Unit 5

ELECTRICAL MACHINES

A magnetic circuit is made up of one or more closed loop paths containing a magnetic flux. The flux is usually generated by permanent magnets or electromagnets and confined to the path by magnetic cores consisting of ferromagnetic materials like iron, although there may be air gaps or other materials in the path. Magnetic circuits are employed to efficiently channel magnetic fields in many devices such as electric motors, generators, transformers, relays etc.

- **Terminologies**
- **Magnetic flux ($\boldsymbol{\phi}$)**

The number of magnetic lines of force created in a magnetic field id known as magnetic flux. Its unit is Weber (Wb).

- **Flux Density ($\boldsymbol{B}$)**

The number of magnetic lines of force created in a magnetic circuit per unit area normal to the direction of flux line is known as flux density.

i.e. $B = \frac{\phi}{A}$

Its unit is $Weber/Sq.m\ \ (Tesla)$.

- **Magneto motive force ($\boldsymbol{F}$)**

Force which drives or tends to drive the magnetic flux through a magnetic circuit is magneto motive force.

i.e. $MMF = No.of\ turns \times current = NI$

Its unit is $AT\ (ampere - turns)$.

- **Magnetic field strength ($\boldsymbol{H}$)**

The magneto motive force per meter length of the magnetic circuit is known as magnetic field strength.

i.e. $H = \frac{NI}{l}$

Its unit is $AT/meter$.

- **Permeability ($\boldsymbol{\mu}$)**

A property of a magnetic material which indicates the ability of magnetic circuit to carry electromagnetic flux is known as permeability.

It is also ratio of flux density to the magnetizing force.

$$\mu = \frac{B}{H}$$

Its unit is $Henry/meter$.

Permeability of free space or air or non-magnetic material is:

$\mu_0 = 4\pi \times 10^{-7} H/m$

- **Relative permeability ($\boldsymbol{\mu_r}$)**

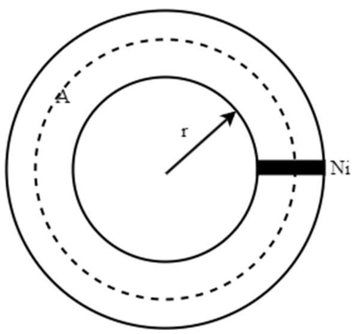
The ratio of the flux density produced by a given MMF in a magnetic material to the flux density produced in a non-magnetic material.

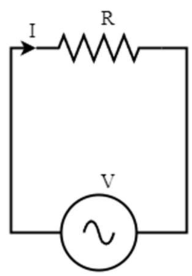
$$\mu_r = \frac{B}{B_0} = \frac{\mu H}{\mu_0 H} = \frac{\mu}{\mu}$$

$\therefore \mu = \mu_0 \mu_r$

- **Magnetic Circuit**

The complete closed path followed by any group of magnetic lines of flux is reformed to a magnetic circuit.





Equivalent electrical circuit

- **Reluctance ($\boldsymbol{S}$)**

It is the opposition of a magnetic circuit to setting up of a magnetic flux in it.

$flux = \phi = BA$

$F = mmf = H.l \qquad \left[H = \frac{\mu I}{l}\right]$

$B = \mu H$

$\frac{\phi}{F} = \left(\frac{\mu_0 \mu_r A}{l}\right) F$

$\phi = \frac{F}{\frac{l}{\mu_0 \mu_r A}} = \frac{F}{S}$

$\therefore \phi = \frac{F}{S} \qquad where, S = \frac{l}{\mu_0 \mu_r A}$

S is called reluctance of the magnetic circuit.

$Reluctance = MMF/Magnetic\ Flux$

Its unit is AT/Wb.

❖ Differences and similarities between electric circuit and magnetic circuit

- **Similarities**

Electric Circuit	Magnetic Circuit

i)	Electromotive force (emf), Volt (v).	i)	Magnetomotive force (mmf), ampere-turns (AT).
ii)	Current, ampere (A)	ii)	Flux, weber.
iii)	Resistance, Ohm (Ω)	iii)	Reluctance, A/Wb.
iv)	Current density, A/m^2	iv)	Flux density, Tesla or Wb/m^2
v)	Conductivity	v)	Permeability

➢ **Differences**

Electric Circuit		**Magnetic Circuit**	
i)	Current flows	i)	Flux is created but does not flow.
ii)	Circuit may be open or closed	ii)	Circuit is always closed.

❖ Transformers

The transformer is very simple static (or stationary) electromagnetic passive electric device that works on the principle of Faraday's law of induction.

It does this by linking together two or more electrical circuits using a common oscillating magnetic circuit which is produced by the transformer itself. A transformer operates on the principle of "electromagnetic induction" in the form of mutual induction.

A transformer is a device that converts one AC voltage to another voltage at the same frequency. It consists of one or more coil(s) of wire wrapped around a common ferromagnetic core. These coils are usually not connected electrically together. However, they are connected through the common magnetic flux confined to the core.

❖ Principle of operations

A single-phase voltage transformer basically consists of two electrical coils of wire, one called the 'primary winding' and another called the 'secondary winding' that are wrapped together around a closed magnetic iron circuit called a 'core'.

This soft iron core is not solid but made up of individual laminations connected to help reduce the cores losses. These two windings are electrically isolated from each other but are magnetically linked through the common core allowing electrical power to be transformer from one coil to the other.

In other words, for a transformer there is no direct electrical connection between the two coil windings, thereby giving it the name also of an isolation transformer.

Generally, the primary winding of a transformer is connected to the input voltage supply and converts or transforms the electrical power into a magnetic field. While the secondary winding converts this magnetic field into electrical power producing the required output voltage as shown below:

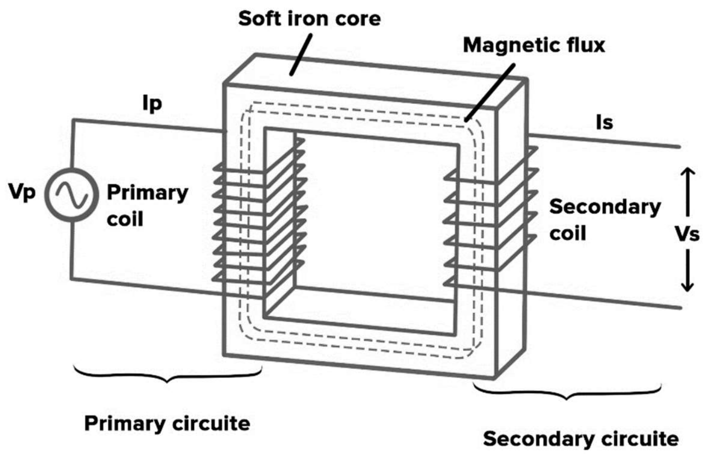


Fig: Construction of Transformer

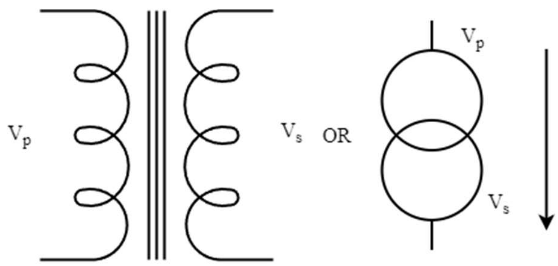


Fig: Transformer Symbols

$Where,$

$V_p = primary\ voltage$

$V_s = Secondary\ voltage$

$N_p = No.of\ primary\ \ windings$

$N_s = No.of\ secondary\ windings$

$\phi = flux\ linkage$

A transformer is all about 'ratios' and the turns ratio of a given transformer will be the same as its voltage ratio. In other words, for a transformer:

$turns\ ratio = voltage\ ratio$

The actual number of turns of wire of any winding is generally not important just the turns ratio and this relationship is given as:

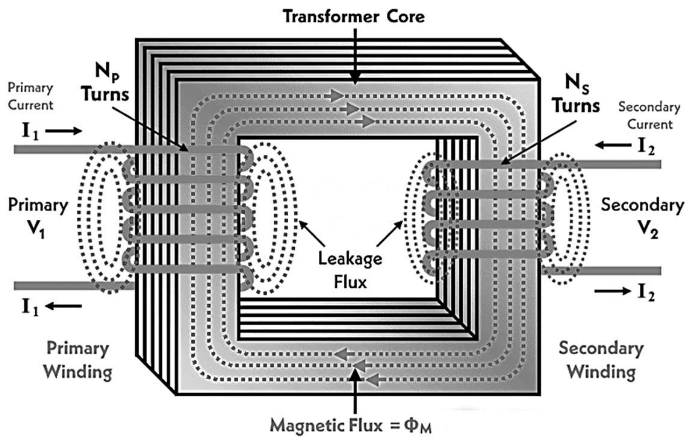
$$\frac{N_p}{N_s} = \frac{V_p}{V_s} = n = Turns\ Ratio$$

Note that the two coil windings are not electrically connected but are only linked magnetically. A single-phase transformer can operate to either increase or decrease the voltage applied to the primary winding.

When a transformer is used to increase on its secondary winding with respect to the primary, it is called a step-up transformer.

When it is used to decrease the voltage on the secondary winding with respect to the primary it is called step-down transformer.

❖ EMF equation of Transformer



As the magnetic flux varies sinusoidally, $\phi = \phi_{max} \sin \omega t$ then the basic relationship between induced emf (E) in a coil winding of N turns is given by:

$$emf = turns \times rate\ of\ change\ of\ flux$$

$$E = N.\frac{d\phi}{dt}$$

$$E = N \times \omega \times \phi_{max} \times \cos \omega t$$

Now, for maximum emf $\cos \omega t = 1$, so we have:

$$E_{max} = N\omega\phi_{max}$$

$$E_{rms} = \frac{N\omega}{\sqrt{2}} \times \phi_{max} \qquad \left[\because E_{rms} = \frac{E_{max}}{\sqrt{2}}\right]$$

$$= \frac{2\pi}{\sqrt{2}} f \times N \times \phi_{max}$$

$$\therefore E_{rms} = 4.44 f N \phi_{max}$$

Thus, $E_p = 4.44 f N_p \phi_{max}$ and $E_s = 4.44 f N_s \phi_{max}$

$Where,$

$f = flux\ frequency\ in\ Hertz$

$N = No. of\ coil\ windings$

$\phi = the\ flux\ density\ in\ Weber$

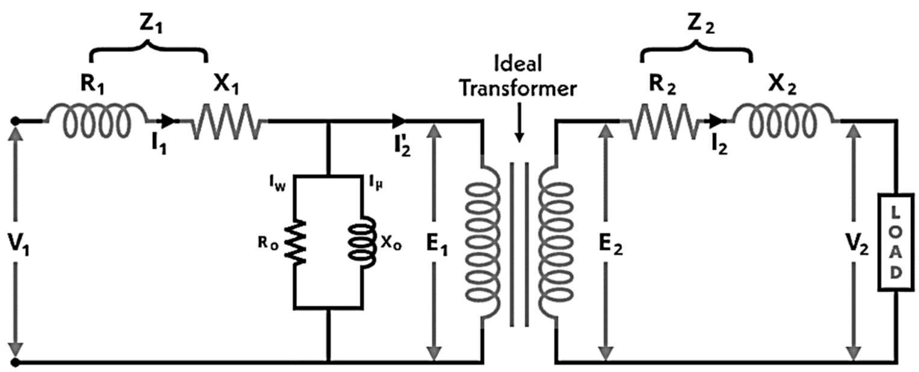
This is known as the transformer emf equation. For primary winding emf, N will be the number of primary turns (N_p) and for the secondary winding emf, N will be the number of secondary turns (N_s).

Transformers require an alternating magnetic flux to operate correctly, transformers can not therefore be used to transform DC voltages or currents, since the magnetic field must be changing to induce a voltage in the secondary winding. In other words, transformer do not operate on DC voltages.

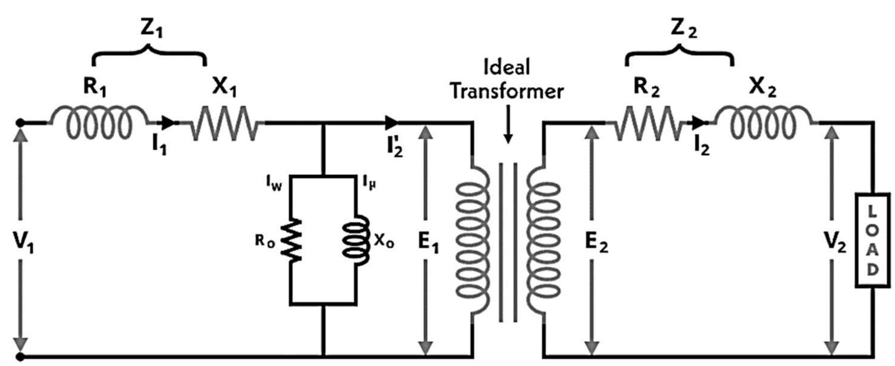
❖ Equivalent circuits of transformer

Equivalent impedance of transformer is essential for estimating different parameters of electrical power system, so it may be required to calculate total internal impedance of an electrical power transformer viewing from primary side or secondary side as per requirement. This calculation requires equivalent circuit of transformer referred to primary or equivalent circuit of transformer referred to secondary sides respectively.

The exact circuit diagram of real transformer:



➢ Equivalent circuit of transformer referred to primary



$Where,$

$V_1 = primary\ voltage$

$X_1 = primary\ inductance$

$R_1 = primary\ resistance$

$Z_1 = primary\ impedance$

$I_\mu = magnetizing\ component\ of\ current$

$I_w = core\ has\ component\ of\ current$

$I_2' = secondary\ current\ component\ of\ current$

$V_2' = secondary\ voltage\ referred\ to\ primary$

$R_2' secondary\ resistance\ referred\ to\ primary$

$X_2' = secondary\ inductance\ referred\ to\ primary$

$Z_2' = secondary\ impedance\ referred\ to\ primary$

$I_1 = I_0 + I_2'$

$I_0 = I_\mu + I_w$

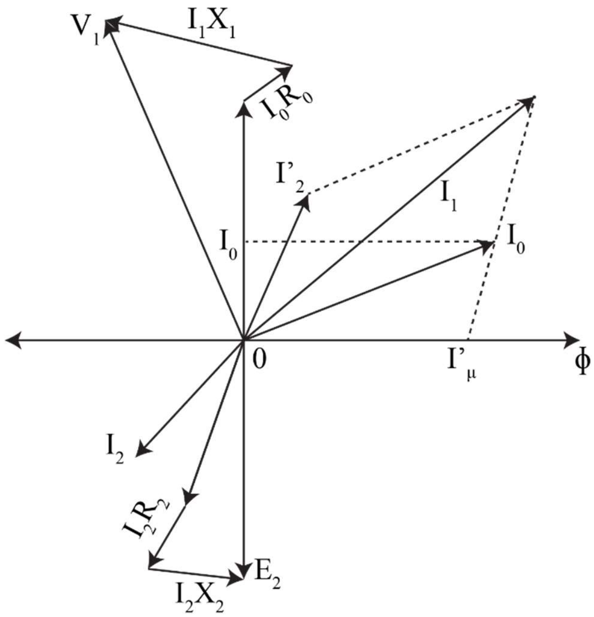


Fig: Vector diagram of transformer on load

Now, it is found that total primary current I_1 has two components one is no load component I_0 and other is load component I_2'. As this primary current has two components or branches so there must be a parallel path with primary winding of transformer. This parallel path of electric current is known as excitation branch of equivalent circuit of transformer.

The resistive and reactive branches of the excitation circuit can be represented as:

$R_0 = \frac{E_1}{I_w}$ and $X_0 = \frac{E_1}{I_\mu}$

Let us consider the transformer ratio be;

$$k = \frac{N_2}{N_1} = \frac{E_2}{E_1}$$

Now, if we see the voltage drop in secondary from primary side then it would be $1/k$ times greater and would be written as:

$Z_2 . I_2 / k$

Again,

$I_2' . N_1 = I_2 . N_2$

- ⇨ $I_2 = \frac{I_2' . N_1}{N_2}$
- ⇨ $I_2 = I_2' / k$

$$\therefore Z_2 . \frac{I_2}{k} = Z_2 . \frac{I_2'}{k^2} = Z_2 . \frac{I_2'}{k^2} = Z_2 . \frac{I_2'}{k^2} = I_2' Z_2'$$

From the above equation, secondary impedance of transformer referred to primary is:

$Z_2' = Z_2 / k^2$

Hence,

$$R_2' = \frac{R_2}{k^2}$$

And, $X_2' = \frac{X_2}{k^2}$

So, the complete equivalent circuit of transformer referred to primary is shown in the figure above.

Approximate Equivalent Circuit of Transformer

Since, I_0 is very small compared to I_1, it is less than 5% of full load primary current, I_0 changes the voltage drop insignificantly. Hence, it is good approximation to ignore the excitation circuit in approximate equivalent circuit of transformer.

The winding resistance and reactance being in series can now be combined into equivalent resistance and reactance of transformer referred to any side. In this case it is side.

Here,

$$V_2' = \frac{V_2}{k}$$

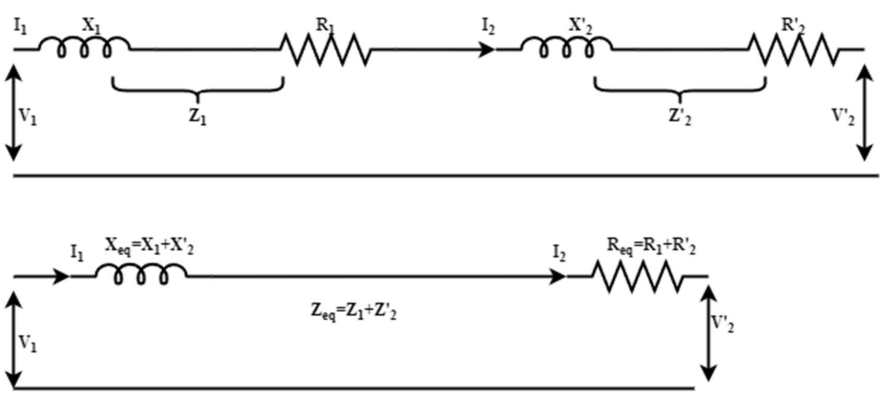


Fig: Approximate equivalent circuit of transformer referred to primary

- **Equivalent circuit of transformer referred to secondary**

In similar way approximate equivalent circuit of transformer referred to secondary can be drawn. Where, equivalent impedance of transformer referred to secondary, can be derives as:

$Z_1' = Z_1.k^2$

$Therefore, R_1' = R_1.k^2$

$and, X_1' = X_1.k^2$

$Here, V_1' = V_1.k$

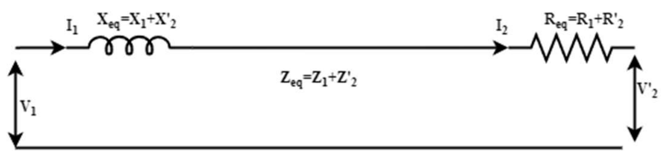


Fig: Approximate equivalent circuit of transformer referred to secondary

- **Efficiency of Transformer**

Transformer efficiency (η) can be explained ad the ration of the output power to the input power.

$$\eta = \frac{output\ power}{input\ power}$$

- **Voltage Regulation of Transformer**

Voltage regulation of transformer is the percentage change in its secondary terminal voltage compared to its original no-load voltage under varying secondary load conditions.

- **Open Circuit Test**

The open circuit test, or no-load test is one of the methods used in electrical engineering to determine the no-load impedance in the excitation branch of a transformer.

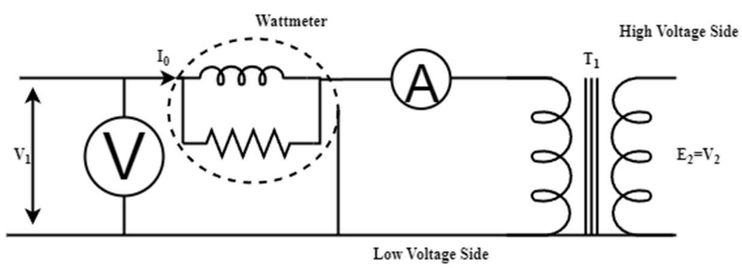


Fig: Circuit for Open Circuit Test

The secondary of the transformer is left open circuited. A wattmeter is connected in series with the primary winding. A voltmeter is optional since the applied voltage is the same as the voltmeter reading. Rated voltage is applied at primary.

Since, the secondary of the transformer is open, the primary draws only no-load current, which will have some copper loss. This no-load current is very small and because the copper loss in the primary is proportional to the square of this current, it is negligible. There is no copper loss in the secondary because there is no secondary current.

Now, the components of no-load circuit

$W = VI \cos\phi$

$\frac{I_\mu}{I_m} = I_0 \sin\phi$ $\qquad I_0 = \sqrt{I_\mu^2 + I_\mu^2}$

$I_w = I_0 \cos\phi$

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

$X_0 = \frac{V_1}{I_m}$

These values are referred to low voltage (LV) side of the transformer.

$Where,$

$W = wattmeter\ reading$

$V_1 = applied\ rated\ volatge$

$I_0 = no - load\ current$

$I_m = magnetizing\ component\ of\ no\ load - current$

$I_w = core\ loss\ component\ of\ no - load\ current$

Hence, it is seen that open circuit test gives core losses of transformer and shunt parameters of the equivalent circuit.

❖ Short Circuit Test

The purpose of short circuit test is to determine the series branch parameters of the equivalent circuit of a real transformer.

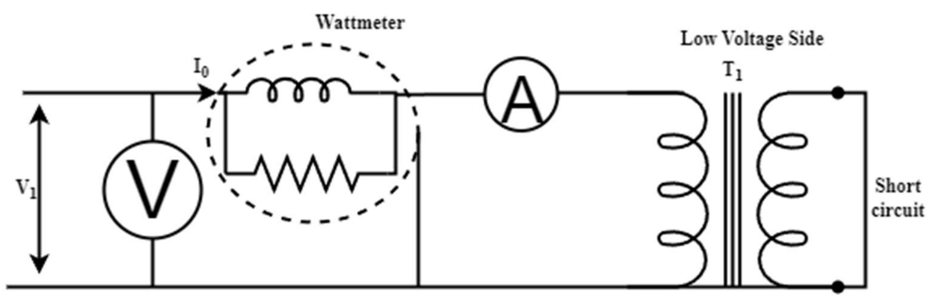


Fig: Circuit for Short Circuit Test

The test is conducted on the high voltage (HV) side of the transformer where the low voltage side or the secondary is short circuited. The supply voltage required to circulate. The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the nominal voltage and this voltage is applied across primary. Thus, the wattmeter reading measures only the full load copper loss.

$W = I_1^2 R_{01}$

$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$Z_{01} = \frac{V_1}{I_1}$ & $R_{01} = \frac{W}{I_1^2}$

These values are referred to the HV side of transformer. Short circuit test gives copper losses of transformer and appropriate equivalent resistance and reactance of the transformer.

$Where,$

$W = full\ load\ copper\ loss$

$V_1 = applied\ voltage$

$I_1 = rated\ current$

$R_{01} = resistance\ as\ viewed\ from\ the\ primary$

$Z_{01} = impedance\ as\ viewed\ from\ the\ primary$

$X_{01} = reactance\ as\ viewed\ from\ the\ primary$

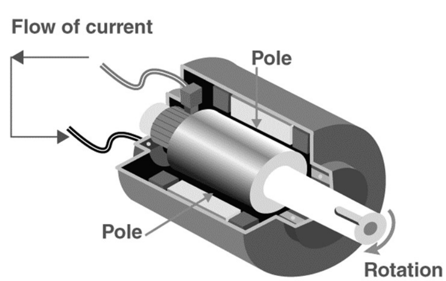
❖ DC Machines

A DC machine is a device which converts mechanical energy into electrical energy and vice-versa. When the device converts mechanical energy into electrical form then it is called generator and if it converts electrical energy into mechanical energy then it is known as motor. Thus, electrical machines can be made to work either a generator or motor.

Generators and motors are very similar to each other in parts and constructions. An electric motor is an electric machine that converts electrical energy into mechanical energy. In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force within the motor.

❖ DC generator

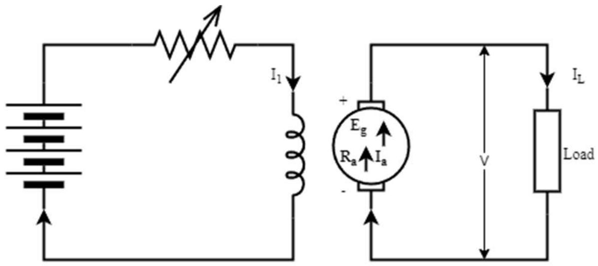
The device which converts mechanical energy into electrical energy is known as generator. There are two types of generators; AC generator and DC generators.



The DC generator is further divided as:

1. **Separately Excited DC Generator**

A DC generator whose field winding (or coil) is energized by a separate or external DC source is called a separately excited DC generator. The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles i.e. flux is directly proportional to the field current both in the saturated region, the flux remains constant separately excited DC generators are rarely used in practice.



Armature current $I_a = I_L$

Terminal voltage $V = E_g - I_a R_a$

Electric power developed $= E_g I_a$

Power delivered to load$= E_g I_a - I_a^2 R_a$

$$= I_a(E_g - I_a R_a)$$

$$= V I_a$$

2. **Self-Excited DC Generator**

These are generators in which the field winding is excited by the output of the generator itself. Self-excited DC generator can again be classified as:

a) Series DC Generator

A series DC generator is shown in figure below in which the armature winding is connected in series with the field winding so that the field current flows current through the load as well as the field winding.

Field winding is a low resistance thick wire of few turns series generators are slow rarely used.

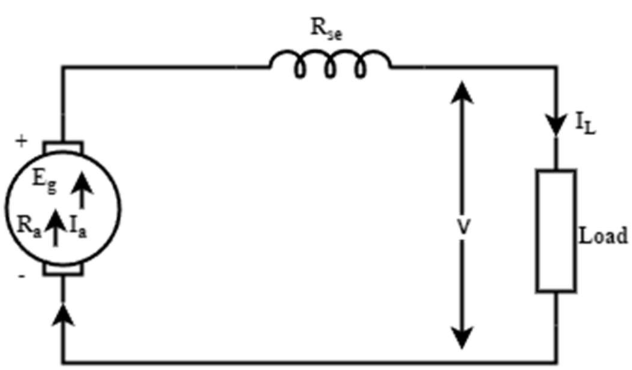


Fig: Series DC Generator

Armature current $I_a = I_{se} = I_L + I\ (say)$

Terminal voltage $V = E_g - I(R_a - R_{se})$

Power developed in armature $= E_g I_a$

Power delivered to load $= E_g I_a - I_a^2(R_a + R_{se})$

$= I_a\left[E_g - I_a(R_a - R_{se})\right]$

$= VI_a \ or \ VI_L$

b) Shunt DC Generator

A shunt DC generator is shown in figure below, in which the field winding is parallel to armature winding so that the voltage across both is same. The field winding has high resistance and a greater number of turns so that only a part of armature current passes through field winding and the rest passes through load.

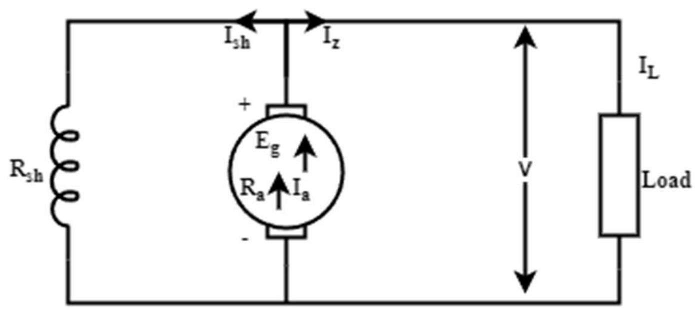


Fig: Shunt DC Generator

Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$

Armature current $I_a = I_L + I_{sh}$

Terminal voltage $V = E_g - I_a R_a$

Power developed in armature $= E_g I_a$

Power delivered to load $= VI_l$

c) Compound DC Generator

A compound DC generator is shown below. It has two field windings namely R_{sh} and R_{se}. They are basically shunt winding (R_{sh}) and series winding (R_{se}).

Compound generators are of following two types:

(i) Short Shunt

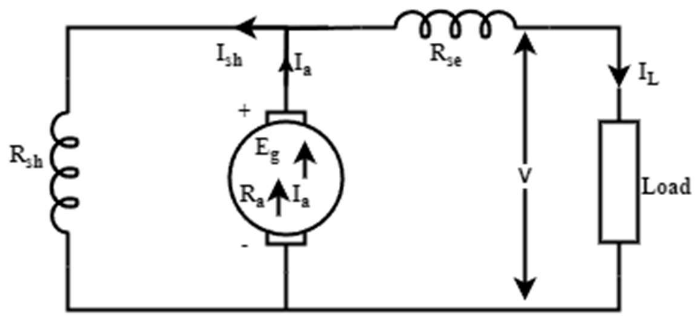


Fig: Short Shunt DC Generator

Here, the shunt field winding is wired parallel to armature and series field winding is connected in series to the load as shown in figure above.

For short shunt;

Series field current $I_{se} = I_L$

Shunt field current $I_{sh} = \frac{(V+I_{se}R_{se})}{R_{sh}}$

Terminal voltage $V = E_g - I_aR_a - I_{se}R_{se}$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

(ii) Long Shunt

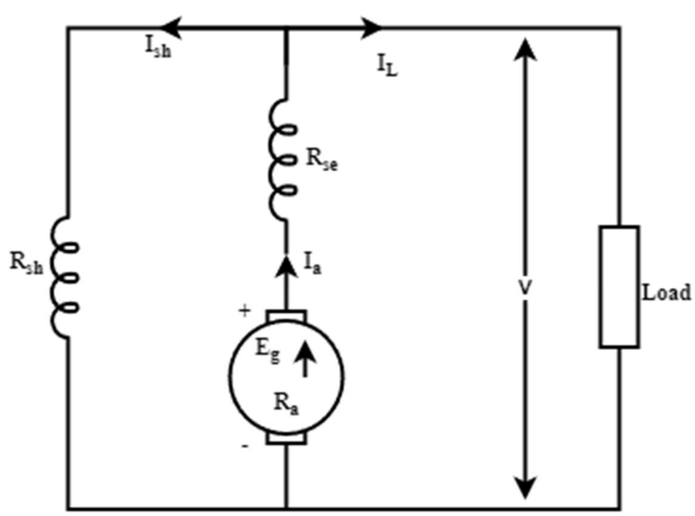


Fig: Long Shunt DC Generator

Here, the shunt field winding is parallel to both armature and series field winding (R_{se} is wired in series to the armature). It is shown in figure above.

For long shunt;

Series field current $I_{se} = I_a = I_L + I_{sh}$

Shunt field current $I_{sh} = \frac{V}{R_{sh}}$

Terminal voltage $V = E_g - I_a(R_a + R_{se})$

Power developed in armature $= E_g I_a$

Power delivered to load $= VI_L$

Now, we can say that these generators are used only for special industrial purposes where there is huge demand for DC production. Otherwise, electrical energy is produced by AC generators and is transmitted from one place to other as AC itself. When a DC power is required, we usually convert AC to DC using rectifiers.

❖ **Basic Characteristics of DC Generators**

i) Load Characteristics

a. Series DC Generator

Let us consider a series DC generator as shown in figure below in which the armature winding is connected in series with field winding so that same field current flows through the load as well as the field winding.

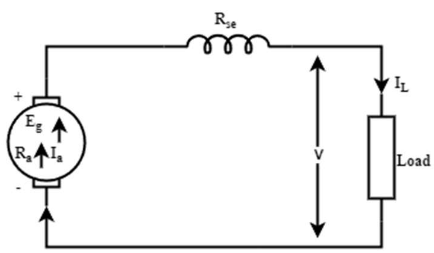


Fig: Series DC Generator

When the load current increases, the armature current as well as field current also increases. Therefore, the voltage drops in armature resistance $(I_a R_a)$ will also increase and other hand the flux per pole also increases. Therefore, the emf will also increases. Hence, a series DC generator have a raising voltage characteristic as shown in figure below;

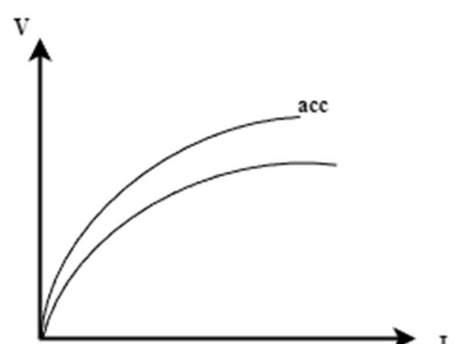


Fig: Load Characteristics

"But at overloaded condition, the voltage starts decreasing due to excessive demagnetizing effect of armature reaction and saturation effect."

b. Shunt DC Generator

Let us consider a shunt DC generator as shown in figure below in which the field winding is connected in parallel to armature winding so that the voltage across both is same.

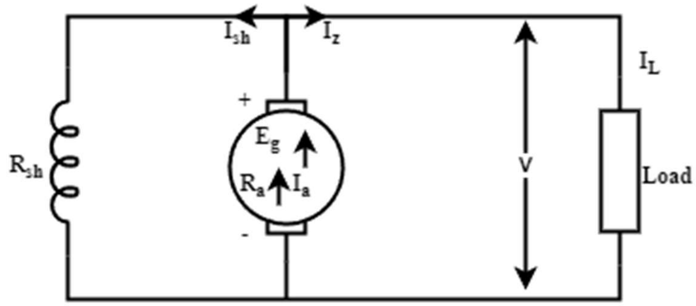


Fig: Shunt DC Generator

When there is no load current, the armature current (I_a) is equal to the field current (I_{sh}) i.e. $I_a = I_{sh}$.

Since, load current (I_L) is equal to zero, which is very small current with compare to full load current. Therefore, the voltage drop in armature is very small. Hence, the terminal voltage V is nearly equal to E_g.

When the generator is loaded then the armature current $(I_a = I_{sh} + I_L)$ will increase. Now, the terminal voltage is given by:

$$V = E_g - I_a R_a$$

Therefore, the terminal voltage V will decrease with increase in load current (I_L) as shown in figure below:

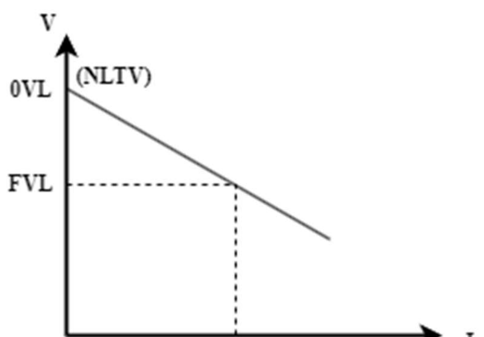


Fig: Load Characteristics

Let, OVL = No load terminal voltage

FLV = full load terminal voltage

Then, voltage regulation is defined as follows:

$$Voltage\ regulation = \frac{0VL - FVL}{0VL} \times 100\%$$

Hence, shunt DC generator have a dropping voltage characteristic.

c. Compound DC Generator

We have seen that; a series DC generator has a raising voltage characteristic and a shunt DC generator has a dropping voltage characteristic. A compound DC generator has a characteristic lying between shun and series D generator.

A shunt DC generator can be modified into a compound generator to supply constant voltage by adding few turns of field winding in series with load or armature as shown below;

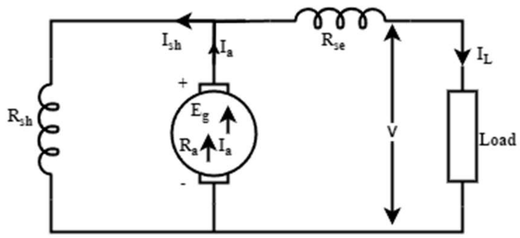


Fig: Short Shunt DC Generator

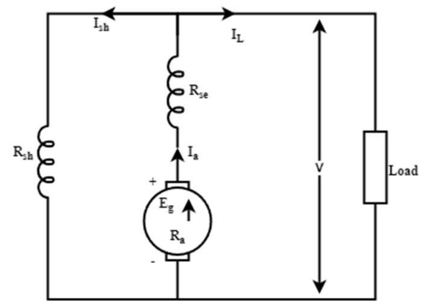


Fig: Long Shunt DC Generator

As the load current increases, the current through the series field winding also increases thereby increasing flux per pole. Due to increase in flux per pole, the emf also increases.

By adjusting the number of series turn the terminal voltage V can be controlled in different ways.

If the series field 'ampere' turns are such that the voltage at rated load and no load voltage are same then the generator is called flat compounded.

If the series field 'ampere' turns are such that the voltage at rated load is greater than no voltge then the generator is called over compounded.

If the series field 'ampere' turns are such that the voltage at rated load is less than the no load voltage then the generator is called under compounded.

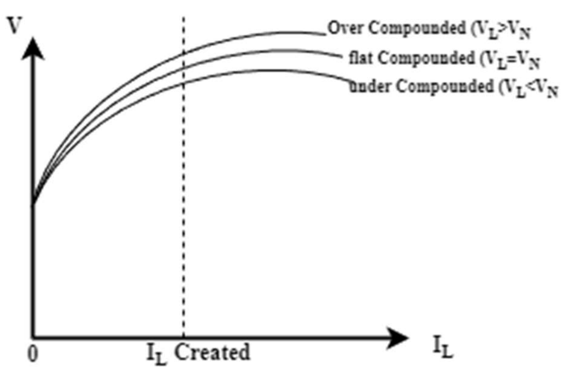


Fig: Load Characteristics

ii) No-load Characteristics

It is a curve showing the values of emf generated across the armature at no load for different values of field current at constant speed.

"The load characteristics of separately excited shunt and series generator can be particularly obtained in a similar way." The circuit arrangement for obtaining the data for no load characteristics curve as shown below:

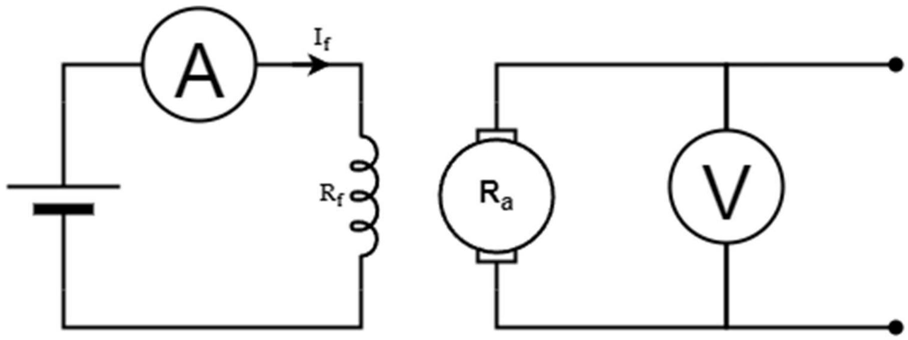


Fig: Circuit Diagram

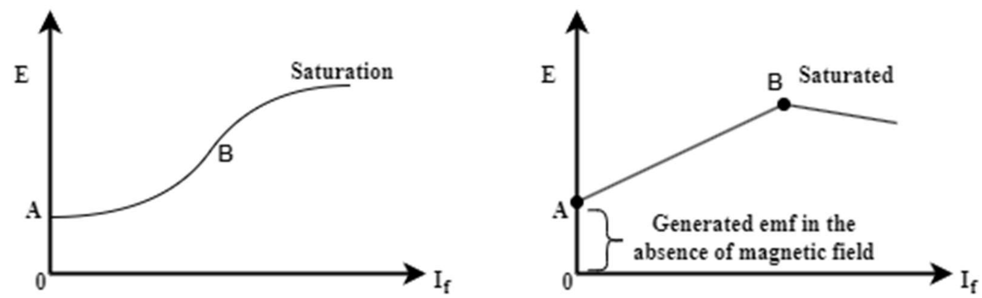


Fig: Open Circuit Curve

In case of shunt and series generator, the field windings must be disconnected temporarily and connected them as shown above.

The armature of the generator is rotated at constant speed "by prime movier" and emf induced across the armature at different value of field current are measured. The resulting curve as shown in above figure, where the emf generated across the armature due to residual flux in the pole even in absence of field current.

We know that:

$$E = \frac{Z\phi N}{60} \times \frac{\rho}{A}\ volt$$

We know,

$\phi \propto I_f$ and $E \propto \phi$ so $E \propto I_f$

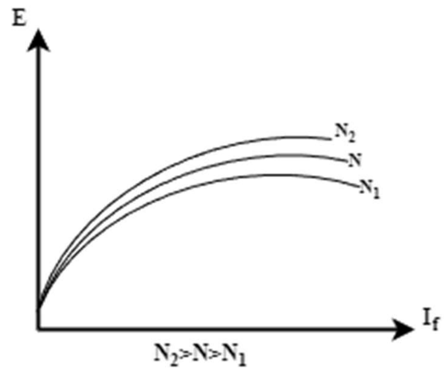
Since, armature current is driven at constant speed at constant speed we can write

$E \propto \phi$

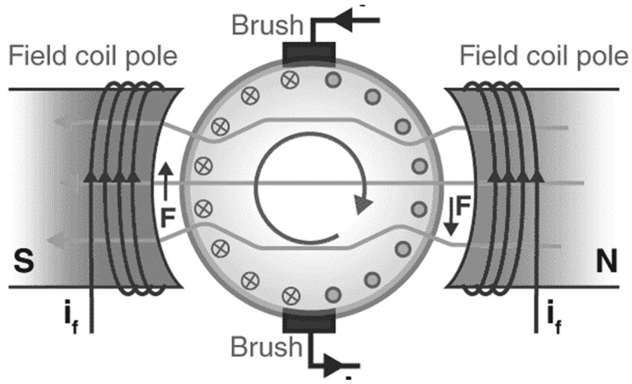
$E \propto I_f$

Therefore, the no-load characteristics curve is a straight line indicating that the emf increases proportionally with I up to point B. After point B the magnetic poles get saturated and emf does not increases even if the I is increased.

Note: No-load characteristic curve for higher speed will be above this curve and for the lower speed it will be below this can be shown as:

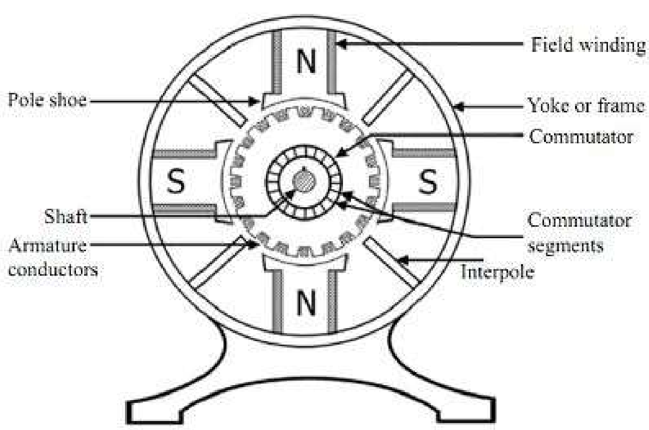


❖ **DC Motors**



A DC motor is an electrical machine that converts electrical energy into mechanical energy. In a DC motor, the input electrical energy is the direct current which is transformed into the mechanical rotation.

Construction of Motor



➢ **Rotor**

In an electric motor the moving part is the rotor which turns the shaft to deliver the mechanical power. The rotor usually has conductors laid into it which carry currents that interact with the magnetic field of the stator to generate the forces that turn the shaft. However, some rotors carry permanent magnets, and stator holds the conductors.

- **Stator**

The stationary part is the stator, usually has either windings or permanent magnets.

- **Air Gap**

In between the rotor and stator, there is the air gap. The air gap has important effects, and is generally as small as possible, as a large gap has a strong negative effect on the performance of an electric motor.

- **Winding**

Windings are wires that are laid in coils, usually wrapped around a laminated soft iron magnetic core. So, as to form magnetic poles when energized with current. Some motors have conductors which consist of thicker metal, such as bars or sheets of metal, usually copper, although sometimes aluminum is used. These are usually powered by electromagnetic induction.

- **Commutator**

A commutator is a mechanism used to switch the input of certain AC and DC machines consisting of slip ring segments insulated from each other and from the electric motor's shaft.

Performance and Operation

EMF Equation of DC Machine

The emf developed by a DC machine may be determined as follows:

Let us define the following symbols;

ϕ = magnetic flux per pole

ρ = number of magnetic poles

N = speed of armature in rotation per minute (rpm)

Z = Total number of armature conductors

A = number of parallel paths in the armature winding

Then, flux cut by one conductor in one rotation $= \phi\rho$

Flux cut by one conductor in N rotations $= \phi N\rho$

Flux cut per second by one conductor in N rotations $= \frac{\phi N\rho}{60}$

Flux cut per second by $\frac{Z}{A}$ conductors $= \frac{\phi N\rho}{60} \times \frac{Z}{A}$

Hence, emf induced in the armature winding

$$E = E_b = \frac{\phi N\rho}{60} \times \frac{Z}{A} = \frac{Z\phi N}{60} \times \frac{\rho}{A}$$

Torque Equation of DC Machine

We know that, the generated electric power is equal to the generated mechanical power in DC machine like motor and generator.

i.e. $E_b I_a = T_a \times 2\pi N \ldots\ldots\ldots..(i)$

$Where,$

$E_b = back\ emf$

$I_a = A.C.$

$T_a = A.T.$

$N = Speed\ in\ rpm$

Since, emf equation of DC machine is given by;

$$E_b = E = \frac{Z\phi N}{60} \times \frac{\rho}{A} \ldots\ldots\ldots.(ii)$$

From equation (i) and (ii) we get,

$$\frac{Z\phi N}{60} \times \frac{\rho}{A} \times I_a = T_a \times 2\pi N$$

$$or, T_a = \frac{Z\phi N\rho I_a}{60 \times A \times\ 2\pi N}$$

$$T_a = \frac{1}{120\pi}\frac{Z\phi\rho I_a}{A}$$

From this equation we can say that

$T_a \propto \phi I_g$

i.e. Torque is directly proportional to the product of armature current and magnetic flux per pole.

- **Basic characteristics of DC Motor**

i) Characteristics of DC Shunt Motor

a. Torque-Armature Current ($T_a - I_a$) Characteristics

It is the curve showing the relationship between torque developed at different values of armature current.

We know that, torque equation of DC machine is

$T_a \propto \phi I_a$

$And, \phi \propto I_f$

In a DC shunt motor the field current is constant provided that the applied voltage is constant.

$\therefore T_a \propto I_a$

Hence, $T_a - I_a$ characteristics of DC shunt motor is a straight line which indicate that the armature torque increases proportionally with the armature current. The net shaft torque is always less than the armature torque because of loss of torque due to friction loss.

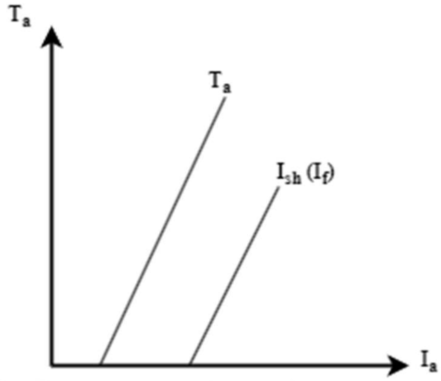


Fig: Torque-Armature Current Characteristics

b. Speed Torque Characteristics

It is a curve showing the speed of the motor at different values of armature torque developed by the motor.

We know that,

$$N \propto \frac{E_b}{\phi}$$

Where, N is speed of DC shunt motor and ϕ is constant for DC shunt motor.

When the speed of motor decreases the back emf E_b will also decreases. Then, armature current $\left(I_a = V - \frac{E_b}{R}{}_a\right)$ will increase as the armature torque (T_a) will also increases but the speed of motor is inversely proportional to the torque of the motor.

Hence, $N - T_a$ characteristics of DC shunt motor will be as follows:

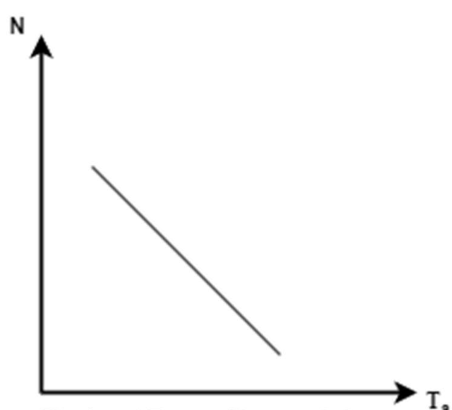


Fig: Speed Torque Characteristics

ii) Characteristics of DC Series Motor

a. Torque Armature Current Characteristics

In a DC series motor, the armature winding and field winding are connected in series. Therefore, the flux per pole is not constant but it varies with the armature current.

We know that;

$T_a \propto \phi I_a$

$But, \phi \propto I_a$

$\therefore T_a \propto I_a^2$

Hence, $T_a - I_a$ (Torque-Armature Current) characteristics of DC series motor is parabolic as shown in figure.

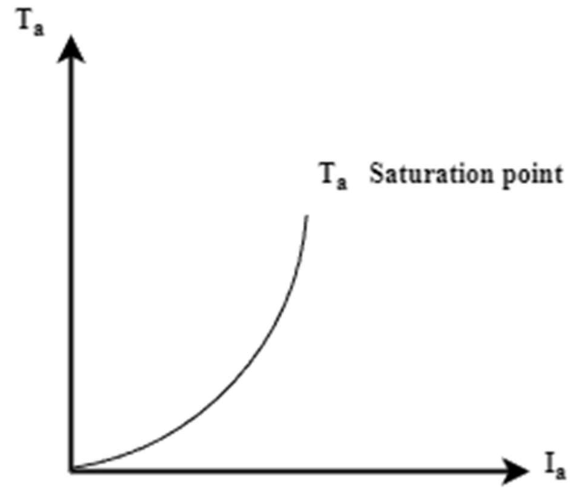


Fig: Torque-Armature Current Characteristics

b. Speed Torque Characteristics

We know that;

$$N \propto \frac{E_b}{\phi}$$

And, $E_b = V - I_a R_a$

And, $T_a \propto \phi I_a$

At heavy load (i.e. at high T_a), the armature current is high. Therefore, the back of emf E_b will reduce to allow high armature current. But flux per pole (ϕ) is proportional to series I_a in series motor. Hence, the speed will be significantly low at high armature.

At no-load (i.e. at low T_a), the armature current is low. Therefore, the back emf E_b will be comparatively high to allow low armature current. Since, the armature current is low the flux per pole will be low. Therefore, the speed will be significantly high at low torque.

Hence, the speed torque characteristics of series motor will be shown as:

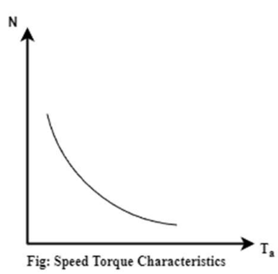


Fig: Speed Torque Characteristics

Form this characteristic at the starting where the speed is very low, DC series motor develops a high torque. On the other hand, at no-load the speed will be very high. Hence a DC series motor should not be started at no-load otherwise, it may develop excess speed and mechanical failure may occurs due to heavy centrifugal force.

❖ **Speed Control of DC Motor by Armature Control Method**

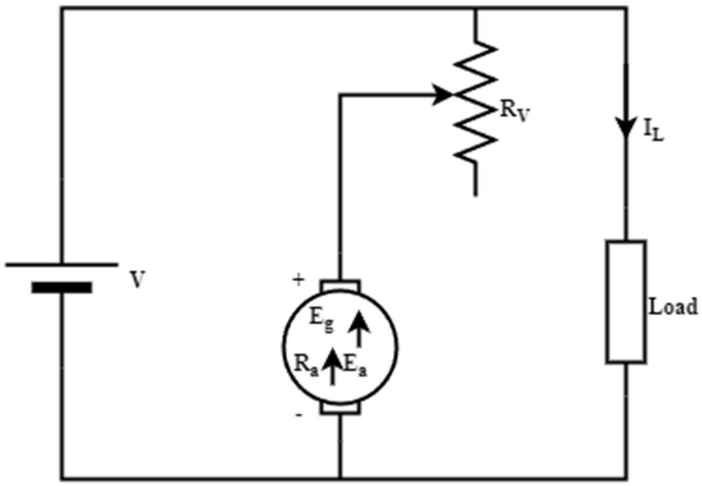


Fig: Speed control of DC motor by armature control method

The armature torque method depends upon magnetic flux per pole and armature current.

i.e. $torque \propto \phi I_a$

If the controller resistance or variable resistance (R_V) is increased keeping the load torque constant but potential difference across the armature will decrease. Hence, speed of armature will decrease.

Let, N_1 be the speed of motor at

$R_V = constant > 0$

Then, back or generated emf is given by;

$E_{b1} = V - I_{a1}R_a$

$E_{b2} = V - I_{a2}(R_a - R_V)$

Now, we have;

$$\frac{N_2}{N_1} = \frac{E_{b1}}{E_{b2}}$$

$$\frac{N_2}{N_1} = \frac{V - I_{a2}(R_a + R_V)}{V - I_{a1}R_a}$$

If $R_V = 0$, speed is maximum (full load)

If $R_V = constant$, speed is minimum (no load)

❖ **AC machines**

An AC motor is a motor that converts alternating current into mechanical power. The stator and the rotor are important parts of AC motors. The stator is the stationary part of the motor, and the rotor is the rotating part of the motor. The AC motor may be single-phase or three-phase. Nikola Tesla invented the first AC induction motor in 1887.

❖ Synchronous Motor

Synchronous motor operates on synchronous (constant) speed; hence this motor develops a constant torque in the direction of rotation.

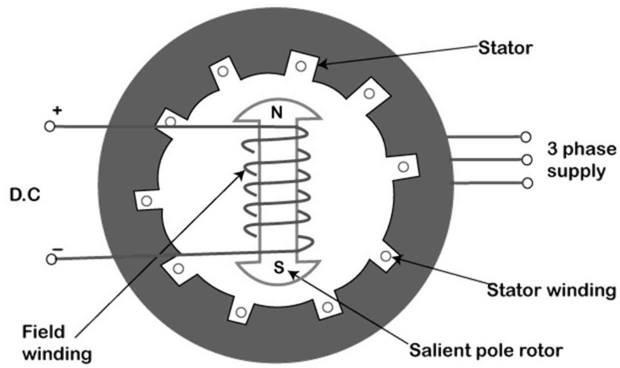


Fig: Synchronous Motor

Synchronous motor is a doubly excited machine i.e. two electrical inputs are provided to it. Its inputs are provided to it. It's stator winding which consists of $3-\phi$ winding is provided with three phase supply and rotor is provided with DC supply. The $3-\phi$ stator winding carrying $3-\phi$ currents due to which produces $3-\phi$ rotating magnetic flux. The rotor carrying DC supply and produces a constant flux.

Synchronous motors are not self-starting such motors require some external trigger signal and bring their speed close to the synchronous speed. The speed of operation of is in synchronism with the supply frequency they behave as constant speed motors. It is capable of being separated under a wide range of power factors both lagging and leading.

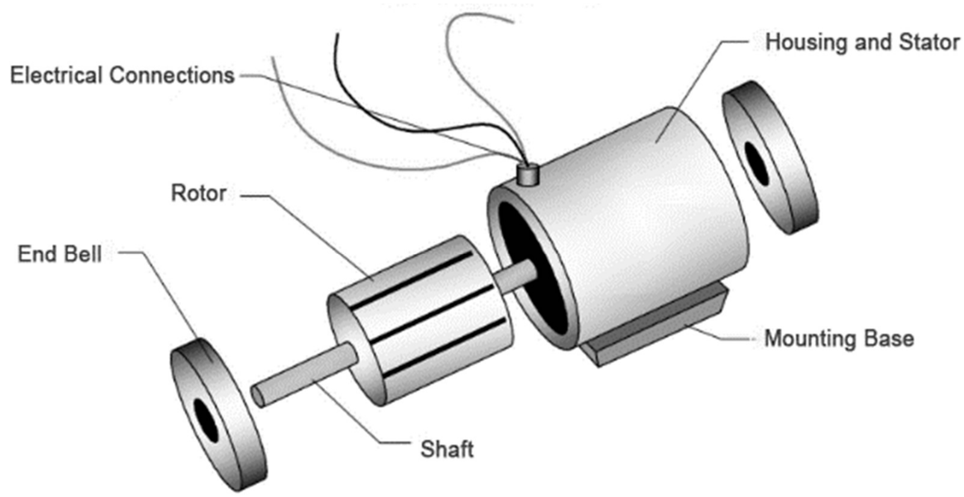
Synchronous motor having no-lead connected to its shaft is used for power factor improvement. Synchronous motor finds application where operating speed is less than (around 500 rpm) and high power is required.

❖ Applications of Synchronous Motor

- They are small, constant speed motors.
- Built for the wide range of output and speed.
- Its power is on the range of $0.001\ kW$ and are used in clocks, control apparatus timing devices.

❖ Single phase induction motors

A single-phase induction motor is a small-size motor with a fractional-kilowatt rating. They work on the principle of electromagnetic induction to create a rotating magnetic field. It is used in domestic appliances like fans, hair dryers, washing machines, vacuum cleaners, mixers, refrigerators, food processors and kitchen equipment employ these motors.



Construction:

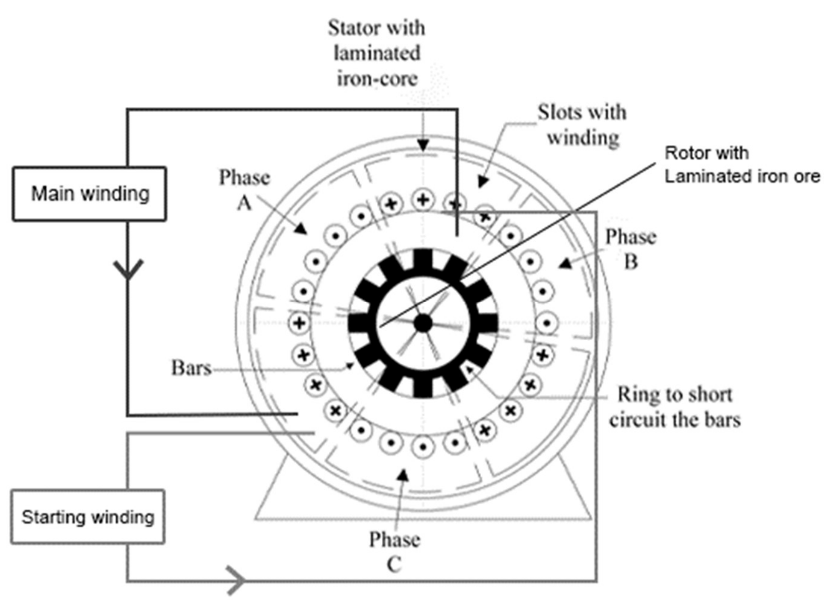
To construct Single Phase Induction Motor, it comprises of two major components which is the rotor and the stator.

- Stator

As the name implies, a stator is a stationary component of an induction motor. The stator of a single-phase induction motor receives a single phase alternating current source.

- Rotor:

The rotor is a rotating component of an induction motor. The rotor transmits mechanical load via the shaft. The squirrel cage rotor is used in the single-phase induction motor.



❖ Three phase induction motors

An electric motor is such an electromechanical device which converts electrical energy into a mechanical energy.

In case of three phase AC operation, most widely used motor is $3-\phi$ induction motor as this type of motor does not require any starting device or we can say that they are self-starting induction motor.

The basic constructional features of this motor consist of two major parts:

a. Stator

Stator of the three-phase induction motor is made up of numbers of slots to construct at 3 phase winding circuit which is connected to 3 phase AC source.

The three-phase windings are arranged in such a manner in the slots that they produce a rotating magnetic field after AC is given to them.

The stator of the motor consists of overlapping windings offset by an electrical angle of $120°$. When the primary winding or the stator is connected to a $3-\phi$ AC source, it establishes a rotating magnetic field which rotates at the synchronous speed.

b. Rotor

Rotor of three-phase induction motor consists of cylindrical laminated core with parallel slots that can carry conductors. Conductors are heavy copper or aluminum bars which fits in each slot and they are short circuited by the end rings.

The number of magnetic poles of the revolving field will be same as the number of poles for which each phase of primary or stator winding is wound or wrapped. The speed at which the field produced by the primary current will revolve is called synchronous speed of motor and is given by:

$$N_s = 120 \times \frac{f}{\rho}$$

$Where,$

N_s is the synchronous speed

f is the frequency

ρ is the no. of poles on stator

The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field of an induction motor has the advantage that no electrical connections need to be made to the rotor.

Thus, the three-phase induction motor is:

- Self-starting
- Robust in construction
- Economical
- Easier to maintain