COMPLETE NOTE

ON

ELECTRIC Machines...

(4th + 5th semester for BEL)

&

(1 semester course for other respective faculties)

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Magnetic Circuits and Induction

The concepts of electricity and magnetism are very much inter-related. So in order to deal with electrical parameters like current, voltage, etc. an engineer needs to strengthen his thoughts governed by basic magnetic laws.

On the simple basis of whether materials interact with magnets or not, they are grouped into magnetic and non-magnetic materials. Paper and plastics are grouped in the former while iron and most metals fall in the latter.

A magnet is a substance which can attract small pieces of magnetic materials and gets attracted to them if the latter is large. On the basis of source, magnets are classified as

(i) Natural magnet.
(ii) Artificial magnet.

The most common example of artificial magnet is electromagnet.

Magnetic field

The space around a magnet upto where force due to a magnet is experienced is known as magnetic field.

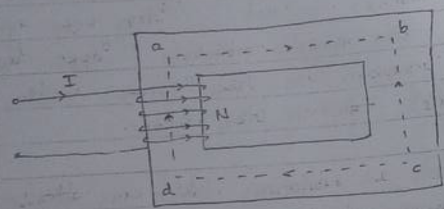
The field is assumed to be occupied by magnetic lines of force originating from N pole and terminating at S pole.

Magnetic flux

Group of magnetic lines of force passing through a specified area is known as magnetic flux. Flux is measured in Weber (Wb).

1.1 Magnetic Circuits

The path followed by a magnetic flux is called as magnetic circuit.



Consider a rectangular frame of iron as shown in the figure given above. If we wind an insulated wire on one side of frame and allow a dc current to flow then mmf acting causes a flux to flow in the magnetic circuit whose direction is given by right hand thumb rule.

Right hand thumb rule basically indicates polarity which is analogous to the direction of magnetic flux. This rule states that "If we hold the iron core by the right hand in such a way that the curling fingers represent the direction of coil current, then the thumb indicates the N pole." As the magnetic lines originate from N pole the direction of flux comes out to be same.

So magnetic circuit is formed by path a-b-c-d.

1.2 Ohm's law for magnetic Circuits

If we consider the same magnetic circuit a-b-c-d, and,

let,

I = current passing through the exciting coil (Amp)

N = number of turns

ϕ = magnitude of magnetic flux (in Weber)

A = cross-sectional area of the core

l = mean length of the path followed by magnetic flux

The magnetic flux density in the core is given by,

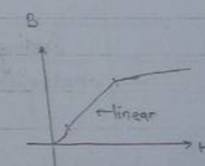
$$B = \phi / A \quad \text{--- (1)}$$

The magnetic field intensity (or magnetising force) inside the core is given by

$$H = \frac{NI}{l} \quad \text{--- (2)}$$

For linear region of magnetisation curve,

$$B = \mu H$$



From (1) and (2),

$$\frac{\phi}{A} = \mu \cdot \frac{NI}{l}$$

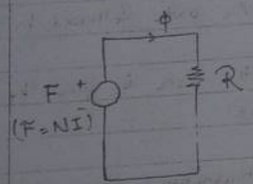
$$\therefore \boxed{\phi = \frac{NI}{\frac{l}{\mu A}} = \frac{mmf}{Reluctance}}$$

'NI' is known as magnetomotive force (mmf) which drives magnetic flux in the magnetic circuit (just like emf drives electric current in the electric circuit).

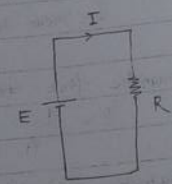
and, $\frac{l}{\mu A}$ is known as reluctance in the magnetic circuit (just like resistance opposes the flow of electric current in electric circuit)

If we compare, $\phi = \frac{mmf}{Reluctance}$ with $I = \frac{V}{R}$ (Ohm's law)

then the former equation can be called as Ohm's law for magnetic circuits.



$\phi = \frac{\mathcal{F}}{\mathcal{R}}$



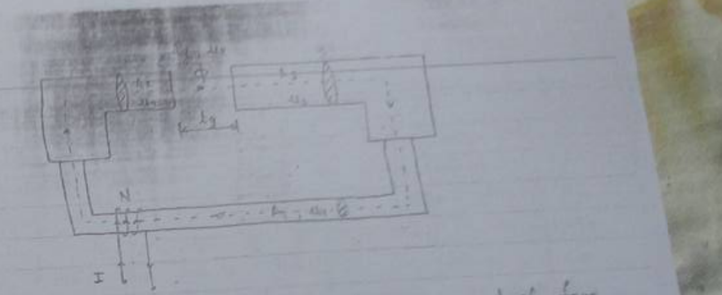
$I = E/R$

Seeing above two circuits we can easily draw analogies between electric and magnetic parameters.

ϕ and I are analogous.
$\mathcal{F}$ and E are analogous.
$\mathcal{R}$ and R are analogous.

1.3 Series and Parallel magnetic circuits

Series magnetic circuit is such magnetic circuit where same magnetic flux passes through all the section of the magnetic circuit. Figure below shows a series magnetic circuit



The magnetic circuit shown above is composed of four different sections of magnetic path including air gap. Each section will have its own reluctance and the total reluctance of the magnetic circuit is obtained by adding them arithmetically.

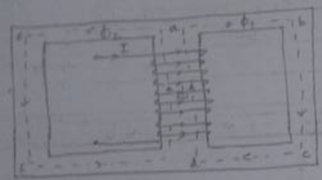
$$\therefore \text{Total reluctance} = \sum \frac{l}{\mu A} = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_g}{\mu_0 A_g} + \frac{l_3}{\mu_3 A_3}$$

and, $$\phi = \frac{NI}{\text{Total reluctance}}$$

Effect of air gap

Since the air gap has very high reluctance with comparison to iron core, it reduces the magnetic flux in the circuit. It is quite similar to addition of very high resistance in series with low resistance in case of series electric circuit.

If main magnetic flux divides into two or more parallel paths, such magnetic circuit is known as parallel magnetic circuit. Figure below shows a parallel magnetic circuit. Here the main magnetic flux divides into two parallel paths - abcd and aefd.



Here,

$$\phi_1 = \frac{NI}{\text{Reluctance of path- abcd}}$$

and,

$$\phi_2 = \frac{NI}{\text{Reluctance of path- aefd}}$$

Total magnetic flux = $\phi_1 + \phi_2$.

1.4 Core with air gap

As discussed earlier, the presence of air gap in magnetic circuit causes reluctance of the circuit to increase drastically. As a result, the flux reduces in its magnitude in comparision of what it would have been if air gap were to be absent. This technique has been exploited during the construction of many electrical machines in modern engineering to keep the flux within desired range to avoid saturation of magnetic materials used in their construction to avoid undesired situations.

1.5 B-H relationship (Magnetisation Characteristics)

Let us consider an unmagnetised bar of iron 'AB' provided with conductive winding over it as shown in the figure below. When dc current is passed through the winding, the iron core will get magnetised. The magnetising force inside the core is $H = \frac{NI}{l}$. The value of H can be increased or decreased by increasing or decreasing the magnitude of current 'I' and accordingly the magnetic flux density 'B' will also increase or decrease.

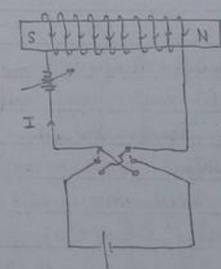


fig:- set up for magnetising piece of iron bar

The variation of magnetic flux density 'B' with magnetising force 'H' for a material is known as its magnetisation characteristics.

The plot which shows how the magnitude of magnetic flux density (B) changes when the magnetising force (H) increases from zero is known as magnetisation curve.

The terms magnetisation characteristics and magnetisation curve are often found being used interchangably.

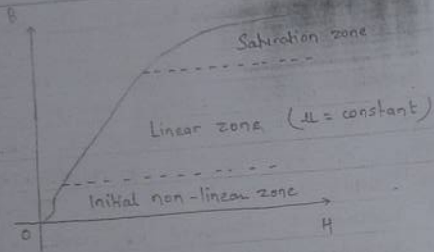


fig:- Magnetisation curve

According to molecular theory of magnetism, an unmagnetised iron consists of very tiny magnets known as molecular magnets. These molecular magnets are oriented in random direction so that net magnetic field of the iron is zero. When the iron core is magnetised by applying magnetising force (H), the molecular magnets start to rearrange in a particular direction and the iron core becomes a magnet.

In the linear zone of magnetisation curve,

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

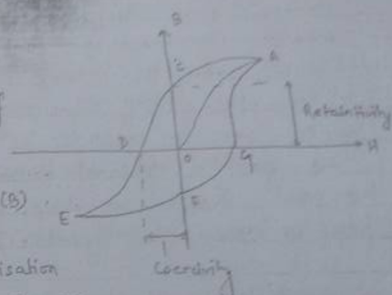
where, $\mu = \mu_o \mu_r$

μ_o = permeability of free space = $4\pi \times 10^{-7}$ H/m

μ_r = relative permeability of the iron core

1.6 Hysteresis with DC and AC excitation

(A) Hysteresis with DC



During the process of magnetisation of an iron bar, the magnetic flux density (B) increases due to increase in magnetisation force (H) if we go on increasing the value of current (I) that passes in the coils wound around bar. However this is not true when magnetic saturation is reached. In the above figure we suppose A is the point where magnetic saturation is reached.

After magnetising the core upto saturation zone, if magnetising force (H) is reduced by decreasing the current (I), the curve follows the path A-C as shown in the figure above. It is clear that B does not reduce to zero even when H is reduced to zero. 'OC' is the amount of magnetic flux density (B) retained by the core. This is known as retaintivity or residual magnetic flux density of the core.

To demagnetise the core to zero flux density, we have to apply the magnetising force (H) in opposite direction by changing the polarity of DC source. 'OD' is the magnitude of magnetising force (H) required to demagnetise the core to zero flux density and is known as Coercivity of the core.

After flux density has been reduced

to zero. If the value of 'H' is further increased in reverse direction, the core again reaches a state of saturation represented by point 'E' in above figure. If we now reduce the value of 'H' to zero (corresponding to the point 'F'), the magnetic flux density retained by the core is equal to 'OF'. If we further magnetise the core in forward direction, the curve follows the path F-G-A completing a closed loop. This closed loop is Known as 'Hysteresis loop'.

According to Weber's molecular theory of magnetism, when a magnetic material is magnetised its molecules are forced to align along a straight line. Therefore energy is spent in this process. If the core has no retaintivity (i.e. the core demagnetise along the same path as that was magnetised), then the energy spent in straightening the molecules could be recovered by reducing the magnetising force (H) to zero. But in case of material having retaintivity, all the energy put into it for straightening the molecules is not recovered when magnetising force (H) is reduced to zero. This energy loss is simply known as hysteresis.

Now we shall proceed to calculate the loss energy per cycle of magnetisation.

let,

l = length of the iron core
A = cross-sectional area of the core
N = number of turns in the winding
B = magnetic flux density at any instant.

Then the magnetic flux at any instant is given by
$\phi = B.A$ which is time varying

The instantaneous value of emf induced in the coil due to time varying flux is given by:

$$e = N\frac{d\phi}{dt} = N\frac{d}{dt}(BA) = NA\frac{dB}{dt}$$

The magnetising force is given by : $H = \frac{NI}{l}$ or $I = \frac{Hl}{N}$

The power or rate of expenditure of energy in maintaining the current 'I' against the emf 'e' is given by

$$p = eI \text{ Watt}$$
$$= NA\frac{dB}{dt}.\frac{Hl}{N}$$

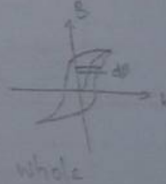
$$\text{or, } p = AlH\frac{dB}{dt}$$

Energy spent in a small fraction of time dt is given by

$$dw = p\,dt = AlH\,dB \text{ Joule}$$

Hence the total energy spent in a cycle of magnetisation is given by

$$W = \oint AlH\,dB \text{ Joule}$$



where, $\oint$ stands for integration over the whole cycle.

$H\,dB$ = shaded area in above figure.
$\therefore \oint H\,dB$ = area of the whole loop

And, energy spent per cycle = $Al \oint H\,dB$

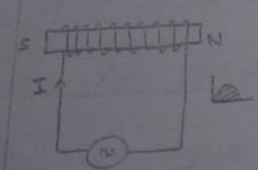
But, $A.l$ = Volume of the iron core.

$\therefore$ $\boxed{\text{Energy spent per cycle per unit volume} = \oint H\,dB = \text{Area of the loop}}$

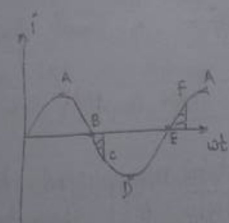
Hysteresis loop measures the energy dissipated due to Hysteresis which appears in the form of heat and raises the temperature of that portion of the core. This energy loss is known as Hysteresis loss.

(B) Hysteresis with AC

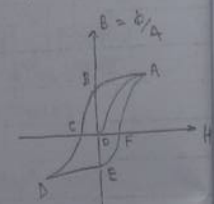
If an electromagnet is excited by ac voltage as shown in fig (a), the iron core will go through magnetic reversal twice in a cycle of ac excitation.



(a) polarity for positive half cycle



(b) waveform of ac excitation current



(c) Hysteresis loop ac excitation

Let us assume that the iron core is completely demagnetised in the beginning. Figure (b) shows the waveform of magnetising current 'i' and figure (c) shows the

corresponding Hysteresis loop for a cycle of current 'I'. Energy proportional to triangular shaded area is lost in every cycle to demagnetize the residual magnetic flux in the core. The area of the hysteresis loop also indicates the energy loss due to Hysteresis. The power loss due to Hysteresis effect is given by

$$W_h = \eta B_m^{1.6} f V \quad \text{(Watts)}$$

where,

B_m = maximum value of magnetic flux density in core

f = Frequency of exciting current.

V = Volume of iron core.

η = Steinmetz constant

= 502 Joules per m^3 for sheet steel.

= 191 Joules per m^3 for Silicon steel.

7. Hysteresis loss and Eddy current loss

Hysteresis loss is defined as the energy lost while magnetising a magnetic material. This is mainly due to the property of material to retain some value of flux density in them even when magnetising force is removed.

In general there are 3 classes of magnetic materials based on relative permeability value. They are

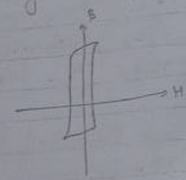
(a) Ferromagnetic material → $\mu_r >> 1$ → μ_r dependent on H.

(b) Paramagnetic material → μ_r or slightly > 1 → μ_r independent on H.

(c) Diamagnetic material → $\mu_r < 1$ → μ_r independent on H.

Ferromagnetic materials are further grouped into soft magnetic materials (narrow hysteresis loop) and hard magnetic materials (broad hysteresis loop).

(a) Hard magnetic material's



(b) Soft magnetic material's

Hard magnetic materials have high retaintivity and coercivity. So it is well suitable for making permanent magnets. Alloys of aluminium, Nickel and steel (called - Alnico) is the example of hard magnetic material.

The materials having small hysteresis loop i.e. Soft magnetic materials have high retaintivity but low coercivity resulting low hysteresis loss. Silicon steel sheet is the example of soft magnetic material. These materials are most suitable for making transformer core and armature core where rapid reversal of magnetisation occurs.

Eddy current loss

As the magnitude of magnetic flux in the core is time varying in nature, emf will induce in the core and some current will circulate within the core. This circulating current is known as

eddy current. This current produces heat in the core. The power loss due to this phenomenon is known as eddy current loss. The eddy current loss depends upon the resistivity of the core and length of the path of this circulating current for a given cross section. In order to reduce eddy current loss in practical applications, high resistivity is acheived by adding silicon to steel and the path length of eddy current is increased by dividing up the solid core into thin lamination along the flow of flux, with each lamination lightly insulated by varnish from the adjoining ones.

Eddy current loss is given by

$$W_e = K B_m^2 f^2 t^2 V \text{ (Watt)}$$

Where,

B_m = Maximum value of magnetic flux density in the core

f = frequency of exciting current

V = volume of iron core

t = thickness of each lamination.

K = constant depending upon the nature of core.

1.8 Faraday's law of Electromagnetic Induction, Statically & Dynamically Induced EMF

In 1831 A.D., Michael Faraday ('The Prince of Experiments') formulated the basic two laws underlying the phenomenon of electromagnetic induction. Those two laws are :-

1st law

Whenever the magnitude of magnetic flux linking with a coil changes w.r.t. time, an emf will be induced in the coil.

2nd law

The magnitude of induced emf is equal to the rate of change of flux-linkage.

Change in magnetic flux linkage of a coil may occur in three ways :-

(i) The coil remains stationary w.r.t. the flux, but the magnitude of flux through the coil changes w.r.t. time. The emf induced by this process is known as Statically Induced emf.

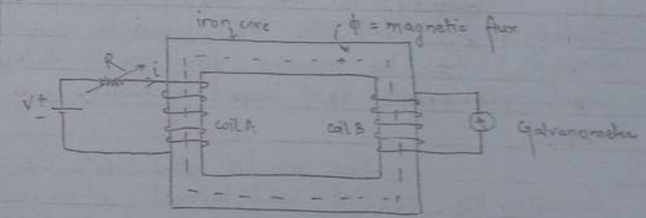
(ii) The magnetic flux density remains constant and stationary but the coil moves relative to the magnetic flux. The emf induced by this process is known as Dynamically Induced EMF.

(iii) Both changes (i) and (ii) occur simultaneously i.e. the

moves through time varying flux. Both statically and dynamically induced emfs are then present in the coil.

(i) Statically induced emf

In this method there is no relative motion between conductor and magnet. Figure given below shows an iron core with conductive coils 'A' and 'B'. A galvanometer is connected across the coil 'B' and coil 'A' is supplied by dc source with a variable resistance in series.



When the current 'i' through the coil 'A' is varied by changing the variable resistance, the galvanometer will show some deflection indicating the induced emf in the coil 'B'. When the current 'i' through the coil 'A' is varied, the magnetic flux will also vary. This time varying flux links with the coil 'B' and emf will induce in the coil 'B'.

let,

N = no. of turns in the coil 'B'

Suppose that magnetic flux changes from an initial value of ϕ_1 to the final value of ϕ_2 in time of 't' sec.

Then emf induced, e = Rate of change of flux linkage

$$= \frac{N\phi_2 - N\phi_1}{t} \quad \text{Volts}$$

Expressing above equation in differential form, we get

$$e = N\frac{d\phi}{dt}$$

The direction of statically induced emf is given by Lenz's law.

According to the Lenz's law, the statically induced emf will drive the current in such a direction that the magnetic flux due to the induced current will oppose the cause by which emf was induced.

Consider the case of emf induced in the coil 'B' due to increasing magnitude of current 'i'. Then in that case the induced current in the coil 'B' has to generate the magnetic flux in the direction to oppose the direction of rising main flux 'ϕ'. Hence the direction of induced current in the coil 'B' will be as shown below.

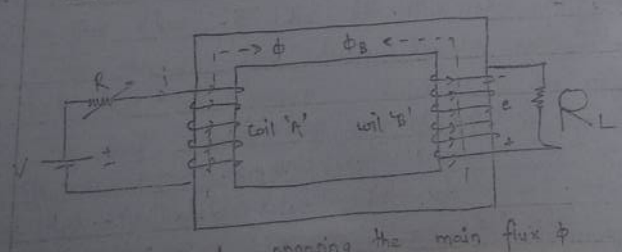


fig:- ϕ_B opposing the main flux ϕ

Consider now the case of emf induced in the coil 'B' due to decreasing magnitude of current 'i'. Then in that case the induced current in the coil 'B' has to generate the magnetic flux in the direction to support the direction of main flux 'ϕ'. Hence the direction of induced current in the coil 'B' will be as shown below.

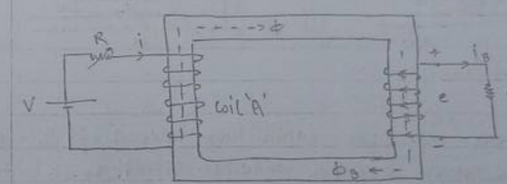
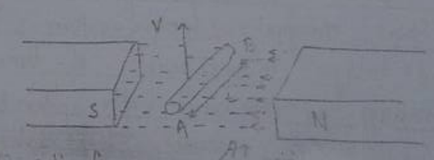


fig:- ϕ_B supporting the main flux ϕ

(ii) Dynamically induced emf

In this method there is relative motion between the conductor and the magnet. Let us consider a conductor A-B placed in the magnetic field as shown in figure below. When the conductor is moved upward or downwards, it will cut the magnetic flux. Therefore according to Faraday's law of EMI, emf will be induced on the conductor A-B. If a circuit is completed across A-B current will flow in the circuit.



magnetic flux

let,
L = length of the conductor lying within the magnetic field (m)
v = velocity of conductor (m/sec)
B = magnetic flux density (Wb/m^2)

(a) (b)

For figure (a),

Distance moved in small time interval of $dt = v \cdot dt$ =
Area swept by the conductor in dt sec = $L \cdot dx$
Flux cut by the conductor in dt sec = $L\,dx\,B$
Rate of change of flux = $\frac{L\,dx\,B}{dt} = \frac{L\,v\,dt\,B}{dt} = B.$

Hence, $e = B \cdot L \cdot v$

If the conductor moves making an angle θ with the direction of magnetic flux as shown on fig (b) then emf generated is given by,

$$e = B \cdot L \cdot v \sin\theta$$

where,
$v\sin\theta$ = component of v in the direction perpe to the direction of magnetic flux

(iii) In static magnetic configuration, inductance 'L' is fixed and independent of time. But in ca of rotating machine both 'L' and 'i' may vary w.r.t. time. In such cases both

statically and dynamically induced emfs will be present in the coil and magnitude of emf shall be calculated as follows:-

$$L = \frac{N \cdot \phi}{i}$$

or, $N \cdot \phi = Li$

or, $N\,d\phi/dt = d(Li)/dt$

$$\therefore e = N\frac{d\phi}{dt} = \underbrace{L\frac{di}{dt}}_{\text{Statically induced EMF}} + \underbrace{i\frac{dL}{dt}}_{\text{dynamically induced EMF.}}$$

1.9 Force on a current carrying conductor

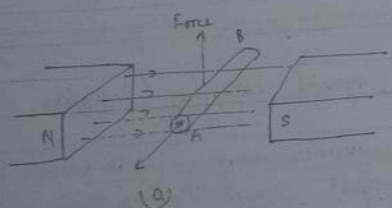
Whenever a current carrying conductor is placed in a magnetic field, a force will develop on the conductor. The magnitude of force is given by

$$F = BIL \quad \text{(Newton)}$$

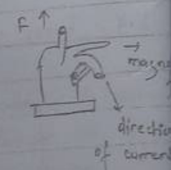
Where,
B = magnetic flux density (Wb/m^2)
I = current passing through the conductor (Amp)
L = Length of the conductor lying within the magnetic field.

The direction of force will be perpendicular to both the direction of magnetic flux and current and is given by Fleming's left hand rule.

Let us consider a conductor A-B carrying a current of 'I' amp from B to A which is placed in a magnetic field as shown in fig below (a). According to Fleming's left hand rule the thumb forefinger and middle finger of the left hand shall be arranged in such a way that they are perpendicular to each other and the forefinger shall direct to the direction of magnetic flux and the middle finger shall directed to the direction of current then the thumb will indicate the direction of force as shown in fig (b).



(a)



(b)

Other important terms in this chapter

$$L = \frac{e}{di/dt} \qquad \left[\because e = \frac{N\, d\phi/dt}{di/dt} \text{ let's put it}\right]$$

$$\Rightarrow L = \frac{N\phi}{i}$$

and $$L = \frac{\mu_0 \mu_r A N^2}{l} \qquad \left[\because \phi = \frac{Ni}{R}\right]$$

$$\left(\text{and } R = \frac{l}{\mu_0 \mu_r A}\right)$$

Also,

$$M = \frac{N_2 \phi_1}{I_1} \quad \text{or,} \quad M = \frac{N_1 \phi_2}{I_2}$$

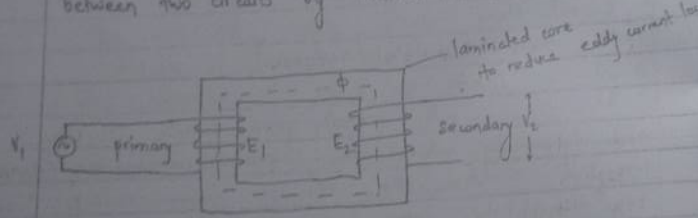
where, M = mutual inductance.

[From my classmate's viewpoint]

A prompt guess about statically and dynamically induced emf can be made by mere inspection where the machine from outside can be thought to have some movement, then it is dynamically induced emf. On the other hand if a machine behaves to be static and silent (from the viewpoint of noise) then it is statically induced emf. I found it to be handy in many cases and true when discussed with a teacher.

2.1 Constructional details, recent trends and Introduction

A transformer is a device which is used to step up voltages than that of generating voltages to acheive economical transmission and to step down these dangerously high voltage levels to suitable standard voltages to acheive safety and distribution. It is a static electric device and used to transfer power between two circuits by mutual induction.



In brief a transformer is a device that

1. transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction and
4. where the two electric circuits are in mutual influence of each other.

The simple elements of transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and the steel core.

There are mainly two types of transformers:-

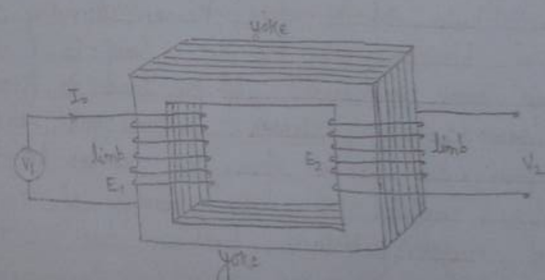
(a) core type transformer
(b) shell type transformer

To distinguish whether a trer is a core type or shell type we use a reference word as 'core'. In core type trer core is surrounded by windings while in shell type trer windings are surrounded by core.

The main advantage of core type trer is better ventilation (cooling). As windings are the part in which current flows and get more heated than core and in this trer, windings are placed exterior thereby giving better heat dissipation and good life to overall transformer structure. Therefore most of the recent engineering practice is seen to use core type trer for safe power handling and distribution.

2.2. Working principle and EMF equation

Basically a transformer consists of an iron core as shown in figure. Two separate coils are provided on two separate limbs of the core. The horizontal member of the core is known as yoke. The coils are made by winding of enamel insulated copper wire.



When one coil is supplied by ac voltage, the coil will draw some current (say I_0). Let us assume that the coil is purely inductive. Hence the current lags the applied voltage by $90°$. The waveform of V_1 and I_0 are shown below. The iron core shown above is the magnetic path for the magnetic flux (ϕ). The magnitude of magnetic flux (ϕ) depends upon the magnitude of I_0 and will be in phase with I_0 as shown.

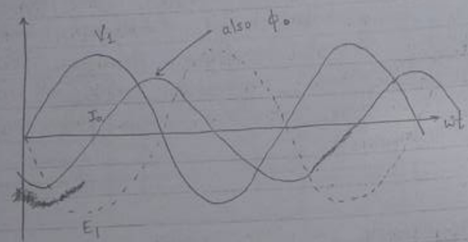
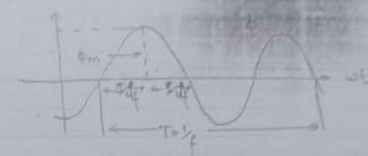


fig:- waveforms of V_1, E_1, I_0 and ϕ_0

The magnetic flux circulating in the core is alternating in nature whose magnitude is changing w.r.t. time. The magnetic flux is linked with the second coil on other limb of the core. Hence, according to Faraday's law of Electromagnetic Induction, emf E_2 will induce across the second coil. If the load is connected across the second coil, electric current will circulate thru transferring the power from first circuit to the second circuit. Therefore the main principle of t/f er is the mutual magnetic induction between two coils.



let, N_1 = No. of turns in primary
N_2 = No. of turns in secondary
ϕ_m = maximum flux in core in webers
$= B_m \times A$
f = frequency of ac input in Hz.

As shown in above figure, flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. $\frac{1}{4f}$ second.

$$\therefore \text{Average rate of change of flux} = \frac{\phi_m}{1/4f}$$
$$= 4f\phi_m \text{ Wb/s or Volt}$$

Now, rate of change of flux per turn means induced emf in volts.

$$\therefore \text{Average emf / turn} = 4f\phi_m \text{ Volt}$$

If flux ϕ varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value with form factor.

$$\text{Form factor} = \frac{\text{rms value}}{\text{Average value}} = 1.11$$

$$\therefore \text{rms value of emf / turn} = 1.11 \times 4f\phi_m = 4.44 f \phi_m \text{ volt}$$

Now ~~rms~~ value of the induced emf in the whole of primary winding
= (induced emf./turn) × No. of primary winding

$$E_1 = 4.44 f \phi_m N_1 = 4.44 f N_1 B_m A$$

Similarly, $E_2 = 4.44 f \phi_m N_2 = 4.44 f N_2 B_m A$.

The above equations are known as emf equations of a transformer.

So, $\boxed{\dfrac{E_2}{E_1} = \dfrac{N_2}{N_1} = K}$

The constant K is known as voltage transformation ratio.

if $K > 1$ → step up-trer
if $K < 1$ → step down-trer

For an ideal trer,

$$V_1 I_1 = V_2 I_2$$

$$\boxed{\dfrac{I_2}{I_1} = \dfrac{V_1}{V_2} = \dfrac{1}{K}}$$

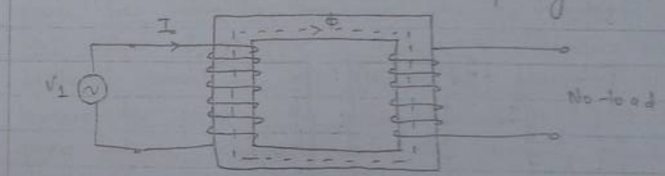
2.3 Ideal transformer

An ideal transformer is that which has purely inductive windings without any resistance, which don't have any magnetic leakage flux and which is 100% efficient without any power loss within the transformer. This is just a mathematical abstraction and such trer can not be made in real practice.

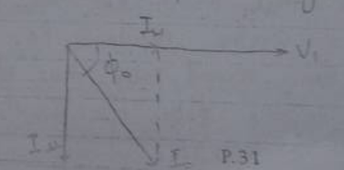
2.4. No-load and load operation

(I) No-load operation of Transformer

When the primary winding of a transformer is supplied by ac voltage of rated magnitude keeping the secondary open, the primary will draw some current (I_0) which is known as no-load primary current.



The primary winding of a real transformer will not be purely inductive. It will have resistance as well. Hence the primary current I_0 will lag the applied voltage V_1 by some angle ϕ_0 which will be less than 90° as shown in phasor diagram.



The no-load current I_0 can be resolved into two components as follows.

$I_w = I_0 \cos\phi_0$ = Loss component of I_0

$I_\mu = I_0 \sin\phi_0$ = Magnetising component of I_0.

The power consumed by the transformer at no-load is given by

$$W_0 = V_1 I_0 \cos\phi_0$$

where,

$\cos\phi_0$ is known as no-load power factor of the transformer. From the phasor diagram it is clear that

$$I_0 = \sqrt{I_w^2 + I_\mu^2}$$

Based on above mathematical analysis, no-load equ circuit of the transformer can be developed as show below.

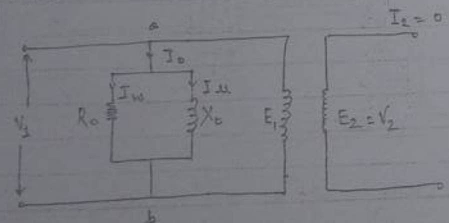


fig:- No-load equivalent ckt

The branch a-b in the equivalent circuit is known no-load branch. This branch has two parallel path. One path has coreless resistance R_0 and it is the path for I_w. The second path has magnetising re X_0 and it is the path for I_μ.

II) Operation of trer with load

When the load is connected across the secondary winding some current I_2 will flow through the secondary circuit. Now the secondary mmf $N_2 I_2$ will set up its own magnetic flux ϕ_2 which direction is opposite to the main flux ϕ.

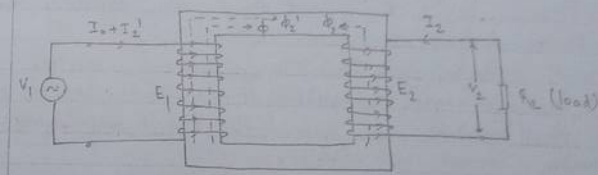


fig:- Transformer with load

At no-load, the output of the transformer $V_2 I_2 = 0$ but the input power is $V_1 I_0$. This input power at no-load is power loss within the transformer. When the transformer is loaded, the output of the trer is $V_2 I_2$ ($\neq 0$). Therefore some additional current I_2' will flow in the primary winding to increase the power in the primary circuit so that there is power balance between primary and secondary circuit. This additional current I_2' in the primary winding will set up its own magnetic flux ϕ_2' whose direction will be opposite to the direction of ϕ_2. The additional power in the primary winding should be equal to the power in the secondary winding.

$$\therefore \quad V_1 I_2' = V_2 I_2$$

$$\text{or, } \frac{I_2'}{I_2} = \frac{V_2}{V_1} = \frac{N_2}{N_1} \Rightarrow N_1 I_2' = N_2 I_2$$

$$\text{or } \frac{N_1 I_1'}{\mathcal{R}} = \frac{N_2 I_2}{\mathcal{R}} \qquad (\mathcal{R} = \text{reluctance})$$

$$\boxed{\therefore \phi_2' = \phi_2}$$

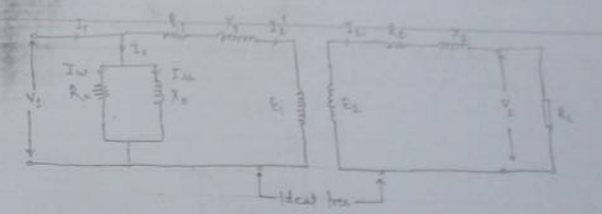
Since, $\phi_2' = \phi_2$ and they act oppositely, they cancel each other.

Hence the net-magnetic flux in the core is always constant at any load and is eq to ϕ. Therefore at any load the emf equation remain same as follows:-

$$E_1 = 4.44 N_1 f \phi_m \text{ volts}$$
$$E_2 = 4.44 N_2 f \phi_m \text{ volts}$$

2.6. Equivalent circuits and phasor diagrams

The power loss in the transformer at no-load has been simulated by the shunt branch resistance R_0 in the no-load equivalent circuit. This power loss remains constant irrespective of the load on the transformer. As the transformer is loaded, primary or secondary current will increase, thereby causing more voltage drop and power loss in both primary and secondary windings. These voltage drop and power losses at loaded condition depend upon the magnitude of currents and simulated by R_1 and R_2 as shown below.



X_1 and X_2 in the above ckt diagram are known as leakage reactance of PW and SW respectively. These are imaginary reactance introduced in the equivalent circuit to simulate the reactive voltage drop due to leakage flux.

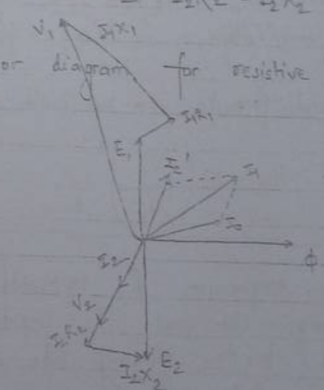
KVL on primary side gives,

$$V_1 = I_1 R_1 + I_1 X_1 + E_1$$

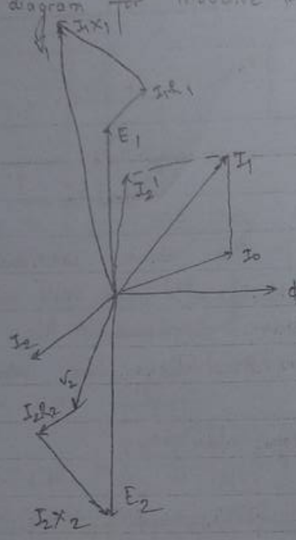
and on secondary side gives,

$$V_2 = E_2 - I_2 R_2 - I_2 X_2$$

The phasor diagram for resistive load can be drawn as



The phasor diagram for inductive load can be drawn as



Impedances on either side of transformer circuit can be transferred to the another side with a certain mathematical variation. $I_2^2 R_2 = I_1^2 R_2'$

For simplicity, $R_2'/R_2 = \left(\frac{I_2}{I_1}\right)^2 = \left(\frac{V_1}{V_2}\right)^2 = \frac{1}{k}$

If a general formula can be built as,

$$R_2' = R_2 \times \left(\frac{V_1}{V_2}\right)^2$$

In the above expression R_2 represents resistance in the secondary ckt and R_2' represents its value when transfered to the primary side. The product term which is further squared is to be taken care of, mostly.

The voltage of the side where we want to transfer is written on the numerator and from where it is transferred is written on the denominator.

Similarly,

$$R_1' = R_1 \times \left(\frac{V_2}{V_1}\right)^2$$

lly, $X_2' = X_2 \times \left(\frac{V_1}{V_2}\right)^2$

$$X_1' = X_1 \times \left(\frac{V_2}{V_1}\right)^2$$

So,

Z_{01} = equivalent empedance on primary side $= \sqrt{R_{01}^2 + X_{01}^2}$

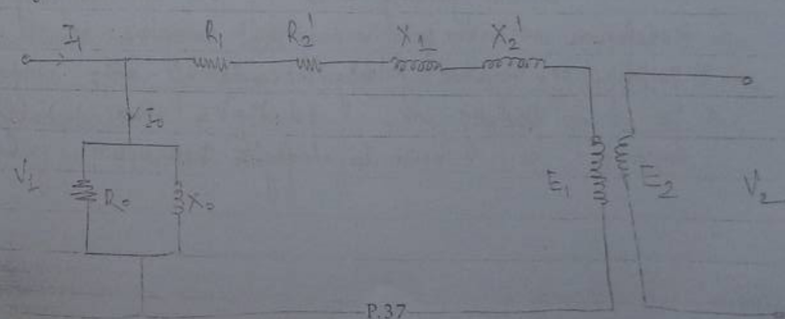
where, $R_{01} = R_1 + R_2'$

$X_{01} = X_1 + X_2'$

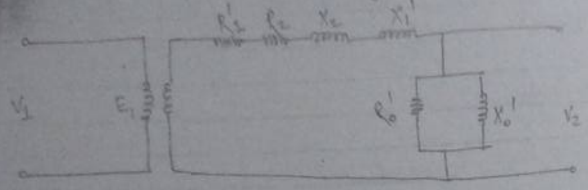
Also,

$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$ with similar definations.

Now we can draw equivalent circuit when referred to primary side,



Also when referred to secondary side,



2.7 Transformer tests

Large transformer can not be tested by direct loading test because of following problems :

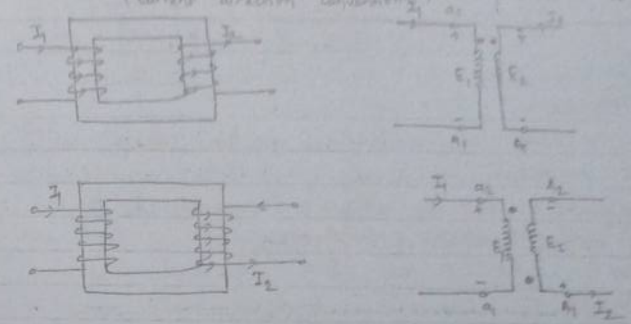
(a) Large amount of energy has to be wasted in such a test
(b) It is not feasible to have a load large enough for direct loading in the lab.

Therefore the performance characteristic of a transformer must be computed from the knowledge of equivalent circuit parameters. The parameters of equivalent circuit can be calculated from the simple transformer tests.

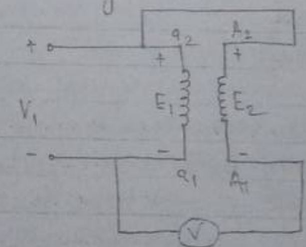
(A) Polarity Test

Similar polarity ends of a two winding transformer are those ends that acquire simultaneously positive or negative polarity because of emfs induced on them. Usually the polarity is indicated by dot convention as shown in figure below :-

As we know,
(current direction convention [illegible])



When there is a doubt about the winding polarity, It can be checked by a simple test called polarity test. In this test, the two windings are connected in series across a voltmeter, while one of the winding is excited by a suitable voltage source as shown in figure below :-

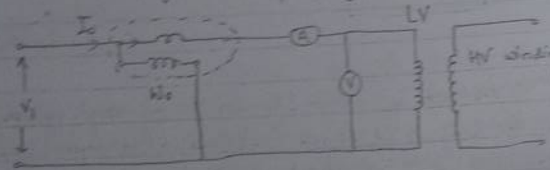


If the polarities of the winding are as marked on the diagram, the voltmeter should read $V = E_1 - E_2$. If the voltmeter reads $V = E_1 + E_2$, the marking of one of the winding must be interchanged.

(B) Open-circuit or No-load test

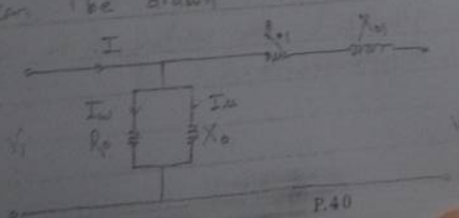
The purpose of this test is to determine no-load loss and no-load I_0 which is helpful in determining R_0 and X_0.

One winding of the transformer - whichever is convinient but usually high voltage winding is left open and the other is connected to its supply of normal voltage and frequency.



let,
V_1 = Voltmeter reading
I_0 = Ammeter reading
W_0 = Wattmeter reading

As the no-load current is very small with compared to full load current and the series resistance and reactance are also small, so copper loss at no-load can be neglected and the wattmeter reading can be considered as no load power loss or iron loss of the transformer. So the equivalent circuit can be drawn as shown below:-



The wattmeter reading is equal to the power consumed by the transformer at no-load and given by:-

$W_0 = V_1 I_0 \cos\phi_0$

where, $\cos\phi_0$ = no-load power factor

Then $\cos\phi_0 = \dfrac{W_0}{V_1 I_0}$ which can be calculated

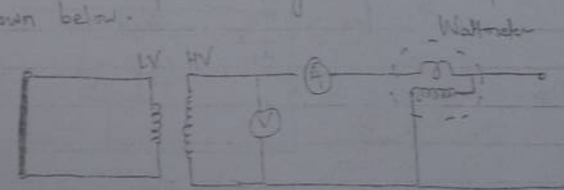
Once the no-load power factor $\cos\phi_0$ is calculated then $I_w = I_0 \cos\phi_0$ and $I_\mu = I_0 \sin\phi_0$, can also be calculated.

Then,

$$R_0 = \frac{V_1}{I_w} \quad \text{and} \quad X_0 = \frac{V_1}{I_\mu}$$

(C) Short-ckt test

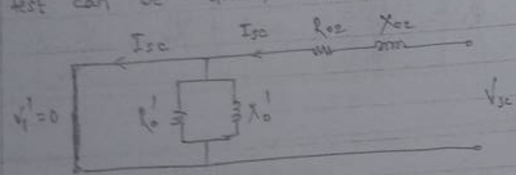
The purpose of this test is to calculate the series leakage reactance and series resistance of a transformer and the copper loss of the transformer at full load. In this test, the low voltage side is short circuited by a thick wire and the High voltage side is supplied by reduced voltage so that full load currents flows through the transformer coil as shown below.



let, V_{sc} = Voltmeter reading

I_{sc} = Ammeter reading
W_{sc} = Wattmeter reading

Since the test voltage V_{sc} is very small (about 5% of normal rated voltage), hysteresis loss is negligible because the iron core does not saturates and eddy current loss is also negligible due to low magnetic flux density in the core. Hence the iron loss in this test can be neglected. Thus, the equivalent circuit of the transformer for short ckt test can be drawn as shown below:-



Here, we can assume that no current will flow through the shunt branch due to short circuit. Hence the Wattmeter reading can be considered as copper loss of the trer at full load.

$$\therefore W_{sc} = I_{sc}^2 \cdot R_{02}$$

$$\text{or, } R_{02} = \frac{W_{sc}}{I_{sc}^2}$$ which can be calculated

Also,
$$Z_{02} = \frac{V_{sc}}{I_{sc}}$$

Then,
$$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$$

2.8. Voltage Regulation

A power supply system should address both consumer's and industrial load demands by a required standard voltage profile. It is therefore necessary that the output voltage of a trer must stay within narrow limits as the load and its power factor vary. When the load on the transformer increases, the coil current will increase and voltage drop in resistance and leakage reactance will increase accordingly. The transformer having minimum voltage drop is said to have better performance.

The figure of merit which determines the voltage drop characteristics is voltage regulation. It is defined as the change in magnitude of secondary terminal voltage, when full load is reduced to no-load with primary voltage held constant.

let, ${}_fV_2$ = full load terminal voltage
${}_oV_2$ = No load terminal voltage

Then the voltage regulation is given by,

$$V_{reg} = \frac{{}_oV_2 - {}_fV_2}{{}_fV_2}$$

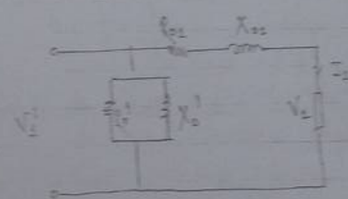
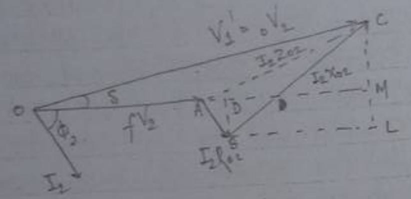


fig: equivalent ckt of a trer referred to secondary

The phasor diagram for above equivalent ckt is,



Here the total voltage drop $= I_2 Z_{02} = AC$
let us assume that angle δ is very small then, $AC \approx AM$

$$\text{or, } AC = AD + DM = AD + BL$$

$$\therefore AC = I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$$

From the phasor diagram,

$$_0V_2 - {}_fV_2 = AC$$

$$\therefore \text{Voltage regulation} = \frac{AC}{_fV_2} = \frac{I_2 R_{02} \cos\phi_2}{_fV_2} + \frac{I_2 X_{02} \sin\phi_2}{_fV_2}$$

$$\text{or, Voltage regulation} = R(pu) \cos\phi_2 + X(pu) \sin\phi_2$$

where, $R \text{ in pu} = \dfrac{I_2 R_{02}}{_fV_2}$ & similar for $X(pu)$

Then, $Z(pu) = \sqrt{R(pu)^2 + X(pu)^2}$ known as pu impedance.

2.9. Losses in a transformer

In a static transformer, there are no friction or windage losses. Hence, the only losses occuring are:-

(i) Core or Iron loss

It includes both hysteresis loss and eddy current loss. Because the core flux in a transformer remains practically constant for all loads, the core loss is practically the same at all loads.

Hysteresis loss $W_h = \eta B_{max}^{1.6} f V$ watt
eddy current loss $W_e = P B_{max}^2 f^2 t^2$ watt
↳ constant (K)

The losses are minimised by using steel of high silicon content for the core and by using very thin laminations. Iron or core loss is found from O.C. test. The input of a transformer when on no load measures the core loss.

(ii) Copper loss

This loss is due to the ohmic resistance of the transformer windings which result in heating. Total Cu loss $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} = I_2^2 R_{02}$. It is clear that Cu loss is proportional to $(\text{current})^2$ or $(\text{kVA})^2$. In other words Cu loss at half the full load is one fourth of that at full load. The value of Cu loss is found from short ckt test.

2.10 Efficiency of a transformer

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}} = \frac{\text{Output}}{\text{Output} + \text{Cu loss} + \text{iron loss}}$$

or,
$$\eta = \frac{\text{Input} - \text{losses}}{\text{Input}} = 1 - \frac{\text{losses}}{\text{Input}}$$

Condition for maximum efficiency

The Cu loss of a transformer is seen being equal to $I_1^2 R_{01}$ when referred to primary side.

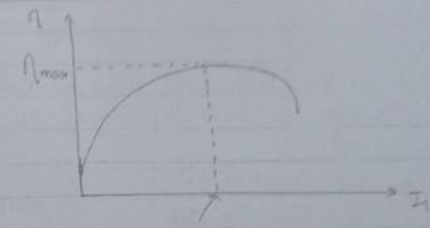
Input power to a transformer can be written as

$$P_{in} = V_1 I_1 \cos\phi_1 \text{ watts}$$

$$P_{out} = P_{in} - \text{Iron loss} - \text{Cu loss}$$

So,
$$\text{efficiency } (\eta) = \frac{V_1 I_1 \cos\phi_1 - W_i - I_1^2 R_{01}}{V_1 I_1 \cos\phi_1} \quad \text{---(1)}$$

From the above equation, it is clear that the efficiency depends upon the load current. If we plot a curve showing the efficiency of transformer at different values of load current, the curve will be as shown below:-



I_1 at max efficiency

Equation (1) can be written as follows

$$\eta = 1 - \frac{W_i}{V_1 \cdot I_1 \cdot \cos\phi_1} - \frac{I_1 R_{01}}{V_1 \cos\phi_1}$$

Differentiating w.r.t. I_1, we get,

$$\frac{d\eta}{dI_1} = 0 - \frac{W_i}{V_1 \cos\phi_1}(-1) \cdot I_1^{-2} - \frac{R_{01}}{V_1 \cos\phi_1}$$

The efficiency η will be maximum when $\frac{d\eta}{dI_1} = 0$

i.e.
$$\frac{W_i}{V_1 \cdot I_1^2 \cos\phi_1} - \frac{R_{01}}{V_1 \cos\phi_1} = 0$$

or,
$$W_i = I_1^2 R_{01} = W_c$$

$$\boxed{\therefore \text{Iron loss} = \text{Copper loss}}$$

Hence for maximum efficiency iron loss must be equal to copper loss.

Further,
$$I_1 = \sqrt{W_i / R_{01}}$$

All day efficiency

It is defined as the ratio of output in KWh to the input in KWh for a time period of 24 hours.

i.e. $\eta_{all\text{-}day} = \dfrac{\text{Output in KWh}}{\text{Input in KWh}}$ (24 hours)

2.11 Instrument Transformers: Potential Transformer (PT) and Current Transformer (CT)

Instrument transformers are special transformers designed for the applications in instrumentation and protection relay schemes. The transformers are designed with highly accurate transformation ratio. There are two types of instrument transformers.

(a) Current Transformer (CT)
(b) Potential Transformer (PT)

(A) Current Transformer

These transformers are designed to sense the high current through primary circuit and steps down the current in a known ratio. The primary winding of CT is supplied by a current source rather than a voltage source. The primary winding of CT will have few turns of thick wire enough to carry the primary high current and is connected in series with the load. The secondary winding will have many no. of turns made of thin wire and connected across a low range ammeter. (step up trer)

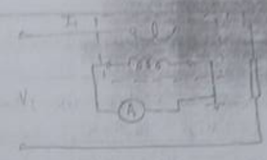
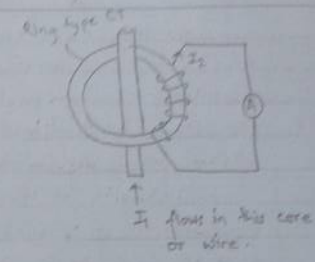


fig:- connection of CT



let,
I_1 = High current through primary circuit to be measured
I_2 = Secondary current through the ammeter
K = transformation ratio $= \dfrac{I_1}{I_2}$ or, $I_1 = KI_2$

Hence the high current I_1 can be estimated from the low range ammeter reading provided the transformation ratio K of CT is known. Measurement of high current with the help of CT and low range ammeter has the following advantages:-

i) The instrument has been transferred to secondary side of CT so that normal instrument may be used and the observer and the instrument can be well far away from the source of danger.

ii) A low range ammeter (usually 5 A) can be used to measure much larger current.

The secondary of a CT should not be kept open without ammeter while the primary is carrying current. If the secondary is kept open, there will be no current through the secondary and the secondary winding will not produce the opposing flux which is required for cancelling the additional flux produced by the primary winding. Hence high voltage will induce in the winding due to higher value of flux density in the core and may cause insulation failure. Hysteresis loss and eddy current loss will be high due to high value of flux density in the core. This may lead to overheating of core which will again damage the insulation of winding. Hence the secondary winding shall be short circuited while the ammeter is disconnected.

(B) Potential Transformer

These are extremely accurate ratio step down transformers and are used in conjunction with standard low range voltmeters (usually 250 volts) whose deflection when divided by transformation ratio (K) gives the true value of voltage on HV side.

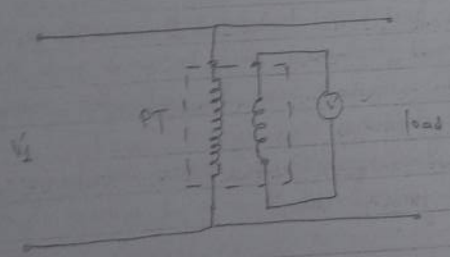


fig:- connection of PT

2.12 Auto-transformer

It is a trer with one winding only part of this winding being common to both primary and secondary side. Such a transformer is particularly economical where the transformation ratio is very close to unity.

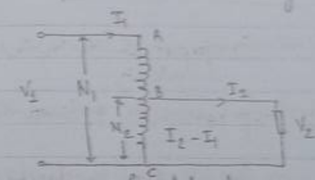


fig:- Auto -trer

The above auto trer has N_1 turns in primary and N_2 turns tapped for lower secondary voltage. The winding section 'BC' of N_2 turns is common to both primary and secondary circuits.

let, I_2 = current drawn by the load
I_1 = primary current

Then the current in the section 'BC' is the vector difference of I_2 and I_1 i.e. $I_2 - I_1$ where, $I_2 > I_1$

Since, $V_1 I_1 = V_2 I_2$

So,

$V_1 > V_2$.

As we know volume and hence weight of Cu is proportional to the length and area of the cross-section of the conductors. Now, length of conductor is proportional to the number of turns and cross-section depends on current. Hence, weight is proportional to the product of current and number of turns

So,

weight of Cu in section AB $\propto (N_1 - N_2) I_1$

weight of Cu in section BC $\propto N_2 (I_2 - I_1)$

$\therefore$ Total weight of Cu in auto-transformer $(W_{auto}) \propto (N_1 - N_2) I_1 + (N_2)(I_2 - I_1)$

If a two winding transformer were to perform the same duty, then

weight of copper in two winding transformer

$$W_{tw} \propto (N_1 I_1 + N_2 I_2)$$

Thus,

$$\frac{W_{auto}}{W_{tw}} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2} = \frac{N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$\text{or, } \frac{W_{auto}}{W_{tw}} = 1 - \frac{2 N_2 I_1}{N_1 I_1 + N_2 I_2}$$

dividing by $N_1 I_1$ here

$$\text{or, } \frac{W_{auto}}{W_{tw}} = 1 - \frac{2 \frac{N_2}{N_1}}{1 + \frac{N_2 I_2}{N_1 I_1}}$$

$$\text{or, } \frac{W_{auto}}{W_{tw}} = 1 - \frac{2 \cdot K}{1 + K \cdot \frac{1}{K}}$$

$$\text{or, } \frac{W_{auto}}{W_{tw}} = 1 - \frac{2K}{2}$$

$$\therefore W_{auto} = (1 - K) \times W_{tw}$$

Thus,

$$\text{Saving of Copper} = W_{tw} - W_{auto}$$
$$= W_{tw} - (1 - K) W_{tw}$$
$$= W_{tw} - W_{tw} + K W_{tw}$$

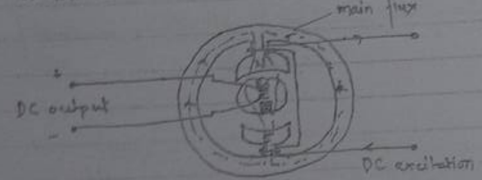
$$\boxed{\text{Saving of Cu} = K \times \text{weight of Cu in two winding trans}}$$

Chapter 3   DC Generator ...

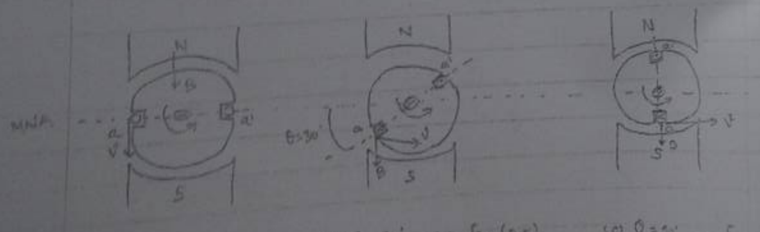
DC generators are rotating electrical machines used to convert mechanical power into electrical output power in DC form after internal commutation.

3.2 Working principle and Commutator Action

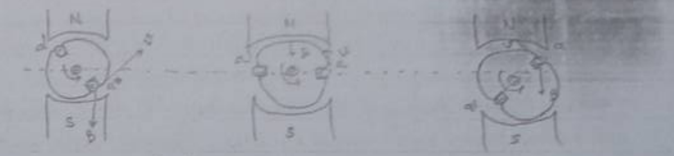
Let us consider a 2-pole elementary DC machine as shown in the figure below. When the winding is excited by DC current, the field pole will get magnetised. If the armature is rotated continuously by the external force, the armature conductors will cut the magnetic flux continuously. Hence, according to Faraday's law of electromagnetic induction emf will induce in the armature coil.



The nature of emf induced in the armature coil can be described from the following illustration.



(a) $\theta = 0°$, $e = 0$ (b) $\theta = 30°$, $e = E_m(0.5)$ (c) $\theta = 90°$, $e = E_m$



(d) $\theta = 135°$, $e = E_m(0.707)$ (e) $\theta = 180°$, $e = 0$ (f) $\theta = 210°$, $e = -E_m(0.5)$

The above figures show a particular position of armature where the plane of the coil is perpendicular to the direction of magnetic flux. The magnitude of emf is given by:-

$$e = B.l.v \sin\theta$$

where,

B = magnetic flux density (Wb/m^2)
l = length of the coil lying in the magnetic field
v = velocity of the conduction.
θ = Angle between the direction of B and v

At a particular instant in fig (a), the angle $\theta = 0°$. Therefore emf induced in the coil is zero. Let us assume this position as initial zero position.

After 30° rotation from this zero position in the anti-clockwise direction, the situation will be as shown in fig (b). The magnitude of emf is given by

$$e = B.l.v \sin\theta$$
$$= B.l.v \sin 30°$$
$$= B.l.v.(1/2) = E_m(0.5)$$

The direction of emf (as determined by Right hand Fleming's rule) will be as shown in fig (b) i.e. the current is flowing in through conductor 'a' and coming out through the conductor 'a''. Here the function of commutator and carbon brushes has not been considered.

After 90° rotation from the zero position, the situation will be as shown in fig(c). Here the conductor cuts the magnetic flux in the perpendicular direction. The magnitude of emf is given by

$$e = B.l.v \sin 90° = Blv = E_m$$

The direction of emf is same as in previous case.

After 135° rotation, $e = E_m (0.707)$ and direction of emf is same as in previous case

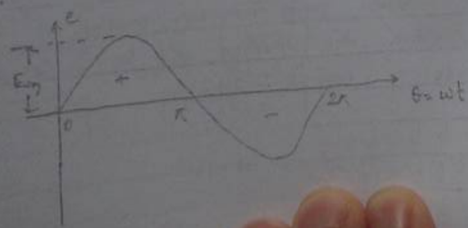
After 180° rotation, $e = 0$

After 210° rotation, $e = -E_m (0.5)$ and direction is reversed.

After 270° rotation, $e = -E_m$

After 360° rotation, $e = 0$ (same as at $\theta = 0°$)

From the above analysis it is clear that the nature of emf induced in the coil a-a' is alternating (ac) in nature and the waveform of emf induced is shown below.



In the absence of commutator segments and carbon brushes there are two major problems in the dc generator.

(i) It is practically impossible to connect a stationary external load across the rotating armature.

(ii) The voltage output from the armature is ac whereas we are looking for DC voltage. [These two problems can be eliminated by introducing commutator segments and carbon brushes.]

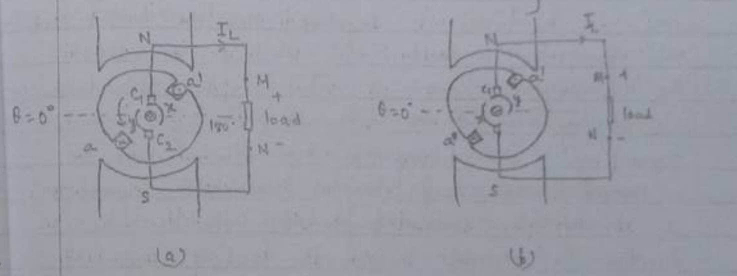
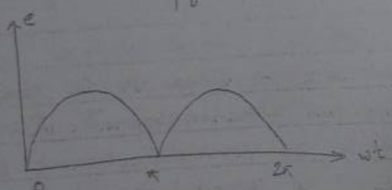


fig:- DC machine with commutator segments and carbon brushes.

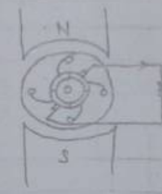
The above figure shows the DC generator with commutator segments and carbon brushes. The conductor 'a' is connected to the commutator segment no. 1 and the conductor a' is connected to the commutator segment no. 2. The commutator segments rotates along with the armature coil but the carbon brushes C_1 and C_2 are fixed touching over the commutator segments surface.

In fig. (a) shows an instant at which emf in the coil is positive. Here the current comes out from the conductor a which is connected to the commutator segment x. Therefore the carbon brush C_1 collects the current from the commutator segment x and delivers to the external load. The current comes back to the commutator segment 'y' through the carbon brush C_2. Hence the direction of current through the load is M to N for positive half cycle of emf in the coil.

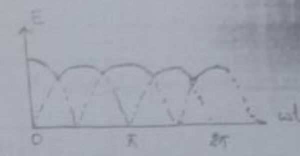
In fig (b) above shows an instant at which emf in the coil is negative. Here the current comes out from the conductor 'a' which is connected to the commutator segment y. Therefore the carbon brush C_1 again collects the current from the commutator segment y and delivers to the external load. The current comes back to the commutator segment x through the carbon brush C_2. Hence the direction of current through the load is again M to N. Therefore the nature of emf across the load will be as shown in fig below.



If we use two armature coils spaced 180° apart as shown below then the nature of emf across the load will be more smoother than in case of a single coil.



(a)



(b)

3.3 Emf equation

let,

ϕ = Magnetic flux per pole (wb)

P = Number of magnetic poles

Z = Total number of armature conductors.

N = Speed of armature in RPM

Average emf generated per conductor $= d\phi/dt$

Magnetic flux cut by each conductor in one revolution $= d\phi = \phi \cdot P$

Time for one revolution $dt = \frac{60}{N}$ sec.

Thus, average emf generated per conductor $= d\phi/dt$

$$= \frac{\phi P N}{60} \text{ volt}$$

let,

A = number of parallel paths in the armature

Then number of conductors in series $= Z/A$

$\therefore$ Total emf across the brushes $E = \frac{\phi P N}{60} \times \frac{Z}{A}$ volts

or, $$\boxed{E = \frac{Z \phi N}{60} \times \frac{P}{A}}$$

where, $A = P$ for lap winding
$= 2$ for wave winding

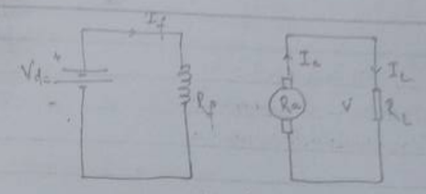
3.4. Method of excitation : Separately and self-excited, Types of DC generator.

The field winding of DC generator needs DC current in order to produce magnetic field. The supply of DC current to the field winding is known as 'Excitation'. According to the method of excitation DC generators can be classified into two types:-

(a) Separately excited DC generators
(b) Self-excited DC generators.

(a) Separately excited DC generators

These are the generators whose field windings are supplied by an independent external DC voltage source. The field windings will not have electrical connection with the armature circuit.



ckt diagram of separately excited DC generator.

Here, $I_f = \frac{V_{dc}}{R_f}$

$I_a = I_L$

Using Kirchoff's voltage law for the armature and load circuit
$E - I_a R_a - I_L R_L = 0$

let,
$V = I_L R_L$ = Terminal voltage across the load.
$\therefore E - I_a R_a = V$

Also,
$V = E - I_a R_a$ - voltage drop due to brushes.

(b) Self-excited DC generators

These are the generators whose field windings are excited by the DC current generated by the armature of the machine itself. No external DC source are required for such generators. The field winding and armature winding have electrical connection. The interconnection of field and armature winding can be done in different ways and accordingly the self excited DC generators can be classified into three types :-

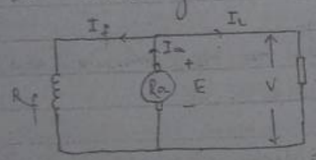
(i) DC shunt generator

(ii) DC series generator.

(iii) DC compound generator

(i) DC shunt generator

In this type of generator, the field winding and armature winding are connected in parallel. The figure below shows the circuit diagram of a DC shunt generator.



R_L = load resistance

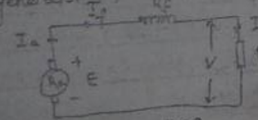
$I_f = \frac{V}{R_f}$

$V = E - I_a R_a$

$I_L = \frac{V}{R_L}$ and, $I_a = I_f + I_L$

(ii) DC series generator

In this type of generator, the field winding is connected in series with the armature circuit. figure below shows the circuit diagram of DC series generator.



Here, $I_a = I_f = I_L$

$V = E - I_a R_a - I_f R_f$

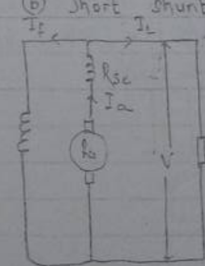
(iii) DC compound generator

This type of generator will have two sets of field windings. One of them is connected in series with the armature or load and the other set is connected in parallel with the armature circuit. Therefore such type of generator will have a mixed type of characteristic lying between shunt and series generator. The series winding is made from thick wire with few turns because it has to carry full load current. Where as shunt field winding is made from thin wire with many number of turns because full rated voltage appears across it.

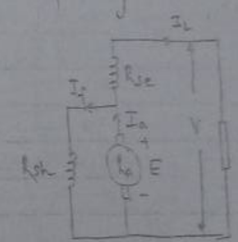
There are two types of DC compound generators:-

(a) Long shunt DC compond generator

(b) Short shunt DC compound generator



Long shunt



Short shunt

$I_f = \frac{V}{R_{sh}}$

$V = E - I_a R_a - I_a R_{se}$

$I_f = \frac{E - I_a R_a}{R_{sh}} = \frac{V_{sh}}{R_{sh}}$

$V_{sh} = E - I_a R_a$

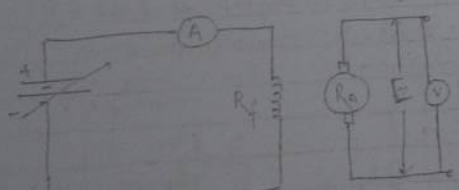
3.5 Characteristics of DC generators

Different types of DC generators have different characteristics. The following two are the main characteristics of DC generators.

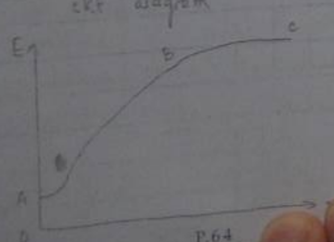
(i) No-load characteristic (or open ckt characteristic).
(ii) Load characteristic

(i) No-load characteristic

No-load characteristic is a curve showing the values of emf generated across the armature for no load for different values of field current at constant speed. The no-load characteristic of separately excited, shunt and series generators can be obtained practically in a similar way. The circuit arrangement for obtaining the data for no-load characteristic curve is shown below. In case of shunt and series generators, the field windings has to be disconnected temporarily and connected exactly the same.



ckt diagram



The armature of the generator is rotated at a constant rated speed by the prime-mover and emf induced across the armature at different values of field current are measured. The resulting curve is shown by the curve above. 'OA' is the emf generated across the armature due to residual flux in the pole even in the absence of field current.

We know,

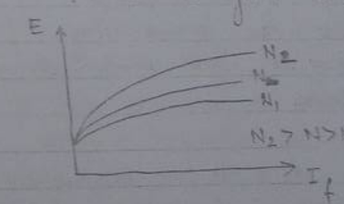
$$E = \frac{Z\phi N}{60} \times \frac{P}{A}$$

Since the armature is driven at constant speed,

$E \propto \phi$

$E \propto I_f$

Therefore the no-load characteristic is a curve (st. line) indicating that the emf increases proportionately with I_f upto the point 'B'. After the point 'B', the magnetic poles gets saturated and emf does not increase even if I_f is increased. It should be noted that no-load characteristic curve (or OCC) for higher speed will be above the given curve and vice versa.

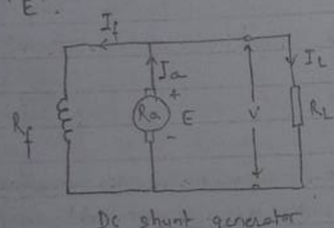


OCC at different speeds.

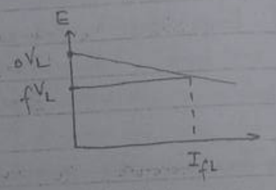
(ii) Load characteristic

- **Shunt generator**

Consider a DC shunt generator as shown in figure below. When there is no load, the armature current $I_a = I_f$ and $I_L = 0$. This armature current is very small when compared to full load current. Therefore the voltage drop in armature is very small. Hence the terminal voltage 'V' is nearly equal to 'E'.



DC shunt generator



load characteristic

When the generator is loaded, the armature current $I_a = I_f + I_L$ will increase. Now the terminal voltage is given by $V = E - I_aR_a$.

Therefore, the terminal voltage 'V' will decrease with the increase in load current as shown in the graph above.

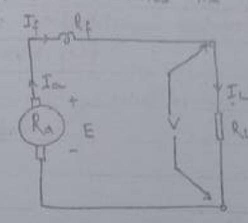
let,

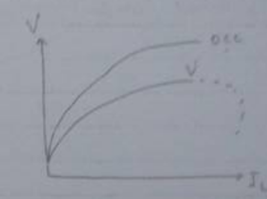
$_oV_L$ = No-load terminal voltage
$_fV_L$ = full-load terminal voltage

Then, voltage regulation $= \dfrac{_oV_L - {_fV_L}}{_fV_L} \times 100\%$

- **Series generator**

Consider a DC series generator as shown below. Here the field winding, armature and load are connected in series. Therefore the field winding, armature and load carries the same current.





In the beginning, as I_L starts to increase the voltage drop in armature (I_aR_a) will increase. But on other hand ϕ increases (due to $I_f \uparrow$) so emf will also increase. Hence a series generator has a rising voltage characteristic as shown above. But at overload condition, the voltage starts decreasing (as shown by the dotted line) due to excessive demagnetising effect of armature reaction and saturation effect.

- **Compound generator**

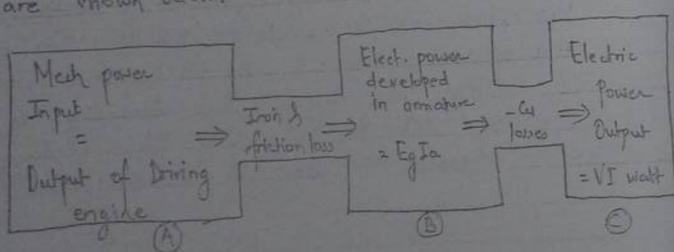
We have seen that a shunt generator has a dropping voltage characteristic and a series generator has a rising voltage characteristic. A compound generator has a characteristic lying between shunt and series generators.

3.6. losses in DC generator

- Total losses
  - Copper loss
    - Armature Cu loss
    - Shunt Cu loss
    - Series Cu loss
  - Iron loss
    - Hysteresis
    - Eddy current
  - Mechanical losses
    - Friction
    - Windage

3.7 Efficiency and Voltage Regulation

Various power stages in the case of DC generators are shown below:



$$\text{efficiency} = \frac{C}{A} = \frac{\text{watts available in load ckt}}{\text{mechanical power supplied}}$$

(also called overall or commercial efficiency)

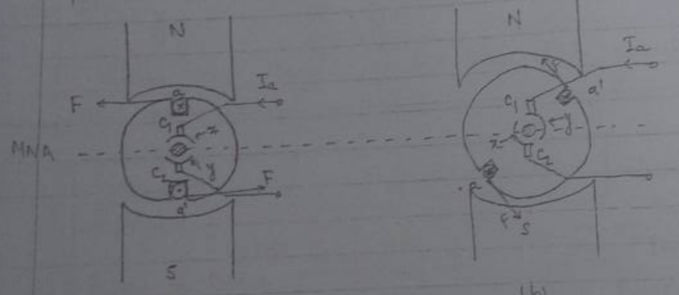
Voltage Regulation is defined as the percentage increase in terminal voltage as the load is reduced from full load to no-load. It is measured relative to full load voltage.

$$\%\ \text{regulation} = \frac{E - V}{V} \times 100\ \%$$

DC motor is an electrical machine used to convert input electrical energy in DC form into mechanical energy involving rotation.

4.1 Working principle and Torque Equation

If the field winding as well as the armature winding are supplied by DC current, then the armature conductors will produce a continuous rotation of armature.



(a) (b)

Let us consider an elementary two pole DC machine with a single turn armature coil a-a' as shown in above figure. The field coils are not shown here which are excited by DC current to generate fixed magnetic poles as shown in the figures. The armature coil is supplied by DC current I_a through the carbon brushes. At a particular instant shown in fig (a) the current is passing in through the conductor a and coming out through conductor a'. Now the current carrying conductors are lying in the magnetic field. Therefore

force will develop on these conductors. The direction of force is determined by using Fleming's left hand rule. Hence the armature rotates in anti-clockwise direction under the action of these couple of forces.

When the conductor crosses the magnetic neutral axis (MNA), the situation will be as shown in fig (b). Here the direction of current in the armature conductors has been reversed due to the action of commutator and carbon brushes. But the direction of force developed by the armature conductors still produces the rotation in anti-clockwise direction. Hence the armature rotates simultaneously in anti-clockwise direction.

let,

N = speed of armature in RPM
r = Radius of the armature coil

Then the armature torque $T_a = F \times r$ (N-m)

Work done by the force in one revolution = $F \times 2\pi r$

Time for one revolution = $\frac{60}{N}$

$\therefore$ power developed by armature = Rate of doing work = P

$$= \frac{F.2\pi r.N}{60}$$

$$\therefore P = \frac{2\pi N T_a}{60} \text{ Watt} \quad \text{--- (1)}$$

When the armature rotates, it cuts the magnetic field continuously. Therefore emf will induce across the armature coil whose magnitude is given by

$$E_b = \frac{Z\phi N}{60} \times \frac{P}{A} \text{ volt}$$

Hence the power developed by the armature also can be written as

$$P = E_b \times I_a \quad \text{——— ②}$$

Equating ① and ②,

$$\frac{2\pi N T_a}{60} = E_b \times I_a$$

or, $T_a = E_b \times I_a \times \frac{60}{2\pi N}$

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

or, $T_a = \frac{1}{2\pi} \phi Z I_a \left(\frac{P}{A}\right)$

$\boxed{\therefore T_a \propto \phi \cdot I_a}$ if other parameters are assumed to be constant.

4.2 Back emf

When the motor rotates, the armature conductors cuts the magnetic flux produced by the poles. Hence according to Faraday's law of electromagnetic induction, emf will induce across the armature conductors. The direction of this emf is opposite to the applied voltage 'V'. This emf is known as back emf.

Significance of back emf are:-

a) No energy conversion from electrical to mechanical would have been possible without back emf. (opposing agent)

b) Back emf protects the armature from short ckt during running condition.

c) Back emf helps the motor to produce the required amount of torque according to increased or decreased load torque.

4.3 Methods of excitation, Types of DC motor

Based on the method of excitation, the DC motors can be classified into three types:-

(i) DC shunt motor
(ii) DC series motor
(iii) DC compound motor

These different types of DC motors have different characteristics. They can be distinguished with the help of following characteristics.

(a) Torque - armature current characteristic (Electrical)
(b) Speed - torque characteristic (Mechanical)

4.4 Performance Characteristics of DC motors

(A) Characteristics of DC shunt motor

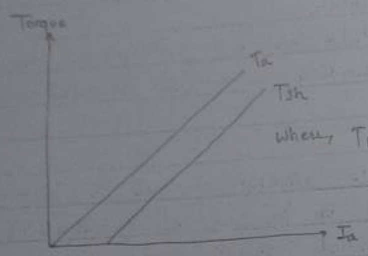
(i) Torque - armature current characteristics

It is a curve showing the armature current effect to armature torque.

We know, $T_a \propto \phi I_a$ and $\phi \propto I_f$

In a DC shunt motor, I_f = constant if V is constant.

$\therefore T_a \propto I_a$
(i.e. curve is a st. line)



where, $T_{sh} = T_a -$ friction loss

fig:- T_a-I_a characteristic of a DC shunt motor

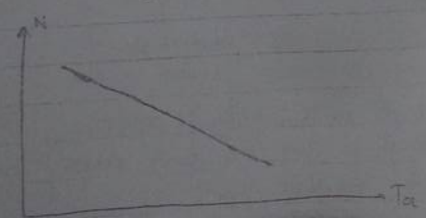
(ii) Speed-torque characteristic

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

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

For DC shunt motor, $N \propto E_b$

As the speed of motor decreases, the back emf E_b will decrease and the armature torque T_a will increase. (because I_a increases as $I_a = \frac{V - E_b}{R_a}$)



(B) Characteristics of DC series Motor

(i) Torque - armature current characteristic

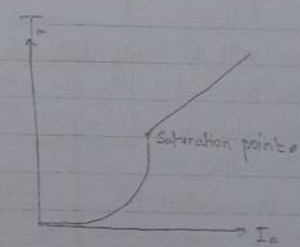
In a DC series motor, the armature winding and field winding are connected in series. Therefore the flux per pole is not constant but it varies with the armature current.

We know,

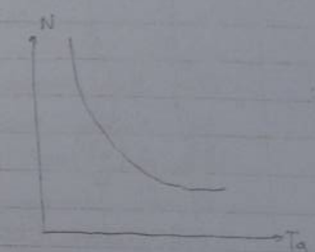
$T_a \propto \phi I_a$ but $\phi \propto I_a$

$\therefore T_a \propto I_a^2$

Hence, $T_a - I_a$ characteristic of a DC motor is parabolic as shown in fig below. After saturation the flux per pole is almost independent of I_a. Hence, $T_a \propto I_a$ only. Therefore the characteristic becomes a straight line after saturation.



$T_a - I_a$ characteristic



Speed-torque characteristic

(ii) Speed - torque characteristic

We know,

$N \propto \frac{E_b}{\phi}$ $\quad E_b = V - I_a R_a$, $T_a \propto \phi I_a$

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

At light load (i.e. at low T_a) the armature current is low. Therefore the back emf E_b will be comparitively 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.

4.5 Starting of DC motors and starters

we know, $I_a = \dfrac{V - E_b}{R_a}$

At the instant of starting, $E_b = 0$

So,

I_a will be very high. (20-30 times rated full load current.)

This high armature current at the starting period will blowout the fuse and prior to that it will damage the commutator and carbon brushes. To avoid these conditions, a DC motor starter is necessary.

A DC motor starter is a variable resistance connected in series with the armature winding (during the starting period only) which limits the starting current to a safe value. The starting resistance is gradually cutout as the motor speeds up and develops back emf

which in turn reduces the armature current. When the armature rotates with full rated speed, the starting resistance will be completely cutout.

The figure below shows a circuit diagram of a DC motor starter. It is called as 3-point starter. The three terminals of the starter are marked as L, A and Z.

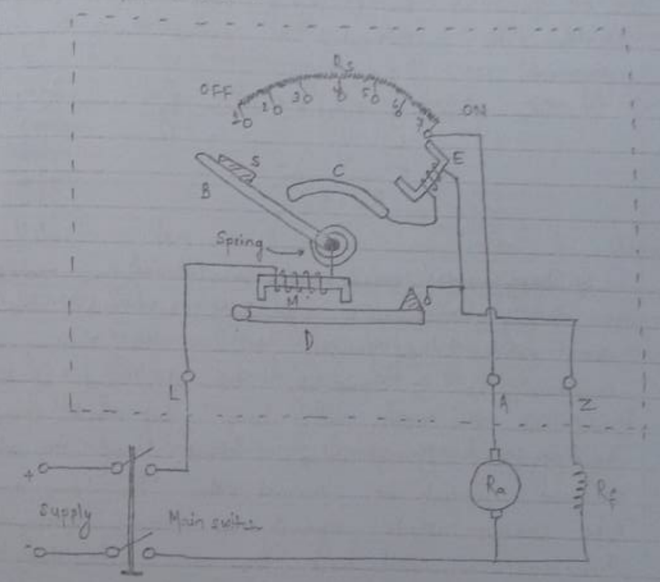


fig: DC motor starter

The negative line of the supply is directly connected to the negative terminal of the armature which is also connected to the negative terminal of the field winding. The positive terminal of the supply is connected to the terminal marked 'L' of the starter, which is further connected to the starting arm 'B' through the over current release 'M'.

To start the motor the main switch is first closed and the starting arm 'B' is slowly moved to the stud no. 1, the field winding gets full supply voltage through the conductive arc 'c' and at the same time full starting resistance R_s is connected in series with the armature.

The starting current drawn by armature is

$$I_a = \frac{V}{R_a + R_s}$$

As the motor speeds up, arm is further moved and the starting resistance is gradually cut out. When the arm reach the position 'ON', the starting resistance R_s is completely cut-out and at the same time the motor will have full rated speed thus producing normal value of back emf to set armature current at normal value. The arm moves over various studs against a strong spring force which tends to pull back the arm to the 'OFF' position. But there is a soft iron piece 'S' attached to the arm which in the 'ON' position is attracted and hold by an electromagnet 'E' (known as hold-coil) energised by the shunt field current.

When the motor is switched off by the main switch, the hold-on coil 'E' will get demagnetised and starting arm 'B'

is thrown back to the 'OFF' position under the action of spring force. It also release the starting arm 'B' to the 'OFF' position at the instant of break in field winding and low voltage condition.

If the motor is overloaded, the motor will draw high current and the electromagnet 'M' will be strong enough to lift up the lever 'D' and it will short circuit the electromagnet 'E'. Then the electromagnet will get de-energised and it will release the starting arm to 'OFF' position.

Note:: Very small motors can even be started without starters from rest because

(a) Such motors have a relatively higher armature resistance than the large motors, hence their starting current is not so high.

(b) Being small, they have low moment of inertia & hence speed up quickly.

4.6. Speed control of DC motors

There may be need to operate DC motors at various speeds under different loading conditions.

The magnitude of back emf developed by the armature is given by

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

or, $N = \frac{E_b \times 60 \times A}{Z \times \phi \times P}$

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

But, $E_b = V - I_a R_a$

$\therefore N \propto \frac{V - I_a R_a}{\phi}$

Therefore the factor controlling the speed of DC motor are:-

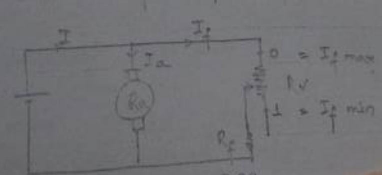
(i) Applied voltage, 'V'
(ii) Armature resistance, R_a
(iii) Flux per pole, ϕ

(A) Speed control of DC shunt motor

(i) Flux control method

we know, $N \propto \frac{E_b}{\phi}$

In this method of speed control, a variable resistance R_v is connected in series with the field winding to regulate the field current thereby regulates the flux per pole.

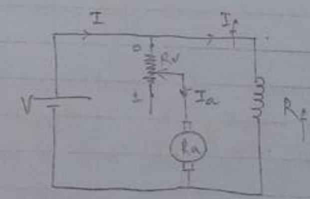


The variable resistance R_v can only reduce the field current below its rated value. Therefore this method is only suitable to control the speed above the rated speed.

At position 0 $\rightarrow I_f\ max \rightarrow \phi_{max} \rightarrow N\ min$.
At position 1 $\rightarrow I_f\ min \rightarrow \phi_{min} \rightarrow N\ max$.

(ii) Armature control method

This method is used when speed below the normal rated speed is required. As the supply voltage is normally constant, the voltage across the armature is varied by inserting a variable resistance R_v in series with the armature circuit as shown below



$$N = K \frac{V - I_a (R_a + R_v)}{\phi}$$

when $R_v = 0$,

$$N_1 = K \frac{V - I_a R_a}{\phi}$$

when $R_v \neq 0$

$$N_2 = K \frac{V - I_a R_a - I_a R_v}{\phi}$$

[Here, load torque is kept constant
So, $T \propto \phi I_a$
$\therefore I_a = \text{constant}$]

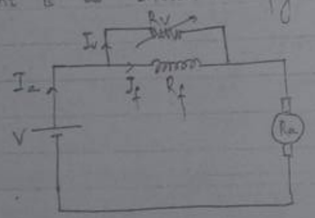
Clearly, $\boxed{N_1 > N_2}$

B) Speed control of DC series Motor

Flux control method: Variation of flux in DC series motor can be done by any one of the following methods.

a) Field diverter method

By this method we can both increase or decrease the speed of DC series motor. The ckt arrangement is as shown in figure below.



Any desired amount of current can be passed through the field winding by adjusting the value of R_v; thus regulating the flux and finally speed.

(b) Armature diverter method

In this method a variable resistance R_v is connected across the armature circuit. As we know $T \propto \phi I_a$ and for a constant load torque if we reduce the value of I_a then ϕ must increase. It increases by drawing more field current i.e. main line current. As $N \propto \frac{1}{\phi}$ speed of the motor decreases. So this method is only used to control speed below normal rated speed.

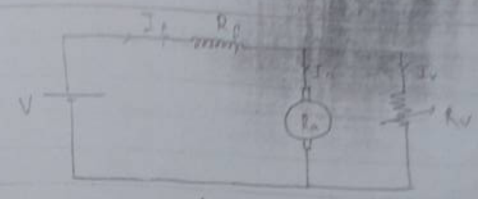
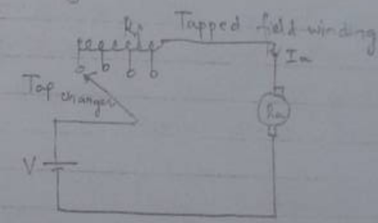


fig.: armature - diverter method

(c) Tapped field control method

In this method, the series field winding is provided with number of tappings. The no. of series field turns in the circuit can be changed by the tap changer. With full field winding, the motor runs at its minimum speed. The speed can be raised in steps by cutting out some series turns.



Induction Machines.....

Induction machines are the most widely used machine in industry. They are also known by the name of asynchronous machines.

Main parts are
(i) Stator
(ii) Rotor

There are two types of rotor
(i) Squirrel cage rotor
(ii) Phase wound rotor (Slip ring)

5.1 Operating principle

When the 3-ϕ stator windings are supplied by three phase balanced voltage source, 3-ϕ current will flow through stator windings. These three phase current will magnetise the stator core. lets proceed to study the nature of magnetic field produced by these three phase currents.

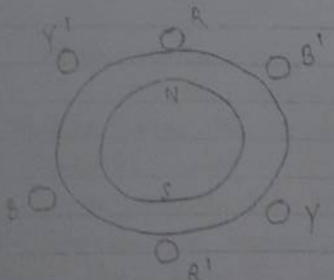


fig:- 2-pole, 3 phase winding

When three phase current flows through the stator windings, each phase winding will produce their own magnetic flux whose nature will be as same as waveforms of three phase current and is shown below. The three flux ϕ_R, ϕ_Y and ϕ_B are alternating in nature and they are 120° out of phase with each other. The mathematical equations are as follows:-

$$\phi_R = \phi_m \sin \omega t$$
$$\phi_Y = \phi_m \sin(\omega t - 120^\circ)$$
$$\phi_B = \phi_m \sin(\omega t + 120^\circ)$$

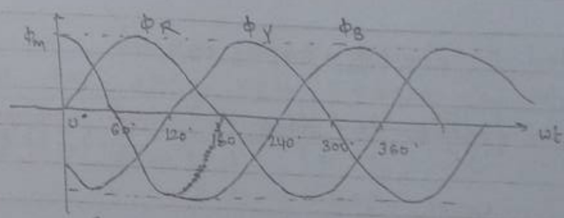
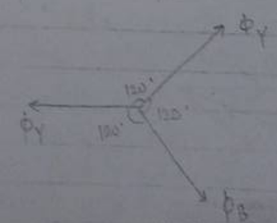


fig:- waveforms of three phase stator magnetic flux

The figure below further shows the phasor diagram of the above magnetic flux showing their positive direction. The net magnetic flux at any time at the central space of the machine will be equal to the vector sum of these flux.

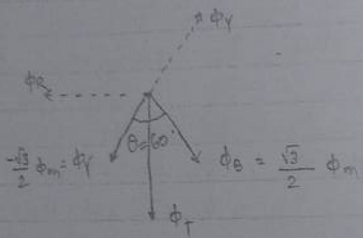


At $\omega t = 0°$

$\phi_R = \phi_m \sin\omega t = \phi_m \sin 0° = 0$

$\phi_Y = \phi_m \sin(\omega t - 120°) = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = \phi_m \sin(120°) = \frac{\sqrt{3}}{2}\phi_m$



$$\phi_T = \sqrt{\phi_Y^2 + \phi_B^2 + 2\phi_Y\phi_B \cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{-\sqrt{3}}{2}\phi_m\right)^2 + 2\cdot\frac{-\sqrt{3}}{2}\phi_m\cdot\frac{\sqrt{3}}{2}\phi_m \cos 60°}$$

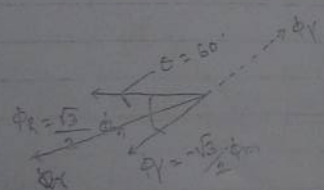
$= 1.5\,\phi_m$

When $\omega t = 60°$,

$\phi_R = \phi_m \sin\omega t = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m$

$\phi_Y = \phi_m \sin(\omega t - 120°) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = 0$



$$\phi_T = \sqrt{\phi_R^2 + \phi_Y^2 + 2\phi_R\phi_Y \cos 60°}$$

$= 1.5\,\phi_m$

The direction in this case has been changed through 60° in the clockwise direction as determined by right hand screw rule.

Similarly, $\omega t = 120°$

$\phi_T = 1.5\,\phi_m$

& ϕ_T has changed its direction by 60° in clockwise direction.

Therefore from the above analysis it is clear that the stator winding produces a rotating magnetic field. The speed of rotating magnetic field is given by

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

↓

'synchronous speed'.

Torque production

The rotating magnetic field produced by the stator cuts the rotor conductor (which are at rest at starting), hence emf will induce on the rotor conductor according to law of Electromagnetic Induction. As the rotor conductors are short-circuited current will circulate within the rotor conductors. Now these current carrying rotor conductors are lying in the magnetic field produced by the stator. Hence force will develop on the rotor conductor. Therefore the rotor starts rotating under the action of this force.

The direction of rotation can be determined by Lenz's law. The direction of force will be in such a way that it oppose the cause by which the emf was induced in the rotor conductor. The main cause of rotor emf is the relative speed between the rotating magnetic field and the rotor. Therefore, in order to reduce this relative speed the rotor will rotate in the same direction of rotating magnetic field.

Slip

The slip of an induction motor is defined as the fraction by which the speed of IM rotor is less than synchronous speed N_s.

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

When the rotor rotates, the frequency of rotor emf is given by $f' = sf$ and the magnitude of rotor emf is given by $E_r = sE_2$

where,

E_r = emf induced in rotor ckt at running

E_2 = emf induced at stand still

Analysis of standstill condition

Stand still condition is the instant of starting. At this instant, the speed of the rotor is zero. Therefore the relative speed $N_s - N$ is maximum, slip is maximum ($s = \frac{N_s - N}{N_s} = 1$) and maximum emf will induce in the rotor ckt (just like in secondary winding in a transformer) and the frequency of emf induced in rotor ckt is same as that of supply voltage frequency 'f' and is given by,

$$f = \frac{N_s \cdot P}{120} \text{ Hz}$$

The equivalent ckt. of the induction motor at standstill condition is very much similar to the equivalent ckt of a transformer. The stator winding is analogous to the primary winding of the transformer and rotor ckt is analogous to the secondary winding of the transformer. The per phase equivalent ckt of a three phase induction motor is shown below:-

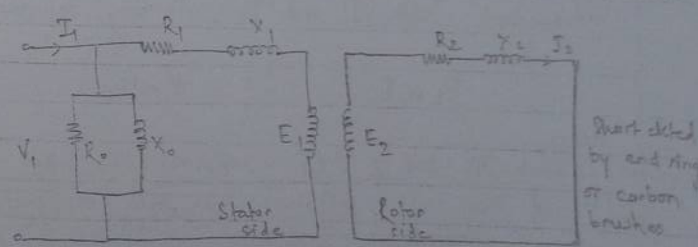


fig:- equivalent circuit of induction motor at standstill condition.

Rotor emf per phase at standstill 'E_2' is given by

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

where, N_1 = Number of turns per phase in stator
N_2 = Number of turns per phase in rotor

Rotor current per phase at stand still is

$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

The current I_2 lags with E_2 by an angle of ϕ_2.

The torque developed by the rotor at standstill is proportional to the product of stator flux per pole and active component of I_2.

$\therefore T_s = K \phi I_2 \cos\phi_2$ where ϕ = stator flux per pole.

Like in the transformer 'ϕ' remains constant and independent with I_1 and I_2. It only depends on E_1

But,

$E_2 \propto E_1$ $\therefore \phi \propto E_2$

Hence,

$$T_s = K_1 E_2 \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \frac{R_2}{\sqrt{R_2^2+X_2^2}}$$

or, $$\boxed{T_s = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2}}$$

Analysis of Running Condition

When the rotor rotates, the relative speed between rotating magnetic flux and the rotor will decrease, there by reducing the rate of cutting the flux with the rotor conductors. Therefore the magnitude of emf induced in the rotor will decrease with compared to emf at standstill. The magnitude of emf induced in the rotor at running condition is given by

$$E_r' = s E_2$$

As the relative speed between rotating magnetic flux and the rotor decreases, the frequency of rotor emf will also decrease with compared to that of standstill condition. The frequency of rotor emf at any speed 'N' is given by

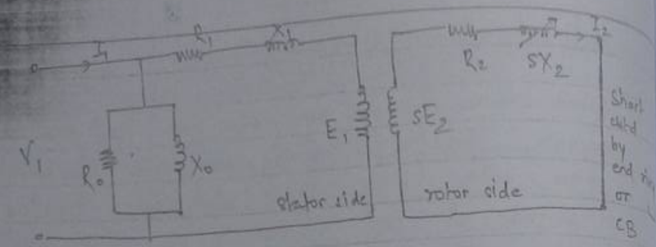
$$f_r = \frac{(N_s - N) P}{120}$$

$$\therefore \frac{f_r}{f} = \frac{(N_s - N) P}{120} \times \frac{120}{N_s P} = \frac{N_s - N}{N_s}$$

$$\therefore f_r = s f$$

At stand still condition $S = 1$, but at running condition 's' is less than 1. Therefore f_r will be less than f. Since reactance depends upon the frequency, the value of rotor leakage reactance will also decrease. The value of rotor leakage reactance at running condition is given by

$$X_r' = s X_2$$



Also,

$$I_R = \frac{E_R}{\sqrt{R_2^2 + X_R^2}} = \frac{sE_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

I_R lags E_R by an angle of ϕ_R
where,

$$\cos\phi_R = \frac{R_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

Torque developed by the rotor at running condition is given by :-

$$T_R = K_1 E_2 \frac{sE_2}{\sqrt{R_2^2 + s^2X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

$$\boxed{\therefore T_R = \frac{sK_1 E_2^2 R_2}{R_2^2 + s^2X_2^2}}$$

5.1.3 Torque Slip Characteristics

It is a curve showing the torque developed by the rotor at various values of slip or speed.

We have general equation of torque,

$$T_R = \frac{K_1 s E_2^2 R_2}{R_2^2 + s^2X_2^2}$$

let, $Y = 1/T_R$ then,

$$Y = \frac{R_2^2 + s^2X_2^2}{K_1 s E_2^2 R_2}$$

or, $$Y = \frac{R_2^2}{K_1 s E_2^2 R_2} + \frac{sX_2^2}{K_1 E_2^2 R_2}$$

Then, $$\frac{dY}{ds} = \frac{-R_2^2}{K_1 s^2 E_2^2} + \frac{X_2^2}{K_1 E_2^2 R_2}$$

Y will be minimum iff $\frac{dY}{ds} = 0$

So, $$s^2 = \frac{R_2^2}{X_2^2}$$

$$\therefore s = \frac{R_2}{X_2}$$ (condition for Y minimum or T_R maximum)

Hence maximum torque will develop at a speed corresponding to slip $s = \frac{R_2}{X_2}$. If the motor is overloaded so that speed goes below this value, the motor will not be able to develop more torque to overcome the increased load.

At normal working speed, i.e. close to N_s the value of s is very small so, $s^2X_2^2 << R_2$.
So,

$$T_R = \frac{K_1 s E_2^2 R_2}{R_2^2}$$

or, $T_R \propto \frac{sE_2}{R_2}$

or, $T_R \propto \frac{s}{R_2}$

$\therefore T_R \propto s$ (if R_2 constant)

(i.e. linear or st. line)

But below normal working speed, $s^2X_2^2 >> R_2^2$ so,

$$T_R = \frac{K_1 s E_2^2 R_2}{s^2 X_2^2}$$

or, $T_R \propto \frac{R_2}{s}$

$\therefore T_R \propto \frac{1}{s}$

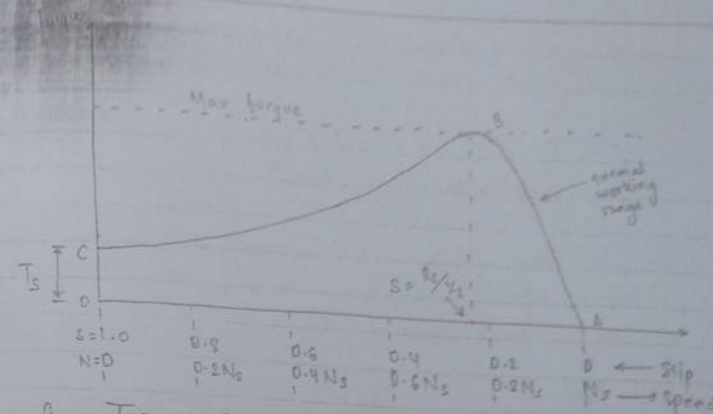


fig:- Torque - slip characteristic of 3-φ induction motor

Testing of Induction Motors

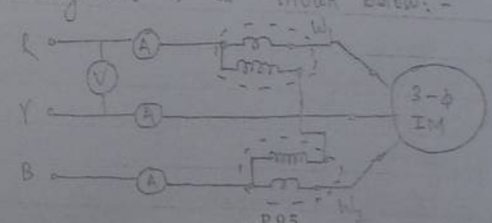
There are mainly two types of test of induction motor to determine the equivalent circuit parameters. They are:-

(a) No-load test (corresponding to open ckt test of trans.)

(b) Blocked rotor test (" " short " " " ")

(a) No-load test

In this test, the motor is run on its shaft at rated voltage and frequency. The ckt arrangement is as shown below:-



let,
input power to the motor at no-load, $W_o = W_{test}$

I_o = no-load stator current (average of readings)
V_o = input voltage (line)

In this case N is very close to N_s. So the value of s is less. Hence sE_2 is less and very small current flows.

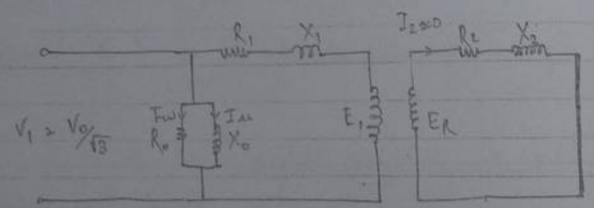
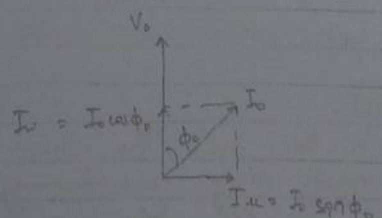


fig. equivalent ckt at no-load

The phasor diagram of current and voltage is



The input power to the motor at no-load 'W_o' represents the no-load loss or iron loss and friction loss of the motor. Now we can write,

$$W_o = \sqrt{3}\, V_o I_o \cos\phi_o$$

$$\text{or, } \cos\phi_o = \frac{W_o}{V_o I_o \sqrt{3}}$$

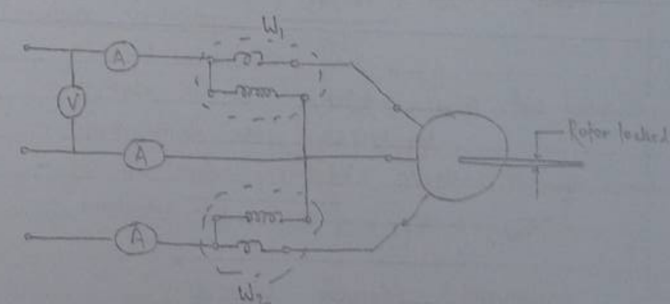
Therefore from the data obtained from the test we can calculate $\cos\phi_o$, I_w and I_μ.

Then R_o and X_o can be calculated as follows:-

$$R_o = \frac{V_o/\sqrt{3}}{I_w} \quad \text{and} \quad X_o = \frac{V_o/\sqrt{3}}{I_\mu}$$

(B) Blocked rotor test

In this test, the rotor is kept locked mechanically and low voltage is applied in the stator winding and the applied voltage is increased gradually till the motor draws rated full load current. Ammeters, voltmeter and wattmeters are connected as shown below:-



let,
$W_{sc} = W_1 + W_2$
I_{sc} = line current during short-ckt test (average of three ammeter reading)
V_{sc} = Voltage applied (line voltage - reading of voltmeter)

Since the rotor is blocked, the speed is zero and slip 's' is unity. Therefore the voltage (V_{sc}) required to circulate the full load current is very small. Therefore the magnetising current through the shunt branch (R_0 and X_m) in the equivalent circuit model will be negligible w.r.t. I_{sc}. Hence the magnetising shunt branch can be neglected.

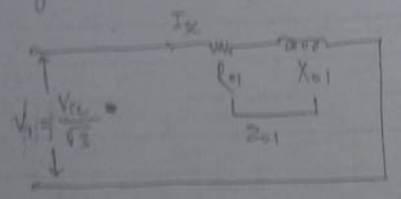


fig:- equivalent ckt during blocked rotor test

Now, $Z_{01} = \dfrac{V_{sc}/\sqrt{3}}{I_{sc}}$

$W_{sc} = 3 I_{sc}^2 R_{01}$

$\therefore R_{01} = \dfrac{W_{sc}}{3 I_{sc}^2}$

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

Note:- An induction motor can also be used as an induction generator by driving it by some prime mover above synchronous speed.

The chapters from here onwards has different syllabus for electrical and other faculties and treated irrespectively.

THREE PHASE SYNCHRONOUS MACHINES

For DC

magnetic field system → always in rotor
conductor system / armature → always resides in rotating part

For AC,

→ They can be anywhere.

* Slip ring and carbon brushes are used to connect to any rotating part in ac and dc machines.

Armature conductor

- situated in rotating part.
- In case of dc generator it is that conductor from which emf is produced.
- In dc motor, voltage is supplied through armature conductor.

Synchronous Generator (Alternator)

- AC machine.
- It always runs at constant speed. $N_s = \frac{120f}{P}$
- output frequency is constant.

Constructions

The construction of synchronous generator is very much similar to that of 3-ϕ induction motor.

Main parts are:-

(i) Stator :- we place 3-ϕ armature winding.

(ii) Rotor :- magnetic field is produced by rotor pole.

(iii) Exciter :- To produce magnetic field in the rotor we give dc voltage to field winding. It is generally DC generator.

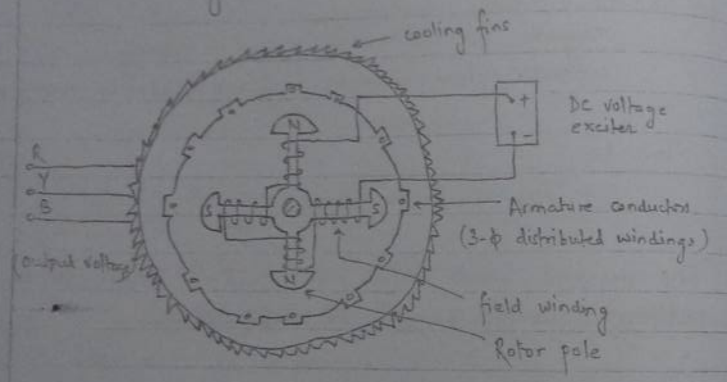
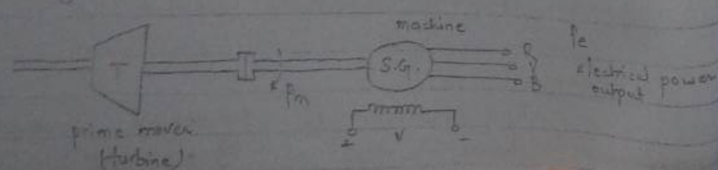


fig:- construction of synchronous generator

The reason behind the rotation of synchronous generator at constant speed is the need of electrical power at constant frequency. This asserts longivity of appliances.

Working principle (Operation)



The working principle of synchronous generator is based on electromagnetic induction phenomenon. The shaft of synchronous generator is rotated or driven by prime mover (turbine) at constant speed equal to the synchronous speed ($N_s = \frac{120f}{P}$) and at the sametime the exciter builds up the voltage and supplies to the field winding. Thus stator conductors or armature conductors are cut by the magnetic flux produced by rotor pole and hence by Faraday's law of electromagnetic induction, emf will be induced in the armature conductor.

As stator has 3-phase distributed windings, these phase voltage will be induced given by

$$e_R = E_m \sin \omega t$$
$$e_Y = E_m \sin(\omega t - 120^\circ)$$
$$e_B = E_m \sin(\omega t - 240^\circ)$$

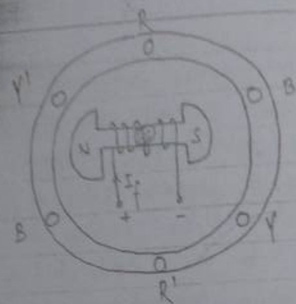
And, the frequency of induced voltage is

$$f = \frac{P}{2} \cdot \frac{N_s}{60}$$

Note:-

In actual power generating stations speed governor is used to keep the speed of machines constant and induced voltage is made constant by AVR (Automatic Voltage Regulator) automatically at any loaded condition.

Emf equation



let us consider,

Z = no. of conductors or coil sides in series per phase
$= 2 \times T$; T = No. of turns or coils
P = No. of poles in rotor (2 here)
f = frequency of induced voltage.
ϕ = magnetic flux per pole
N = speed of rotor in rpm

$$N = N_s = \frac{120f}{P} \quad \text{(synchronous speed)}$$

By Faraday's law,
Average emf induced per conductor $= \frac{d\phi}{dt} = \frac{\text{change in flux}}{\text{change in time}}$

Average change in flux in one revolution of rotor, $d\phi = P\phi$
time taken for one revolution, $dt = \frac{60}{N}$ sec

$\therefore$ Average emf per conductor per phase, $e = \frac{d\phi}{dt}$

$$\text{or, } e = \frac{P\phi}{60/N}$$

$$\therefore e = \frac{P\phi N}{60}$$

Putting the value of $N = N_s$,

$$e = \frac{P\phi}{60} \times \frac{120f}{P}$$

$$\text{or, } e = 2\phi f$$

So,
Average emf induced per phase $= \begin{pmatrix}\text{emf induced per}\\ \text{conductor per}\\ \text{phase}\end{pmatrix} \times \begin{pmatrix}\text{total no.}\\ \text{of cond.}\end{pmatrix}$

$$= 2\phi f \times Z$$
$$= 4T\phi f$$

We know,
form factor $= \frac{\text{RMS Value}}{\text{Average Value}} = 1.11$ for sine wave

$\therefore$ Rms value of emf induced per phase
$= 4.44\, Tf\phi$

So, instantaneous emf induced in R, Y, B phase is given by

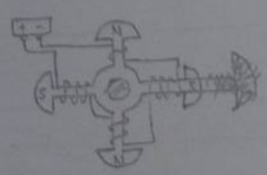
$$e_R = E_m \sin\omega t = \sqrt{2} \times (4.44\,Tf\phi) \sin\omega t$$
$$e_Y = \sqrt{2} \times (4.44\,Tf\phi) \sin(\omega t - 120^\circ)$$
$$e_B = \sqrt{2} \times 4.44\,Tf\phi \sin(\omega t - 240^\circ)$$

Assumptions in above equations:-
(a) Coils have got full pitch
(b) All the coils of a phase are concentrated in one stator slot.

Otherwise, $E = 4.44\, K_p K_d\, Tf\phi$ Volt/phase

Types of Rotor in synchronous machine

(i) Salient - pole Rotor
(ii) cylindrical Rotor



(i)
Salient - pole rotor structure

(ii)
cylindrical pole rotor structure

Salient - pole rotor structure

The term salient means projecting or protruding. Thus the salient pole rotor has got the projected magnetic poles from the surface of rotor core. The rotor core is also made up of steel laminations to reduce the eddy current loss. The construction of this kind of rotor is easier and cheaper. Such type of rotors are usually used in the generator driven by low speed prime mover such as water turbine.

Cylindrical pole rotor structure

Such type of rotor are also called as non-salient pole rotor. This type of rotor has got smooth magnetic poles in form of closed and compact cylinder as shown in fig (ii). The construction of this type of rotor is more compact and robust when compared to salient pole rotor. These are generally

used in generator driven by high speed prime movers like steam turbine, gas turbines, etc.

Example of 3-ϕ stator winding / Armature winding

3-ϕ stator windings are uniformly distributed windings and are spaced 120° apart from each other. Stator windings are made of enamel insulated copper wire.

let,

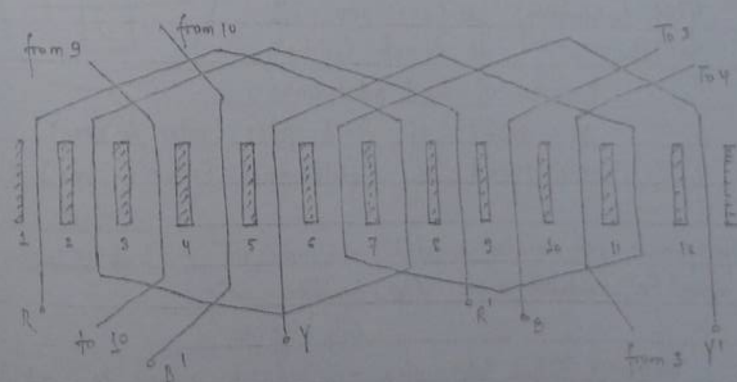
No. of slots = 12

No. of pole = 2

$$\therefore \text{coil span} = \frac{\text{No. of slots}}{\text{No. of poles}} = \frac{12}{2} = 6$$

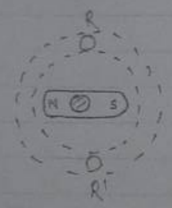
No. of slots per phase = $12/3 = 4$

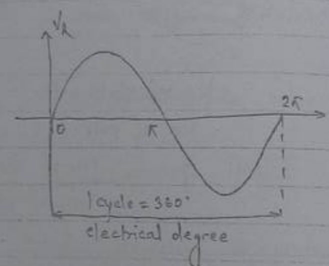
No. of coils per phase = $4/2 = 2$ coils



Speed and frequency of generated voltage

The frequency of induced voltage depends upon the no. of field poles and the speed at which field poles are rotated. One complete cycle of emf is generated when a pair of field poles (one N-pole and one S-pole) passes over a coil or conductor.





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

$$f = \frac{NP}{120}$$

let,

P = no. of field poles

N = speed of field poles (rotor in RPM)

n = speed of field poles (rotor in rps) $= N/60$

So, pair of field poles $= P/2$

Thus, in one revolution an armature coil is cut by $P/2$ pairs of poles.

Since, one cycle of emf is generated by a pair of field poles passing over the coil, the

number of cycle generated in one revolution of rotor will be equal to number of poles pair.

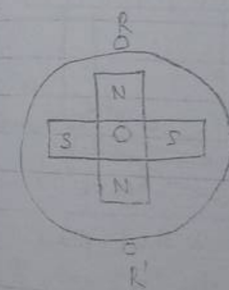
$\therefore$ frequency = no. of cycles per second

$$= \frac{\text{no. of cycle}}{\text{revolution}} \times \frac{\text{revolution}}{\text{second}}$$

$$\therefore \boxed{f = \frac{P}{2} \times \frac{N}{60}}$$

Electrical degree and Geometrical Degree

Electrical degree $= \frac{P}{2} \times$ geometrical degree



eg:- for $P = 4$

E.d. $= \frac{4}{2} \times 360° = 2 \times 360°$

In one revolution (geometrical 360°) electrical degree of 720° will be completed.

Pitch factor

Pole pitch :- The angular distance between the centres of two adjacent pole on a machine is known as pole pitch.

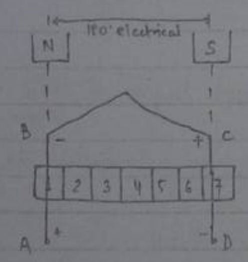
One pole pitch = 180° electrical

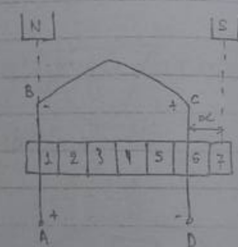
Coil pitch (coil span) :- The distance between two sides of a coil is called coil pitch.

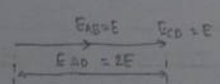
If coil pitch = pole pitch ⟶ full pitch coil
coil pitch < one pole pitch ⟶ short pitch coil or fractional pitch coil.

Pitch factor (K_p)

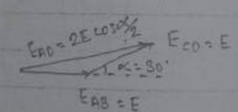
Ideally coil span (pitch) of armature winding is equal to the pole pitch. But in actual machine the coil span may be less than pole pitch (i.e. less than 180° electrical)







(a) full pitched coil



(b) short-pitched

e.g. slots = 24
pole = 4

$\therefore$ coil span $= \frac{24}{4} = 6$

$\frac{1}{2}$ one slot $= \frac{180°}{6} = 30°$ electrical

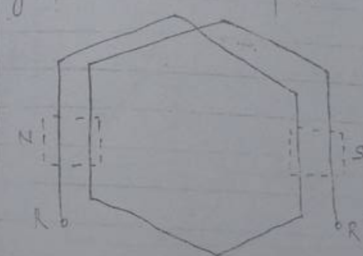
$$K_p = \frac{\text{emf induced in short pitched coil}}{\text{emf induced in full pitch coil}}$$

or, $K_p = \frac{2E\cos\alpha/2}{2E}$

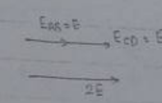
$\therefore K_p = \cos\alpha/2$

Distribution factor (K_d)

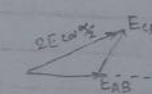
In actual machine, the armature windings are not concentrated in a single slot but windings are distributed over many no. of slots to form a polar group under each pole.



Here,



(a) concentrated



(b) distributed

If the coil sides AB and CD are bunched into a single slot then total emf induced in two coil sides would be in phase as shown in fig (a). However the voltage induced in coil sides constituting a polar group are not in same phase but differ by an angular displacement equal to that of slot. Thus the resultant emf will be less than their algebraic sum.

The distribution factor is defined as,

$$K_d = \frac{\text{emf induced in distributed}}{\text{emf induced in concentrated}}$$

$$K_d = \frac{2E\cos\alpha/2}{2E}$$

$$\therefore K_d = \cos\alpha/2$$

Operation of Synchronous Generator with Load

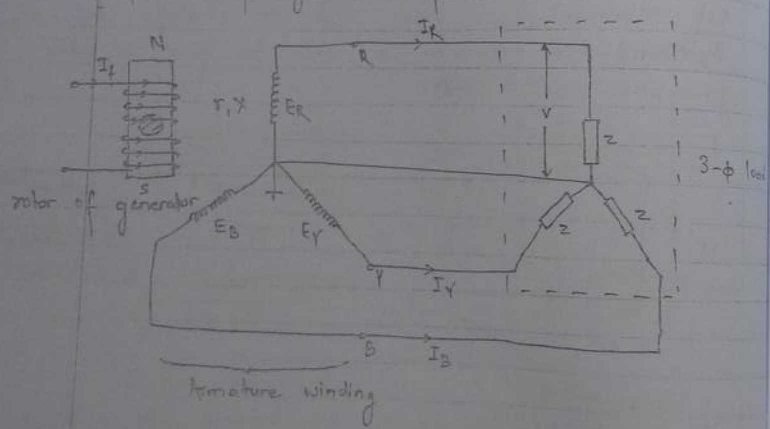


fig:- synchronous generator with load

When the synchronous generator is connected to the load as shown in figure, current flows from armature winding to the load. The voltage across the load i.e. terminal voltage V is less than induced voltage or emf E because of the following three reason.

(a) voltage drop in armature winding resistance.
(b) voltage drop due to leakage reactance of armature winding.
(c) voltage drop due to the effect of armature reaction.

let, E be emf induced per-phase.
V be terminal voltage per phase.

At no load condition

$$|I_R| = |I_Y| = |I_B| = 0$$

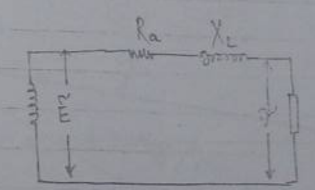
$$\therefore |E| = |V|$$

But, at loaded condition $|I_R| \neq 0$ so,

$$\tilde{V} = \tilde{E} - \text{voltage drop}$$

$$\tilde{V} = \tilde{E} - \tilde{I}_a (R_a + jX_L)$$

$$\therefore \tilde{V} = \tilde{E} - \tilde{I}_a R_a - j\tilde{I}_a X_L$$



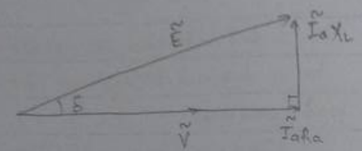
R_a = Armature resistance
X_L = Armature leakage reactance

fig:- per phase equivalent ckt

Note:- Terminal voltage depends upon the pf of the load.

Case I : load pf is unity (cos φ = 1) purely resistive load

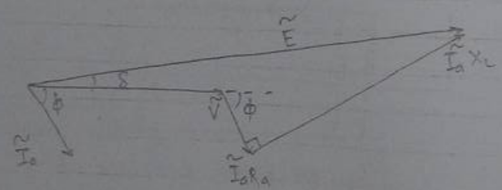
$V, I_a \quad \phi = 0°$



δ → power angle (angle between induced voltage and terminal voltage)

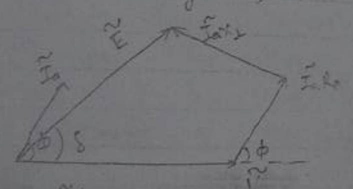
Case II lagging pf load (inductive load)

(I_a lags V by ϕ)



Case III leading pf load (capacitive load)

(I_a leads V by ϕ)



Here, $|\tilde{E}| < |\tilde{V}|$

Armature Reaction in Synchronous Generator

When synchronous generator is loaded armature current will flow through R, Y, B windings. This armature current will produce its own magnetic flux which is rotating in nature. The effect of this armature field on the rotor flux (main flux) is called armature reaction. The nature of effect of armature reaction depends upon the types of load.

Case-I : Resistive load

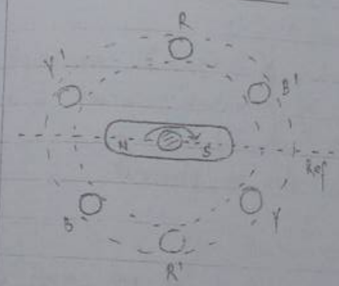


fig:- Rotor at zero position

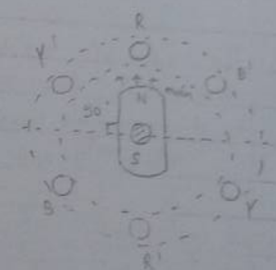
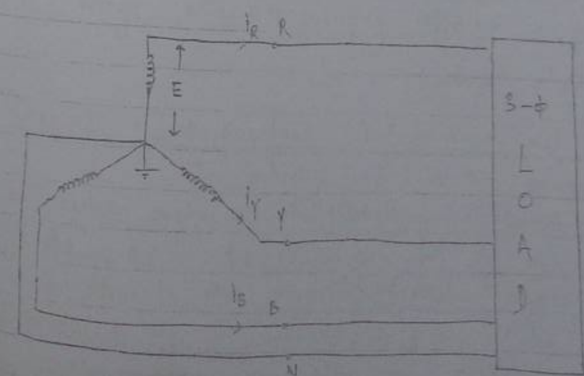


fig:- position after 90°



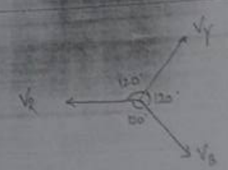


fig:- phasor of output voltage

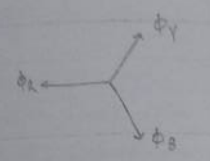


fig:- phasor of armature flux.

We have, the equations of armature fluxes,

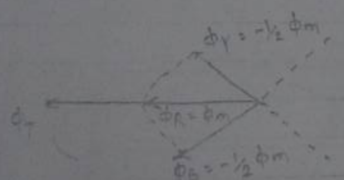
$$\phi_R = \phi_m \sin \omega t$$
$$\phi_Y = \phi_m \sin(\omega t - 120°)$$
$$\phi_B = \phi_m \sin(\omega t - 240°)$$

In case of resistive load, V and I are in phase. And, also flux produced by armature current ϕ is in phase with current (ϕ and I)

i.e. V and ϕ are also in phase.

At $\omega t = 90°$, To find the net resultant of armature flux.

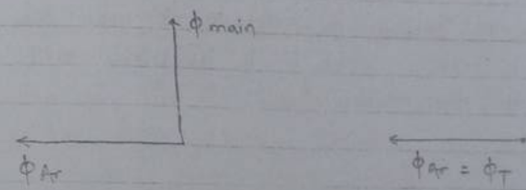
$$\phi_R = \phi_m$$
$$\phi_Y = -\tfrac{1}{2}\phi_m$$
$$\phi_B = -\tfrac{1}{2}\phi_m$$



$$\phi_{YB} = \sqrt{\phi_B^2 + \phi_Y^2 + 2\phi_B\phi_Y \cos 120°}$$
$$= \sqrt{\tfrac{1}{4}\phi_m^2 + \tfrac{1}{4}\phi_m^2 + 2\cdot\left(-\tfrac{1}{2}\phi_m\right)\left(-\tfrac{1}{2}\phi_m\right)\left(-\tfrac{1}{2}\right)}$$
$$= \sqrt{\tfrac{1}{4}\phi_m^2}$$
$$= \frac{\phi_m}{2}$$

$$\therefore \phi_T = \phi_R + \phi_{m/2} = 1.5\,\phi_m$$

So after 90° rotation, the net armature flux acts in the direction as indicated below -



Thus it is seen that armature flux (ϕ_{Ar}) lags the main flux by 90°.

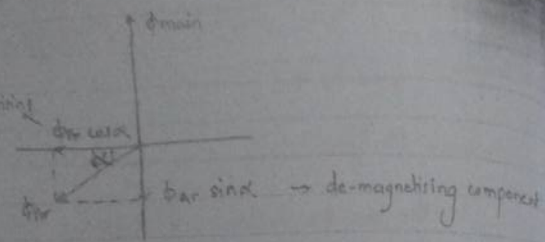
Hence, armature flux distorts the main flux but doesnot directly oppose or support the main flux. Thus it brings cross-magnetising effect.

Case - II : Inductive load (I lags V by α)

In inductive load as the current lags voltage by certain angle α the waveforms of armature flux i.e. ϕ_R, ϕ_Y, ϕ_B will also lag by an angle of α w.r.t. that in the case of resistive load. Here, ϕ is produced by I. So, ϕ lags V by α.

So, after 90° rotation, the net

armature flux acts in the direction indicated below.



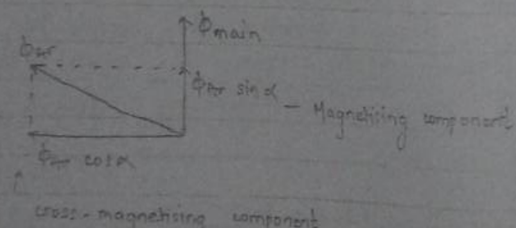
Two components of armature reaction

(a) $\phi_{ar} \sin\alpha$, which is in direct opposition to main flux and weakens the strength of main flux.

(b) $\phi_{ar} \cos\alpha$, which is in quadrature w.r.t. ϕ_{main}. This distorts the main flux.

Case-III Capacitive load (I leads V by α)

Here, ϕ leads V by α.



Two components of armature reaction are:-

(a) $\phi_{ar} \sin\alpha$, which is in direct support to the main flux and it increases the strength of main flux.

(b) $\phi_{ar} \cos\alpha$, which is in quadrature w.r.t. ϕ_{main}. This distorts the main flux.

Synchronous Impedance and Synchronous Reactance

The voltage drop due to the armature reactions may be accounted in the equivalent circuit by assuming the presence of reactance X_a in series with the armature winding.

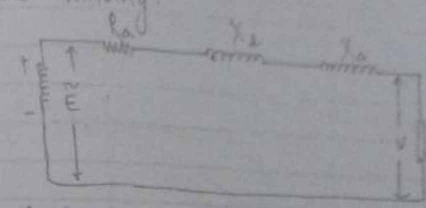


fig:- per phase equivalent circuit of synchronous gen

The value of X_a is such that $I_a X_a$ represents the voltage drop due to armature reactions.

So, from above circuit

$$\tilde{V} = \tilde{E} - \tilde{I}_a (R_a + jX_\ell + jX_a)$$

$$\text{or, } \tilde{V} = \tilde{E} - \tilde{I}_a (R_a + jX_s)$$

$$\text{or, } \tilde{V} = \tilde{E} - \tilde{I}_a Z_s$$

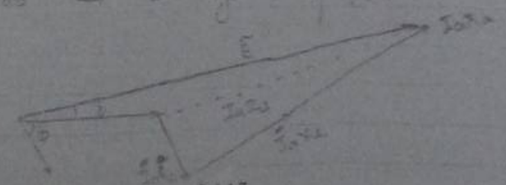
where,

$X_s = X_\ell + X_a$ → synchronous reactance.

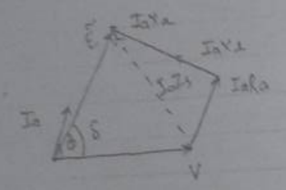
$Z_s = R_a + jX_s$ → Synchronous impedance.

Phasor diagram

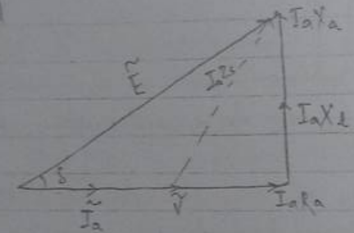
(i) Inductive load → I lags V by ϕ.



b) Capacitive load → I leads V by ϕ



(c) Resistive load



Voltage Regulation in synchronous generator

When the load on generator changes from no load condition to full load assuming the generator is running at constant speed and excitation, the terminal voltage across the load will change due to voltage drop in Internal resistance and reactance of stator winding.

The magnitude and nature of voltage drop depends upon the nature of power factor of the load. Hence the voltage regulation of synchronous generator is defined as % rise in terminal voltage as the load is changed from full load to no load, the speed and excitation of machine being constant.

$$\% \, VR = \frac{\text{No-load voltage} - \text{full load voltage}}{\text{full load voltage}} \times 100\%$$

$$\% \, VR = \frac{E_0 - V}{V} \times 100\%$$

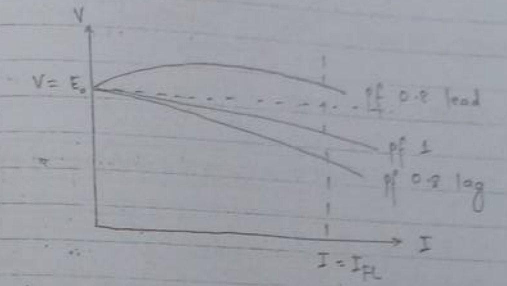


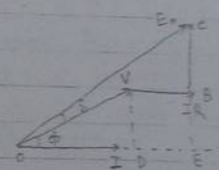
fig:- terminal voltage for different power factor

Determination of voltage regulation

i) for lagging pf case

E_0 = no load voltage

V = full load terminal voltage



In $\triangle OCE$,

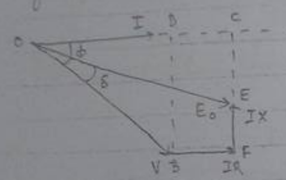
$$OC^2 = OE^2 + EC^2$$

$$OC = \sqrt{OE^2 + EC^2}$$

$$OC = E_0 = \sqrt{(V\cos\phi + IR)^2 + (V\sin\phi + IX)^2}$$

Then we can find $\% \, VR = \frac{E_0 - V}{V} \times 100\%$

(ii) for leading pf case



In ΔOCE,

$$OE^2 = OC^2 + CE^2$$

$$E_0 = \sqrt{(V\cos\phi + IR)^2 + (V\sin\phi - IX)^2}$$

$$\therefore \% VR = \frac{E_0 - V}{V} \times 100\% \quad (-ve)$$

Parallel operation of Synchronous Generator

In actual power system, a no. of generators are connected in parallel according to consumer demand and from reliability point of view.

The process of connecting two or more alternators (synchronous generators) in parallel is known as synchronisation.

Infinite bus :- The infinite bus is the bus in the power system whose voltage and frequency doesnot change irrespective of change in load.

For proper synchronisation of two alternators or synchronising an alternator to the infinite bus, the

following conditions are to be satisfied.

1) Terminal voltage of both alternators should be equal.
2) The frequency of both alternators should be equal.
3) The waveform of emf generated by both alternators should be in phase.
4) The percentage impedance of both alternators should be same.
5) The phase sequence of both alternators must be same.

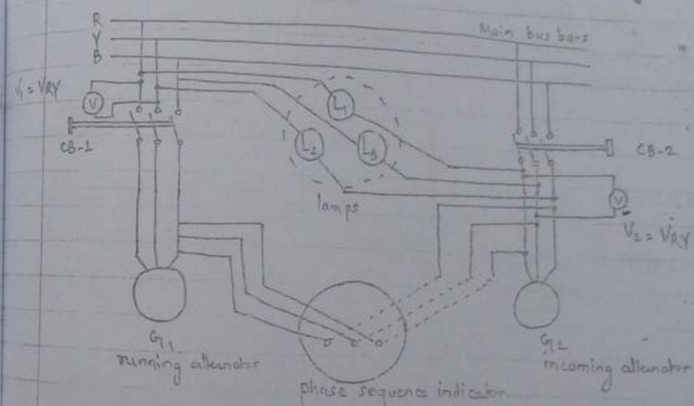


fig:- parallel operations of alternators

RYB - phase sequence check

Before synchronising an alternator to the infinite bus or second generator, their phase sequence must be checked. Phase sequence is checked by phase sequence indicator, which is a small 3-ϕ induction motor, which rotates in one direction for one phase sequence and in opposite direction for other phase sequence.

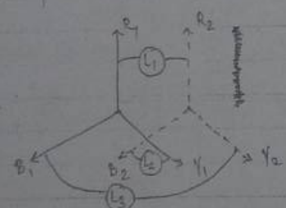
As shown in figure the incoming generator

G_2 is rotated by prime mover approximately upto its synchronous speed. Keeping circuit breaker CB-2 open. The excitation of G_2 is adjusted so that its generated voltage V_2 is same as that of V_1.

For frequency check, there may be following 3 cases:-

Case I $f_1 = f_2$

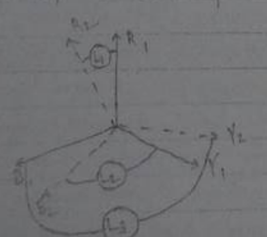
Here, $R_2 - Y_2 - B_2$ phasors rotate with the same speed as $R_1 - Y_1 - B_1$.



$L_1 \rightarrow$ between R_1 and $R_2 \rightarrow$ dark.
$L_2 \rightarrow$ between Y_1 and $B_2 \rightarrow$ bright.
$L_3 \rightarrow$ between B_1 and $Y_2 \rightarrow$ bright.

Case II $f_2 > f_1$

Here, $R_2 - Y_2 - B_2$ phasors rotate faster than $R_1 - Y_1 - B_1$

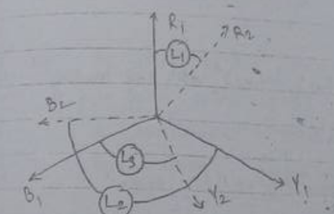


$L_1 \rightarrow$ starts to glow
$L_2 \rightarrow$ Brightness decrease
$L_3 \rightarrow$ brightness increase

In such a condition, the speed of generator G_2 has to be reduced until $f_1 = f_2$ where L_1 is dark & L_2 and L_3 glow with equal brightness. Then CB-2 is closed.

Case III $f_2 < f_1$

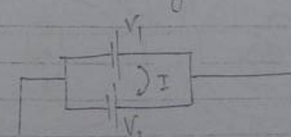
Here, $R_2 - Y_2 - B_2$ phasors rotate slower than $R_1 - Y_1 - B_1$.



In such a case,
$L_1 \rightarrow$ starts to glow
$L_2 \rightarrow$ brightness increases
$L_3 \rightarrow$ brightness decreases

In such a condition the speed of generator G_2 has to be increased until $f_1 = f_2$, where L_1 is dark and L_2 & L_3 glow with equal brightness.

Note:- If terminal voltage, frequency and phase sequences are not same then circulating current will flow between the generators.



Synchronous Motor

- construction same as synchronous generator
- converts electrical energy into mechanical energy

Features

- It always runs at constant speed at any loading condition.
- It is not self starting motor. It needs some auxiliary means to start.
- The synchronous motor can be operated at wide range of both lagging and leading.

Why not self starting?

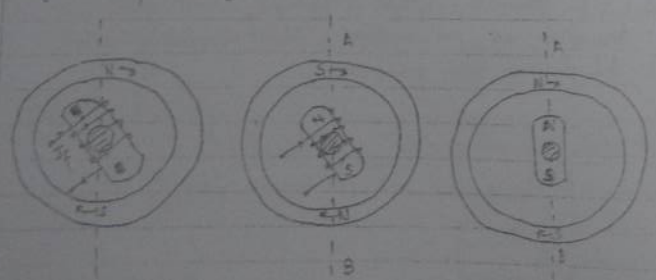


fig (a) fig (b) fig (c)

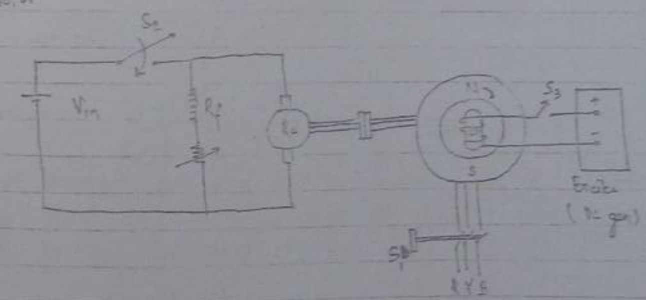
- When stator winding is supplied by 3-ϕ voltage,

rotating magnetic field will be set-up and at the same instant if rotor field windings are excited by dc current, the rotor poles will get magnetized. The stator poles rotate at a very fast speed of synchronous speed but the rotor poles rotate very slowly (at the time of starting). Due to this oscillation is seen because of force experienced in different direction.

- As discussed above the interaction between stator pole and rotor poles will not be able to produce a continuous rotation which is illustrated in the above figure.

Starting Methods of Synchronous motor

(i) Use of DC motor coupled to the shaft of synchronous motor



Procedure

(i) Initially keep S_1 and S_3 open.

(ii) Switch on S_2 and adjust the speed of DC motor near to the synchronous speed (N_s) of synchronous motor.

(iii) Then switch on S_1 and S_3 and open switch S_2.

2) Using the exciter of synchronous motor as DC motor for starting.

✓ Same as first method, except that the rotor of synchronous motor is initially operated as DC motor and when the speed reaches near the N_s, 3-ϕ supply is given to armature and DC voltage from exciter.

3. Use of small induction motor of at least one pair of poles less than synchronous motor

e.g.: SM → P = 8 then rated speed $N_s = \frac{120f}{P} = 750$ rpm

Induction motor pole, P = 6

$$N_s = \frac{120f}{P} = 1000 \text{ rpm}$$

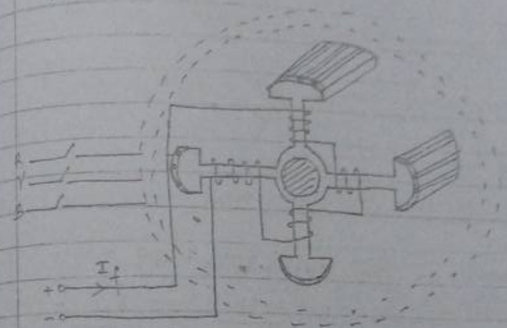
$$N = N_s(1-s) \qquad s = 0.2 \text{ (say)}$$

$$N = (0 - 800)$$

So, the speed of IM may vary from 0 to 800. We need to keep the speed of IM as that of N_s of SM (may vary 70-80% of N_s of SM.)

✓ To control the speed of induction motor, supply voltage can be reduced, when the speed reaches near the synchronous speed of SM armature and field of synchronous motor can be supplied.

4) Use of damper winding as a squirrel cage induction motor



from dc exciter

✓ The rotor poles has a damper winding and shorted by end rings and thus a complete squirrel cage winding is formed.

✓ Initially motor is started as 3-ϕ induction motor, with no DC supply to the field windings.

✓ After the motor has gained speed near to synchronous speed the DC supply to the field winding is given and then rotor comes in synchronism and starts rotating with synchronous speed.

PRECAUTION

✓ Field winding of rotor is not left (kept) open during starting to protect the insulation failure of rotor winding rather it is made short ckt during starting

No-load and loaded operation of synchronous motor

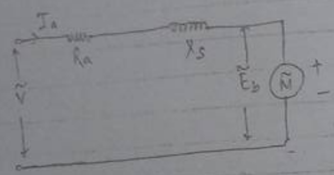


fig:- per phase equivalent circuit

Armature current I_a from the input is :-

$$I_a = \frac{\tilde{V} - \tilde{E}_b}{Z_s} = \frac{\tilde{V} - \tilde{E}_b}{R_a + jX_s} = \frac{\tilde{E}_R}{R_a + jX_s}$$

and, $\tilde{V} = \tilde{E}_b + \tilde{I}_a Z_s$

Where,
$\tilde{E}_b$ = Backemf produced in armature
$\tilde{E}_R$ = Resultant voltage across the armature
$\tilde{V}$ = Supply voltage.

No-load and loaded operation (excitation same)

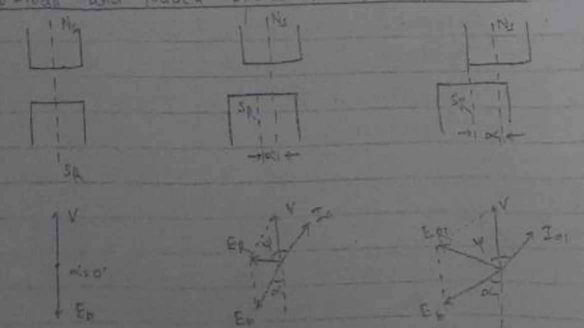


fig:- No load (Ideal) No-loss   fig:- No-load (Actual m/c)   fig:- with load

In the above fig:- $\alpha_1 > \alpha$

Armature current, $I_a = \frac{E_R}{Z_s}$

ψ = internal angle = Angle between Resultant voltage E_R & ~~Armature~~ current I_a

$= \tan^{-1}\left(\frac{X_s}{R_a}\right)$

α = power angle / rotor angle
[If P ↑ then α ↑ so called power angle]

At no-load case and if there is no power losses (ideal case) the stator poles and rotor poles will be along the same axis and the phase difference between V and Eb (back emf) will be exactly 180° (i.e. out of phase) and hence resultant voltage will be zero and no armature current will be drawn. But in actual machine there is some power losses due to Iron and friction losses and hence the rotor poles lags stator poles by certain angle α which is small enough to govern the no load losses.

When load on synchronous motor increases the rotor poles lags stator poles by some larger angle α_1 so that resultant voltage E_R will increase and hence armature current will also increase.

Effect of excitation current

The magnitude of back emf is dependent on speed and flux per pole.

i.e. $E_b \propto N_s \cdot \phi$

As the speed is constant in syn. motor so,

$E_b \propto \phi \propto I_f$

The electrical power input to the motor is

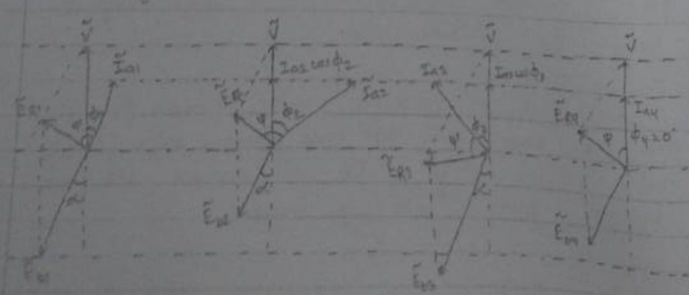
$P = V I_a \cos\phi$

As V is almost constant so, $P \propto I_a \cos\phi$

If load on the motor is constant (i.e. $P \to$ constant) then $I_a \cos\phi$ should be constant.

Hence, if excitation E_f is changed keeping load torque constant then armature current (I_a) & input power factor $(\cos\phi_a)$ will change.

The input p.f. $(\cos\phi)$ may be lagging or leading according to excitation.



(a) normal excitation $|E_b| = |V|$ (b) under excitation $|E_b| < |V|$ (c) over excitation $|E_b| > |V|$ (d) unity pf case

Description

(a) Normal excitation

Here, $|E_b| = |V|$

- power factor is lagging.
- I_{a1} lags V by ϕ_1.

So active component of current is $I_{a1} \cos\phi_1$.

(b) Under-excitation

- $|E_b| < |V|$
- pf is lagging and poorer than previous case.
- $I_{a2} > I_{a1}$.

(c) Over-excitation

$|E_b| > |V|$

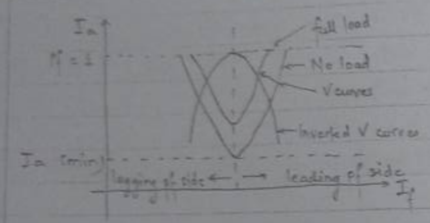
- Here field current I_f is increased
- pf is leading
- Due to leading pf motor will supply reactive power.
- SM is also called synchronous condenser in this case.

(d) Unity pf case

At some value of excitation current or back emf the armature current will be in phase with V and pf is unity.

- I_a is minimum here.
- $I_a = \dfrac{P}{V\cos\phi} = \dfrac{P}{V}$

V curves and Inverted V curves



V curve → plot of I_a vs I_f
Inverted V → pf vs I_f

It is observed that magnitude of armature current varies with the excitation and has minimum value at certain excitation where pf is unity.

The variation of armature current with excitation current are known as V-curves.

The variation of power factor with excitation when plotted are known as inverted V-curves. It is noted that the minimum armature current corresponds to unity pf and at either side of unity pf line the current is maximum and powerfactor is leading (right side) and lagging (left side).

Power angle (P-δ) characteristics of cylindrical rotor synchronous machine

Let us consider a synchronous machine connected to infinite bus having a voltage of V_t and also resistance R_a of m/c neglected and X_s is only considered.

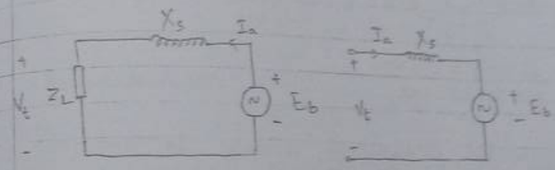
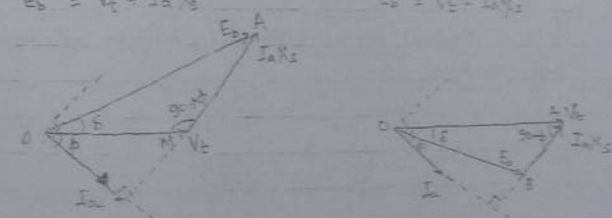


fig (a) generator mode   fig (b) :- motor mode

$V_t = E_b - I_a X_s$ $V_t = E_b + I_a X_s$
$E_b = V_t + I_a X_s$ $E_b = V_t - I_a X_s$



From phasor diagram,

ΔOAM, $\dfrac{E_b}{\sin(90+\phi)} = \dfrac{I_a X_s}{\sin\delta}$ —— (i)

ΔOAB, $\dfrac{E_b}{\sin(90-\phi)} = \dfrac{I_a X_s}{\sin\delta}$ —— (ii)

Combining (i) and (ii),

$$\frac{E_b}{\sin(90 \pm \phi)} = \frac{I_a X_s}{\sin\delta} \quad \text{—— (III)}$$

+ → for generator mode
− → for motor mode

or, $\dfrac{E_b}{\cos\phi} = \dfrac{I_a X_s}{\sin\delta}$

or, $I_a \cos\phi = \dfrac{E_b \sin\delta}{X_s}$

Multiplying both sides by V_t

$$V_t I_a \cos\phi = \frac{E_b V_t \sin\delta}{X_s} \quad \text{—— (IV)}$$

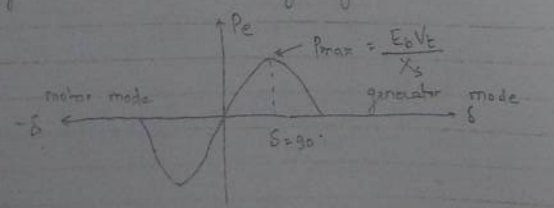
Here, electrical power exchanged between infinite bus and machine is

$$P_{elec} = V_t I_a \cos\phi$$

So,

$$P_e = \frac{E_b V_t}{X_s} \sin\delta$$

This equation is known as power (P) − angle (δ) equation of synchronous machine having cylindrical rotor.



Two - Reaction model of a Salient - pole machine

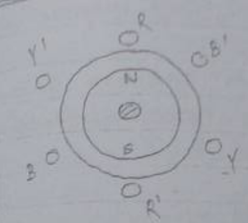


fig:- cylindrical rotor

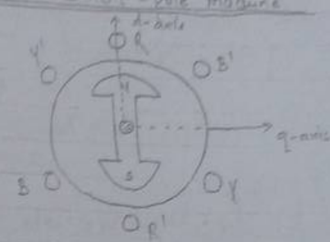


fig:- salient pole rotor

In case of cylindrical rotor machine the reluctance to the air gap flux is uniform at any position of rotor and therefore effect of armature reaction fluxes and voltage induced can be treated in a simple way. But in the case of salient-pole machine the reluctance to the air gap flux is not uniform at any position of rotor due to the asymmetrical construction of rotor. So, inductance and hence reactance of armature coil is not constant unlike in cylindrical rotor.

According to two reaction concept, a synchronous machine has two field pole axis called

(a) direct axis (d-axis) which is along the main field pole, and

(b) quadrature axis (q-axis) which passes through the interpolar space.

Accordingly the effect of armature reaction is resolved into two parts namely d-axis component & q-axis component.

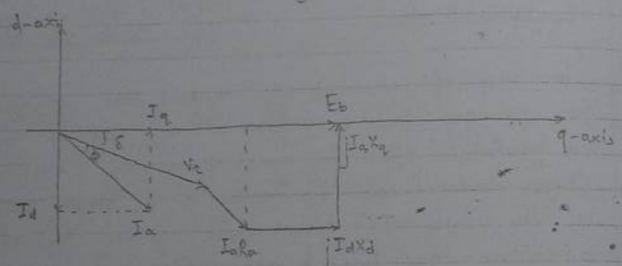
We have,

$$X_s = X_\ell + \underbrace{X_{ar}}_{\text{varying in salient pole m/c}}$$

Here,
X_{ar} can be resolved into d-axis component & q-axis component

$X_d = X_l + X_{ar}^d$ = d-axis synchronous reactance
$X_q = X_l + X_{ar}^q$ = q-axis synchronous reactance.

Voltage equation is
$$E_b = V_t + I_a R_a + jI_d X_d + jI_q X_q$$



If R_a is neglected for above phasor diagram,
$$E_b = V_t \cos\delta + I_d X_d$$
or, $$I_d = \frac{E_b - V_t \cos\delta}{X_d} \quad \text{--- (a)}$$

Also,
$$V_t \sin\delta = X_q I_q \implies I_q = \frac{V_t \sin\delta}{X_q} \quad \text{--- (b)}$$

The electrical power output of a salient-pole m/c is
$$P_e = V_t \cdot I_a \cos\phi$$

Active component of current $= I_a \cos\phi$
$$= I_q \cos\delta + I_d \sin\delta$$

putting the value of I_d and I_q from eqn (a) and (b)
$$= \frac{V_t \sin\delta}{X_q} \cos\delta + \frac{E_b - V_t \cos\delta}{X_d} \sin\delta$$

So electrical output
$$P_e = V_t (I_a \cos\phi)$$
$$= \frac{V_t^2 \sin 2\delta}{2X_q} + \frac{E_b V_t \sin\delta}{X_d} \quad \frac{V_t^2}{2X_d} \sin 2\delta$$
$$= \underbrace{\frac{E_b V_t \sin\delta}{X_d}}_{A} + \underbrace{\frac{V_t^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right] \sin 2\delta}_{B}$$

A → cylindrical rotor power
B → Reluctance power

Part A in above power expression is same as that of power of cylindrical rotor machine and part B is known as reluctance power which varies as $\sin 2\delta$ and it is independent of field excitation voltage, E_b.

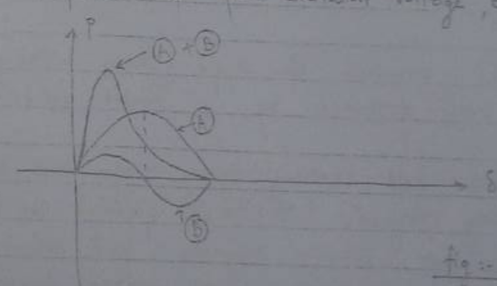


fig :- P-δ curve for salient m/c

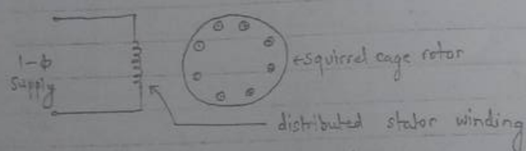
Note:- The synchronous motor with salient pole but without field excitation or field winding is known as reluctance motor.

FRACTIONAL KILOWATT MOTORS ...

These motors are build in smaller size and are widely used in fans, air conditioners, mixture, vacuum cleaners, washing machines other kitchen equipments, etc...

(I) **SINGLE PHASE INDUCTION MOTOR**

Most of the induction type have cage rotors and a single-phase distributed stator winding. A schematic diagram of a single-phase induction motor is shown below.



- Single phase induction motor inherently does not develop any starting torque and therefore will not start to rotate if the stator winding is connected to an ac supply. This is because of production of pulsating magnetic field. However, if the rotor is given a spin or started by auxiliary means it will continue to run.

The operation of single phase induction motor can be explained by "Double field Revolving Theory".

Double field Revolving theory states that any stationary pulsating magnetic field (vector quantity) can be resolved into two rotating magnetic field each of equal magnitude but rotating in opposite direction.

The induction motor responds to each of the magnetic field separately and the net torque in the motor is equal to the sum of the torques due to each of the magnetic field.

let,

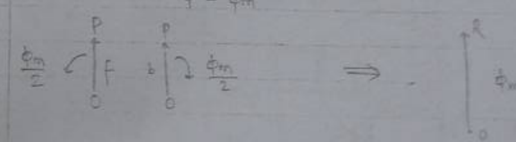
$$\phi = \phi_m \cos\omega t$$

$$\text{or, } \phi = \phi_m \left[\frac{e^{j\omega t} + e^{-j\omega t}}{2} \right]$$

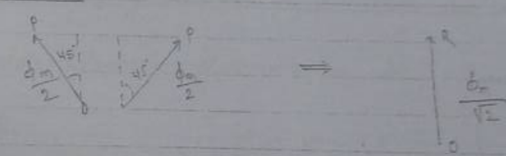
$$\therefore \boxed{\phi = \underbrace{\frac{\phi_m}{2} e^{j\omega t}}_{\phi_f} + \underbrace{\frac{\phi_m}{2} e^{-j\omega t}}_{\phi_b}}$$

At $\omega t = 0$

$$\phi = \phi_m$$



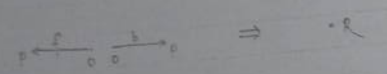
At $\omega t = 45°$



$$OR = \sqrt{\left(\frac{\phi_m}{2}\right)^2 + \left(\frac{\phi_m}{2}\right)^2 + 2\cdot\frac{\phi_m}{2}\cdot\frac{\phi_m}{2}\cdot\cos 90}$$

$$\therefore OR = \frac{\phi_m}{\sqrt{2}}$$

At $\omega t = 90°$:



So a pulsating field produced by stator current may be regarded as the resultant of two rotating field (f & b) of same magnitude but rotating in opposite direction.

Thus a single phase induction motor keeps on oscillating but can't run in one direction.

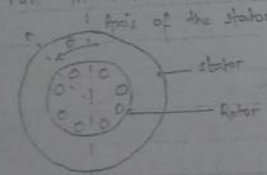


fig:- cross section of a single-phase induction motor

Mathematically, for a sinusoidally distributed stator winding the mmf along θ is,

$$F(\theta) = Ni \cos\theta$$

where, N = no. of turns

Let, $i = I_m \cos\omega t$

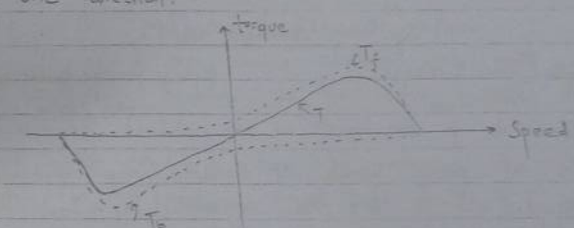
Then, $F(\theta, t) = NI_m \cos\theta \cos\omega t$

$$= \frac{NI_m}{2}\left[\cos(\omega t - \theta) + \cos(\omega t + \theta)\right]$$

$$\boxed{\therefore F = F_f + F_b}$$

F_f represents the rotating mmf in the direction of θ and F_b represents the rotating field in opposite direction of θ. These two mmf produces rotating fluxes in opposite direction and both flux produces the induction motor torque although in opposite direction.

At standstill (during starting) condition, these two torques, forward torque (T_f) and backward torque (T_b) are equal in magnitude and hence net torque is zero, thus motor cannot start (run). But at any other speed the two torques are unequal and the resultant torque keeps the motor rotating in one direction.



Slip

Assume that the rotor is rotating in the direction of the forward rotating field at a speed n rpm and the synchronous speed is n_s rpm.

The slip w.r.t the forward field is,

$$s_f = \frac{n_s - n}{n_s} = s$$

The rotor rotates opposite to the rotation of the backward field. Therefore the slip w.r.t. the backward field is

$$S_b = \frac{n_s - (-n)}{n_s}$$

$$= \frac{n_s + n}{n_s}$$

$$= \frac{2n_s - n_s + n}{n_s}$$

$$\boxed{\therefore S_b = 2 - s}$$

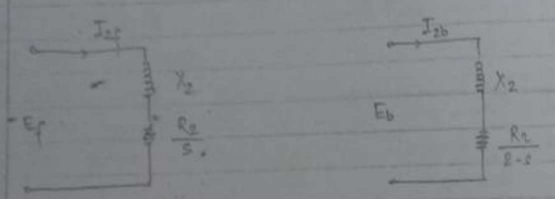


fig:- Rotor equivalent ckts

fig(a):- for forward rotating flux wave

fig(b):- for backward rotating flux wave.

In the above circuits at standstill, the impedances are equal and so are the currents ($I_{2f} = I_{2b}$). Their mmf's affect equally (oppose) the stator mmf's and therefore the rotating forward and backward fluxes in the air gap are equal in magnitude. However, when the rotor rotates, the impedances of the rotor circuits are unequal and the rotor current I_{2b} is higher (and also at a lower power factor) than the rotor current I_{2f}. Their mmf's which oppose the stator mmf's will result in reduction of the backward rotating flux. Consequently as the speed increases, the forward flux increases while the backward flux decreases; but the resultant flux remains essentially constant to induce voltage in the stator winding, which is almost the same as the applied voltage, if the voltage drop across the winding resistance and the leakage reactance are neglected. Hence, with the rotor in motion the forward torque increases and the backward torque decreases.

Starting of single phase induction motors

This type of motors must have an auxiliary means to start. For this we can place a winding with its axis displaced 90° electrical degrees with stator axis in space. Then they draw currents which are phase-shifted and can produce a starting torque.

In the running condition only main winding is sufficient. Therefore as the motor speeds up, the auxiliary winding can be taken out of circuit. In most motors this is done by connecting a centrifugal switch in the auxiliary circuit. At about 75% of the synchronous speed, the centrifugal switch operates and disconnects the auxiliary winding from the supply.

Classification of Motors

Single phase induction motors are known by various names. The names usually describe of the methods used to produce the phase difference between the currents

In the main and auxiliary windings. Some of the commonly used types of single-phase induction motors are described here:-

Split - Phase Motors

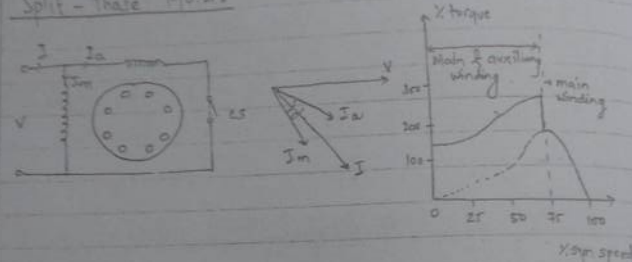
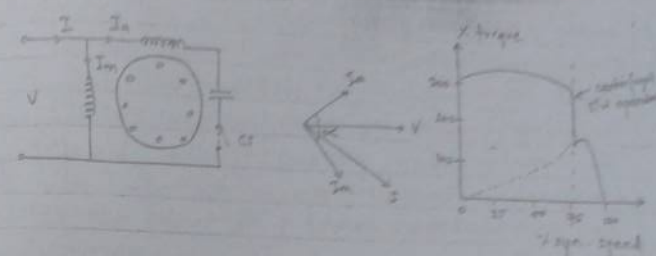


fig:- split phase IM

In the above diagram the auxiliary winding has a higher resistance-to-reactance ratio than the main winding so the two currents are out of phase. The high resistance to reactance ratio is usually obtained by using finer wire for the auxiliary winding. This is permissible because the auxiliary winding is in the circuit only during the starting period. The centrifugal switch cuts it out at about 75% of the synchronous speed.

The starting torque of this motor is between low to moderate and it depends upon the two currents and the phase angle between them. The starting torque can be increased by inserting a series resistance in the auxiliary winding.

Capacitor - Start Motors



In this motor a capacitor is connected in series with the auxiliary winding to obtain a higher starting torque. The connection of capacitor in this way increases the phase angle between the winding currents as shown in phasor diagram. The capacitor is an added cost here. A typical capacitor value for a 0.5 hp motor is 300 uF. Because the capacitor is in the circuit only during the starting period, it can be an inexpensive ac electrolytic type. High starting torque is the outstanding feature of this arrangement.

Capacitor - Run Motors

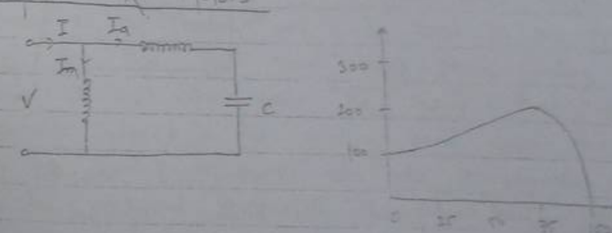
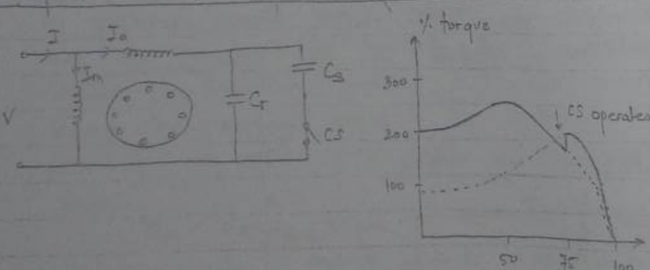


fig:- capacitor run motor

In this motor the capacitor that is connected in series with the auxiliary winding is not cut after starting and is left in the circuit all the time. This simplifies the construction and decreases the cost because the centrifugal s/w is not needed. The power factor, torque pulsation and efficiency are also improved because the motor runs as a two-phase motor. The motor will run more quietly.

The capacitor value is of the order of 20-50 μF and because it operates continuously, it is an ac paper oil type. The capacitor is a compromise between the best starting and running values and therefore starting torque is sacrificed.

Capacitor - Start Capacitor Run Motors



Two capacitors, one for starting and one for running can be used. Theoritically, optimum starting and running performing can be acheived by having two capacitors. The starting capacitor

C_s is larger in value and is of the ac electrolytic type. The running capacitor C_r, permanently connected in series with the auxiliary winding is of the smaller value and is of the paper oil type. Typical values of these capacitors for a 0.5 hp motor are $C_s = 300$ μF, $C_r = 40$ μF. This motor is though expensive compared to other, however provides the best performance.

Shaded - pole Motors

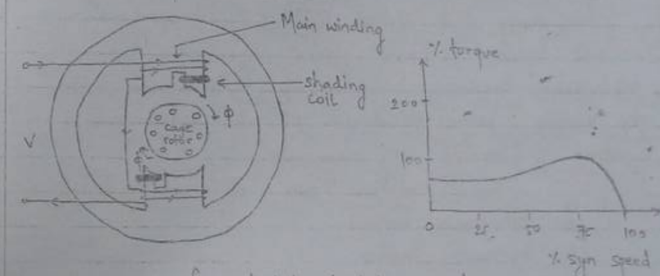


fig:- shaded pole induction motor

These motors have a salient pole construction. A shaded band consisting of a short-ckted copper turn, known as a shading coil, is used on one portion of each pole. The main single-phase winding is wound on the salient poles. The result is that the current induced in the shading band causes the flux in the shaded portion of the pole to lag the flux in the unshaded portion of the pole. Therefore the flux in the shaded portion reaches its maximum after the flux in the unshaded portion reaches its maximum.

This is equivalent to the progressive shift of the flux from the unshaded to the shaded portion of the pole. It is similar to a rotating ~~pole~~ field moving from the unshaded to the shaded portion of the pole. As a result, the motor produces a starting torque. They are the least expensive of fractional kilowatt motors.

II) SINGLE-PHASE SYNCHRONOUS MOTORS

For many low power applications that require constant speed, single phase synchronous motors are used because the 3-φ synchronous motors are usually large machines of the order several hundred kilowatts or megawatts.

These motors are of two types :-

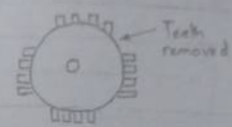
(a) reluctance motors
(b) hysteresis motors

These motors do not require dc field excitation nor do they use permanent magnets. Therefore they are simple in construction.

A) RELUCTANCE MOTORS

A single phase synchronous reluctance motor is essentially the same as the single-phase induction motor except that some modification is done in rotor structure by removing some teeth of rotor at the appropriate places to provide the required

no. of poles.



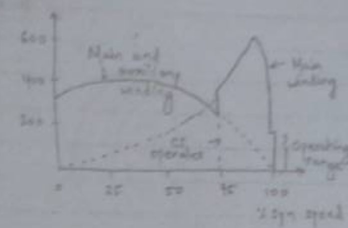


Fig:- 4-pole structure of rotor for a 4-pole reluctance motor

If motor rotates at synchronous speed the saliency of the motor will cause a reluctance torque to be developed. This torque arises from the tendency of the rotor to align itself with the rotating field.

When the speed is close to the synchronous speed the rotor tends to align itself with the synchronously rotating forward air gap flux wave and eventually snaps into synchronism and continues to rotate at synchronous speed.

B) HYSTERESIS MOTOR

Hysteresis motor use the hysteresis property of magnetic materials to produce torque. The rotor has a ring of special magnetic material such as magnetically hard steel, cobalt or chromium mounted on a cylinder of aluminium or other non-magnetic material. The stator windings are distributed windings to produce a sinusoidal space distribution of flux. The stator windings are normally the capacitor run type. The capacitor is chosen to make the two stator windings behave as much like a balanced two-phase system as possible.

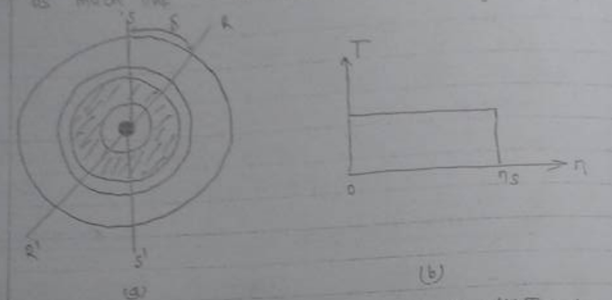


fig:- Hysteresis motor (a) Stator and rotor field (b) T-n characteristic

When the stator windings are connected to a single phase supply a rotating field is produced, revolving at synchronous speed. This revolving field induces eddy currents in the rotor and, because of hysteresis the magnetisation of the rotor lags behind the inducing revolving field. In the above figure, the axes SS' and RR' of the stator and rotor flux waves are displaced by the hysteresis lag angle δ. As long as the rotor speed is less than the synchronous speed, the rotor material is subjected to a repetitive hysteresis cycle at slip frequency. The angle δ depends upon the hysteresis loop and is independent of the rate at which the rotor materials are subjected to these hysteresis loop. A constant torque is therefore developed up to the synchronous speed as shown in figure. As the rotor approaches synchronous speed the frequency of the eddy currents decreases and at synchronous speed the rotor materials become permanently magnetised in one

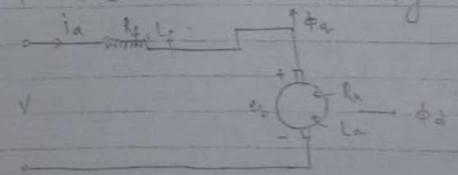
direction as a result of the high retentivity of the rotor material.

The constant torque-speed characteristic is one of the advantages of a hysteresis motor. Because of this feature it can synchronise any load that it can accelerate no matter how great the inertia is. On the other hand, a reluctance motor must "snap" its load into synchronism from an induction motor torque-speed characteristic. The hysteresis motor is quiet and smooth running because of smooth rotor periphery. However a high torque hysteresis motor of good quality is more expensive than a reluctance motor of the same hp rating.

III) Single Phase Series or Universal Motors (commutator type motor)

Single phase series motors can be used with either a dc source or a single phase ac source and therefore are called universal motors. As obvious, they are most widely used 1-ϕ motors.

Universal motors are mostly operated from a single phase ac source. Therefore both the stator and rotor structures are made of laminated steel to reduce core losses and eddy current.



DC excitation

When the polarity of dc series motor is reversed the motor will continue to run in same direction. The direction of torque developed in dc series motor is determined by both field polarity and direction of current through armature. ($T \propto \phi i_a$)

Here the torque developed and voltage induced are,

$$T = K_a \phi_d I_a$$

$$E_b = K \phi_d \omega_m$$

In this case the motor has high torque at low speed and low torque at high speed.

AC excitation

If eddy current is neglected, then i_a and ϕ_d are in phase.

let, $i_a = I_{am} \cos\omega t$ —(1)

$\phi_d = \phi_{dm} \cos\omega t$

Then,

$$e_b = K_a \phi_d \omega_m = K_a \phi_{dm} \omega_m \cos\omega t \quad -(2)$$

The rms value of back emf is

$$E_b = K_a \frac{\phi_{dm}}{\sqrt{2}} \omega_m$$

$$E_b = K_a \phi_d \omega_m$$

where, ϕ_d is the rms value of d-axis flux.

From (1) and (2) we see that e_b and i_a are in phase. The instantaneous torque is

$$T = K_a \phi_d i_a = K_a \phi_{dm} I_{am} \cos^2\omega t$$

$$T = K_a \frac{\phi_{dm}}{2} I_{am} (1 + \cos 2\omega t)$$

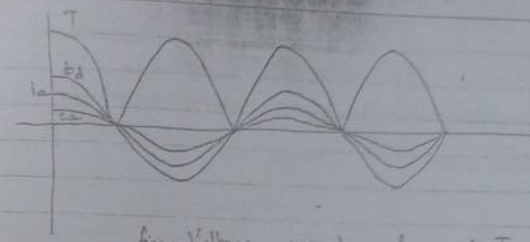


fig:- Voltage, current, flux and Torque waveforms

Although current and voltage are bidirectional, the instantaneous torque is unidirectional and so make the rotor run in the direction of rotation. Pulsating torque is produced with twice the supply frequency.

A DC series motor when operated by AC suffers following:-

a) ~~b~~ efficiency is low due to hysteresis and eddy
b) pf is low due to large interaction of field & armature
c) the sparking at brushes is excessive.

So modifications made. In order to effect the armature reaction, thereby improving the commutation and reducing armature reaction (reactance), a compensating winding is used in series with armature. The axis of compensating winding is 90° with the main winding.

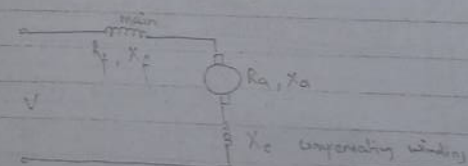


fig:- compensated motor

Special Purpose Machines

- Stepper motor
- Schrage motor
- Servomotor

(A) STEPPER MOTOR

A stepper motor rotates by a specific number of degrees in responce to an input electrical pulse. Typical step sizes are 2°, 2.5°, 5°, 7.5° and 15° for each electrical pulse. The stepper motor is an electromagnetic incremental actuator that can convert digital pulse inputs to carry analog shaft motion output. These type of motors are extensively used in digital control systems.

Some of the typical applications of stepper motors requiring incremental motion are printers, tape drives, disk drives, machine tools, process control systems, X-Y recorders and robotics.

There are mainly two types of stepper motors. They are :-

(a) Variable reluctance type.
(b) the permanent magnet type.

Variable Reluctance Stepper Motor

A variable reluctance stepper motor can be of the single-stack type or the multiple-stack type.

Single stack Stepper Motor

A basic circuit configuration of a four phase, two-pole single stack variable reluctance stepper motor is shown below.

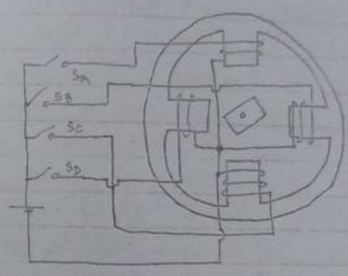


fig:- basic ckt for a 4-phase two-pole stepper motor

When the stator phases are excited with dc current in proper sequence the resultant air gap field steps around and the rotor follows the axis of the air gap by virtue of reluctance torque. This reluctance torque is generated because of the tendency of the ferromagnetic rotor to align itself along the direction of resultant magnetic field.

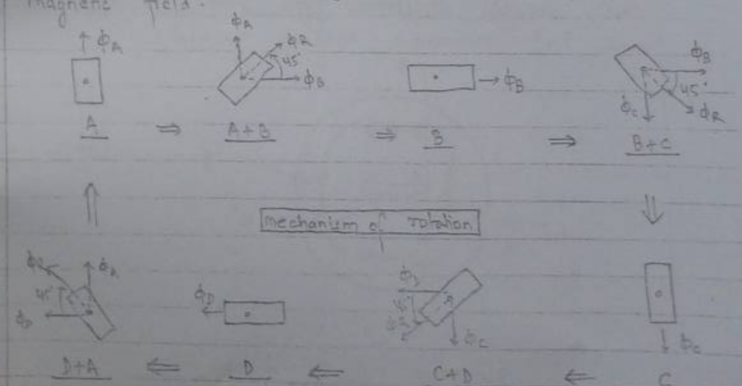


Figure above shows mode of operation for 45° step in the clockwise direction. The windings are energied in the sequence A, A+B, B, B+C and so forth and this sequence is repeated.

When winding A is excited, the rotor aligns with the axis of phase A. Next, both windings A and B are excited, which makes the resultant mmf axis move 45° in the clockwise direction. The rotor aligns with the resultant mmf axis. Thus at each transition the rotor moves through 45° as the resultant field is switched around.

The direction of rotation can be reversed by reversing the sequence of switching the windings A, A+D, D, D+C and so on.

Permanent Magnet Stepper Motor

The permanent magnet stepper motor has a stator construction similar to that of the single-stack variable reluctance type, but the rotor is made of permanent magnet material.

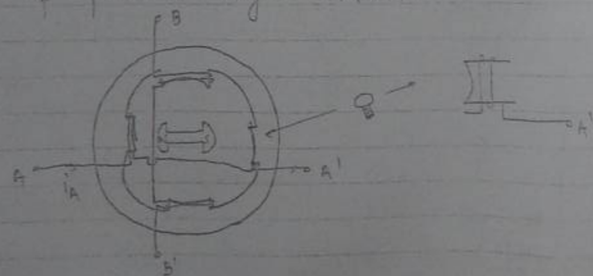


fig:- permanent magnet stepper motor

The rotor poles align with two stator teeth (or poles) according to the winding excitation. The above figure shows the alignment if phase A winding is excited. If the excitation is switched to phase B the rotor moves by a step of 90°. The current polarity is important in the permanent magnet stepper motor, because it decides the direction in which the motor will move. The above figure also illustrates the rotor position for positive current in phase A. A switch over to positive current in phase B winding will produce a clockwise step, whereas a negative current in phase B winding will produce an anticlockwise step. It is difficult to make a small permanent magnet rotor with large no. of poles and therefore stepper motors of this type are restricted to larger step sizes in the range 30 to 90 degrees.

Permanent magnet stepper motors have higher inertia and therefore slower acceleration than variable reluctance stepper motors. The permanent magnet stepper motor produces more torque per ampere stator current than the variable-reluctance stepper motor.

3) Schrage motor

It is a rotor fed commutator type 3-phase induction motor which has built-in arrangement for speed control. Speed control is acheived by controlling the voltage injected to the stator winding (secondary ckt or winding) from the commutator segment.

The connection diagram of a Schrage motor is shown below:-

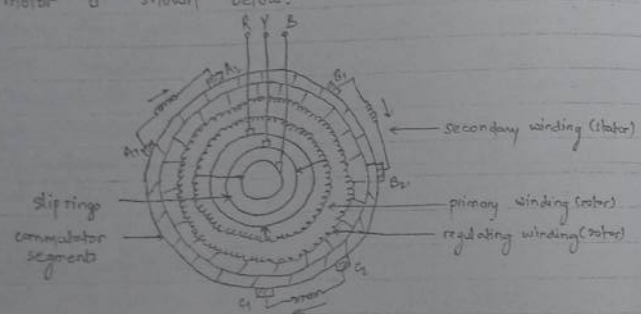


fig:- schrage motor

It consits of 3 windings: two windings known as primary and regulating winding in the rotor and one winding in stator known as secondary winding.

(a) Primary winding is provided in the lower part of rotor which is supplied by 3-phase voltage through slip-rings.

(b) Regulating winding is provided in the upper part of rotor which is connected to the commutator segments. It is also called as compensating or tertiary or auxiliary winding.

(c) Secondary winding is provided in the stator and ends of these 3-phase windings are connected to the commutator through pair of carbon bruches.

Working / operation

When 3-ϕ voltage is given to the primary winding, rotating magnetic field is produced. Emf is induced in the secondary winding (stator) according to induction motor principle and emf is also induced in the regulating winding according to normal transformer action.

Therefore, secondary winding is under the stress of two voltage.

let,

S_E = induced voltage in the secondary winding

E_K = injected voltage in the secondary winding from commutator segments.

Here the magnitude of E_K can be changed by changing the position of carbon bruches.

Due to induced voltage, current will flow in the secondary winding and as the current carrying conductor is lying in the rotating magnetic field, torque will be developed.

$$SE_2 = E_K + I_2Z_2$$

$$\therefore s = \frac{E_K + I_2Z_2}{E_2}$$

By controlling value of s we can control the speed. (by changing E_K)

Advantages of Schrage Motor

a) Continuous speed regulation within the required range can be obtained.
b) high power factor for high speed setting.
c) high efficiency at all speed except synchronous speed.

Applications

a) Schrage motor is used only where adjustable speed is required as in printing machine, machinery, etc
b) used in Knitting and ring spinning machines.

Drawbacks

a) Major drawback is that its operating voltage is limited to 700 V as power is supplied through slip rings.
b) high initial cost
c) low pf at very low speed setting.

c) SERVOMOTORS

These motors are also called control motors as they are mainly used in feedback control system as output actuators. They have high speed of response, which requires low rotor inertia. These motors are therefore smaller in diameter and longer in length. They normally operate at low or zero speed and thus have a larger size for their torque or power rating than conventional motors of similar rating.

Applications

robots, radars, computers, machine tools, tracking and guidance system and process controllers.

There are two types of servomotors:-
(a) DC Servomotors.
(b) AC Servomotors.

DC Servomotors

DC Servomotors are separately excited dc motors or permanent magnet dc motors. These are normally controlled by armature voltages. The armature is designed to have large resistance so that the torque-speed characteristics are linear and have a large negative slope. The negative slope provides viscous damping for the servo drive system. As we know, armature mmf and excitation mmf are in quadrature in a dc machine, we get a fast torque response because flux and torque are decoupled. Therefore a step change in the armature voltage (or current) results in a quick change in the position or speed of the rotor.

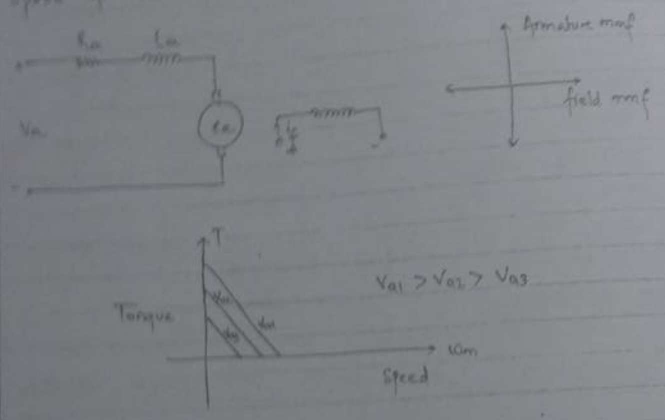


fig:- DC servomotor (a) Schematic diagram (b) Armature mmf and field mmf (c) Torque-speed characteristic

AC Servomotors

AC servomotors are used for low-power applications. Most ac servomotors used in control systems are of the two-phase squirrel cage induction type. The frequency is normally rated at 60 or 400 Hz. The higher frequency is preferred in aeroplane systems.

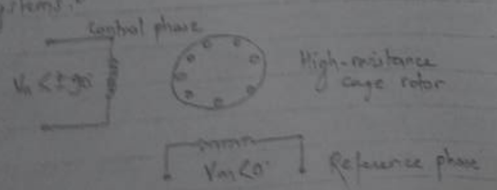


fig:- schematic diagram of ac servomotor

The figure above shows a 2-phase ac servomotor. The stator has a two distributed windings displaced 90 electrical degrees apart. One winding, called the reference or fixed phase is connected to a constant phase $V_m < 0°$. The other winding, called the control phase, is supplied with a variable voltage of same frequency as the reference phase but is phase displaced by 90 electrical degrees. The control winding voltage is usually supplied from a ~~__~~ servo amplifier. The direction of rotation of the motor depends on the phase relation, leading or lagging, of the control phase voltage w.r.t. the reference phase voltage.

For balanced two-phase voltages, $|V_a| = |V_m|$ the torque-speed characteristic of the motor is similar to that of a three-phase induction motor. For low rotor resistance this characteristic is non-linear. Such a torque-speed characteristic is unacceptable in control systems. However, if the rotor resistance is high, the $T-\omega_m$ characteristic is essentially linear over a wide speed range.

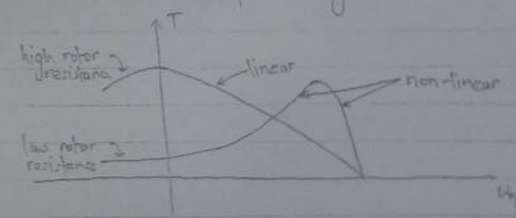


fig:- Torque - speed characteristic