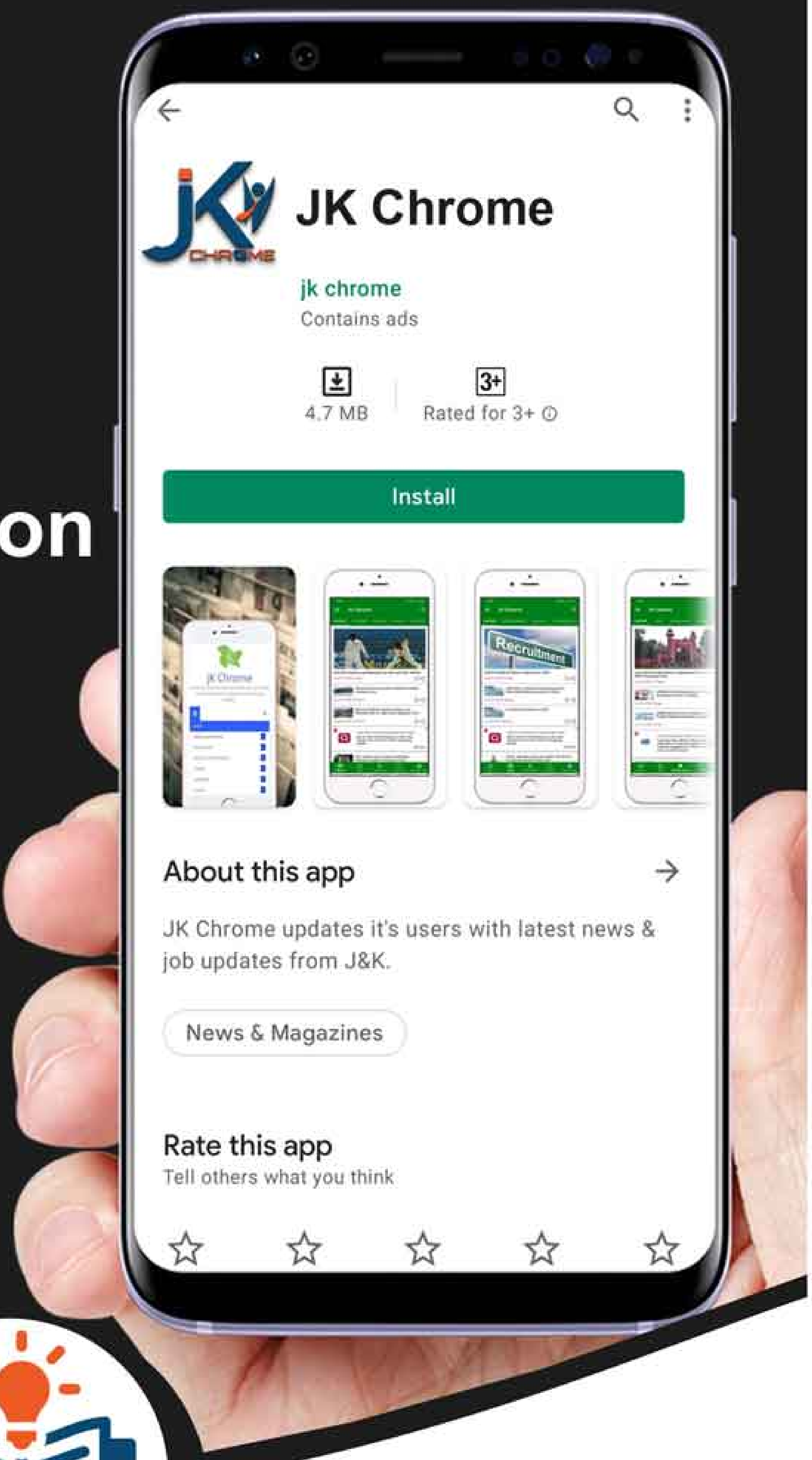


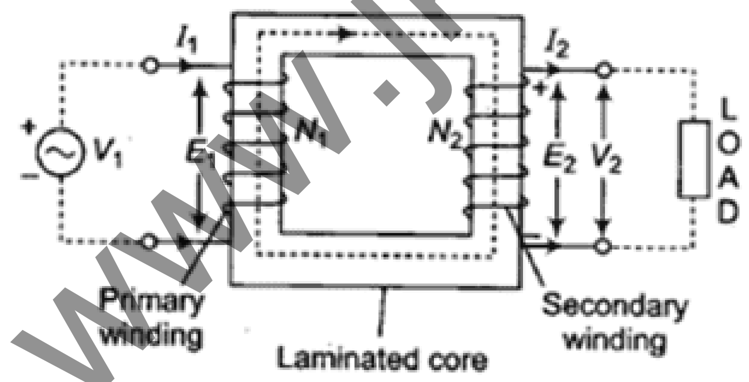
Electrical Machines

Index

Transformers

In this article, you will find the complete study notes on **Transformer.**

- A basic transformer consists of two separate windings of insulated wires wound around a common iron core.
- The power source or supply is hooked to the primary winding, the load to be served is hooked to the secondary winding.
- Primary windings, connected to the alternating voltage source, and Secondary windings, connected to the load. Iron core used to link the flux in both windings.
- When the primary winding is energized an electromagnetic field builds up and then collapses in the iron core, this field cuts through the secondary coil winding inducing power to the load hooked to the secondary.
- This power build up and collapse is called magnetic flux and occurs at a frequency of sixty times a second (60 Hz) in an a.c. circuit.
- Unlike in rotating machines, there is no energy conversion.
- Transformers are based on the principle of “mutual-induction.” When current flows through a wire a magnetic field is produced.
- When a conductor passes through a magnetic field, a current flow will be induced through the wire.
- The method of transferring electrical energy by a transformer is done indirectly. Electrical energy is first converted into magnetic energy, then reconverted back into electrical energy at a different voltage and ampacity. Magnetism and electricity are closely related.



Two winding transformer

- By altering the number of windings on the primary and secondary, we can alter the amount of volts and amps between the source and the load.
- The current in the secondary coil always changes by the inverse of the ratio by which the voltage changes.

- If the voltage is raised to n times its original value by the transformer, the current in the secondary coil will be reduced to one- n th the value of the current in the primary coil.
- The rms value of induced emf can be find as:
    - Primary induced emf $E_1 = 4.44\ f\ N_1\ \varphi_m$ volt
    - Secondary induced emf $E_2 = 4.44\ f\ N_2\ \varphi_m$ volt.
    - where, N_1 = Number of turns in primary winding, N_2 = Number of turns in secondary winding, f = Supply frequency in Hz, and φ_m = Maximum value of the magnetic flux in Wb

Transformer Ratio:

- The input winding to a transformer is called the primary winding.
- The output winding is called the secondary winding.
- Step Down Transformer: If there are more turns of wire on the primary than on the secondary, the output voltage will be lower than the input voltage.
- Step Up Transformer: If there are more turns of wire on the secondary than on the primary, the output voltage will be higher than the input voltage.

Turns Ratio = (Number of turns on the Primary) / (Number of turns on the Secondary)

Turns Ratio = (Primary Voltage) / (Secondary Voltage)

Turns Ratio = (Secondary Current) / (Primary Current)

Transformer Rating:

- Transformers are rated in volt-amperes (VA) or kilovolt-amperes (kVA)
- When the volt-ampere (or kilovolt-ampere) rating is given, along with the primary voltage, then the primary full-load current can be determined as:

Full Load Current = VA rating / Voltage

Full Load Current = (kVA rating * 1000) / Voltage

Turns Ratio = (Secondary Full Load Current) / (Primary Full Load Current)

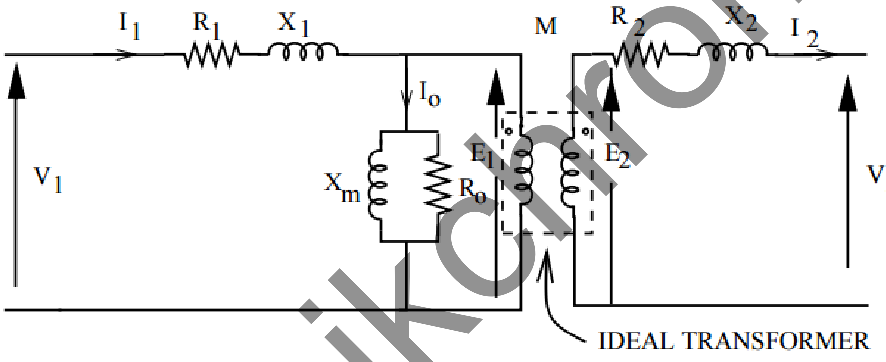
Types of Transformers:

1. *Insulating transformers :* Common two-winding transformers are often called insulating transformers. The primary winding and the secondary winding are separate and not connected.
2. *Auto transformers :* An autotransformer has its windings interconnected so that the primary and the secondary share the same windings.
3. *Constant output voltage transformers :* Constant output voltage transformers or voltage regulating transformers produce a nearly constant output voltage, even though the input voltage may not be constant.

Ideal Transformer:

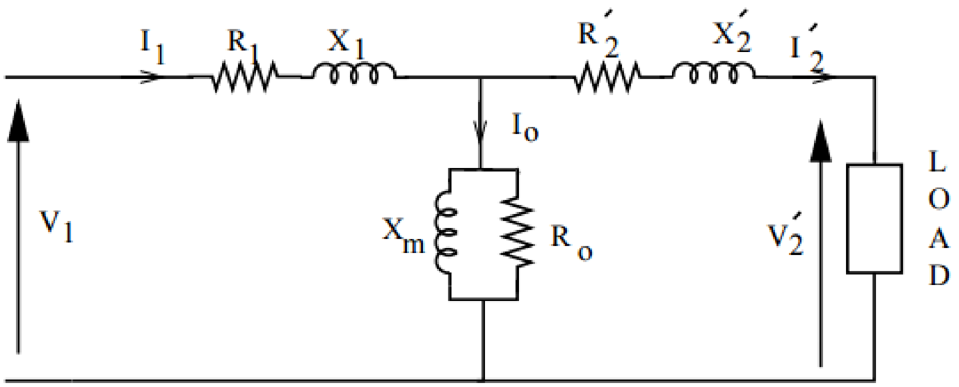
In ideal transformer shown below, which has the following assumptions

1. Its windings have no ohmic resistance, therefore it has no I^2R loss (copper loss).
2. There is no magnetic leakage, hence which has no core losses.
3. The core has infinite permeability



This equivalent circuit can be further simplified by referring all quantities in the secondary side of the transformer to primary side.

Equivalent Circuit: The equivalent circuit of a machine is the circuit representation in terms of standard circuit elements which truly represents the performance of the particular equipment (see the below figure).



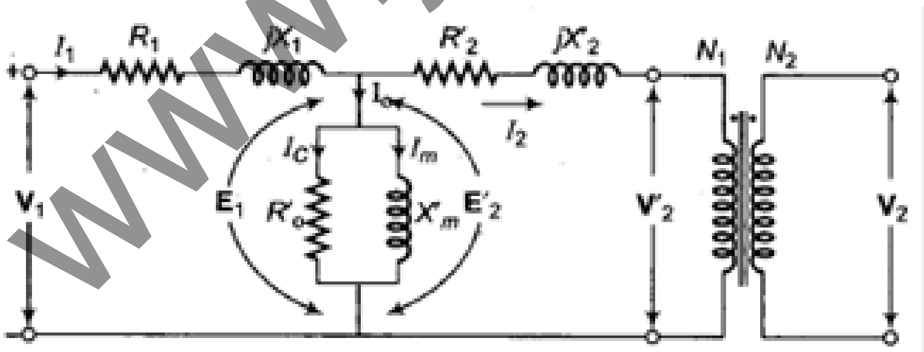
$$F = I\int_C dl \times B$$

- Parameters : R_1 = Primary winding resistance, R_2 = Secondary winding resistance, X_1 = Primary winding reactance, X_2 = Secondary winding reactance, I_0 = No load or exciting current, $I_{c=}$ Core loss component of exciting current, I_m = magnetising component of exciting current, R_c = Core loss equivalent resistance, X_m = Magnetising reactance, V_1 = Primary voltage source, and V_2 = Secondary terminal voltage.

Equivalent Circuit Referred to Primary Side: When all parameters are referred to primary side.

Here,

$$\left(\frac{N_1}{N_2}\right) = K$$



Equivalent circuit referred to primary side

- **R'_2** is Secondary resistance referred to primary side
- **X'_2** is Secondary leakage reactance referred to primary side

- **I'_2** is Secondary current referred to primary side
- **V'_2** is Secondary voltage referred to primary side

$$R'_2 = R_2\left(\frac{N_1}{N_2}\right)^2$$

$$X'_2 = X_2\left(\frac{N_1}{N_2}\right)^2$$

$$I'_2 = I_2\left(\frac{N_2}{N_1}\right)$$

$$V'_2 = V_2\left(\frac{N_1}{N_2}\right)$$

- Secondary induced emf referred to primary side:

$$E'_2 = E_2\left(\frac{N_1}{N_2}\right)$$

- Equivalent resistance referred t0 primary side:

$$R_{e_1} = R_1 + R'_2 = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2 = R_1 + K^2 R_2$$

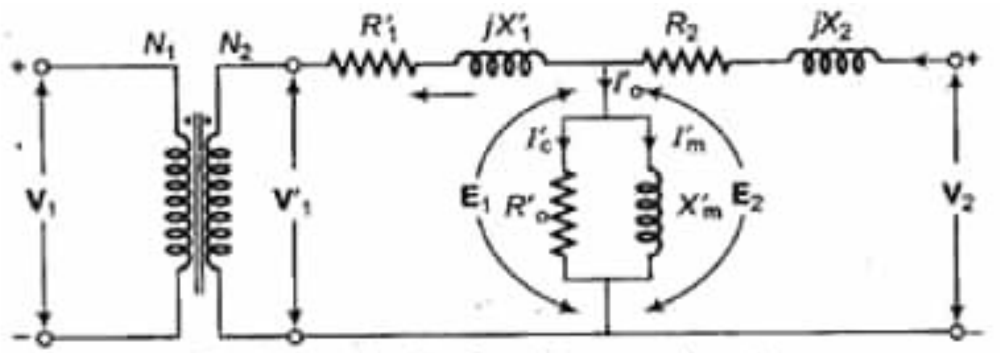
- Equivalent reactance referred to primary side:

$$X_{e_1} = X_1 + X'_2 = X_1 + X_2\left(\frac{N_1}{N_2}\right)^2 = X_1 + K^2 X_2$$

- Equivalent impedance referred to primary side:

$$Z_{e_1} = Z_1 + Z'_2 = Z_1 + Z_2\left(\frac{N_1}{N_2}\right)^2 \quad \text{or} \quad Z_{e_1} = \sqrt{R_{e_1}^2 + X_{e_1}^2}$$

Equivalent Circuit Referred to Secondary Side: When all parameters refereed to secondary side.



Equivalent circuit referred to secondary side

- Primary resistance referred to secondary side:

$$R_1' = R_1\left(\frac{N_2}{N_1}\right)^2$$

- Primary leakage reactance referred to secondary side:

$$X_1' = X_1\left(\frac{N_2}{N_1}\right)^2$$

- Primary induced emf referred to secondary side:

$$E_1' = E_1\left(\frac{N_2}{N_1}\right)$$

- Primary current referred to secondary side:

$$I_1' = \frac{I_1}{\left(\frac{N_2}{N_1}\right)} = I_1\left(\frac{N_1}{N_2}\right)$$

- Equivalent resistance referred to secondary side:

$$R_{e2} = R_2 + R'_1 = R_2 + R_1\left(\frac{N_2}{N_1}\right)^2 = R_2 + K^2 R_1$$

- Equivalent reactance referred to secondary side:

$$X_{e_2} = X_2 + X_1' = X_2 + X_1\left(\frac{N_2}{N_1}\right)^2$$

Voltage Regulation: Voltage regulation is defined as the raise in secondary terminal voltage expressed as a fraction of full load rate voltage when full load is removed while maintains input (primary) voltage constant.

Voltage regulation:

$$\frac{|\text{No load voltage}| - |\text{Full load voltage}|_{(\text{rated})}}{|\text{Full load voltage}|_{(\text{rated})}}$$

it is same as

$$\frac{|V_{2nl}| - |V_{2fl}|}{|V_{2fl}|} \times 100\%$$

- Voltage regulation (at tagging power factor):

$$\frac{I_2R_{e_2}\cos\phi_2 + I_2X_{e_2}\sin\phi_2}{V_2}$$

- Voltage regulation (at leading power factor):

$$\frac{I_2R_{e_2}\cos\phi_2 - I_2X_{e_2}\sin\phi_2}{V_2}$$

Losses in Transformer

- **Iron or Core Loss (Constant):** The losses which occur in a transformer are as follows:
    - $P_i = P_h + P_e$ Where, P_i = Iron or core loss, P_h = Hysteresis loss, and P_e = Eddy current loss.

  - This loss in the sum of hysteresis (P_h) and eddy current loss (P_e). It is denoted by $P_{i.}$
- **Eddy Current Loss:**

$$P_e = K_e f^2 B_m^2 t^2$$

where, K_e = Proportionality constant depends upon core material, f = Supply frequency, B_m = Maximum flux density in the core, and t = Thickness of laminations.

But,

$$\therefore P_m \propto V^2$$

Eddy current loss is proportional to the square of the applied voltage and independent of frequency. It can be reduced by thin lamination.

- **Hysteresis Loss**

$$P_h = K_n f B_m^x$$

and

$$B_m \propto \frac{V}{f}$$

There, fore

$$P_h \propto \frac{V}{f}$$

Where, x = Steinmetz constant (range from 1.6 to 2.5). Hysteresis loss depends upon both the applied voltage and frequency.

- **Copper Loss or I^2R Loss (Variable):**
  - Total copper loss in transformer = primary winding copper loss + secondary winding copper loss.

$$P_c = I_1^2 R_{e_1} + I_2^2 R_{e_2}$$

Transformer Efficiency

- Transformer Efficiency (η) = Output power / Input power
- Transformer Efficiency (η) = Output power / (Output power + Losses)
- Transformer Efficiency (η) = output power / (output power+ iron losses + copper losses)

$$\eta = \frac{\text{Output power}}{\text{Output power} + P_i + P_c} \quad \text{or} \quad \eta = 1 - \frac{\text{Losses}}{\text{Input power}}$$

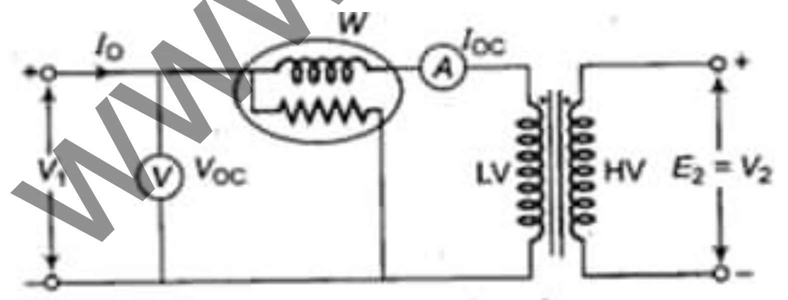
Where, P_i = Iron or core loss, P_c = Copper loss

Transformer Tests

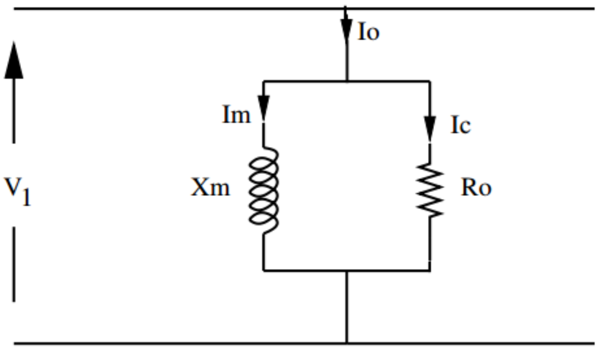
Open circuit and short circuit test are performed to determine the circuit constants efficiency and regulation without actually loading the transformer.

1. **Open Circuit (OC) Test:**

- OC test is carried out at rated voltage usually on low voltage side with high voltage side open.
- This test is used to determine the core loss at rated voltage condition.
- Since, the secondary terminals are open (no load is connected across the secondary), current drawn from the source is called as no load current.
- Under no-load condition the power input to the transformer is equal to the sum of losses in the primary winding resistance and core loss.
- Since, no load current is very small, the loss in winding resistance is neglected. Hence, on no load the power drawn from the source is dissipated as heat in the core.



Open circuit test on a transformer



Equivalent Circuit on No–Load

- Wattmeter reading = iron or core loss P_i
- Voltmeter reading = primary rated voltage x (V_1)
- Ammeter reading = no load current (I_0)

$$P_i = V_1 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{P_i}{V_1 I_0}$$

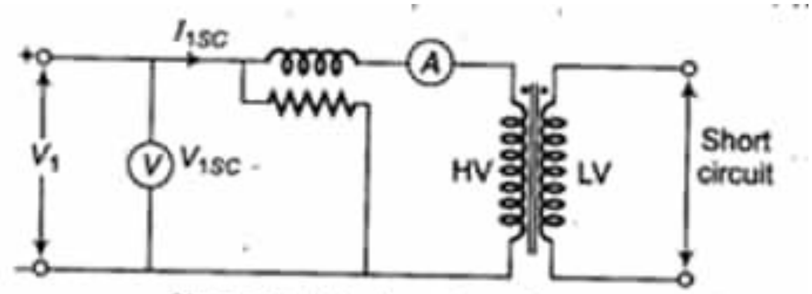
$$I_c = I_0 \cos\phi_0, I_m = I_0 \sin\phi_0$$

$$R_0 = \frac{V_1}{I_c}$$

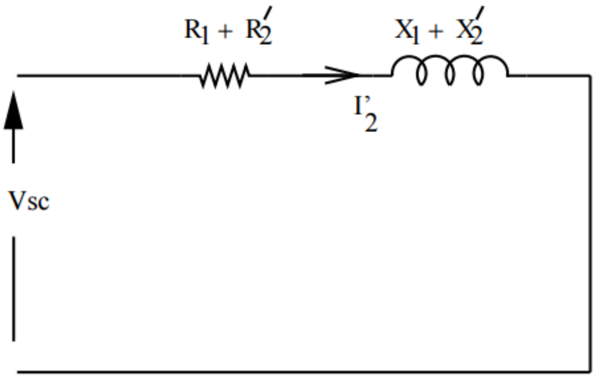
$$X_m = \frac{V_1}{I_m}$$

1. **Short Circuit Test:**

- Suppose the input voltage is reduced to a small fraction of rated value and secondary terminals are short-circuited. A current will circulate in the secondary winding.
- Since a small fraction of rated voltage is applied to the primary winding, the flux in the core and hence the core loss is very small. Hence, the power input on short circuit is dissipated as heat in the winding
- Short test is carried out at rated current to determine the full load copper loss.



Short circuit test on a transformer



Equivalent Circuit on Short Circuit

- Wattmeter reading = full load copper loss of transformer (P_{cfi})
- Voltmeter reading = short circuit voltage (I_{1SC})
- Ammeter reading = full load primary current f(I_{1SC})

$$P_{cfi} = V_{1SC} I_{1SC} \cos\phi_{1SC}$$

- Equivalent resistance:

$$R_{e_1} = \frac{P_{cfi}}{I_{1SC}^2}$$

$$V_{1SC} = I_{1SC} Z_{e_1}$$

and

$$X_{e_1} = \sqrt{Z_{e_1}^2 - R_{e_1}^2}$$

Autotransformer

This single winding is “tapped” at various points along its length to provide a percentage of the primary voltage supply across its secondary load. Then the *autotransformer* has the usual magnetic core but only has one winding, which is common to both the primary and secondary circuits.

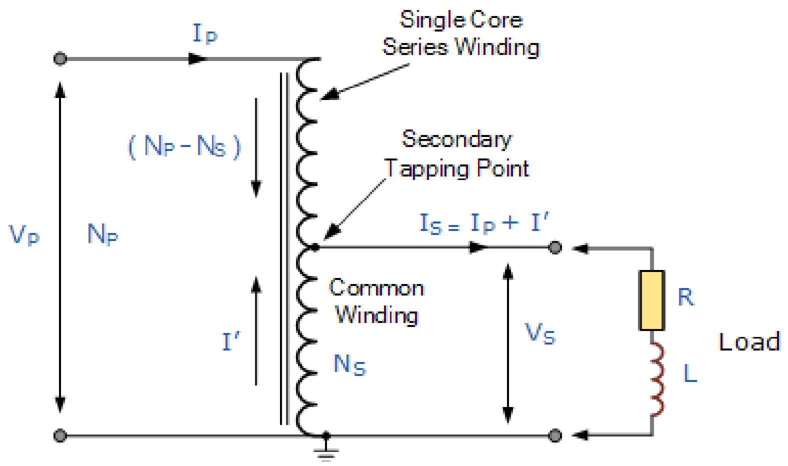
There fore in an autotransformer, the primary and secondary windings are linked together both electrically and magnetically. The main advantage of this type of transformer design is that it can be made a lot cheaper for the same VA rating, but the biggest disadvantage of an autotransformer is that it does not have the primary/secondary winding isolation of a conventional double wound transformer.

The section of winding designated as the primary part of the winding is connected to the AC power source with the secondary being part of this primary winding. An autotransformer can also be used to step the supply voltage up or down by reversing the connections. If the primary is the total winding and is connected to a supply, and the secondary circuit is connected across only a portion of the winding, then the secondary voltage is “stepped-down” as shown

This single winding is “tapped” at various points along its length to provide a percentage of the primary voltage supply across its secondary load. Then the *autotransformer* has the usual magnetic core but only has one winding, which is common to both the primary and secondary circuits.

Therefore in an autotransformer the primary and secondary windings are linked together both electrically and magnetically. The main advantage of this type of transformer design is that it can be made a lot cheaper for the same VA rating, but the biggest disadvantage of an autotransformer is that it does not have the primary/secondary winding isolation of a conventional double wound transformer.

The section of winding designated as the primary part of the winding is connected to the AC power source with the secondary being part of this primary winding. An autotransformer can also be used to step the supply voltage up or down by reversing the connections. If the primary is the total winding and is connected to a supply, and the secondary circuit is connected across only a portion of the winding, then the secondary voltage is “stepped-down” as shown.



The voltages developed in the windings are dependent on the flux linkages. The windings are wound on the same magnetic core so they link the same flux.

- $V1 / N1 = V2 / N2$.

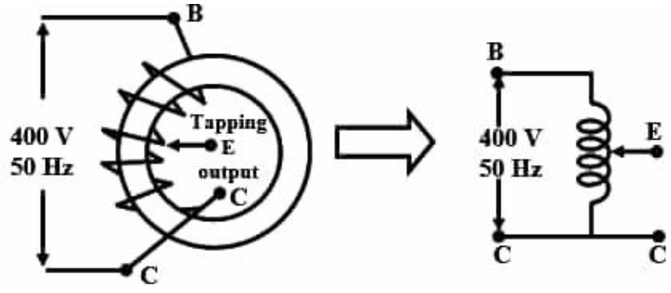
So whenever voltage V1 exist across primary winding, then voltage V2 will be induced across the secondary winding irrespective of changes in connections.

Similarly the magnetic circuit demands that mmf should be balanced. It implies the primary side ampere turn should equal the secondary side ampere turn.

- $I1 . N1 = I2 . N2$

Here,

- Autotransformers are also used for voltage regulation in distribution networks, for starting of induction motors and as lighting dimmers. Autotransformers are also used in electric traction.
- One main disadvantage about autotransformer is that the primary and secondary are electrically connected. So the electrical disturbance i.e. high voltage transients from one side can be easily transmitted to the other side.
- The other disadvantage is that the impedance of the autotransformer is considerably low, so the short circuit current will be more.
- More over an open circuit in common winding results in full primary side voltage across the load which is harmful.



Disadvantages of an Autotransformer

- The main disadvantage of an autotransformer is that it does not have the primary to secondary winding isolation of a conventional double wound transformer. Then an autotransformer can not safely be used for stepping down higher voltages to much lower voltages suitable for smaller loads.
- If the secondary side winding becomes open-circuited, current stops flowing through the primary winding stopping the transformer action resulting in the full primary voltage being applied to the secondary terminals.
- If the secondary circuit suffers a short-circuit condition, the resulting primary current would be much larger than an equivalent double wound transformer due to the increased flux linkage damaging the autotransformer.
- Since the neutral connection is common to both the primary and secondary windings, earthing of the secondary winding automatically Earth's the primary as there is no isolation between the two windings. Double wound transformers are sometimes used to isolate equipment from earth.

The *autotransformer* has many uses and applications including the starting of induction motors, used to regulate the voltage of transmission lines, and can be used to transform voltages when the primary to secondary ratio is close to unity.

An autotransformer can also be made from conventional two-winding transformers by connecting the primary and secondary windings together in series and depending upon how the connection is made, the secondary voltage may add to, or subtract from, the primary voltage.

Three Phase Transformer

Three phase transformers are used throughout industry to change values of three-phase voltage and current. Since three-phase power is the most common way in which power is produced, transmitted, and used, an understanding of how three phase transformer connections are made is essential.

- A three-phase transformer is constructed by winding three single phase transformers on a single core.
- These transformers are put into an enclosure which is then filled with dielectric materials such as air, plastic or oil.
- The dielectric material performs several functions.
- Since it is a dielectric, a non-conductor of electricity, it provides electrical insulation between the windings and the case.
- It is also used to help provide cooling and to prevent the formation of moisture, which can deteriorate the winding insulation.

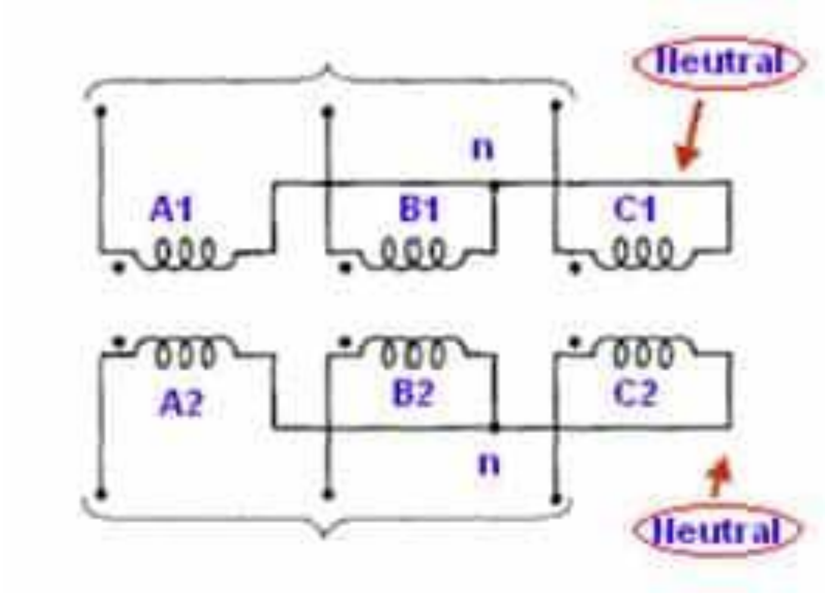
Three-Phase Transformer Connections

- Three-phase transformers can consist of either three separate single-phase transformers, or three windings on a three-legged, four-legged, or five-legged core.
- The high-voltage and low-voltage sides can be connected independently in either wye or delta.
- As a result, the ratio of the 3-phase input voltage to the 3-phase output voltage depends not only upon the turns ratio of the transformers but also upon how they are connected.

There are only 4 possible transformer combinations:

1. Delta-to-Delta Connection: It is used for industrial applications.
2. Delta to Wye Connection: It is popular for stepping up transmission lines to four-wire services when neutrals are needed.
3. Wye to Delta Connection: It is used to step-down utilities high line voltages.
4. Wye-to-Wye Connection: It is commonly used for interior wiring systems

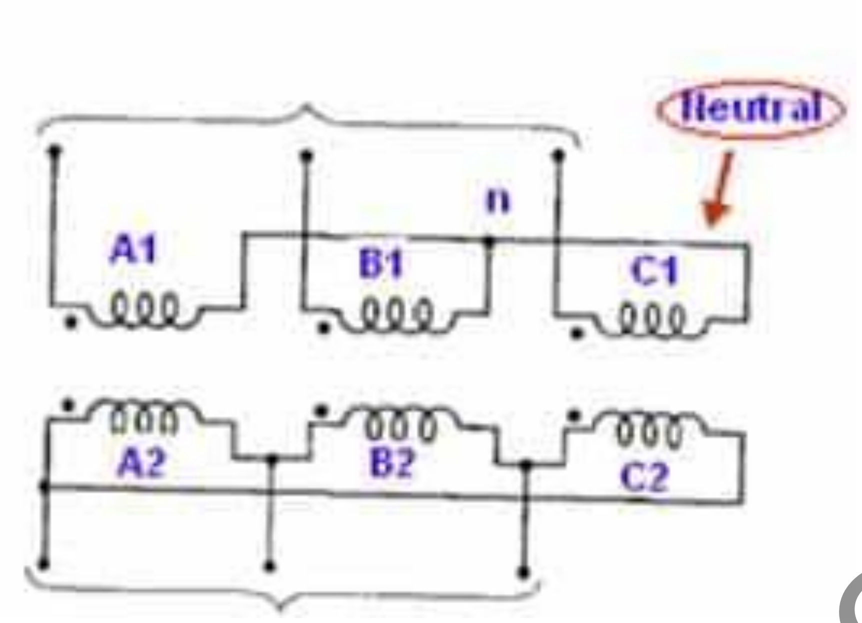
Y/Y Connection: A Y/Y connection for the primary and secondary windings of a three-phase transformer is shown in the figure below.



Y/Y connected three-phase transformer

- The line-to-line voltage on each side of the three-phase transformer is √3 times the nominal voltage of the single-phase transformer.
- The main advantage of Y/Y connection is that we have access to the neutral terminal on each side and it can be grounded if desired.
- Without grounding the neutral terminals, the Y/Y operation satisfactory only when the three-phase load is balanced.
- The electrical insulation is stressed only to about 58% of the line voltage in a Y-connected transformer.

Y/Δ Connection: This connection as shown in the figure below is very suitable for step-down applications.

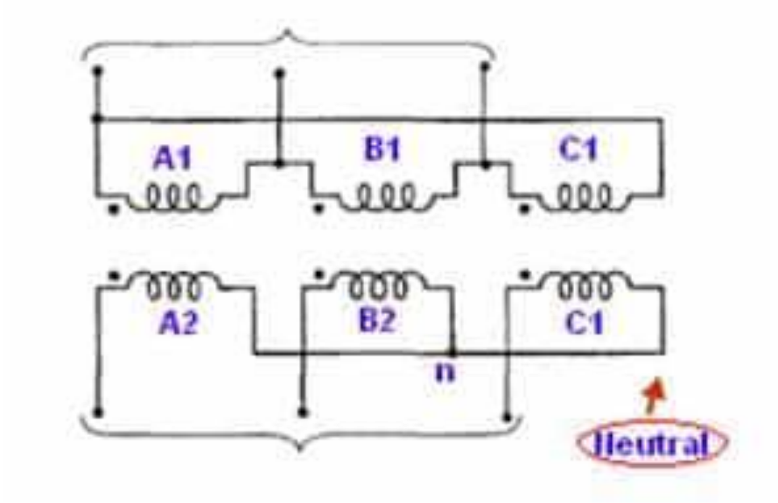


Y/Δ connected three-phase transformerThe secondary winding current is about 58% of the load current.

- On the primary side the voltages are from line to neutral, whereas the voltages are from line to line on the secondary side.
- Therefore, the voltage and the current in the primary are out of phase with the voltage and the current in the secondary.
- In a Y/Δ connection, the distortion in the waveform of the induced voltages is not as drastic as it is in a Y/Y-connected transformer when the neutral is not connected to the ground the reason is that the distorted currents in the primary give rise to a circulating current in the Δ-connected secondary.

Δ/Y Connection: This connection as shown in figure below is proper for a step-up application.

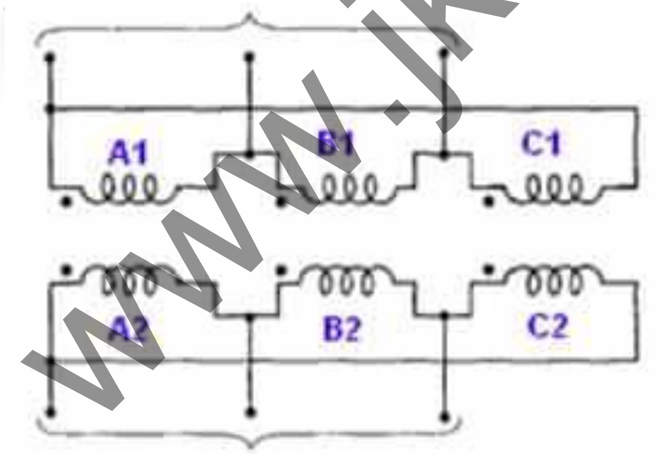
Δ/Y connected three-phase transformer



- However, this connection is now being exploited to satisfy the requirements of both three-phase and the single-phase loads.
- In this case, we use a four-wire secondary.
- The single-phase loads are taken care of by the three line-to-neutral circuits.
- An attempt is invariably made to distribute the single-phase loads almost equally among three-phases.

Δ/Δ Connection: as shown below the three transformers with the primary and secondary windings connected as Δ/Δ.

Δ/Δ connected three-phase transformer



- The line-to-line voltage on either side is equal to the corresponding phase voltage. Therefore, this arrangement is useful when the voltages are not very high.

- The advantage of this connection is that even under unbalanced loads the three-phase load voltages remain substantially equal.
- This disadvantage of Δ/Δ connection is the absence of a neutral terminal on either side.
- Another drawback is that the electrical insulation is stressed to the line voltage.
- Therefore, a Δ-connection winding requires more expensive insulation than a Y-connected winding for the same power rating.

DC Machines

In this article, you will find the study notes on **DC Machines.**

- DC machine is a highly versatile and flexible machine.
- It can satisfy the demands of load requiring high starting, accelerating and retarding torques.
- If the conversion is from mechanical to electrical energy, the machine is called as Generator.
- If the conversion is from electrical to mechanical energy, the machine is called as Motor.

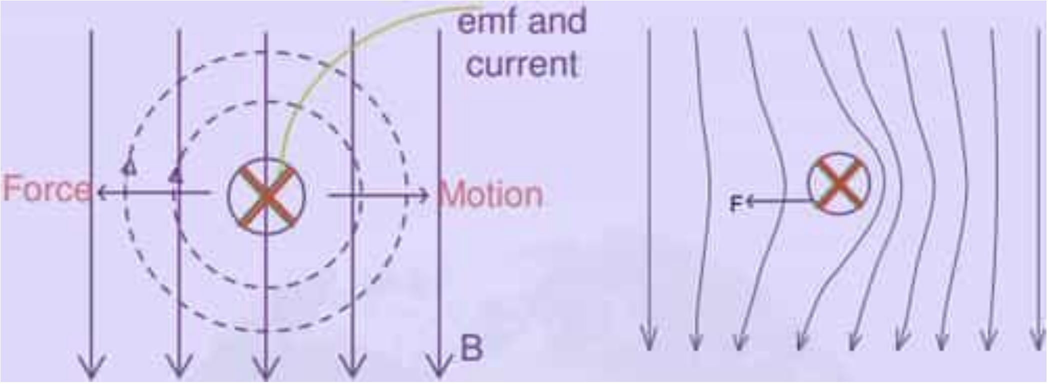
To understand, design and use these machines the following laws must be studied.

- **Electric circuit laws - Kirchoff's Laws**
- **Magnetic circuit law - Ampere's Law**
- **Law of electromagnetic induction - Faraday's Law**
- **Law of electromagnetic interaction -BiotSavart's Law**

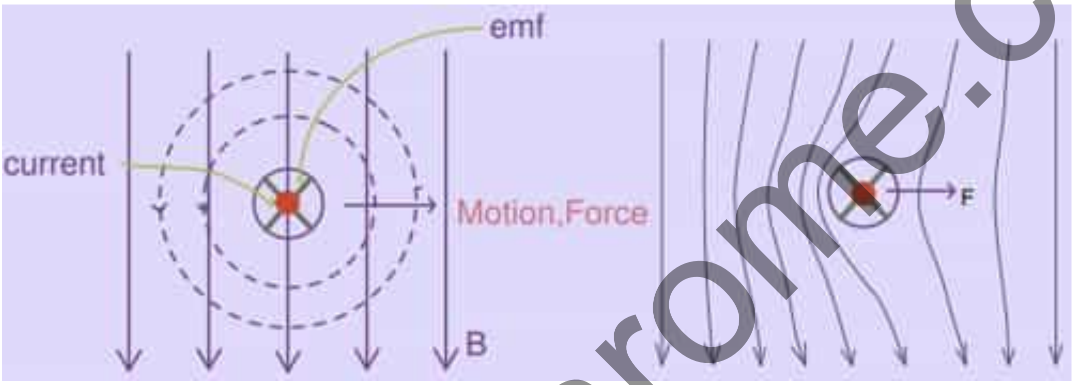
Most of the present day machines have one or two electric circuits linking a common magnetic circuit. In subsequent discussions the knowledge of electric and magnetic circuit laws is assumed. The attention is focused on the **Faraday’s law** and **Biot Savart’s law** in the present study of the electrical machines.

Application of Faraday's law according to electro mechanical energy conversion results in the generation of both transformer and rotational emf to be present in the coil moving under a changing field. This principle is utilized in the induction machines and a.c. commutator machines. The direction of the induced emf is decided next. This can be obtained by the application of the Lenz’s law and the law of interaction.

Law of induction-Generator action



Law For Motoring Action



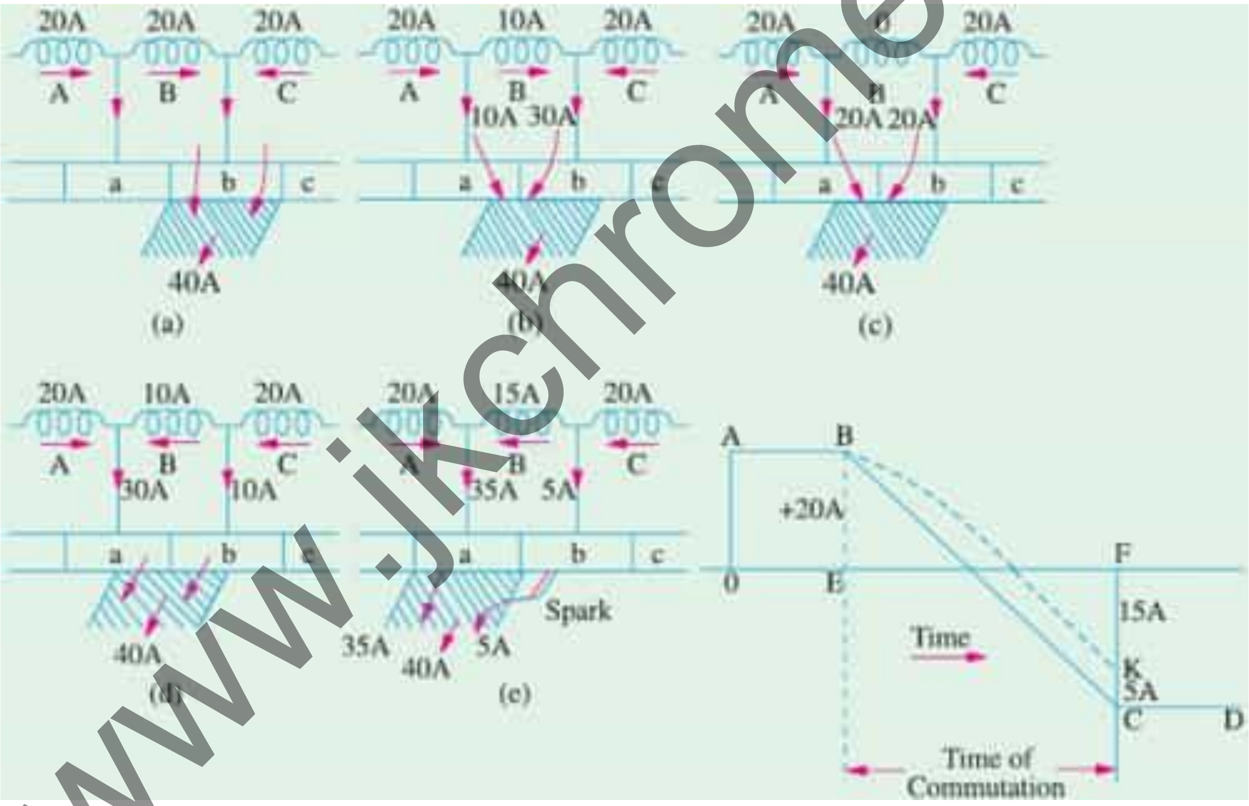
Armature Reaction in DC Motor

The effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. The armature magnetic field has two effects:
(i) It Demagnetizes or weakens the main flux and
(ii) It cross-magnetises or distorts it.

- **Armature reaction** in motors for a given polarity of the field and sense of rotation, the **motoring and generating modes differ only in the direction of the armature current.** Alternatively, for a given sense of armature current, the direction of rotation would be opposite for the two modes. The leading and trailing edges of the poles change positions if direction of rotation is made opposite. Similarly when the brush leads are considered, a forward lead given to a generator gives rise to weakening of the generator field but strengthens the motor field and vice-versa. Hence it is highly desirable, even in the case of non-reversing drives, to keep the brush position at the geometrical neutral axis if the machine goes through both motoring and generating modes.

- The **second effect of the armature reaction** in the case of motors as well as generators is that the induced emf in the coils under the pole tips get increased when a pole tip has higher flux density. This increases the stress on the 'mica' (micanite) insulation used for the commutator, thus resulting in increased chance of breakdown of these insulating sheets. To avoid this effect the flux density distribution under the poles must be prevented from getting distorted and peaky.
- The **third effect** of the **armature reaction mmf distorting the flux density** is that the armature teeth experience a heavy degree of saturation in this region. This increases the iron losses occurring in the armature in that region.The increase in iron loss could be as high as 50 percent more at full load compared to its no-load value.

Commutation



- The currents induced in armature conductors of a d.c. generator are alternating. These currents flow in one direction when armature conductors are under N-pole and in the opposite direction when they are under S-pole.
- As conductors pass out of the influence of a N-pole and enter that of S-pole, the current in them is reversed. This reversal of current takes place

along magnetic neutral axis or brush axis i.e. when the brush spans and hence short circuits that particular coil undergoing reversal of current through it.

- This process by which current in the short-circuited coil is reversed while it crosses the M.N.A. is called commutation. The brief period during which coil remains short-circuited is known as commutation period Tc.
- If the current reversal i.e.the change from **+I** to zero and then to **−I** is completed by the end of short circuit or commutation period, then the commutation is ideal. If current reversal is not complete by that time, then sparking is produced between the brush and the commutator which results in progressive damage to both.
- The brush width is equal to the width of one commutator segment and one mica insulation.

Types of DC Machines:

- The types of DC machine depends upon the excitation of DC machine.
- The production of magnetic flux in the machine by circulating current in the field winding is called excitation.
- DC Machines can be classified according to the electrical connections of the armature winding and the field windings.

There are two methods of excitation namely, separate excitation and self-excitation.

- In separate excitation, the field coils are energised by a separate DC source. The terminals of the winding can be connected across the input voltage terminals or fed from a separate voltage source.
- In self-excitation,the current flowing through the field winding is supplied by the machine itself. The field winding can be connected either in series or in parallel with the armature winding

Speed Control of DC Motors

Speed of a DC motor can be varied by varying flux, armature resistance or applied voltage. Different speed control methods for different DC shunt and series methods are there.

$$E_a = V - I_a R_a$$

Or

$$K\phi\omega_m = V - I_a R_a \Rightarrow \omega_m = \frac{V - I_a R_a}{K\phi}$$

Speed Control of Shunt Motors:

- Flux control method
- Armature and Rheostatic control method
- Voltage control method
    1. Multiple voltage control
    2. Ward Leonard system

Speed Control of Series Motors:

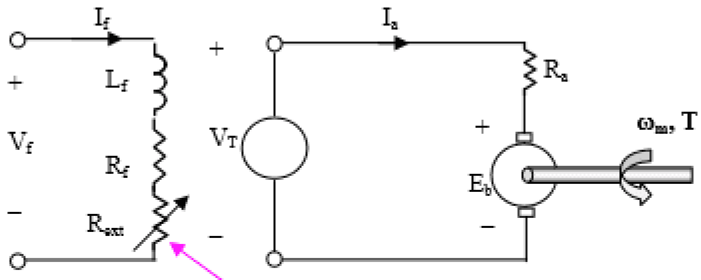
- Flux control method
    1. Field diverter
    2. Armature diverter
    3. Trapped field control
    4. Paralleling field coils
- Variable Resistance in series with motor
- Series -parallel control method

Speed Control Methods

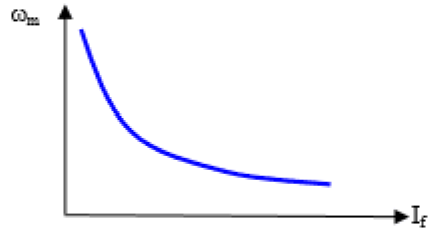
Flux Control Method:

- In this flux control method, speed of the motor is inversely proportional to the flux. Thus, by decreasing flux and speed can be increased vice versa.
- To control the flux, he rheostat is added in series with the field winding will increase the speed (N), because of this flux will decrease.
- The field current is relatively small and hence I^2R loss is decreased. This method is quite efficient.

In this method of speed control, Ra and V_T remain fixed.



Variable resistance for speed control



Therefore, from equation

ω_m α $1/\varphi$

Assuming magnetic linearity, **φ α I_f**

Or,

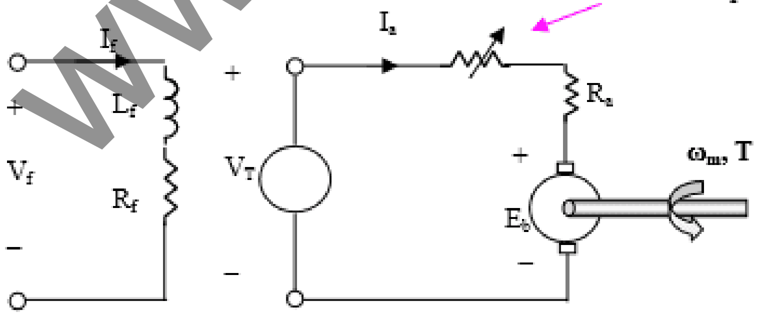
ω_m α $1/I_f$

i.e., Speed can be **controlled by varying field current I_f.**

Armature Control Method:

- In the armature control method, the speed of the DC motor is directly proportional to the back emf (E_b) and $E_b = V - I_aR_a$.
- When supply voltage (V) and armature resistance Ra are kept constant, the Speed is directly proportional to armature current (I_a).
- If we add resistance in series with the armature, the armature current (I_a) decreases and hence speed decreases.

Variable resistance for speed control



From **speed-torque characteristics** equation, we know that

$$T_{dev} = \frac{K\phi}{R_a}(V_T - K\phi\omega_m)$$

For a load of constant torque, if V_T and φ are kept constant, as the armature resistance Ra is increased, speed decreases. As the actual resistance of the armature winding is fixed for a given motor, the overall resistance in the armature circuit can be increased by inserting an additional variable resistance in series with the armature.

Voltage control method:

- ***Multiple voltage control:*** In this method shunt field of motor is connected to a fixed exciting voltage, but the armature is supplied with different voltages by connecting it across one of the several voltages with the help of a switch. The intermediate speeds can be obtained by adjusting the field regulator. This method is very rarely used.
- ***Ward-Leonard system:*** This system is used where very large variation in speed is required. In this method axillary machines along with DC motor whose speed is to be varied. The motor is supplied by a generator which is driven by a motor. Very sensitive and smooth speed control can be obtained by this system. Thus this method can be used in colliery winders, electric excavators, elevators and the main drives in steel mills.

This method is usually applicable to separately excited DC motors. In this method of speed control, R_a and V_t are kept constant.
In normal operation, the drop across the armature resistance is small compared to E_b and therefore: **$E_b \alpha V_t$**

Since, **$E_b = K\Phi\omega$**
ω_m is the Angular speed can be expressed as:

$\omega_m = V_t/K\Phi$

- If flux is kept constant, the speed changes linearly with V_T.
- As the terminal voltage is increased, the speed increases and vice versa.

Types of DC Machines:

- The types of DC machine depends upon the excitation of DC machine.
- The production of magnetic flux in the machine by circulating current in the field winding is called excitation.

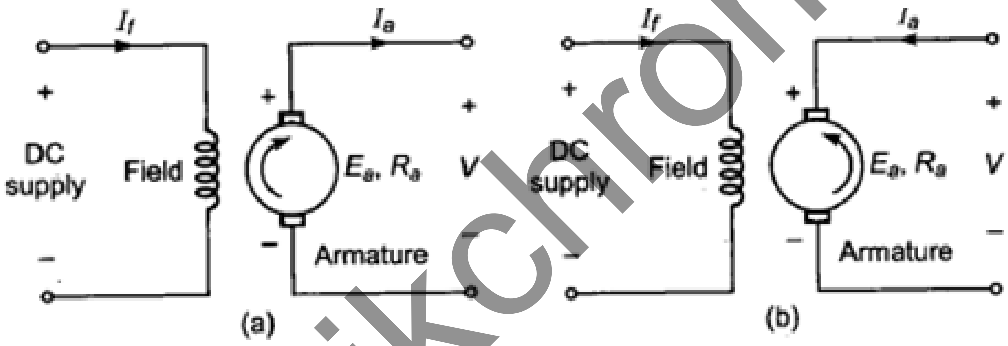
- DC Machines can be classified according to the electrical connections of the armature winding and the field windings.

There are two methods of excitation namely, separate excitation and self-excitation.

- In separate excitation, the field coils are energised by a separate DC source. The terminals of the winding can be connected across the input voltage terminals or fed from a separate voltage source.
- In self-excitation,the current flowing through the field winding is supplied by the machine itself. The field winding can be connected either in series or in parallel with the armature winding

Separately Excited DC Machine

As the name implies, the field coils are energized by a separate DC source. The armature and field winding are electrically separate from each other.



(a) Separately excited DC generator, and (b) Separately excited DC motor

Here, $I_a = I_L$, and R_a = Armature resistance.

- **For Generator**

$E_a = V + I_aR_a$

or $P_a = VI_L + I_a^2R_a$

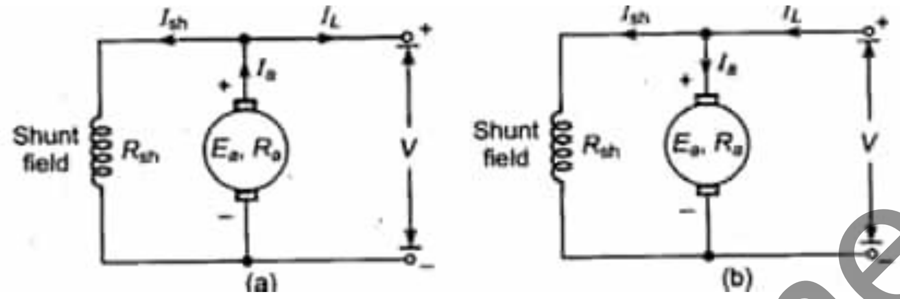
- **For Motor**

$E_a = V - I_aR_a$ or $P_a = VI_L - I_a^2R_a$

Armature power = $P_a = E_aI_a$, Output = VI_L, and Armature copper loss = $I^2_a R_a$

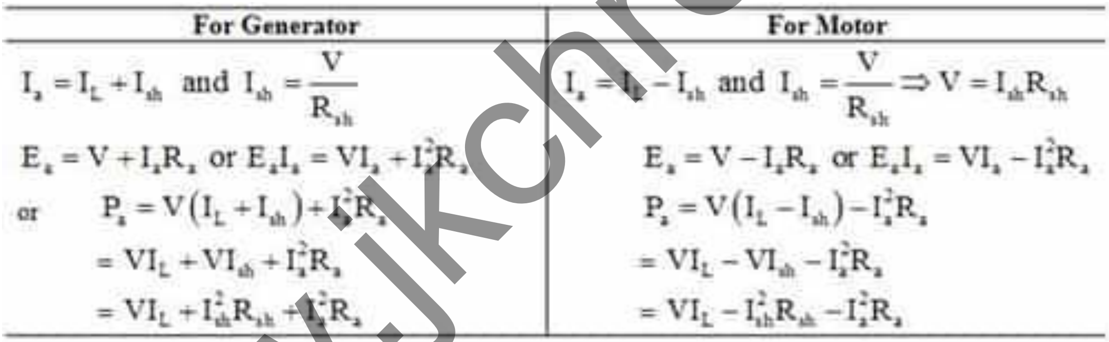
Shunt Wound DC Machine

- The armature and field winding are connected in parallel.
- A machine in which the field coils are connected in parallel with the armature is called a shunt machine.
- The armature voltage and field voltage are the same.



(a) Shunt wound DC generator, and (b) Shunt wound DC motor

Characteristics Equations:



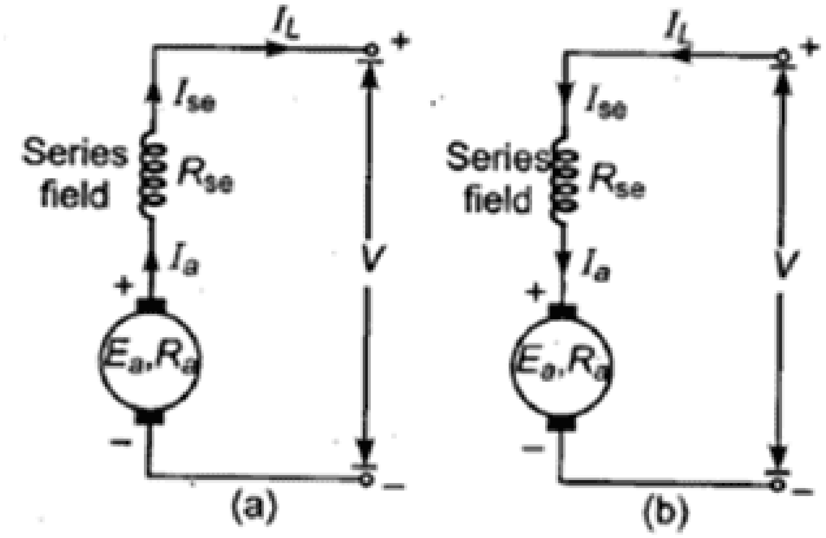
For Generator	For Motor
$I_a = I_L + I_{sh}$ and $I_{sh} = \frac{V}{R_{sh}}$	$I_a = I_L - I_{sh}$ and $I_{sh} = \frac{V}{R_{sh}} \Rightarrow V = I_{sh}R_{sh}$
$E_a = V + I_aR_a$ or $E_aI_a = VI_a + I_a^2R_a$	$E_a = V - I_aR_a$ or $E_aI_a = VI_a - I_a^2R_a$
or $P_a = V(I_L + I_{sh}) + I_a^2R_a$	$P_a = V(I_L - I_{sh}) - I_a^2R_a$
$= VI_L + VI_{sh} + I_a^2R_a$	$= VI_L - VI_{sh} - I_a^2R_a$
$= VI_L + I_{sh}^2R_{sh} + I_a^2R_a$	$= VI_L - I_{sh}^2R_{sh} - I_a^2R_a$

where, $P_a = E_aI_a$ = Armature power (developed power), $I^2_{sh} R_{sh}$= shunt field Cu loss, $I^2_a R_{sh}$ = Armature Cu loss, and VI_L= Power delivered.

Series Wound DC Machine

- A DC machine in which the field coils are connected in series with the armature is called a series machine.

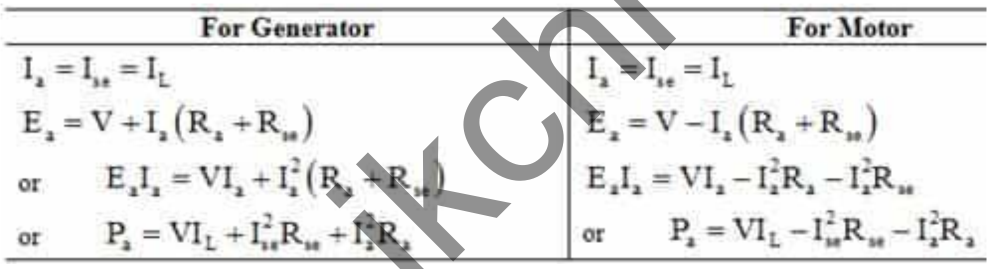
- The field winding carries the same current as the armature winding.



(a) DC series generator (b) DC series motor

- A series wound motor is also called a universal motor. It is universal in the sense that it will run equally well using either an ac or a dc voltage source.

Characteristics Equations:



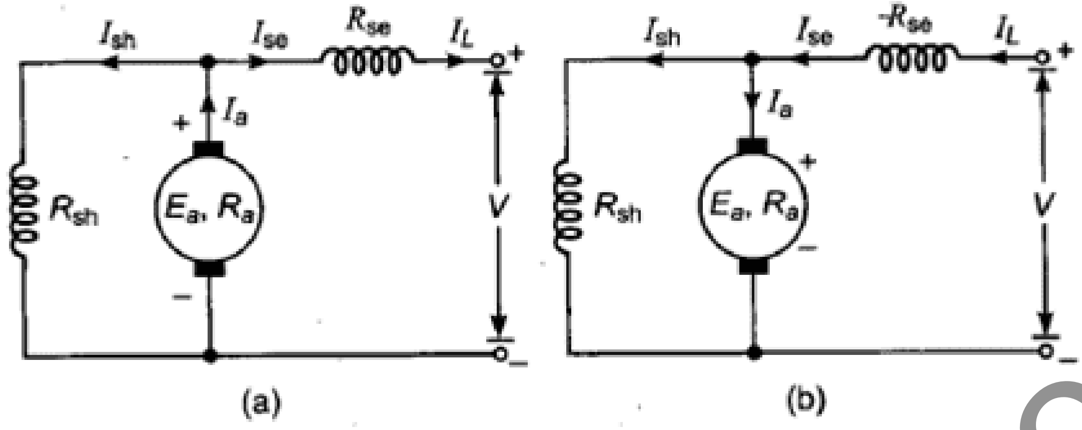
For Generator	For Motor
$I_a = I_{se} = I_L$	$I_a = I_{se} = I_L$
$E_a = V + I_a(R_a + R_{se})$	$E_a = V - I_a(R_a + R_{se})$
or $E_a I_a = VI_a + I_a^2(R_a + R_{se})$	$E_a I_a = VI_a - I_a^2 R_a - I_a^2 R_{se}$
or $P_a = VI_L + I_{se}^2 R_{se} + I_a^2 R_a$	or $P_a = VI_L - I_{se}^2 R_{se} - I_a^2 R_a$

where, $P_a = E_a I_a$ = Armature power (developed power), VI_L = Power delivered, and $I^2_{se} R_{se}$= Series field Cu loss.

Compound Wound DC Machine

- A DC machine, having both shunt and series fields is called a compound machine.
- In a compound machine, the series field winding is connected in series with the armature, and the shunt field winding is connected in parallel.

Short-shunt compound DC Machine:



(a) (b)

Here, Figure (a) is Short-shunt compound DC generator, and (b) is Short-shunt compound DC motor.

- **For generator**

$$I_a = I_{sh} + I_{se} = I_{sh} + I_L$$

$$E_a = V + I_{se}R_{se} + I_aR_a$$

$$E_aI_a = VI_a + I_aI_{se}R_{se} + I_a^2R_a$$

$$= V\left(I_{sh} + I_L\right) + \left(I_{se} + I_{sh}\right)I_{se}R_{se} + I_a^2R_a$$

$$= VI_L + VI_{sh} + I_{se}^2R_{se} + I_{sh}I_{se}R_{se} + I_a^2R_a$$

$$= VI_L + I_{sh}\left(V + I_{se}R_{se}\right) + I_{se}^2R_{se} + I_a^2R_a$$

$$P_a = VI_L + I_{sh}^2R_{sh} + I_{se}^2R_{se} + I_a^2R_a$$

- **For motor**

$$I_a = I_L - I_{sh} \text{ and } I_{se} = I_L$$

$$P_a = VI_L - I_{sh}^2 R_{sh} - I_{se}^2 R_{se} - I_a^2 R_a$$

Similarly in motor,

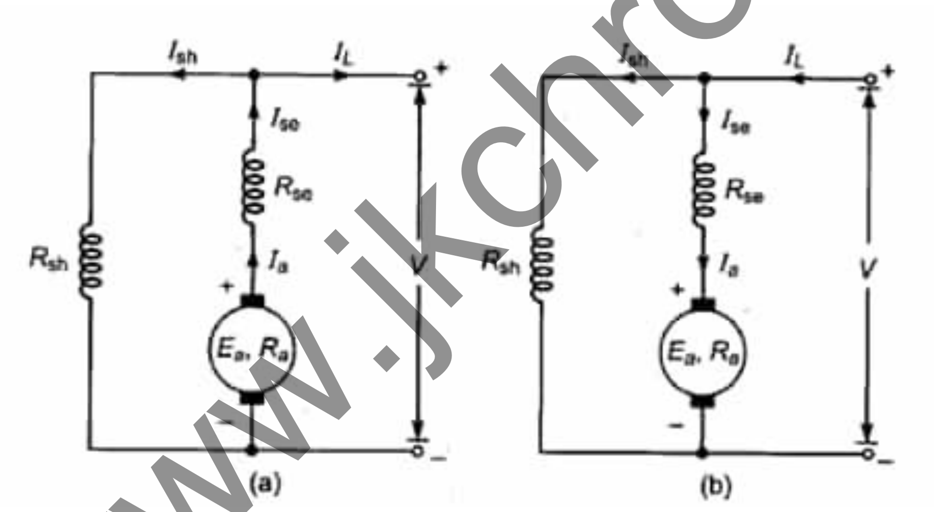
where, P_a = Power developed, VI_L = Power delivered, $I^2_{se} R_{se}$= Series field Cu loss, and $I^2_{sh} R_{sh}$= Shunt field Cu loss.

Two types of arrangements are possible in compound motors:

- Cumulative compounding : If the magnetic fluxes produced by both series and shunt field windings are in the same direction (i.e., additive), the machine is called cumulative compound.
- Differential compounding : If the two fluxes are in opposition, the machine is differential compound.

In both these types, the connection can be either short shunt or long shunt.

Long-shunt compound DC Machine:



(a) Long-shunt DC generator (b) Long-shunt DC motor

- **For generator**

$$I_a = I_{se} = I_L + I_{sh}$$

$$E_a = V + I_a(R_a + R_{se}) \text{ or } E_a I_a = VI_a + I_a^2(R_a + R_{se})$$

$$= V\left(I_L + I_{sh}\right) + I_a^2 R_a + I_a^2 R_{se}$$

or

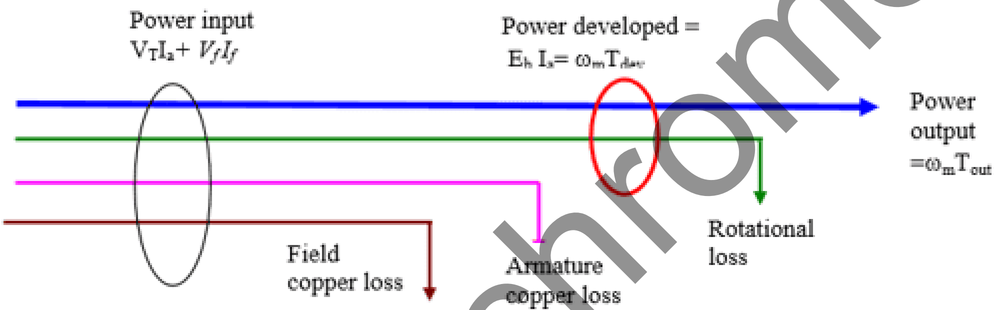
- **Similarly, in motor**

$$P_a = VI_L - I_{sh}^2 R_{sh} - I_{se}^2 R_{se} - I_a^2 R_a$$

where, P_a = Developed power, and VI_L = Delivered power.

Power Flow In DC Machines

Here the case given to understand is for DC Motor



Single & Three Phase Induction Motors

In this article, you will find the study notes on **Three Phase Induction machine and Single Phase Induction machine.**

3-Phase Induction Machine

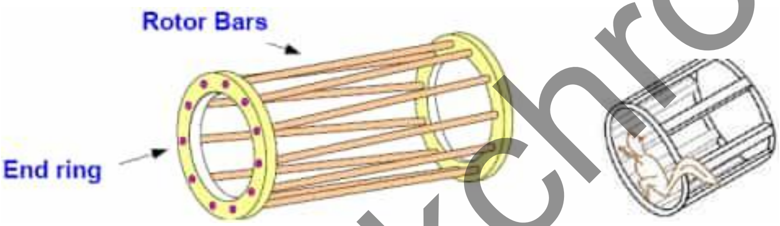
- Basically an **induction motor (IM)** is a type of **asynchronous AC motor** where power is supplied to the rotating device by means of electromagnetic induction.
- Technological development in the field has improved to where a 100 hp (74.6 kW) motor from 1976 takes the same volume as a 7.5 hp (5.5 kW) motor did in 1897. Currently, the most common induction motor is the cage rotor motor.
- In an induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Induction

motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.
- Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and the ability to control the speed of the motor.
- It is a single excited AC machine. Its stator winding is directly connected to AC source, whereas its rotor winding receives its energy from f stator by means of induction (i.e., transformer action).

Type of rotors Rotor

- Squirrel cage rotor
- Wound rotor

Squirrel-Cage Rotor
In the squirrel-cage rotor, the rotor winding consists of single copper or aluminium bars placed in the slots and short-circuited by end-rings on both sides of the rotor. Most of single phase induction motors have Squirrel-Cage rotor. One or 2 fans are attached to the shaft in the sides of rotor to cool the circuit.



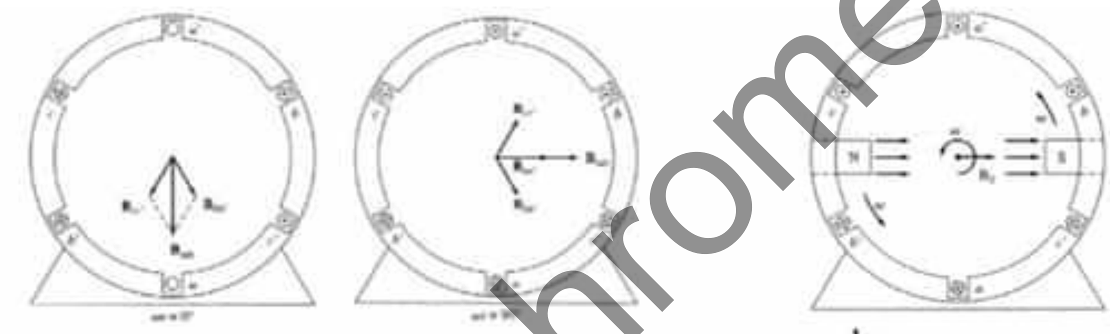
Wound Rotor

- In the wound rotor, an insulated 3-phase winding similar to the stator winding wound for the same number of poles as stator, is placed in the rotor slots. The ends of the star-connected rotor winding are brought to three slip rings on the shaft so that a connection can be made to it for starting or speed control. It is usually for large 3 phase induction motors.

- Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, so it is not so common in industry applications.
- Rotor has a winding the same as stator and the end of each phase is connected to a slip ring.

PRINCIPLE OF OPERATION

An AC current is applied in the stator armature which generates a flux in the stator magnetic circuit.This flux induces an emf in the conducting bars of rotor as they are “cut” by the
flux while the magnet is being moved (**E = BVL (Faraday’s Law)**),A current flows in the rotor circuit due to the induced emf, which in term produces a force, (F = BIL) can be changed to the torque as the output.



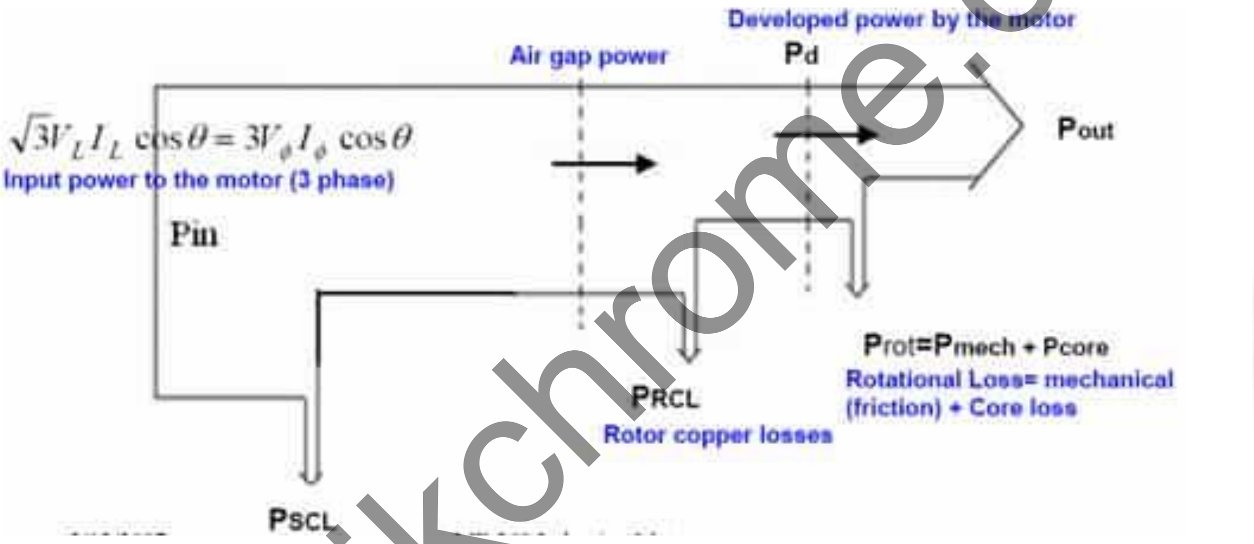
For a two pole machine, $f_e(Hz) = f_m(rps) = \frac{1}{60} n_s(rpm)$

For a p-pole machine, $f_e(Hz) = \frac{p}{2} f_m(rps) = \frac{p}{120} n_s(rpm)$

- In a 3-phase induction motor, the three-phase currents **Ia, Ib and Ic**, each of **equal magnitude**, but differing in **phase by 120°**. Each phase current produces a magnetic flux
and **there is physical 120 °shift between each flux**.
- The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in thee-phase windings is called a rotating magnetic flux or rotating magnetic field (RMF).
- RMF rotates with a constant speed (Synchronous Speed). Existence of a RFM is an essential condition for the operation of an induction motor. If stator is energized by an ac current, RMF is generated due to the applied current to the stator winding.

- This flux produces magnetic field and the field revolves in the air gap between stator and rotor. So, the magnetic field induces a voltage in the short circuited bars of the rotor. This voltage drives current through the bars.
- The interaction of the rotating flux and the rotor current generates a force that drives the motor and a torque is developed consequently. The torque is proportional with the flux density and the rotor bar current (F=BLI).
- The motor speed is less than the synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

POWER FLOW



Per phase induced emf In stator winding, $E_1 = 4.44\ N_l f_1 \varphi k\omega_1$ volt

In rotor winding, $E_2 = 4.44\ N_2 f_2 \varphi k\omega_2$ volt

where and = Winding factors of stator and rotor winding

N_1 = Number of turns in stator winding

N_2 = Number of turns in rotor winding

f_1 and f_2 = Frequencies of supply in stator and rotor windings respectively.

Slip: The difference between the synchronous speed (N_s) and the actual rotor speed (N_r).

$$Slip\ s = \frac{N_s - N_r}{N_s}$$

where, N_s = Synchronous speed

N_r = Rotor speed

Equivalent Circuit of an Induction Motor:

The energy is transferred from primary (stator) winding to secondary (rotor) winding entirely by induction therefore, induction motor is essentially a transformer. At standstill, the induction motor is actually a static transformer having its secondary (rotor) winding short-circuited.

Here, stator emf per phase

$$E_1 = \sqrt{2}\pi f k_{w_1} \phi N_1$$

where, N_1 = Number of stator turns per phase

φ = Flux per pole

= Stator winding factor

Rotor emf at standstill

$$E_2 = \sqrt{2}\pi f k_{w_2} \phi N_2$$

$$\therefore \frac{E_1}{E_2} = \frac{k_{w_1} N_1}{k_{w_2} N_2} \simeq \frac{N_{e_1}}{N_{e_2}} = a$$

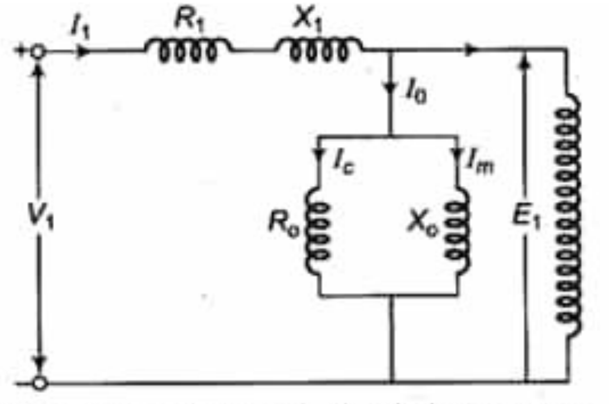
where, N_{e_1} = Effective stator turns per phase =

$k_{w_1} N_1$

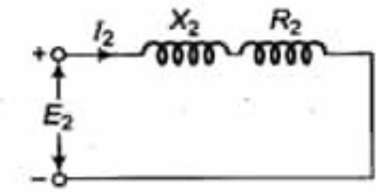
N_{e_2} = Effective rotor turns per phase =

$k_{w_2} N_2$

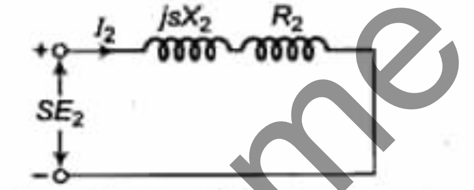
a = Reduction factor



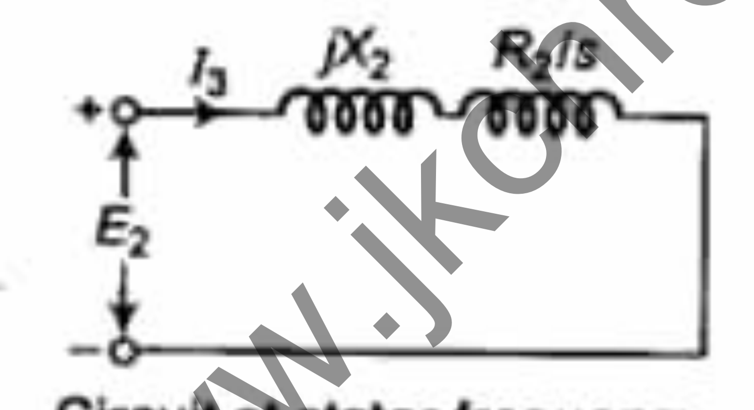
Stator equivalent circuit of an inductor motor



Rotor at standstill



Rotor in motion circuit at rotor frequency

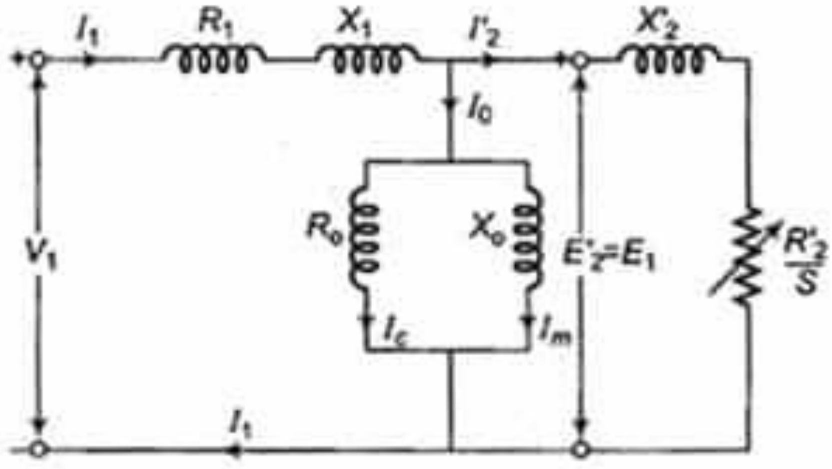


Circuit at stator frequency

$sE_2 = I_2R_2 + jI_2sX_2$

or

$$E_2 = I_2\frac{R_2}{s} + jI_2X_2$$



All parameters are referred to stator side

Rotor equivalent circuit

Rotor Torque: The torque developed by the rotor of an induction motor is directly proportional to (a) rotor current I_2 (b) stator flux per pole φ and (c) power factor of the rotor circuit $\cos \varphi_2$

$\because T \propto \varphi I_2 \cos \varphi_2$

But $E \propto \varphi$

$T \propto E_2 I_2 \cos \varphi_2$

or $T = kE_2 I_2 \cos \varphi_2$ where k is constant.

Rotor Frequency: In rotor the frequency of current and voltage must be same as the supply frequency

$f_r = sf$

where, f = Supply frequency.

STARTING OF 3-PHASE INDUCTION MOTORS

There are two important factors to be considered in starting of induction motors:

- The starting current drawn from the supply, and
- The starting torque.

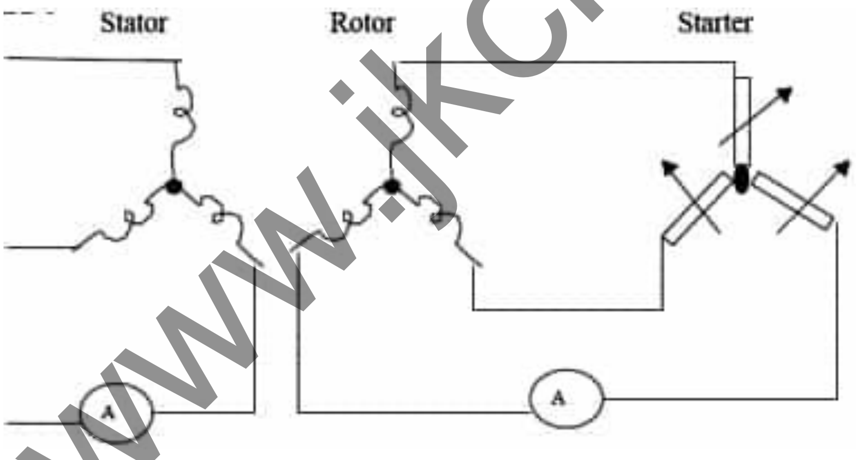
The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

- At synchronous speed, s = 0, and therefore, $\mathbf{R_2/s = \infty \Rightarrow so\ I_2' = 0}$. The stator current therefore comprises only the magnetising current i.e. $I1 = I\varphi$ and is quite therefore quite small.
- At low speeds, $\mathbf{R_2'/X + jX_2 = \infty}$ is small, and therefore $\mathbf{I_2'}$ is quite high and consequently $\mathbf{I_1}$ is quite large.
- Actually the typical starting currents for an induction machine are **~ 5 to 8** times the normal running current.

Hence the starting currents should be reduced. The most usual methods of starting 3-phase induction motors are:

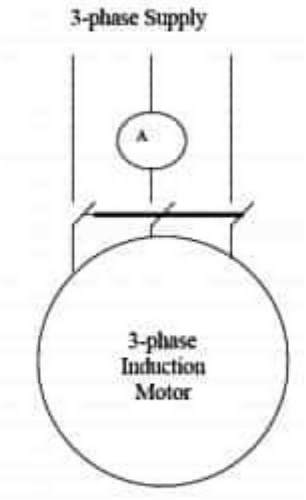
- **Rotor resistance starting For slip-ring motors**
- **For squirrel-cage motors**
  (i) Direct-on -line starting
  (ii) Star-delta starting
  (iii) Autotransformer starting.

Rotor Resistance Starting



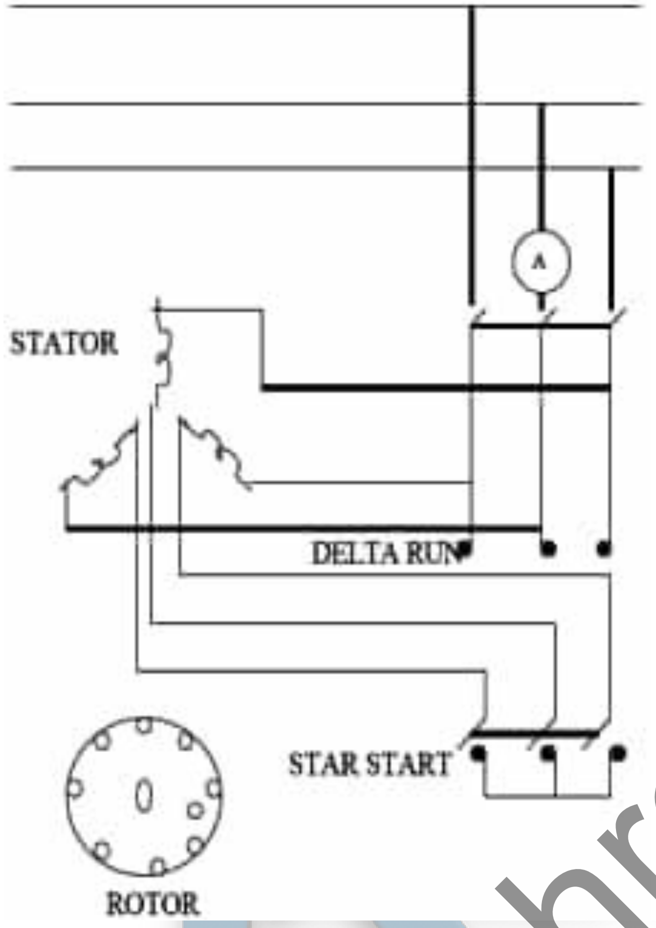
- By adding eternal resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period.
- The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.

Direct-On-Line Starting



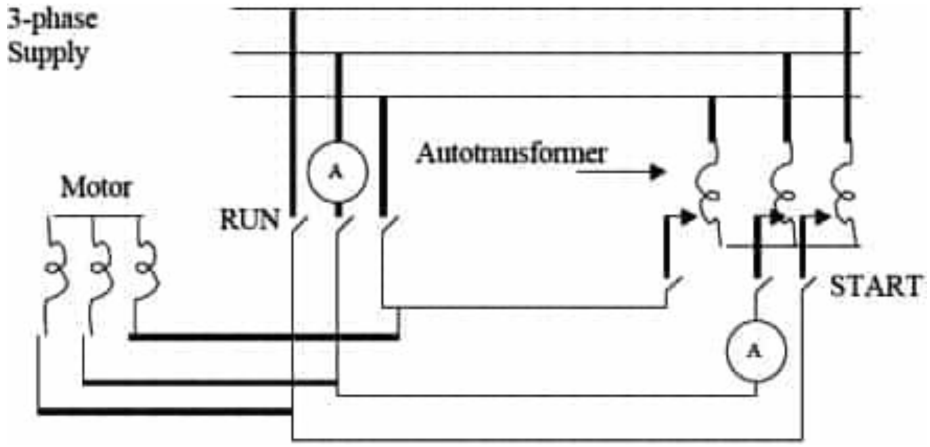
- This is the most simple and inexpensive method of starting a squirrel cage induction motor. The motor is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque.
- To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors only.
- To decrease the starting current cage motors of medium and larger sizes are started at a reduced supply voltage.

Star-Delta starting



- This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change -over switch.
- For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation.
- The phase voltages & the phase currents of the motor in star connection are reduced to **1/√3** of the direct -on -line values in delta. The line current is **1/3** of the value in delta.
- A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to **1/3 of its delta value**.

Auto-Transformer Starting



- This method also reduces the initial voltage applied to the motor and therefore the starting current and torque.The motor,which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped auto -transformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position.
- The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjusted to the required value, by taking the correct tapping on the autotransformer. This method is more expensive because of the additional autotransformer.

Starting Torque: The torque developed the motor at the instant of starting is called starting torque.

$$T_{st} = kE_2 = \frac{E_2}{\sqrt{R^2 + X_2^2}}\frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$T_{st} = k\frac{E_2^2 R_2}{R^2 + X_2^2}$$ or

$$T_{st} = \frac{3}{2\pi N_s}\frac{E_2^2 R_2}{\left(R^2 + X_2^2\right)} N - m$$

where,

$$k = \frac{3}{2\pi N_s}$$

N_s = Synchronous speed in RPS

E_2 = Rotor emf per phase at standstill

R_2 = Rotor resistance per phase

X_2 = Rotor reactance per phase at standstill

- Condition for maximum starting torque

$R_2 = X_2$

- Starting torque, $T_{st} \propto$ (supply voltage)^2

$T_{st} \propto V^2$

Torque Under Running Conditions

$$T = \frac{KsE_2^2R_2}{R_2^2 + (sX_2)^2} = \frac{3}{2\pi N_s}\frac{sE_2^2R_2}{R_2^2 + (sX_2)^2} N-m$$

Key Points

- Condition for maximum torque under running conditions **$R_2 = sX_2$**
- Slip corresponding to maximum torque **$s = R_2/X_2$**
- Maximum torque

$$T_{\max} = \frac{3}{2\pi N_s}\frac{E_2^2}{2X_2} N-m$$

Full Load Torque and Maximum Torque

$$\frac{T_f}{T_{\max}} = \frac{2as_f}{a^2 + s_f^2}$$

Where

$$a = \frac{R_2}{X_2} = \left(\frac{\text{Resistance}}{\text{Standstill reactance}}\right)\text{per phase}$$

S_f = Slip corresponding to full load torque

Note In general,

$$\frac{Operating\ torque\ at\ slip(s)}{Maximum\ torque} = \frac{2as}{a^2 + s^2}$$

Starting Torque and Maximum Torque

$$\frac{T_{st}}{T_{\max}} = \frac{2a}{1 + a^2}$$

where

$a = \left(\frac{R_2}{X_2}\right)$ per phase

Rotor Torque and Breakdown Torque: The rotor torque at any slip s can be expressed in .terms of the maximum torque

$$T = T_b \left[\frac{2}{(s_b / s) + (s / s_b)}\right]$$

where, T_b = Maximum (or breakdown) torque

s_b = Breakdown or pull out slip

No Load Test:

Power input = P_0

No load current = I_0 (average of 3 ammeter reading)

Voltage = V_0 (line to line voltage)

$$P_0 = \sqrt{3} V_0 I_0 \cos\phi_0$$

$\mathbf{I_m = I_0 \sin \varphi_0}$

$\mathbf{I_c = I_0 \cos \varphi_0}$

$R_o = V_o/I_o$ & $X_o = V_o/I_m$

and

Rotation loss

$$P_R = 3\left(P_0 - I_0^2 R_1\right)$$

Note: This test gives rotational losses and X_0

Blocked Rotor Test: The shaft of the motor is clamped so that it cannot move and rotor winding is short-circuited.

V_{BR} = Stator voltage (line to line) required to circulate I_{BR} when rotor is blocked.

I_{BR} = Stator current (average of three ammeter reading)

P_{BR} = Total copper loss on full load at standstill

Blocked rotor impedance

$$Z_{BR} = \frac{V_{BR}/\sqrt{3}}{I_{BR}}$$

Blocked rotor resistance

$$R_{BR} = \frac{P_{BR}/3}{I_{BR}^2}$$

Blocked rotor reactance

$$X_{BR} = \sqrt{\left(Z_{BR}^2 - R_{BR}^2\right)}$$

Note:

- $$\frac{\text{Starting line current with star delta starting}}{\text{Starting line current with direct switching in delta}} = \frac{1}{3}$$

- $$\frac{\text{Starting torque with star delta starting}}{\text{Starting torque with direct switching in delta}} = \frac{1}{3}$$

Speed Control of Induction Motors: The rotor speed of an induction motor is given by

$N_r = (1 - s)N_s$ and $N_s = 120f/P$

also $N_s = \frac{120f}{P}(1-s)$

∴

Speed Control by Frequency Changing: The synchronous speed of an induction motor is given by

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

The synchronous speed and therefore, the speed of the motor can be controlled by varying the supply frequency. The emf induced it the stator of the induction motor is given by

$$E_1 = 4.44 k_{w_1} f \phi T_1$$

Speed Control by Pole Changing: The number of stator poles can be changed by (a) multiple stator windings, (b) method of consequent poles and (c) Pulse-Amplitude Modulation (PAM).

- Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the
  synchronous speed of the induction machine is given by **$n_s = f.s/p$** (in rev./s).

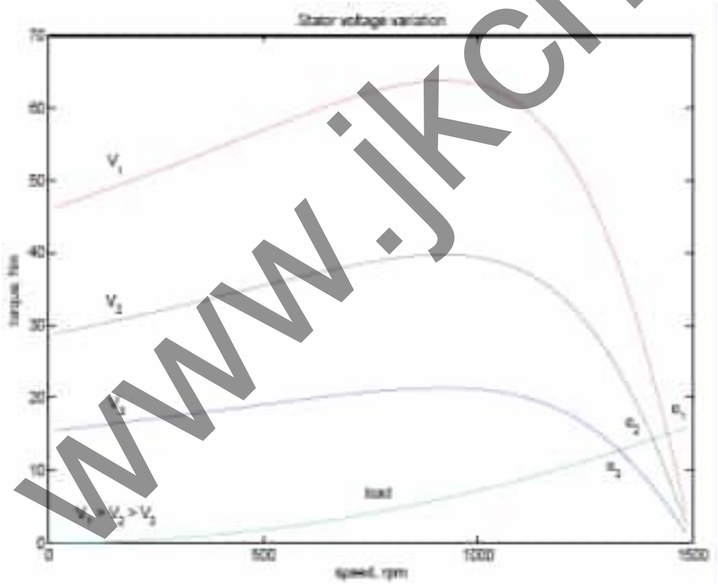
where p is the number of pole pairs, this would correspond to changing the synchronous speed.With the slip now corresponding to the new synchronous speed, the operating speed is changed.

- This method of speed control is a stepped variation and generally restricted to two steps. If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections.
- If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called
  constant-horsepower type.

Speed Control by Slip Changing: There are three ways of controlling slip. (i) Voltage control, (ii) Rotor-resistance control, (iii) Secondary foreign voltage control, and (iv) Speed control by cascade arrangement.

Voltage control

From the torque equation of the induction machine, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in figure below. These curves show that the slip at maximum torque remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

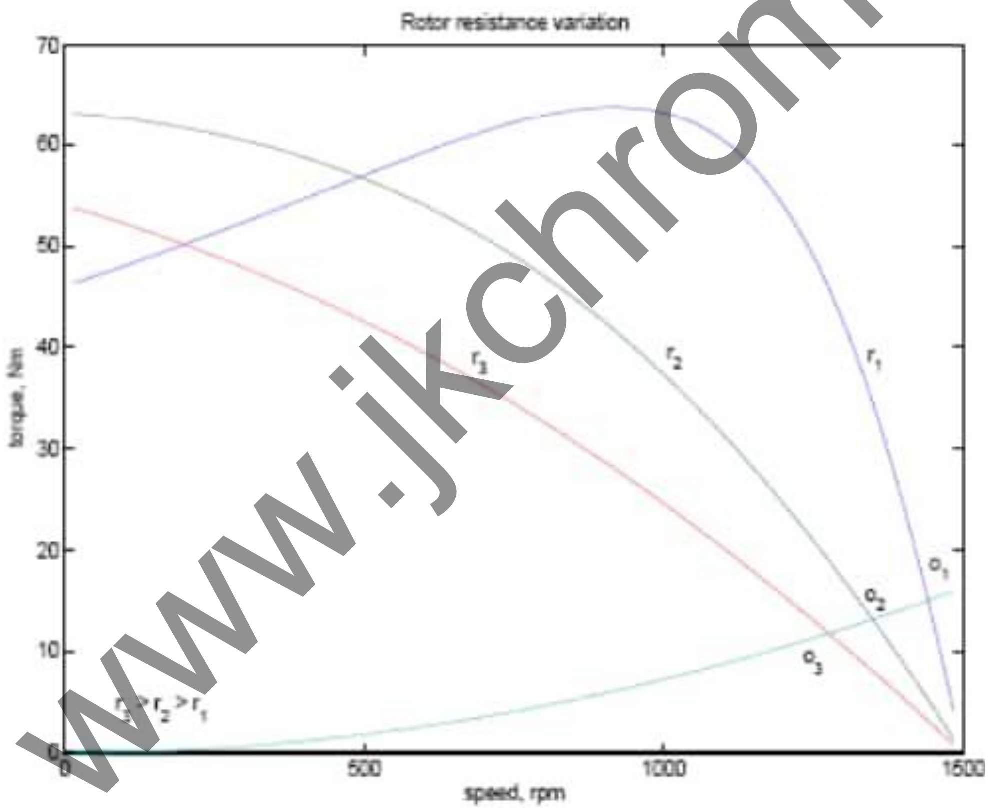


- Further, we also note that the starting torque is also lower at lower voltages. Thus,even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

In this article, you will find the study notes on **Electric Drives** which will cover the topics such as **Electric drives Principle , Electric drives D.C Machines ,4-Quadrant D.C Motor,Application of Electric Drives,Advantage of Electric drives.**

Rotor Resistance Control

From the expression for the torque of the induction machine, torque is dependent on the rotor resistance. The maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Figure below shows a family of torque-speed characteristic obtained by changing the rotor resistance.



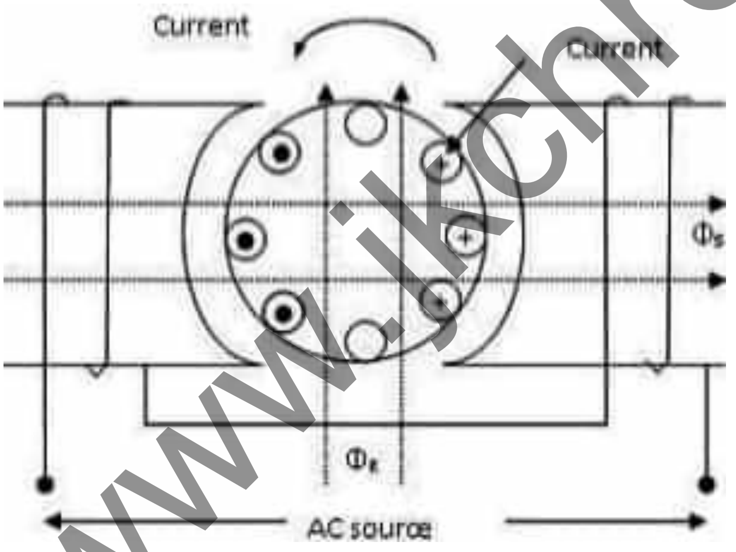
- The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A ‘solid-state’ alternative to a rheostat is a chopper controlled resistance where the duty ratio control of of the chopper presents a variable resistance load to the rotor of the induction machine.

Principle of Operation of Single Phase Induction Motor

A single-phase induction motor is not self starting but requires some starting means.The single-phase stator winding produces a magnetic field that pulsates in strength in a sinusoidal manner. The field polarity reverses after each half cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel-cage rotor. However, if the rotor of a single-phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation. As a matter of fact, the rotor quickly accelerates until it reaches a speed slightly below the synchronous speed. Once the motor is running at this speed, it will continue to rotate even though single-phase current is flowing through the stator winding. This method of starting is generally not convenient for large motors.

The single-phase induction motor operation can be described by two methods

Cross-Field Theory

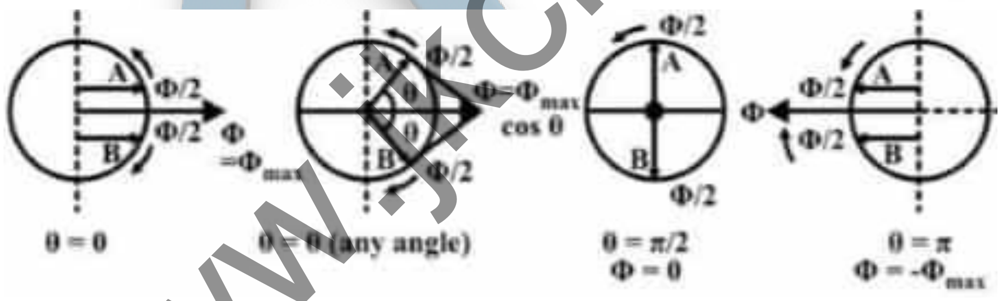


- The principle of operation of a single-phase induction motor can be explained from the **cross-field theory**. As soon as the rotor begins to turn, a speed emf E is induced in the rotor conductors, as they cut the stator flux $\mathbf{F_S}$.
- This voltage increases as the rotor speed increases. It causes current $\mathbf{I_r}$ to flow in the rotor bars facing the stator poles.

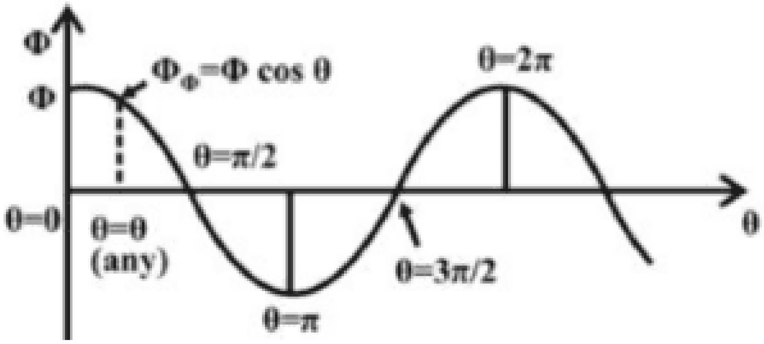
- These currents produce an ac flux **F_R** which act at right angle to the stator flux Fs. Equally important is the fact that **F_R** does not reach its maximum value at the same time as **F_S** does, in effect, **F_R** lags almost **90º** behind **F_S**, owing to the inductance of the rotor The combined action of **F_S** and **F_R** produces a revolving magnetic field, similar to that in a three-phase motor.
- The value of **F_R** increases with increasing speed, becoming almost equal to **F_S** at synchronous speed. The flux rotates counterclockwise in the same direction as the rotor and it rotates at synchronous speed irrespective of the actual speed of the rotor. As the motor approaches synchronous speed, **F_R** becomes almost equal to **F_S** and a nearly perfect revolving field is produces.

Double-Field Revolving Theory

- When the stator winding carries a sinusoidal current which is being fed from a single-phase supply, a sinusoidal space distributed mmf, whose peak or maximum value pulsates (alternates) with time, is produced in the air gap.
- The sinusoidal varying flux (**φ**) is the sum of two rotating fluxes or fields, the magnitude of which is equal to half the value of the alternating flux (**φ/2**), and both the fluxes rotating synchronously at the speed, in opposite directions.



- The above figure show the resultant sum of the two rotating fluxes or fields, as the time axis (angle) is changing from **θ=(0°-180°)**.



The above figure shows the alternating or pulsating flux (resultant) varying with time or angle.

Types of Single-Phase Motors

Single-phase motors are generally built in the fractional-horsepower range and may be classified into the following four basic types:

- **Single-phase induction motors**
  (i) split-phase type (ii) capacitor start type (iii) capacitor start capacitor run type (iv) shaded-pole type
- **A.C. series motor or universal motor**
- **Repulsion motors**
  (i) Repulsion-start induction-run motor (ii) Repulsion-induction motor
- **Single Phase Synchronous motors/Reluctance Motor**

Single-Phase Induction Motors

These motors are most commonly used in domestic, commercial and industrial applications such as in fans, refrigerators, mixers, vacuum cleaners, washing machines etc. These are small size motors of fractional kilowatt ratings. These motors are simpler in construction as compared to 3-phase but their analysis is more complex.

Equivalent Circuit of a Single-Phase Induction Motor

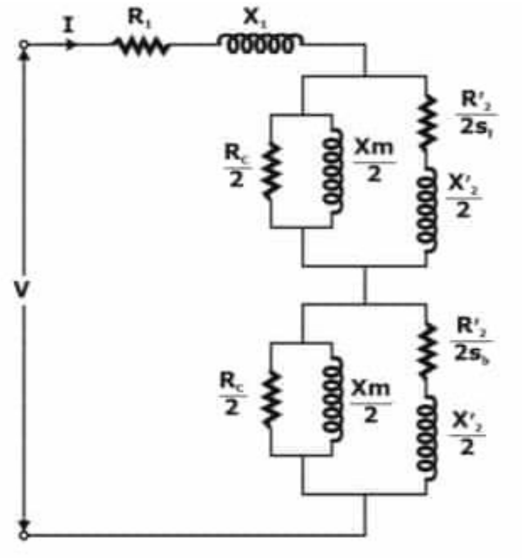
Let R_l = Resistance of the main stator winding

X_l = Leakage reactance of the main stator winding

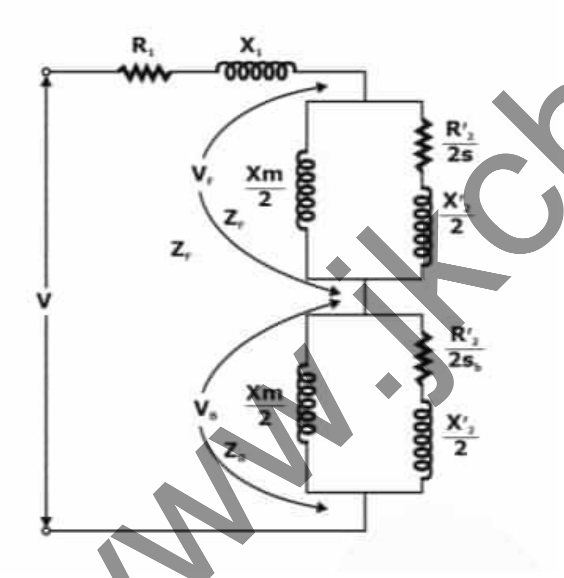
X_m = Magnetizing reactance

R_2 = Standstill rotor resistance referred to the main stator winding

X_2 = standstill rotor leakage reactance referred to the main stator winding



The simplified equivalent circuit of a single-phase induction motor with only its main winding energized is shown in figure.



The current in the stator winding is:

$$I_m = \frac{V_m}{Z_{1m} + Z_f + Z_b}$$

Speed Torque Characteristic of Single Phase Induction Motor

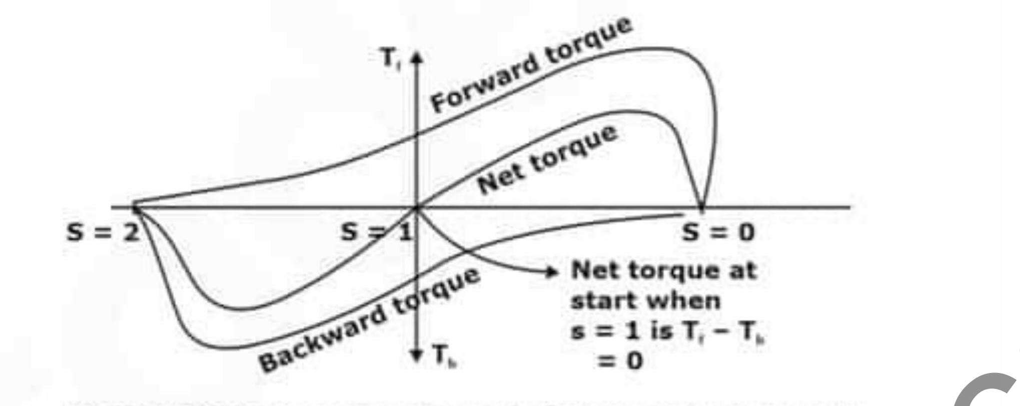


Figure: Torque Vs slip characteristics of 1 phase IM

Here we can assume that the rotor is started by spinning the rotor or by using auxiliary circuit, in say clockwise direction. The flux rotating in the clockwise direction is the forward rotating flux (φ_f) and that in the other direction is the backward rotating flux (φ_b).

- **The rotor rotates opposite to the rotation of the backward flux. If its slip with respect to forward field is s, what is the slip with respect to the backward field therefore, the slip w.r.t. the backward flux will be**

Forward slip $s_f = \frac{N_s - N}{N_s} = s$ Backward slip $s_b = \frac{N_s - (N) + N_s - N_s}{N_s} = 2 - s$

Making Single-Phase Induction Motor Self-Starting

- Since we have already know that the single-phase induction motor is not self starting and it is undesirable to resort to mechanical spinning of the shaft or pulling a belt to start it.
- To make a single-phase induction motor self-starting, we should somehow produce a revolving stator magnetic field. This may be achieved by converting a single-phase supply into twophase supply through the use of an additional winding.
- When the motor attains sufficient speed, the starting means (i.e., additional winding) may be removed depending upon the type of the motor.

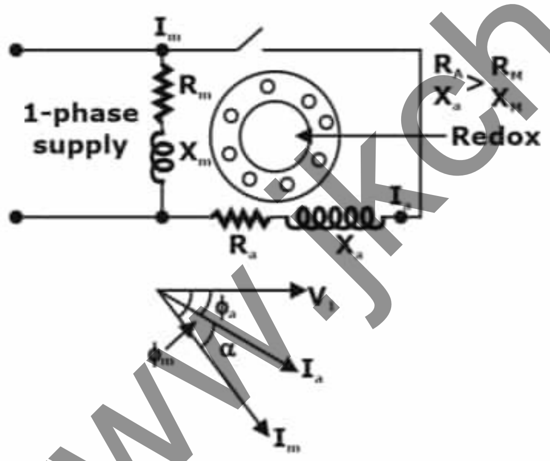
Making Single-Phase Induction Motor Self-Starting

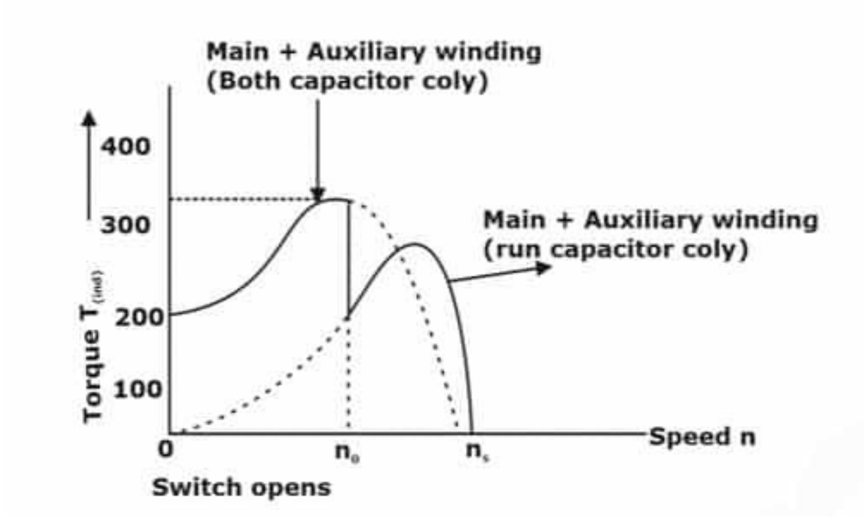
- Since we have already know that the single-phase induction motor is not self-starting and it is undesirable to resort to the mechanical spinning of the shaft or pulling a belt to start it.
- To make a single-phase induction motor self-starting, we should somehow produce a revolving stator magnetic field. This may be achieved by converting a single-phase supply into two-phase supply through the use of an additional winding.
- When the motor attains sufficient speed, the starting means (i.e., additional winding) may be removed depending upon the type of the motor.

So as a matter of fact, single-phase induction motors are classified and named according to the method employed to make them self-starting.

- Split-phase type
- Capacitor start type
- Capacitor start capacitor run type
- Shaded-pole type

(i) Split-Phase Type





The stator of a split-phase induction motor is provided with an auxiliary or **starting winding S** in addition to the **main or running winding M**.

- The starting winding is located **90°** electrical from the main winding and operates only during the brief period when the motor starts up.
- The two windings are so resigned that the starting winding S has a high resistance and relatively small reactance while the main winding M has relatively low resistance and large reactance to be as inductance (the current delay with voltage) to make shifting current as shown in Figure.
- Consequently, the currents flowing in the two windings have a reasonable phase difference (**25° to 30°**) as shown in the pharos diagram this shifting in current its necessary for starting torque.

Operation

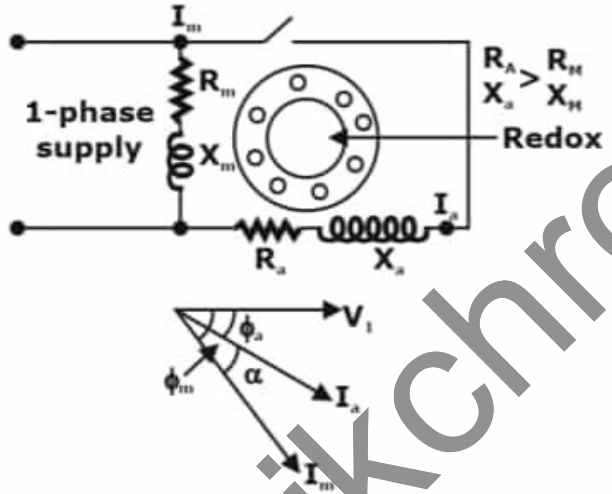
- When the two stator windings are energized from a single-phase supply, the main winding carries current Im while the starting winding carries current Is.
- Since main winding is made highly inductive while the starting winding highly resistive, the currents Im and Is have a reasonable phase angle a (25° to 30°) between them.
- Consequently, a weak revolving field approximating to that of a 2-phase machine is produced which starts the motor.
- When the motor reaches about 80% of synchronous speed, the centrifugal switch opens the circuit of the starting winding.
- The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed. The normal speed of the

motor is below the synchronous speed and depends upon the load on the motor.

(ii) Capacitor Start Motor

The capacitor-start motor is identical to a split-phase motor except that the starting winding has as many turns as the main winding. The picture of capacitor start induction motor is shown in figure below,

Moreover, a capacitor **C** (**3-20 μF)** is connected in series with the starting winding as shown in Figure. The value of the capacitor is so chosen that **I_S** leads **I_m** by about **80°** which is considerably **greater than 25°** found **in the split-phase motor**.



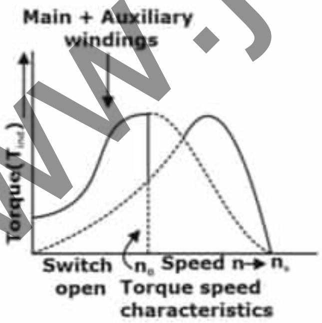


Figure: Torque vs speed characteristics

Operation

- When the two stator windings are energized from a single-phase supply, the main winding carries current **I_m** while the starting winding carries current **I_S**.
- Due to capacitance, the currents Im and Is have a reasonable phase angle an (**80°**) between them.
- When starting torque is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about **80% of synchronous speed**.
- The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.
- Capacitor-start motors are used where high starting torque is required and where the starting period may be long e.g., to drive:

(i) compressors **(ii)** large fans **(iii)** pumps **(iv)** high inertia loads The power rating of such motors lies between **120 W and 7-5 kW.**

(iii) Capacitor Start-Capacitor Run Motor

- This motor is identical to a capacitor-start motor except that starting winding is not opened after starting so that both the windings remain connected to the supply when running as well as at starting.
- **Two designs are generally used**

1. In first it shows a picture of capacitor start capacitor run induction motor. This design eliminates the need for a centrifugal switch and at the same time improves the power factor and efficiency of the motor.
2. In the other design, two capacitors **C_1** and **C_2** are used in the starting winding. The value of the capacitor is so chosen that Is leads I_m by about **80°**.

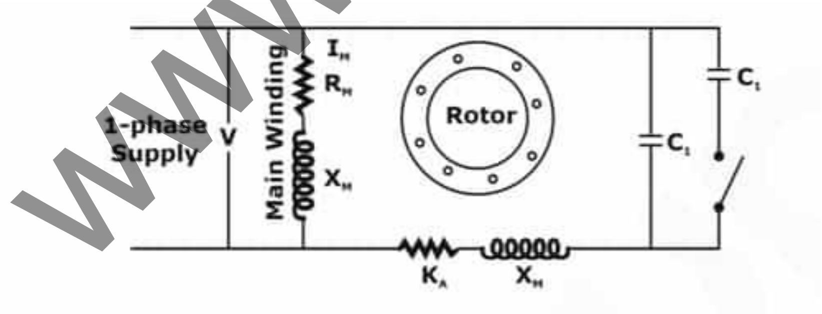
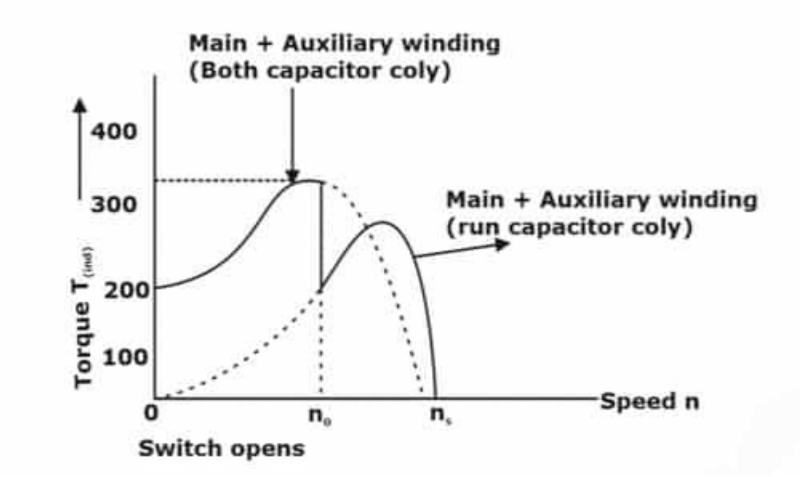


Figure: Circuit diagram of Two value capacitor motor



- The smaller capacitor C_1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C_2 is connected in parallel with C_1 for optimum starting and remains in the circuit during starting.
- The starting capacitor C_2 is disconnected when the motor approaches about 80% of synchronous speed. The motor then runs as a two-phase induction motor.

Operation

- When the two stator windings are energized from a single-phase supply, the main winding carries current Im while the starting winding carries current Is.
- Due to capacitance C1 the currents Im and Is have a reasonable phase angle an (80°) between them.
- When The starting capacitor C2 is disconnected when the motor approaches about 80% of synchronous speed. The motor then runs as a two-phase induction motor.

Characteristics

- The starting winding and the capacitor can be designed for perfect 2-phase operation at any load. The motor then produces a constant torque and not a pulsating torque as in other single-phase motors.
- **Because of constant torque, the motor is vibration free** and can be used in: (a) hospitals (b) studios and (c) other places where silence is important.

(iv) Shaded-Pole Motor

The shaded-pole motor is very popular for ratings below 0.05 H.P. (~40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel cage rotor as shown in Figure.

A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.

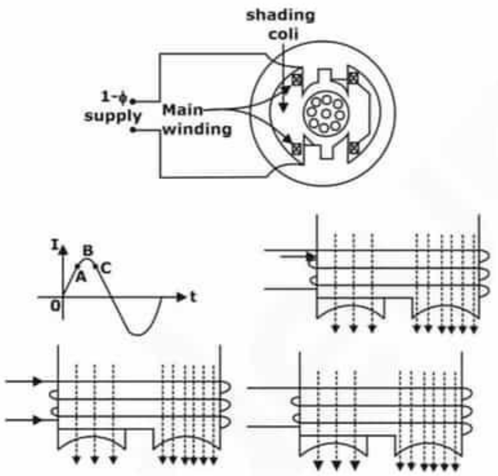


Figure: (i)-(v) Working of Shaded pole motor

The reversal of the direction of rotation, where desired, can be achieved by providing two shading coils, one on each end of every pole, and by open-circuiting one set of shading coils and by short-circuiting the other set.

- The above is true due to the fact that the shaded-pole motor is single-winding (no auxiliary winding) self-starting one, makes it less costly and results in rugged construction.
- The motor has low efficiency and is usually available in a range of 1/300 to 1/20 kW. It is used for domestic fans, record players and tape recorders, humidifiers, slide projectors, small business machines, etc.
- The shaded-pole principle is used in starting electric clocks and other single-phase synchronous timing motors.

Synchronous Machines

In this article, you will find the study notes on **Synchronous Machines.**

Synchronous Machines

- Synchronous machines are one of two types: the stationary field or the rotating dc magnetic field. The stationary field synchronous machine has salient poles mounted on the stator—the stationary member. The poles are magnetized either by permanent magnets or by a dc current.
- The armature, normally containing a three-phase winding, is mounted on the shaft. The armature winding is fed through three slip rings (collectors) and a set of brushes sliding on them. This arrangement can be found in machines up to about 5 kVA in rating.
- For larger machines—all those covered in this book—the typical arrangement used is the rotating magnetic field. The rotating magnetic field (also known as revolving-field) synchronous machine has the field-winding wound on the rotating member (the rotor), and the armature wound on the stationary member (the stator).
- A dc current, creating a magnetic field that must be rotated at synchronous speed, energizes the rotating field-winding. The rotating field winding can be energized through a set of slip rings and brushes (external excitation), or from a diode-bridge mounted on the rotor (self-excited).
- A synchronous generator is an electrical machine producing alternating emf (Electromotive force or voltage) of constant frequency.
- The synchronous motor operates at a precise synchronous speed, and hence is a constant-speed motor. Unlike the induction motor, whose operation always involves a lagging power factor, the synchronous motor possesses a variable-power-factor characteristic and hence is suitable for power-factor correction applications.
- A synchronous motor operating without mechanical load is called a compensator. It behaves as a variable capacitor when the field is overexcited, and as a variable inductor when the field is under-excited. It is often used in critical positions in a power system for reactive power control.

Types of Synchronous Machines: *According to the arrangement of the field and armature windings, synchronous machines may be classified as:*

- Rotating-armature type
- Rotating-field type

Rotating-Armature Type:

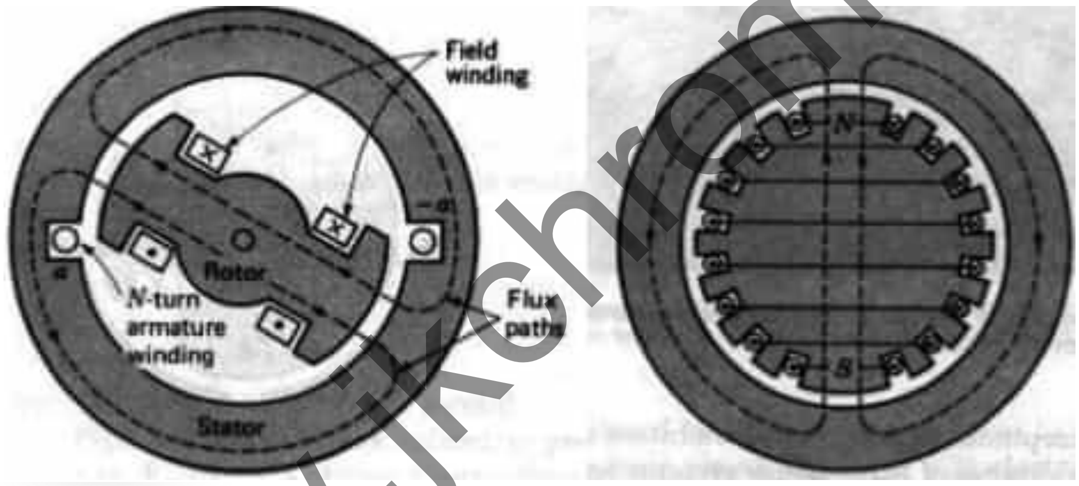
- The armature winding is on the rotor and the field system is on the stator.
- The generated current is brought out to the load via three (or four) slip-rings.

- Insulation problems, and the difficulty involved in transmitting large currents via the brushes, limit the maximum power output and the generated electromagnetic field (emf).
- This type is only used in small units, and its main application is as the main exciter in large alternators with brushless excitation systems.

Rotating Field Type

- The armature winding is on the stator and the field system is on the rotor.
- Field current is supplied from the exciter via two slip-rings, while the armature current is directly supplied to the load.
- This type is employed universally since very high power can be delivered.
- Unless otherwise stated, the subsequent discussion refers specifically to rotating-field type synchronous machines.

According to the shape of the field, synchronous machines may be classified as:



- Cylindrical-rotor (non-salient pole) machines and
- Salient-pole machines

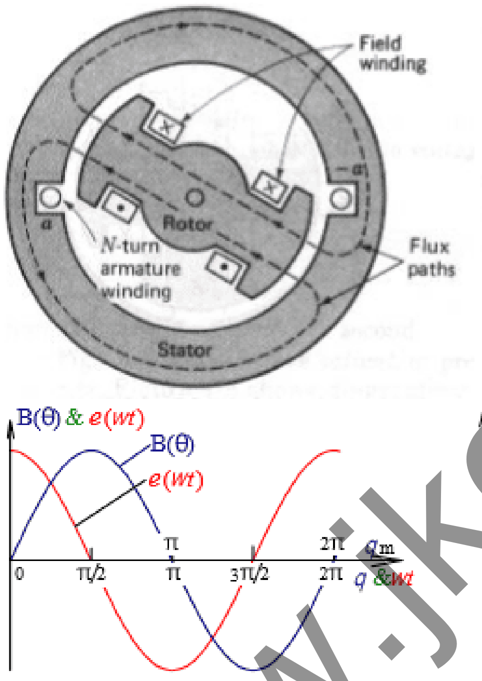
Cylindrical Rotor Machines

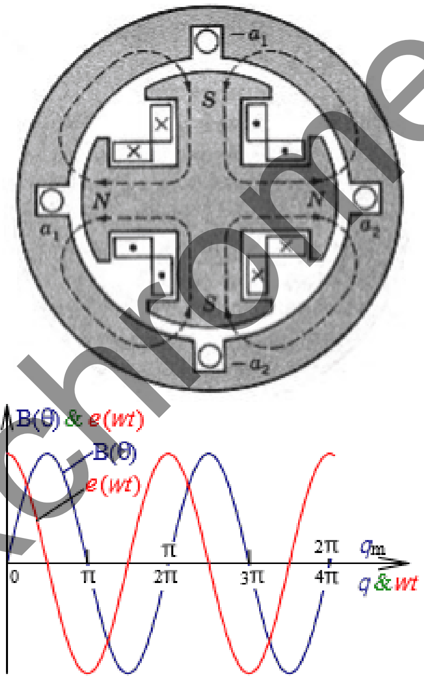
- The cylindrical-rotor construction is used in generators that operate at high speeds, such as steam-turbine generators (usually two-pole machines).
- This type of machine usually has a small diameter-to-length ratio, in order to avoid excessive mechanical stress on the rotor due to the large centrifugal forces.

Salient-pole machines

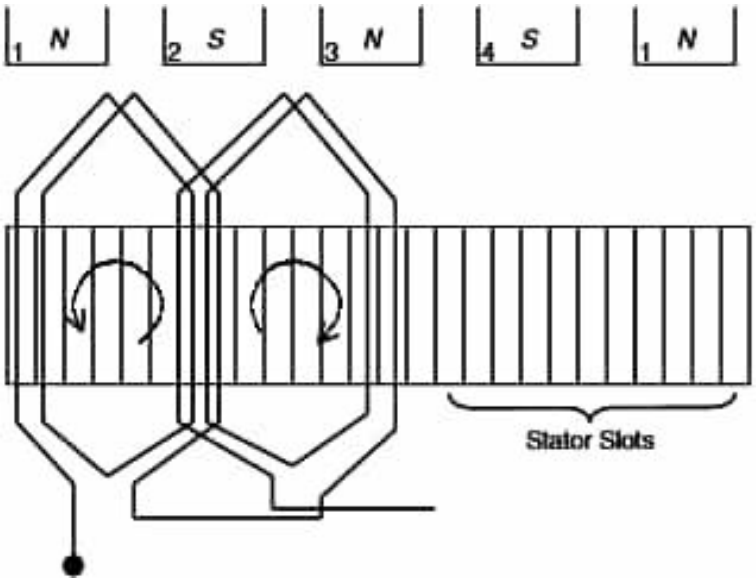
- The salient-pole construction is used in low-speed alternating current (AC) generators (such as hydro-turbine generators), and also in synchronous motors.
- This type of machine usually has a large number of poles for low-speed operation, and a large diameter-to-length ratio.
- The field coils are wound on the bodies of projecting poles.
- A damper winding (which is a partial squirrel-cage winding) is usually fitted in slots at the pole surface for synchronous motor starting and for improving the stability of the machine.

Flux Density Distribution in the air gap & the induced EMF in the Phase winding of Two pole & Four pole Machine

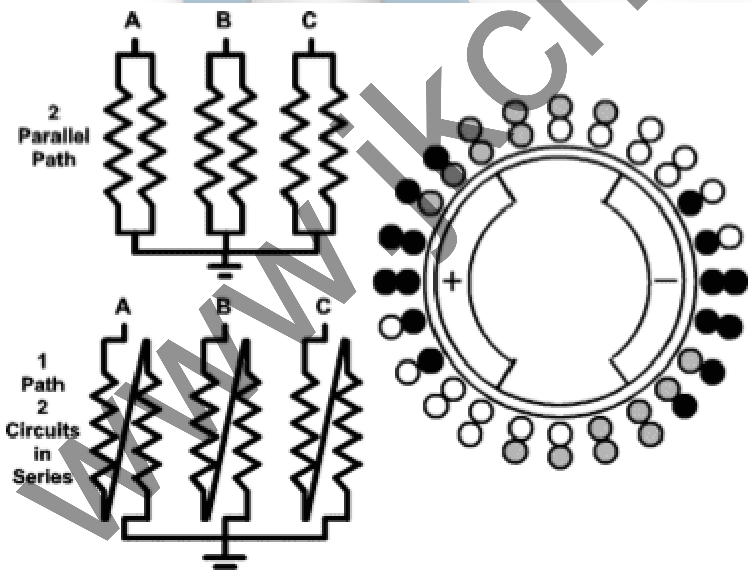




BASIC OPERATION OF THE SYNCHRONOUS MACHINE



- In the above pictorial representation “Developed” view of a four-pole stator, showing the slots, the poles, and a section of the winding. The section shown is of one of the three phases. It can be readily seen that the winding runs clockwise under a north pole, and counterclockwise under a south pole. This pattern repeats itself until the winding covers the four poles. A similar pattern is followed by the other two phases, but located at 120 electrical degrees apart.



Schematic view of a two-pole generator with two possible winding configurations

- Two parallel circuits winding
- A two series connected circuits per phase.

- On the right, the three phases are indicated by different tones.
- Here we can see that some slots only have coils belonging to the same phase, while in others, coils belonging to two phases share the slot.

No-Load Operation

When the ideal machine is connected to an infinite bus, a three-phase balanced voltage **(V_1)** is applied to the stator winding (within the context of this work, three-phase systems and machines are assumed).

As described above, it can be shown that a three-phase balanced voltage applied to a three-phase winding evenly distributed around the core of an armature will produce a rotating (revolving) magneto-motive force **(MMF)** of constant magnitude **(Fs)**. This MMF, acting upon the reluctance encountered along its path, results in the magnetic flux **(φ_s)** previously introduced.

The speed at which this field revolves around the center of the machine is related to the supply frequency and the number of poles is **N_S** called as **Synchronous Speed** by the following expression

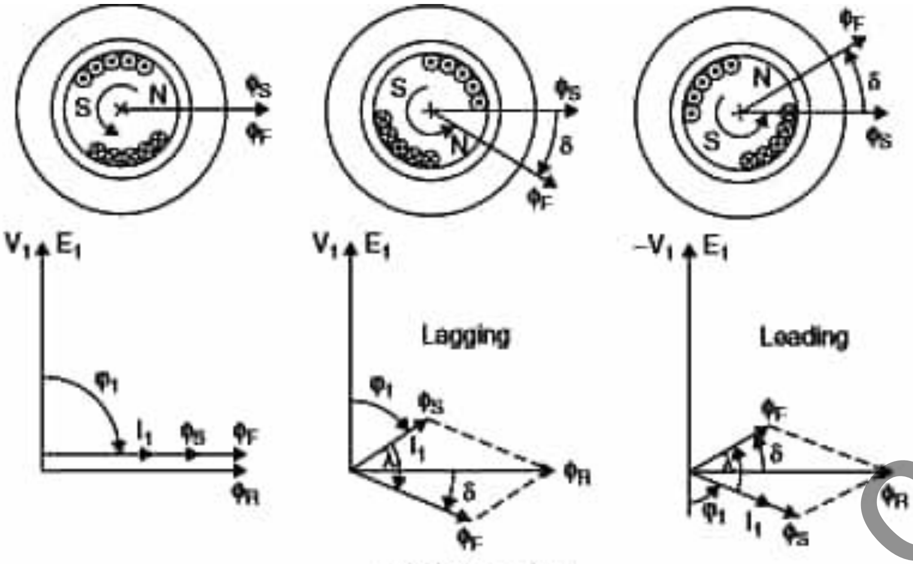
N_s = 120/P

f = electrical frequency in Hz

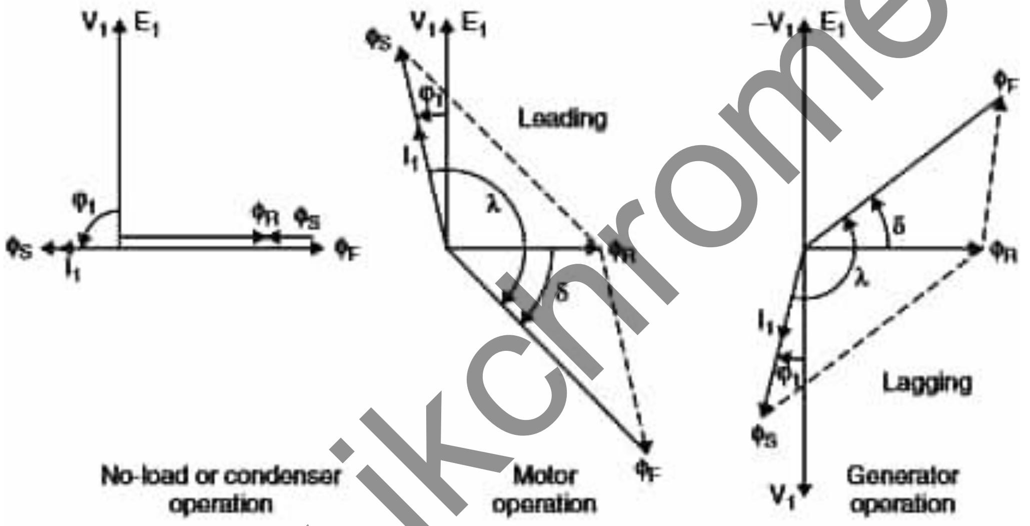
P = number of poles of the machine

Ns = speed of the revolving field in revolutions per minute (rpm)

Phasor Diagrams of Cylindrical-Rotor Ideal Machine



(a) Underexcited



(b) Overexcited

- If no current is supplied to the dc field winding, no torque is generated, and the resultant flux (φ_r), which in this case equals the stator flux (φ_s), magnetizes the core to the extent the applied voltage (V_1) is exactly opposed by a counter electromotive force (C_{emf}) (E_1).
- If the rotor's excitation is slightly increased, and no torque is applied to the shaft, the rotor provides some of the excitation required to produce (E_1), causing an equivalent reduction of (φ_s). This situation represents the under-excited condition shown in condition no load (a) in above figure.

Motor Operation

However, this section presents an introductory discussion of the synchronous machine, and thus the motor mode of operation is also covered. If a braking torque is applied to the shaft, the rotor starts falling behind the revolving-armature-induced magnetomotive force (MMF) ($\mathbf{F_s}$). In order to maintain the required magnetizing MMF ($\mathbf{F_r}$) the armature current changes. If the machine is in the under-excited mode, the condition motor in the Figure (a) represents the new phasor diagram.

On the other hand, if the machine is overexcited, the new phasor diagram is represented by Motor in Figure (b). The active power consumed from the network under these conditions is given by

Active power=$V_1 \times I_1 \times \cos\phi_1$ (per phase)

- If the braking torque is increased, a limit is reached in which the rotor cannot keep up with the revolving field. The machine then stalls. This is known as “falling out of step,” “pulling out of step,” or “slipping poles.” The maximum torque limit is reached when the angle δ equals π/2 electrical.
- The convention is to define δ as negative for motor operation and positive for generator operation. The torque is also a function of the magnitude of φr and φf. When overexcited, the value of φf is larger than in the under-excited condition.
- Therefore synchronous motors are capable of greater mechanical output when overexcited. Likewise, the under-excited operation is more prone to result in an “out-of-step” situation.

Generator Operation

- Let’s assume that the machine is running at no load and a positive torque is applied to the shaft; that is, the rotor flux angle is advanced ahead of the stator flux angle. As in the case of motor operation, the stator currents will change to create the new conditions of equilibrium.
- If the machine is initially underexcited, condition (a) in Figure.
- On the other hand, if the machine is overexcited, condition (b) in Figure.
- It is important to note that when “seen” from the terminals, with the machine operating in the underexcited mode, the power factor angle (ϕ_1) is leading (i.e., I_1 leads V_1).This means the machine is absorbing reactive power from the system. The opposite occurs when the machine is in the overexcited mode.
- As for the motor operation, an overexcited condition in the generating mode also allows for greater power deliveries. As generators are normally

called to provide VARs together with watts, they are almost always operated in the overexcited condition.

A 3-φ synchronous machine is double excited AC machine. Its field winding is excited by a DC source and its armature winding is excited by AC source.

Synchronous speed:

$$N_s = \frac{120f}{p} \text{rpm}$$

where f = Supply frequency, and p = Number of poles

Apparent power and Power factor

Two factors limiting the power of electric machines are

- Mechanical torque on its shaft (usually, the shaft can handle much more torque)
- Heating of the machine's winding.

The practical steady-state limits is set by heating in the windings. The maximum acceptable armature current sets the apparent power rating for a generator

$$S = 3V_\phi I_A$$

If the rated voltage is known, the maximum accepted armature current determines the apparent power rating of the generator

$$S = 3V_{\phi,rated} I_{A,\max} = \sqrt{3} V_{L,rated} I_{L,\max}$$

The power factor of the armature current is irrelevant for heating the armature windings.

Synchronous Machine Ratings

The purpose of ratings is to protect the machine from damage. Typical ratings of synchronous machines are voltage, speed, apparent power (kVA), power factor, field current and service factor.

- **Voltage, Speed, and Frequency:** The rated frequency of a synchronous machine depends on the power system to which it is connected. The commonly used frequencies are 50 Hz (Europe, Asia), 60 Hz (Americas), and 400 Hz (special applications: aircraft, spacecraft, etc.). Once the operation frequency is determined, only one rotational speed in possible for the given number of poles.

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

The change in frequency would change the speed. Since **E_a= Kφω**, the maximum allowed armature voltage changes when the frequency changes. Specifically, if a 60 Hz generator will be operating at 50 Hz, its operating voltage must be derated to **50/60 or 83.3 %**.

Synchronous Machine Temperature Rating

The maximum temperature rise that a machine can stand depends on the insulation class of its windings. The four standard insulation classes with they temperature ratings are:

- A – 60^{o}C above the ambient temperature
- B – 80^{o}C above the ambient temperature
- F – 105^{o}C above the ambient temperature
- H – 125^{o}C above the ambient temperature

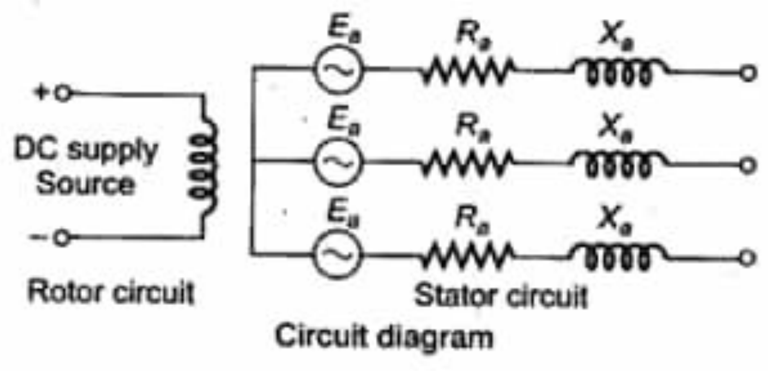
The higher the insulation class of a given machine, the greater the power that can be drawn out of it without overheating its windings.

Note: The overheating is a serious problem and synchronous machines should not be overheated unless absolutely necessary. However, power requirements of the machine not always known exactly prior its installation. Because of this, general purpose machines usually have their service factor defined as the ratio of the actual maximum power of the machine to the rating on its plate. For instance, a machine with a service factor of 1.15 can actually be operated at 115% of the rated load indefinitely without harm.

Cylindrical Rotor Synchronous Generator

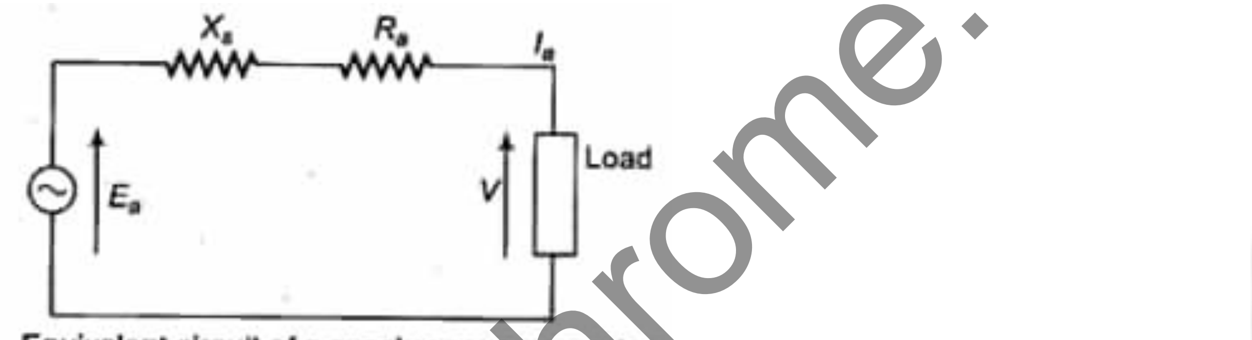
The alternator is operating on no load i.e., the rotor is rotating and energized and the stator is open-circuited.

- Its circuit diagram is shown in below.



Circuit diagram

- An equivalent circuit of a synchronous generator shown in below.



Equivalent circuit of a synchronous generator

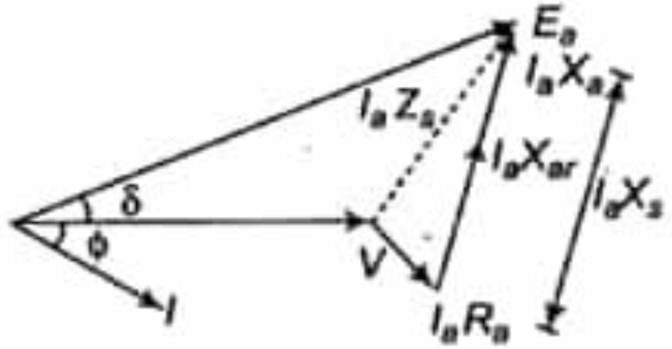
- Let X_s = Synchronous reactance, X_{ar} = Fictitious reactance, X_a = Armature reactance, R_a = Armature resistance, and Z_s = Synchronous impedance.

$X_s = X_{ar} + X_a$

$Z_s = R_a + j X_s$

$E_a = V + I_a Z_s$

Phasor Diagram

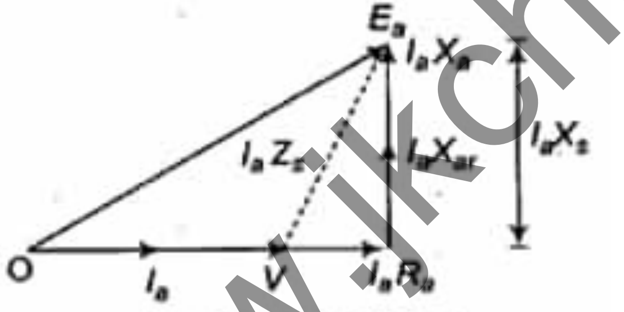


At lagging power factor

- The phasor diagram for inductive, purely resistive and capacitive loads are shown in the figure below. All these phasor diagrams apply to one phase of a 3-φ machine.
- At lagging, power factor:

$$E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$$

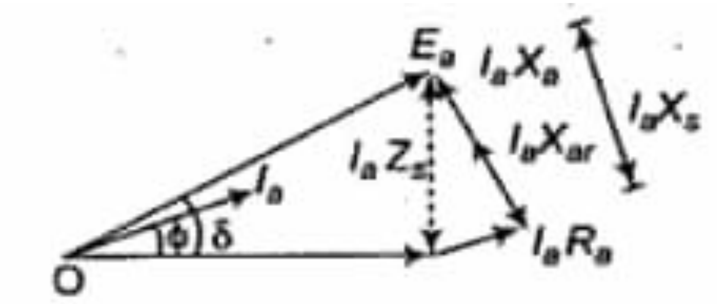
- At unity, power factor:



At unity power factor

$$E_a = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$$

- At leading, power factor:



At leading power factor

$$E_a = \sqrt{\left(V\cos\phi + I_aR_a\right)^2 + \left(V\sin\phi - I_aX_s\right)^2}$$

Power Relationship

- Mechanical power input to the generator $P_{mechanical} = T_s\omega_s$
- DC power input to a wound rotor P_{in} electrical$= I_f$
- Total power input: $P_{in} = T_s\omega_s + I_f$
- Real power output:

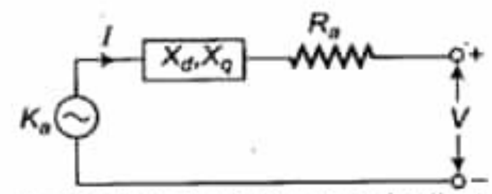
$$P_{out} = \frac{VE_f}{X_s}\sin\delta$$

- Reactive power output:

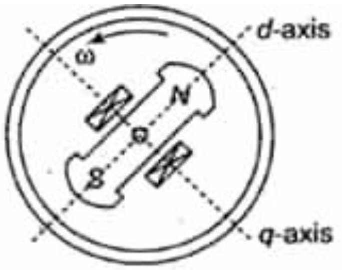
$$Q_{out} = \frac{VE_f}{X_s}\cos\delta - \frac{V^2}{X_s}$$

where, V = Terminal voltage per phase, and E_f = Excitation voltage per phase = Phase angle between E_f and V, and X_s = Synchronous reactance

Salient Pole Synchronous Machine



Equivalent circuit diagram of salient pole synchronous machine



Axes view of synchronous machine

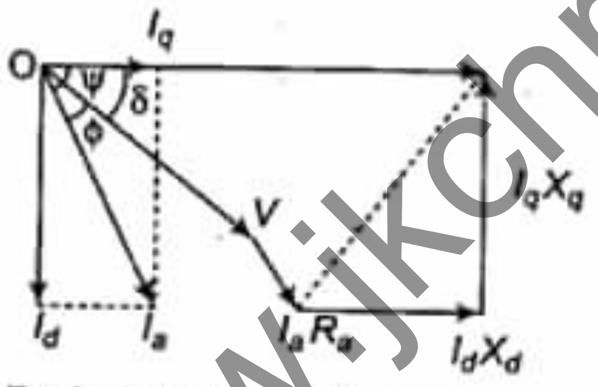
The component currents I_d and I_q provide component voltage drops $jI_d X_d$ and $jI_d X_q$ as shown in the figure.

$E_a = V + I_aR_a + jI_dX_d + jI_qX_q$

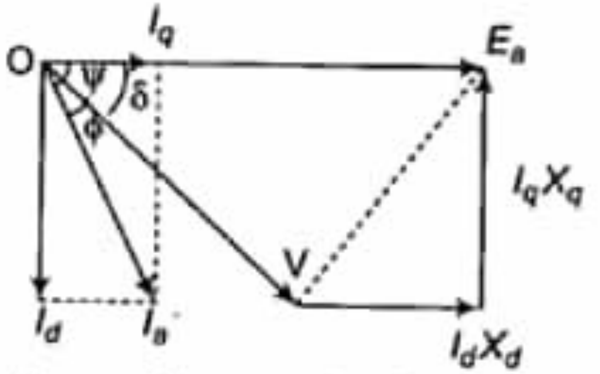
$I = I_d + I_q$

If R_a is neglected, $E_a = V + jI_dX_d + jI_qX_d$

- **Phasor Diagram**



Equivalent phasor diagram



Phasor diagram when R_a is neglected

- **For Generating Mode:**

$$\tan\psi = \frac{V\sin\phi + I_aX_q}{V\cos\phi + I_aR_a}$$

- **For Motoring Mode:**

$$= \frac{V\sin\phi - I_aX_q}{V\cos\phi - I_aR_a}$$

Note: δ = ψ − φ (generating mode), and δ = φ − ψ (motoring mode)

- **Power Angle**

$$\tan\delta = \frac{I_aX_q\cos\phi}{V \pm I_aX_q\sin\phi}$$

Use + for synchronous generator, and - for synchronous motor (here R_a is neglected)

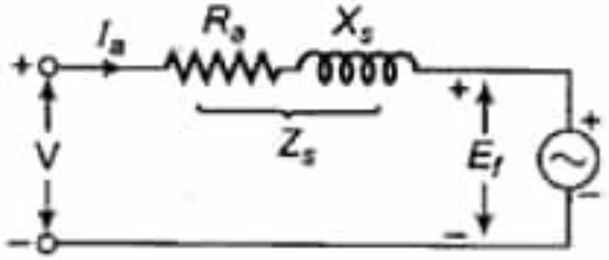
- **Output Power**

$P_0 = 3V(I_d \sin \delta + I_d \cos \delta)$

- **Total Power Developed**

$$P_d = \frac{3E_f V}{X_d}\sin\delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

Cylindrical Rotor Synchronous Motor

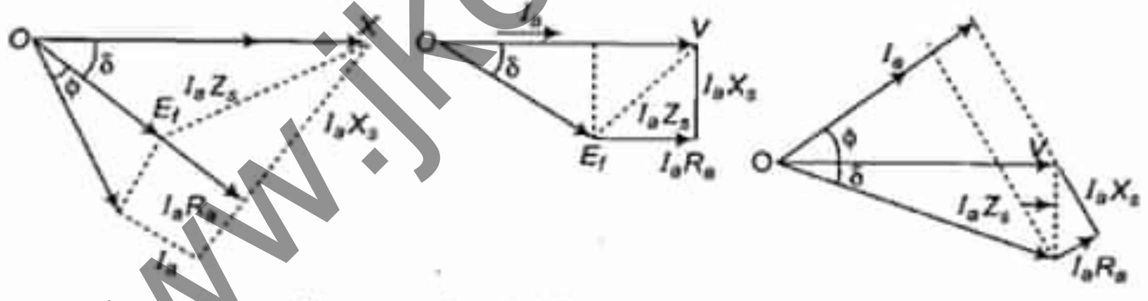


Equivalent circuit of cylindrical rotor synchronous motor

where, V = Terminal phase voltage applied to the armature, E_f = Excitation voltage, R_a = Effective armature resistance/phase, X_s = Synchronous reactance/phase, Z_s = Impedance/phase.

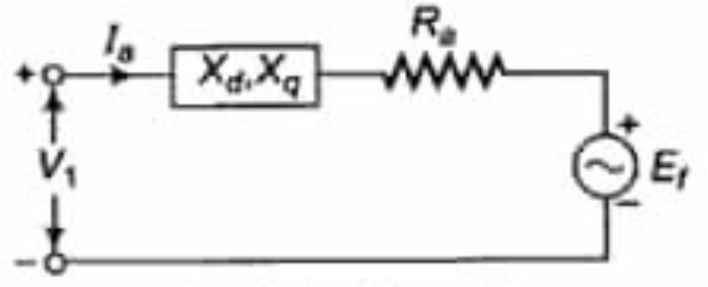
$E_a = V - I_aR_a - jI_aX_s$

- **Phasor Diagram**



Phasor diagrams of cylindrical rotor synchronous motor

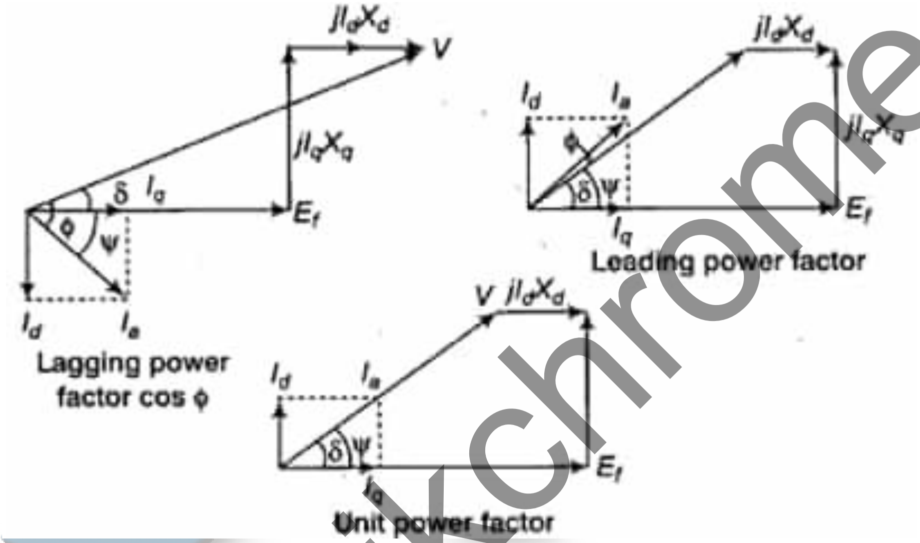
Salient Pole Synchronous Motor



Equivalent circuit

$E_a = V - I_aR_a - jI_aX_q - jI_d(X_d - X_q)$

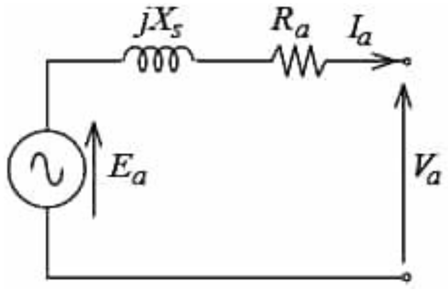
- **Phasor Diagram:**

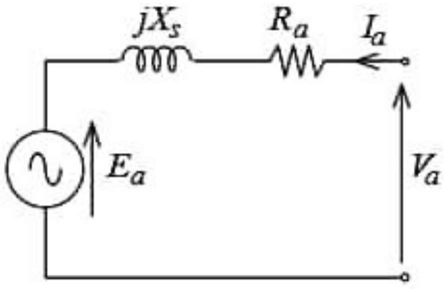


- **Power Developed:**

$$P_{3\phi} = \frac{3VE_f}{X_d}\sin\delta + \frac{3V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

Experimental Determination of Circuit Parameters





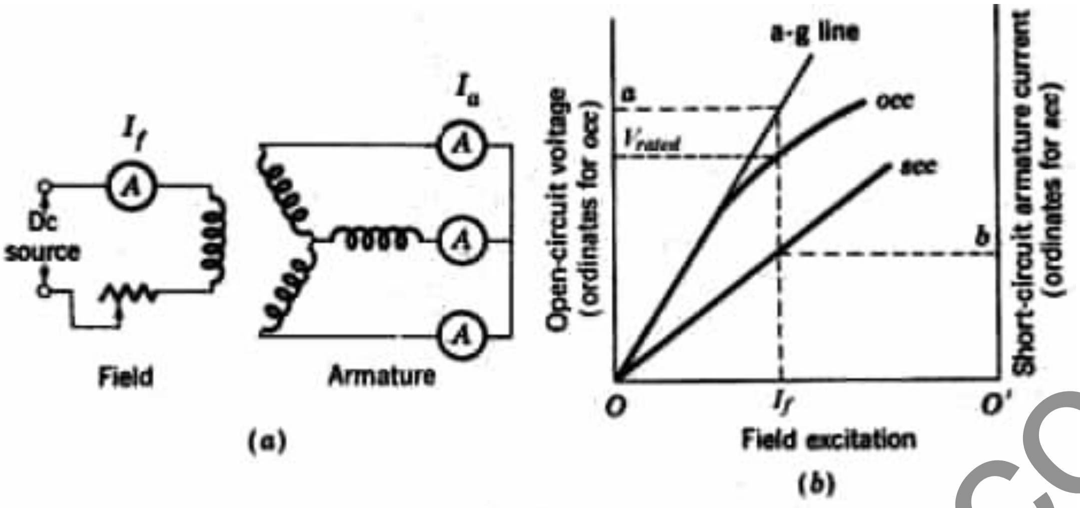
In the per phase equivalent circuit model illustrated above **first for Generator & Second For Motor**, there are three parameters need to be determined: winding resistance Ra, synchronous reactance Xs, and induced emf in the phase winding Ea. The phase winding resistance Ra can be determined by measuring DC resistance of the winding using the volt-ampere method, while the synchronous reactance and the induced emf can be determined by the open circuit and short circuit tests.

Open Circuit Test

Drive the synchronous machine at the synchronous speed using a prime mover when the stator windings are open circuited. Vary the rotor winding current, and measure stator winding terminal voltage. The relationship between the stator winding terminal voltage and the rotor field current obtained by the open circuit test is known as the open circuit characteristic of the synchronous machine.

Short Circuit Test

Reduce the field current to a minimum, by using the field rheostat, and then open the field supply circuit breaker. Short the stator terminals of the machine together through three ammeters; Close the field circuit breaker; and raise the field current to the value noted in the open circuit test at which the open circuit terminal voltage equals the rated voltage while maintaining the synchronous speed. Record the three stator currents. (This test should be executed quickly as the stator currents may be greater than the rated value).



(a) Connections for short-circuit test; (b) open- and short-circuit characteristics.

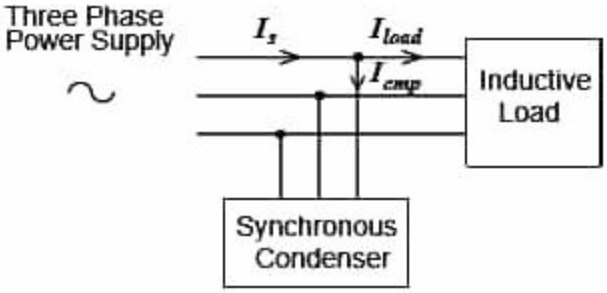
- Under the **assumptions** that the synchronous reactance **Xs** and the induced emf **Ea** have the same values in both the open and short circuit tests,

and that **Xs >> Ra**, we have

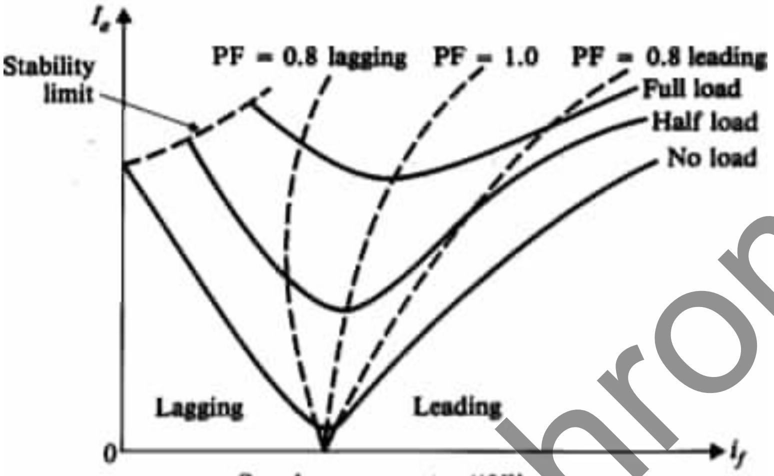
$$X_s = \frac{\text{Open circuit per phase voltage}}{\text{Short circuit per phase current}}$$

Effect of Excitation

By controlling the rotor excitation current such that the synchronous condenser draws a line current of leading phase angle, whose imaginary component cancels that of the load current, the total line current would have a minimum imaginary component.



Power factor compensation for an inductive load using a synchronous condenser



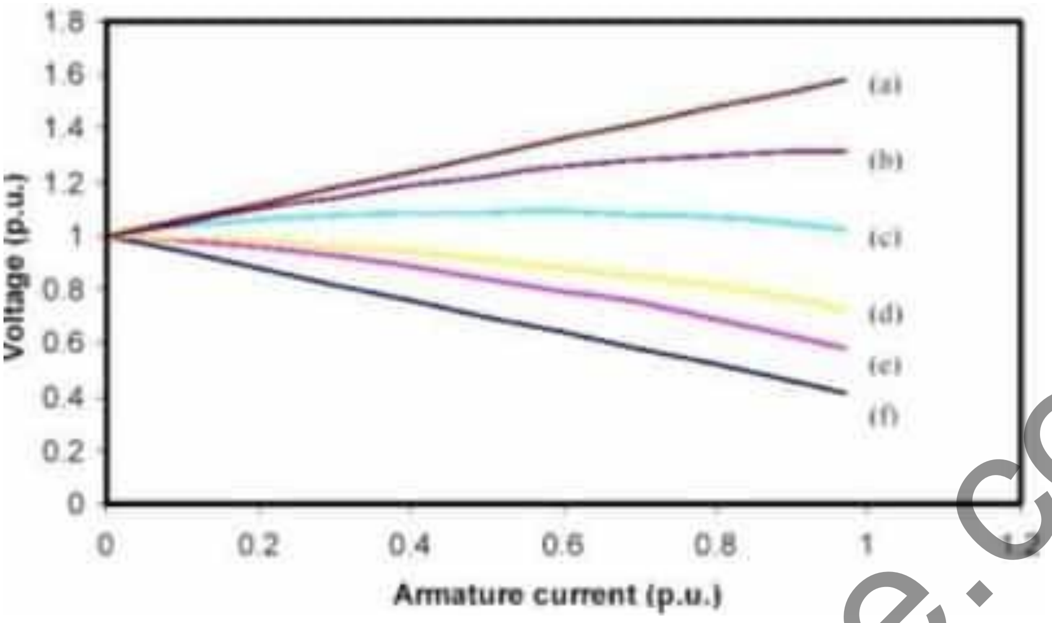
Synchronous motor "V" curves

Therefore, the overall power factor of the inductive load and the synchronous condenser would be close to one and the magnitude of the overall line current would be the minimum.

It can also be seen that only when the power factor is a unit or the stator current is aligned with the terminal voltage, the magnitude of the stator current is minimum.

By plotting the magnitude of the stator current against the rotor excitation current, a family of “V” curves can be obtained. It is shown that a larger rotor field current is required for a larger active load to operate at unity power factor.

Voltage Regulation



The variation in the terminal voltage with load is called voltage regulation, hence

Per-unit voltage regulation = **$(|V_{NL}|-|V_{FL}|)/|V_{FL}| = |E_f|-|V|/|V|$**

- (a) zero power factor leading
- (b) 0.8 power factor leading
- (c) 0.9 power factor leading
- (d) unity power factor
- (e) 0.9 power factor lagging
- (f) zero power factor lagging.

Special Machines

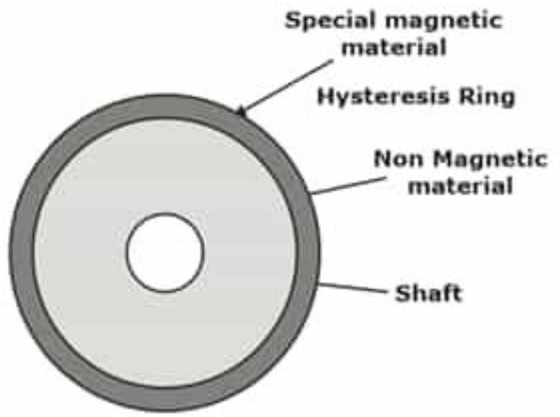
1. HYSTERESIS MOTOR

A **Hysteresis Motor** is a synchronous motor with a uniform air gap and without DC excitation. It operates both in single and three phase supply. The Torque in a Hysteresis Motor is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.

The rotor of the motor is made up of smooth chrome steel cylinder and it has no winding. It has high retentivity and because of this, it is very difficult to change the magnetic polarities once they are caused by the revolving flux of the rotor. The rotor of the hysteresis motor moves synchronously because the pole of the motor magnetically locks with the stator which has opposite polarities.

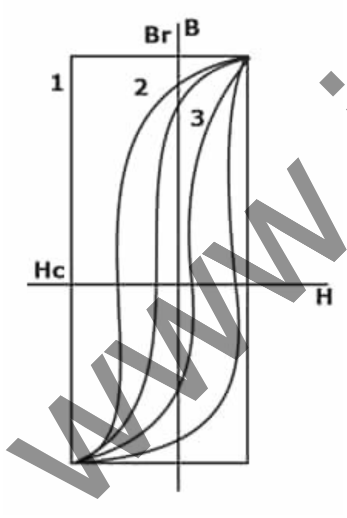
Construction of Rotor of Hysteresis Motor

The rotor of the hysteresis motor consists of the core of aluminium or some other non-magnetic material which carries a layer of special magnetic material. The figure below shows the rotor of the hysteresis motor.



Construction of Hysteresis rotor

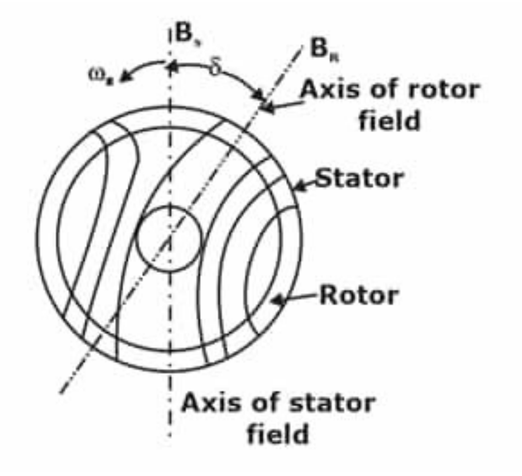
The outer layer has several thin rings forming a laminated rotor. The rotor of the motor is a smooth cylinder, and it does not carry any windings. The ring is made of hard chrome or cobalt steel having a large hysteresis loop as shown in the figure below.



Hysteresis loops

Operation of a Hysteresis Motor

The following illustration shows the basic functioning of a hysteresis motor.



Working principal of hysteresis motor

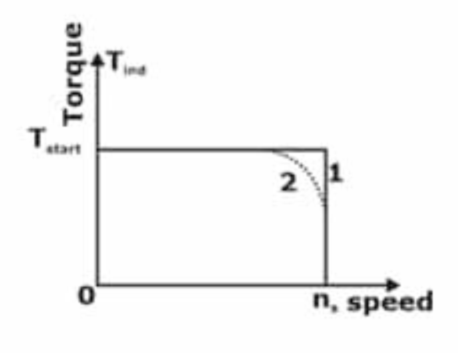
When supply is given applied to the stator, a rotating magnetic field is produced. This magnetic field magnetises the rotor ring and induces pole within it. Due to the hysteresis loss in the rotor, the induced rotor flux lags the rotating stator flux. The angle δ between the stator magnetic field B_S and the rotor magnetic field B_R is responsible for the production of the torque. The angle δ depends on the shape of the hysteresis loop and not on the frequency.

Thus, the value of Coercive force and residual flux density of the magnetic material should be large. The ideal material would have a rectangular hysteresis loop as shown by loop 1 in the hysteresis loop figure. The stator magnetic field produces Eddy currents in the rotor. As a result, they produce their own magnetic field.

As the electromagnet torque is developed by the motor is because of the hysteresis loss and remains constant at all rotor speed until the breakdown torque. At the synchronous speed, the eddy current torque is zero and only torque due to hysteresis loss is present.

Torque Speed characteristic of Hysteresis Motor

The speed torque curve of the motor is shown below:



Torque-Speed Characteristics

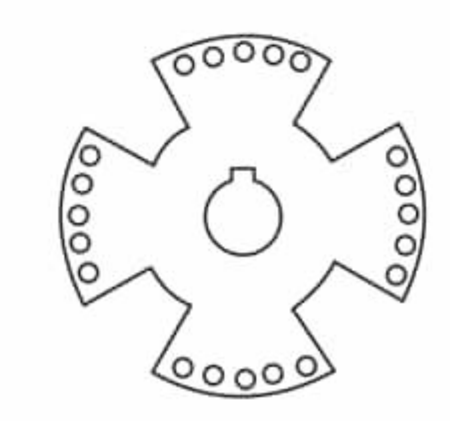
Curve 1 is the ideal curve, and the curve 2 is the practical hysteresis motor curve. The torque-speed characteristic of the hysteresis motor is different from an induction motor. Since, at the synchronous speed, the torque developed by an induction motor becomes zero, whereas in the hysteresis motor the torque is constant at all the speed even at the synchronous speed. Thus, from the curve, it is seen that the locked rotor, starting and pull out torque is equal.

The noise level of the hysteresis motor is very low as compared to the induction motor because it operates at a constant speed and its rotor is smooth. This type of motor is smoothest running, quietest single-phase motor and is used for quality sound reproduction equipment like record players, tape recorders, etc. It is also employed in electric clocks and other timing devices.

2. RELUCTANCE MOTOR

A single-phase synchronous **Reluctance Motor** is basically the same as the single cage type induction motor. The stator of the motor has the main and auxiliary winding. The stator of the single phase reluctance and **induction motor** are same. The rotor of a reluctance motor is a squirrel cage with some rotor teeth removed in the certain places to provide the desired number of salient rotor poles.

The figure below shows the 4-pole reluctance type **synchronous motor**.



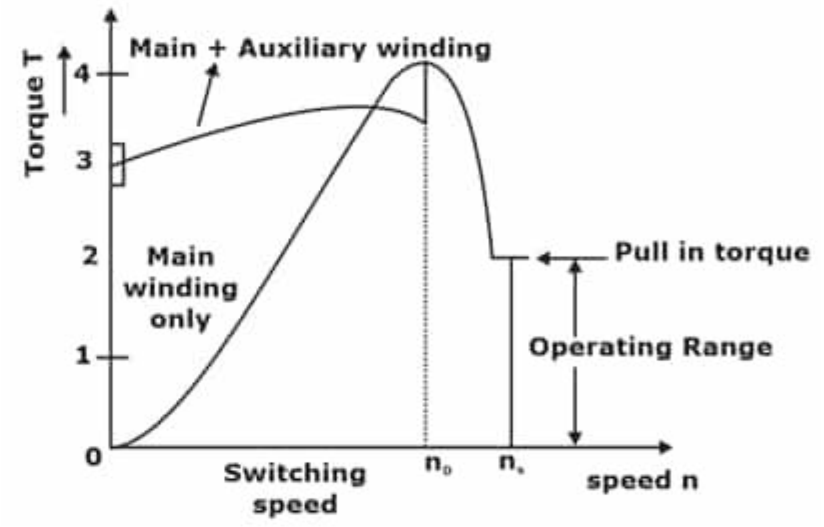
Four-pole reluctance type synchronous motor

In the above figure the teeth have been removed in four locations to produce a 4-pole structure. The two end rings are short circuited. When the stator is connected to a single-phase supply, the motor starts as a single-phase induction motor. A centrifugal switch disconnects the auxiliary winding as soon as the speed of the motor reaches about 75% of the synchronous speed. The motor continues to speed up as a single-phase motor with the main winding in operation.

A reluctance motor torque is produced due to the tendency of the rotor to align itself in the minimum reluctance position, when the speed of the motor is close to the synchronous speed. Thus, the rotor pulls in synchronism. The load inertia should be within the limits, for proper effectiveness. At synchronism, the induction torque disappears, but the rotor remains in synchronism due to synchronous reluctance torque.

Torque Speed Characteristic

The **Torque Speed Characteristic** of a single-phase Reluctance Motor is shown below.



Torque-speed characteristics

The starting torque depends upon the rotor position. The value of the starting torque varies between 300 to 400 % of its full load torque. As we know that as motor attains speed nearly of synchronous speed the auxiliary winding is disconnected, and the rotor continues to rotate at the synchronous speed.

The motor operates at a constant speed up to a little over than 200% of its full load torque. If the loading of the motor is increased above the value of the pull-out torque, the motor loose synchronism but continues to run as a single-phase induction motor up to over 500% of its rated torque. At the starting the motor is subjected to **Cogging.** This can be reduced by skewing the rotor bars and by having the rotor slots not exact multiples of the number of poles.

The rotor of a Reluctance Motor is unexcited; therefore, the power factor is low as compared to the induction motor. As the motor has no DC field excitation so the output of a reluctance motor is reduced. Hence, the size of the motor is large as compared to synchronous motor.

Applications of a Reluctance Motor

The various applications of the Reluctance Motor are as follows:

- Simple construction as there is no slip rings, no brushes and no DC field windings).
- Low cost
- Maintenance is easy.

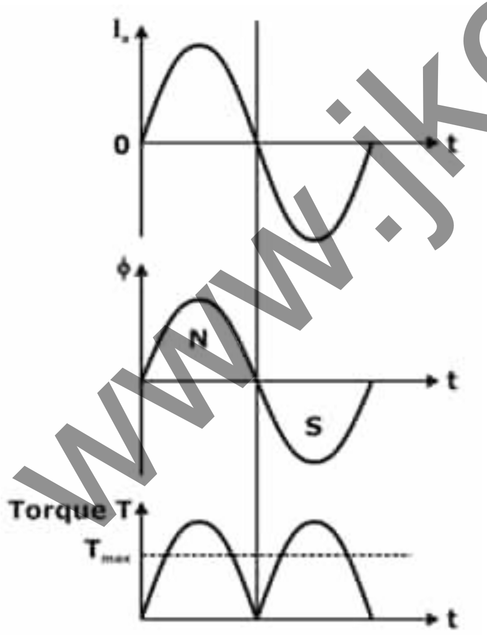
- It is used for many constant speed applications such as electric clock timer, signalling devices, recording instruments etc.

3. UNIVERSAL MOTOR

The motors which can be used with a single-phase AC source as well as a DC source of supply and voltages are called as **Universal Motor**. It is also known as **Single Phase Series Motor**. A universal motor is a **commutation** type motor. If the polarity of the line terminals of a DC Series Motor is reversed, the motor will continue to run in the same direction.

The direction is determined by both field polarity and the direction of current through the armature. As torque is proportional to the flux and the armature current. Let the DC series motor be connected across a single-phase AC supply. Since the same current flows through the field winding and the armature winding. The AC reversal from positive to negative or vice-versa will affect the field flux polarity and the current direction through the armature.

The direction of the developed torque will remain positive, and direction of the rotation will be as it was before. The nature of the torque will be pulsating, and the frequency will be twice that of line frequency as shown in the waveform below.



Characteristics of universal motor

Thus, a Universal motor can work on both AC and DC. However, a series motor which is mainly designed for DC operation if works on single phase AC supply suffers from the following drawbacks.

- The efficiency becomes low because of hysteresis and eddy current losses.
- The power factor is low due to the large reactance of the field and the armature windings.
- The sparking at the brushes is in excess.

In order to overcome the above following drawbacks, certain modifications are made in a DC series motor so that it can work even on the AC current. They are as follows:

- The field core is made up of the material having a low hysteresis loss. It is laminated to reduce the eddy current loss.
- The area of the field poles is increased to reduce the flux density. As a result, the iron loss and the reactive voltage drop are reduced.
- To get the required torque the number of conductors in the armature is increased.

The construction of the universal motor is same as that of the series motor. In order to minimize the problem of commutation, high resistance brushes with increased brush area are used. To reduce **Eddy current losses** the stator core and yoke are laminated. The Universal motor is simple and less costly. It is used usually for rating not greater than 750 W.

The characteristic of Universal motor is similar to that of the DC series motor. When operating from an AC supply, the series motor develops less torque. By interchanging connections of the fields with respect to the armature, the direction of rotation can be altered.

Speed control of the universal motors is obtained by solid state devices. This motor is most suitable for applications requiring high speeds. Since the speed of these motors is not limited by the supply frequency and is as high as 20000 rpm.

Applications of Universal Motor

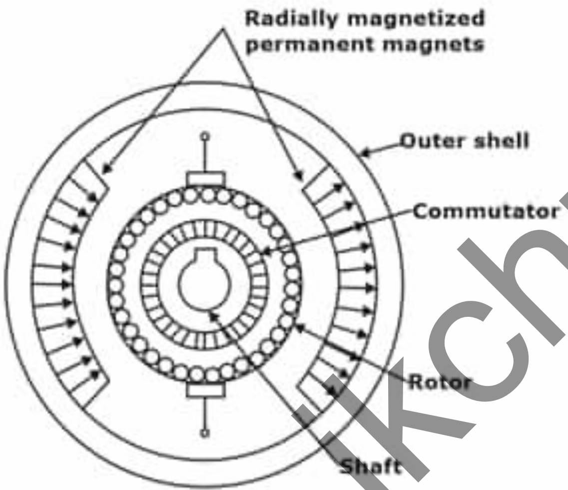
The Universal motor is used for the purposes where speed control and high values of the speed are necessary. The various applications of the Universal Motor are as follows:

- Portable drill machine.
- Used in hair dryers, grinders and table fans.
- A universal motor is also used in blowers, polishers and kitchen appliances.

4. PERMANENT MAGNET DC MOTOR

A DC Motor whose poles are made of Permanent Magnets is known as **Permanent Magnet DC (PMDC) Motor**. The magnets are radially magnetized and are mounted on the inner periphery of the cylindrical steel stator. The stator of the motor serves as a return path for the magnetic flux. The rotor has a DC armature, with commutator segments and brushes.

The cross-sectional view of the 2 pole PMDC motor is shown in the figure below.



The cross-sectional view of the 2-pole PMDC motor

The Permanent Magnet DC motor generally operates on 6V, 12V or 24 Volts DC supply obtained from the batteries or rectifiers. The interaction between the axial current carrying rotor conductors and the magnetic flux produced by the permanent magnet results in the generation of the torque.

The circuit diagram of the PMDC is shown below.

In conventional DC motor, the generated or back EMF is given by the equation shown below.

$F = k\phi N$ … … … (1)

The electromagnetic torque is given as

$T_e = k\phi\ Ia$ … … … (2)

In Permanent Magnet DC motor, the value of flux ϕ is constant. Therefore, the above equation (1) and (2) becomes

$E = K_1 N$ … … … (3)

$T_e = K_1 I_a$ … … … (4)

Considering the above circuit diagram, the following equations are expressed.

$V = E + I_a R_a$ … … … (5)

Putting the value of E from the equation (3) in equation (5) we get

$V = K_1 N + I_a R_a$ or

Where $k_1 = k\ \phi$ and is known as speed-voltage constant or torque constant. Its value depends upon the number of field poles and armature conductors.

The speed control of the PMDC motor cannot be controlled by using flux control method as the flux remains constant in this type of motor. Both speed and torque can be controlled by armature voltage control, armature rheostat control, and chopper control methods. These motors are used where the motor speed below the base speed is required as they cannot be operated above the base speed.

Applications of the Permanent Magnet DC Motor

The PMDC motors are used in various applications ranging from fractions to several horsepower. They are developed up to about 200 kW for use in various industries. The following applications are given below.

- PMDC motors are mainly used in automobiles to operate windshield wipers and washers, to raise the lower windows, to drive blowers for heaters and air conditioners etc.
- They are also used in computer drives.
- These types of motors are also used in toy industries.
- PMDC motors are used in electric toothbrushes, portable vacuum cleaners, food mixers.

- Used in a portable electric tool such as drilling machines, hedge trimmers etc.

5. **SERVO MOTOR**

Servo Motor are also called Control motors. They are used in feedback control systems as output actuators and does not use for continuous energy conversion. The principle of the Servomotor is similar to that of the other electromagnetic motor, but the construction and the operation are different. Their power rating varies from a fraction of a watt to a few hundred watts.

The rotor inertia of the motors is low and have a high speed of response. The rotor of the Motor has the long length and smaller diameter. They operate at very low speed and sometimes even at the zero speed. The servo motor is widely used in radar and computers, robot, machine tool, tracking and guidance systems, processing controlling, etc.

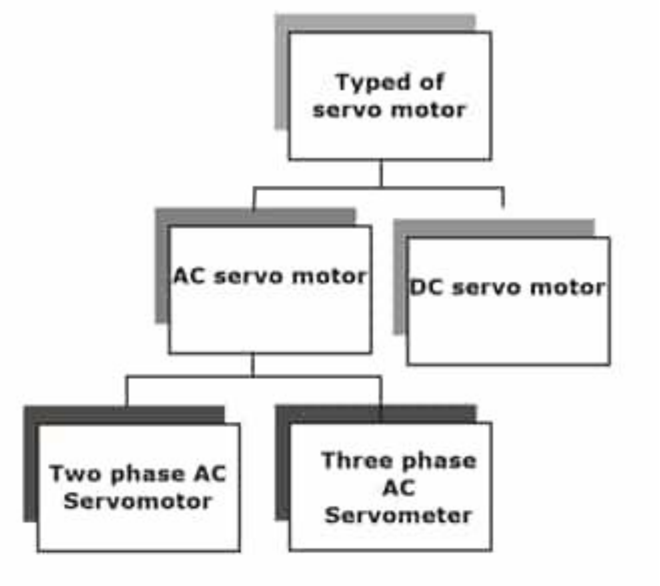
Applications of the Servo Motor

The power rating of the servo motor may vary from the fraction of watts to few hundreds of watts. The rotor of servo motor has low inertia strength, and therefore they have a high speed of inertia. The Applications of the Servomotor are as follows:

- They are used in Radar system and process controller.
- Servomotors are used in computers and robotics.
- They are also used in machine tools.
- Tracking and guidance systems.

Classification of Servo Motor

They are classified as AC and DC Servo Motor. The AC servomotor is further divided into two types.



Classification of Servo motor

DC Servo Motor

DC Servo Motors are separately excited DC motor or permanent magnet DC motors. The figure (a) shows the connection of Separately Excited DC Servo motor and the figure (b) shows the armature MMF and the excitation field MMF in quadrature in a DC machine.

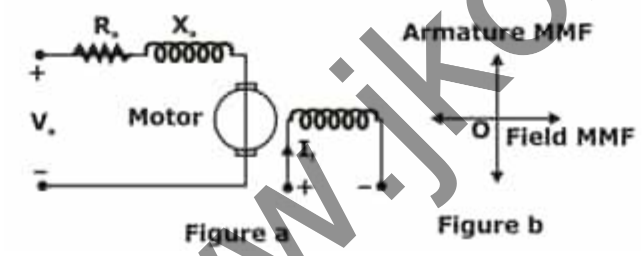
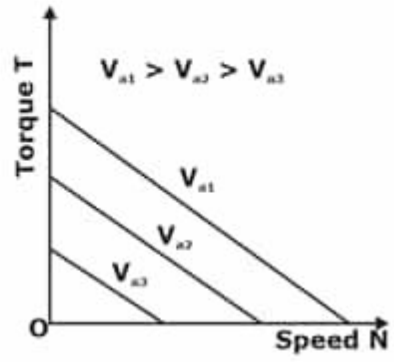


Figure a Figure b

This provides a fast torque response because torque and flux are decoupled. Therefore, a small change in the armature voltage or current brings a significant shift in the position or speed of the rotor. Most of the high-power servo motors are mainly DC.

The Torque-Speed Characteristics of the Motor is shown below.



Torque-speed Characteristics

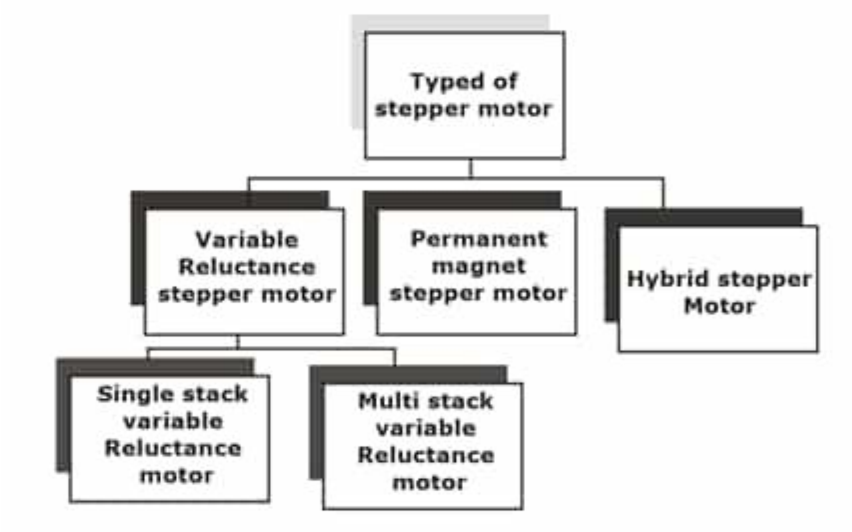
As from the above characteristics, it is seen that the slope is negative. Thus, a negative slope provides viscous damping for the servo drive system.

AC Servo Motor

The AC Servo Motors are divided into two types 2 and 3 Phase AC servomotor. Most of the AC servomotor are of the two-phase squirrel cage induction motor type. They are used for low power applications. The three-phase squirrel cage induction motor is now utilised for the applications where high-power system is required.

6. STEPPER MOTOR

The name **Stepper Motor** itself shows that the rotor movement is in the form of various steps or discrete steps. It is also known as Stepping Motor. The number of pulses fed into the controller circuit determines the angular rotation of the motor. Each input pulse produces one step of the angular movement. The drive is considered as an analog to digital converter. It has an inbuilt logic, which causes appropriate windings to be energised and de-energized by the solid-state switches in the required sequence.



Step Angle in Stepper Motor

Step angle is defined as the angle which the rotor of a stepper motor moves when one pulse is applied to the input of the stator.

The positioning of a motor is decided by the step angle and is expressed in degrees. The resolution or the step number of a motor is the number of steps it makes in one revolution of the rotor. Smaller the step angle higher the resolution of the positioning of the stepper motor.

The accuracy of positioning of the objects by the motor depends on the resolution. Higher the resolution greater will be the accuracy. Some precision motors can make 1000 steps in one revolution with a step angle of 0.36 degrees. A standard motor will have a step angle of 1.8 degrees with 200 steps per revolution. The various step angles like 90, 45 and 15 degrees are common in simple motors.

Advantages of Stepper Motor

The various benefits of the Stepping Motor are as follows:

- The motor is simple in construction, reliable.
- At the standstill condition, the motor has full torque.
- The motors are less costly.
- They require little maintenance.
- The stepper motor has an excellent and accurate starting, stopping and reversing response.

Disadvantages of Stepper Motor

The various disadvantages of the stepping motor are as follows:

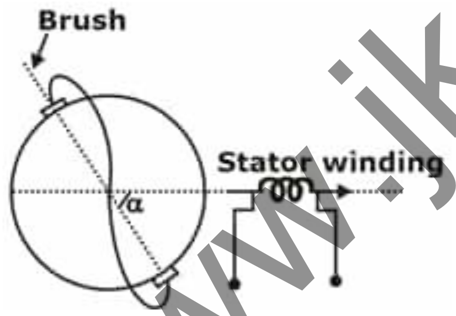
- The motor uses more current as compared to the **DC motor**.
- At the higher speed, the value of torque reduces.
- Lower efficiency.
- The Resonance condition arises and requires micro stepping.
- At the high speed, the control is not possible.

7. REPULSION MOTOR

Repulsion Motor is a special kind of single-phase AC motor which works due to the repulsion of similar poles. The stator of this motor is supplied with 1 phase AC supply and rotor circuit is shorted through carbon brush.

Construction of Repulsion Motor

The main components of repulsion motor are stator, rotor and commutator brush assembly. The stator carries a single-phase exciting winding similar to the main winding of single-phase induction motor. The rotor has distributed DC winding connected to the commutator at one end just like in DC motor. The carbon brushes are short circuited on themselves.



Working of Repulsion Motors

In the above figure, the stator winding has single phase AC winding which produces the working MMF in the air gap. The brushes on rotor are shown to be shorted. As the rotor circuit is shorted, the rotor receives power from stator by **transformer action**. The basic principle behind the working of repulsion motor is that "similar poles repel each other." This means two North poles will repel each other. Similarly, two South poles will repel each other.

Advantages of Repulsion Motor

The advantages of repulsion motor include the following:

- Starting torque is high.
- Good speed regulation.
- For sudden heavy loads, the torque can be developed.
- Starting current will be reduced.

Disadvantages of Repulsion Motor

The disadvantages of repulsion motor include the following:

- Sparks will occur at brushes
- The power factor is very less at less speed.
- The speed at no-load condition is extremely high & unsafe.
- Brushes & commutator exhaust quickly due to heat generation & arcing at the assembly of the brush.

Applications of Repulsion Motor

The applications of repulsion motor include the following:

- Hoists
- Machines in Textile
- Printing presses
- Air compressors
- Pumps & Fans
- Mixing machines
- Machine tools
- Air pump
- Mining tools
- Petrol pumps
- Drive compressors