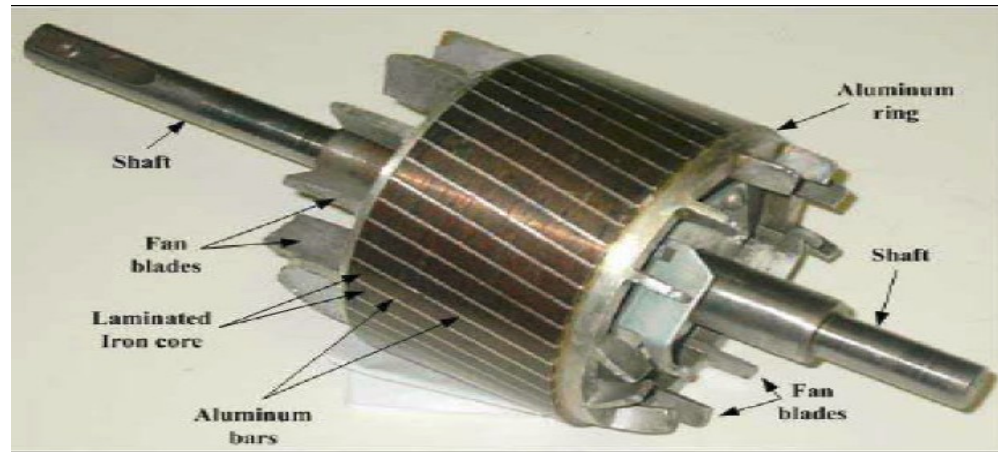


Figure 3-1 Squirrel Cage rotor

The rotor slots are usually **not quit parallel** to the shaft but are purposely **give a slight skew**. This is useful in two ways :

- ✚ it helps to make the motor **run quietly** by **reducing the magnetic hum and**
- ✚ it helps in **reducing the locking tendency of the rotor** i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two

b) Wound-rotor

It has different rotor construction to that of cage rotor IM.

- ❖ It consists of a laminated cylindrical core and carries a complete set of 3- phase windings exactly as the stator.
 - ❖ These windings are uniformly distributed in the rotor slots and is usually star-connected.
 - ❖ They are not short circuited, but the ends of the three rotor windings are connected to 3 slip rings on the rotor shaft.
 - ❖ . In this way, the rotor circuit is accessible.
- ➡ These are helpful in adding external resistors during starting, to get a large starting torque.

Cont...

- ❖ The three brushes are connected to a 3-phase star-connected rheostat as shown in Fig. 3-2 (b).
- ❖ The variable speed **induction motor has wound rotor**

Advantages of wound rotor IM

- High starting torque
- Low starting current
- Good speed control

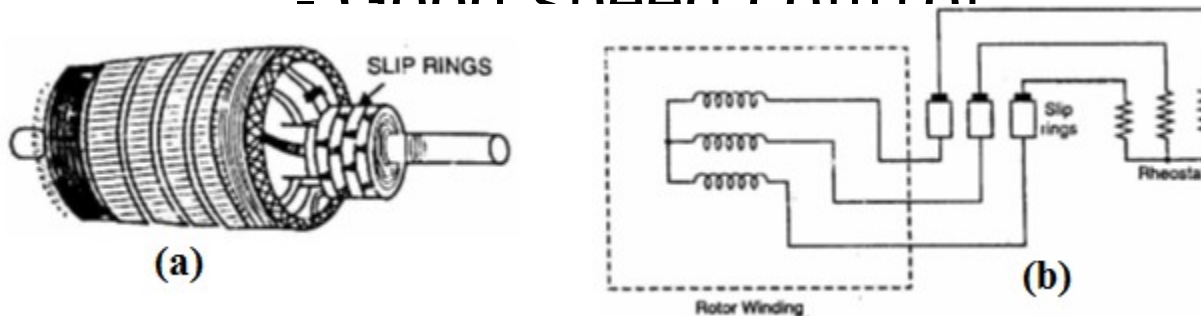


Figure 3-2 Wound rotor

Cont...

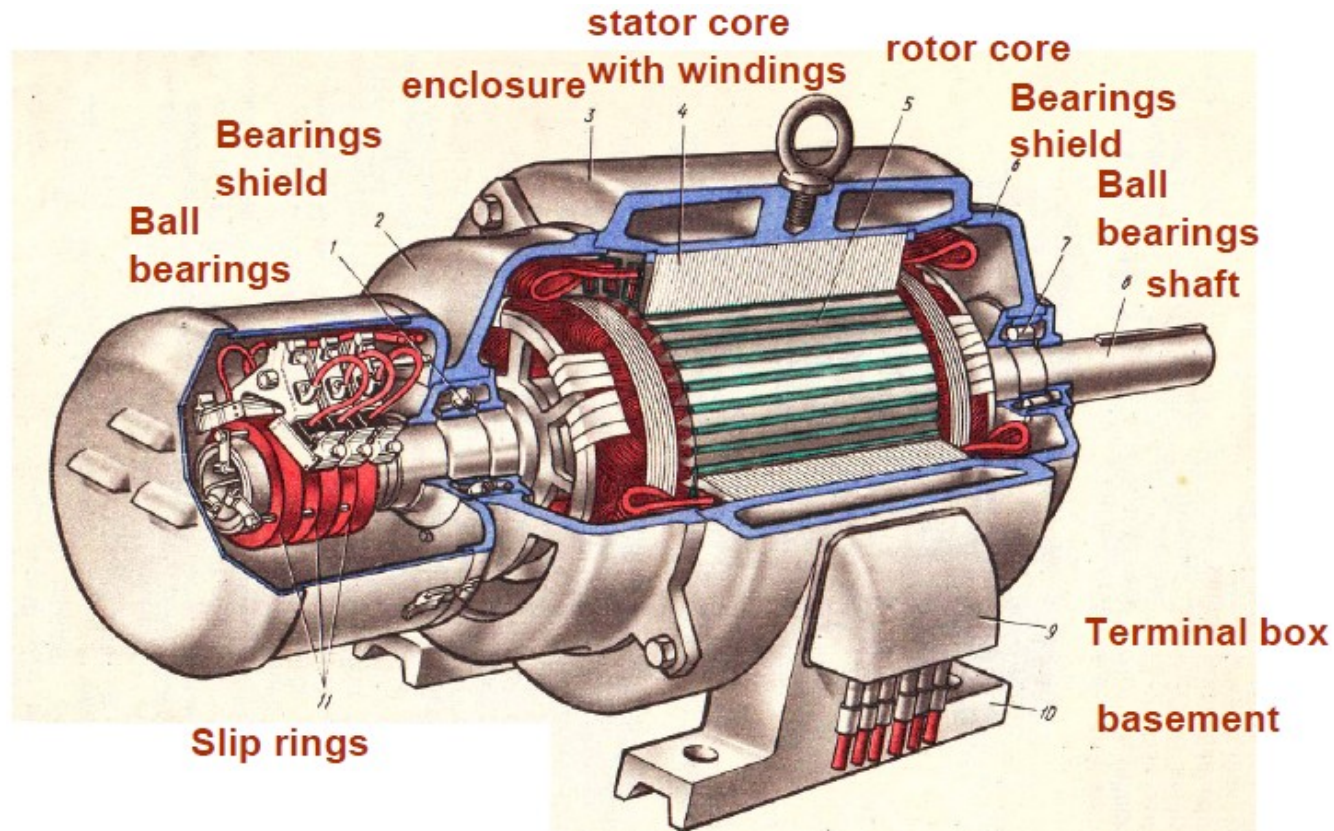


Figure (c) 3-3 Cut way in a typical Wound rotor IM

The squirrel cage motor has the following advantages as compared with the wound rotor machine

- No slip rings and brush so **it has higher efficiency.**
- It has simple and more economical construction.
- It has better space factor for rotor slots, a shorter overhang and consequently a **smaller copper loss.**
- It has **smaller rotor overhang leakage** which gives a **better power factor and greater pull out torque and overload capacity.**

Principle of operation of an IM

- When 3ϕ stator winding is energized from a 3ϕ supply, a rotating magnetic field which rotates at N_s is set up
- Due to the relative speed between the rotating field and the stationary rotor, e.m.f.s are induced in the rotor windings
- Since the rotor windings are short circuited, the induced voltage results flow of current in the rotor windings and produces another magnetic field,
- The interaction of these two fields produces Torque
- Now to reduce the relative speed the rotor tends to rotate in the same direction as the

Cont...

- According to this principle the rotor of an IM starts rotating and achieves a rotor speed (N_m).
- In practice, the rotor can never reach the speed of stator field.
- If it did, there would be **no relative speed** between the stator field and rotor conductors, **no induced rotor currents** and, therefore, **no torque** to drive the rotor.
- Hence, in order to induce an EMF in rotor it must be run as a speed less than (N_s)
- Due to this reason IM are also known as **asynchronous** motors meaning not

Induction motor speed

➤ At what speed will the IM run?

Can the IM run at the synchronous speed, why?

- ✓ If rotor runs at N_s , which is the speed of 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 voltage in the rotor, no flow of current through the rotor and no rotor magnetic flux will be produced so no torque is generated
- ✓ **Thus, in order to produce Torque, IM will always run at a speed lower than N_s**

Cont...

- The difference between the actual motor speed and the synchronous speed is called the *Slip speed*

$$N_{slip} = N_{sync} - N_m$$

- **SLIP:** Actually the term slip is descriptive of the way in which the $\frac{N_s - N_m}{N_s}$ “**slips back**” from synchronism.

Slip may be expressed as a percentage by multiplying the above eq. by 100.

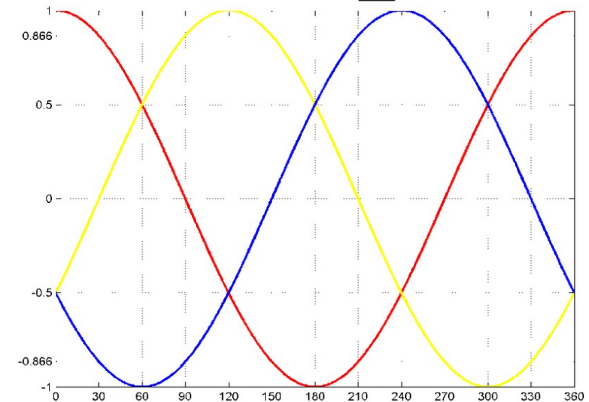
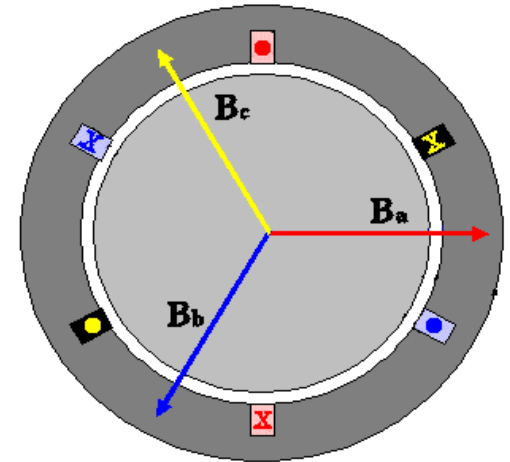
- Notice that the slip is a ratio and doesn't have units

- ✓ if the rotor is stationary ($N_m = 0$) slip $S = 1$ or 100%

- ✓ if the rotor runs at synchronous speed (N_m

Rotating Magnetic Field

➤ When a balanced 3 ϕ -windings, mechanically displaced 120 degrees from each other, fed by a 3 ϕ supply, a revolving magnetic field rotating at N_s with constant magnitude is produced and given by

$$N_{synchronous} = \frac{120f}{P} \text{ rpm}$$


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

Induction Motor and Transformer Compared

- Both IM and transformer works on the principle of induced voltage
- **Transformer:** voltage applied to the **primary** windings produce an induced voltage in the **secondary** windings
- **Induction motor:** voltage applied to the **stator** windings produce an induced voltage in the **rotor** windings
- An IM may be considered to be a transformer with a rotating short circuited secondary.

However, there are the following differences between them

1. The excitation current I_0 in the IM is as high

Cont...

- ➡ This is because the magnetic circuit of an IM has an **air gap** which **increases the reluctance** of the magnetic circuit, as a result, an **IM draws a large magnetizing current** to produce the **required flux in the air gap**
- 2. Due to the rotation of the rotor, the induced voltage in the rotor **doesn't** have the **same frequency to that of** the stator or supply voltage frequency
- ❖ Thus, the **rotor voltage and its frequency are both proportional to slip S.**

Frequency of induced voltage in rotor

- ❖ Due to the rotation of the rotor, the induced voltage in the rotor doesn't have the same frequency to that of the supply frequency.
- For a rotor speed N_m , the relative speed between the rotating flux and the rotor is given by:

$$N_s - N_m = \frac{120f_r}{P}$$

Consequently, the rotor current frequency f_r

is given $f_r = \frac{(N_s - N_m)P}{120}$,

$$= \frac{(SN_s)P}{120}$$

$$f_r = S f_e$$

but $S = \frac{N_s - N_m}{N_s}$

Thus, $SN_s = N_s - N_m$

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

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

Cont...

- Therefore, the frequency of the rotor's induced voltage at any rotor speed N_m is given by: $f_r = S f_e$
- When the rotor is blocked ($s = 1$), $f_r = f_e$
- On the other hand, if the rotor runs at synchronous speed ($s = 0$), $f_r = S f_e = \text{zero}$
- Thus when the rotor starts rotation f_r depends up on slip
- ✓ When the rotor speed increases both Slip and rotor current frequency decreases

Equivalent circuit of IM

- Developing an equivalent circuit model is useful to study and predict the performance characteristics of the induction machine with reason:

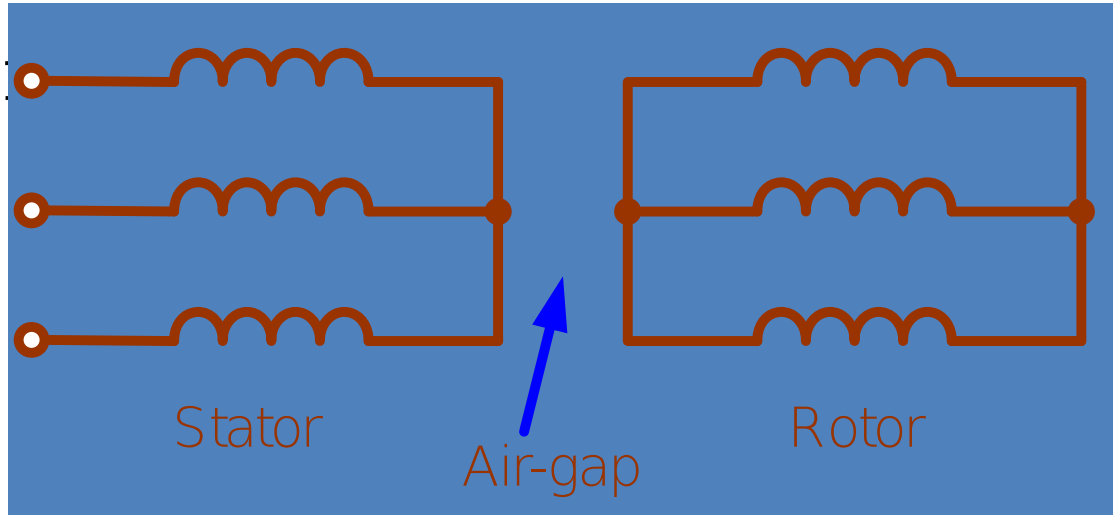


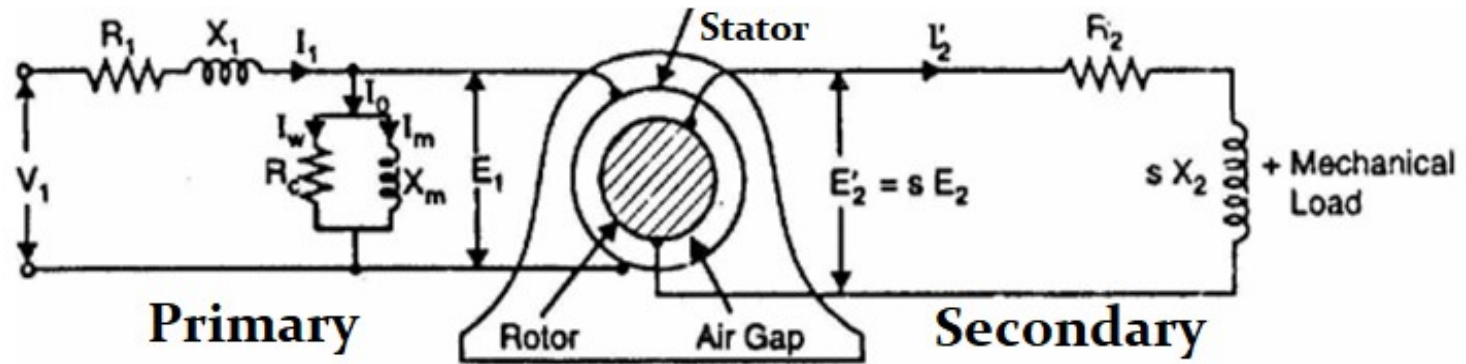
Fig. 3-4 Three Phase induction machines equivalent circuit model

- If currents flow in both stator and rotor windings, resultant rotating magnetic fields will be produced in the air gap.

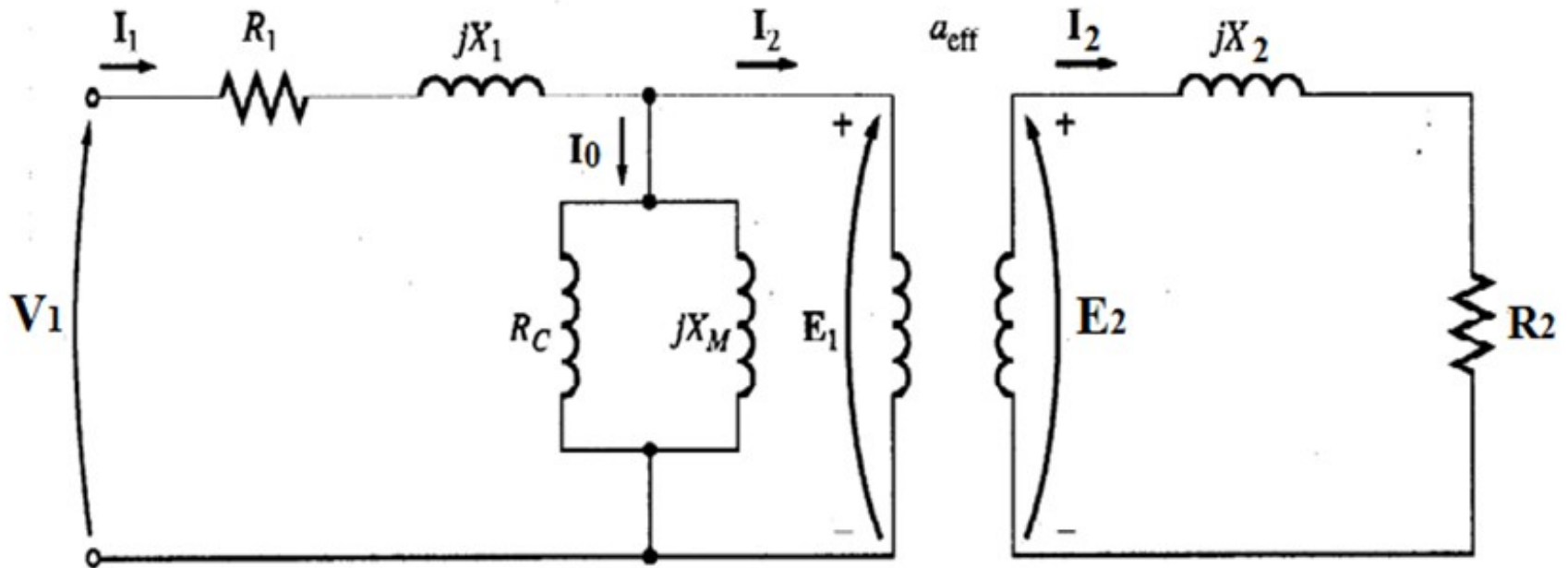
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- This resultant air gap field will induce voltages in both stator windings (at supply frequency f_e) and rotor windings (at rotor frequency f_r).
- It appears that the equivalent circuit may assume identical to that of a transformer equivalent circuit
- Therefore it can be developed from the knowledge of a transformer equivalent circuit and from knowledge of **variation of rotor frequency with speed in IM.**
- The only difference is on account of the fact that the rotor winding of an IM rotates and electrical energy converts to mechanical Energy.

Cont...



(a)



(b)

Fig. 3-5 Equivalent circuit per phase for an IM

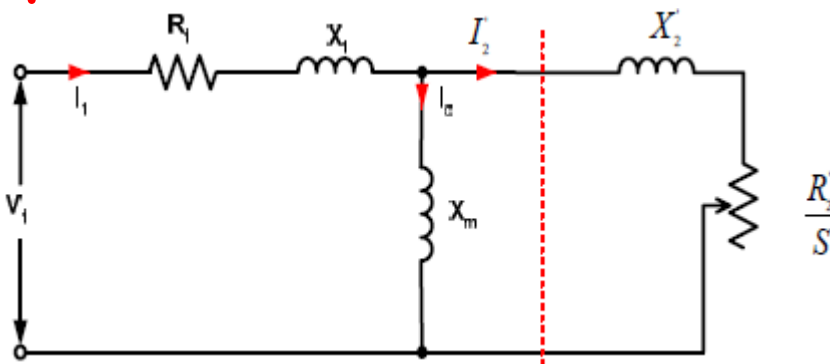
Cont...

- ✓ Note that if the IM is connected to a **supply of fixed voltage and frequency** the **stator core loss is fixed**.
- ✓ At **no load**, the machine will operate close to N_s . Thus, the f_r is very small and hence rotor core loss is very small.
- ✓ i.e. the higher the speed of the motor (up to N_s), the lower its core losses.
- ✓ At a lower speed, f_r increases and so does the rotor core loss.
- ✓ Thus, the **total core losses thus increase as the speed falls**.
- ✓ On the other hand, **at no load, friction and windage losses are maximum and as speed falls these losses decrease**.

Cont...

- Therefore, if a machine operates from a constant voltage and frequency source, the **sum of core, friction and windage losses remains essentially constant at all operating speeds**, since the component losses change in opposite directions with a change in speed.
- These losses can thus be **lumped together and termed the constant rotational losses of the induction machine**.

- If the core loss and friction and windage losses are lumped together, the equivalent circuit of the induction machine can be represented as follows:



windage
from the

Effect of Slip on the Rotor Circuit

- When the rotor is blocked, i.e. $s = 1$, the largest voltage and rotor frequency are induced in the rotor, **Why?**
- On the other hand, 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?**

$$E_R = S E_{ro}$$

Where E_{ro} is the largest value of the induced rotor e.m.f / phase obtained at $s = 1$ (locked rotor)

$$f_r = s f_e$$

- The same is true $X = \omega L = 2\pi f L$, i.e.
- It is known that

Cont...

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

Where X_{r0} is the rotor reactance at the supply frequency (at blocked rotor, $N_m = 0$ and $S=1$)

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

✓ 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

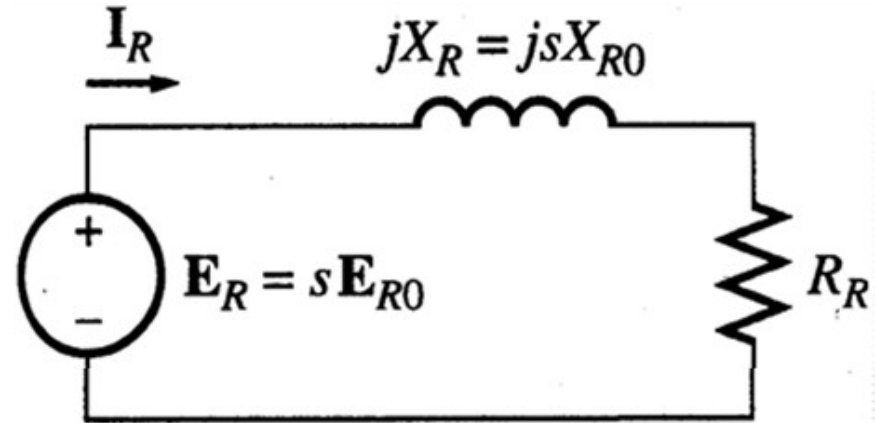


Fig. 3-6 Equivalent circuit of rotor

Cont

Now we can calculate the rotor current as

$$I_R = \frac{E_R}{Z_R} = \frac{E_R}{(R_R + jX_R)} = \frac{sE_{R0}}{(R_R + jsX_{R0})}$$

Dividing both the numerator and denominator by S. so nothing change

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

Where E_{R0} is the induced voltage and X_{R0} is the rotor reactance at blocked rot

✓ Then, we can have the

rotor equivalent circuit

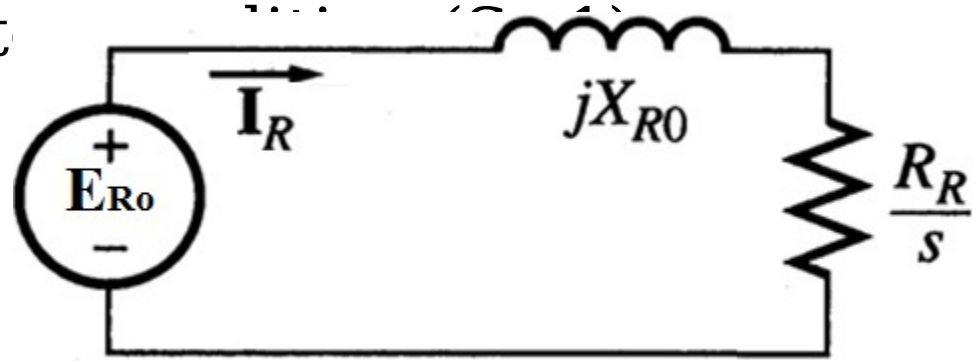


Fig. 3-7

Cont...

- Therefore, to solve the induced voltage and different frequency problems, we can combine the rotor and stator circuits in one equivalent circuit.
- The transformation is done by using effective

Where

$$a_{eff} = \frac{N_{stator}}{N_{rotor}}$$

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

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

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

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

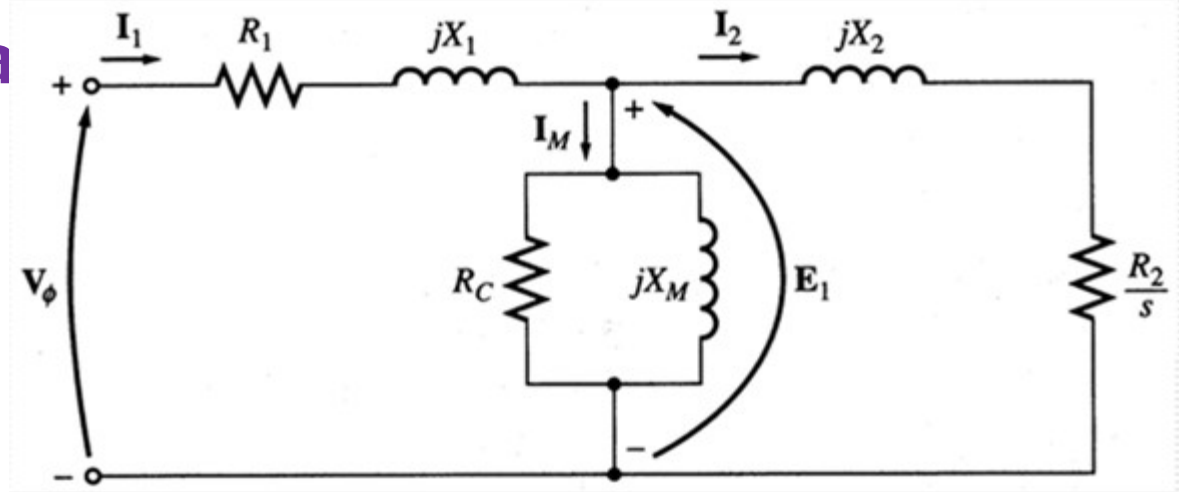


Fig. 3-8 Equivalent circuit per phase for an IM

Power Loss in an Induction Motor

- The input electric power fed to the stator of an IM is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1. Fixed losses

- (i) Stator iron loss
- (ii) Friction and windage loss

- The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

2. Variable losses

- (a) Stator copper loss
- (b) Rotor copper loss

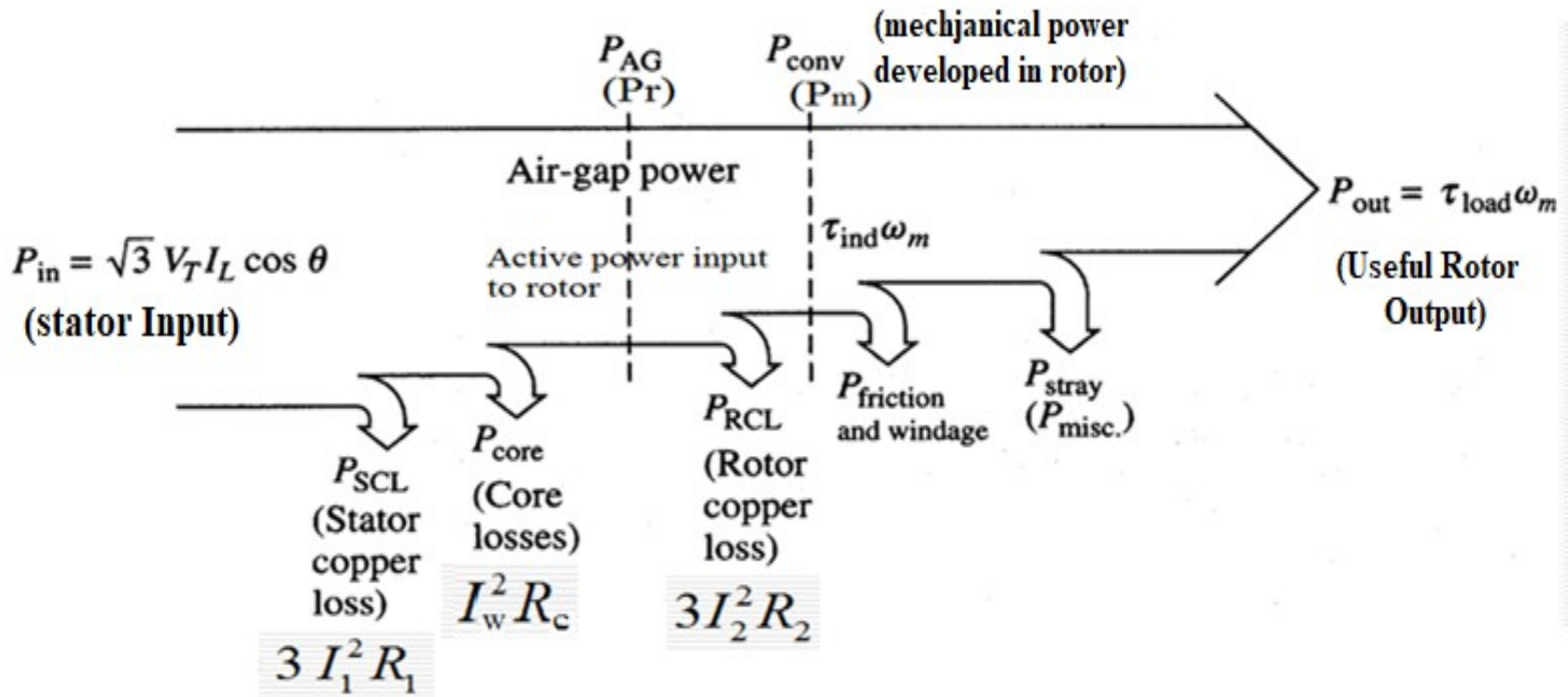


Fig. 3-9 Power flow Diagram of an IM

❖ Figure 3.9 above shows how Electrical power fed to the stator of an IM associated losses and finally converted into mechanical power.

Cont....

- (i) Stator input, $P_{in} = \text{Stator output} + \text{Stator losses}$
 $= P_{ag} + \text{Stator Iron loss} + \text{Stator Cu loss}$
- (ii) Rotor input, $P_{ag} = \text{Stator output} = P_{conv} + P_{Rcu}$
 - ✓ P_{ag} is entirely transferred to the rotor through air gap by electromagnetic induction
- (iii) Mechanical power available, $P_{conv} = P_{ag} - \text{Rotor Cu loss}$
 - ✓ This mechanical power available is the gross rotor output and will produce a gross torque (induced torque), T_g
- (iv) Mechanical power at shaft, $P_{out} = P_{conv} - (P_{f \&w} + P_{stry})$
 - ✓ P_{out} available at the shaft produces a load torque (T_{sh})

Cont...

The mechanical power P available from any electric motor can be expressed as:

$$P_{out} = \frac{2\pi N_m T_{sh}}{60} = T_{sh} \omega_m \text{ Watts}$$

Where N_m = speed of the motor in r.p.m.

T_{sh} = torque developed in N-m

$$T_{sh} = \frac{60 P_{out}}{2\pi N_m} = \frac{P_{out}}{\omega_m} \text{ N-m}$$

The gross torque T_g developed by an IM is given by:

$$T_g = \frac{60 P_m}{2\pi N_m} = \frac{P_m}{\omega_m} \text{ N-m in terms of } (N_r \text{ \& } P_m)$$

$$T_g = \frac{60 \times P_{ag}}{2\pi N_s} = \frac{P_{ag}}{\omega_s} \text{ N-m...in terms of } (N_s \text{ \& } P_{ag})$$

Note that shaft torque T_{sh} will be less than T_g by the torque required to meet windage and frictional losses.

Power balance equation in an IM

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

$$P_{SCL} = 3 I_1^2 R_1 \quad P_{Siron} = I_w^2 R_c$$

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

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

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

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

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

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

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

Torque

- While the input to the IM 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.

➤ Shaft Torque is related to the motor

$$T_{\text{load}} = \frac{P_{\text{out}}}{\omega_m} \text{ N.m}$$

$$= \frac{60 P_{\text{out}}}{2\pi N_m} \text{ N.m}$$

where

$$\omega_m = \frac{2\pi N_m}{60} \text{ rad/s}$$

Cont...

- ✓ The torque T developed by the rotor is directly proportional to:

a) rotor current

b) rotor e.m.f.

$$\therefore \hat{T} \propto \hat{E}_2 I_2 \cos \phi_2 \quad \text{circuit}$$

or
$$T = K E_2 I_2 \cos \phi_2$$

where I_2 = rotor current at standstill

E_2 = rotor e.m.f. at standstill

$\cos \phi_2$ = rotor p.f. at standstill

Note. The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

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 R_{Th}

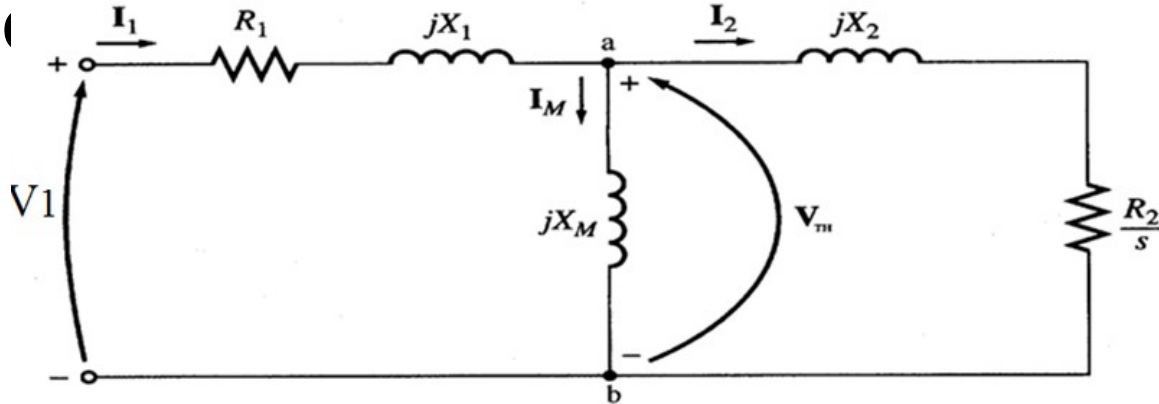


Fig. 3-10

In order to simplify computations V_1 , R_1 , X_1 and X_m can be replaced by Thevenin's equivalent circuit values V_{Th} , R_{Th} and X_{Th} as shown in fig 3-11 below

Cont...

The stator part of the equivalent circuit (together with the magnetizing branch) can be replaced by Thevenin equivalent circuit. In the Thevenin circuit, the stator phase voltage has been

$$V_{TH} = V_1 \frac{jX_M}{R_1 + j(X_1 + X_M)} \quad |V_{TH}| = |V_1| \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}}$$

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

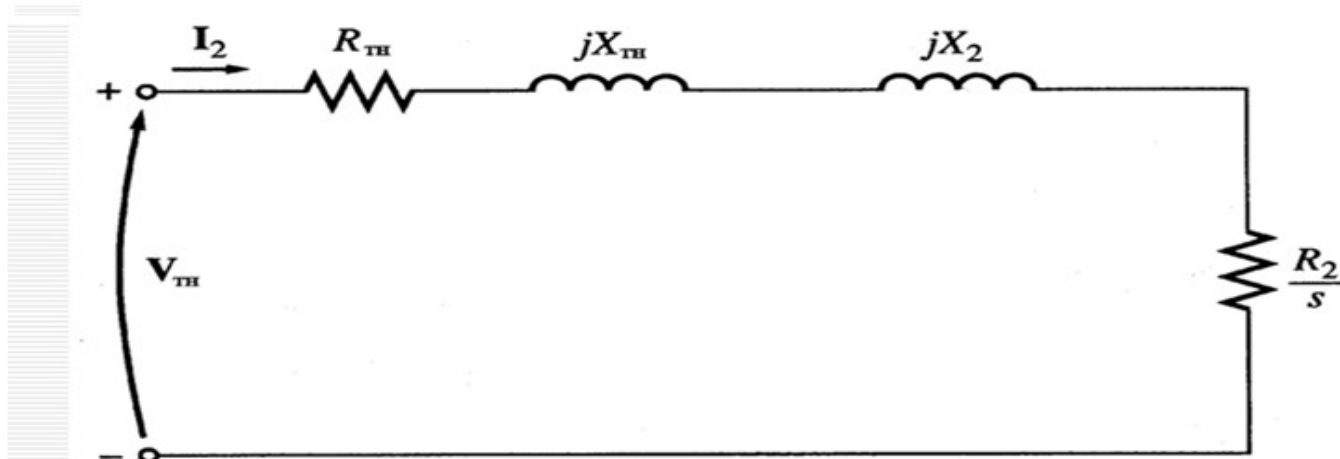


Fig. 3-11 Thevenin Equivalent Circuit

Cont...

$$\text{If } R_1^2 \ll (X_1 + X_m)^2,$$

$$V_{th} \approx V_1 \frac{X_m}{X_1 + X_m}$$

- The impedances have been replaced by Thevenin eq

$$\mathbf{Z}_{TH} = (\mathbf{R}_1 + j\mathbf{X}_1) \parallel j\mathbf{X}_m$$

$$Z_{th} = \frac{jX_m(R_1 + jX_1)}{R_1 + j(X_1 + X_m)} = R_{th} + jX_{th}$$

$$\mathbf{Z}_2 = \frac{\mathbf{R}_2}{s} + j\mathbf{X}_2$$

$$\mathbf{Z}_T = \mathbf{Z}_{th} + \mathbf{Z}_2$$

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

Cont...

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

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

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

And the internal mechanical torque (T_{conv})

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

Cont...

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

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

Torque-Speed Characteristics of IM

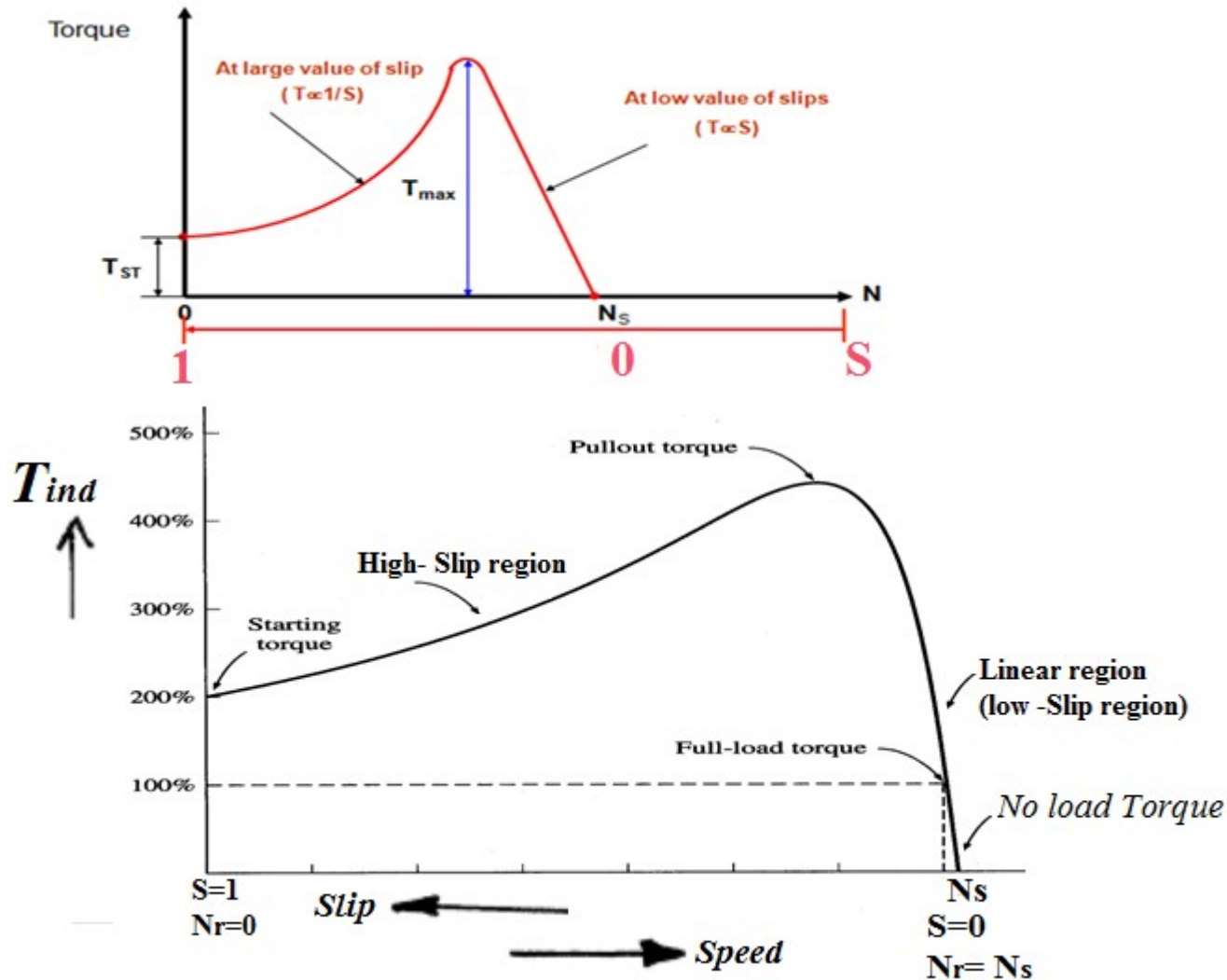


Figure 3.12 Torque-Speed characteristics of induction motor

Cont....

- ✓ The torque developed by a 3ϕ IM depends on its speed but the relation between the two cannot represent by a simple equation.
- ✓ It is easier to show the relationship in the form of a curve (figure 3-12).
 1. The induced torque is zero at synchronous speed. Why?
 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 and torque increase linearly with the slip.

Cont...

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**.
4. The **starting torque** of the motor is slightly higher than its full-load torque, so the motor will start heavy load.
4. **Torque** of an IM for a given slip varies as the square of the applied voltage. (i.e. $T \propto V^2$)
5. If the rotor **run faster than synchronous speed, it will run as a generator** which converts mechanical power to electric power.

Mode of operation

- Depending on the value of slip, an IM can have the following operating regions.

a) Motoring mode , $1 \geq S \geq 0$

- The slip varies from 1 at standstill to zero at N_s , i.e. $1 \geq S \geq 0$
- The corresponding speed values are zero ($S=1$) and N_s ($S=0$).

b) Generating mode , $S < 0$,

- For this operating modes, slip is negative, and the rotor speed is above synchronous speed (N_s)

c) Breaking mode , $S > 1$,

- $S > 1$ can be obtained by driving the rotor , with a prime mover, opposite to the direction of rotating field. (eg. plugging action)

Complete Speed-torque c/c

All the three regions of operation (braking, $S=2$ to $S=1$; motor region, $S=1$ to $S=0$ and generator region, $S=0$ to $S=-1$) are illustrated in figure (3-13) below.

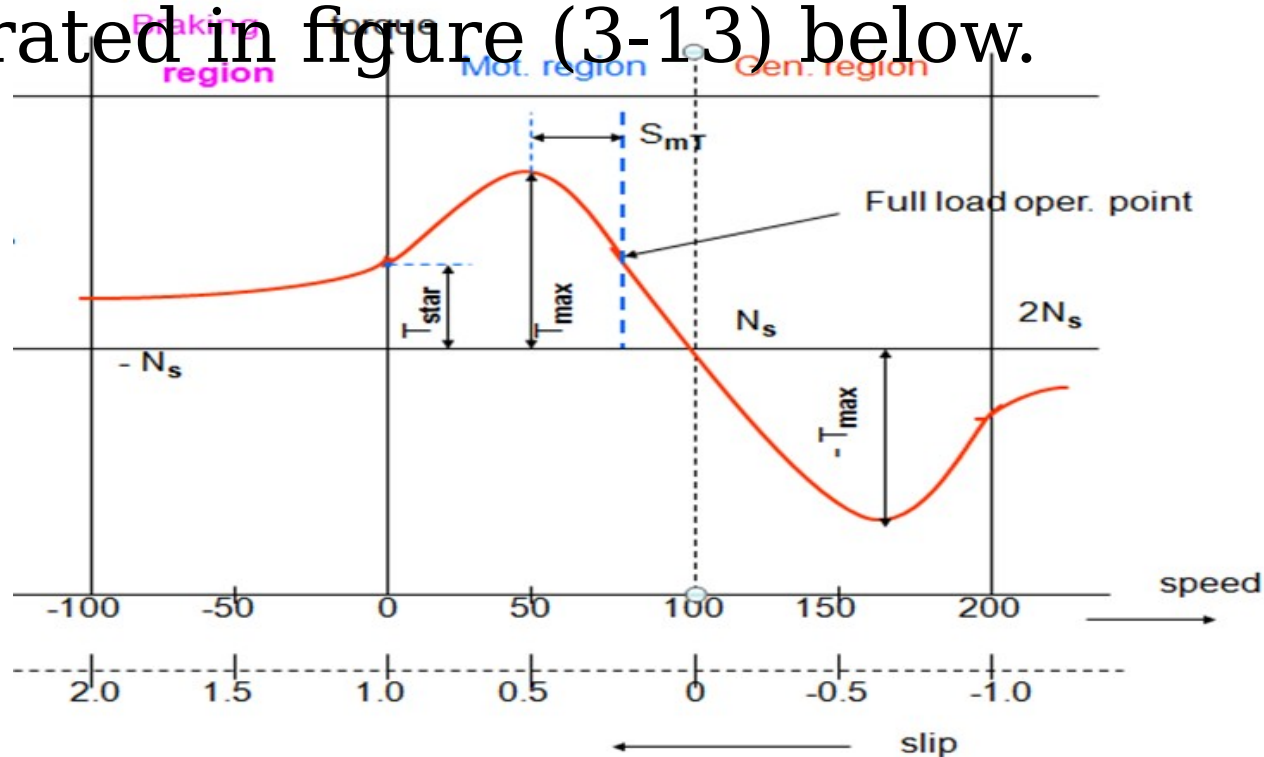


Figure 3-13 Torque-Speed characteristics for 3-modes of operation of IM

Determining maximum internal torque of IM

- Maximum torque is referred as **Stalling torque; Pull out torque or Break down torque.**
- Maximum torque occurs when the **power transferred to R_2/s is maximum.**
- Maximum internal torque can be obtained by using the maximum power transfer theorem of a circuit theory.
- Maximum power will transfer when the load impedance is equal to the source impedance
- This condition occurs when $R_2/s = R_{TH} + j(X_{TH} + X_2)$

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

Cont...

The slip for maximum torque or pull out torque is

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

- The corresponding maximum torque of an induction motor equals

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

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

The maximum torque is independent of R_2

- 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.

Cont...

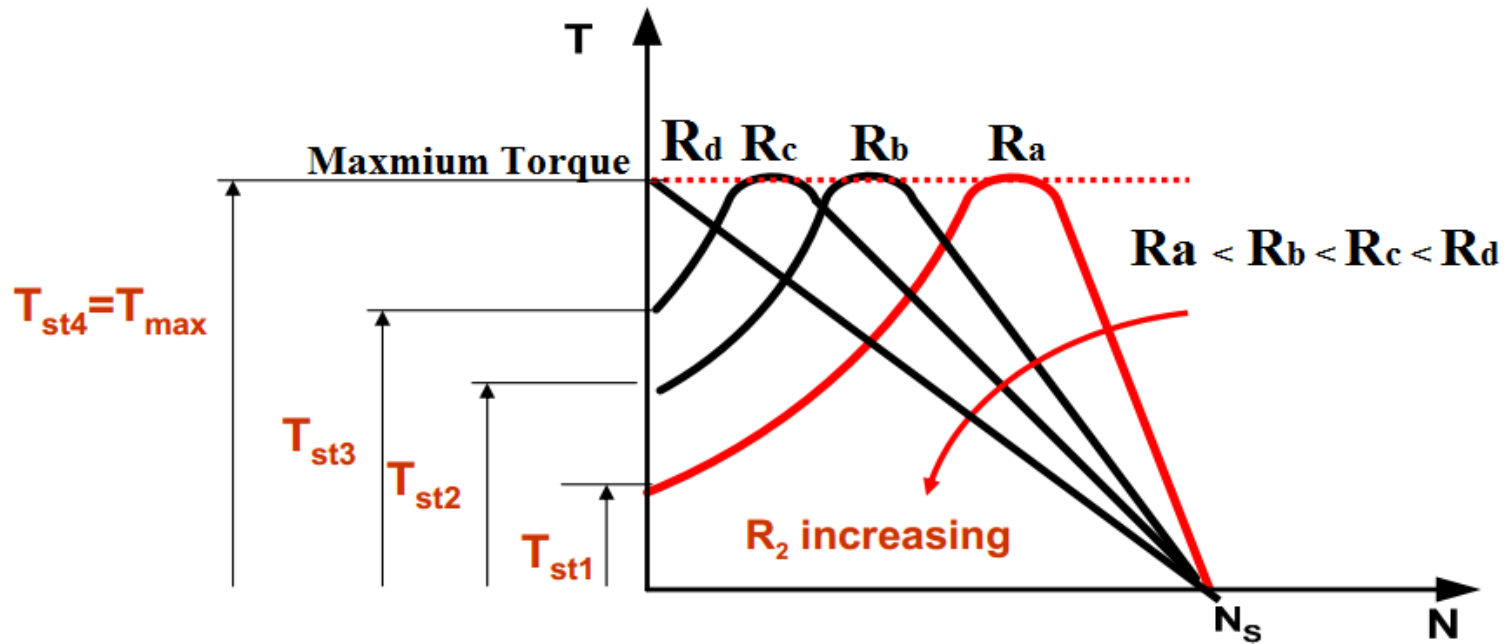


Figure 3-14 Effect of Rotor Resistance on Torque-Speed characteristics

➤ Note that the motor develops the **same maximum torque** regardless of its rotor resistance as illustrated in Fig. 3-14 above.

➤ Thus, **T_{max} is independent of the rotor resistance**.

➤ The rotor resistance affects only the breakdown speed (or breakdown speed) at which the torque is

Cont...

- ▶ In a wound-rotor induction motor, external resistance is added to the rotor circuit to make the maximum torque occur at standstill so that high starting torque can be obtained.
- ▶ A high R_2 produces high starting Torque and relatively small starting current desirable for motor starting.
- ▶ As the motor speeds up, the external resistance is gradually decreased and finally taken out completely.
- ▶ Some induction motors are designed to produce maximum torque at start, that is, at zero speed (T_{st4}).

Starting Torque of IM - T_{st}

- The torque developed by the motor at the instant of starting is known as starting Torque
- The rotor resistance (R_2) of Squirrel cage IM is fixed and small as compared to its reactance (X_2) especially at the start.
- Because at stand still, the frequency of rotor current equals supply frequency. (i.e $f_r = f_e$)
- Thus, rotor current (I_2) lags behind the rotor e.m.f. E_2 by a large angle, the power factor is low which results low T_{st}
- T_{st} of wound rotor IM is increased by improving its power factor by adding external resistance to the rotor circuit

Cont...

- But the effect of improved power factor predominates and the starting torque is

$$\begin{aligned}\therefore \text{ Starting torque, } T_s &= K E_2 I_2 \cos \phi_2 \\ &= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}} \\ &= \frac{K E_2^2 R_2}{R_2^2 + X_2^2} \quad \text{Where } K = 3/2 \pi N_s.\end{aligned}$$

It is evident from the above equations that:

- i) The maximum torque varies inversely as the standstill reactance (X_2).
- Therefore, it should be kept as small as possible.
- ii) The maximum torque varies directly with the

Cont...

- It can be shown that $K = 3/2 \pi N_s$.

$$\therefore T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

The starting torque is proportional to V_{TH}^2 and determined by the relation:

$$T_{start} = \frac{3V_{TH}^2 R_2}{\omega_{sync} [(R_{TH} + R_2)^2 + (X_{TH} + X_2)^2]}$$

PERFORMANCE CHARACTERISTICS OF IM

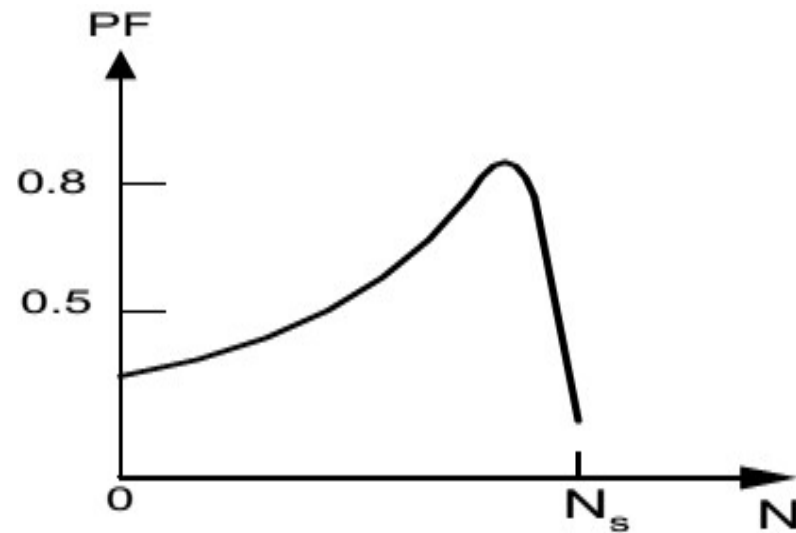
- The equivalent circuits derived in the preceding section can be used to predict the performance characteristics of the IM.
- The output parameters of IM are **speed** and **torque** and their inter relation during starting, steady state and braking are going to be seen.
- The important performance characteristics in the steady state are:
 - The efficiency
 - Power factor
 - Current
 - Starting torque
 - Maximum (or pull-out) torque and
 - So forth.

Cont...

- Steady state operating characteristics of an IM can be shown graphically as the shaft load increases from **zero to full load**.
- These operating characteristics during starting, steady state, and braking are governed mainly by:-
 - rotor resistance,
 - air gap length, and
 - shape of stator and rotor slots

Input Power Factor

- ✓ The supply power factor is given by $PF = \cos\theta_1$, where θ_1 is the phase angle of the stator current I_1 .
- ✓ This phase angle θ_1 is the same as the impedance angle of the equivalent circuit
- ✓ **Speed** : At no load, the rotor speed is near to N_s ; therefore, the no-load slip is very small. Also, the no-load torque, sufficient to overcome the loss-torque required by friction and windage, is very
- ✓ **Stator current**: The no-load stator current is about 30 to 50% of rated current, the larger values being applicable to smaller sizes. With the increase in load, the current rises correspondingly.



- In order to determine the efficiency of the IM as a power converter, the various losses in the machine are first identified.
- These losses are illustrated in the power flow diagram.
- ✓ Fixed losses = (core loss + friction and windage loss) and variable load losses (Copper Loss)
- ✓ At no load, the shaft power output is zero, therefore, efficiency is zero.
- ✓ As the load is increased, the efficiency also rises and becomes maximum **when fixed losses and variable losses are equal.**
- ✓ Maximum efficiency occurs at about 80 to 95% of rated output rapidly than the output, consequently the efficiency decreases

Cont...

- The **efficiency is highly dependent on Slip**. If all losses are neglected except those in the resistance of the

$$P_{ag} = P_{in}$$

$$P_{rcu} = S P_{ag}$$

$$P_{out} = P_m = (1 - S)P_{ag}$$

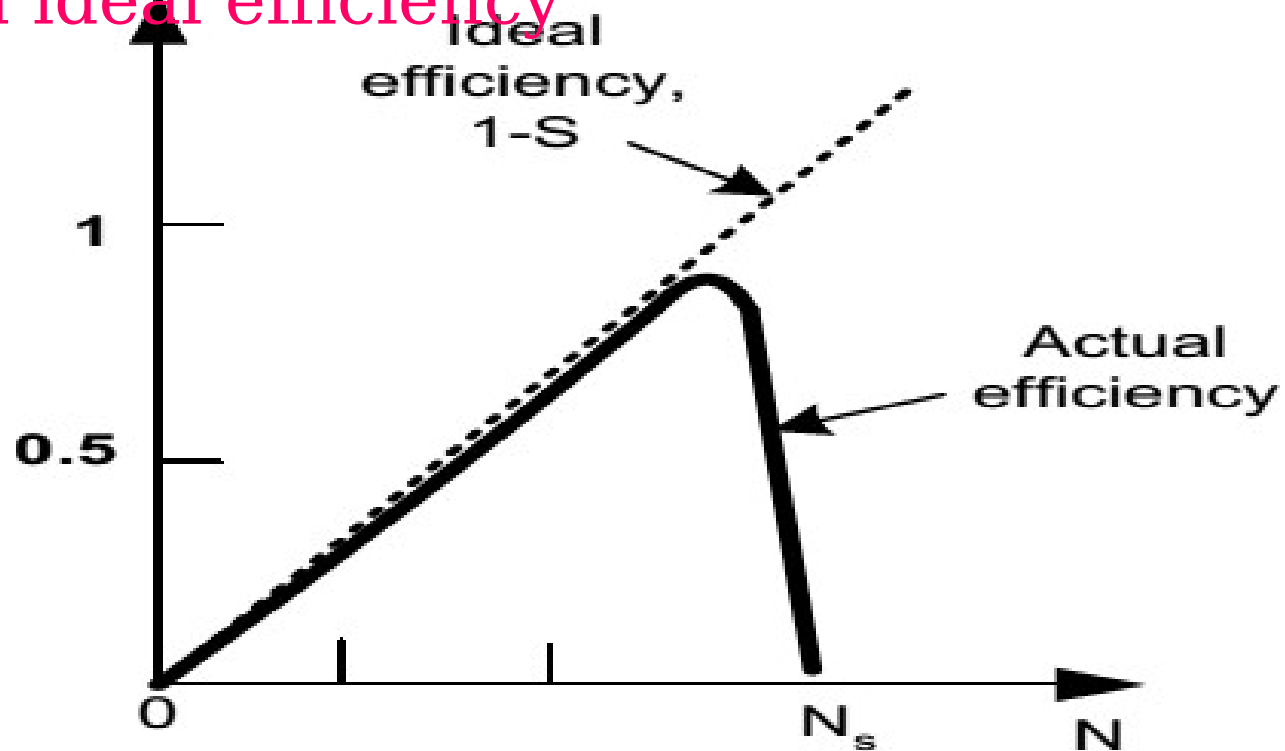
Thus the ideal Efficiency is, $\eta(ideal) = \frac{P_{out}}{P_{in}} = 1 - S$

- Some times $\eta(ideal)$ is also called the **internal efficiency** as it represents the **ratio of the output power to the air gap power**
- It indicates that an **IM must operate near its Ns if high efficiency is required**
- This is why the **slip is very low** for normal operation of IM

Cont...

Thus, the higher the speed of operation, the higher the efficiency.

If other losses are included, actual efficiency is lower than ideal efficiency



Determining Equivalent circuit model parameters of IM.

- The response of an IM to changes in load can be determined from the equivalent circuit of the motor.
- The parameters R_1 , X_1 , R_2 , X_2 , X_m can be determined by performing a series of tests on the IM.
 - a) No-load test
 - b) DC test for stator resistance
 - c) Blocked Rotor test
- These tests need precision because the resistances vary with temperature and the rotor resistance also varies with rotor

No-load test

➤ The IM is made to run at no load at rated voltage and frequency

➤ Per phase values of applied stator voltage V_{nl} , input current I_{nl} and input power P_{nl} are recorded

(by two wattmeter method).

➤ The resistance R_c is omitted, and the core loss is lumped with the windage & friction losses.

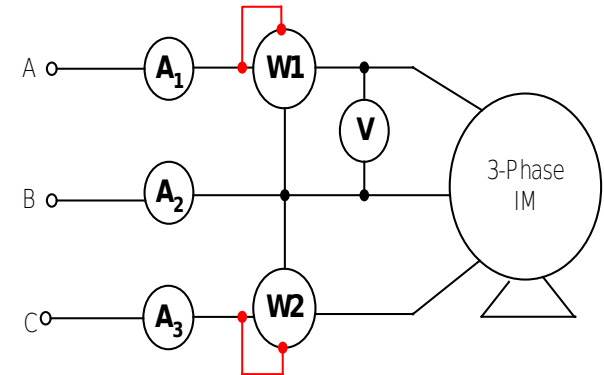


Fig. 3.15 Circuit diagram for no-load and blocked-rotor Test.

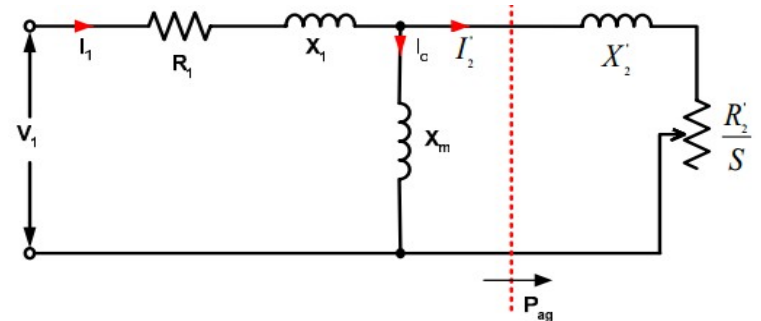


Fig. 3.16 IEEE RECOMMENDED EQUIVALENT CIRCUIT

Cont...

- The **no load Slip S is very small**, therefore, r_2/s at no load is very large as compared to X_m .
- Thus, the total impedance of parallel branches consisting of jX_m and $(r_2/s + jX_2)$ is almost equal to jX_m .

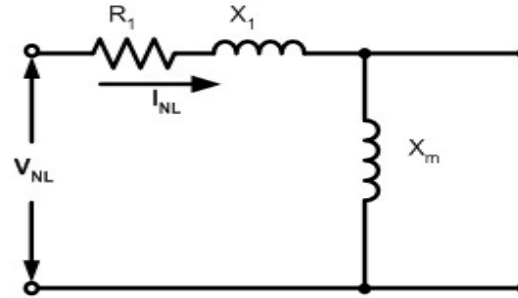


Fig 3.17. Equivalent circuit under no-load test.

Then, the no-load reactance X_{nl} seen from the stator terminals is equal to $X_1 + X_m$

$$\text{i.e. } j X_{nl} = j X_1 + j X_m$$

Where X_1 is the stator self

reactance.

Cont...

From the instrument readings at no load test,

$$V \quad Z_{nl} = \frac{V_{nl}}{I_{nl}}, \quad R_{nl} = \frac{P_{nl}}{I_{nl}^2}, \quad X_{nl} = \sqrt{Z_{nl}^2 - R_{nl}^2}$$

$$X_{nl} = X_1 + X_m \quad \text{If } X_1 \text{ is known, } X_m \text{ can be determined.}$$

- The rotational losses (friction, windage loss and core loss) are usually assumed constant and can be obtained $P_{rot} = m(P_{nl} - I_{nl}^2 r_1)$

Where: m is the number of stator phases and r_1 is the per phase stator resistance

Cont...

- Thus the no-load test gives and the rotational losses .
- The no load **P_{in}** recorded by the two watt meter includes:
 - i) small stator Cu loss ii) stator core loss
 - iii) Friction and windage loss
- ❖ The losses (ii) and (iii) are fixed losses, because they are **independent of load**
- Note that, the only load during no-load test is friction and windage loss.
- The mechanical power ($P_m = P_{ag} - P_{rot}$) is

DC Test for Stator resistance

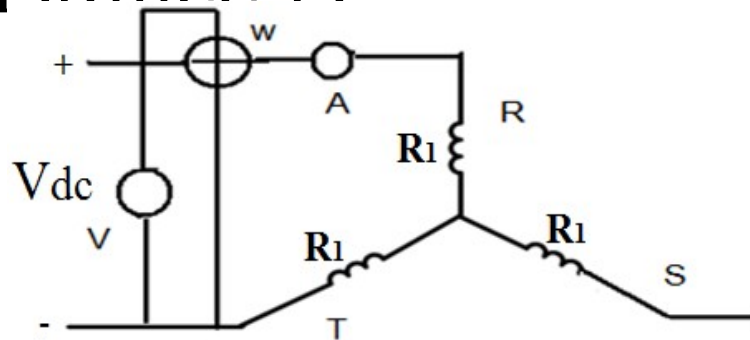
- The rotor resistance R_2 plays an extremely critical role in the operation of an IM. i.e.
 - It determines the shape of the speed torque curve.
 - It determines the speed at which the pull-out torque occurs.

To determine R_2 , it is necessary to find R_1 of the stator.

- Thus, a DC voltage is applied to the stator windings of an IM.
- The current in the stator is adjusted to the rated value & the voltage is measured.
- Since it is DC supply, $f = 0$, hence no induced current in the rotor circuit. Current will flow only through the stator circuit.

Cont...

➤ If the dc supply voltage is connected between the two phases, (the 3rd phase being open) then, the dc current flows through the two phase windings and the required phase stator resistance is:-



$$2R_1 = \frac{V_{dc}}{I_{dc}},$$

$$R_1 = \frac{V_{dc}}{2I_{dc}}$$

3.18 Circuit for DC test to determine stator resistance

▪ This test is important to determine the stator resistance R_1 .

Now, we can calculate rotor resistance $R_2 = R_{br} - R_1$

Blocked rotor test

- During this test;
 - An Ac voltage is applied to the stator; and the current is adjusted to the rated value.
 - The rotor is blocked so that it can not rotate.
- Per phase values of applied voltage V_{br} ; input current I_{br} and the input power P_{br} are measured.
- Since the rotor is blocked, $S = 1$, rotor resistance is quite a small value

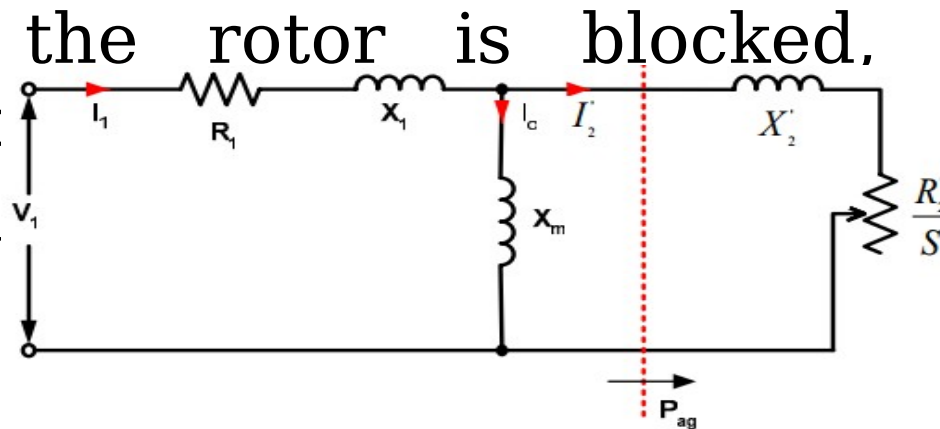
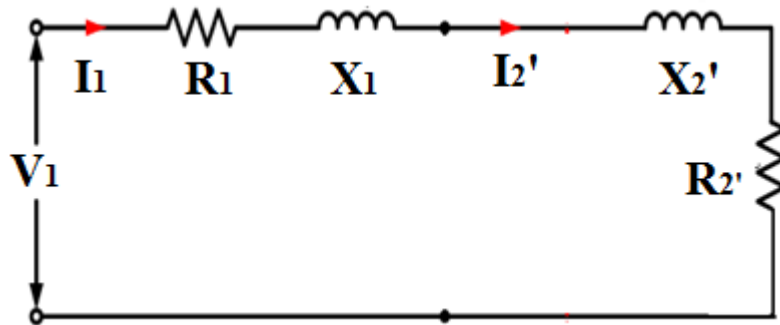


Fig. 3.19 IEEE RECOMMENDED EQUIVALENT CIRCUIT

Cont...

➤ Compared with X_m , R_2 & X_2 are small, so that the whole input current flows through them (through R_2 & X_2).

➤ The equivalent circuit under this condition looks a series combination of R_1 , X_1 , X_2' , R_2' .



$$P_{in} = \sqrt{3} V_L I_L \cos \theta$$

$$\cos \theta = \frac{P_{in}}{\sqrt{3} V_L I_L}$$

$$\theta = \arccos \left(\frac{P_{in}}{\sqrt{3} V_L I_L} \right)$$

Figure 3-20 Equivalent circuit during blocked rotor test

Cont...

Impedance of the IM during block rotor test is:-

$$Z_{br} = \frac{V_{br}}{I_{br}} \quad R_{br} = \frac{P_{br}}{I_{br}^2}$$

$$X_{br} = \sqrt{Z_{br}^2 - R_{br}^2}$$

$$Z_{br} = R_{br} + jX_{br} = Z_{br} \cos \theta + j Z_{br} \sin \theta$$

$$R_{br} = r_1 + r_2 \quad r_2 = R_{br} - r_1$$

$$X_{br} = X_1 + X_2 \quad \text{Where, } X_{br} \text{ is the reactance of stator \& rotor}$$

In practice, it is difficult to get separately stator and rotor reactance, and are usually taken from experimental data from tables.

- In general, motor starter have the following functions to be performed
 - a. Start and stop the motor:** this is the fundamental job of every starter. It shall be capable of switching the motor “ON” and “OFF” safely and quickly.
 - b. Limit the motor in rush current:** where necessary. This may be achieved by
 - Actual reduction of voltage at the motor terminal
 - Temporary reconnection of stator winding
 - Connecting resistance in rotor circuit temporarily
 - c. Permit automatic control when required**
 - d. Protect motor and other connected equipment**

Starting of IM.

- At stand still, $S = 1$, a 3ϕ - IM has positive finite starting Torque
- That is., when connected to a 3ϕ source, a 3ϕ IM begins to rotate on its own. It is self-starting motor.
- **However, during starting a 3ϕ IM behaves like a transformer with short circuited secondary.**
- Therefore, it takes **high starting current** if started at full voltage.
- This large I_{st} will produce **large voltage drop** in the line resulting in reduced voltage across the motor.
- It is also adversely affect the operation of other electrical equipment connected to the same lines

Starting of Squirrel-Cage motors

- For cage motors, the choice of any particular method of starting depends on:
 - i. Size and design of the motor
 - ii. capacity of the power lines and
 - iii. type of the driven load.
- There are primarily two methods of starting of squirrel-cage induction motors:
 - a) full-voltage starting and
 - b) reduced-voltage starting
- The full-voltage starting consists of DOL (direct-online) starting only.

Direct-on-line (across-the-line) starting

- As the name suggests, this method involves the direct switching of 3ϕ - IM to the supply mains.
- In this method of starting cage motors the rate of temperature rise is high and the motor may get damaged if the starting period is large, which may be due to
 - Excessive load, insufficient rotor resistance and excessive voltage drop in the supply lines.
- The starting period usually lasts a few seconds because starting torque for IM is about twice the full load torque.
- The motor takes starting current of 5 to 8 times its full-load current, depending upon its size and design.

Cont...

DOL starting is used for small capacity (up to 7.5 kW) cage rotor IM.

This starting method is not recommended if smooth start

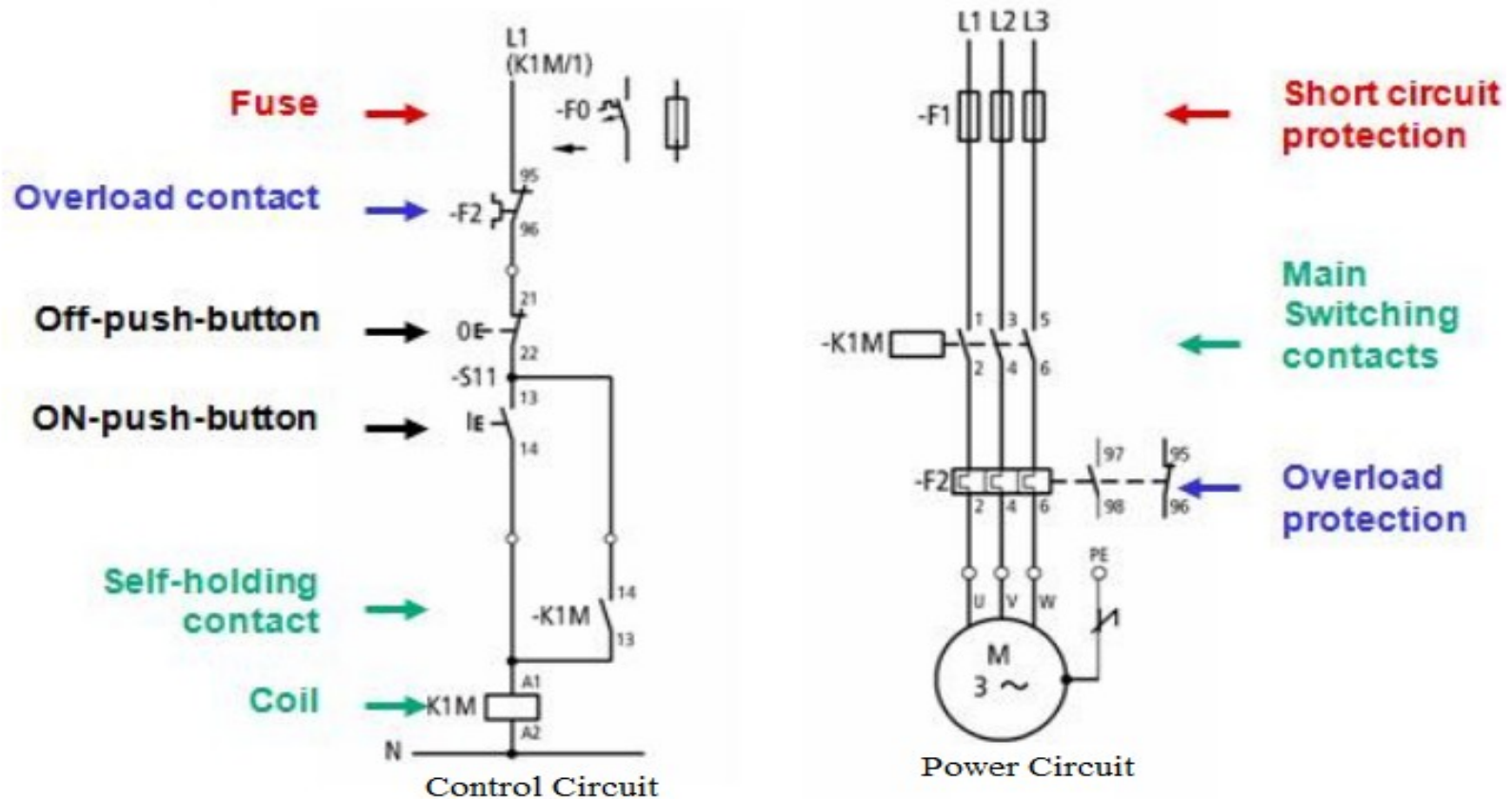


Figure 3-21 DOL Magnetic Starter

Reduced-voltage starting

- The reduced-voltage starting has the advantage of reducing the starting current, but it produces an objectionable reduction in the starting torque, on account of the fact that the starting torque of $T_{st} \propto V^2$ IM is directly proportional to the square of the applied voltage ().
- i.e ,if the applied voltage is reduced, the starting torque also reduces.
- Despite this, reduced-voltage starting is the most popular method of starting 3 ϕ squirrel-cageIM and consists of
 - stator resistor (or reactor) starting,
 - auto-transformer starting and

Stator resistor (or reactor) starting

- In this method, a resistance or a reactor is connected in series with each phase of stator winding during starting.
- This causes voltage drop across the resistances so that voltage available across motor terminals is reduced
- This reduces the per-phase starting current I_{st} drawn by the motor from the supply mains.
- The starting resistances are gradually cut out in steps from the stator circuit as the motor picks up speed.
- When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the motor.

Cont...

This method suffers from two drawbacks.

- i) The reduced voltage applied to the motor during the starting period **lowers the starting torque and hence increases the accelerating time.**
- ii) **A lot of power is wasted in the starting resistances.**

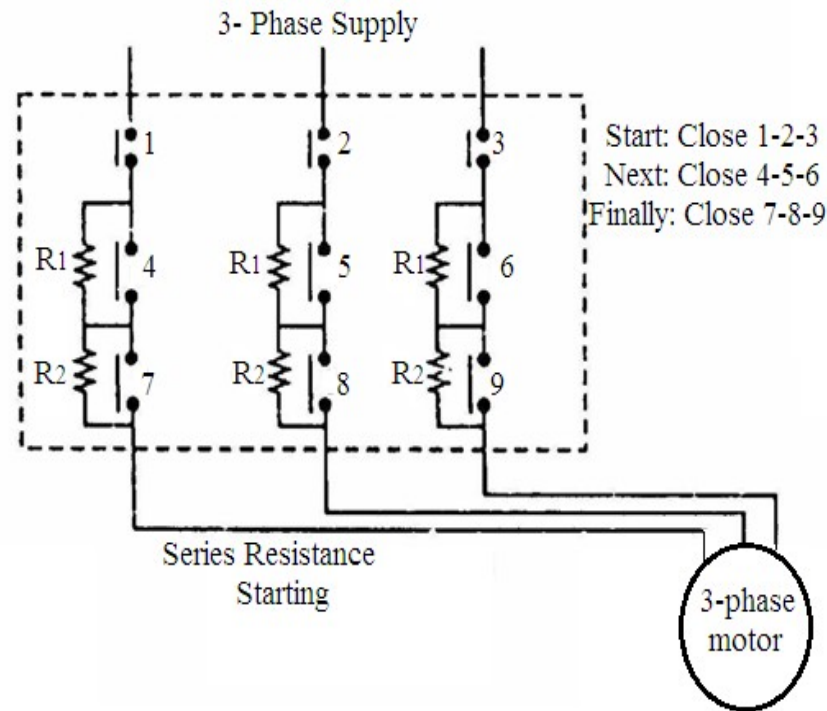


Figure 3-22 Circuit arrangement for Stator Resistance Starting

Autotransformer starting

- A fraction of xV_1 of the supply voltage V_1 is applied to the stator terminals at the time of starting, by means of an autotransformer as shown in fig.3-23 below
- This reduces the motor current and also the current drawn from the supply.
- After the motor has accelerated near to its operating speed, auto-transformer is disconnected and full line voltage is applied to the IM by connecting it directly across the supply mains.
- Note that here x is less than 1

Cont...

With autotransformer, per phase starting current in motor winding $= \frac{xV_1}{Z_{sc}} = x I_{sc}$ by:

Autotransformer starting has several advantages, such as **low power loss, low starting current, low heat.**

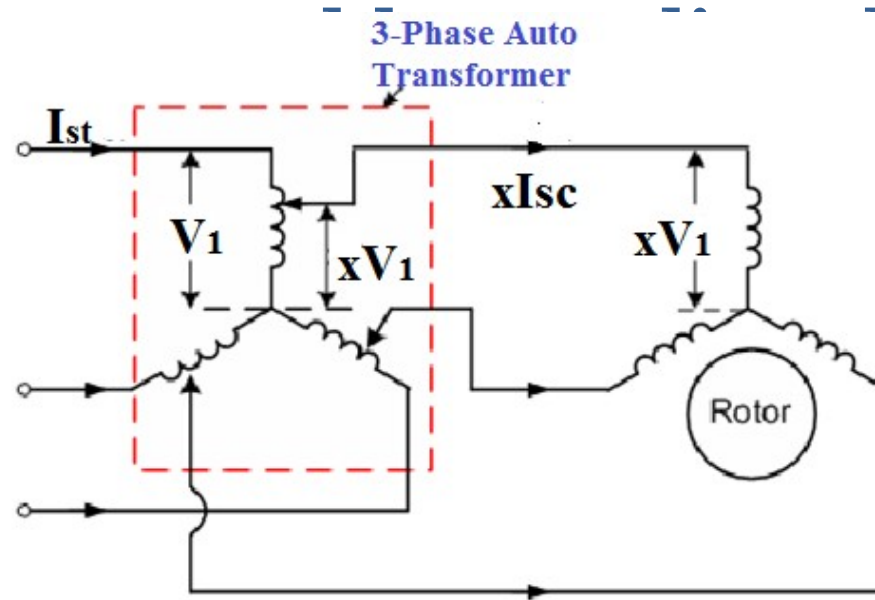


Figure3-23 Circuit arrangement for Auto transformer starting

Star Delta Startering

- It is suitable for those 3 ϕ cage rotor IM in which all the six terminals of the stator winding are brought out
- During starting the stator winding connects in star across the rated supply voltage and energized with 58 % of the supply voltage to each of the windings
- Then it is de-energized and then ^{1/ $\sqrt{3}$} reconnected with windings in delta with full line voltage across each line

• The $I_Y = \frac{V_{ph}}{Z_{ph}} = \frac{V_L}{\sqrt{3} Z_{ph}}$

Line current in Star connection

$I_{\Delta} = \sqrt{3} \frac{V_L}{Z_{ph}}$

Lin current in Delta connection

of
by

the same factor

Cont...

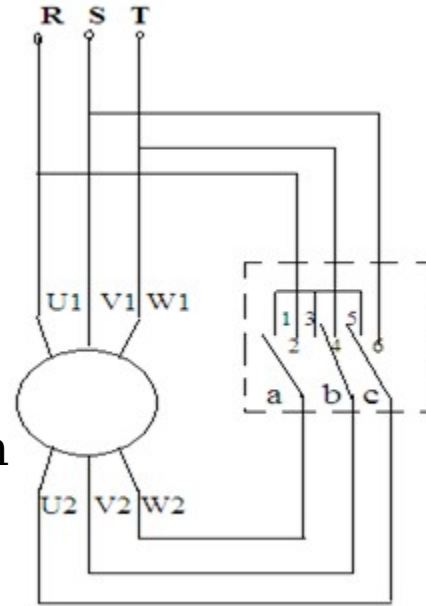


Figure3-24 Star- Delta Switch

**Note: star Connection
Connection**

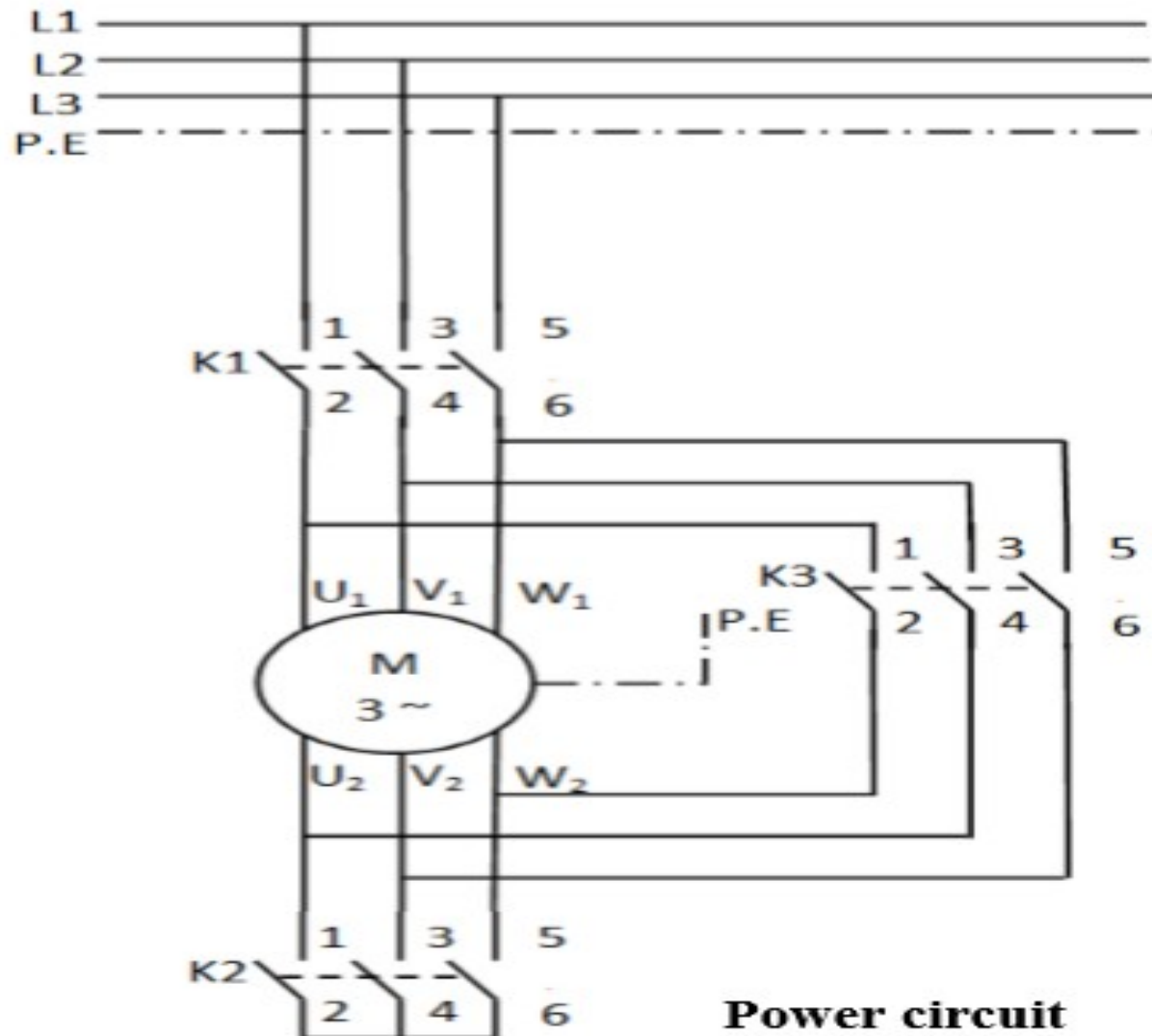
Delta

1a, 3b, 5c

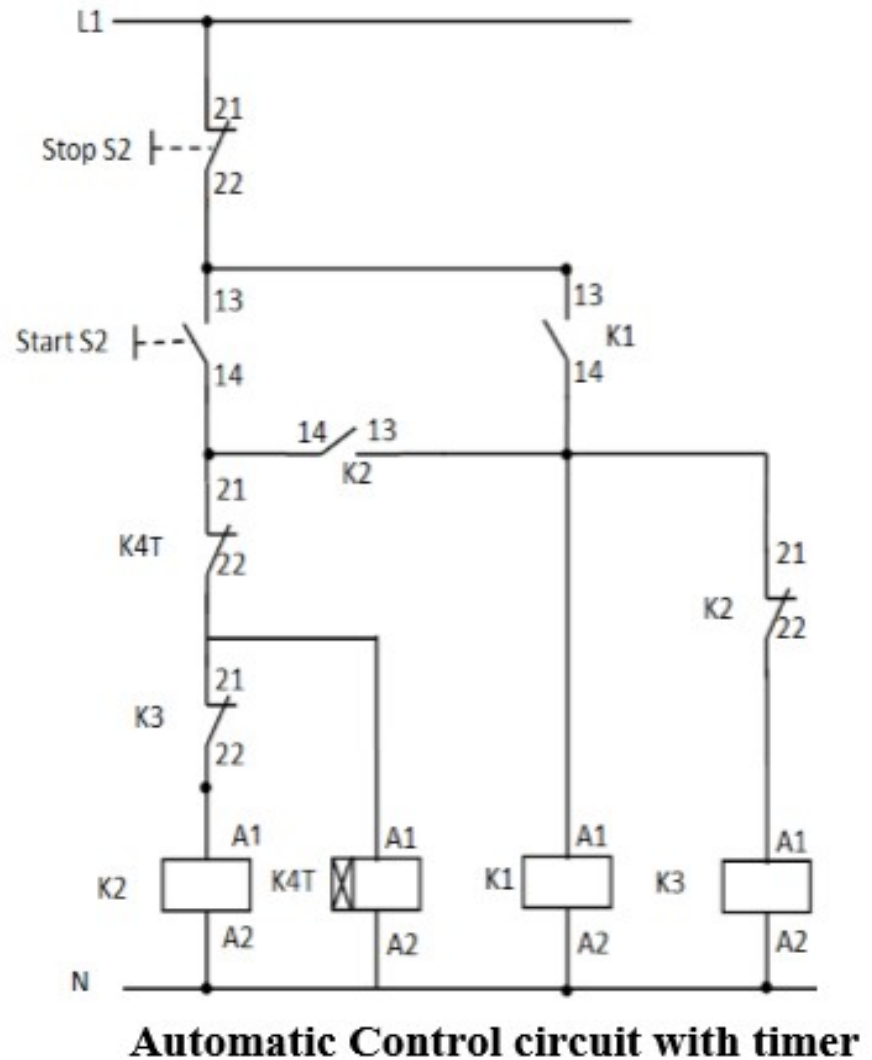
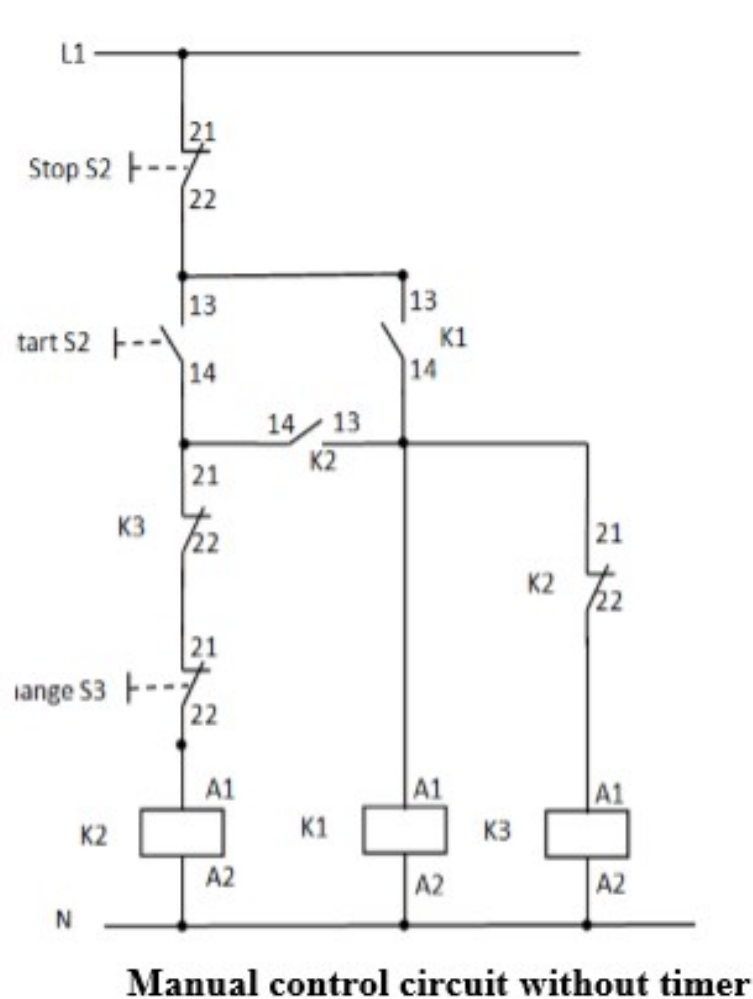
2a, 4b, 6c

To start the motor, the handle is moved from OFF to STAR position and when the motor peaks up the speed it is changed to DELTA. The star delta switch design ensures that the motor can't start in delta unless the starter is first brought to star position.

Star Delta Starting using magnetic contactor



Control Circuit



- The N_s of an IM is related to supply frequency f and poles P by the equation.

$$N_{sync} = \frac{120f}{P} \text{ rpm}$$

- The rotor speed is given by $N_m = (1-S)N_s$
- From the above two equations the basic methods of speed control of an IM are:
 - a) by changing the number of poles and
 - b) by varying the line (input) frequency.
- The slip can be changed by the following methods.
 - c) by varying the input voltage
 - d) by varying the rotor resistance
- The methods (c) and (d) are applicable to Wound rotor IM, whereas only method (c) can be applied to machines with cage rotor.

By changing the number of poles (Consequent Pole changing method)

- In this method, the stator winding of each phase is divided into two equal groups of coils.
- These coil groups are connected in series and parallel with the current direction being reversed only in one group, to create two different numbers of poles (even) in the ratio 2:1 respectively.
- When the connection is changed from series to parallel or vice versa, the current in one group of coils is also reversed at the same time.
- This technique is termed as, the consequent pole changing method, and is applied to all three windings (phases).
- **This type of IM has always the squirrel cage rotor, which can adapt to any number of stator poles.**

Eight-Poles connection

- Figure 3-25 Shows schematically only four coils of one phase of the windings connected in series, along with the direction of current in them, producing eight poles in the stator

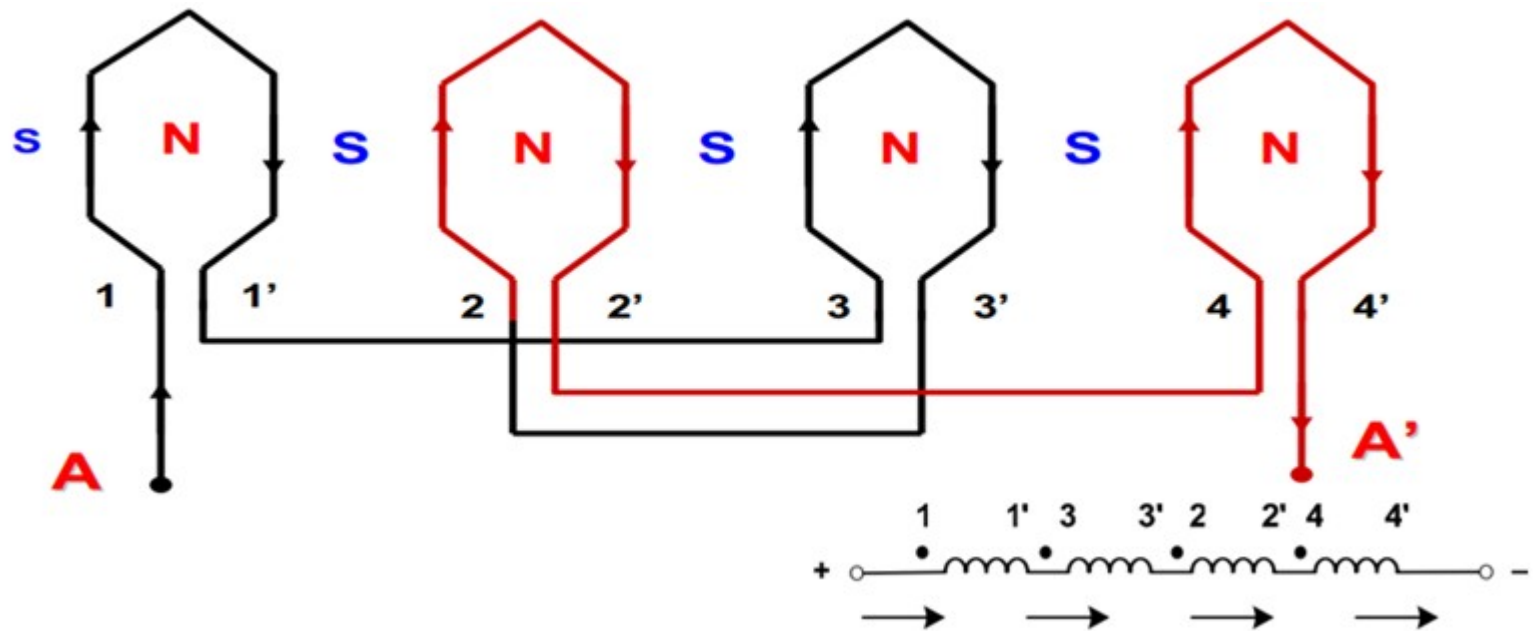


Figure 3-25 Eight pole (Series)

Four-Poles connection

- If the **current in coils 2 and 4 is reversed** and the connection is changed **to parallel with two coils (1 and 3, and 2 and 4)** connected in series for each path, four poles are formed in the stator shown in fig.3-26 below
- Note that the terminals **A** and **A'** remain

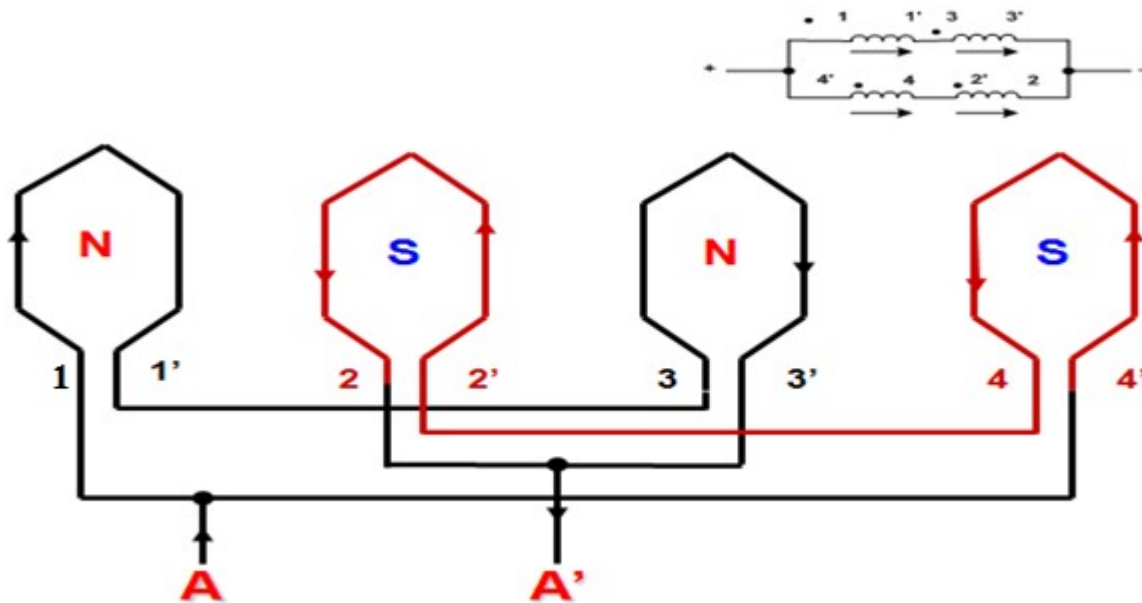


Figure 3-26 Four pole (Parallel)

Constant torque and constant horsepower operations

- This type of pole changing in the stator results in constant torque or constant power operations.
- For **constant torque operation**, the change of stator winding is made from **series-star to parallel- star**,
- While for **constant power** operation the change is made from **series-delta to parallel-star**.
- Regenerative braking takes place during changeover from higher to lower speeds.

Constant Torque operation :

Cont

➤ The changeover for constant torque operation takes place as shown in figure 3- 27 (a) and (b).

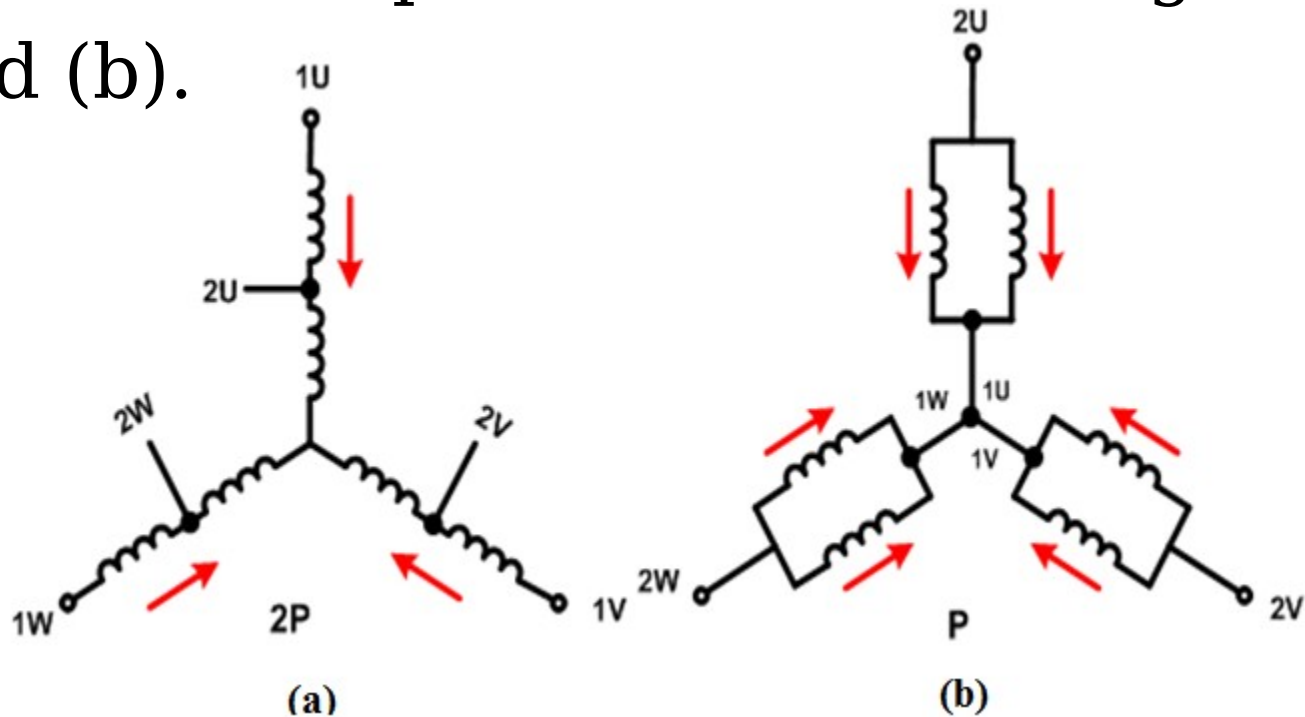


Figure 3-27 (a) Series Star, (b) Parallel Star

Cont...

Let V – Line voltage

I – Maximum current that the winding can carry

Then the power drawn from the supply is given by:-

$$P_Y = \sqrt{3}(VI \cos \phi_Y)$$

1. For series-star (Y) connection (Fig. 3-27a)
2. For parallel-star connection (fig. 3-27b)

$$P_{YY} = 2\sqrt{3}(VI \cos \phi_{YY})$$

▪ It is assumed that the power factor remains unchanged and the motor losses are negligible.

▪ With the changeover of stator winding from series star to parallel star, the power drawn from the supply is doubled.

▪ Simultaneously, the speed is also doubled. So the motor torque remains constant. Constant torque

Cont

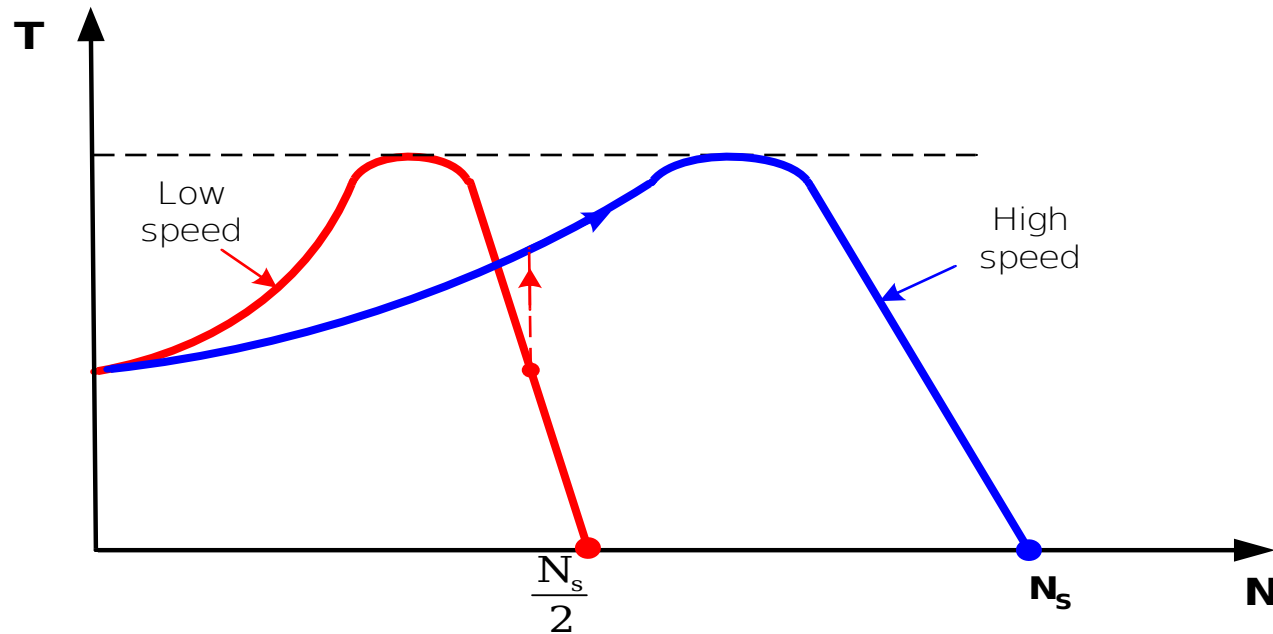


Figure 3-28. Torque-speed characteristics for constant torque operation

Constant horsepower operation: (Δ/YY)

➤ The power drawn from the supply is given by:

1. For series-delta (Δ) connection (Fig. 3- 29a.)

$$P_{\Delta} = 3(VI \cos \phi_{\Delta})$$

2. For parallel-star connection
 (Fig. 3-29b.)

$$P_{YY} = 2\sqrt{3}(VI \cos \phi_{YY}) = 3.46(VI \cos \phi_{YY})$$

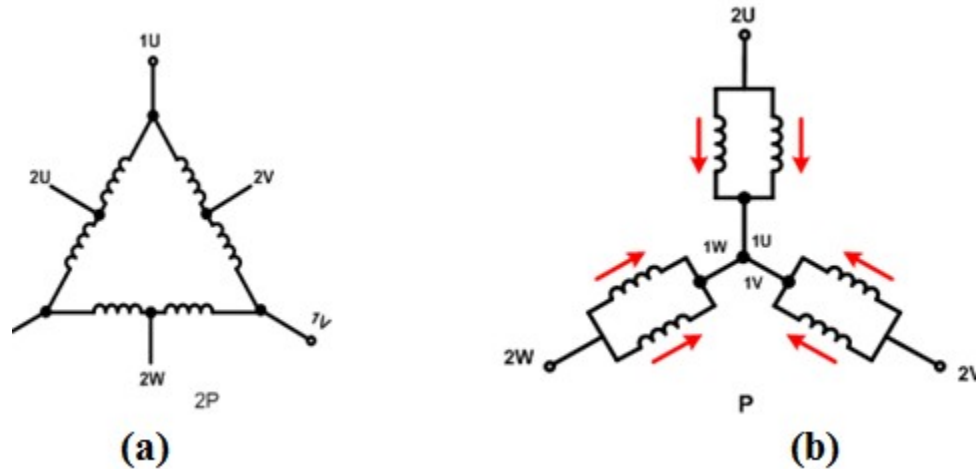


Figure 3-29

Cont...

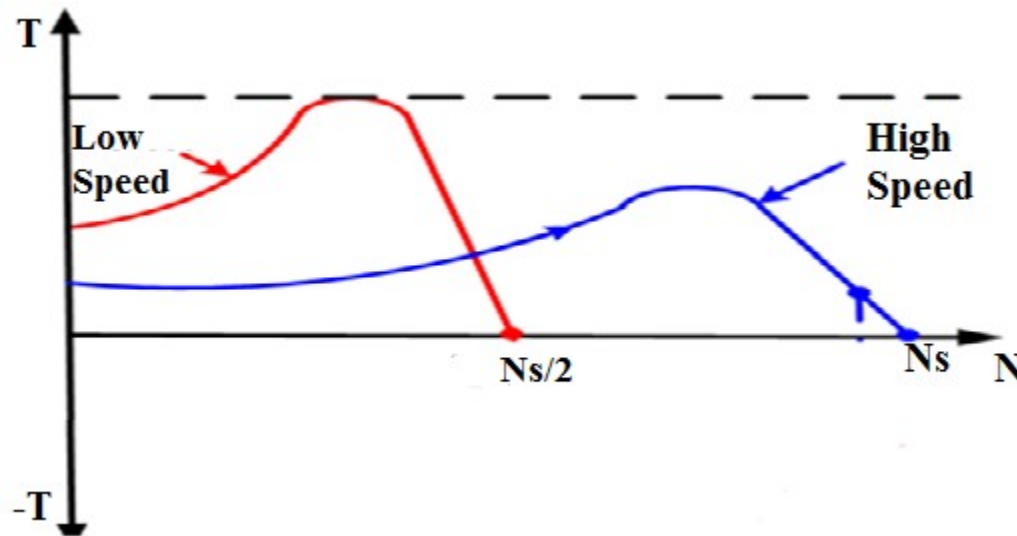


Figure 3-30 Torque-speed characteristics for constant power operation

- ❖ After changeover from series-delta to parallel-star, the power increases slightly (about 15%), if power factor is assumed to remain constant.
- ❖ The constant horsepower connection is the most expensive, because in this case the motor size becomes large.

By varying the line (input) frequency

- In this case a variable frequency supply is used as the key factor in speed control of induction motors.

Constant Volt/Hz operation

- The e.m.f per phase of an induction motor is given by $E = 4.44 \Phi_m f N_{ph} K_w$

- The induced emf E is nearly equal to the applied voltage $\frac{V}{f}$ (neglecting drop in stator impedance). $\frac{V}{f} = 4.44 \Phi_m f N_{ph} K_w$ $\frac{V}{Hz}$

- Then, we can write;

Cont...

- When the frequency is reduced, the applied voltage must be reduced proportionally so as to maintain constant flux, otherwise the core will get saturated resulting in excessive iron losses and magnetizing current
- This type of control is used for speed control below base frequency (line frequency of 50Hz).

Advantages of constant volt/Hz operations are :

1. Smooth speed control,
2. Small input current and improved power factor at low frequency start, and
3. Higher starting torque for low cage rotor resistance

By varying the line voltage

- Recall that the torque developed in an IM is proportional to the square of the terminal voltage.
- The reduction in operating speed of an IM can be achieved by reducing the applied voltage.
- A set of torque-speed characteristics with various terminal voltages is shown in figure 3-31.

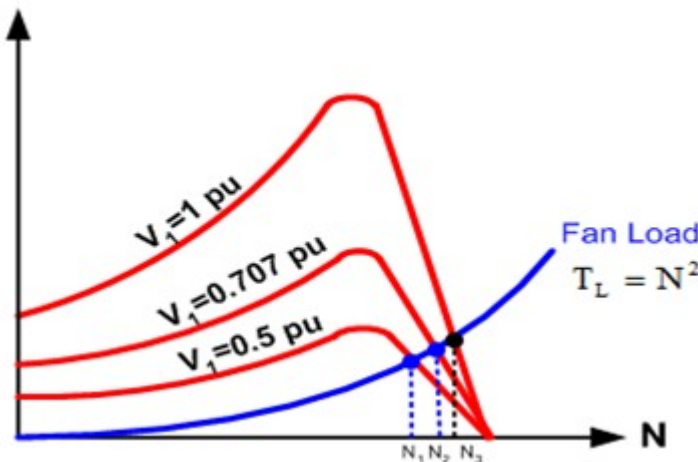


Figure 3-31 Torque-speed characteristics with various terminal voltage

Cont...

- In this method of speed control the slip increase at lower speeds, making the operation inefficient.
- However, for fans, or, similar centrifugal loads in which torque varies approximately as the square of the speed, the power decreases significantly with decrease in speed.
- Therefore, even if the power lost in the rotor circuit (**sPag**) may be a significant portion of the air gap power, the air gap power itself is small and therefore the rotor will not overheat.
- The voltage controller circuits are simple and, suitable for fan, pump, and similar centrifugal drives.

By varying the rotor resistance

- The speed of a wound-rotor IM can be controlled by connecting external resistance in the rotor circuit through slip-rings. However, an increase in the rotor resistance causes
 - (i) An increase in the rotor copper loss,
 - (ii) An increase in the operating temperature of motor
 - (iii) A reduction in the motor efficiency.

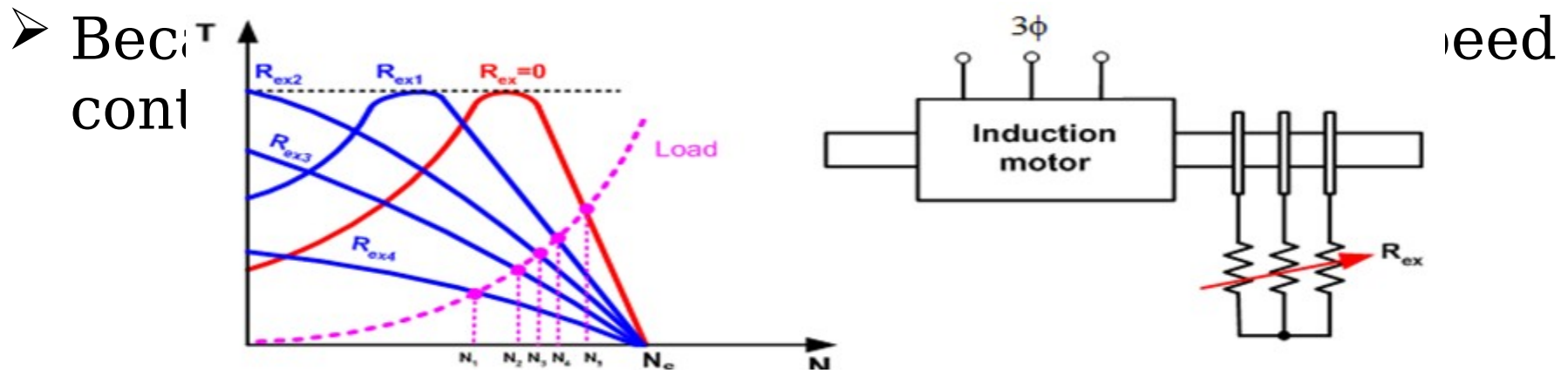


Figure 3-32 Torque-Speed Characteristics for four external resistances

Cont...

- The load torque-speed characteristic is also shown by dashed line.
- By varying the external resistance $0 < R_{ex} < R_{ex4}$, the speed of the load can be controlled in the range of $N_1 < N < N_5$.
- **Note that by proper adjustment of the external resistance ($R_{ex}=R_{ex2}$), maximum starting torque can be obtained for the load.**
- The **major disadvantage** of this method is that **the efficiency is low at reduced speed because of higher slips** and
- Due to **additional losses in the external resistors** connected in the rotor circuit.

Cont...

- However, this control method is often employed because of its simplicity.
- A typical application of the rotor resistance control method is the hoist drive of a shop crane.
- Because of low cost and high torque capability at low speeds, this method is used in fans, pump drives where speed variation over a small range near the top speed is required.

**THANK
YOU**