INTRODUCTION:

It is an electrical machine which converts mechanical energy in to electrical energy .

CONSTRUCTION OF D.C. GENERATOR

It consist of the following main parts .

A. YOKE OR MAGNETIC FRAME
B. POLE CORES AND POLE SHOES
C. FIELD WINDING
D. ARMATURE
E. COMMUTATOR
F. BRUSH

or Stator → i) Yoke / Frame
ii) Field poles → pole core, pole shoe, field wdg

Rotor → Armature core
→ Armature wdgs
→ brushes
→ commutator

A. Yoke or Magnetic Frame

→ It is made of cost iron . → small machine
→ cast steel (large machine)

→ It's function is to protect the inner parts of the machine from mechanical injury . or it acts as protective covers for entire m/c .

→ It holds the inner parts of the machine .

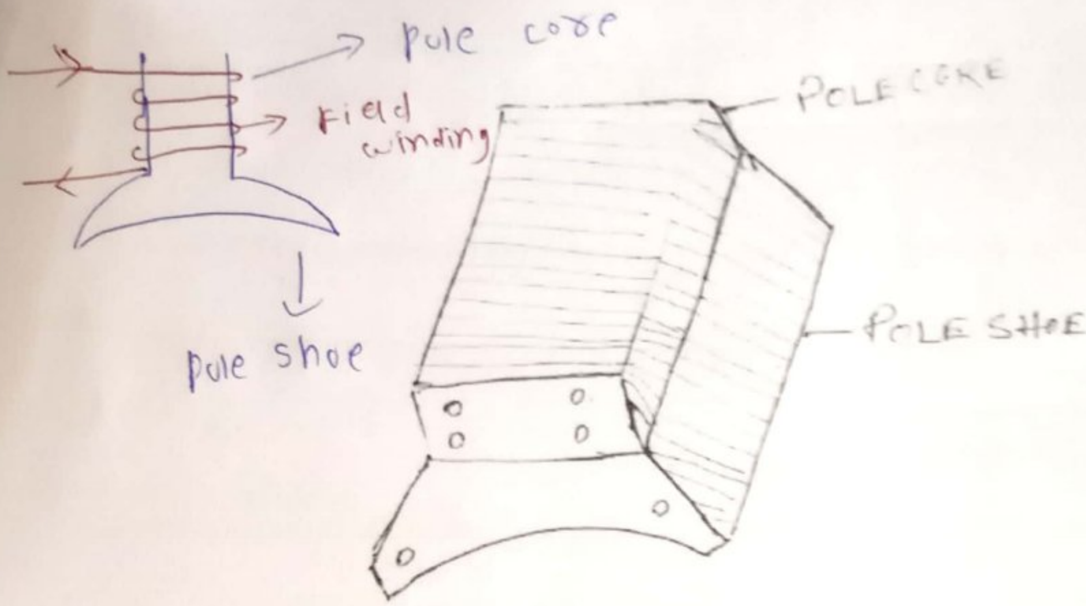
→ It will not allow the magnetic flux which is produced in the field poles to go out.

B. Pole Cores And Pole Shoes

It is made of laminated silicon steel material . The order of lamination is 0.35mm to 0.5mm . The shape of pole shoes as shown in figure . They spread out the flux on the air gap and also being of larger crossection to reduce the reluctance of the magnetic path . so that the flux produced by the poles will be more…

Pole core : cast steel
i) It carries field winding & provides mechanical support to the pole shoe .
ii) It acts as electromagnet when the field windings are excited .

Pole shoe : Cast steel laminations
i) It distributes magnetic field uniformly in the air gap .



Silicon steel material is used to reduce the hysteresis loss . The support the field coils .

C. Field Winding

It consists of thick copper wires wound over the pole cores .

When D.C current passes through than the electromagnetic is converted in to magnet and it will produce necessary magnetic flux .

D. Armature

-> It is the rotating part of the machine .

It is made of laminated silicon steel material in cylindrical shape . The lamination are approximately 0.5mm thick .

There are so many slots in its outer periphery where the armature winding are placed .

F. Commutator

-> It is made of hard-drown copper material .

-> It is in cylindrical shape .

imp -> The function of commutator is to collect the current from the armature conductor and convert the alternating current which is induced in the armature in to unidirectional D.C current.

The no. of commutator segmants is equal to the no. of coils. Each commutator segment is separated from another by the help of mica insulation.

3

BRUSH

- It is made of carbon due to it's (-) ve temperature co-efficient of resistance property.
- imp. It slip over the commutator and it's function is to collect current from the commutator and supply to the external load cicuit.

WORKING PRINCEPLE

- D.C Generator works according to the principle of Faraday's laws of electromagnetic induction.
- When ever a conductor cuts the magnetic lines of force an emf is induced in it. Here the mechanical power is utilized to rotate the armature. The armature cut and the magnetic filed an emf is induced on the armature conductors. The induced emf is

$$\boxed{e = -N\frac{d\emptyset}{dt}}$$

TYPES OF ARMATURE WINDING

There are two types of armature windings.

A. LAP WINDING
B. WAVE WINDING

LAP WINDING

- In case of lap winding the no. of poles is equal to no. of parallel paths. (A=P)
- It is used where high current and law voltage is required.

$\boxed{A = P}$

WAVE WINDING

In case of wave winding the no. of parallels paths is always equal to two (A=2).

It is used where high voltage and law current is required.

$\boxed{A = 2}$

EMF EQUQTION OF DC GENERATOR

Let P = No of poles

$\emptyset$ = Flux per pole in weber

3 Z = Total no. of conductor

N = Speed of armature in r. p.m 4

A = No. of parallel paths

$\frac{Z}{A}$ = Number of conductors / parallel paths

The emf induced in the armature due to flux linkage in the conductor is given

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

Emf induced per conductor

$e = \frac{d\phi}{dt}$ ($\therefore$ N = 1)

Now flux cut per conductor in one revolution . $d\phi = p\phi$ $d\phi = P\phi$

N = Number of rotation per minute .

Number of rotation per second = $\frac{N}{60}$

Time taken to complete one revolution

$$dt = \frac{1}{N/60} = 60/N \qquad dt = \frac{1}{(N/60)} = \frac{60}{N}$$

Now emf generated per conductor

$$e = \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60}$$

$$e = \frac{d\phi}{dt} = \frac{P\phi}{(60/N)} = \frac{P\phi N}{60}$$

Emf induced per parallel path

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

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

Generated emf (Eg) = $\frac{P\phi ZN}{60A}$

I.e Eg = $\frac{P\phi ZN}{60A}$

$$\boxed{E_g = \frac{P\phi Z N}{60A}} \text{ Volts}$$

→ For lap , $A = P$, $E_g = \frac{\phi Z N}{60}$ volts 6

→ For wave , $A = 2$, $E_g = \frac{P\phi Z N}{120}$ volts .

Imp

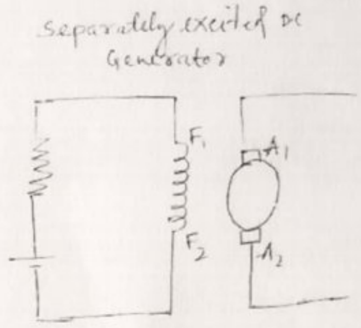
CLASSIFICATION OF D.C GENERATOR

5

D.C Generator are classified in to two types according to their excitation .

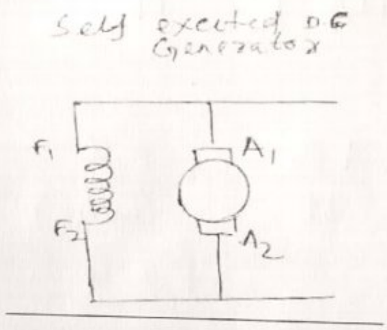
A. SEPARATLY-EXCITED D.C GENERATOR
B. SELF-EXCITED D.C GENERATOR

SEPARATLY-EXCITED D.C GENERATOR



If the field winding is excited by some external independent dc source then it is known as separately excited D.C generator .

SELF-EXCITED D.C GENERATOR

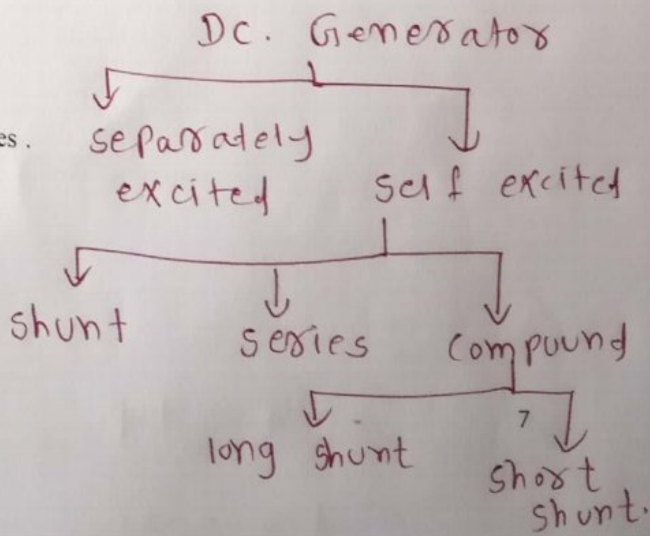


If the field magnets are excited by its own current , then it is known as self excited D.C Generator . It does not require any external sorce .

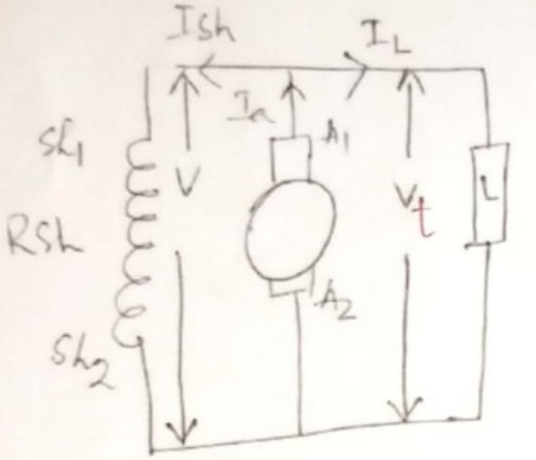
According to the connection of the field .

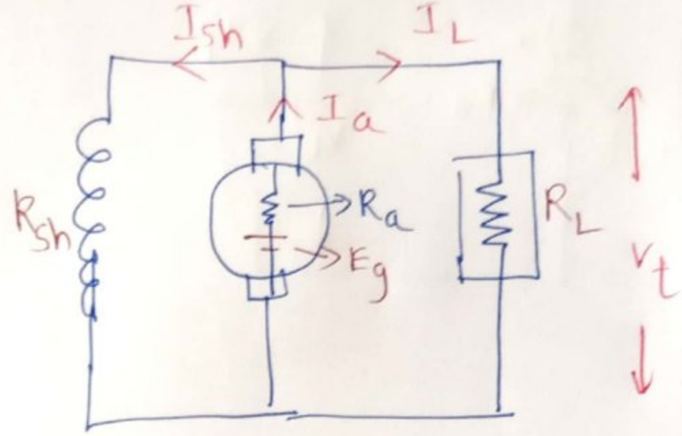
Winding Self-excited generators are classified in to 3 types .

A. D.C Shunt Generator
B. D.C Series generator
C. D.C Compound Generator



D.C Shunt Generator





The field winding is connected in parallel with the armature . The filed winding is excited by the termind voltage .

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

$$\boxed{I_{sh} = \frac{V_t}{R_{sh}}}$$

$$\boxed{I_a = I_L + I_{sh}}$$

Where V_t = Terminal voltage or voltage across the load .

Rsh = shunt field resistance

$E_g \cancel{=} - I_a R_a - B.D = V_t$

or $\boxed{E_g = V_t + I_a R_a + B.D}$

Ia = Ish+I_L

Eg = V+Ia Ra +b.d

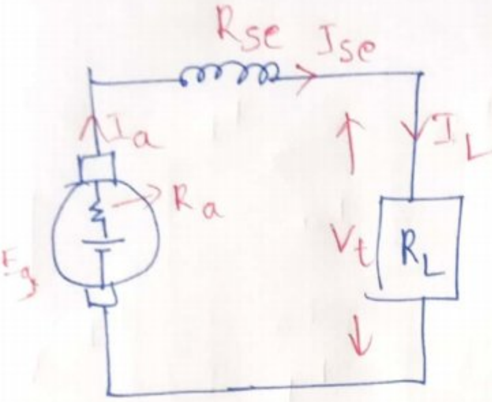
Where . Ra = Armature resistance which is very very small .

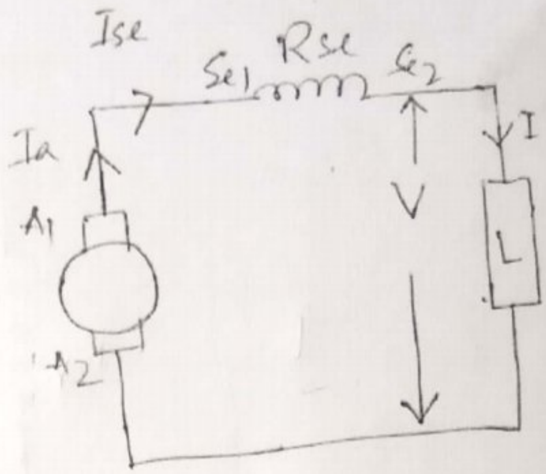
Ia Ra = Armature Resistance drop

B.d = Brush contact drop

Eg = Generated emf in the armature .

D.C SERIES GENERATOR





D.C Series Generator.

The field winding is connected in series with the armature .

Here ~~Ia = Isc = I~~ here $\boxed{I_a = I_{se} = I_L}$

~~Eg = V +Ia (Ra+Rsc)+b.d~~

$$E_g - I_aR_a - I_{se}R_{se} - B.D = V_t$$

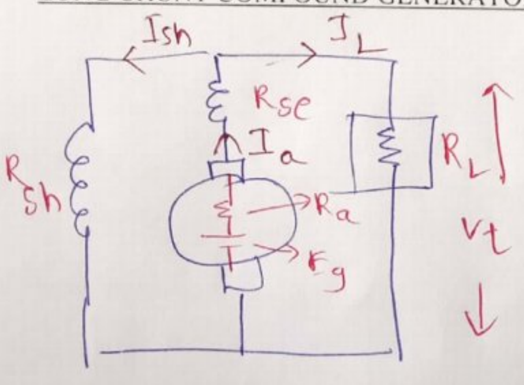
$$\Rightarrow \boxed{E_g = I_aR_a + I_{se}R_{se} + B.D + V_t}$$

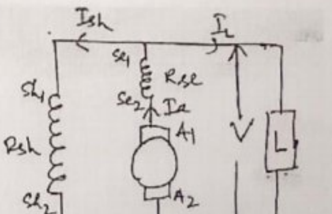
Here the field is excited by the load current .

D.C COMPOUND GENERATOR

It is the combination of series of field and shunt field .

LONG-SHUNT COMPOUND GENERATOR





LONG SHUNT COMPOUND D.C GEN.

$\text{Ish} = \frac{V}{Rsh}$ $\qquad I_{sh} = \frac{V_t}{R_{sh}}$ $\qquad \boxed{I_a = I_{sh} + I_L}$

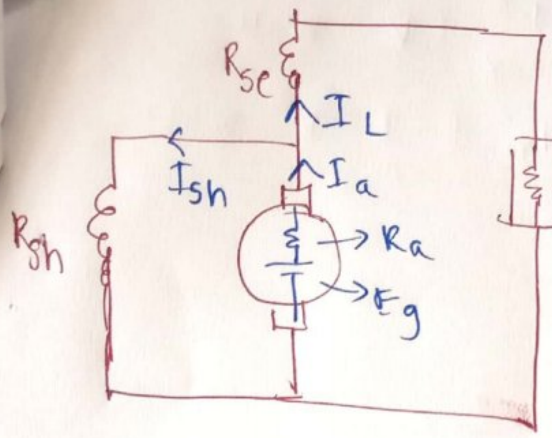
Ia = I+Ish

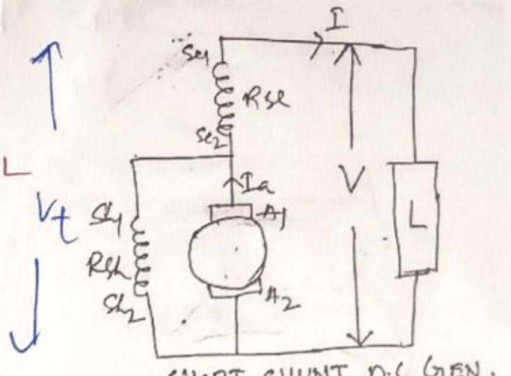
Eg = v+IaRa+IaRse+b.d

$$E_g - I_aR_a - I_aR_{se} - B.D = V_t$$

$$\Rightarrow \boxed{E_g = I_aR_a + I_aR_{se} + B.D + V_t}$$

SHORT-SHUNT COMPOUND GENERATOR





SHORT SHUNT D.C GEN.

$$\boxed{I_L + I_{sh} = I_a}$$

Here Ise = I

$$Ish = \frac{V + IseRse}{Rsh}$$

Ia = I+Ish

$$\boxed{Eg = V + IaRa + IRse + b.d}$$

$$E_g - I_a R_a = V \qquad \frac{V}{R_{sh}} = I_{sh}$$

$$V - I_L R_{se} = V_t$$

A. Commulatively Compound dc generator .

B. Differentially Compound D.C generator .

LOSSES IN A.D.C MACHINE .

There are 3 types of losses in a D.C machine .

A. Copper loss = I^2R

B. Iron / Core / Magnetic Loss

C. Mechanical loss

COPPER LOSS (30-40%)

The loss occurs due to the resistance . It is about 30-40%

i. Armature copper loss = Ia^2Ra ✓ $I_a^2 R_a$

ii. Series field copper loss = Is^2eRse $I_{se}^2 R_{se}$

iii. Shunt field copper loss = $I^2_{sh}Rsh$ $I_{sh}^2 R_{sh}$

IRON / CORE / MAGNETIC LOSS (20-30%)

The losses occur in the machine armature and field core .

It consists of

i. Hysteresis loss = W_h=hkBmax$x^{1.6}$ fV wats $W_h = \eta B_{max}^{1.6} f V$ watts

ii. Eddy current loss = We = kBmaxx^2 $f^2 t^2$v wats $W_e = \eta B_m^2 f^2 t^2 V^2$ watts.

9

Where h = steinmertz co-efficient of hysteresis constant .

Bmax = Max . Flux density in wb/m^2

f = Frequency in HZ

t = Thickness of lamination

V = Volume of material

For reducing hysteresis loss silicon steel material is preferred .

For reducing eddy current loss laminated sheets are used . lamination is done in order to reduce eddy current loss.

MECHANICAL LOSS (10-20%)

It consists of friction and windage loss of rotating machine . air shunt .

STRAY LOSS

It is the sum of iron loss and mechanical loss stray loss = Iron loss + Mechanical loss

CONSTANT LOSS (Wc)

It is the sum of stray loss and shunt field copper loss .

Wc (Constant Loss) = stray loss + shunt field copper loss

= Iron loss + mechanical loss + shunt field copper loss

Since shunt field current is constant the shunt field copper loss is also constant .

EFFICIENCY OF A D.C MACHINE

Efficiency is defined as the ratio of out put to input of a machine

$$\text{Efficiency } (h) = \frac{output}{input}$$

$$= \frac{output}{output + loss}$$

$$\text{Efficiency } (\eta) = \frac{O/P}{I/P} = \frac{O/P}{O/P + \text{losses}}$$

CONDITION FOR MAXIMUM . EFFICIENCY OF D.C GENERATOR

10

Efficiency = $\frac{O/P}{I/P} = \frac{output}{output+losses}$

efficiency = $\frac{O/P}{O/P + losses}$

$= \frac{O/P}{O/P + Wc + Ia^2Ra}$

$= \frac{O/P}{O/P + W_c + I_a^2 R_a}$

$= \frac{VI}{VI + Wc + Ia^2R}$ ($\because Ia \gg I$)

$= \frac{VI}{VI + W_c + I_a^2 R}$

$= \frac{VI}{VI + Wc + I^2Ra}$ ($\because$Ia = I)

$= \frac{VI}{VI + W_c + I_a^2 R_a}$

The efficiency will be maximum when $\frac{dh}{dI} = 0$

$\frac{d\eta}{dI} = 0$

$\Rightarrow \frac{d}{dI}\left(\frac{VI}{VI+Wc+I^2Ra}\right) = 0$

$\Rightarrow \frac{v[vI+Wc+I^2Ra]-vI[v+2IRa]}{(VI+Wc+I^2Ra)^2} = 0$

$\Rightarrow \boxed{W_c = I^2 R_a}$

$\Rightarrow$ v[vI+wc+I^2Ra]$-v^2I + 2$vIRa = 0

$\Rightarrow$ v[vI+wc+I^2Ra]$-$vI[v+2IRa] = 0

$\Rightarrow$ [vI+wc+I^2Ra] = I[v+2IRa]

$\Rightarrow$ vI+wc+I^2Ra = vI +2I^2Ra

$\Rightarrow$ wc$-I^2Ra$+2I^2Ra

$\Rightarrow$ wc = I^2Ra

Efficiency will be maximum when constant loss is equals to variable loss .

The load current corresponding to maximum efficiency is given by I = $\sqrt{\frac{wc}{Ra}}$

$I = \sqrt{\frac{W_c}{R_a}}$

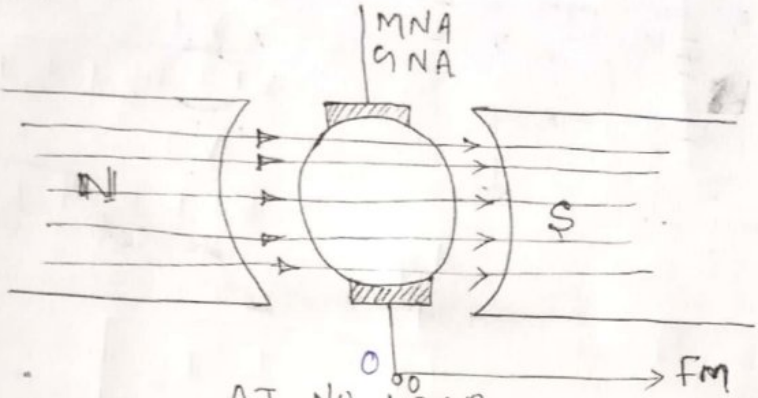
ARMATURE REACTION

When current flows through the armature conductors a magnetic field is produced .

This magnetic field due to armature current weakens and distorts the main magnetic field produced by the field poles .This effect is known as armature reaction .

AT NO- LOAD

The armature current is zero or small volume . This is due to the field flux . The ~~vectur of m~~ vector $\overrightarrow{OF_m}$ represents the MMF producing the main field . Here MNA (Magnetic Natural Axis)and GNA (Geometrical Natural Axis) are co-incident with each other . The MNA and GNA are perpendicular to field .

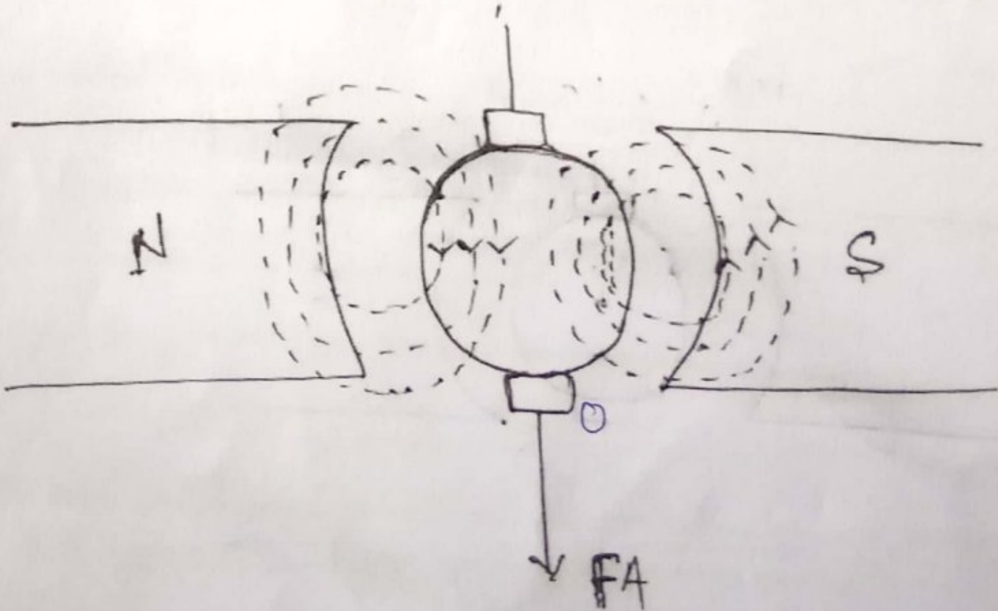


AT NO LOAD

AT LOAD

When the generator is loaded . It will produce a magnetic field considering only the armature current .

The vector of OF_A represents both in magnitude and direction of the MMF due to armature winding.

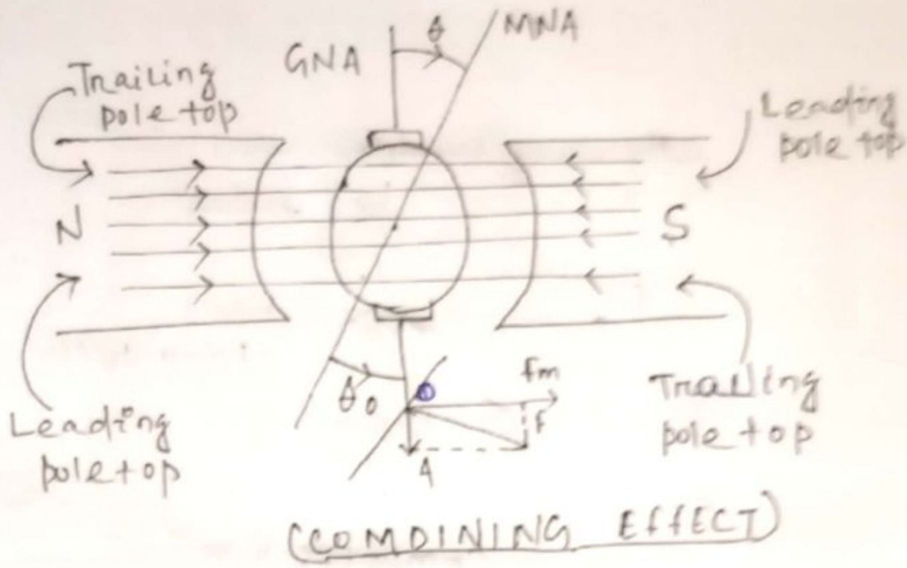


AT LOAD

COMBINING EFFECT

Under actual load condition , the above two effects exists simultaneously in the generator

The flux through the armature (resultant flux) is no longer uniform and symmetrical about the pole axis.

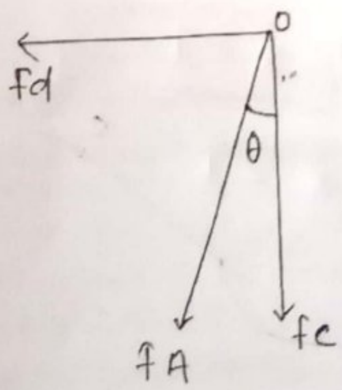


The resultant is OF , which is the vector sum of OFm and OFa . The new position of MNA is displaced from it's original position by an angle θ, because MNA is always perpendiculars .

The armature MMF is found to lie in the direction of MNA .

The armature MMF is now represented by the of F_A . Which is vertical but is inclined by an angel Ø to the left . It can now be resolved in to two component.

We find that



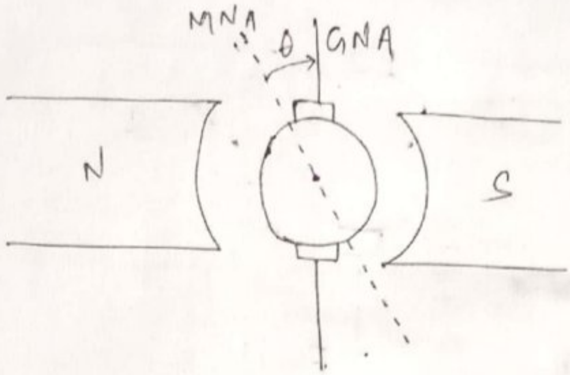
I. Component OFc is at right angle to the vector OFm representing the main MMF . It produce distortion in main field and is hence called the cross magnetising or ~~distarting~~ distorting component of the armature reaction .

13

II. The component OFd is in direct opposition to OFm which represent the main MMF . It exerts a demagnetizing influence on the main pole flux . It is the demagnetizing component of the armature reaction which weakens the main flux .

III. IN CASE OF MOTOR

When the machine act as motor . The current direction is reversed and hence MNA is shifted by an angle □ in the backward direction.



DEMAGNETISING AMPERE TURN

Let Z = Total Number of armature conduction

I = Armature current → $I_a/2$ → wave

in each conductor → I_a/P → lap

$\emptyset m$ = Mechanical degree in forward movment .

Total no. of armature conduction in angle

$\angle AOC$ and $\angle BOD = \frac{Z}{360} \times 4\emptyset m$ $\quad \frac{Z}{360} \times 4\emptyset m$

No. of turn under $\angle AOC$ and LBOD $= \frac{Z}{360} \times 2\emptyset m$ (∴ *two* conduction constitute one turn)

Demagnetizing ampere turns per pair of poles $= \frac{ZI}{360} \times 2\emptyset m$ $\quad \frac{2\theta m}{360} \times ZI$

Demagnetizing ampere turns per pole $= \frac{ZI}{360} \times \emptyset m$ $\quad \frac{\theta m}{360} \times ZI$

CROSS MAGNETISING AMPERE TURN

Total no of conductors per pole = $\frac{Z}{P}$

Demagnetizing conductors per pole = $\frac{Z}{360} \times 2\emptyset m$ $\qquad \frac{Z \times 2\emptyset m}{360}$

Cross magnetizing conductors pole=Total no of conductors per pole

$= \frac{Z}{P} - \frac{Z}{360} \times \frac{2\emptyset m}{360}$

$= Z\left(\frac{1}{P} - \frac{2\emptyset m}{360}\right)$

Cross magnetizing Ampere turns per pole

$= \frac{Z}{P} - \frac{Z}{360} \times \frac{2\emptyset m}{360}$ $\qquad ZI\left(\frac{1}{2P} - \frac{\theta m}{360}\right)$

$= Z\left(\frac{1}{P} - \frac{2\emptyset m}{360}\right)$

$\emptyset mech = \frac{\emptyset elect}{Pair\ of\ poles}$ (If the angle is given in electrical degrees)

$\boxed{\theta(mech.) = \frac{\theta(elect)}{\text{Pair of Poles}}}$

COMMUTATION

The emf ~~include~~ induced in the armature conductors of a mechine is an altraneting in nature .The current in a conductor for in one direction when it is under north pole and in reverse direction when it is under south pole .

The reversal of current of current from (+) I to (-)I has to occure when two commtator segments to which the armature coil is connected are short circuited by a brush .This process is known as commutation period .The current is in the coil has to reach its full value when in the reversed direction at the end of commutation period .If this does not happen the difference of current would pass from commentator to brush in the form of an A.C. arc .This arcing causes sparking pitting and roughing of the commentator surface

Two major effect of disturb the commutation process are armature reaction and reactance voltage . The armature reaction causes a shift of the M.N.P(Magnetic Natural Plane)in the forward direction for the generator and in the back direction for the motors . For proper commutation in the commutator brush should short-circuited .

The commutator segments at the instants when voltage across them is zero . Because of the shift of M.N.P ,the voltage between the segments has a finite value of the brush are in the G.N.P . The result is a current flowing between the short circuited commutator segments and arcing . The shifting of brushes the new M.N.P depends on the magnitude of load current Greater this current greater is the needed shifting greater is the load current since it is practically impossible to shift the brushes every time as the load current charges the brushes are always kept in G.N.P .

15

In the end the commutation problem is due to the reactance voltage . The time of commutation is very short if a machine is running at 1000 R.P.M. and has 50 commutator segment them is segment moves under a brush and clears it again in time of 0.0012 and seconds . If the current changes from (+) 100A to(-)100A the rate of change of current is $\frac{dI}{dt}$. $\frac{dI}{dt}$ = 166667 amp/ sec rate of changes of current is $\frac{dI}{dt}$.

The coil under going commutation has an inductance therefore induced emf L $\frac{dI}{dt}$ is set up in the coil . Through the magnitude of inductance of very high and therefore the magnitude of induced emf coil be appreciable . This EMF is known as reactance voltage and oppose the reversal of current . Thus sparking occurs at the brushes .

Commutation problem can be minimized by different method .

i. Emf commutation
ii. By using interpoles
iii. By resistance commutation
iv. By using compensating winding

<u>By Emf Commutation</u>

In this method a voltage which cancels the reactance voltage is used to ensure good commutation . One way to cancel the reactance voltage is by shifting the brush a little forther then the M.N.P . so that they lie in the fringe of the field of the next pole . The Emf induced in the coil opposes the reactance voltage and opposes forces the reversal of current in the coil . However this method is not used because the extend of shifting of brushes depends on the load current and it is not practicable to shift the brushes every time as the load current changes .

<u>By Using Interpoles Or Compoles</u>

The interpoles helps on reducing the sparking due to commutation problem of current from A.C to D.C . They are small poles fixed to the yoke and placed in between to main poles . The windings of these poles has few turns of thick copper wire and is connected in series with the armature ckt . There fore the mmf of an interpole is proportional to armature current . The function of interpole is to .

i. Ensure automatic neutrallization of reactance voltage .
ii. Cancellation of cross-magnetization effect of armature reaction

Reactance Commutation

The next approach to achive two commutation by the use of brushes with high contact resistance then the brushes made from other materials. Hence carbon is used as a brush universally . Also carbon has (-) ve temperature co-efficient of resistance properly .

Compensating Winding

In order to neutrallisation the cross magnetizing effect , compensating winding are used . It is used only in case of large machine . These windings are ambeded in slots in the pole shoes in series with armature in such a way that the current in them flows in opposite direction to that of in the armature induction directly below the poles-shoes .

No. of compensating winding appear turns per pole = $\frac{0.7 \times ZI}{2P}$

$= \frac{0.7 \times Z}{2P}$

DUMMY COILS

When a machine has a wave winding is very necessary to use extra coils to maintains the mechanical balance of the armature . This coil is completely insulated from the remaining winding and it is used for only mechanical balance .

It is known as dummy coils

$Yc = \frac{2(C \pm 1)}{P}$

$\boxed{Yc = \frac{Z \pm 2}{P}}$ C = No. of coils

Yc = Commutator pitch

P = No. of poles

17

EQUALLISER RING

The existence of many parallel path in a lap winding leads to be serious problems of circulting currents . The fluxes from all the poles are not exactly equal because of wear and tear on the bearing, the air gap doesnot remain uniform around the whole periphery . As the armature conductor rotates the voltages induce in different parallel paths will be slightly different . Hence armature winding . Due to circulating current energy loss and heating effect results . Therefore equalizer rings are necessary which will be connected to make some potential different parallel path . Each rings are insulated from which others . By using equalizer rings induced emf can be made equal no. of equalizer rings

$$= \frac{\text{Total No.of Conductors}}{\text{N.of Pair of Poles}}$$

$$= \frac{Z}{\frac{P}{2}}$$

$$= \frac{2Z}{P} \quad (\therefore \text{No. of equalliser rings} = \frac{2Z}{P}).$$

CRITICAL FIELD RESISTANCE OF A SHUNT GENERATOR

The maximum emf generayed is oc ,if the shunt field resistance is increased, then the maximum generated emf is represented by oc . so that if becomes a tanjent to the curve . the value of field resistance corresponding to the point of intersection of the field resistance for a given speed again it is seen that ,if the field resistance is increased further beyond the criticial ristance the generator does not excite at all in other words the critical field resistance Rc of a shunt generator is the maximum value of field resistance beyond which the generator can't build of voltage .

CRITICAL SPEED OF A SHUNT GENERATOR

The speed for which a given shunt field resistance acts as critical field resistance is known as critical speed .

If E1 and E2 be the respective values indused emf for the same excitation current at speed N1 and N2

Then $\frac{E1}{E2} = \frac{N1}{N2}$

CHARACTERISTICS OF D.C GENERATOR

There are three different types of characteristic

(1)-NO-load /magnetization/ open circuit characteristics (o.c.c)

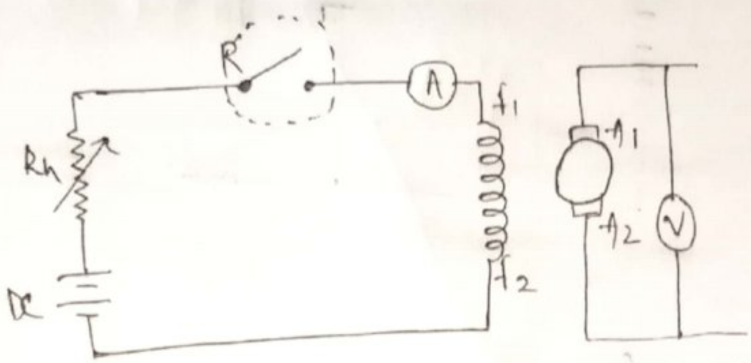
(2)-Internal characteristics

(3)-Load/External characteristics

(1)-NO LOAD/MAGNETISATION/OPEN CIRCUIT CHARACTERISTICS(O.C.C)

It is graphical relationship between generated emf and field current (Eg~If) 18

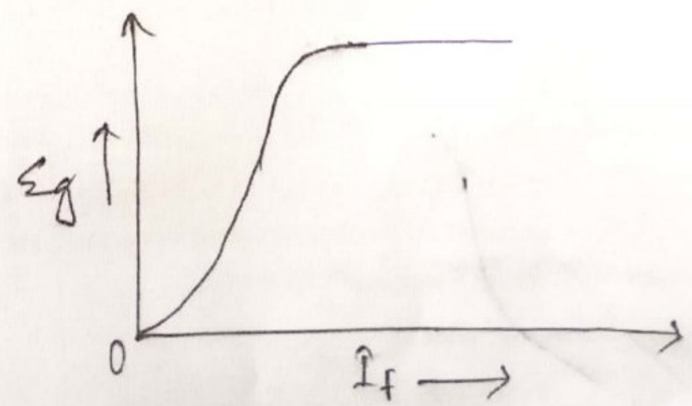
FOR A SEPARATEEY EXCITED D.C GENERATOR



[For a seperateev excited] DC Generator

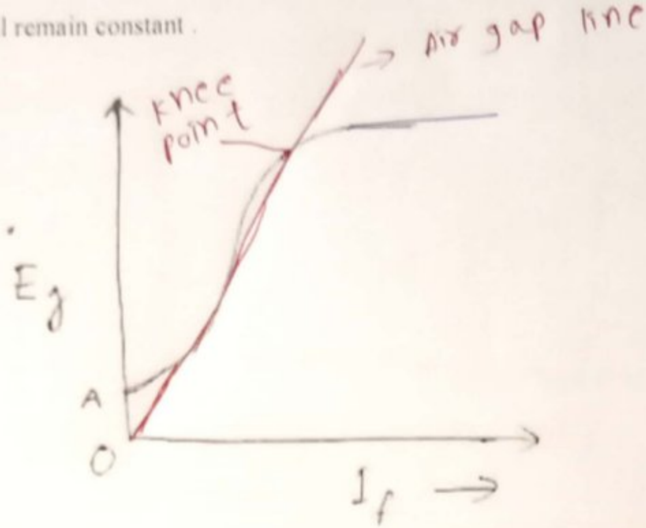
Let the switch is open ,but the generator is driven by some external source (Prime-mover or dc motor).It is seen that the generated emf is zero,since the flux is zero .

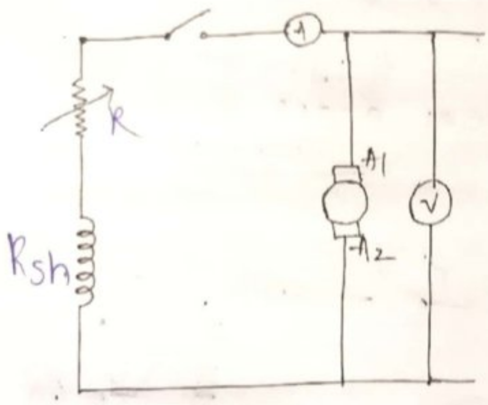
Now the switch is closed and the field current increases gradually .it is seen that as the field current increases, the generated emf is proportional to the field flux .This will continue till saturation. After saturation of magnet fild, the fild current may be increases but the fild flux remains constant. So the generated emf remains constant ever if the field current increases.



FOR SELF-EXCITED DC GENERATOR

When the field current is zero, the EMF induced in the armature is 'OA'. This is due to the presence of residual magnetization. Again if the field current increases the EMF increase and it will continue up to the point of saturation. After saturation the field current may increases but field flux remain constant . So that EMF induced will remain constant . 19





(2). INTERNAL CHARACTERISTICS:-

It is the graphical relationship between voltage and armature current $E_0 \approx I_a$ .when the armature current is zero, the generated EMF is equal to the no load voltage. As the armature current increase the armature resistance drop is ($I_a R_a$ drop) increases. So the terminal voltage decreases. At heavy loads, due to armature reaction the terminal voltage decreases to a lower value.

We know that,

$$E_g = V + I_a R_a$$

$$V = E_g - I_a R_a$$

(3)EXTERNAL/LOAD CHARACTERISTICS :- (V~ I)

20

It is the graphical relationship between the two terminal voltage and the load current .

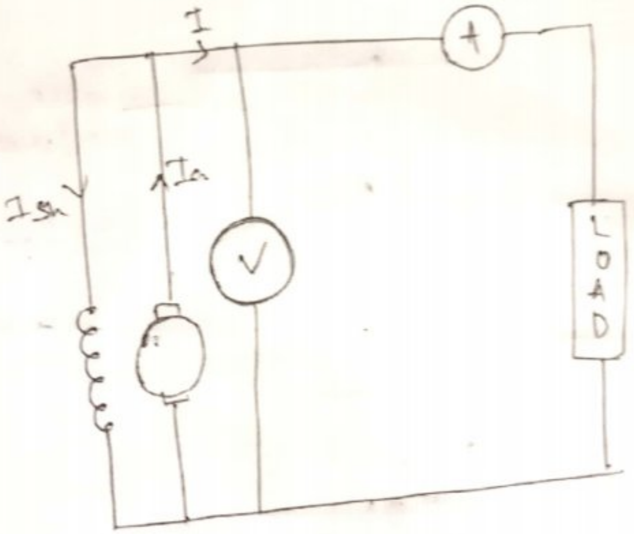
V~I

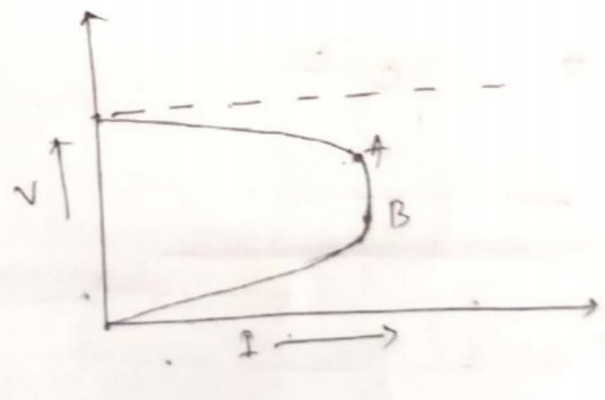
FOR SHUNT GENERATOR

It is seen that when the load current increase, the terminal voltage decreases. As the load current increase $I_a R_a$ drop increases .

But at point 'A' if further the load increases, the terminal voltage decreases suddenly. This is due to the armature reaction .

$V = E_g - I_a R_a$





The drops are due to,

(1) Armature resistance drop ($I_a R_a$ drop)

(2) Armature reaction

(3) The combining effect, the terminal voltage decreases suddenly as the load current increase, it is represented by A to B.

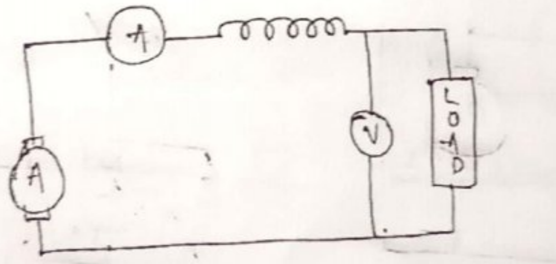
If further the load increases, the generator will come to its unstability condition, which is shown by dotted lines. If the load increases further the terminal voltage decreases to a very lower value and the generator cannot main-tion its stability. Automatically it will come to 'OFF' position.

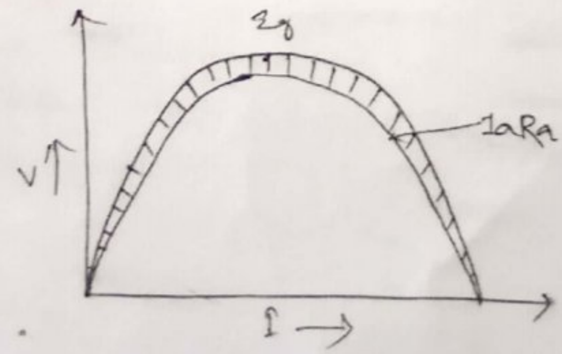
This is known as dropping characteristic of D.C shunt generator. Due to this reason it is suitable for lighting purpose and battery charging purpose.

FOR SERIES GENERATOR:-

It is seen that load current increases the terminal voltage increases. This is due to the load current passes through the field..It continue up to the point of saturation. After saturation, if the load current increases, then the terminal voltage decreases. This is known as rising characteristics of a D.C series generator so it is used as a booster.

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





Curve..........

The drops are due to

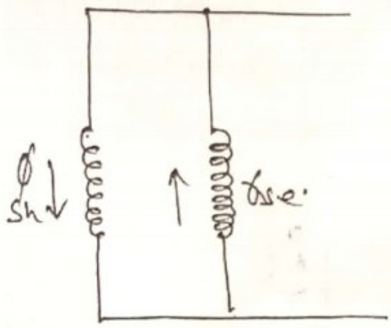
(1) $I_a R_a$ drop

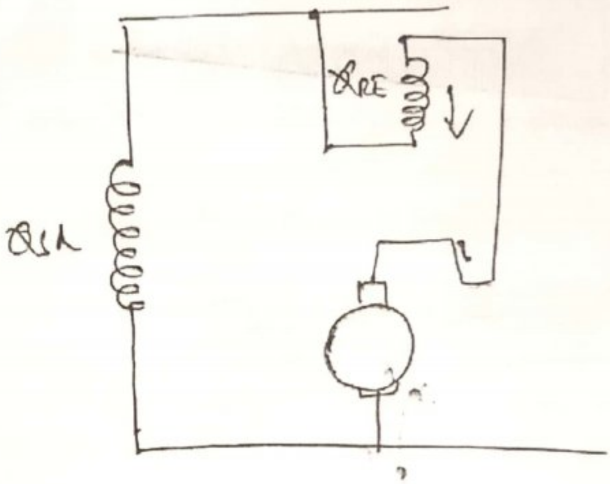
(2) $I_a R_{se}$ drop

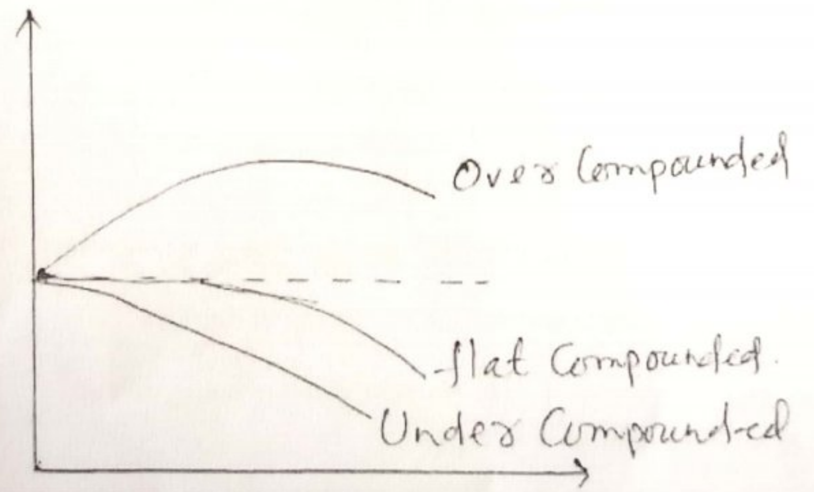
(3) Armature Reaction

22

FOR COMPOUND GENERATOR:-







Differential Compound D.C generator Net Phase = $\emptyset_{sh} - \emptyset_{sc}$

Commulatively Compound D.C Generator Net Phase = $\emptyset_{sh} + \emptyset_{sc}$

23

OVER COMPOUND/COMMULATIVELY COMPOUND:-

In case of commulatively compounded D.C Generator the series field flux aids to the shunt field flux. As the load current increases series field flux increases. As the load current increases, the terminal voltage increases. If the terminal voltage is more than the no load voltage then it is known as over compounded D.C Generator.

UNDER COMPOUNDED/DIFFERENTILLY COMPOUNDED:-

In case of defferentially compounded D.C Generator the series field flux opposes the shunt flux. As the load current increases, the net flux decreases. Hence generated EMF decreases. As the load current increases the terminal voltage decreases, then no load voltage as the load current increases. It is known as external characteristics of under compounded D.C Generator.

FLAT COMPOUNDED:-

The change in no load voltage to full load voltage is negligible is known as flat compounded D.C Generator. As the load current increases, the terminal voltage decreases slightly.

CONDUCTION FOR BUILT UP A SELF-EXCITED D.C GENERATOR:-

*There must be some residual magnetism in the poles.

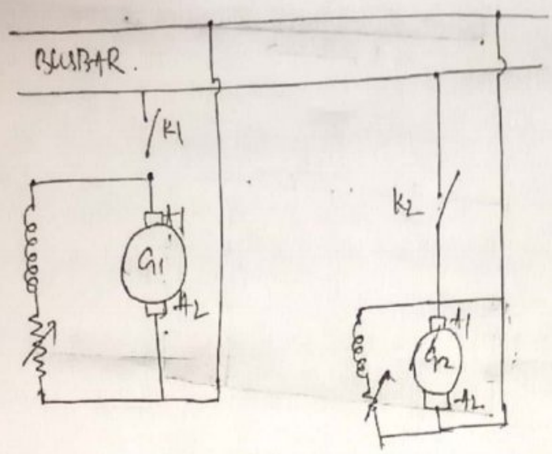
*For the given direction of rotation, the shunt field poles should be connected properly to the armature.

*If excited on open circuit, its shunt field resistance should be less than the critical resistance.

*If excited on load, then the shunt field resistance should be more than a certain minimum value of resistance which is given by internal characteristics.

*The series generator should be started with load.

PARALLEL OPERATION OF A DC GENERATOR



24

CONDITION FOR PARALLEL OPERATION

I. Polarity must be maintained.

II. The terminal voltage of generator must be equal to the bus bar voltage $V_1 = V_2 = V$

III. The load sharing should be equal.

LOAD EQUAL

Load sharing two generators which have unequal no-load voltage.

Let, E_1 = No load voltage of G_1

E_2 = No load voltage of G_2

R_{a1} = Armature resistance of G_1

R_{a2} = Armature resistance of G_2

V = Bus bar voltage

= Common terminal voltage

$\Rightarrow \quad I_{a1} = \frac{E_1 - V}{R_{a1}}$

$\Rightarrow \quad I_{a2} = \frac{E_2 - V}{R_{a2}}$

$\Rightarrow \quad \frac{I_{a2}}{I_{a1}} = \frac{E_2 - V}{E_1 - V} * \frac{R_{a1}}{R_{a2}}$

$$\Rightarrow \quad \frac{K_2 N_2 \Phi_2 - V}{K_1 N_1 \phi_1 - V} * \frac{K_{a1}}{R_{a2}}$$

From the above equation it is seen that the bus bar voltage can be kept constant by increasing ϕ_2 or N_2 or by reducing N_1 and ϕ_1. 25

N_1 and N_2 are changed by the help of resulting shunt field resistance .

- Two parallel shunt Generator having equal no-load voltage share the load in a ratio that the load current of each machine produces the same drop in each generator .
- In case of 2 generator having un-equal no-load voltage ,the load current produces sufficient voltage drop in each .so as kept their terminal voltage same .

SERIES GENERATOR IN PARALLEL

Suppose E_1 and E_2 are initially equal generators, supply equal current and have equal series resistance .suppose E_1 increases slightly . so that $\frac{E_1}{E_2}$

In this case I_1 becomes grater then I_2 .Now the field of machine G_1 is strong then .Then increases E_1 further the field of machine G_1 is weakened .

Then decreases E_2 further a final stage is reached , when the machine G_1 is supplied not only the whole load but also power to the machine G_1 which starts remaining as a motor .This can be prevalent by using equal bus bar machines pass approximately equal currents to the load.

It essential that series field resistances are inversely proportional to the generator rating .

COMPOUND GENERATOR IN PARALLEL

It is same as in series Generator for maintaining division of load from no- load to full-load .

I. The regulation of each generator is same
II. The series field resistance are inversely proportional to the generator rating .

Generator

1. A short shunt Compound DC generator delivers a load Current of 30 A at 220V, and has armature, series field and shunt field resistance of 0·05 Ω, 0·30 Ω and 200 Ω respectively. Calculate the induced emf ~~Current~~ and armature Current. Allow 1·0V per brush for Contact drop.

Sol^n

Given data:

$I = 30\ A$.

$V = 220V$.

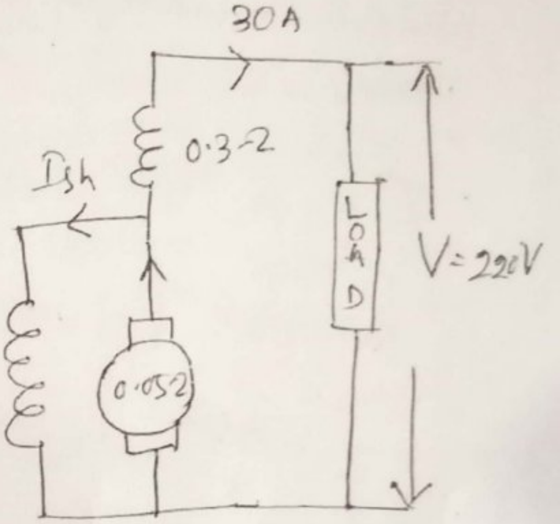
$r_a = 0{\cdot}05\ \Omega$.

$R_{se} = 0{\cdot}30\ \Omega$

$R_{sh} = 200\ \Omega$

$I_a = ?$

$E_g = ?$



Shunt field Voltage drop = V + series field drop

$= 220 + I \times 0{\cdot}03$

$= 220 + 30 \times 0{\cdot}03 = 229V$.

$I_{sh} = \cancel{\frac{220}{229}}\ \frac{229}{200} = 1{\cdot}145A$.

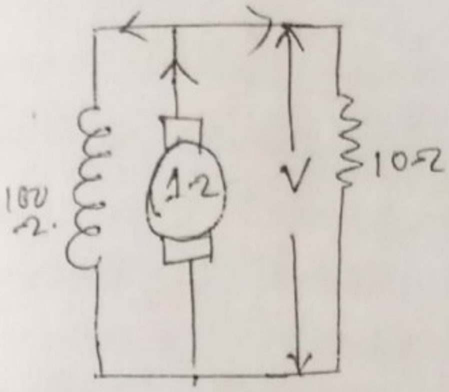
$$\boxed{I_a = I + I_{sh} = 30 + 1{\cdot}145 = 31{\cdot}145A.}$$

$E_g = V + IR_{se} + I_a \times r_a$.

$= 220 + 30 \times 0{\cdot}03 + 31{\cdot}145 \times 0{\cdot}05$

2. A 4-pole, d.c shunt generator with a shunt field resistance of 100 Ω and an armature resistance of 1 Ω has 378 wave-connected conductors in its armature. The flux per pole is 0.02 wb. If a load resistance of 10 Ω is connected across the armature terminals and the generator is driven at 1000 rpm, Calculate the power absorbed by the load. 27.

Soln



Given data

$P = 4$

$R_{sh} = 100\,\Omega$.

$r_a = 1\,\Omega$.

$Z = 378$

$A = 2$.

$\phi = 0.02\,wb$.

$R_L = 10\,\Omega$.

$N = 1000$ rpm.

$$E_g = \frac{P\phi ZN}{60A} = \frac{4 \times 0.02 \times 378 \times 1000}{60 \times 2}$$

$$= 252\,V.$$

V is the terminal Voltage:

$$I_{\cancel{d}} = \frac{V}{10}, \quad I_{sh} = \frac{V}{100}\ A.$$

$$\text{Armature Current} = \frac{V}{10} + \frac{V}{100}$$

$$= \frac{11V}{100}$$

V = Eg − armature drop.

$$= 252 - I_a' R_a = \cancel{252} = 227$$

DC Motor

→ ~~DC motor is a machine that converts i/p DC signal supply to~~

→ DC motor is a machine that converts ~~mechanical~~ Electrical Energy to mechanical Energy.

Electrical (i/p) → $\boxed{\text{DC motor}}$ → mechanical (o/p)

→ It's operation is based on the Lorentz's principle. i.e. Whenever a current carrying conductor is placed inside a magnetic field, the conductor experiences a mechanical Force.

→ The direction of the Force is given by FLHR & magnitude is $\boxed{F = BIL \text{ Newton}}$

→ Generator action will also take place in the motor, due to motor action, armature conductors are rotating in the magnetic field, they cut the magnetic flux & dynamically induced emf is produced. The direction of this induced emf is acting opposite to the supply voltage. That's why this induced emf is called back emf or counter emf.

→ The armature current is proportional to the potential difference $(V - E_b)$.

$$\boxed{I_a = \frac{V - E_b}{R_a}}$$

where E_b = back emf
R_a = Armature resistance
V = supply voltage

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Significance of back emf

→ The presence of back emf makes the DC motor a self-regulating machine i.e. it makes the motor to draw as much armature current as is just sufficient to develop the required by the load

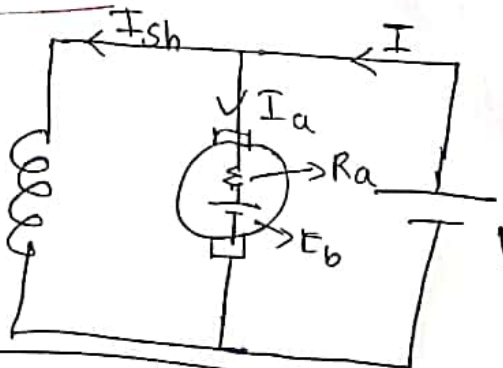
$$\text{Armature current } (I_a) = \frac{V - E_b}{R_a}$$

→ when the motor is running on no-load, small torque is required to overcome the friction & windage losses. so I_a is small & the back emf is nearly equal to the applied voltage.

→ If the motor is suddenly loaded, the first ~~came~~ effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced & hence the back emf E_b falls. The decreased back emf allows a larger current ~~through~~ to flow through the armature & large current means increased driving torque.

→ If the ~~motor is~~ load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated.

Voltage eqn of DC motor



V = Applied voltage

E_b = back emf

R_a = Armature resistance

I_a = Armature current

$$I_a = \frac{V - E_b}{R_a} \Rightarrow \boxed{V = E_b + I_a R_a}$$

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Power equation

$V = E_b + I_a R_a$

Multiply I_a on both sides

$$\boxed{V I_a = E_b I_a + I_a^2 R_a}$$

$V I_a$ = Electrical power supplied to armature

$E_b I_a$ = Electrical equivalent of mechanical power developed by armature.

$I_a^2 R_a$ = Armature cu. loss

$P_{in} = P_{mech} +$ Arm. cu loss

$$\boxed{P_{mech} = E_b I_a = T_{em} \times \omega \qquad T_{em} = \frac{P_{mech}}{\omega_r} = \frac{E_b I_a}{\omega_r}}$$

Cond^n for maximum power

Mechanical power developed by the motor is $P_m = E_b I_a$

Now $P_m = V I_a - I_a^2 R_a$

As (V, R_a Fixed)

$\frac{dP_m}{dI_a} = V - 2 I_a R_a = 0 \qquad I_a R_a = \frac{V}{2}$

Now $V = E_b + I_a R_a = E_b + \frac{V}{2}$ $\qquad \boxed{\therefore E_b = \frac{V}{2}}$

$\therefore$ Hence mechanical power developed by the motor is maximum when back emf is equal to the applied voltage.

Armature torque of DC motor

→ Torque is the turning moment of a force about an axis & is measured by the product of Force (F) & radius (r) at right angle to which the force acts

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i.e. $T = F \times r$ (N-m)

work done by this force in one revolution

$= \text{Force} \times \text{distance}$

$= F \times 2\pi r$ Joule

power developed $= (F \times 2\pi r) N$ Joule/second or watt

$= (F \times r) \times 2\pi N$ watt

$2\pi N$ = Angular velocity ω in radians/second

and Torque $(T) = F \times r$

power developed $= T \times \omega$ watt or $\boxed{P = \omega T \text{ watt}}$

moreover, if N is rpm,

$$\omega = \frac{2\pi N}{60} \text{ rad/sec}$$

$$P = \omega T = \frac{2\pi N}{60} \times T \qquad P = \frac{2\pi}{60} . NT \qquad \boxed{P = \frac{NT}{9.55}}$$

Armature torque of a motor

Let T_a be the torque developed by the armature of a motor running at N r.p.s.

$P = T_a \times 2\pi N$ watt

we know that ~~developed~~ converted into elect. power

mechanical power $P_m = E_b I_a$ watt.

$P = P_m$

$$T_a \times 2\pi N = E_b I_a$$

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

$$T_a = \frac{1}{2\pi} \frac{P \phi Z}{60 A} \times I_a$$

$$\boxed{T_a = 0.159 \, \phi Z I_a \left(\frac{P}{A}\right) \text{ N-m}}$$

$$\boxed{T_a \propto \phi I_a}$$

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For series motor

$\phi \propto I_a$ so $\boxed{T_a \propto I_a^2}$

For shunt motor ($\phi = \text{const}$)

$\boxed{T_a \propto I_a}$

$T_a = \dfrac{E_b I_a}{2\pi N}$ in rps

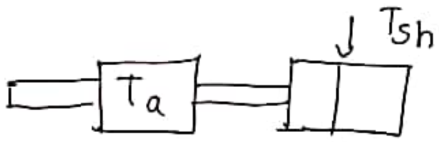
in rpm, $T_a = \dfrac{E_b I_a}{(2\pi N/60)}$

$= \dfrac{60\, E_b I_a}{2\pi N} = \dfrac{60}{2\pi} \cdot \dfrac{E_b I_a}{N}$

$$\boxed{T_a = 9.55 \frac{E_b I_a}{N} \ \text{N-m}}$$

Shaft torque (T_{sh})

→ The torque which is available for doing useful work is known as Shaft torque (T_{sh}).



$O/P = T_{sh} \times 2\pi N$ watt N in rps, T_{sh} in N-m

$T_{sh} = \dfrac{O/P \text{ in watts}}{2\pi N}$ N-m

$T_{sh} = \dfrac{60}{2\pi} \dfrac{O/P}{N}$ in rpm $\Rightarrow 9.55 \dfrac{O/P}{N}$ N-m

$$\boxed{T_{sh} = 9.55 \times \frac{O/P}{N} \ \text{N-m}}$$

→ $T_{sh} < T_a$. because of iron & frictional loss

$$\boxed{T_a - T_{sh} = \text{lost torque}}$$

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Speed of DC motor

$$E_b = V - I_a R_a$$

$$\Rightarrow \frac{P\phi Z N}{60A} = V - I_a R_a \Rightarrow N = \frac{V - I_a R_a}{\phi} \times \frac{60A}{PZ}$$

$$\Rightarrow N = K\left(\frac{V - I_a R_a}{\phi}\right) \Rightarrow N = K\frac{E_b}{\phi}$$

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

→ if DC motor has initial values N_1, ϕ_1, E_{b1} & Final values N_2, ϕ_2, E_{b2}

then $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$

For shunt motor

$\phi_1 = \phi_2$ $\quad \boxed{\therefore \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}}$

For series motor

$\phi \propto I_a$ (before Saturation) $\quad \boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}}$

Speed regulation

The speed regulation of a motor is the change in speed from F.L to No-load and is expressed as a percentage of speed at F.L.

$$\boxed{\%\ \text{speed regulation} = \frac{\text{N.L speed} - \text{F.L. speed}}{\text{F.L speed}} \times 100}$$

Torque & Speed of a DC motor

i) $N \propto \frac{E_b}{\phi}$ $\qquad$ ii) $T \propto \phi I_a$

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(7)

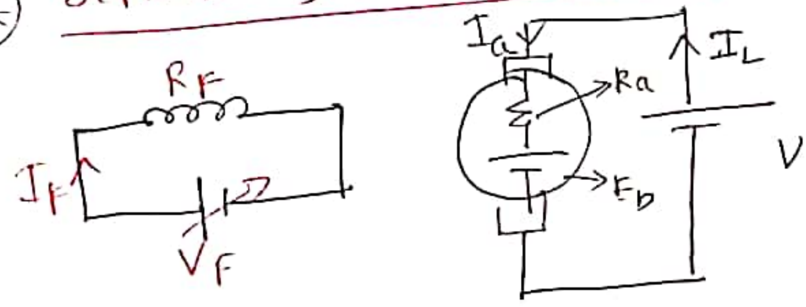
→ If flux is decreased slightly by decreasing field current.

(1) E_b drops instantly (but speed remains constant due to inertia of heavy armature)

(2) As $E_b \downarrow$, $I_a \uparrow$, $I_a\uparrow = \frac{V - E_b\downarrow}{R_a}$. A small reduction in flux produces a proportionately large current in armature.

(3) $T_a \propto \underset{\text{small}}{\underset{\downarrow}{\phi}}\, I_a \rightarrow \uparrow(\text{more})$. A small decrease in flux is more than counterbalanced by a large increase in I_a with a result that net increase in T_a.

(A) Separately excited DC motor



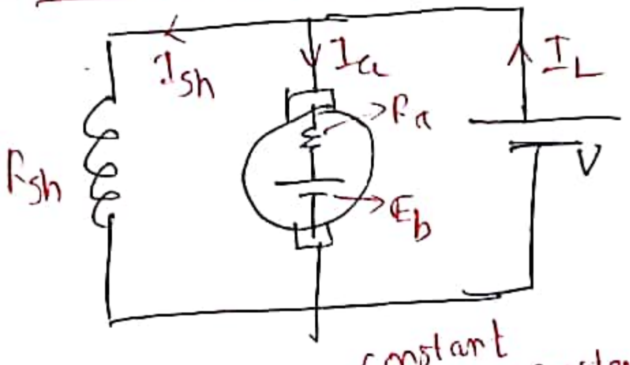
$E_b = V - I_a R_a - B.D$

$\boxed{I_L = I_a}$

∴ If B.D neglected

$P_{input} = V I_L$

(A) DC shunt motor



$\boxed{I_L = I_a + I_{sh}}$

$I_a = I_L - I_{sh}$,

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

$\boxed{E_b = V - I_a R_a - B.D.}$

$\underset{\text{Flux constant.}}{\underset{\downarrow}{\phi}} \propto I_{sh}$, $I_{sh} = \frac{V \rightarrow \text{constant}}{R_{sh} \rightarrow \text{constant}} \rightarrow \text{constant}$

→ DC shunt motor is a constant flux motor.

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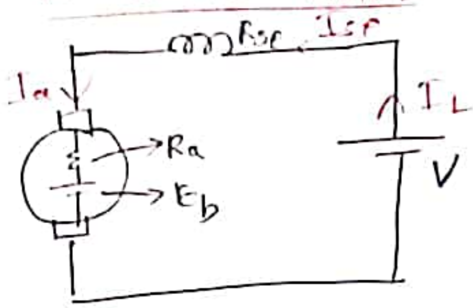
(4) DC Series motor



$$\boxed{I_L = I_{se} = I_a}$$

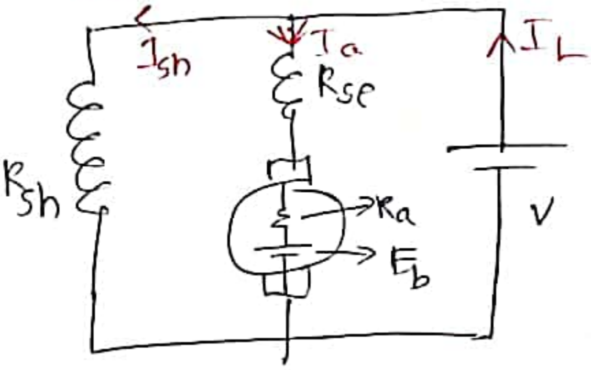
$$V = E_b + I_a R_a + I_a R_{se} + B.D$$

$$\boxed{E_b = V - I_a R_a - I_a R_{se} - B.D}$$

$$\boxed{E_b = V - I_a(R_a + R_{se}) - B.D}$$

(5) DC compound motor

→ long shunt



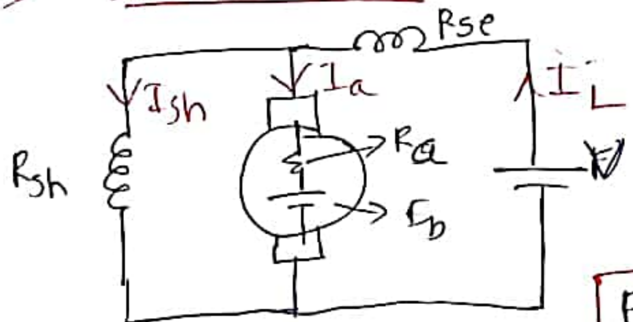
$$\boxed{\begin{aligned} I_L &= I_a + I_{sh} \\ I_a &= I_L - I_{sh} \end{aligned}}$$

$\phi_{se} \propto I_a$

$\phi_{sh} \propto I_{sh} = \frac{V}{R_{sh}}$

$$\boxed{E_b = V - I_a(R_a + R_{se}) - B.D}$$

→ short shunt



$\phi_{se} \propto I_L$

$\phi_{sh} \propto I_{sh}$

KCL $I_L = I_a + I_{sh}$

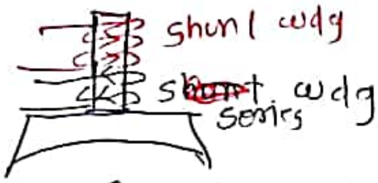
$I_a = I_L - I_{sh}$

$$\boxed{E_b = V - I_a R_a - I_L R_{se} - B.D}$$

$$\boxed{I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}}$$

$\phi_{se} \uparrow \uparrow \phi_{sh}$ $\phi_T = \phi_{se} + \phi_{sh}$

→ cumulative compound motor.



$\phi_{se} \downarrow$

$\phi_{sh} \uparrow$

→ $\phi_T = \phi_{sh} - \phi_{se}$

→ differential compound motor

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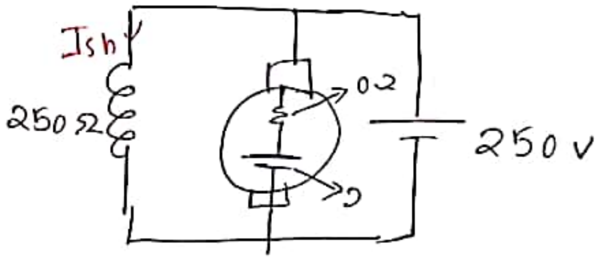
Q) (1) A 250V shunt motor runs at 1000 r.p.m at No-load and takes 8A. The total armature & shunt field resistances are 0.2 Ω & 250 Ω respectively. Calculate the speed when loaded & taking 50A?

A: $\frac{N}{N_0} = \frac{E_b}{E_{b0}} \times \frac{\phi_0}{\phi}$ since shunt motor flux is constant, $\phi = \phi_0$

so $\boxed{\frac{N}{N_0} = \frac{E_b}{E_{b0}}}$



$I_{sh} = \frac{250}{250} = 1\,A$

$E_{b0} = V - I_{a0} R_a$

$= 250 - 7 \times 0.2$

$= 248.6$ volt

$I_{a0} = 8 - 1 = 7$ at No-load

$I_a = 50 - 1 = 49$ at load

$E_b = V - I_a R_a$

$= 250 - 49 \times 0.2$

$= 240.2$ volt

$\frac{N}{1000} = \frac{240.2}{248.6} \Rightarrow N = \cancel{966.1}$ rpm

966.21 rpm

(2) A DC series motor operates at 800 r.p.m with a line current of 100A from 230 V mains. $R_a = 0.15\,\Omega$, $R_{se} = 0.1\,\Omega$. Find the speed at which motor runs at a line current of 25 A. Assuming flux at this current is 45% of the flux at 100A?

A: $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$ $\quad \phi_2 = 0.45\,\phi_1$ $\quad \frac{\phi_1}{\phi_2} = \frac{1}{0.45}$.

$E_{b1} = 230 - (0.15 + 0.1) \times 100 = 205$ Volt

$E_{b2} = 230 - 25 \times 0.25 = 223.75$ Volt

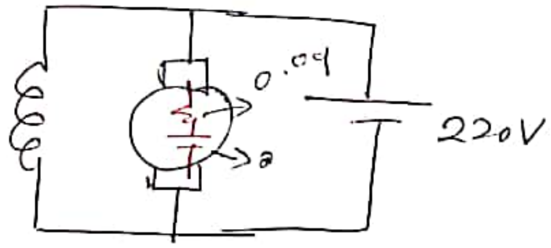
$\frac{N_2}{800} = \frac{223.75}{205} \times \frac{1}{0.45}$ $\boxed{\Rightarrow N_2 = 1940 \text{ r.p.m}}$

Q) A 4 Pole, 220V - shunt motor has 540 lap wound conductor. It takes 32 Amp from the mains supply & develops o/p power of 5.595 kW. The field only takes 1A. Ra = 0.09Ω, ϕ = 30 mwb

calculate i) speed ii) torque in N-m

A: $Z = 540$

LAP, $A = P = 4$



$I_L = 32$ Amp, $\phi = 30 \times 10^{-3}$

$I_{sh} = 1$ Amp

$I_a = 32 - 1 = 31$ Amp

$E_b = V - I_a R_a$

$= 220 - 31 \times 0.09 = 217.2$ volt

$E_b = \frac{P \phi Z N}{60 A} \Rightarrow N = \frac{E_b \times 60 \times \cancel{A}}{\cancel{P} \phi Z} = \frac{217.2 \times 60}{30 \times 10^{-3} \times 540}$

$\boxed{N = 804.4 \text{ rpm}}$

$\rightarrow T_{sh} = 9.55 \times \frac{\text{o/p in watts}}{N}$

$= 9.55 \times \frac{5.595 \times 10^3}{804.4} = 66.5$ N-m

Formula in motor

$E_b = \frac{P \phi Z N}{60 A}$ $\quad E_b = V - I_a R_a$ (shunt)

$T_a = 0.159\ \phi Z I_a \left(\frac{P}{A}\right)$ N-m

$T_a = 9.55 \times \frac{E_b I_a}{N}$

$T_{sh} = 9.55 \times \frac{o/p}{N}$ $\quad T_a - T_{sh} =$ lost torque

$T \propto \phi I_a$

$T \propto I_a \rightarrow$ shunt (ϕ = const.)

$T \propto I_a^2 \rightarrow$ series

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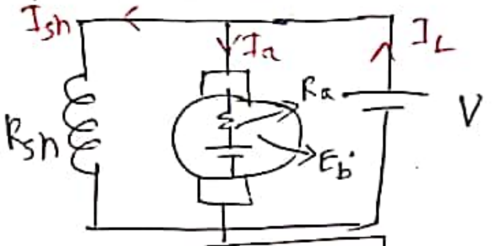
Characteristics of DC motor

1. Speed vs Armature current (N vs I_a) ⎤
2. Torque vs Armature current (T vs I_a) ⎦ → Electrical characteristic
3. Speed vs torque. (N vs T) → mechanical characteristics

Shunt motor



$\phi \propto I_{sh} = \frac{V}{R_{sh}} = \text{constant}$.

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

① $\boxed{N \text{ vs } I_a}$

At No load

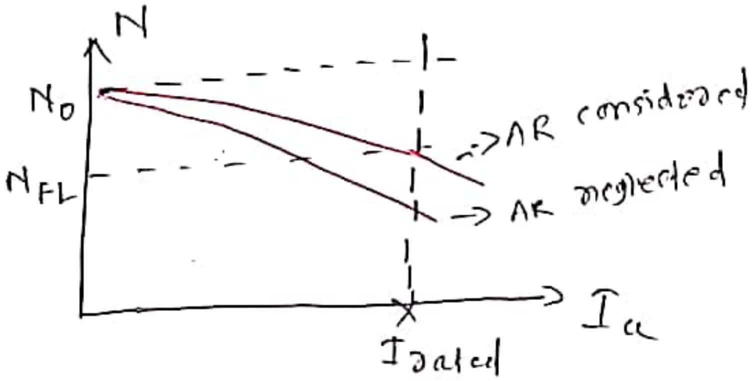
$I_a = 0$, $N \propto V$

→ when load ↑, I_a ↑

$\downarrow N \propto V - (I_a \uparrow R_a)\uparrow$

due to Armature reaction

$\phi\downarrow$, $N\uparrow$, $N \propto \frac{1}{\phi\downarrow}$



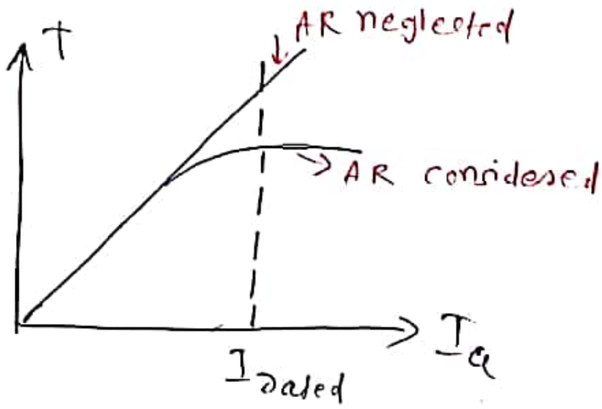
→ DC shunt motor is a constant speed motor.

② $\boxed{T \text{ vs } I_a}$ $\because T \propto \phi I_a$

$T \propto I_a$ as $\phi = \text{constant}$.

if AR considered

$\downarrow T \propto \phi\downarrow I_a$



∴ T vs I_a characteristics is linear.

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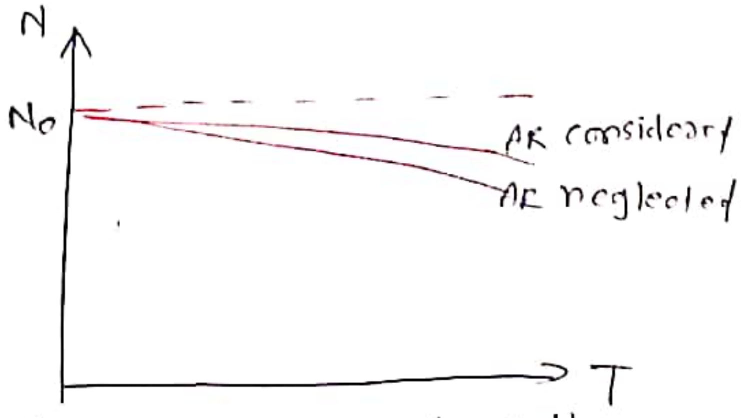
③ N vs T

$T \propto I_a \quad \therefore T = k_1 I_a \quad I_a = \frac{T}{k_1}$

$N \propto \frac{\cancel{V} - \frac{T}{k_1}\cancel{R_a}}{\phi}$



(speed falls somewhat as the load torque increases)

At N.L

$I_a = 0$, $T_{em} = 0$, $N \propto \frac{V}{\phi}$

loaded

load ↑, T_{em} ↑, N ↓

with AR

ϕ ↓, N ↑,

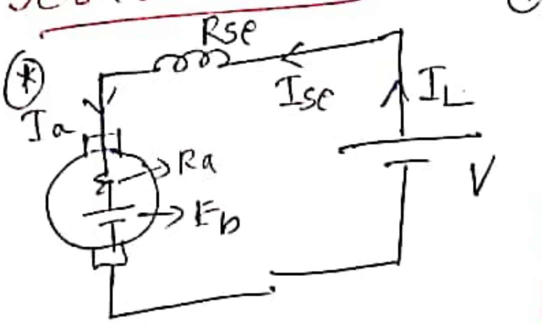
Application

Fan, centrifugal pump, lathe, machine tools, line shafting

Important

The direction of rotation of D.C. motor can be reversed either by changing the field terminals or armature terminals but not both.

Series motor



(*) $\phi \propto I_a$ (before saturation)

$N \propto \frac{E_b}{\phi} \propto \frac{V - I_a(R_a + R_{se})}{I_a}$

$\boxed{N \propto \frac{1}{I_a}}$

$T \propto \phi I_a$

$\boxed{T \propto I_a^2}$

After saturation

$\phi = \phi_{sat} = \text{constant}$

$N \propto V - I_a(R_a + R_{se})$

$\boxed{T \propto I_a}$.

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(1) N vs I_a (13)

$\boxed{E_b = V - I_a(R_a + R_{se})}$

At No-load

$I_a(R_a + R_{se}) \rightarrow$ drop very small

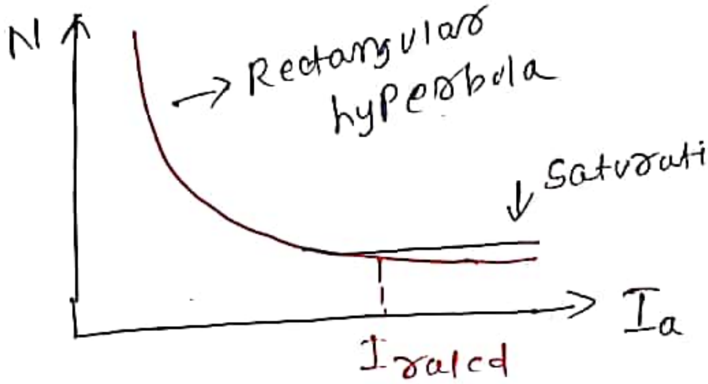
$I_a \simeq 0$, $\left(N \uparrow^{\infty} \propto \frac{1}{I_a \simeq 0}\right)$

→ No-load speed DC series motor is dangerously high speed.

→ Never start DC series motor without load.

At load

Mech load ↑, I_a ↑, N ↓



Note:

series motor is a variable flux machine, At over load cond^n field poles saturated and flux becomes constant.

(2) T vs I_a

$T \propto \phi I_a$

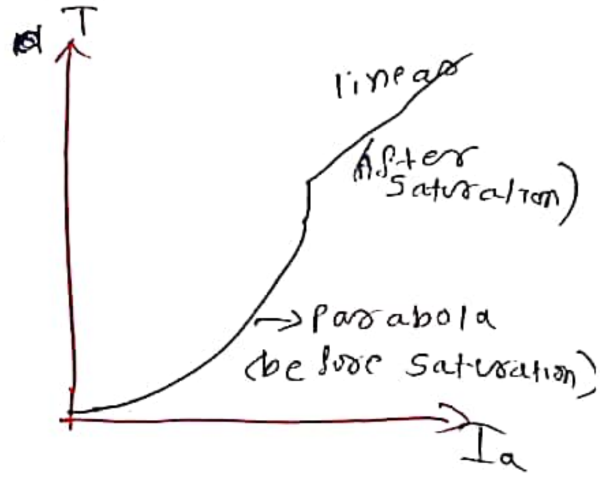
→ upto magnetic saturation $\phi \propto I_a$.

⇒ $\boxed{T \propto I_a^2}$ → parabola

After saturation ϕ = constant

⇒ $\boxed{T \propto I_a}$ → straight line

→ Series motor has high starting torque.



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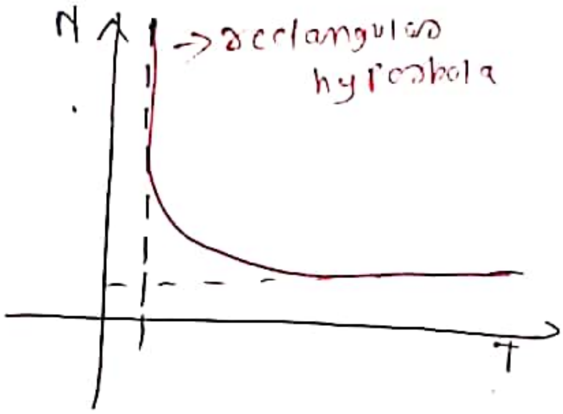
(3) N vs T

$I_a \propto \sqrt{T}$

$N \propto \frac{1}{I_a}$ i.e. $\boxed{N \propto \frac{1}{\sqrt{T}}}$



No-load

$T_{em} = 0$, $N = \infty$

load ↑, T_{em} ↑, N ↓

if P = const. P = ωt

$\boxed{N \propto \frac{1}{T}}$

→ DC series motor behaves as a constant power device.

Applications

→ It is a Variable speed motor & it has high starting torque,

→ Elevators, Air compressors, Electric traction, crane, Sewing machine.

Important

→ Series motor should never be started at No-load condition.

→ ~~Speed of DC series~~

→ Direction of rotation of a DC series motor can be changed by changing either field terminals or armature terminals.

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Compound motor characteristics

$N \propto \frac{E_b}{\phi_T}$ $\qquad \phi_T = \phi_{sh} \pm \phi_{se}$ $\qquad + \rightarrow$ cumulative, $- \rightarrow$ differential

$\phi_{sh} \propto I_{sh} = \frac{V}{R_{sh}} =$ constant. $\qquad \phi_{se} \propto I_a$

$T \propto \phi I_a$

$T \propto (\phi_{sh} \pm \phi_{se}) I_a$

$$\boxed{T_{cm} \propto \phi_{sh} I_a \pm \phi_{se} I_a}$$

① N vs I_a

At No-load $\quad I_a \simeq 0, \; \phi_{se} = 0 \qquad N \propto \frac{E_b}{\phi_{sh}} \propto \frac{V}{\phi_{sh}}$

$E_b \propto \frac{V - \cancel{I_a}(R_a + R_{se})}{\phi_T}$ $\;\; \rightarrow 0 \qquad N = N_0$

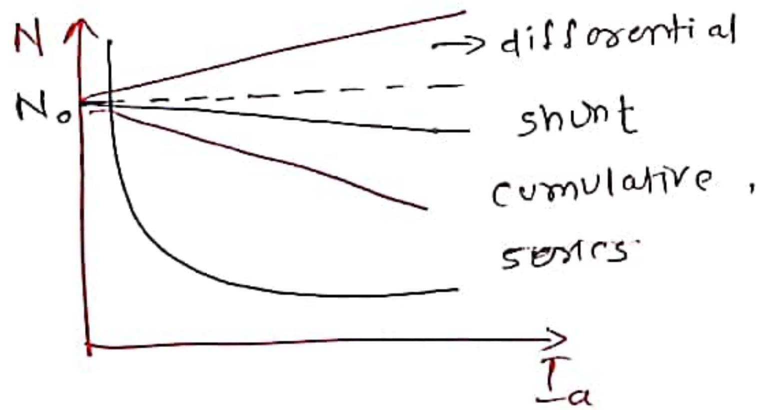
load ↑, I_a ↑, ϕ_{se} ↑

cumulative

$\downarrow N \propto \frac{E_b}{(\phi_{sh} + \uparrow\phi_{se})\uparrow}$

differential

$\uparrow N \propto \frac{E_b}{(\phi_{sh} - \phi_{se}\uparrow)\downarrow}$



② T vs I_a

$T \propto (\underbrace{\phi_{sh} I_a}_{\text{shunt}} \pm \underbrace{\phi_{se} I_a}_{\text{series}})$.

At No-load, $\; I_a = 0, \; T = 0$

load $\quad T =$ constant

$\downarrow(\phi_{sh} - \phi_{se})\, I_a \uparrow =$ constant

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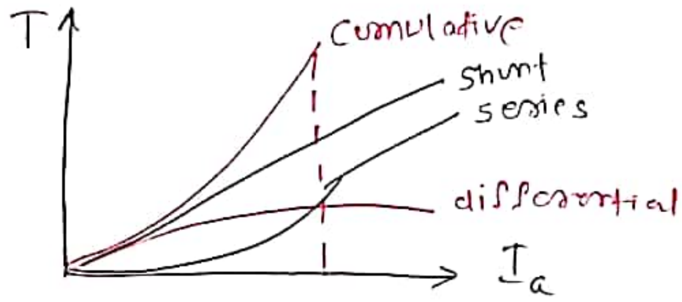


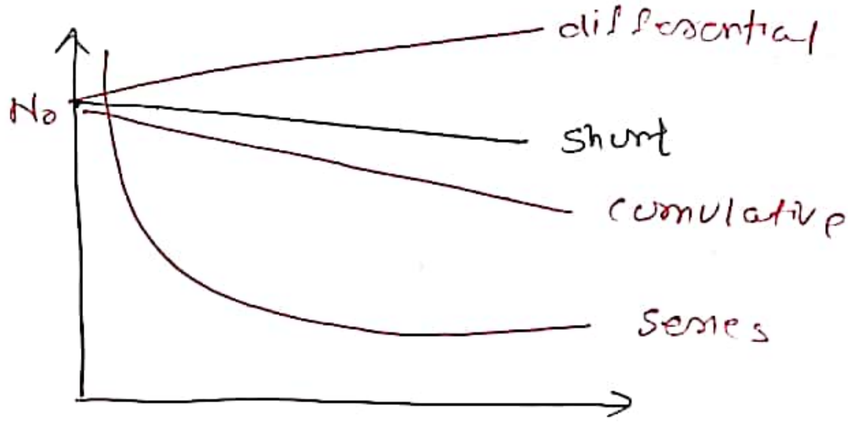
③ N vs T

At No-load

$T=0$, $I_a=0$, $N=N_0$

At load

$T\uparrow$, $N\downarrow$



Application

→ Moderate Torque at limited No-load speed

i) punching machine
ii) drilling machine
iii) steel mills
iv) cement mills
v) Paper mills

} cumulative compound.

→ Differential compound m/cs have very limited Application.

→ Speed regulation of shunt motor is +ve.

" series motor is too. (poorest speed regulation)

" cumulative compound is +ve,

" differential " is −ve.

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Speed control of DC motors

Base speed or rated speed

→ It is the speed of the motor at rated supply voltage & at rated flux.

$N \propto \frac{V - I_a R_a}{\phi}$ or $N \propto \frac{E_b}{\phi}$ → load on the Machine = constant.

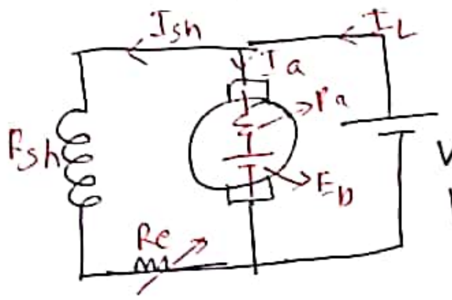
3 methods of speed control

i) Flux control method / Field weakening method
ii) Armature resistance control method
iii) Armature voltage control method

shunt motor

① Flux control method

$I_{sh} = \frac{V}{R_{sh} + R_e}$ and $N \propto \frac{V - I_a R_a}{\phi}$



$(R_{sh} + R_e)\uparrow$ → variable resistance is added in shunt field

$R_{sh}\uparrow, I_{sh}\downarrow, \phi\downarrow,$

$\phi\downarrow, N\uparrow$

→ In this method a variable resistance is placed in series with shunt field wdg.

→ shunt field rheostat reduces the shunt field current I_{sh} & hence flux (ϕ) is reduced. Hence speed is increased.

Imp → Flux control method is used for above rated speed.

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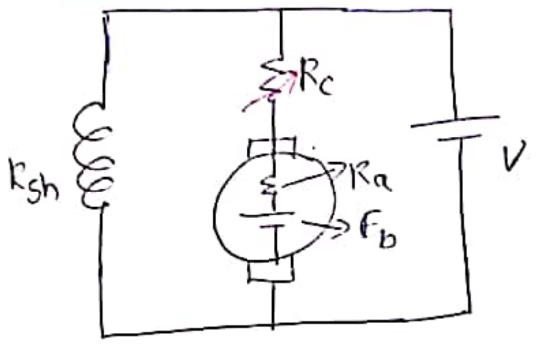
(2) Armature Resistance control



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

$\downarrow N \propto [V - I_a(R_a + R_c)\uparrow]\downarrow$

→ This is done by inserting a variable resistance (R_c) known as controller resistance.

→ Due to extra drop in controller resistance (R_c), E_b is decreased. Hence speed is reduced.

→ The heighest speed obtained when $R_C = 0$ i.e. normal speed. Hence this method can provide speeds below the normal speed.

disadvantages

i) A large amount of power is wasted in the R_c, since it carries full armature current I_a.

ii) o/p & efficiency of the motor reduced.

iii) This method results in poor speed regulation.

→ Due to this disadvantage, this method is rarely used incase of DC shunt motor speed control.

(3) Armature Voltage control method

Ward-Leonard speed control

→ In this method, the motor is operating as separately excited motor.

→ In this method, both above & below speed control is possible.

For below rated speed

→ A variable voltage is applied to the armature motor by using field of Generator.

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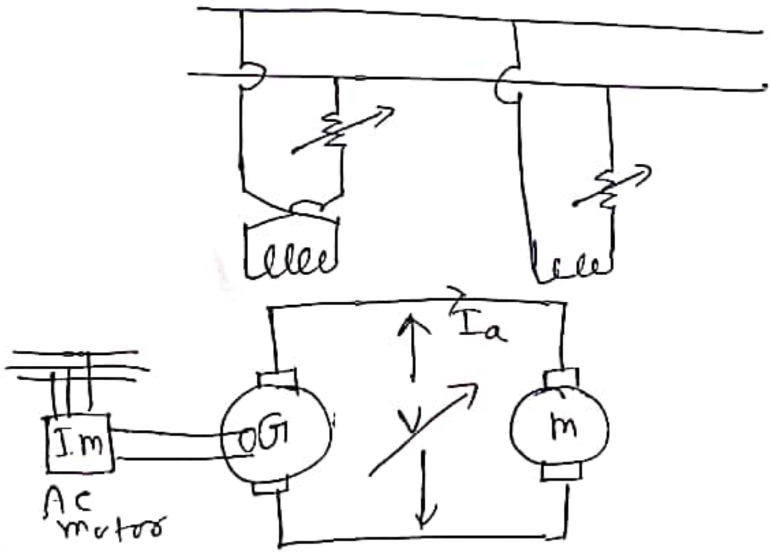
→ As voltage ↑, N ↑, E_b ↑

$V - E_b \simeq$ constant.

⇒ Armature current & flux becomes constant.

∴ $T \propto \phi I_a$ is constant.



For above rated speed

→ Flux control method is used. By varying the field ~~Generator~~ regulator of motor, the flux can be controlled to below a rated value there by speed can be controlled to above a rated value,

→ As ϕ ↓, N ↑, T ↓.

Advantages

1. The speed of the motor can be controlled in wide range.
2. wide range of speed control possible in either direction.
3. Used for speed control of large motors.

disadvantages

→ High initial cost.

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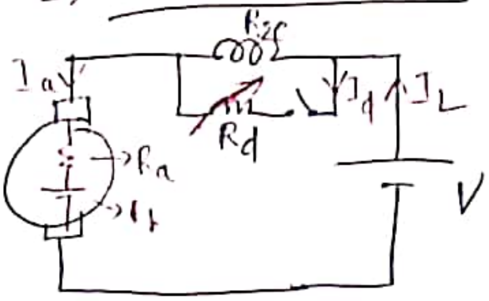
Speed control of DC series motor

(1) Flux control method

Flux of series motor can be controlled by using the following methods.

i) diverter control
ii) Tapped field control
iii) series & parallel connection of field

1) Diverter control



without diverter
$I_{se} = I_a$, N_1 = rated speed
with diverter, $I_{se} \neq I_a$

$$I_{se} = I_a - I_d = I_a \cdot \frac{R_d}{R_d + R_{se}}$$

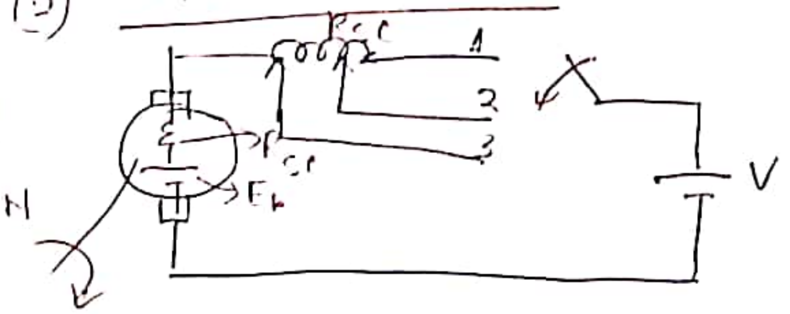
→ Now I_{se} is less than I_a & flux will decrease.

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

$$\Rightarrow \frac{N_2}{N_1} = \left\{ \frac{V - I_a\left[(R_{se} \parallel R_d) + R_a\right]}{V - I_a(R_{se} + R_a)} \right\} \times \frac{I_a}{I_{se}}$$

→ In this method, a variable resistance called diverter resistance is connected in parallel with series field wdg.
→ It's effect is to shunt some portion of line current to field diverter. $\left(N \uparrow \propto \frac{1}{\phi \downarrow}\right)$. This method can only provide speeds above the normal speed.

(2) Tapped field control



A.C (1) $\phi_1 \propto T_1$
(2) $\phi_2 \propto T_2$
(3) $\phi_3 \propto T_3$
$T_1 > T_2 > T_3$
$\phi_1 > \phi_2 > \phi_3$
$N_1 < N_2 < N_3$

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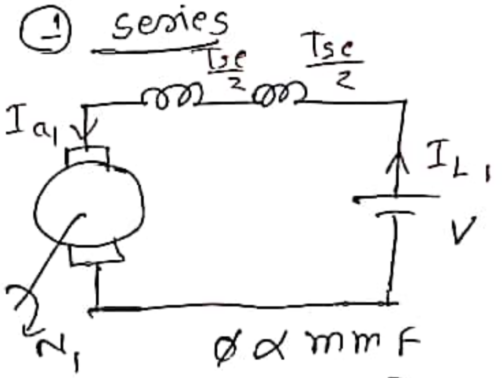
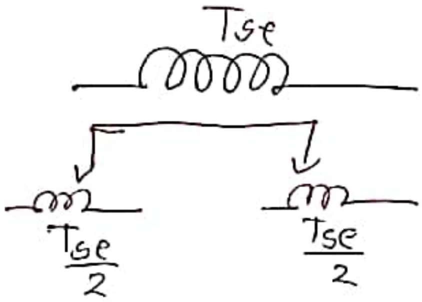
→ In this method, the flux is reduced hence speed is increased by decreasing the number of turns of the series field winding.

→ With full turns of the field winding, the motor runs at normal speed and as the field turns are cut-out, speeds higher than the normal speed are achieved.

(3) Series, parallel connection

(1) Series



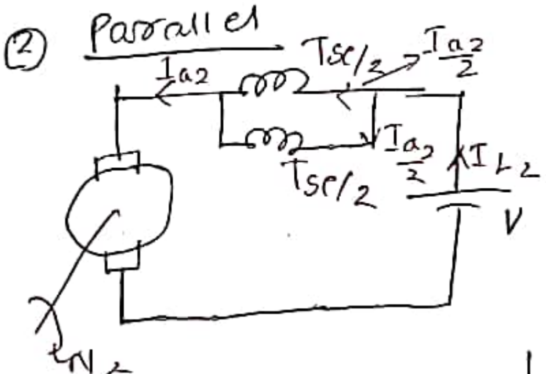


$\phi \propto mmf$

$= I_{a_1}\frac{T_{se}}{2} + I_{a_1}\frac{T_{se}}{2}$

$\phi_1 \propto I_{a_1} T_{se}$

(2) Parallel



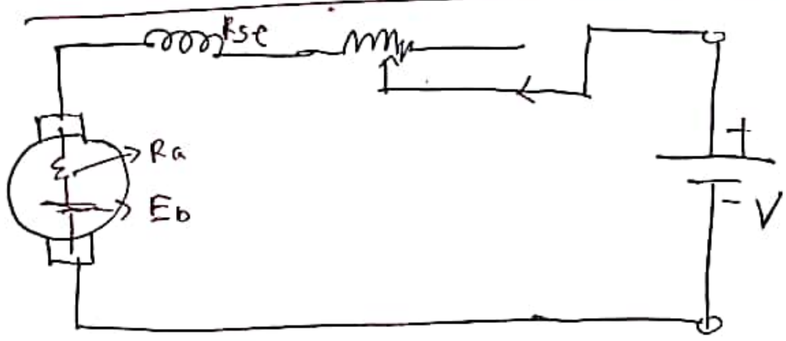
$\phi_2 \propto mmf$

$\frac{T_{se}}{2} \times \frac{I_{a2}}{2} + \frac{T_{se}}{2} \times \frac{I_{a2}}{2}$

$\phi_2 \propto \frac{T_{se} I_{a2}}{2}$

→ mmf becomes $\frac{1}{2}$ & speed becomes double as compared to series connection.

(4) Armature resistance control method



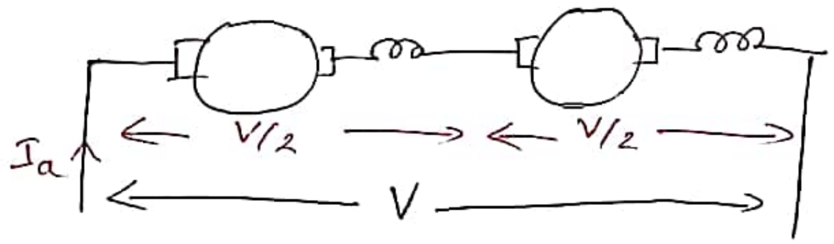
→ In this method, a variable resistance is directly connected in series with the supply to complete motor.

→ This reduces voltage available across the armature & hence speed falls.

3) Armature voltage control method

→ series parallel method is used for speed control of DC series motor. In this method which is widely used in traction machine, two similar DC series motors are mechanically coupled to the same load.

Series

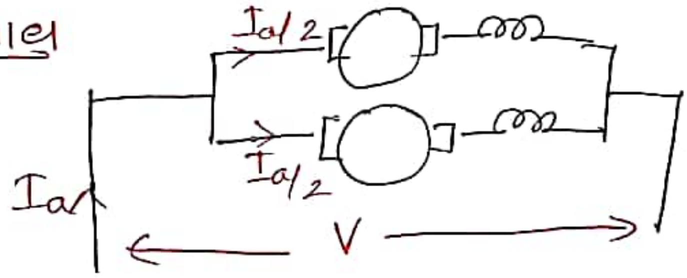


$N_{se} \propto \frac{E_b}{\phi}$ in series $\phi \propto I_a$

Neglecting $I_a(R_a + R_{se})$ drop

$N_1 \propto \frac{V/2}{I_a}$ $\quad N_1 \propto \frac{V}{2 I_a}$. (i) $\quad T_{se} \propto I_a^2$. (ii)

Parallel



$N_p \propto \frac{E_b}{\phi_2}$

$\phi_2 \propto \left(\frac{I_a}{2}\right)$ $\quad N_p \propto \frac{V}{(I_a/2)}$ $\quad N_p \propto \frac{2V}{I_a}$ ..(iii)

$T_p \propto \left(\frac{I_a}{2}\right)^2$. (iv)

$\frac{(iii)}{(i)} \Rightarrow \frac{N_p}{N_{se}} = \frac{2V}{I_a} \times \frac{2 I_a}{V} = 4 \Rightarrow \boxed{N_p = 4 N_{series}}$

$\frac{(iv)}{(ii)} \Rightarrow \frac{T_p}{T_{se}} = \frac{(I_a/2)^2}{(I_a)^2} = \frac{\cancel{I_a^2}}{4 \cancel{I_a^2}} \Rightarrow \boxed{T_p = \frac{1}{4} T_{se}}$

$T_{se} = 4 T_p$

↓ traction.

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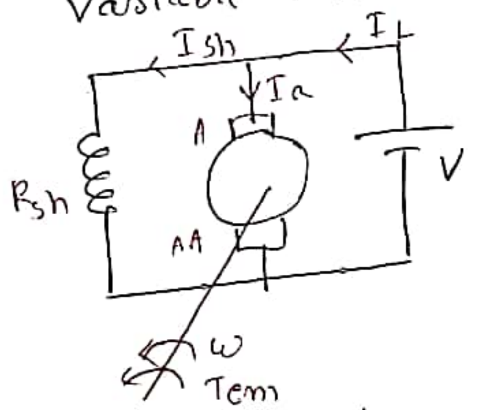
Electric braking

- It is of '3' types.
  - i) Dynamic braking or Rheostat braking
  - ii) Plugging (or) reverse current braking
  - iii) Regenerative braking

(1) Dynamic braking or Rheostatic braking

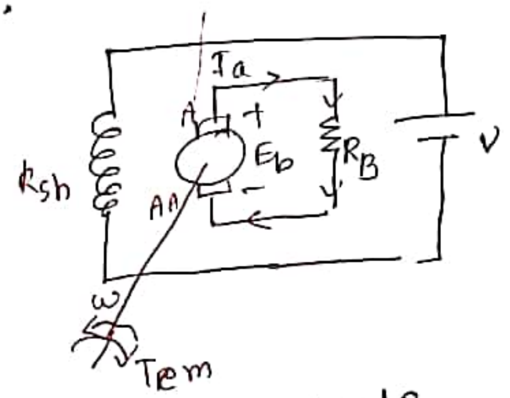
→ In this method, the armature of the running motor is disconnected from the supply & is connected across a variable resistance R.



motoring mode

$T_{em} \propto \phi I_a$

⇒ torque direction counterclockwise.



Braking mode

$T_{em} \propto \phi(-I_a)$

⇒ torque direction ~~counter~~- clockwise.

→ In braking mode, motor acts as a generator.

Braking current, $I_{aB} = \frac{E_b}{R_a + R_B}$

$T_B \propto N$

∴ Therefore braking torque decreases as the motor speed decreases.

→ This type of braking is used extensively in connection with the control of elevators & hoists and in other applications in which the motor must be started, stopped & reversed frequently.

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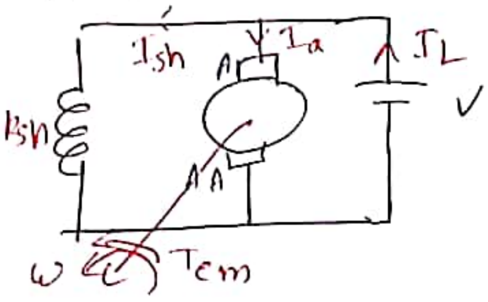
(2) Plugging

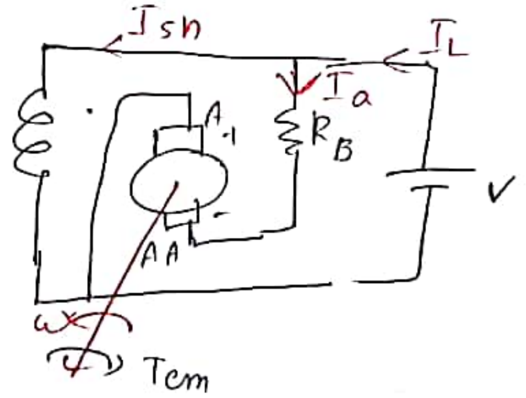
→ In this method, connections of the armature are reversed so that motor tends to rotate in the opposite direction, thus necessary braking is provided.

→ When the motor comes to rest, the supply must be cut off otherwise the motor will start rotating in the opposite direction.



motoring mode

→ ccw rotating



→ braking mode

→ cw rotation

→ Due to reversal of armature connections, applied voltage V & E_b start acting in the same direction around the circuit.

→ braking current $I_{aB} = \frac{V + E_b}{R_a + R_B}$

→ Here R_B is required to limit the armature current.

⇒ $\boxed{T_B = K_1 + K_2 N}$

→ During plugging the electromagnetic torque opposes the rotation. Then speed will be reduced gradually to zero.

→ Before coming to zero, supply has to be disconnected and mechanical brakes are applied.

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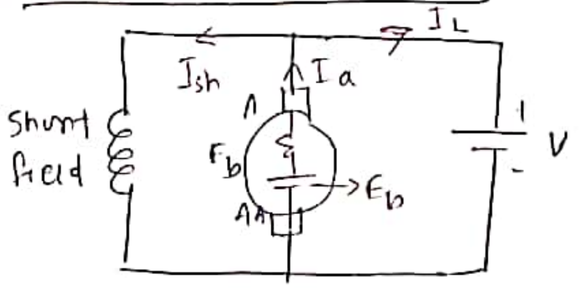
③ Regenerative braking



Regenerative braking

→ $E_b < V$ → motoring operation

→ $E_b > V$ → Regenerative braking operation

→ In motoring operation, motor consumes the power from busbar. if $E_b > V$, then power flow is reversed i.e. direction of armature current I_a is reversed, so torque will reverse, braking action takes place.

losses in DC Machine

- Cu loss
  1) Armature copper loss
  2) Shunt copper loss
  3) series field Cu. loss
- Iron loss
  ① Hysteresis loss
  $W_h = \eta B_m^{1.6} f V$
  ② eddy current loss
  $W_e = K B_m^2 f^2 V^2 t^2$
- mechanical losses
  1. Frictional losses (at brushes & bearings)
  2. Windage loss (b/w stator & rotor)

Constant losses

→ The losses which remains constant at all loads are known as constant losses.

① Iron loss
② mechanical loss
③ shunt field losses

Variable loss

: These losses vary with load are called variable loss.

① Cu. loss in Armature winding
② Cu. loss in series winding.

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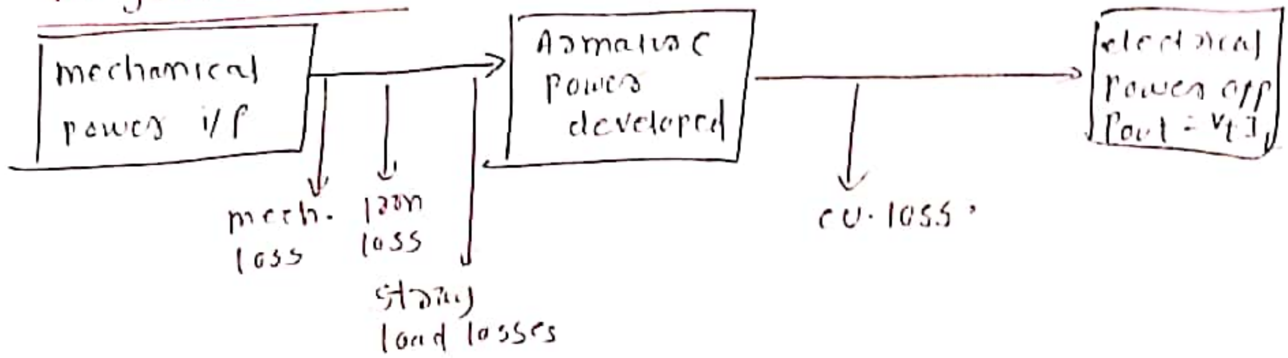
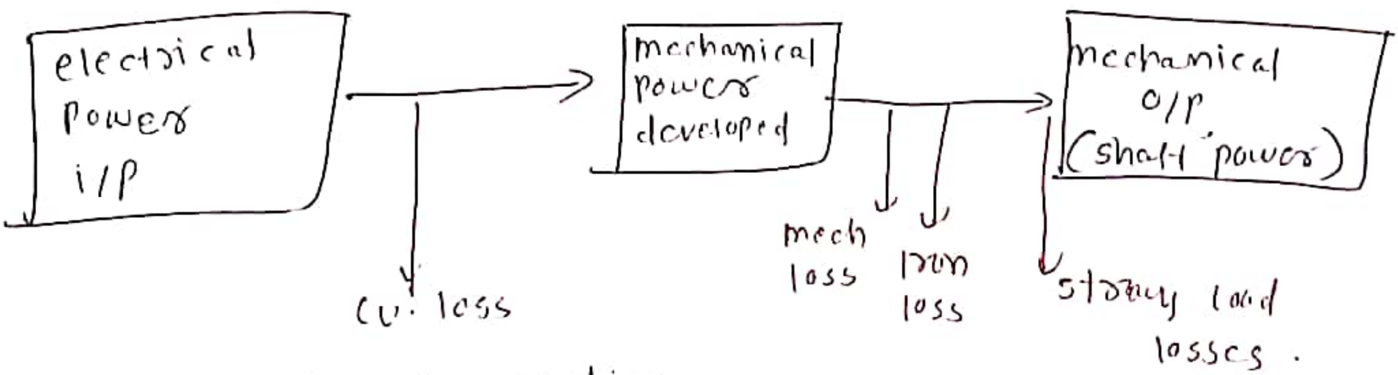
Power stages

In generator



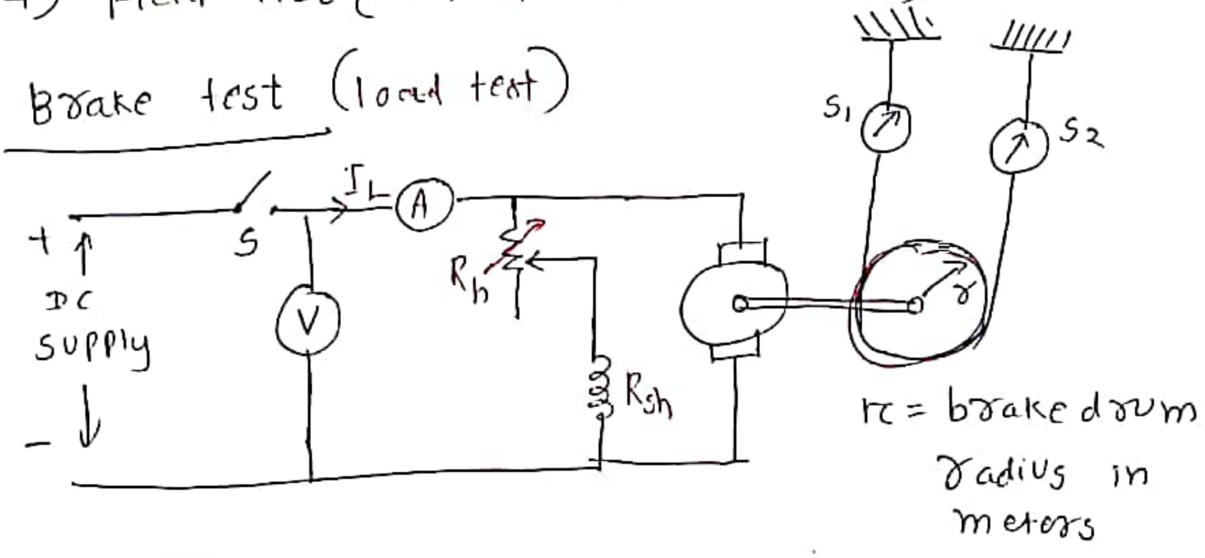
In motor



Testing of DC machine

1) Brake test / direct load test
2) Swinburne's test / No-load test / indirect load test
3) Hopkinson's test / Regenerative / back to back test
4) Field test (only for series motors)

Brake test (load test)



→ To determine directly the efficiency of comparatively small motors, the motor is loaded directly by means of a mechanical brake.

→ Brake test is a direct method i.e. the motor or generator put on full load and whole of the power developed by it is wasted.

→ This method is not suitable for large rating machine, because more frictional losses at brake drum.

$P_{in} = V I_L$, $P_o = \omega \times T = \frac{2\pi N T}{60}$ watts

$T_{sh} = F \times$ (perpendicular distance)

$T_{sh} = mg \times r$

$$\boxed{T_{sh} = (S_1 \sim S_2) \times 9.81 \times r}$$

S_1, S_2 = reading of spring balance in kg.

r = radius of brake drum

efficiency $\boxed{\% \eta = \frac{P_{out}}{P_{in}} \times 100}$, $P_{out} = \frac{2\pi N T_{sh}}{60}$

Advantage

→ machine performance is checked at actual loaded condⁿ.

disadvantage

→ Total power i/p is wasted. Hence it is uneconomical & not suitable for large DC machine.

→ spring balance reading are not studied.

(2) Swinburne's test (No-load test)

In this method the losses are calculated, then efficiency is calculated. Therefore this test is indirect test.

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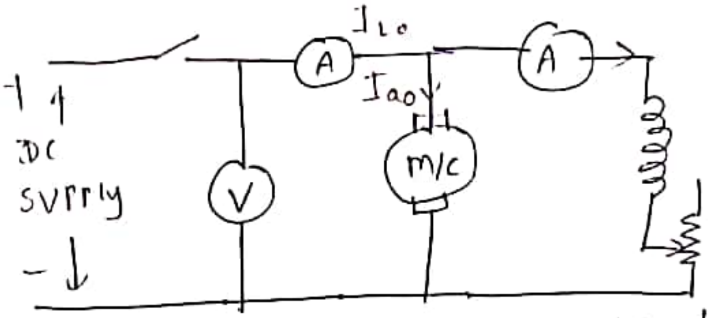


→ since this is a no-load test, it is not suitable for series motors because under no load condition it rotate with dangerously high speed.

⊛ This test is suitable for constant flux machine (shunt & compound)

→ This machine will be operated as a motor though it is a generator.

→ The m/c is operated under no-load condⁿ. Therefore the constant losses are measured and with the knowledge of constant losses the efficiency can be predetermined at any desired load condition.

$P_{in} = P_{out} + \text{losses}$ $\boxed{\text{No load} \Rightarrow P_{out} = 0}$

$V I_{Lo} = 0 + \text{losses}$

$V I_{Lo} = \text{losses (cu-loss + constant loss)}$

$V I_{Lo} = I_{ao}^2 R_a + W_c$

$\Rightarrow \boxed{W_c = V I_{Lo} - I_{a_0}^2 R_a}$

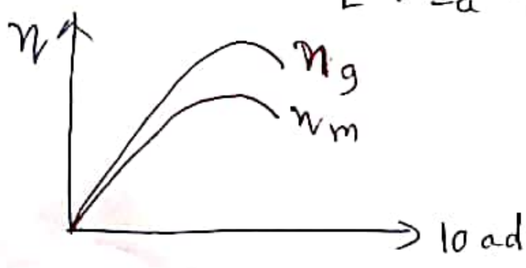
$\eta = \frac{P_o}{P_{in}} = \frac{P_o}{P_o + \text{losses}} \times 100$

For Generator

$\% \, \eta_{FL} = \frac{V I_L}{V I_L + I_a^2 R_a + W_c}$

For motor → $\frac{P_{out}}{P_{in}} = \frac{P_{in} - \text{losses}}{P_{in}}$

$\% \, \eta_{FL} = \frac{V I_L - I_a^2 R_a - W_c}{V I_L}$



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Advantages

(21)

1) The power drawn from the supply is only to meet the losses. SC experiment is economical.

11) Large rating of machine can also be tested.

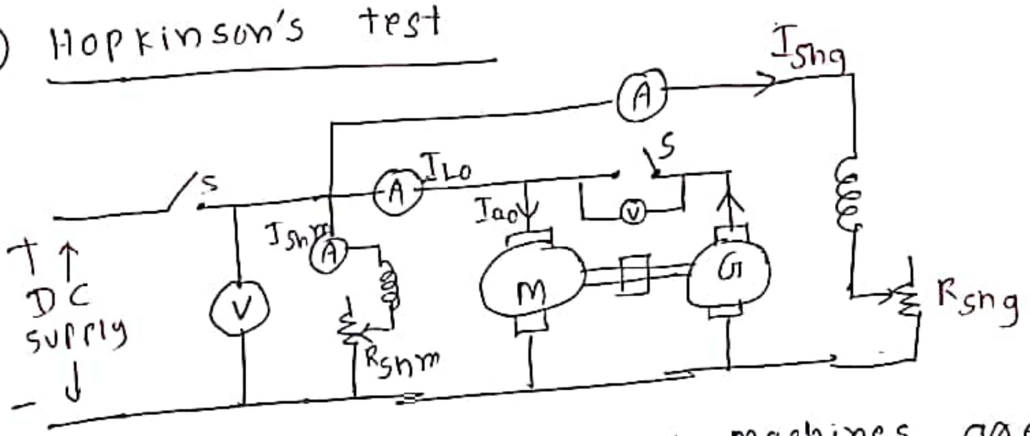
disadvantage

i) Machine performance is not checked at actual loaded condn i.e. the effect of Armature reaction, commutation & temperature rise are not considered.

ii) efficiency is more as stray load losses are not considered.

iii) not suitable for series motors.

③ Hopkinson's test



→ For this test 2 identical machines are required.

→ Both the machines are connected mechanically & electrically coupled. One of them works as a motor & another one is generator.

→ load on the motor is generator & load on generator is motor. power drawn from the supply is only for supplying internal losses of two machines.

→ This test is a Regenerative test for determining efficiency of Machines.

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Operation

→ When the supply is given, the motor rotates & its speed is adjusted to rated value.

→ Since the Generator is mechanically coupled to motor, the generator also rotates & generates its voltage. Since field winding is connecting to supply adjust the field regulator of generator such that voltmeter reads zero. Then both are said to be at same potential & polarity.

→ By closing the switch across the voltmeter, the two machines are connected in parallel but no power Flow b/w the two. It is said to be floating on the bus bar.

→ The field of the generator is strengthned and simultaneously field of motor is weakened so that Ia is adjusted to its rated value. The o/p of the generator is given to motor & mechanical power o/p of motor is given to the generator, the two m/cs are exchanging their powers. The load on the generator is motor & load on the motor is generator.

→ If there is no loss in the machines, the power drawn from supply is zero. But to compensate the loss it will draw the power is VI_{Lo}.

→ stray ~~load~~ losses are measured, equally divided both for Generator & motor.

VI_{Lo} = Total losses in both machines excluding Shunt copper losses.

$= I_{ag}^2 R_{ag} + I_{am}^2 R_{am} +$ stray losses in both Machines.

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stray losses $(W_s) = VI_{Lc} - I_{ag}^2 R_{ag} - I_{am}^2 R_{am}$

stray loss for each machine $= \frac{W_s}{2}$

efficiency can be determined

Generator

$$\eta_g = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + losses}$$

$$= \frac{VI_{ag}}{VI_{ag} + I_{ag}^2 R_{ag} + I_{shg}^2 R_{shg} + \frac{W_s}{2}} \times 100$$

Motor

$$\eta_m = \frac{P_{out}}{P_{in}} = \frac{P_{in} - losses}{P_{in}}$$

$$\eta_m = \frac{V(I_{am} + I_{shm}) - I_{am}^2 R_m - I_{shm}^2 R_{shm} - \frac{W_s}{2}}{V(I_{am} + I_{shm})} \times 100$$

Advantages

i) machine is performance is checked at actual loaded condition. Therefore effect of AR, commutation & temp. rise is considered.

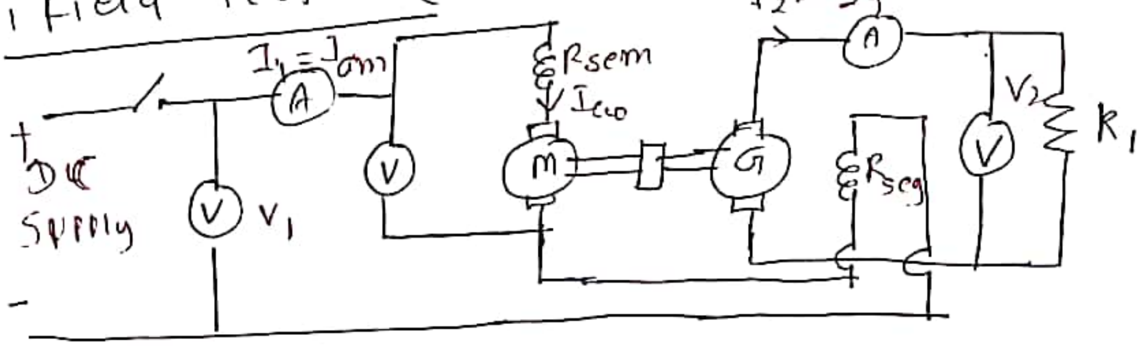
ii) This test is economical, because power required to meet the losses in both the m/cs.

disadvantage

i) Two identical m/cs are required.

ii) Equal divison of stray lood losses are not justified because generator field current is greater than motor field current in Hopkinson's test.

Field test (suitable for series motor)



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→ This test is suitable for series machine. Two identical machines are required, one acting as generator & other one as motor.

→ Both are mechanically coupled but electrically isolated. The field winding of generator is connected in motor circuit so that the stray load losses can be equally divided for two machines.

→ In this test stray losses are measured & equally divided for two m/cs.

Advantages

→ Actual performance of the machine is verified.

→ stray load losses are considered & they are equally divided which is Justified.

disadvantage

→ Two identical m/cs are required.

→ The entire power drawn from supply is wasted across load resistance.

Starters

→ Function of starter is to limit the high starting current.

→ $I_a = \frac{V - E_b}{R_a}$ At the time of starting $N=0$, $E_b=0$

$I_{st} = \frac{V}{R_a}$ is very high due to absence of opposing emf or back emf.

by using a starter, I_{st} becomes as $I_{st} = \frac{V}{R_a + R_s}$

→ I_{st} decreases.

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(33)

Types of starter

1. 3-point starter
2. 4-point starter

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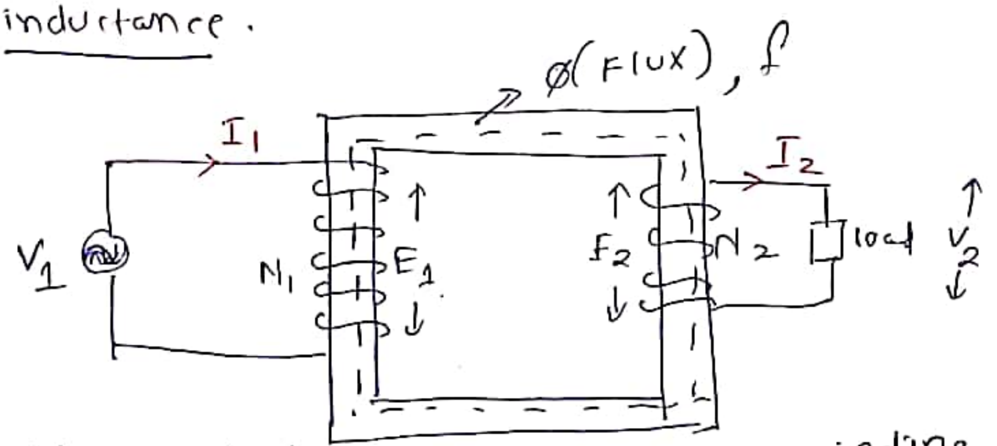
Transformer

~~Working Principle~~

→ A transformer is a static device by means of which electric power in one circuit is transferred into electric power into another circuit ~~whi~~ without change in frequency.

→ Transformer works on the principle of mutual inductance.



→ It essentialy consists of two windings, the primary & secondary.

V_1 = Applied input voltage

V_2 = load voltage / output Voltage

N_1 = No. of primary turns

N_2 = No. of secondary turns

E_1 = self induced emf

E_2 = mutually induced emf

ϕ_m = Maximum flux in core in webers

f = frequency in AC input in Hz

Working principle

→ When an alternating voltage V_1 is applied to the primary, an alternating flux (ϕ) is set up in the core. This alternating flux links both the windings & induces e.m.f's E_1 & E_2 in them

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according to Faraday's laws of electromagnetic induction. The emf E_1 is termed as primary emf & E_2 is termed as secondary e.m.f.

$$E_1 = -N_1 \frac{d\phi}{dt} \quad , \quad E_2 = -N_2 \frac{d\phi}{dt} \qquad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = k \longrightarrow \text{voltage transformation ratio}$$

i) if $N_2 > N_1$ i.e. $k > 1 \rightarrow$ step-up transformer

ii) if $N_2 < N_1$ i.e. $k \not> 1 \rightarrow$ step-down transformer

turn's ratio (a)

$$a = \frac{N_1}{N_2} = \frac{E_2}{E_1} = \frac{1}{k}$$

For an ideal transformer $\boxed{V_1 I_1 = V_2 I_2}$

$$\Rightarrow \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{k}$$

$\boxed{\text{input VA = O/P VA}}$

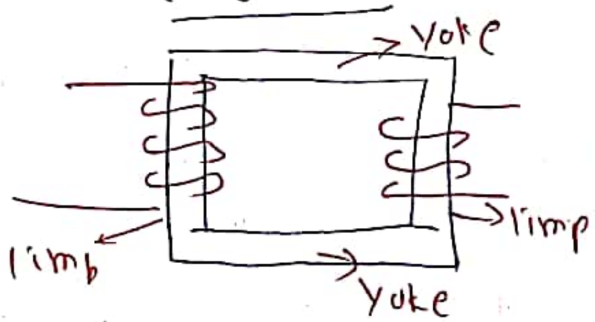
Transformer core $\rightarrow$ cold rolled grain oriented silicon steel (CRGO steel) with lamination

Transformer winding $\rightarrow$ copper (For power transformer)
Aluminium (For distribution transformer)

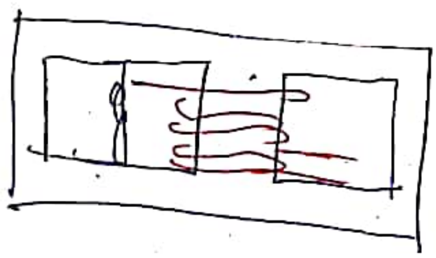
Types of core

1) core type $\rightarrow$ 2 yoke, 2 limbs
2) shell type $\rightarrow$ 2 yoke, 3 limbs

core type



shell type



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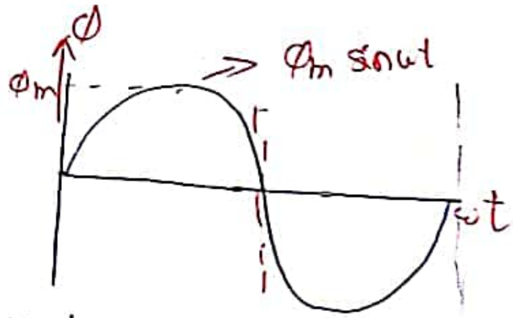
Core type	Shell type
i) windings placed on both the limbs & core is surrounded by windings. Hence protection to core is less.	i) windings are surrounded by core. Hence protection is more to winding.
ii) All limbs have same cross-sectional area.	ii) outer limbs are half of middle limb cross section.
iii) Analogous to series magnetic circuit.	iii) Analogous to parallel magnetic circuit.
iv) leakage flux is more.	iv) leakage flux is less.
v) less insulating material & more copper is required.	v) more insulation & less copper is required.
vi) High voltage, small KVA rating T/F.	vi) Low voltage high KVA rating T/F.

E.m.f eqn of Transformer



→ Consider that an alternating voltage V_1 of frequency 'f' is applied to the primary.

→ The sinusoidal flux (ϕ) produced by the primary is $\phi = \phi_m \sin\omega t$

$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin\omega t)$$
$$= -\omega N_1 \phi_m \cos\omega t$$
$$= -2\pi f N_1 \phi_m \cos\omega t$$
$$= 2\pi f N_1 \phi_m \sin(\omega t - 90^\circ)$$

$E_{1max} = 2\pi f N_1 \phi_m$, rms value $E_{1\,rms} = \frac{E_{1\,max}}{\sqrt{2}}$

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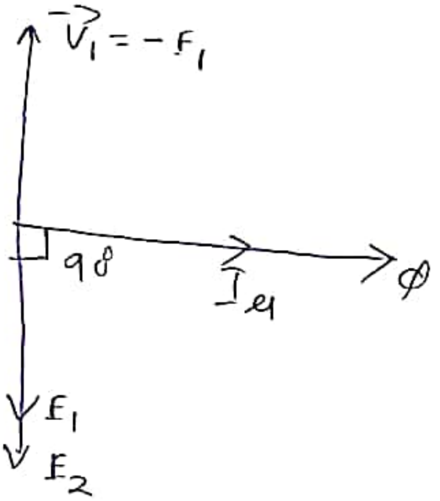
1

$\boxed{E_1 = 4.44 f N_1 \phi_m}$

similarly $E_2 = 4.44 f N_2 \phi_m$

$\phi_m = B_m A_n$

$\Rightarrow \boxed{E_1 = 4.44 f N_1 B_m A_n}$ (rms)



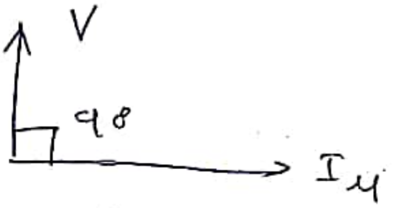
Transformer at No-load

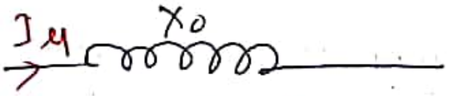
The No load primary current (I_0) is divided into 2 types.

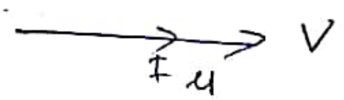
magnetising component of current (I_μ)	iron loss component (I_w)
→ required to produce flux in transformer core.	→ to meet the iron losses at No. load.

so $\boxed{\vec{I_0} = \vec{I_\mu} + \vec{I_w}}$ i.e. $\boxed{I_0 = \sqrt{I_\mu^2 + I_w^2}}$

→ Analogous to reactive power component or wattless component	→ Analogous to active power component or wattful component.
→ I_μ lags 'V' by 90°.	→ I_w inphase with 'V'.







4 to 6% of I_{FL}

→ 1 to 2% of I_{FL}

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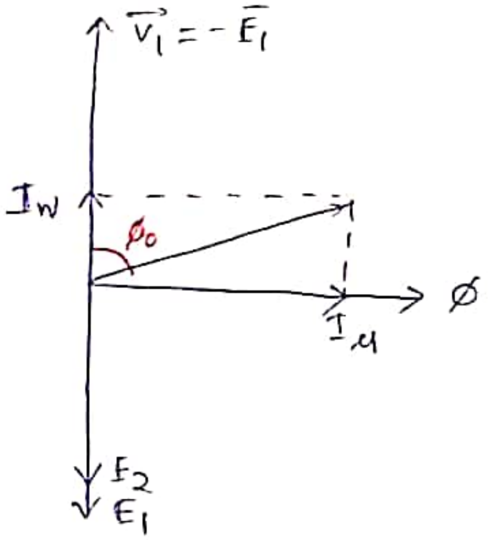
$\boxed{I_\mu >> I_W}$

T/F Phasor diagram under No-load condn:



ϕ_0 = No-load phase angle of T/F

· $\phi_0 = 70$ to $75°$

$\cos\phi_0$ = No-load Power Factor $= 0.2$ lag

$$\boxed{\begin{aligned} I_W &= I_0 \cos\phi_0 \\ I_\mu &= I_0 \sin\phi_0 \end{aligned}}$$

No-load power consumption of T/F $= V_1 I_0 \cos\phi_0$

$\Rightarrow W_0 = V_1 I_W$ = Iron loss-occur.

Ideal Transformer

An ideal transformer is that which has

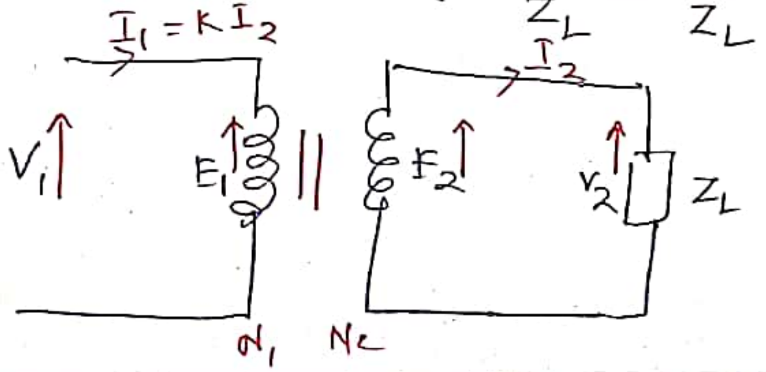
i) no winding resistance

ii) no leakage flux i.e. the same flux links both the windings

iii) no iron losses (i.e. eddy current & hysteresis loss) in the core

Ideal T/F on load

→ Let us connect a load Z_L across the secondary of an ideal transformer. The secondary emf E_2 will cause a current I_2 to flow through the load. $I_2 = \frac{E_2}{Z_L} = \frac{V_2}{Z_L}$



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→ we have considered inductive load so that current I_2 lags behind V_2 or E_2 by ϕ_2.

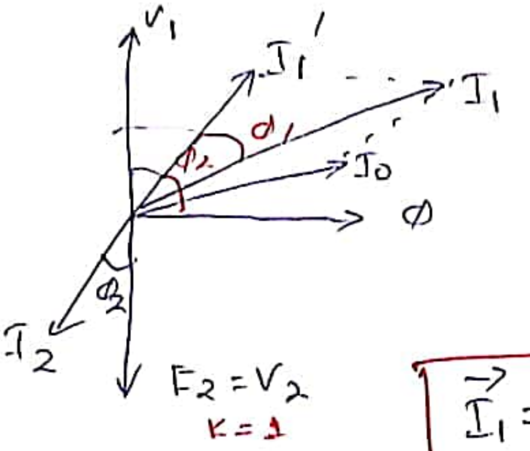
→ I_2 sets up an m.m.f $N_2 I_2$ which produces a flux in the opposite direction to the flux ϕ originally set up in the primary. This reduces the net flux in the core.

→ In order to minimise the reduction, the primary draws an additional current I_1' which must develop an mmf $N_1 I_1'$ which counterbalances the secondary MMF $N_2 I_2$.

so $N_1 I_1' = N_2 I_2$ $\Rightarrow$ $\boxed{I_1' = K I_2}$

$\Rightarrow I_1' = \frac{N_2}{N_1} I_2$

Hence Flux in the core remains constant.



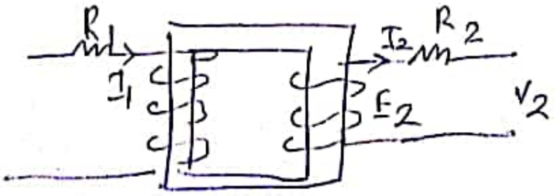
I_1' = load component of primary current

I_0 = No-load primary current

I_1 = primary current at load

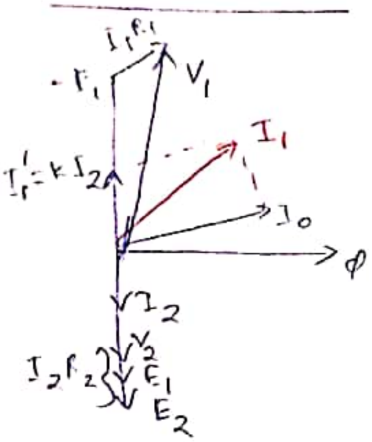
$\boxed{\vec{I_1} = \vec{I_0} + \vec{I_1'}}$ $\boxed{I_1 = \sqrt{I_0^2 + I_1'^2}}$

Transformer with winding resistance but no magnetic leakage reactance

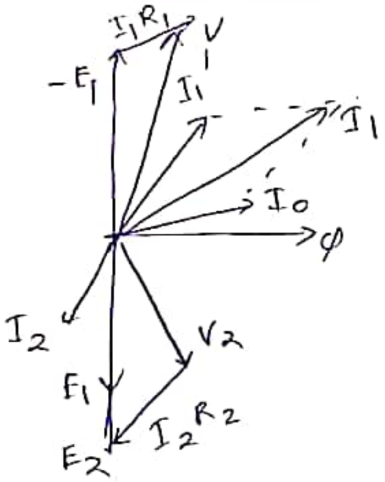


$$\left.\begin{aligned} V_2 &= E_2 - I_2 R_2 \\ E_1 &= V_1 - I_1 R_1 \end{aligned}\right\}$$ due to presence of winding resistance.

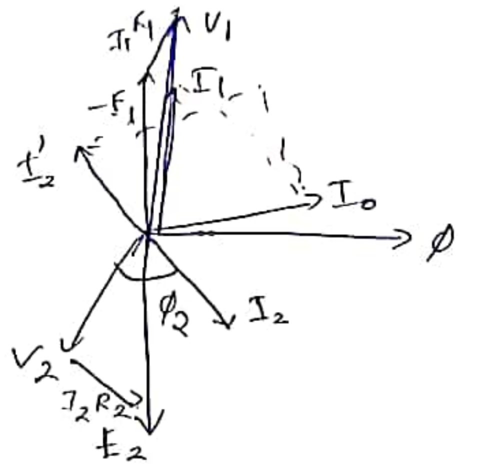
resistive load



Inductive load

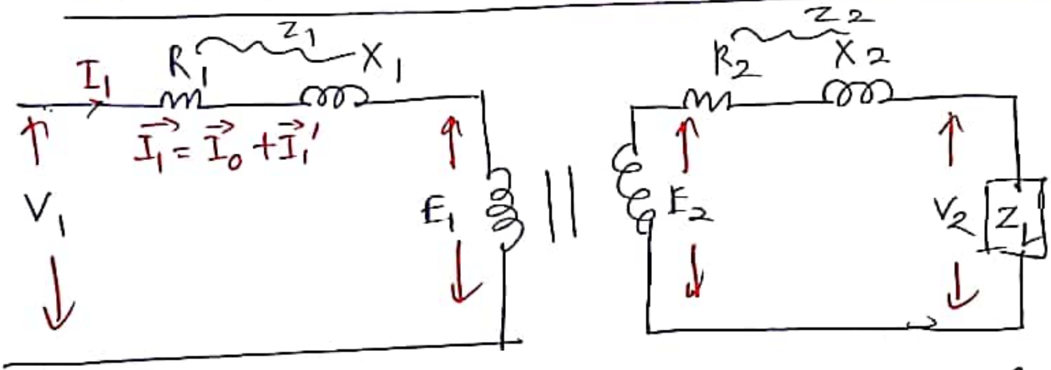


capacitive load



~~For inductive load~~

Transformer with resistance & leakage reactance



$$V_1 = -E_1 + I_1(R_1 + jX_1)$$
$$= -E_1 + I_1 Z_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$
$$= E_2 - I_2 Z_2$$

For inductive load

ϕ_0 = N.L. P.F angle

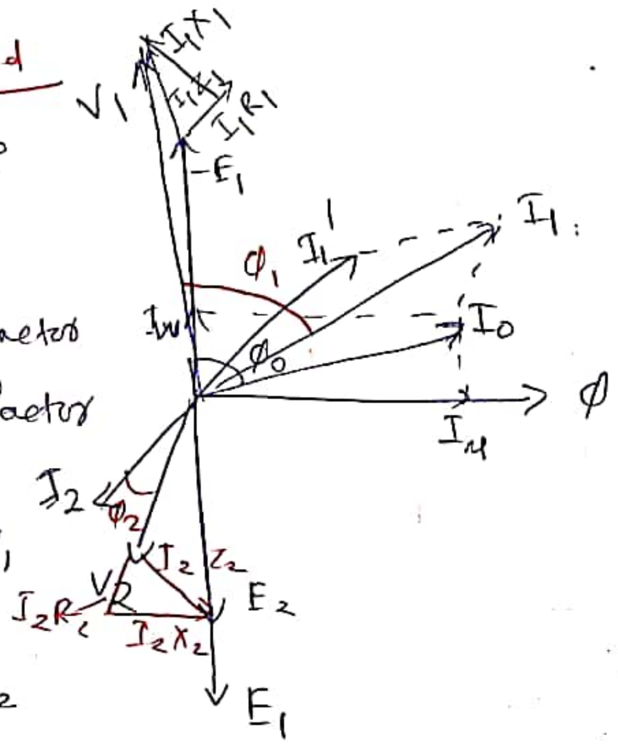
$\cos\phi_0$ = N.L. power factor

$\cos\phi_2$ = load power factor

$\cos\phi_1$ = i/p power factor

i/p power to T/F $= V_1 I_1 \cos\phi_1$

o/p power of T/F $= V_2 I_2 \cos\phi_2$



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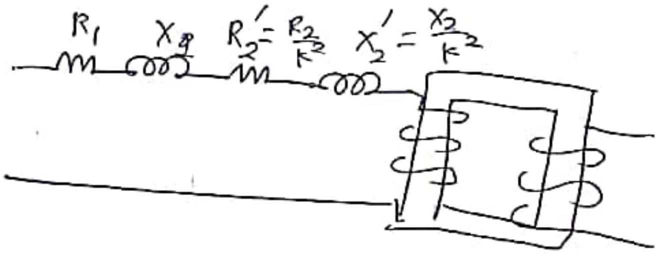
Impedance ratio

$$\frac{R_2}{R_1} = k^2, \quad \frac{X_2}{X_1} = k^2, \quad \frac{Z_2}{Z_1} = k^2$$

(8)

(A) shifting to primary or referred to primary

$$\boxed{\begin{aligned} R_{01} &= R_1 + R_2' = R_1 + \frac{R_2}{k^2} \\ X_{01} &= X_1 + X_2' = X_1 + \frac{X_2}{k^2} \end{aligned}}$$

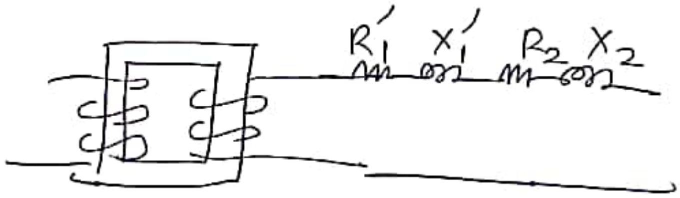


equivalent impedance of T/F referred to primary $\boxed{Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}}$

(B) shifting to secondary or referred to secondary

$$R_{02} = R_2 + R_1' = R_2 + k^2 R_1$$

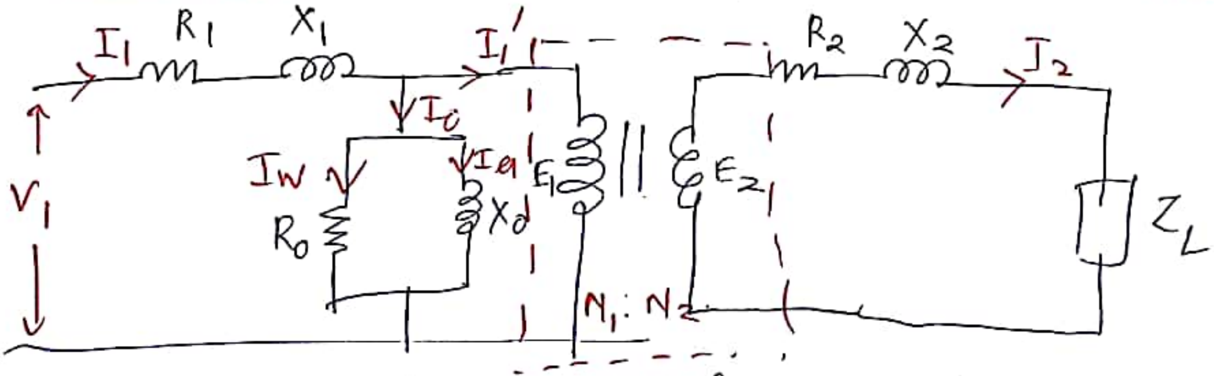
$$X_{02} = X_2 + X_1' = X_2 + k^2 X_1$$



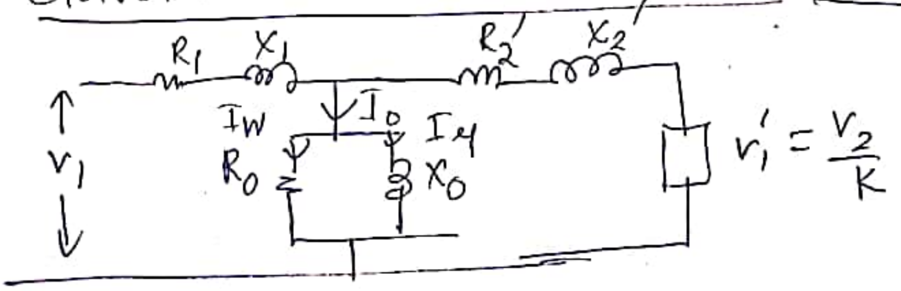
equivalent impedance of T/F referred to 2°

$$\Rightarrow \boxed{Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}}$$

Exact equivalent circuit of a loaded Transformer



equivalent circuit of transformer refer to 1°



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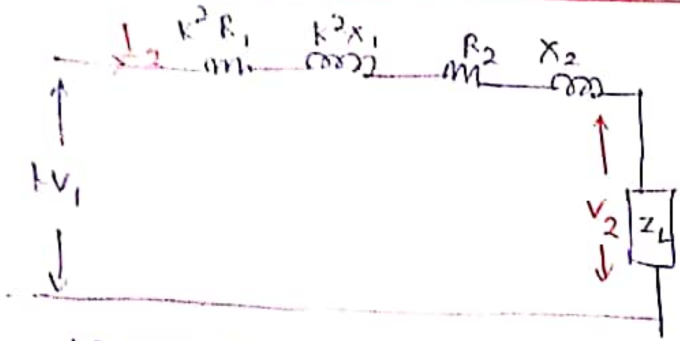
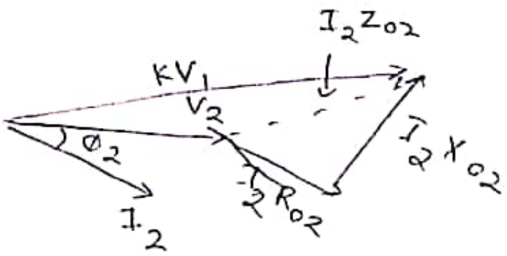
Approximate voltage drop in transformer





Approximate drop in secondary voltage

$= I_2R_{02}\cos\phi_2 \pm I_2X_{02}\sin\phi_2$ $+ \rightarrow$ lagging P.F load

$- \rightarrow$ leading PF load

Voltage regulation

The voltage regulation of a transformer is the arithmatic difference b/w the no-load secondary voltage ($_0V_2$) & the secondary voltage V_2 on load. as expressed as a percentage of no-load voltage,

$$\boxed{\% \, V.R = \frac{{}_0V_2 - V_2}{{}_0V_2} \times 100}$$

$\rightarrow$ ~~VR is not for~~ ~~lagging~~ PF loads & ~~zero~~

losses in Transformer

The power losses in a Transformer are of two types

1. core or Iron loss
2. copper losses

1 core or Iron loss

$\rightarrow$ These consists of hysteresis & eddy current losses & occur in the transformer core due to alternating flux.

$\rightarrow$ Hysteresis loss $= (W_h) = \eta B_{max}^{1.6} f V$

where η = steinmentz constant

f = frequency of supply

V = Volume of core.

Eddy current loss $\Rightarrow W_e = K_e B_m^2 f^2 v^2 t^2$

where t = thickness of lamination

B_m = maxm flux density

f = frequency of operation

K_e = eddy-current co-efficient (value depends on magnetic material)

→ These losses are minimised by using steel of very high Silicon content for the core & by using very ~~high~~ thin laminations.

(2) Copper loss This loss is due to the ohmic resistance of the transformer windings.

→ Total Cu. loss $= I_1^2 R_1 + I_2^2 R_2$

$= I_1^2 R_{01}$ or $I_2^2 R_{02}$

- Total losses in Transformer $= W_i + W_{cu}$

W_i → iron loss or constant loss

W_{cu} → copper loss or variable loss

Efficiency of Transformer

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}$$

$$= \frac{\text{output}}{\text{output} + \text{cu. loss} + \text{iron losses}}$$

$$\eta = \frac{\text{input} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}}$$

~~Condn for maxn~~

Full-load iron loss $= W_i$ → from open circuit test

Full-load Cu. loss $= W_{cu}$ → from short circuit test

Total F.L. losses $= W_i + W_{cu}$

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(11)

Full-load efficiency of the transformers at any p.f.

$$\eta_{F.L} = \frac{\text{Full-load VA} \times \text{p.f}}{(\text{Full-load VA} \times \text{p.f}) + W_i + W_{cu}}$$

$$= \frac{E_2 I_2 \cos\phi_2}{E_2 I_2 \cos\phi_2 + W_i + W_{cu}}$$

W_{cu} → From s.c. test

W_i → From o.c test

For any load equal to x of F.L.

$$\eta_x = \frac{x\, E_2 I_2 \cos\phi_2}{x\, E_2 I_2 \cos\phi_2 + W_i + x^2 W_{cu}}$$

condn for maxm efficiency

$\boxed{\text{Cu. loss = Iron loss}}$

o/p KVA corresponding to maximum efficiency

$$= \text{Full-load KVA} \times \sqrt{\frac{\text{Iron loss}}{\text{F.L. cu loss}}}$$

All day efficiency

$$\eta_{\text{all day}} = \frac{\text{o/p in kWhr}}{\text{i/p in kWhr}} \text{ (For 24 hours)}$$

→ All day efficiency is less then commercial efficiency.

→ It is used for distribution transformers whose secondary is subject to variable losses.

Q) Why transformer rating in KVA?

A: Cu. loss of a T/F depends on current

iron loss " " " " voltage.

total T/F loss depend on volt-ampere (VA) & not phase angle b/w voltage & current, i.e. it is independent of Power Factor. So T/F rating is in KVA not in kW.

Transformer tests

÷ 2 tests

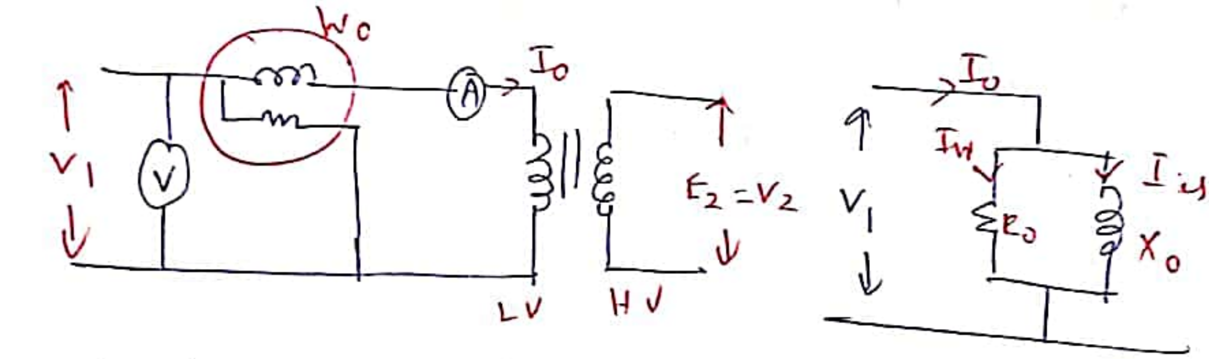
i) open circuit test
ii) short circuit test

① open circuit or No-load test

This test is used to determine
i) Iron loss or core losses or constant losses
ii) R_0 & X_0 (shunt branch parameters)
iii) separation of iron loss into W_h & W_e.

→ In this method, the rated voltage is applied to the low voltage side i.e. primary & secondary is left open circuited.

→ The i/p voltage V_1 is measured by the voltmeter, the no-load current I_0 by ammeter & no-load i/p power ~~by~~ W_0 by wattmeter.



→ As the normal rated voltage is applied to primary iron loss will occur in primary. Small amount of copper loss also occurs which can be neglected.

Wattmeter reading W_0 = Iron loss = W_i

No-load current = I_0 = Ammeter reading

Applied voltage = V_1 = Voltmeter reading

i/p Power, $W_0 = V_1 I_0 \cos\phi_0$

No-load P.F $(\cos\phi_0) = \dfrac{W_0}{V_1 I_0}$

$$\boxed{I_W = I_0 \cos\phi_0 \qquad I_\mu = I_0 \sin\phi_0}$$

$$\boxed{R_0 = \frac{V_1}{I_W},\ X_0 = \frac{V_1}{I_\mu}}$$

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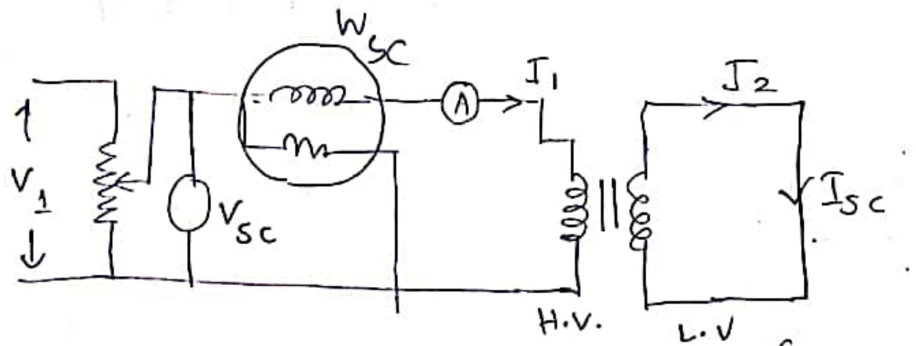
(2) Short circuit test

(1) This test is conducted to determine

i) Full load copper losses of the transformer

ii) Series branch parameters R_{01} & X_{01}



→ In this test, the secondary (usually L.V. winding) is short circuited & a variable low voltage is applied to the primary.

→ The low i/p voltage is gradually raised till at voltage V_{sc}, full load current I_1 flows in the primary & I_2 in the secondary also has full load value

→ There is no output from the transformer under short-circuit conditions. So i/p power is all loss & entirely copper loss. Since V_{sc} is small ironloss is small & can be neglected,

F.L. cu. loss (W_{sc}) = wattmeter reading

Applied voltage (V_{sc}) = Voltmeter reading

F.L. primary current (I_1) = Ammeter reading

$$W_{sc} = I_1^2 R_1 + I_1^2 R_2' = I_1^2 R_{01}$$

$$\boxed{R_{01} = \frac{W_{sc}}{I_1^2}}$$

Total impedance, $\boxed{Z_{01} = \frac{V_{sc}}{I_1}}$, $\boxed{X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}}$

Short circuit p.f ($\cos\phi_2$) $= \dfrac{W_{sc}}{V_{sc} I_1}$

→ S.C. test gives F.L. cu. loss, R_{01} & X_{01}.

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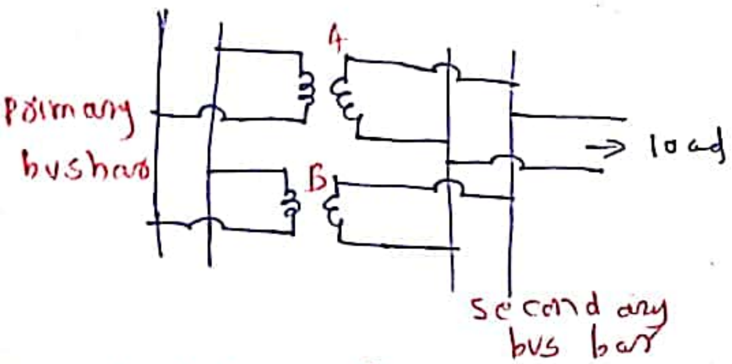
Parallel operation of transformer

→ Two transformers are said to be in parallel if the primary windings are connected to supply bus bars & secondary windings are connected to load busbars.



→ Transformer A & B are in parallel.

Condition for parallel operation of two transformer

i) Transformer should be properly connected with regard to their polarities.

ii) The voltage ratings & voltage ratio of the transformer should be same,

iii) The p.u. or percentage impedances of the T/F should be same,

iv) The $\frac{X}{R}$ ratio of the transformers should be same,

Single phase equal voltage ratio T/F in parallel

→ Two-single phase equal voltage ratio transformer A & B in parallel. The secondary E.m.f s of the two transformers are equal (i.e. $E_A = E_B = E$) because they have the same turns ratio and have their primaries connected to the same supply.

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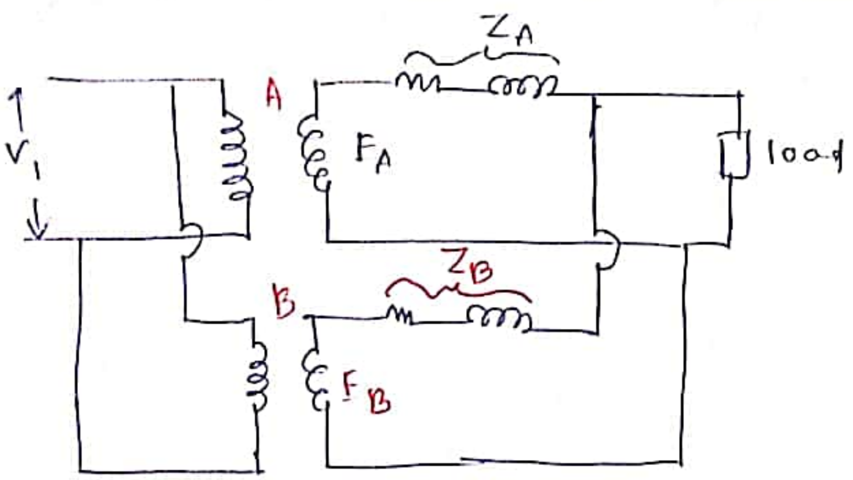


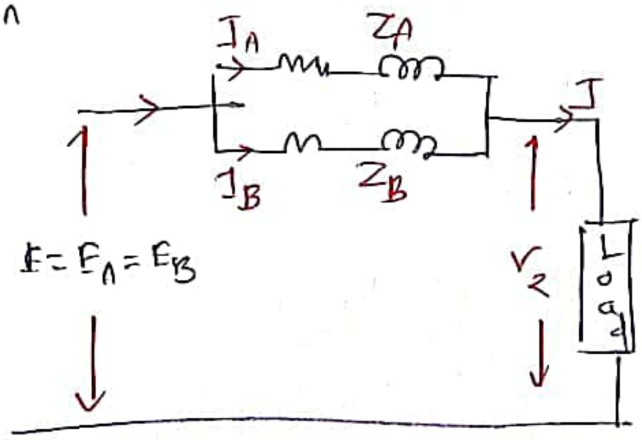
→ If the magnetising current is ignored, the two transformers can be represented by their equivalent circuits referred to secondary. It is clear that the transformers will share total load in the same way as two impedances in parallel.

Let Z_A, Z_B = impedances of transformers referred to secondary

I_A, I_B = respective currents

V_2 = common terminal voltage

I = total load current



$I_A + I_B = I$

$I_A Z_A = I_B Z_B$

$I_A = I_B \dfrac{Z_B}{Z_A}$

$I_B \left(1 + \dfrac{Z_B}{Z_A}\right) = I$

Similarly $I_A = I \dfrac{Z_B}{Z_A + Z_B}$

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KVA carried by each transformer

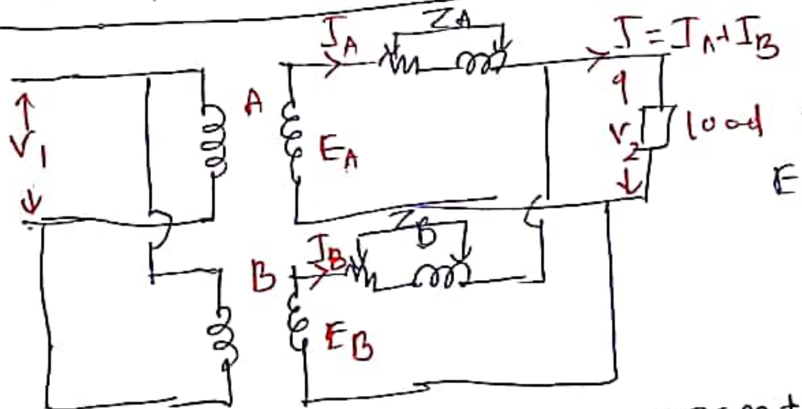
Let S = total load KVA

S_A = KVA carried by transformer A

S_B = " " " " B

$$\boxed{S_A = S \times \frac{Z_B}{Z_A + Z_B}} \qquad \boxed{S_B = S \times \frac{Z_A}{Z_A + Z_B}}$$

1-φ unequal voltage ratio transformers in parallel



here $E_A > E_B$

At no-load, the circulating current I_c is

$$I_C = \frac{E_A - E_B}{Z_A + Z_B}$$

$$V_1 = \left[\frac{E_A Z_B + E_B Z_A}{Z_A Z_B + Z_L(Z_A + Z_B)}\right] Z_L$$

$$V_2 = \frac{E_A Z_B + E_B Z_A}{\frac{Z_A Z_B}{Z_L} + Z_A + Z_B}$$

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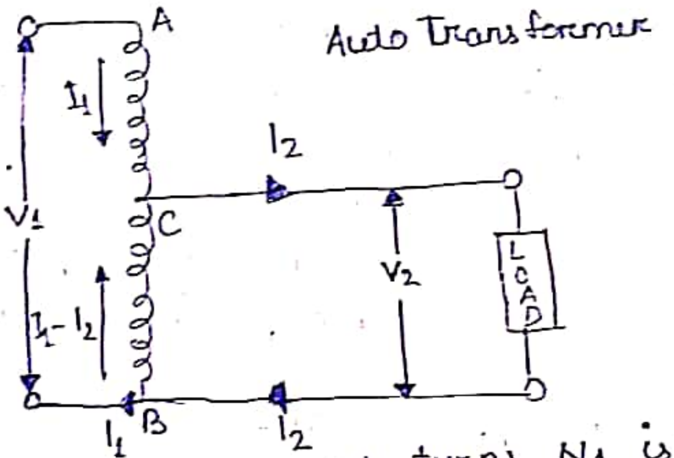
An auto-transformer is a kind of electrical transformer where primary and secondary shares same common single winding. So basically it's a one winding transformer.

THEORY - In an auto transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose. A circuit diagram of auto transformer is shown below -



The winding AB of total turns N_1 is considered as primary winding. This winding is tapped from point 'c' and the portion BC is considered as secondary. Let's assume the number of turns in between points 'B' and 'c' is N_2.

If V_1 voltage is applied across the winding i.e in between 'A' and 'c'.

So voltage per turn in this winding is $\frac{V_1}{N_1}$

Hence, the voltage across the portion BC of the winding, will be,

$\frac{V_1}{N_1} \times N_2$ and from the figure above, the voltage is V_2.

$$\text{Hence, } \frac{V_1}{N_1} \times N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = \text{constant} = K$$

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As BC portion of the winding is considered as secondary, it can easily be understood that value of constant 'k' is nothing but turns ratio or voltage ratio of that auto transformer. when load is connected between secondary terminals i.e. between (B) and (c) – load current I_2 starts flowing. ~~The~~ The current in the secondary winding or common winding is the difference of I_2 and I_1. ②

Copper Savings in Auto Transformer :-

Now we will discuss the savings of copper in auto transformer compared to conventional two winding transformer.

we know that weight of copper of any winding depends upon its length and cross-sectional area. Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns and rated current of the winding.

Therefore, weight of copper in the section AC proportional to,

$$(N_1 - N_2) I_1.$$

and similarly, weight of copper in the section BC proportional to,

$$N_2 (I_2 - I_1)$$

Hence, total weight of copper in the winding of auto transformer proportional to,

$$(N_1 - N_2) I_1 + N_2 (I_2 - I_1)$$

$$\Rightarrow N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1$$

$$\Rightarrow N_1 I_1 + N_2 I_2 - 2N_2 I_1$$

$$\Rightarrow 2N_1 I_1 - 2N_2 I_1 \left(\text{Since, } N_1 I_1 = N_2 I_2\right)$$

$$\Rightarrow 2(N_1 I_1 - N_2 I_1)$$

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In similar way it can be proved, the weight of copper in two winding transformer is proportional to, ③

$N_1 I_1 - N_2 I_2$

$\Rightarrow 2N_1 I_1$ (since, in a transformer $N_1 I_1 = N_2 I_2$)

$N_1 I_1 + N_2 I_2$

$\Rightarrow 2N_1 I_1$ (Since, in a transformer $N_1 I_1 = N_2 I_2$)

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

Hence, $\frac{W_a}{W_{tw}} = \frac{2(N_1 I_1 - N_2 I_1)}{2(N_1 I_1)}$

$= \frac{N_1 I_1 - N_2 I_1}{N_1 I_1} = 1 - \frac{N_2 I_1}{N_1 I_1}$

$= 1 - \frac{N_2}{N_1} = 1 - k$

$\therefore W_a = W_{tw}(1-k)$

$\Rightarrow W_a = W_{tw} - kW_{tw}$

$\therefore$ saving of copper in auto transformer compared to two winding transformer,

$\Rightarrow W_{tw} - W_a = kW_{tw}$

Advantages :-

(1) The leakage flux is less & cu. used is less.

(2) The auto transformer has high ~~effeen~~ efficiency.

(3) Auto transformer has better voltage regulation.

Uses of Auto transformer

i) starting of induction motor

ii) used to regulate the voltage of transmission line known as booster transformer.

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Tap changer

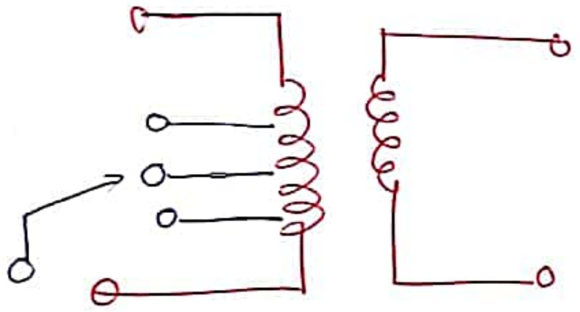
-> A tap changer basically changes the no. of turns of the winding which changes the voltage level.

-> For close control of voltage taps are usually provided on the high voltage winding of the transformer.

It is of 2 types i) off-load tap changing transformer,

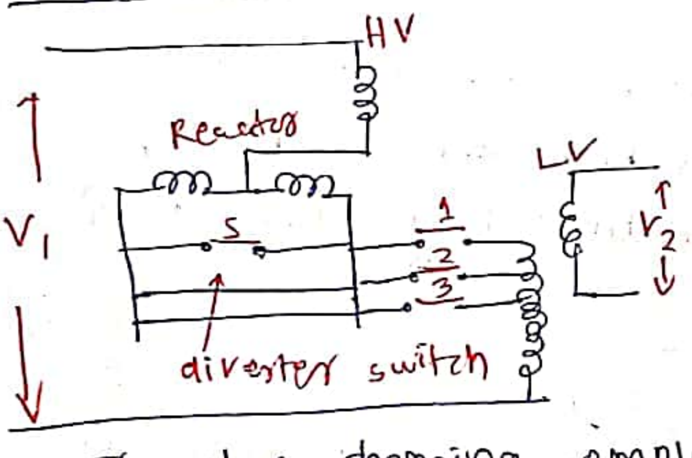
ii) on-load tap changing transformer.

(1) Off-load tap changing transformer



-> In this method, the transformer is disconnected from the main supply when the tap setting is to be changed. The tap setting is to be done manually.

(2) on-load tap-changing transformer



-> The tap changing employing a center tapped reactor R. S is the diverter switch, 1, 2, 3 are selector switch. The transformer is in operation with switches 1 & S closed.

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→ switch 1 is then opened, & 5 closed to complete the tap change. It is to be ~~operated~~ noted that the diverter switch operates on load, & no current flows in the selector switches during tap changing.

→ It is to be noted that the diverter switch operates on load & no current flows in the selector switches during tap changing. During the tap change, only half of the reactance which limits the current is connected in the circuit,

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Instrument transformer

→ These Transformer's are used in conjuction with meters for the measurement of high current & high voltage.

→ It is of 2 types i) current transformer (CT)
ii) Potential transformer (PT)/ Voltage transformer (VT)

1. **Transformation ratio (R) :-**

It is the ratio of primary Phasor to secondary phasor.

$$R = \frac{I_P}{I_S}\Big|_{CT} \qquad R = \frac{V_P}{V_S}\Big|_{PT}$$

2. **Nominal ratior (K_n) :-**

ratio of rated primary phasor to rated secondary phasor.

$$K_n = \frac{\text{rated } I_P}{\text{rated } I_S}\Big|_{CT}, \qquad K_n = \frac{\text{rated } V_P}{\text{rated } V_S}\Big|_{PT}$$

3. **Turn's ratio (n) :-**

$$n = \frac{N_S}{N_P}\Big|_{CT} \text{ (step up TF)} \qquad n = \frac{N_P}{N_S}\Big|_{PT} \text{ (Step down T/F)}$$

4. **Ratio correction Factor** $\div \left(\frac{R}{K_n}\right) = \frac{\text{Actual ratio}}{\text{nominal ratio}}$

5. **Burden** :- load on T/F will be specified with the name of burden. It will be expressed in V-A.

current transformer (CT)

→ current transformer is used to step down the current to a lower level to make it feasible to be measured by small rating Ammeter.

→ usually 1A will be used for measurement & 5A for protection.

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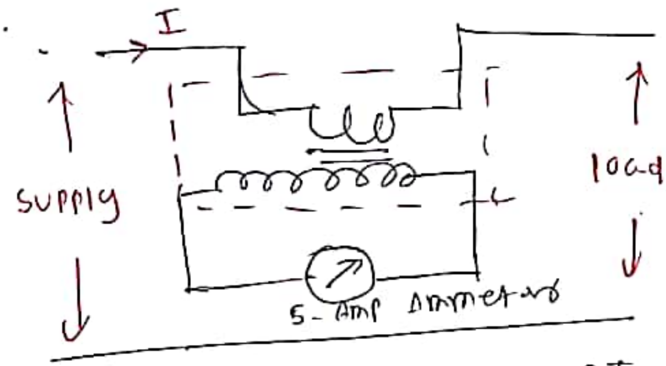
→ The conductor constitute a one-turn primary winding. The secondary consists of a large no. of turns of much fine wrapped around the core,

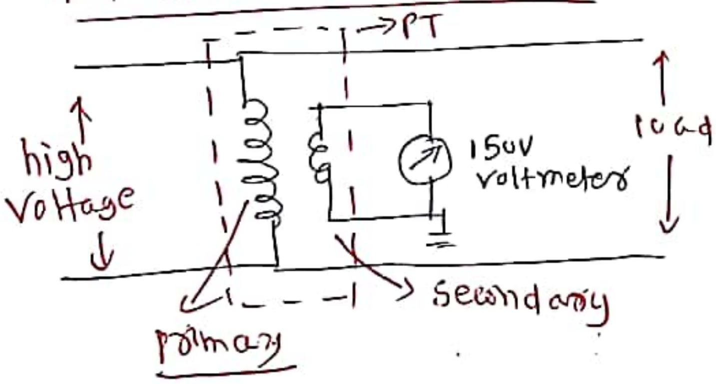
→ Due to transformer action, the secondary current is transformed to a low value which can be measured by ordinary meters.

$$\boxed{I_s = I_p \times \frac{N_p}{N_s}}$$



The secondary of a CT should never be left open under any circumstances.

Potential transformer



i) These transformers are extremly accurate-ratio stepdown transformers and are used in conjuction with standard low-~~voltage~~ range voltmeter (100-120 V) which deflection when divided by transformer ratio gives the true voltage on the primary or high voltage side.

③

(i) In general, they are of shell type & do not differ much from the ordinary two-winding transformers except their power rating is extremly small. Since their secondary windings are required to operate instruments or relays or pilot lights, their rating is usually of 40W to 100W.

(ii) For safety, the secondary is completely insulated from the high voltage primary & in addition, grounded for protection of the operator.

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