LECTURE NOTES ON

ENERGY CONVERSION-I

SEMESTER- 4th

PREPARED BY

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SINGLE PHASE TRANSFORMER

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Transformer is a static piece of device or electrostatic device by means of which electric power or energy in one circuit is transformed into electric power of same frequency in another circuit by mutual induction. It can raise or lower the voltage in circuit but with a corresponding decrease or increase in current.

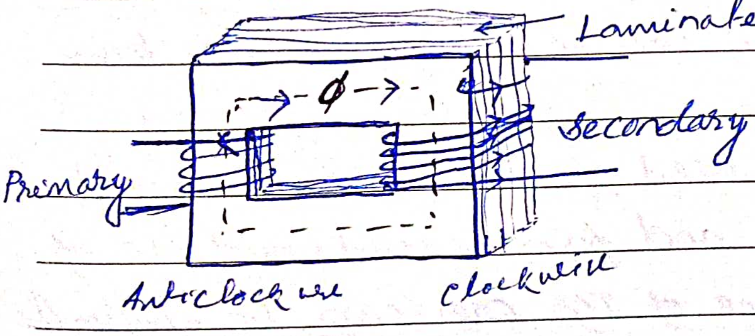
Working Principle :-

It works on the principle of mutual induction of two coils or Faraday law's of Electromagnetic Induction.

If one coil of transformer is connected to a source of an alternating voltage, an alternating flux is setup in the laminated core, most of which is linked with the other coil in which it produces mutually induced emf.

In brief Transformer is a device that

* Transfors electric power from one circuit to another.
* It does so without a change of frequency
* Transfer with the principle of Electromagnetic Induction
* The two electrical circuit are linked by mutual induction.



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

Construction :-

The simple elements of a transformer consist of two coils having mutual inductance & laminated steel core. The two coils are insulated from each other and from steel core. Device also needs some suitable container for the assembled core and windings, a medium with which the core and windings can be insulated. Suitable bushings either porcelain, oil filled or capacitor-type for insulating and bringing out the terminals of windings from the tank. The T/F core is made up of or constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-gap included.

✓ The steel should have high permeability and low hysteresis loss. For this to happen, the steel should be made up of high silicon content and must also be heat treated. By effectively laminating the core, the eddy current losses can be reduced, the laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface.

Type of Transformer :-

According to the design T/F can be classified into two :-

ⓐ Core type T/F :-

✓ The winding or coil used for this T/F surround a considerable part of core and form wound and are of cylindrical type. Such a type of T/F ~~can~~ can be applicable for small sized and large sized T/Fs.

In small sized type the core will be rectangular shape and coil used are cylindrical, which are either circular or rectangular in form.

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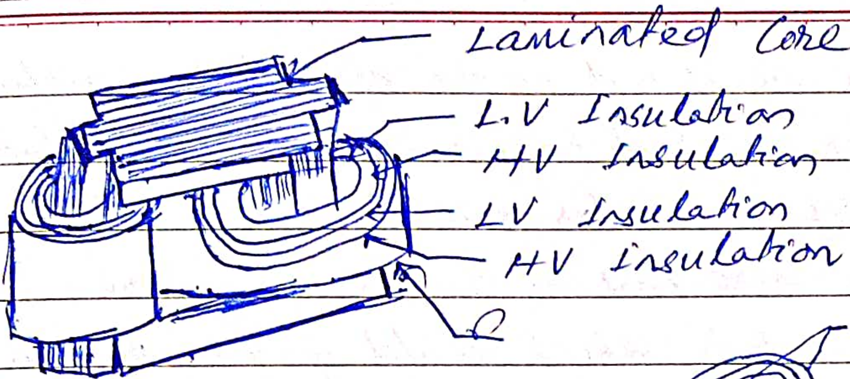
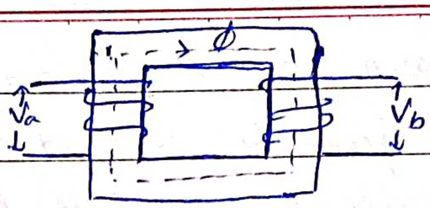
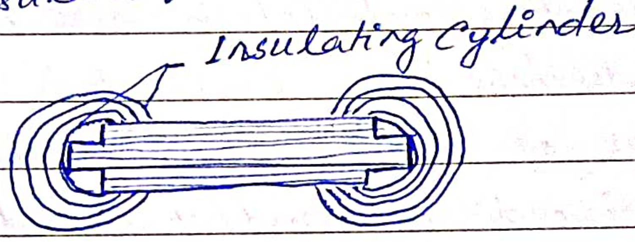




[Core type Transformer
cruciform section]

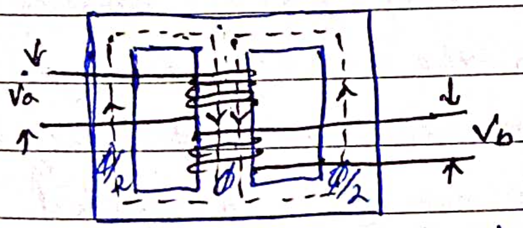


→ The cylindrical coils will have different layers and each layer will be insulated from each other with the help of material like paper, cloth, micarta board and so on.

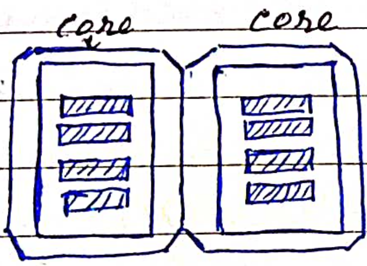
* These are popular in High Voltage application like Distribution T/F, Power T/F and Auto T/F

Ⓑ Shell-Type T/F :-

In shell-type T/F, the core surrounds a considerable portion of the windings. The coils are form-wound but are multilayer disc type usually wound in the form of pancakes.



(3 Limb shell type)



Paper is used to insulate the different layers of the multi-layer discs. The whole winding consist of discs stacked with insulation spaces between the coils. These form horizontal cooling & insulating ducts.

Both H.V & L.V coils are wound on the central limb surface the quantity of conductor required for woundings of shell type T/F is less than that of a similar core type T/F. The insulating material is more here as the winding are sandwitched on each other which would give rise to a risk of short-circuit faults.

Forced air and/or forced oil cooling is essential in shell type T/F as heat generated during working can't get dissipated easily from windings due to surrounding yoke and limbs.

shell type T/F are mainly used for Low Voltage (LV) applications and are very often used in low voltage power circuits as well as in electronics circuits.

→ The sides of insulating tank, oil used in the T/F ~~provide~~ needed to circulate through the device and cool the coils. It is also responsible for providing the additional insulation for the device when it is left in the air. When the smooth tank surface will not be able to provide the needed cooling are. In such cases the sides of the tank are assembled with radiators on the sides of the device.

⇒ Breather is used to absorb the moisture present in air before intering into the tank during expansion and contraction oil in the tank.

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Type according to the type of cooling employed:-

(A) Oil filled self cooled type :-

- It is used by small and medium sized distribution T/F. The assembled windings and core of such T/F are mounted in a welded, oil-tight steel tanks provided with a steel cover. The tank is filled with purified, high quality insulating oil as soon as the core is put back at its proper place. The oil helps in transforming the heat from core and the winding to the surroundings. For smaller size tanks are, usually smooth surfaced but for large size T/F greater surface area is needed and is achieved by frequently corrugating the case.

(B) Oil filled water cooled type :-

It is same as oil filled self cooled type, only difference is that a cooling coil is mounted near the surface of the oil, through which cold water keep circulating. This design is usually implimented on T/Fs that are used in high voltage transmission lines.

(C) Air Blast type :-

This type is used for T/Fs that use voltage below 25 KV. The transformer is housed in a thin sheet metal box open at both ends through which air is blown from the bottom to the top.

Sine of Angle = Cosine of its Complement.

$\sin\theta = \cos(90-\theta)$

$\cos\theta = \sin(90-\theta)$ or $\sin(90+\theta)$

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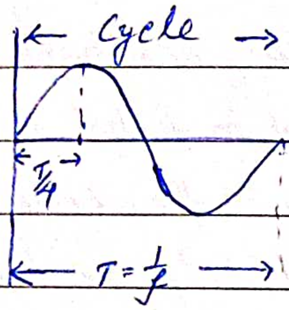
E.M.F Equation of a Transformer :-

Let N_1 = No of turns in primary N_2 = No of turns in Secondary

ϕ_m = Max flux in core in Weber, $\phi_m = B_m \times A$

f = frequency of a.c input in Hz.



flux increases from zero to max value ϕ_m in one quater of the cycle

$\therefore$ Average rate of change of flux $= \frac{\phi_m}{T/4}$

$= 4f\phi_m$ Wb/s or Volt

The rate of change of flux per turns means induced emf in volt. i.e

Average emf/turn $= 4f\phi_m$ Volt.

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

RMS Value = Form factor × Average Value

RMS Value of emf/turn $= 1.11 \times 4f\phi_m = 4.44 f\phi_m$ Volt

RMS Value of the induced emf in the whole of primary winding

= Induced emf/turn × No of primary turns

$E_1 = 4.44 f N_1 \phi_m = 4.44 f N_1 B_m A$ — ①

Similarly rms value of the emf induced in secondary is

$E_2 = 4.44 f N_2 B_m A$ — ②

From Eqn ① and ②

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f B_m A$$

OR $\phi = \phi_m \sin \omega t$ $\quad e = -N\frac{d\phi}{dt} = -N\frac{d}{dt}(\phi_m \sin\omega t) = -N\phi_m \cos\omega t \cdot \omega = -N_1\phi_m\omega \sin(90-\omega t)$

$\Rightarrow e_1 = N_1 \phi_m \omega \sin(\omega t - 90)$

RMS value $E_1 = \frac{N_1\phi_m\omega}{\sqrt{2}} = \frac{N_1\phi_m(2\pi f)}{\sqrt{2}} = 4.44 N_1 \phi_m f$

* Voltage Transformation Ratio (K) $= \frac{E_2}{E_1} = \frac{N_2}{N_1}$

* Turn Ratio $= \frac{N_1}{N_2}$

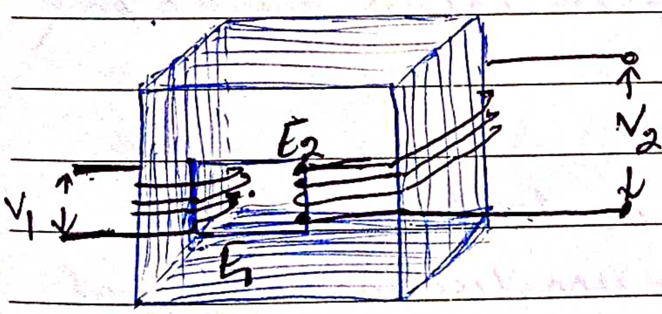
For ideal transformer input VA = output VA

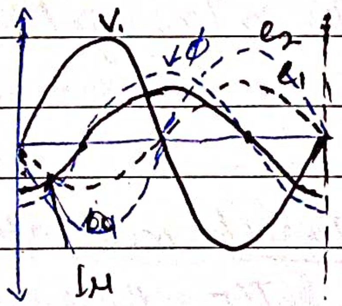
$V_1 I_1 = V_2 I_2$ or $\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$ $\Big\}$ Here $E_1 = V_1$ & $E_2 = V_2$

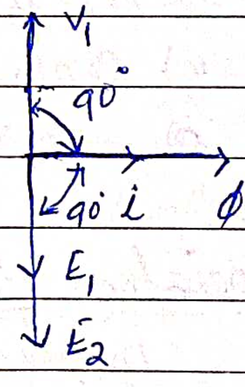
Ideal Transformer :-

An ideal T/F is one which has no losses i.e its winding have no ohmic resistance, there is no magnetic leakage and hence which has no I^2R and core losses. In other word, an ideal T/F consist of two purely inductive coils wound on a loss-free core.

Consider an ideal T/F whose secondary is open and primary is connected to sinusoidal alternating voltage V_1.







The potential difference causes an alternating current to flow in primary. Since primary coil is purely inductive and there is no output (secondary being open) the primary draws the magnetising current (I_μ) only.

I_μ is small in size and lags V_1 by 90°. I_μ produces an alternating flux ϕ which is proportional to the current and is in phase with it. Because of change in flux linkage with primary and secondary windings, it produces self-induced emf (E_1) equal and opposite to V_1. Similarly in secondary side emf (E_2) is induced, known as mutually induced emf is antiphase with V_1

Care and Maintenance of Transformer :-

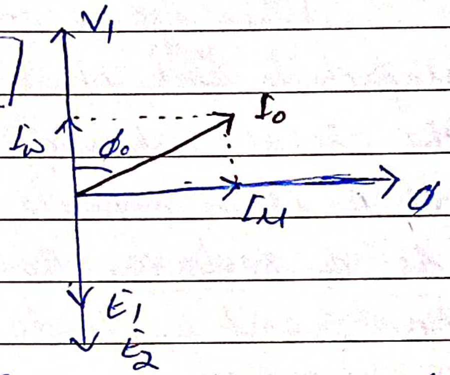
1) Oil level in the oil cap must be checked on a monthly basis.
2) Keep the breathing holes in the silica gel breather clean to ensure proper breathing action.
3) If T/F has oil filling bushing, make sure that the oil is filled to the correct level.
4) Replace the silica gel if its colour changes to pink.

Operation of Transformer at no-load.

In practical T/F there is iron loss in the core and copper loss in the winding and these are not entirely negligible. When T/F is on no-load, the primary input current is not wholly reactive. Primary no load current (I_0) has to supply
i) Iron losses in the core i.e hysteresis loss (W_h) and Eddy current losses (W_e) and ii) Very small

amount of copper loss in primary. So I_0 is not at $90°$ behind V_1 but lags it by angle $\phi_0 < 90°$

No Load Power Input $(W_0) = V_1 I_0 \cos\phi_0$



[Phasor diagram of No-Load T/F]

I_0 has two components I) one in phase with V_1 is known as active or working or Iron loss components I_w.

$I_w = I_0 \cos\phi_0$

* I_w supplies the iron loss and small quantity of primary cu. loss.

II) Other component is in quadrature with V_1 and is known as magnetising components I_μ, because its work is to sustain the alternating flux in core,

$I_\mu = I_0 \sin\phi_0$

Here $\vec{I_0} = \vec{I_w} + \vec{I_\mu}$, hence $I_0 = \sqrt{I_\mu^2 + I_w^2}$

* I_0 is very small and is 1% of full Load current.
* As I_0 is very small, so no-load primary cu. loss is negligible small hence No-Load Primary input is practically equal to the Iron loss in T/F. W_0
* core loss or iron loss is responsible for shifting the current vector. hence ϕ_0 is known as hysteresis's angle of advance

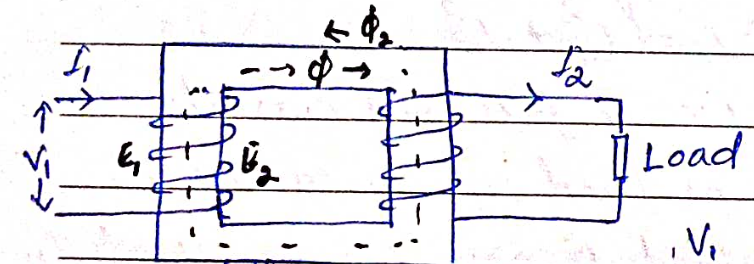
Transformer on Load :-

When the secondary is Loaded, the current I_2 is set up. Magnitude And phase of I_2 with respect to V_2 is determined by the characteristics of Load. I_2 set up its own mmf ($= N_2 I_2$) or ϕ_2 and it is opposite to the main flux.

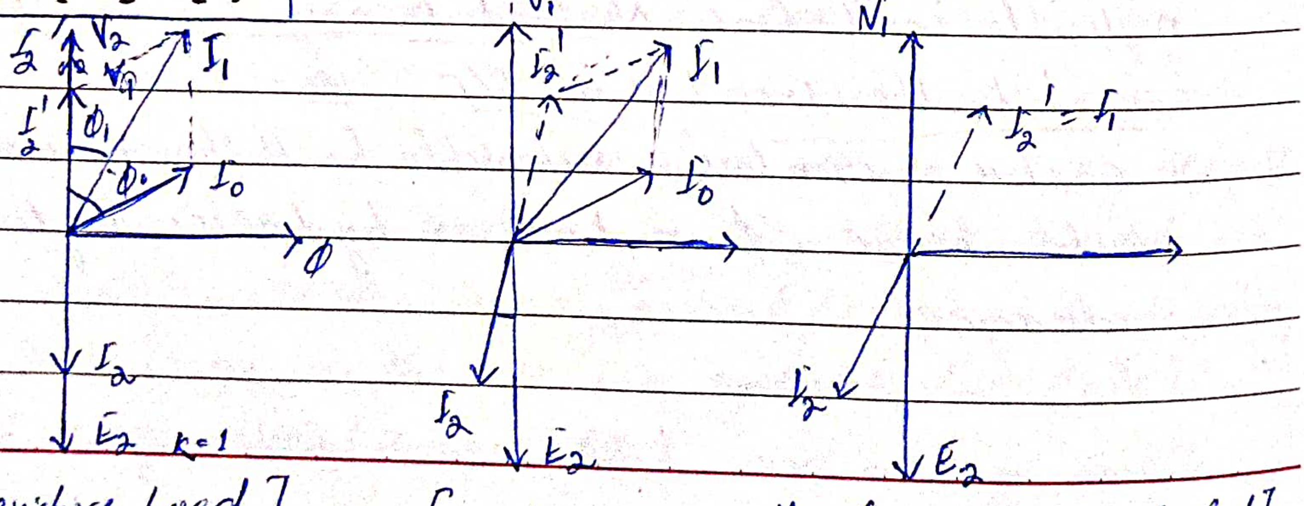
As ϕ_2 reduces the main flux (ϕ) momentarily, hence primary back emf E_1 tends to be reduced. For a moment V_1 gain the upper hand and primary current increases and this additional current be I_2' and is antiphase with I_2 and setup its own flux ϕ_2', opposite to ϕ_2.

* So net flux passing through the core is approximately the same as at no-load. Hence core loss is also practically same under all load condition.

As $\phi_2 = \phi_2'$ ∴ $N_2 I_2 = N_1 I_2'$ ∴ $I_2' = \frac{N_2}{N_1} I_2 = K I_2$



$I_1 = I_0 + I_2'$



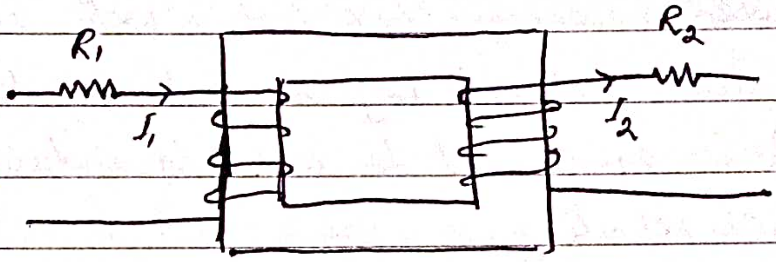
[(a) Resistive Load] [(B) - Lagging Load] [(c) I_0 is Neglected]

ϕ_1 is slightly greater than ϕ_2. If we neglect I_0 as compared to I_2' then $\phi_1 = \phi_2$

Hence $N_1 I_2' = N_2 I_2 = N_1 I_1$ $\therefore \frac{I_2'}{I_2} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$

(As $I_1 = I_2'$)

Equivalent Resistance, Reactance and Impedance :-



Primary & secondary winding, having resistance R_1, R_2 respectively is shown in figure.

The resistance of the two winding can be transferred to any one of the two winding. It makes calculations very simple and easy because one has to work one winding only.

Where R_1' = The equivalent primary resistance as referred to secondary

& R_2' = " secondary " " Primary.

These can be calculated by considering the same losses (I^2R Loss)

$I_1^2 R_2' = I_2^2 R_2 \Rightarrow R_2' = \left(\frac{I_2}{I_1}\right)^2 R_2 \Rightarrow \boxed{R_2' = \frac{R_2}{K^2}}$

Similarly $\boxed{R_1' = K^2 R_1}$

$\therefore$ Effective or Equivalent resistance of T/F as referred to primary $(R_{01}) = R_1 + R_2'$

$= R_1 + R_2/K^2$

& " " " to secondary $(R_{02}) = R_2 + R_1'$

$= R_2 + K^2 R_1$

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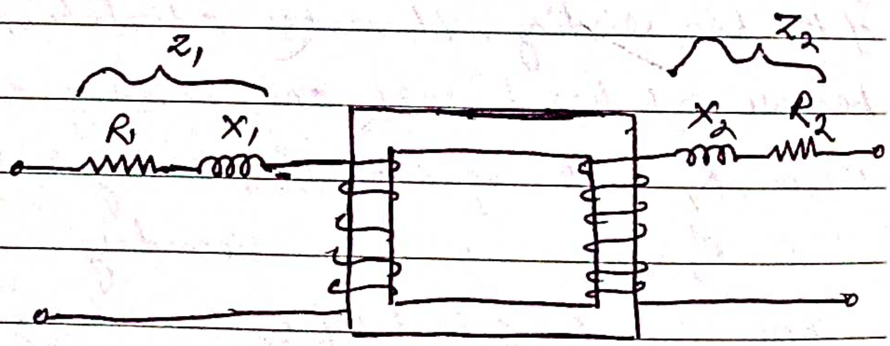
* A resistance of R_1 in Primary is equivalent to K^2R_1 in Secondary
* ,, R_2 in Secondary ,, R_2/K^2 in Primary

* But in practical all the flux linked with primary
* does not link the secondary, it is known as primary Leakage flux
* This leakage flux depends on primary and secondary current. Leakage flux linking with each winding produces a self induced emf in that winding. Hence in effect it is equivalent to a small inductive coil in series with each winding.

→ The primary voltage V_1 will have to supply reactive drops I_1X_1 in addition to I_1R_1 and E_2 have to supply I_2R_2 and I_2X_2

$Z_1 = \sqrt{R_1^2 + X_1^2}$

$Z_2 = \sqrt{R_2^2 + X_2^2}$



$V_1 = E_1 + I_1(R_1 + jX_1)$ & $E_2 = V_2 + I_2(R_2 + jX_2)$

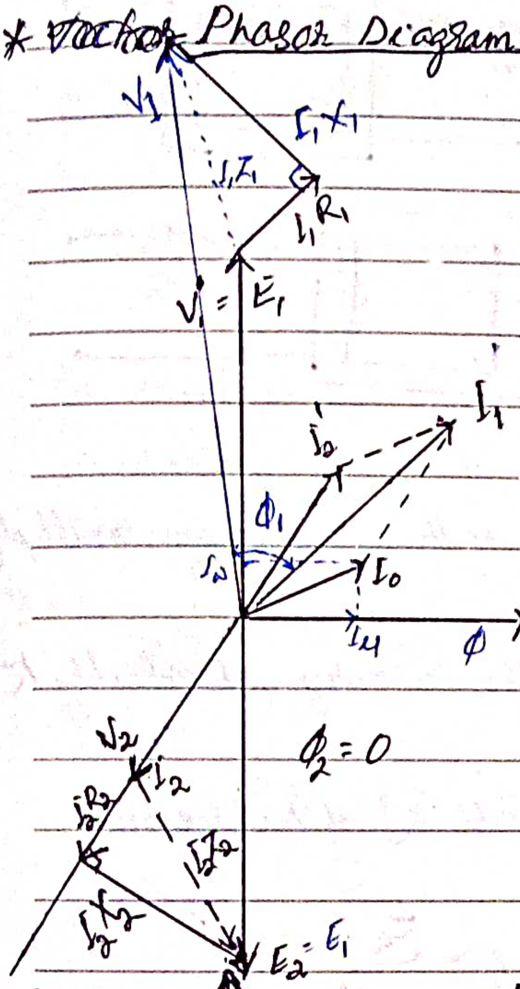
$\Rightarrow V_1 = E_1 + I_1 Z_1$ $\Rightarrow E_2 \Rightarrow V_2 + I_2 Z_2$

Leakage reactances can also be transferred from one winding to the other in the same way as resistance

$X_2' = X_2/K^2$ & $X_1' = K^2X_1$

And $X_{01} = X_1 + X_2' = X_1 + X_2/K^2$ and $X_{02} = X_2 + X_1' = X_2 + K^2X_1$

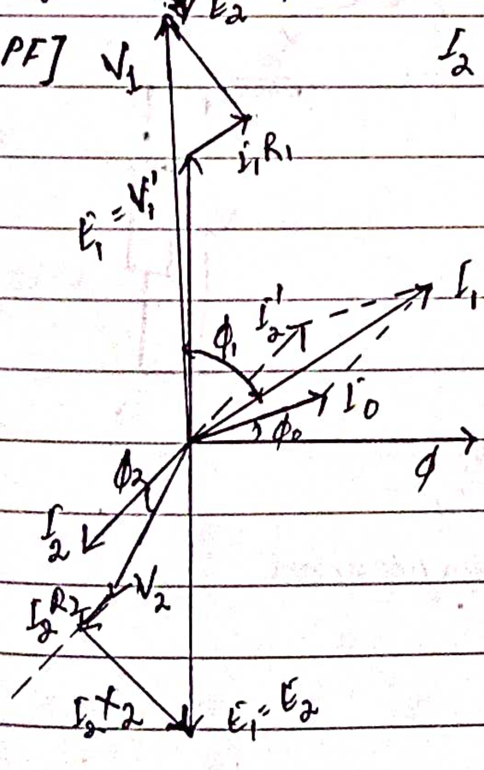
* ~~Vector~~ Phasor Diagram of T/F (With winding Resistance & Leakage Reactance And With UPF, Lagging P.F & Leading PF)



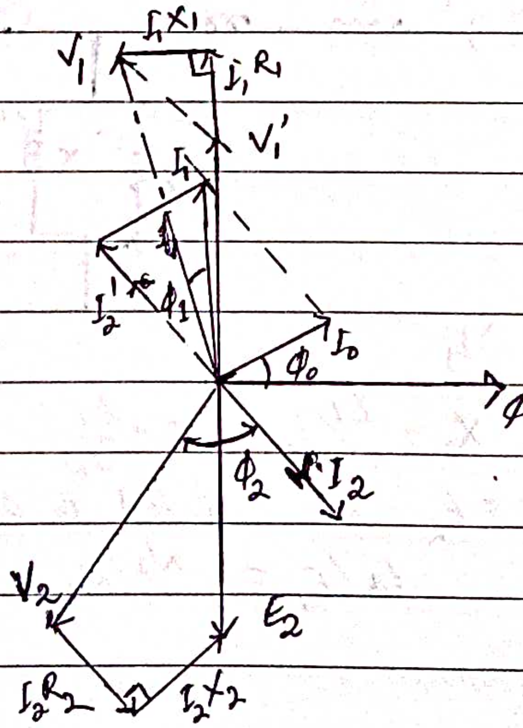
[UPF]

V_1 = Voltage drop in the primary winding
I_1 = Primary current
I_0 = Primary No load current
I_2' = Load component of Primary current
E_1 = Induced emf (Primary)
I_μ = Magnetising component of No load current
I_w = Active or working " "
E_2 = Induced emf (secondary side)
I_2 = secondary current
V_2 = secondary terminal voltage.

$I_2 = I_2'$

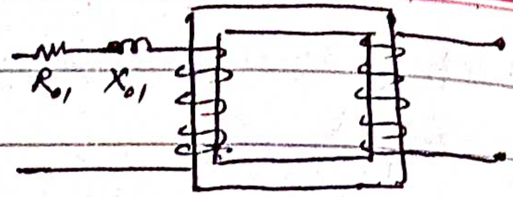


[Lagging P.F]



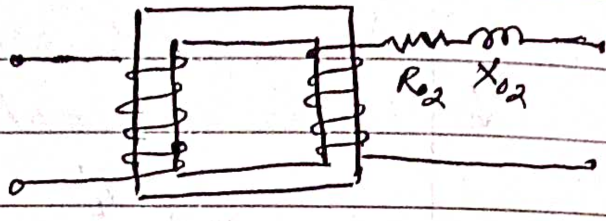
[Leading PF]

The total impedance of transformer referred to Primary & Secondary is :-



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

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

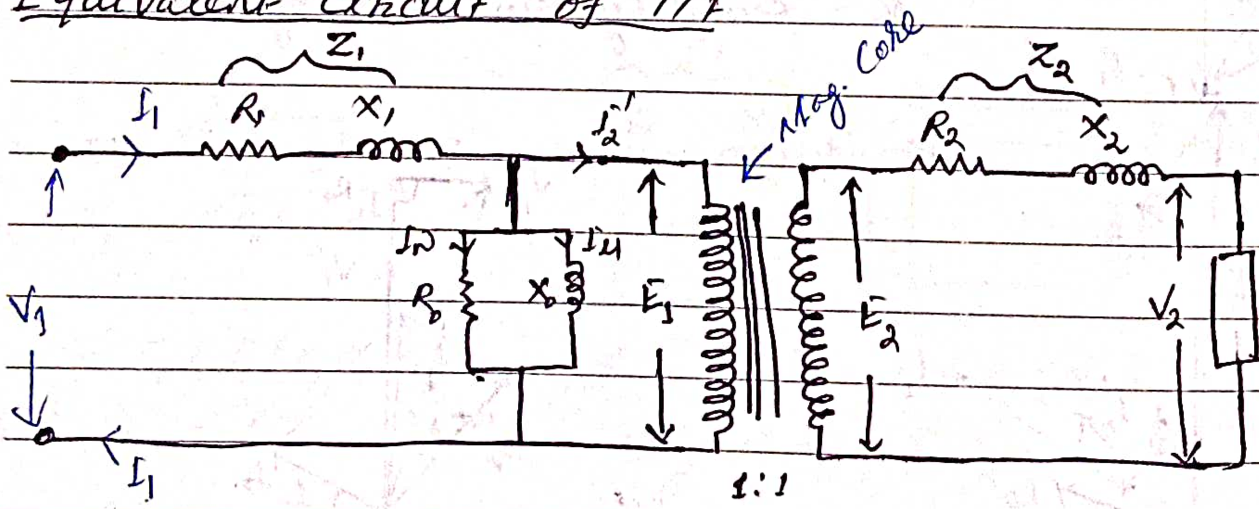


$R_{01} = R_1 + R_2'$ $\quad R_{02} = R_2 + R_1'$

$X_{01} = X_1 + X_2'$ & $X_{02} = X_2 + X_1'$

- When shifting any Resistance & Reactance to the secondary, multiply it by K^2 i.e (transformation Ratio)^2
- When shifting any Resistance & Reactance to the primary, divide it by K^2
- When shifting voltage use 'K' only
- When shifting current (I) primary to secondary divide 'K' & vice versa

Equivalent circuit of T/F



$X_0 = E_1/I_0$, $R_0 = \frac{E_1}{I_w}$ again $X_0 = \frac{V_1}{I_\mu}$

E_1 & E_2 are related to each other by expression

$E_2/E_1 = N_2/N_1 = K$

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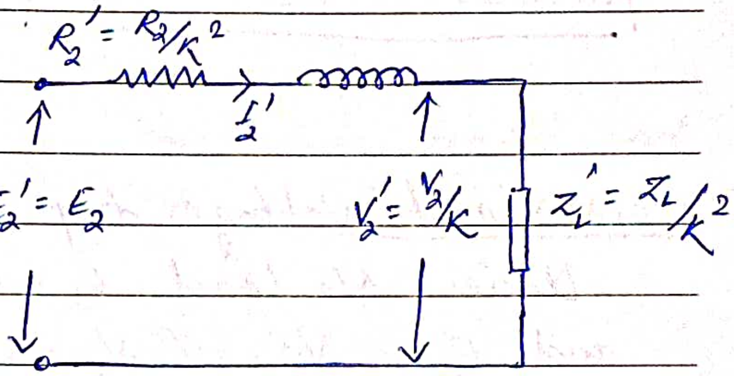
To make transformer calculation simpler, it is preferable to transfer voltage, current & impedence.

i.e. $E_2' = E_2/K = E_1$ (as $K=1$)

$V_2' = V_2/K$, $I_2' = KI_2$, $R_2' = R_2/K^2$, $X_2' = X_2/K^2$ & $Z_2' = Z_2/K^2$

So primary equivalent of secondary circuit can be drawn as →



Total Equivalent circuit of the T/F is obtained by Primary equivalent of secondary to the Primary.

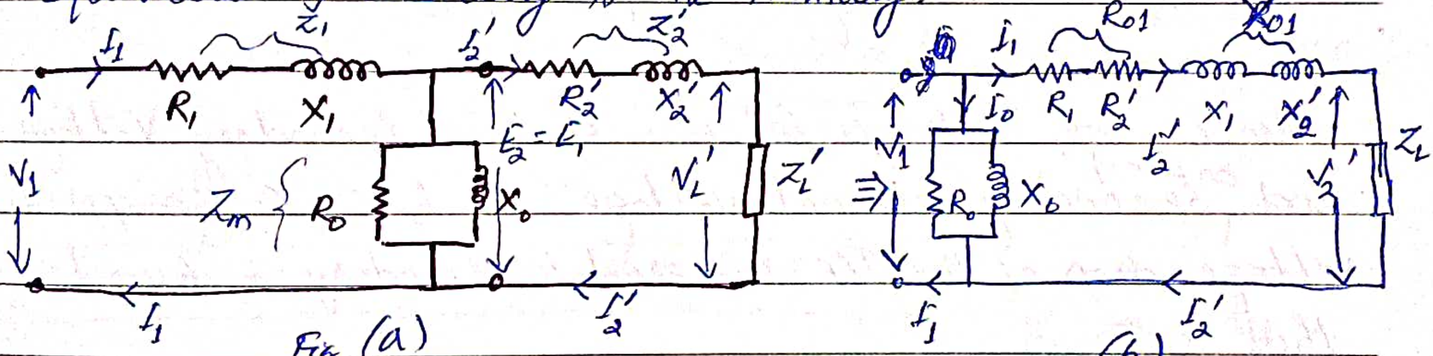
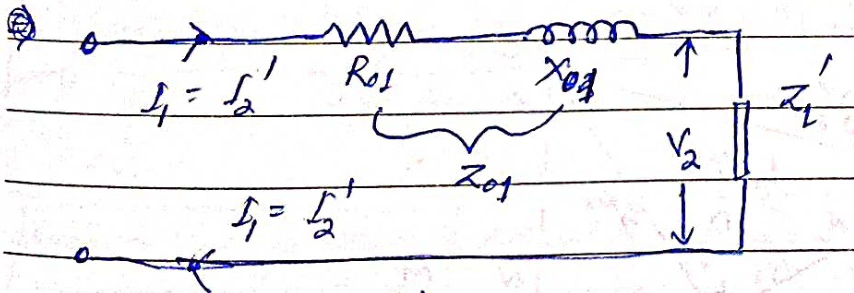


Fig (a) (b)

At Last, the circuit is simplified by omitting I_0



(c)

From Fig (a) the equivalent Impedance between Input is

$Z = Z_1 + Z_m || (Z_2' + Z_L')$

From

i.e $Z = Z_1 + \dfrac{Z_m (Z_2' + Z_L')}{Z_m + Z_2' + Z_L'}$ $\quad$ Z_m = Impedance of Exciting circuit

$$\therefore \boxed{V_1 = I_1 \left[Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + Z_2' + Z_L'} \right]}$$

Approximate voltage drop in a T/F

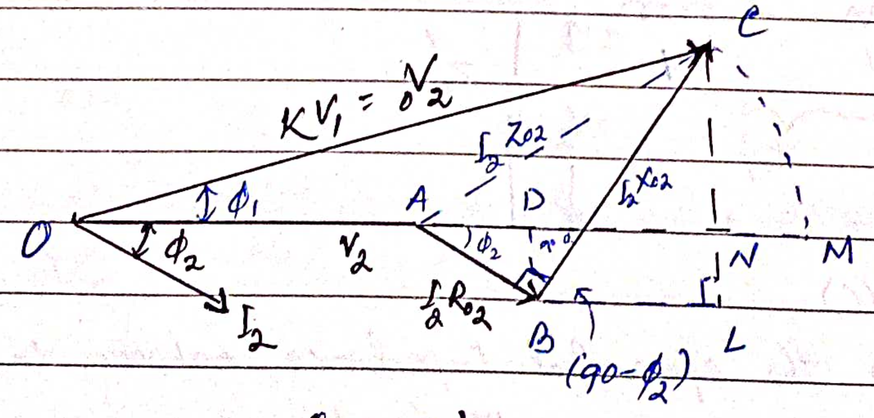
Under No Load $E_2 = KE_1 = KV_1$ (V_1 is approximately equal to E_1)

and $E_2 = {}_0V_2$ $\quad$ (${}_0V_2$ = No Load secondary terminal voltage)

$\therefore \quad {}_0V_2 = KV_1$

V_2 = secondary voltage on Load.

Hence difference between No load secondary voltage and on Load secondary terminal voltage is $I_2 Z_{02}$. & The approximate voltage drop of the T/F referred to secondary is found thus :-



(Fig A)

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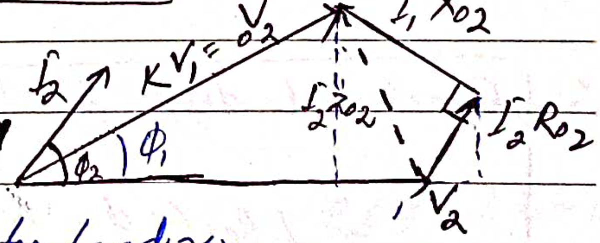
From Fig 'A' total voltage drop $I_2 Z_{02} = AC = AM$
which is approximately equal to AN
To calculate approximate voltage drop 'AN',
i) Perpendicular line on AM is drawn from point 'D'
ii) " " on AM from C and is extended downwards.
iii) Parallel line w.r.t AM from point B is drawn and it intersect extended CN to point 'L'
Now,
Approximate Voltage drop (AN) = AD + DN

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

Again where $\phi_1 = \phi_2 = \phi$ (Approx)
So $AN = I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi$ for Lagging P.F

Similarly for Leading P.F
Approximate Voltage drop $= I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi$



In general app. Volt drop $= I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi$
+ve for Lagging & -ve for Leading

Again Voltage drop referred to primary $= I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi$

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Exact Voltage Drop

From fig 'A' exact voltage drop can be calculated by adding NM to AN.

Considering right angle Δ OCN

$$NC^2 = OC^2 - ON^2 = (OC+ON)(OC-ON) = (OC+ON)(OM-ON)$$

{as OC = OM (Radius)} and $OC \simeq ON$ so $OC+ON = 2OC$

$$\Rightarrow NC^2 = 2OC \times NM$$

$\Rightarrow NM = NC^2/2OC$ Now $NC = LC - LN = LC - BD$

$$\therefore NC = I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi$$

And
$$NM = \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2 \, {}_0V_2}$$

∴ Exact Voltage drop for Lagging p.f is

$$= (I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi) + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2 \, {}_0V_2}$$

∴ Exact Vol. drop for Leading p.f is

$$= I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2 \, {}_0V_2}$$

In general Voltage drop is $= (I_2 R_{02} \cos\phi \pm I_2 X_2 \sin\phi) + \frac{(I_2 X_2 \cos\phi - I_2 R_2 \sin\phi)^2}{2 \, {}_0V_2}$

$$\% \text{ Drop} = \frac{I_2 R_{02} \cos\phi \pm I_2 X_2 \sin\phi}{{}_0V_2} \times 100 + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2 \, {}_0V_2^2}$$

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Regulation of T/F

When a T/F is Loaded with a constant primary Voltage, the secondary Voltage decreases for Lagging PF and increases for leading PF because of its internal resistance and leakage reactance.

Let ${}_0V_2$ = No Load secondary Terminal voltage
$= E_2 = EK_1 = KV_1$ because impedance drop is negligible at no-load.

V_2 = secondary terminal voltage on full Load.

Regulation of T/F is the change in secondary terminal voltage from no-load to full load ie $({}_0V_2 - V_2)$

✓ % Voltage Regulation (down) = $\frac{{}_0V_2 - V_2}{{}_0V_2} \times 100$

✓ " (UP) = $\frac{{}_0V_2 - V_2}{V_2} \times 100$

or Approximate % V.R = ~~$\frac{I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi}{V_1} \times 100 + \frac{1}{200}$~~

$$= \frac{I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi}{V_1} \times 100 + \frac{1}{2V_1}\left(I_2X_{02}\cos\phi - I_2R_{02}\sin\phi\right)^2 \times 100$$

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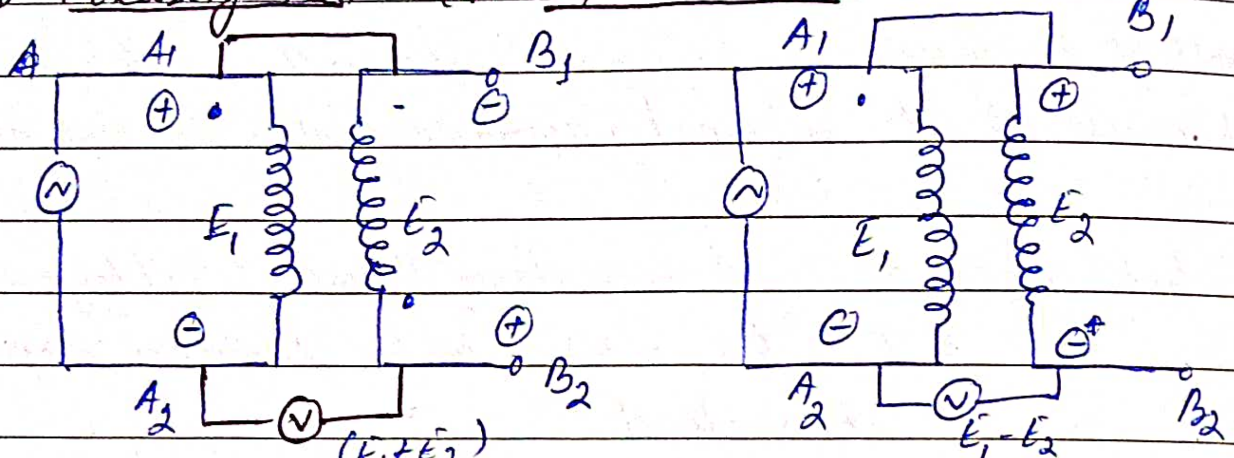
Testing of Transformer:-

(A) Polarity Test (A) DOT Notation



Terminal A1 and B1 are shorted and Voltmeter is connected across terminal A_2 and B_2 and observe the Voltmeter reading.

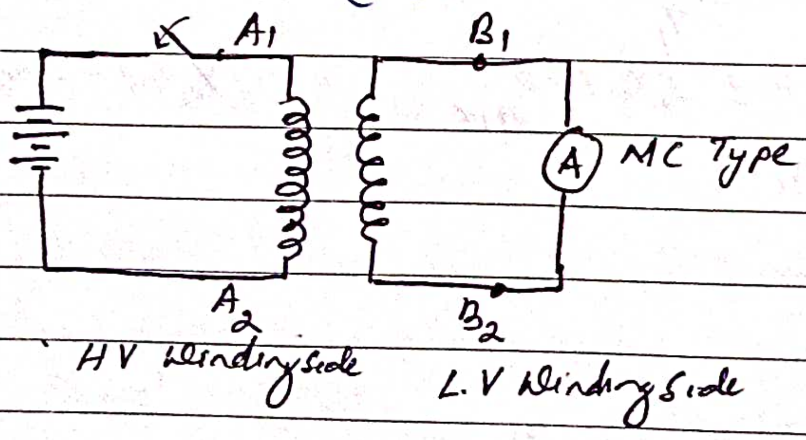
If Voltmeter Reading is

(i) $V = E_1 + E_2$ → Then series Additive polarity

ii) if $V = E_1 - E_2$ (i.e less than E_1 or E_2) then terminal are series substractive.

* Suitable for Low Voltage range only. (dot Notation)

(B) DC Kick Test



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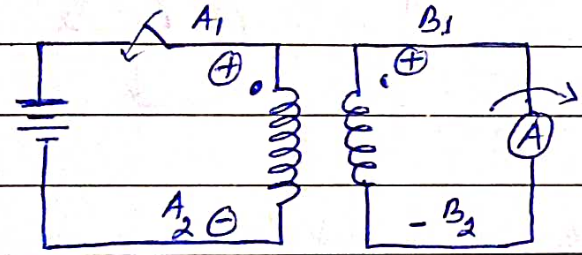
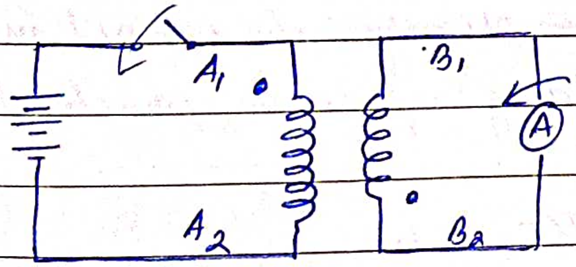
The High Voltage side winding is momentarily excitted with dc supply or dc source. H.V side is connected to dc source because there is a large value of Resistance. And ammeter is is connected at low Resistance side.

As switch is closed or during Excitation a small amount of current flows in the secondary. observe the ammeter deflection.

* If Forward kick (A) then secondary terminals are indicated with same polarities.



* If Backward kick (A) then secondary terminals are indicated with opposite polarities.



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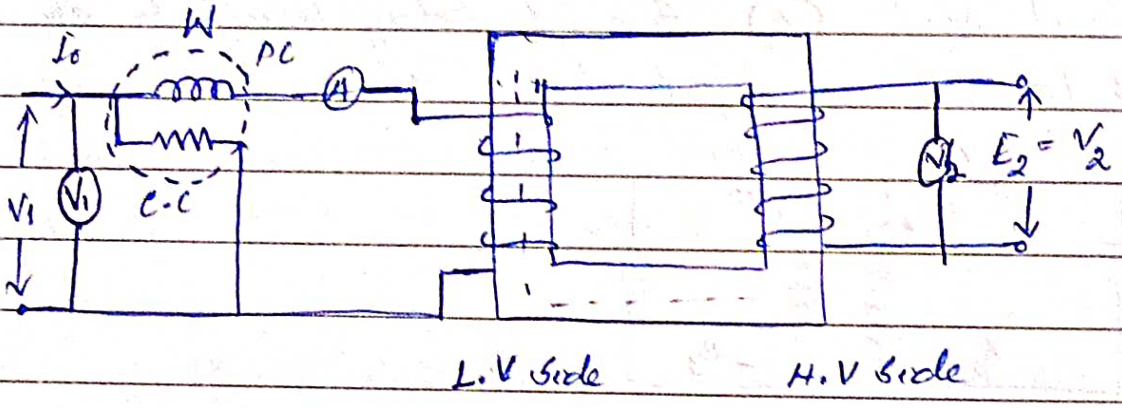
Open circuit test :-

The purpose of open ckt. test is to determine the no-load current (I_0) and losses of transformer and because of which their no load parameters R_0 and X_0 are determined.

→ This test is performed on Low Voltage side of Transformer and high voltage winding is left open and other side is connected to nominal supply. (Voltage in high voltage side is too high and cannot be measured & current is very high, which can't be measured)



Wattmeter, ammeter and Voltmeter are connected to their L.V side as shown in figure above.

The value of I_0 is very small (i.e 2-to 10% of rated Load current) so Cu. loss negligibly small in primary side and nil in secondary side. Hence the wattmeter reading represents practically the core loss under no-load.

(W) ⇒ Reads Core loss of T/F = W_0

→ As I_0 is very small, the pressure coil of wattmeter and voltmeter are connected such that the current doesn't pass through the current coil of wattmeter

→ High resistance voltmeter is connected across the secondary

(V_2) → Reads Induced emf in secondary side = E_2

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(A) → Reads No. load current 'I_0'

As. $W_0 = V_1 I_0 \cos\phi_0$ ⟹ $\cos\phi_0 = W_0 / V_1 I_0$

∴ $I_\mu = I_0 \sin\phi_0$, $I_w = I_0 \cos\phi_0$

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

As $I_0 \simeq I_\mu$ (As current is all exciting current at no-load) and voltage drop is very small.

Exciting admittance $(Y_0) = \frac{I_0}{V_1}$

" conductance (G_0) is given by $W_0 = V_1^2 G_0$ ⟹ $G_0 = \frac{W}{V_1^2}$

Exciting susceptance $B_0 = \sqrt{(Y_0^2 - G_0^2)}$

Core loss depends on the frequency and maximum flux density when volume and the thickness of core laminations are given & const.

Core loss = Hysteresis Loss (W_h) + Eddy current Loss (W_e)

⟹ $= \eta B_{max}^x f V + K B_{max}^x f^2 t^2$

⟹ $W_i = Af + Bf^2$

$$\Rightarrow \frac{W_i}{f} = A + Bf$$

Short-Circuit or Impedance Test.

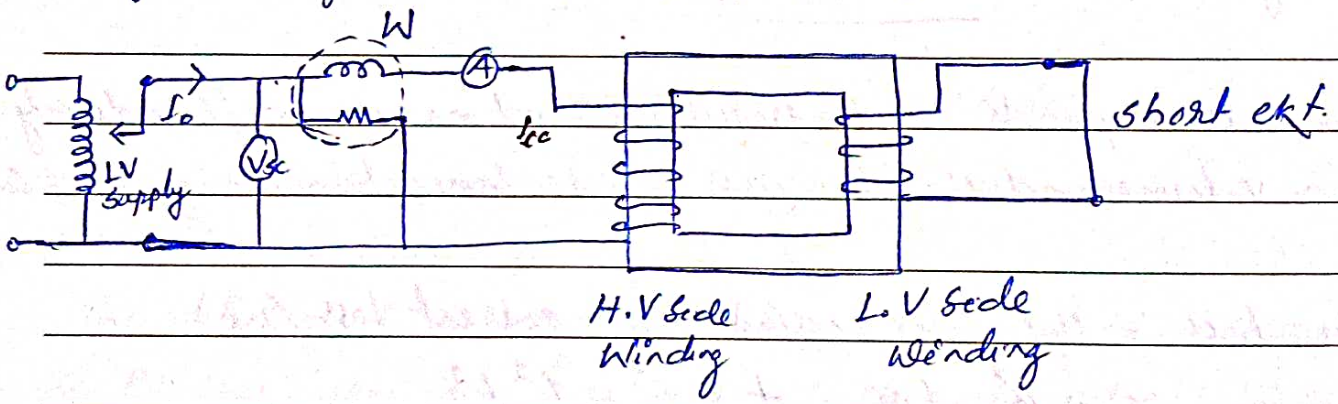
The economical method for determining

i) Equivalent impedance (Z_{01} or Z_{02}) Leakage reactance (X_{01} or X_{02}) and total resistance (R_{01} or R_{02})

ii) To find variable loss i.e cu loss at full load and Efficiency

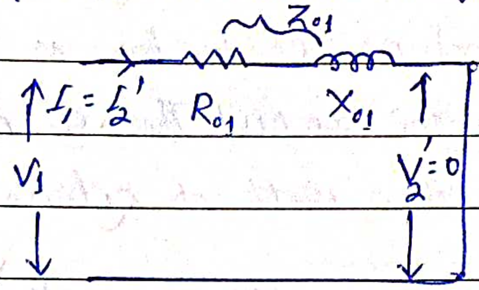
-) This test is performed on the secondary winding side i.e High Voltage side

Wattmeter, Voltmeter and ammeter are connected to the high voltage side as shown below.



A low voltage (usually 5 to 10% of normal primary voltage) at correct frequency is applied and is continuously increased till full load current are flows in both primary & secondary side indicated by respective Ammeter.

As applied voltage is small percentage of normal voltage the mutual flux ϕ is also small and hence core loss is very small. The result that the wattmeter reading represent the full load cu. loss or I^2R loss. of whole T/F. Equivalent circuit under short ckt. can be drawn as fig.c



W_{sc} = Wattmeter Reading or I^2R loss

V_{sc} = Voltmeter Reading or voltage required to circulate rated load current

I_{sc} = Ammeter Reading or Rated full load current

As $W_{sc} = I_{sc}^2 R_{01}$ $\Rightarrow$ $R_{02} = \dfrac{W_{sc}}{I_{sc}^2} = \dfrac{\text{Wattmeter Reading}}{(\text{Ammeter Reading})^2}$

$V_{sc} = I_{sc} \times Z_{01}$ $\Rightarrow$ $Z_{02} = \dfrac{V_{sc}}{I_{sc}}$

then

$X_{02} = \sqrt{(Z_{02}^2 - R_{02}^2)}$ $\qquad R_{01} = \left(\dfrac{N_1}{N_2}\right)^2 R_{02}$

Why Transformer Rating in KVA ?

* As cu loss of a T/F depends on current and iron loss on voltage i.e total loss depends on volt-ampere (VA) and not on phase angle between voltage and current. That is why rating of T/F is in KVA and not in kWatt.

*

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Efficiency of Transformer :-

The efficiency of a T/F at a particular Load and power factor is defined as the output devided by the input. The two being measured in the same units (either watt or kilowatt)

$$\text{Efficiency}(\eta) = \frac{\text{output (kW)}}{\text{Input (kW)}} = \frac{\text{output}}{\text{output} + \text{Losses}}$$

Though T/F being efficient piece of equipment, has very small loss, hence it is impractical to try to measure efficiency by measuring input & output.

* A better method is to determine the losses & then to calculate efficiency.

$$\eta = \frac{\text{output}}{\text{output} + \text{Losses}} = \frac{\text{output}}{\text{output} + \text{Cu. Loss} + \text{Iron Loss}}$$

$$= \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{Losses}}{\text{Input}}$$

* Cu. Loss can be calculated from short circuit test
* Iron loss or core loss from open circuit test.

$$\eta_{FL} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$ Referred to Primary

$$\eta_{FL} = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + \underset{(I_2^2 R_{02})}{\text{FL Cu loss}} + \underset{(W_i)}{\text{Iron Loss}}} \times 100$$

$$\eta_{x \text{ of FL at given PF}} = \frac{x \times \text{Full Load KVA} \times P.f}{(x \times \text{Full load KVA} \times P.F) + x^2(I_2^2 R_{02}) + W_i} \times 100$$

where x = Ratio of actual to full load KVA

Condition for Max. Efficiency :-

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

for η to be maximum $\frac{d\eta}{dI_1} = 0$

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

$$\Rightarrow \frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \Rightarrow W_i = I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

$\therefore$ **Cu. loss = Iron Loss**

To get maximum efficiency cu. loss of a T/F must be equal to core loss (Iron loss) or constant Loss.

All day Efficiency :-

All day efficiency means the power consumed by the transformer throughout the day.

$$\text{All day Efficiency } (\eta_{all\,day}) = \frac{\text{Output in KWh}}{\text{Output} + \text{losses}} \quad (\text{for } 24 \text{ hours})$$

All day efficiency can track the performance of distribution T/F

⇒ **Load corresponding to Max. Efficiency**

Let 'x' be the ratio of actual to full load at which efficiency is maximum.

We know the condition for max efficiency is Cu. loss = Iron loss

Hence.

Cu. loss at x of F.L = Iron Loss

$$\Rightarrow x^2 I_2^2 R_{02} = W_i$$

$$\Rightarrow x = \sqrt{\frac{W_i}{I_2^2 R_{02}}} \quad \text{i.e} \quad \boxed{x = \sqrt{\frac{\text{Iron Loss}}{\text{FL Cu. Loss}}}}$$

$$\boxed{\text{Load KVA for } \eta_{max} = \text{F.L KVA} \times \sqrt{\frac{\text{Iron Loss}}{\text{F.L. Cu Loss}}}}$$

Variation of Efficiency with Power Factor :-

$$\eta = 1 - \frac{\text{Loss}}{\text{Input}} = 1 - \frac{\text{Losses}}{V_2 I_2 \cos\phi_2 + \text{Losses}}$$

Let Losses/$V_2 I_2$ = y then

$$\eta = 1 - \frac{\text{Losses}/V_2 I_2}{\cos\phi_2 + \text{Losses}/V_2 I_2} = 1 - \frac{x}{\cos\phi_2 + x}$$

$$\Rightarrow \boxed{\eta = 1 - \frac{x/\cos\phi_2}{1 + x/\cos\phi_2}}$$

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Parallel operation of Transformer

* If two or more transformer are connected to a same supply on the primary side and to a same load on the secondary side, then it is called as parallel operation of transformer.

Necessity of Parallel operation :- (Need)

1) Increased Load :- Necessary to supply the increased load when Load exceeds the capacity of existing Transformer.
2) Non Availability of Large T/F :- When a large transformer is not available to meet the total requirement of load, then two or more small T/F are connected in parallel.
3) Increased reliability :- ~~If~~ Any ~~T/F~~ ~~got~~ fault T/F can can be taken for maintenance uninterrupting to serve the load.
4.) Transportation is easier for small T/F :- If installation site is located far away, then transportation is easier ~~for~~ and economical for smaller units.

Conditions for parallel operation of T/F :-

1) The line voltage ratio of two T/F must be equal.
2) The per unit impedance of each T/F ~~must~~ should be equal and they should have same ratio of equivalent leakage reactance to the resistance. (X/R)
3) The T/F should have same secondary winding polarity.
4) " " " " phase sequence.
5) The " " the zero relative phase displacement between secondary line voltage (3∅ T/F)

Desir(able) ← 2)

Necessary ← 3)

Auto - Transformer

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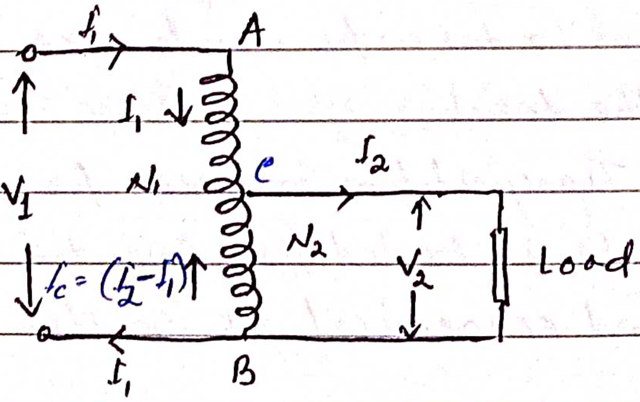
A transformer in which a part of the winding is common to both the primary and secondary circuit is called an Auto-transformer.

→ In Auto-transformer the primary and secondary winding are not electrically isolated from each other as in case of two-winding Transformer.

Principle of operation :-

The principle of operation is same as that of common transformer. It works on the principle of Faraday's law of Electromagnetic - Induction.

AB is the primary winding having N_1 turns and BC is the secondary winding having N_2 turns



$N_1 : N_2$

[Fig (2)]

*Neglecting iron losses and No load current

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

As current in primary and secondary are practically in phase opposition and I_2 is greater than I_1. So (Lenz's Law)

So Common Current $(I_c) = I_2 - I_1$

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* Saving of Cu. (Comparing Auto-transformer with two winding Transformer)

In case of stepdown T/F as shown in Fig-(i), $K < 1$

Volume and hence weight of Cu. is proportional to the length and area of the cross-section of conductor

Length of conductor $\propto$ Number of turn (N)

& Cross section $\propto$ current (I)

$\therefore$ Weight $\propto$ Product of current and Number of turn (i.e NI)

Referring figure-(i)

Total weight of Cu. in Auto T/F (W_a) $\propto$ weight of Cu in section AC + weight of Cu in section BC

$$\Rightarrow W_a \propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1) \quad \text{--- eq (1)}$$

Total weight of Cu. in two winding T/F (W_o) $\propto$ weight of Cu. in Primary Side + Weight of Cu. in secondary side

$$\Rightarrow W_o = N_1 I_1 + N_2 I_2 \quad \text{--- eq}^n (2)$$

from Eq^n (1) and Eq^n (2)

$$\therefore \frac{\text{Wt. of Cu. in auto. T/F}}{\text{Wt. of Cu. in Ordinary T/F}} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$= \frac{N_1 I_1 + N_2 I_2 - N_2 I_1 - N_2 I_1}{N_1 I_1 + N_2 I_2} = 1 - \frac{2 N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{2 N_2 I_1 \times \frac{1}{N_1 I_1}}{(N_1 I_1 + N_2 I_2) \frac{1}{N_1 I_1}} = 1 - \frac{2 \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1} \times \frac{I_2}{I_1}}$$

$$= 1 - K \quad \left[\text{as } \frac{N_2}{N_1} = K \text{ and } \frac{I_1}{I_1} = K\right]$$

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i.e. $\boxed{\dfrac{W_a}{W} = 1-K}$ or $\boxed{\dfrac{\text{Wt of Cu. in Auto T/F}}{\text{Wt. of Cu. in Ordinary T/F}} = 1-K}$

∴ Weight of Cu. in Auto T/F = $(1-K)$ Weight of Cu. in Ordinary Transformer

Saving = $W_o - W_a$ = $W_o - (1-K)W_o$

⇒ $\boxed{\text{Saving} = KW_o}$

* Saving of Cu. will increases as 'K' approaches unity (1)

⇒ The power transformed inductively = $(1-K)$ Input

⇒ Rest Power = $K \times$ Input is conducted directly from the source to load i.e it is transferred conductively to the load.

Uses of Auto-transformer :-

1) It is used as a starter to give 50 to 60% of full voltage to starter of a squirrel cage induction motor during starting
2) It is used to give a small boost to a distribution cable to correct the voltage drop.
3) It is used as a Voltage Regulator
4) Used as interconnecting T/F in 132 KV/330 KV power system.
5) Used in control equipment for 1ϕ and 3ϕ electrical locomotives.

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Tap changer with Transformer.

The change of voltage in affected by changing the number of the transformer provided with taps. For efficiently close control of voltage, tap are usually provided on the high voltage winding of the T/F.

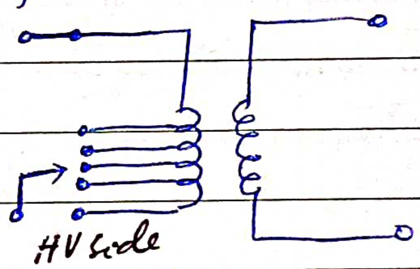
Type of tap-changing T/F

a) Off-Load tap changing T/F

b) On-Load tap changing T/F

a) OFF-Load tap changing T/F :-

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



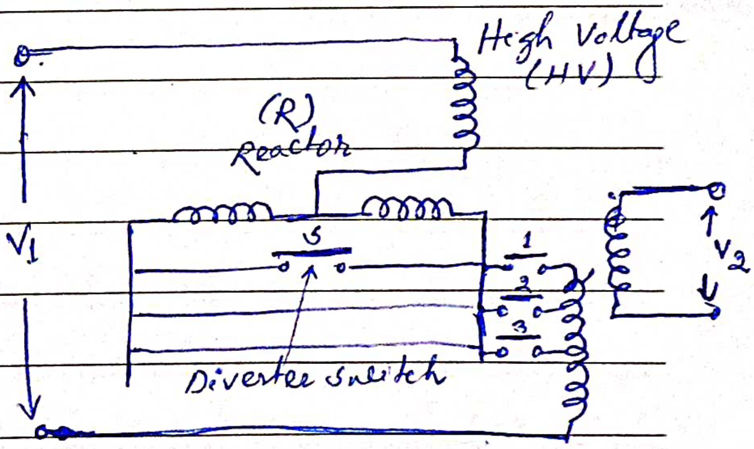
[OFF-Load tap changing T/F]

b) ON-Load tap changing T/F

On load tap changing is used to supply uninterrupted power supply. While tapping, two essential conditions are to be filled

(i) The Load circuit should not be broken to avoid arcing and prevent the damage of contacts.

(ii) No part of the winding should be short-circuited while adjusting the tap.



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The transformer is in operation with switch-1 and 3' closed. To change to tap 2, switch 3' is opened and 2 is closed. Switch 1 is then opened, and 3' is closed to complete the tap change. It is to be noted that the diverter switch operates on load and no-current flows through selector switch 3' during tap changing. During the tap change only half of the reactance which limits the current is connected in the circuit.

THREE PHASE TRANSFORMER

Mo Tu We Th Fr Sa Su

Date / /

Even though most of the equipments are connected by the single phase transformer, but these are not preferred for large power distribution in aspect of economy. The 3ϕ power is used in almost all field of electrical power system such as power generation, transmission and distribution. Therefore 3ϕ T/F is used to step-up or step-down the voltage in 3ϕ system.

→ 3ϕ T/F is smaller and lighter in construction for the same power handling capacity and better operating characteristics

⇒ In order to reduce the power loss to the distribution end, the power is transmitted at higher voltage (132KV or 400KV) with 3ϕ T/F and again to step down at transmission and distribution end to level of 6600V, 400V, 230V. etc

* Due to single 3ϕ T/F amount of iron in the core and insulation materials are saved.

Construction :-

A 3ϕ T/F can be constructed by using common magnetic core for both primary & secondary winding. This can be of a bank of three ϕ core type T/F (3-core type single phase T/F are combined). Similarly a bank of 3ϕ shell type T/F (3 shell type single phase are combined)

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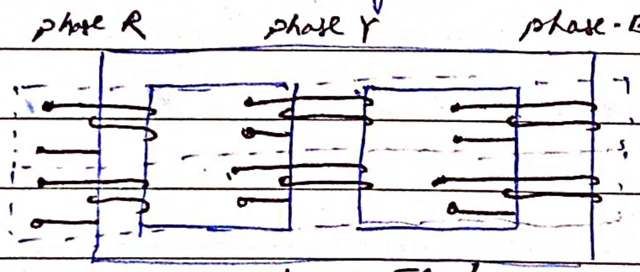
a) Core type

Core of 3ϕ T/F is made up of three limbs or leg & two yokes. Magnetic path is formed between these Yokes and limbs. on each limb both primary and secondary windings are wounded concentrically.

→ Circular cylindrical coils are used as the winding.

→ Both winding (primary & secondary) of one phase are are wound on one leg.

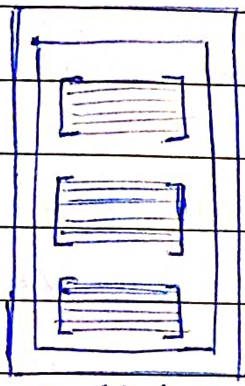
→ Under balanced condition, the magnetic flux in each phase of the leg adds up to zero. Therefore, under normal condition, no return path (leg) is needed. But in unbalanced load, high circulating current flows and hence it may be best to use three single phase T/F.



[core type T/F]

(b) Shell type

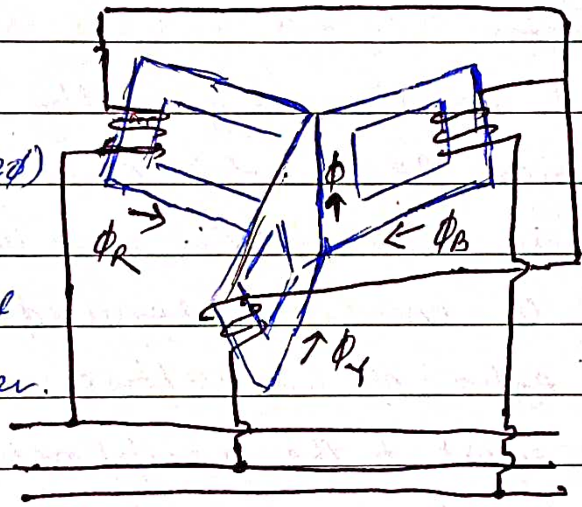
in shell type, 3ϕ are more Independent because each phase has independent magnetic circuit compared with core type T/F. It is same as single phase shell type T/F. The magnetic circuit are in parallel. Due to this, the saturation effects in common magnetic paths are neglected. However shell type constructed T/F are rarely used in practice



Shell type

Working :-

Consider a transformer (3φ) is connected in star fashion. The 3 core are arranged at an angle of 120° to each other.



When primary is excited with 3φ supply source, the current I_R, I_Y and I_B starts flowing individual phase winding. These produces flux ϕ_R, ϕ_Y and ϕ_B. Since centre leg is common, the sum of all three core flux are carried by it. But in three phase balance system the sum of all the current is zero, so flux is also zero. Hence the centre leg doesn't carry any flux at any instant. So on removal of centre leg, it makes no difference in other condition of T/F.

So if centre leg of T/F is removed, then any two conductors, or leg acts as return path of the flux for third leg.

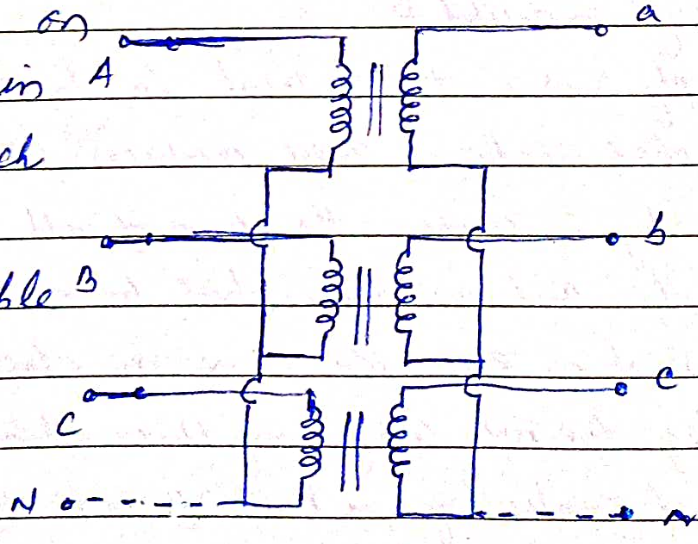
3-ϕ T/F connection

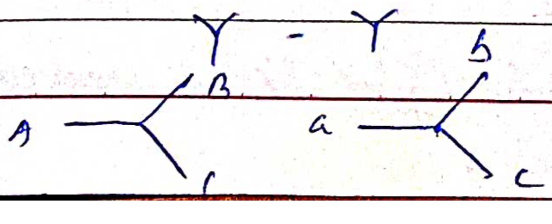
~~On the basic~~ Winding of a three phase T/F can be connected in various configuration as

i) Star-Star (Y-Y) ii) Delta-delta (Δ-Δ) iii) Star-delta (iv) delta-star (v) open delta and (vi) scott connection

(2) Star-Star (Y-Y)

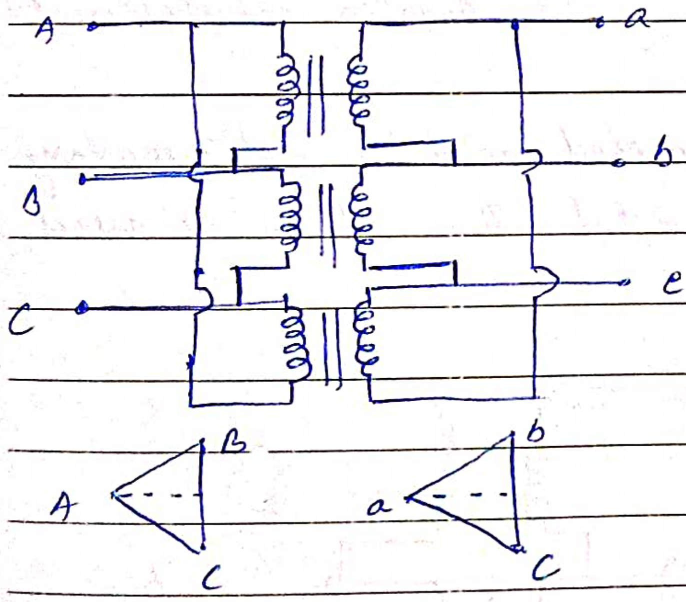
- Y-Y connection is generally used for small, high-Voltage transformer. Because of Y connection, number of required turn/phase is reduced (as phase voltage is $1/\sqrt{3}$ times of line voltage) so insulation required is also reduced.
- The ratio of line voltage on the primary and secondary side is equal to the transformation ratio of the transformer.
- Line voltage on both side are in phase with each other.
- This is suitable for balanced load only.





(ii) Delta - Delta (Δ - Δ)

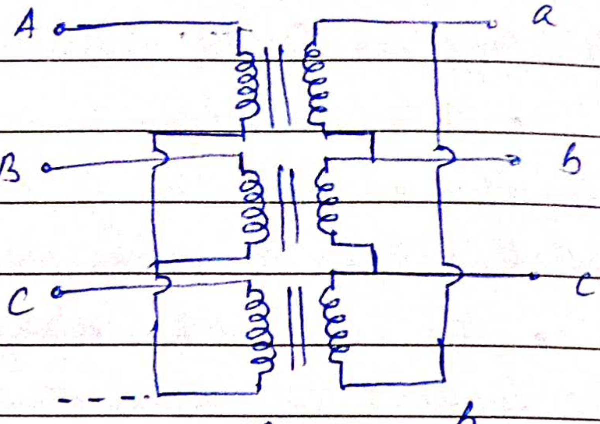
- This connection is generally used for large, low-Voltage transformers. Number of turns/phase is relatively greater than that for star-star connection
- The ratio of line voltage on primary and secondary side is equal to the transformation ratio.
- This can be used even for unbalanced loading.
- This can be operated in open delta connection, if one transformer is disable, but with reduced capacity.

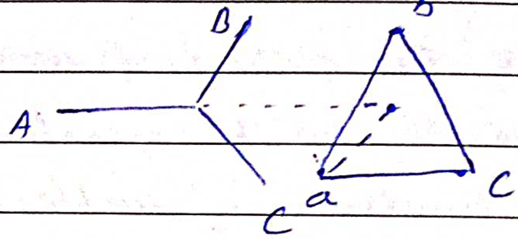


(iii) Star - Delta (Y - Δ)

- The primary winding is star (Y) with ground neutral and secondary winding is delta connected.
- This is used in step-down transformer at the sub-station end of the transmission line

- The ratio of secondary to primary line voltage is $1/\sqrt{3}$ time of transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

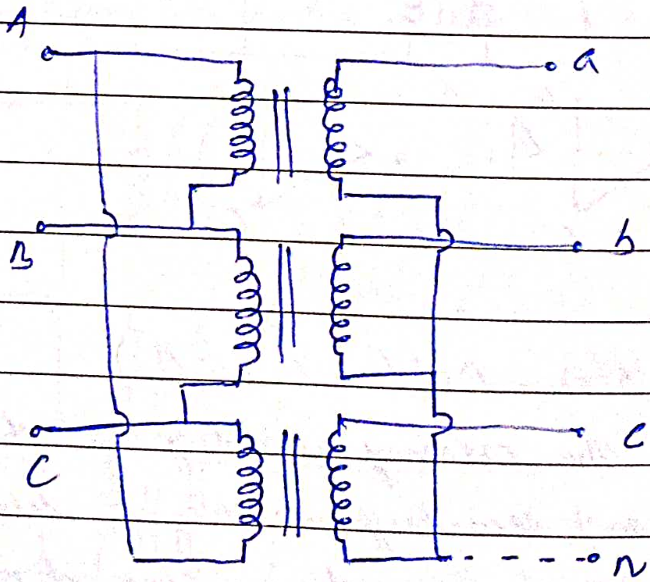




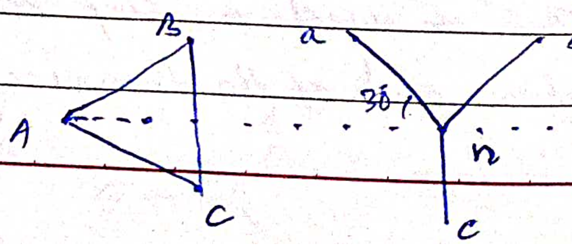
(30° Angular displacement)

(iv) Delta-star (Δ-Y)

- The primary winding is connected in delta and secondary is star with neutral grounded. Thus it can be used to 3ϕ 4wire service.
- This type of connection is mainly used in step-up transformer at the begining of transmission line.
- Ratio of secondary to primary line voltage is $\sqrt{3}$ times the transformation ratio.



- There is 30° shift between primary & secondary line voltage.



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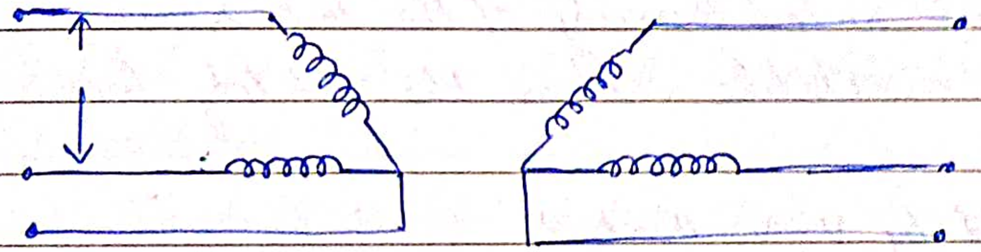
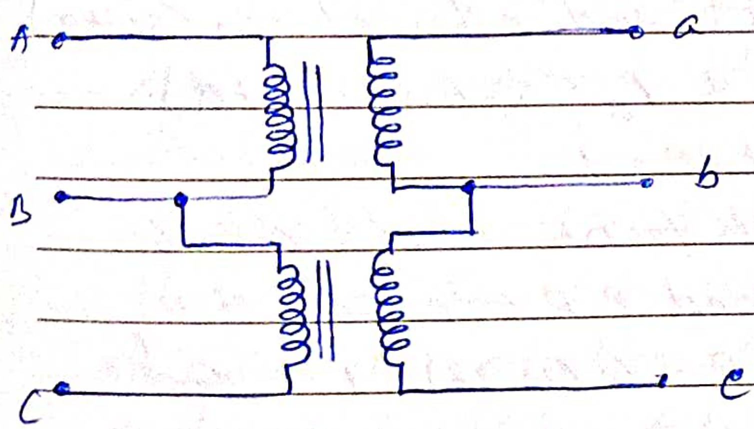
(V) Open Delta

Open delta transformer uses only two winding of primary and secondary and transform a 3ϕ Voltage. It is not used commonly. Typically used for small load where cost is important. Alternatively they could be used as an emergency measure, should one winding only of a transformer fail.



(Primary Connection) (Secondary Connection)



Power delivered ≈

in delta connection

I_L (Line current) $= \sqrt{3}\, I_{ph}$

$V_L = V_{ph}$

Power O/P $= \sqrt{3}\, V_L I_L$

$= \sqrt{3}\, V_L \sqrt{3}\, I_{ph}$

open delta

$I_L = I_{ph}$

$V_L = V_{ph}$

Power O/P $= \sqrt{3}\, V_L I_L$

$= \sqrt{3}\, V_L I_{ph}$

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$$\frac{V\text{-}V \text{ Capacity}}{\Delta\text{-}\Delta \text{ Capacity}} = \frac{\sqrt{3}\, V_L I_{ph}}{3\, V_L I_{ph}} = 0.577 \text{ or } 57.7\%$$

* open delta will only deliver 57.7% of the power of conventional T/F (not 2/3 i.e 66.7% as may be expected)

OR

Only 86.6% of rated capacity of the two remaining transformer is available. It is the utility factor

Power supplied by V-V Bank :-

When a V-V bank of two T/F supplies a balanced 3-ϕ load of power factor $\cos\alpha$ then one T/F operates at a P.F of $\cos(30-\alpha)$ and other at $\cos(30+\alpha)$.

$P_1 = KVA \cos(30^\circ - \alpha)$ & $P_2 = KVA \cos(30 + \alpha)$

1)* When $\alpha = 0^\circ$ i.e load PF = 1

Each T/F has power factor $\cos 30^\circ = 0.866$

* (ii) When $\alpha = 30^\circ$ i.e load P.F = 0.866

One T/F will have P.F = $\cos(30-30) = 1$ and

other " " " = $\cos(30+30) = 0.866$

* iii) When $\alpha = 60^\circ$ i.e load PF - $\cos 60^\circ = 0.5$

One T/F will have P.F = $\cos(30-60^\circ) = 0.866$ &

other " " = $\cos(30+60) = 0$

i.e second T/F will not supply any load and first one will supply entire load.

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Use of open delta connection :-

- used for small 3-ϕ load.
- used where the current load is less and may increase in future
- There is no shifting in output, so can be used for unbalanced load and where harmonics are involved.

Parallel Operation of 3ϕ Transformer :-

Conditions

i) The line voltage ratio of the transformer must be same.

ii) The transformers should have equal per unit leakage impedance

iii) The ratio of equivalent leakage reactance to equivalent resistance should be same for all the transformers.

iv) The transformers should have the same polarity.

Along with these four condition which are applicable for parallel operation of 1ϕ T/F, two more condition should be fulfilled for parallel operation of 3ϕ T/F.

(v) The relative phase displacement between the secondary line voltage of all transformers should be zero. This means that transformers to be connected in parallel must belongs to same group like Yy0 and Dd0

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vi) The phase sequence of secondary line voltages of all the transformers should be same

Maintenance of Power Transformer

Maintenance is done at regular interval for trouble free operation and to prevent breakdown of transformer from service.

There is a check list of maintenance point being carried out as per time duration of daily, monthly, 3 month, 6 months, yearly, once in 2 years and once in 7 to 10 years.

a) Daily checkpoint :-

1) Chek oil level of main conservator and OLTC tank. It should be as per specified level.

2) Chek oil leakage from any point of T/F.

3) Chek oil level in bushing, and temperature of oil and winding whether they are normal or not

(b) Monthly Chek Point

1) Check oil level in oil cap under silica gel breather and breathing holes in silica gel

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breather and clean properly if required.
silica gel breather is blue in colour if its colour is pink then replacement or heating of silica gel is required.
2) Check oil level in buchholz relay.

c) Check point for 3 months interval is
1) Check for dust deposition on bushing and tightness of oil filling plug and examine the crack in porcelain discs.
2) Check for cooling fan and lubricate for bearing if required.

(d) Yearly check point is
1) Check the insulation of Transformer Oil.
2) Check mechanical function of Buchholz relay.
3) Check resistive value of earth connection (< 1 ohm)

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Q1. For a 5kVA 400/200V, 50Hz. T/F
open circuit test : 400V, 1A, 60Watt ← Low Voltage R_0, I_0 & iron loss
Short circuit test : 15V, 12.5A, 50Watt [Primary] ← High Voltage
find (i) R_0 & I_0
(ii) Equivalent winding resistance & leakage reactance refered to primary.
(iii) Iron & Copper losses at full load
(iv) Efficiency at full load with PF at 0.8
(v) Regulation at full load with PF at 0.8

Ans OC test

$V_{oc} = V_1 =$ Voltmeter reading $I_0 =$ Ammeter reading or No load current

Iron loss (W_i) = Wattmeter reading.

$V_{oc} = V_1 = 400V$, $I_0 = 1A$, $W_i = 60 Watt = V_1 I_0 \cos\phi_0$

$\therefore I_0 \cos\phi_0$ (workful component of No Load current) or I_w $= \frac{W_i}{V_{oc}}$

$\Rightarrow I_w = \frac{60}{400} = 0.15 A$

$\therefore I_M = \sqrt{I_0^2 - I_w^2} = 0.988 A$ (Magnetizing Component)

$R_0 = \frac{V_{oc}}{I_w} = \frac{400}{0.15} = 2666.66 \Omega$

$X_0 = \frac{V_{oc}}{I_M} = \frac{400}{0.988} = 404.8 \Omega$

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Short Circuit (secondary)

$V_{sc} = 15\,V$, $I_{sc} = 12.5\,A$, $W_{sc} = 50$ Watt

$R_{02} = \frac{W_{sc}}{I_{sc}^2} = \frac{50}{12.5^2} = 0.32\,A$ $I_{2FL} = \frac{kVA}{V_2} = \frac{5\,kVA}{400} =$

$Z_{02} = \frac{V_{sc}}{I_{sc}} = \frac{15}{12.5} = 1.2\,\Omega$

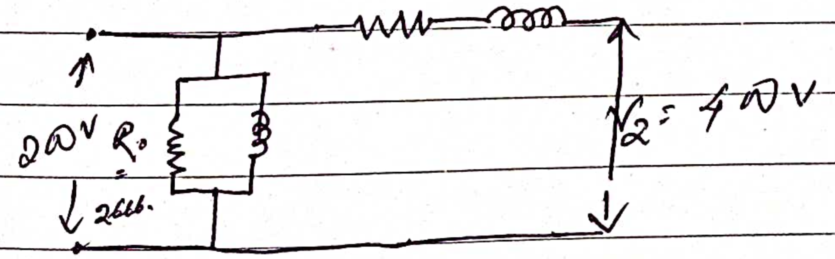
$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{1.34} = 1.56\,\Omega$

Refered to Primary

$R_{01} = \left(\frac{N_1}{N_2}\right)^2 R_{02}$ or $\frac{1}{K^2} R_{02} = \frac{1}{2^2} \times R_{02} = \frac{1}{4} \times 0.32$

$R_{01} = 0.8\,\Omega$

$X_{01} = \frac{1}{4} \times 1.56 = 0.39\,\Omega$



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DC Machine

- Machine
  - Static (T/F)
  - Rotating (Electromechanical conversion principle)
  - Linear operating M/c
- DC Machine
- Advantages
- Application

Machine is The device which reduces our effort to accomplish a job/work.

Rotating E.M. (Electromechanical conversion of Energy)

- Motor: Electrical Energy → Mech. Energy
  - AC
  - DC ✓
- Generator: Mech. E → Elect. Energy
  - AC
  - DC ✓

Depending upon the type of winding the DC machine both Motor & generator are divided into

DC Machine

- Self Excited DC M/c
- Separately Excited DC. M
- Permanent Mag DC Machine

Application & Advantages

↳ 1) At lower speed it can provide higher torque & vice versa.

App. – Blowers, RC Drone (Brushless), Elevators or Crane (cst. speed & torque)
Robotics (servo, stepper motor), Electric Locomotive

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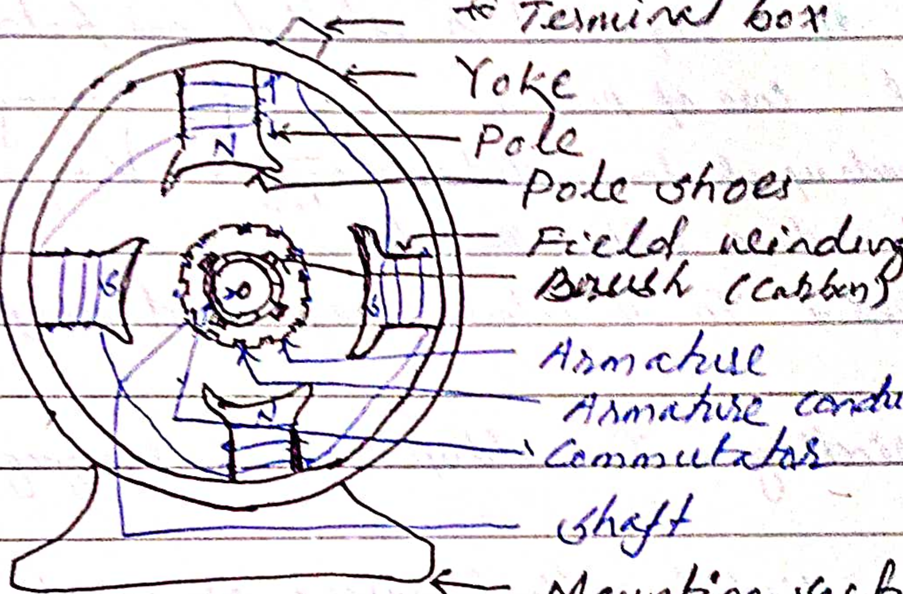
DC Generator - Converts mechanical energy to electrical energy and it is of direct current nature
Use :- Electroplating, electric arc, electric welding

Construction (DC Gen & DC Motor)



DC generator can be used as dc motor & these work on electromechanical conversion of energy.
[construction wise no change depending upon permanent magnet motor or brush less type]

Construction of d.c machine

Stator section (stationary)   Rotor section (Rotating part)

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Yoke : Outermost part of machine. It provides protection from external condition
- Must be form low reductance path (to create path for mag. flux)

Pole : It is required to establish mag. field. & distribute it. core of pole is made up of laminated sheet to reduce eddy current loss.

Pole shoes : To distribute mag. field uniformly

Field winding : To buildup pole by supplying the current

Brush : Used to collect current or supply current to armature wire. It is made up of carbon or graphite

Armature core : The system or portion on which armature winding is done. It is laminated

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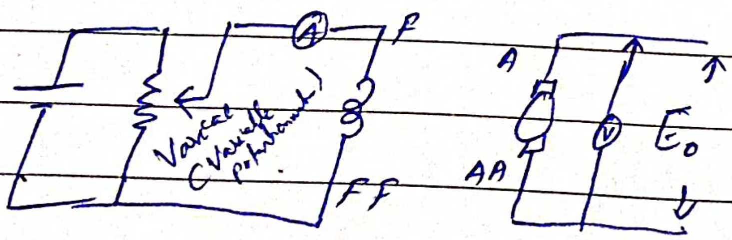
Characteristics of DC Generator

Separately Excited:

1) Open circuit characteristics (OCC) E_0 Vs I_f / N = cst.
   No load characteristics or magnetisation characteristics
2) Load characteristics V_t Vs I_f / I_a = cst. N = cst.
3) External characteristics V_t Vs I_a / N = cst.
4) Internal characteristics E_g Vs I_a / N = cst.
5) Regulation characteristics I_f Vs I_L / V = cst. N = cst.

→ First two characteristics field current is varied other remaining / keeping cst. so this can be done in case of separately exited dc generator. And other is in case of self Excited.

① OCC



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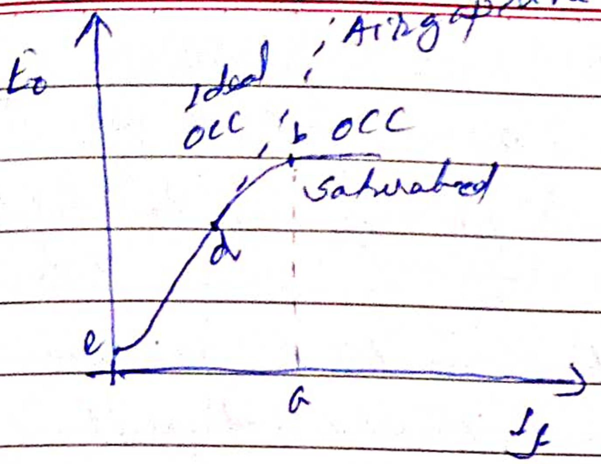
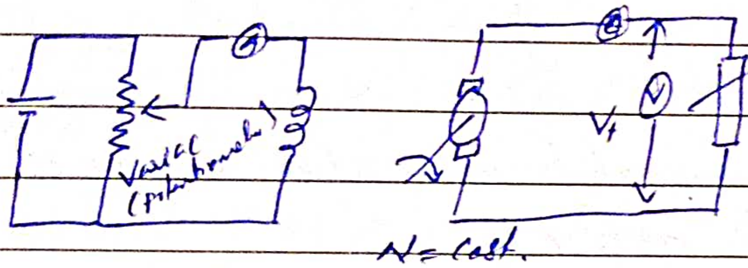


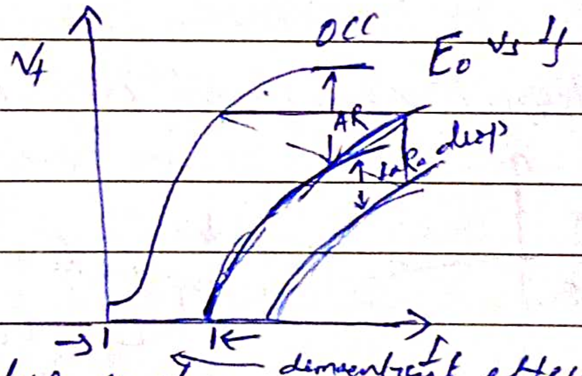
Due to the residual magnetism even though the field current is zero some emf will be induced.

② Load characteristics. I_a = const.



{ Voltage drop
A.R drop
I_aR_a drop

I_f	V_t



As I_a is const so AR & I_aR_a drop is const.

As I_a is const. so Armature reaction is const. So the OCC curve will shift downwards. This shift is due to demagnetising

→ or value of I_f required to overcome the demagnetising effect of armature reaction.

There is one more I_aR_a drop so it drops further downward and it is const. as I_a is const.

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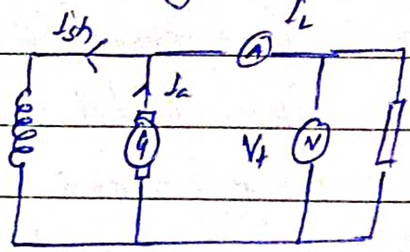
(3) Shunt Generator



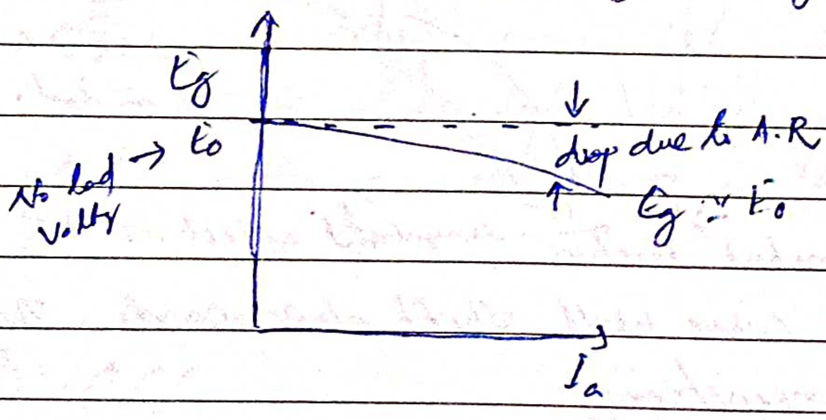
Different currents are

$I_{sh} = \frac{V}{R_{sh}}$, $I_a = I_L + I_{sh}$
$\approx I_L$

Diff. drops are due to armature reaction, (2) $I_a R_a$ drop (3) due to 1st & 2nd effect automatically drop in terminal voltage happens. When this happens I_{sh} decreases (as $I_{sh}\downarrow = \frac{V\downarrow}{R_{sh}}$) or further extend drop to decrease in I_{sh} or f_f

As V_t decreases the generated emf also decreases this is cummulative action.

(2) Internal characteristics E_g Vs I_a / N = cst.



* E_0 is not constant as in case of ~~OP~~ No load characteristics because armature reaction depends on armature current (I_a)

So. E_g will go on decaying with I_a

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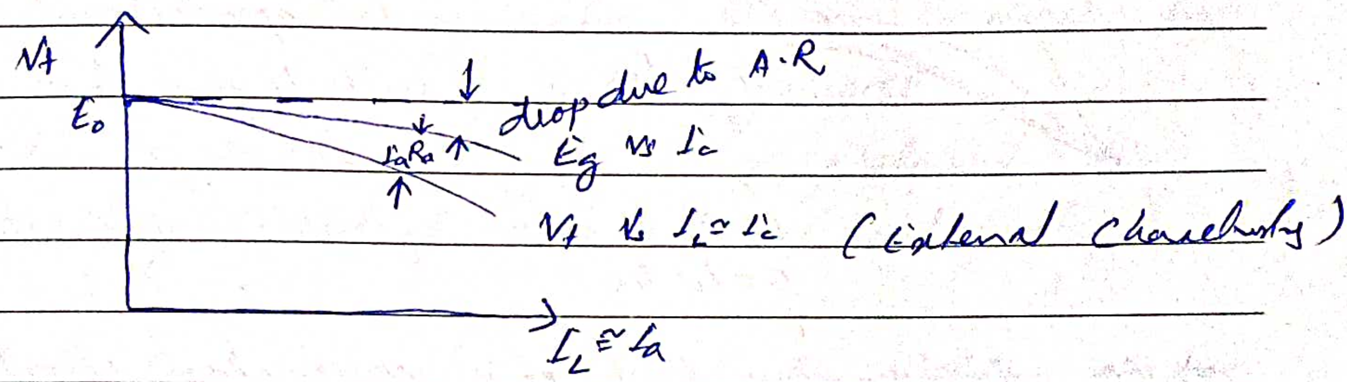
(4) External characteristics



So from above two we can say that

$E_g = V_t + I_aR_a$

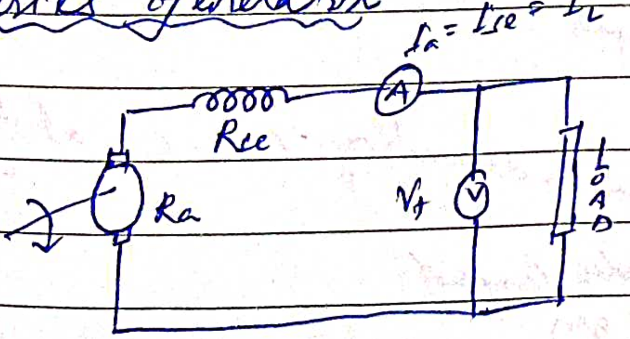
No load Voltage → $E_0 = V + I_aR_a$ + drop due to A.R

⇒ Characteristics of shunt generator is drooping characteristics

⇒ Shunt generator can be considered as const. flux & const. voltage machine. (Voltage drops from No-load to full load is very less)

Application :- used as voltage source for lighting
as an exciter in alternator (dc field)

Series Generator

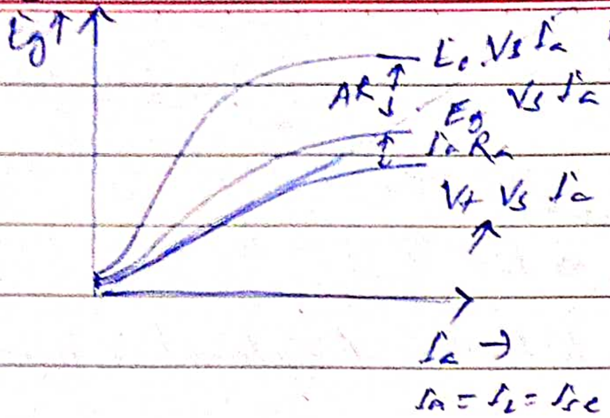


$E_g = \frac{\phi Z N}{60} \times \frac{P}{A}$

or $E_g \propto \phi$

or $\propto I_a$

(ii) Internal characteristics $R_f = R_{se} + R_a + R_L$



We can say OCC because under open circuit nothing will be generated as $I_{se} = 0$

⇒ So we can say that it is of rising characteristics
* As load increases the terminal voltage will increases

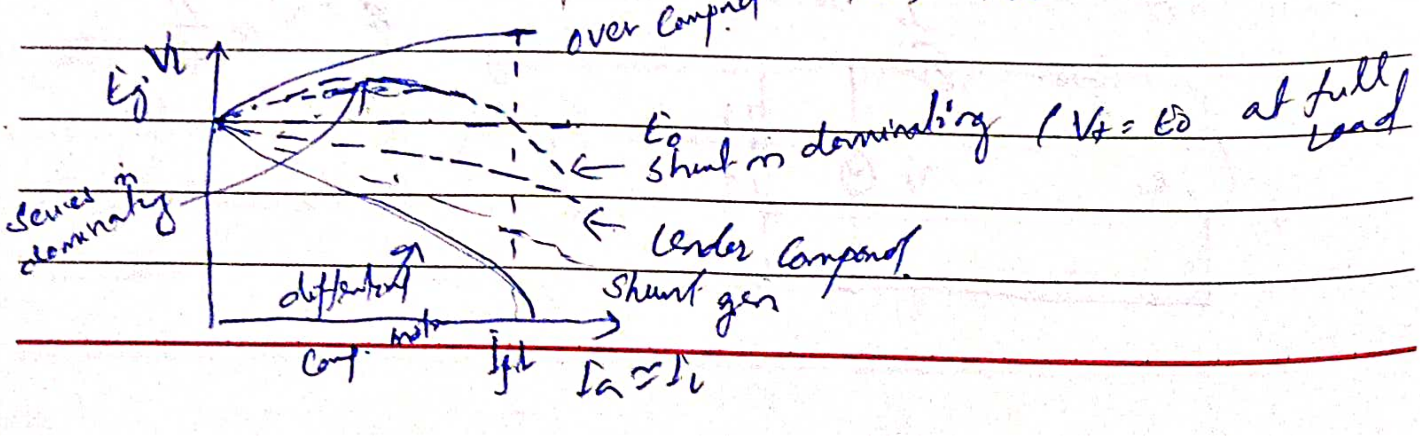
Application : used as voltage buster

* R_a & R_L are also included in field circuit resistance so $R_{se} + R_a + R_L$ should be less than critical field resistance then only we can generate some emf

Compound Generator (series + shunt field coil)

cummulative compound (ϕ) = $\phi_{sh} + \phi_{se}$ — over compound / flat compound / under compound

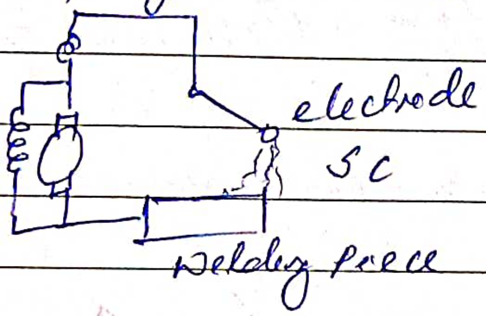
Differential ,, = $\phi_{sh} - \phi_{se}$



Application

* Cummulative Comp. generator can be used for Voltage sources for lighting purpose.
* Flat & level comp. gen. are prefered for exciting field of alternator. (field exciter)

* Diff. Comp. generator is used for welding purpose.



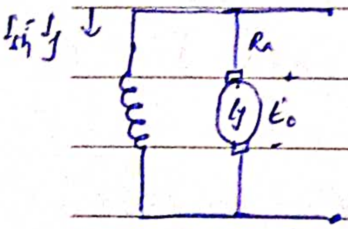
As Load ↑ ⇒ V_t ↓

When V_t drops automatically the E_g (generated emf drops) hence ϕ_2 decreases (I_a ↓)

Because of this the current (s.c. ckt) will be come down to limited range of generator & it doesn't damages the generator.

Voltage Build up

* Voltage buildup depends on the presence of residual flux in the pole of generator.



(Shunt Gen.)

E_o initial is due to residual flux

i.e $E_{o_{res}} = k\,\phi_{res}\,\omega$ ($\simeq$ 1-2 volt)

$\uparrow I_f = \frac{E_{o\,res}}{R_f} \rightarrow \phi \uparrow$ (initial I_f was zero)

The flux must be greater than residual flux so.

$\rightarrow E_o \uparrow$

$\hookrightarrow V_t \uparrow$

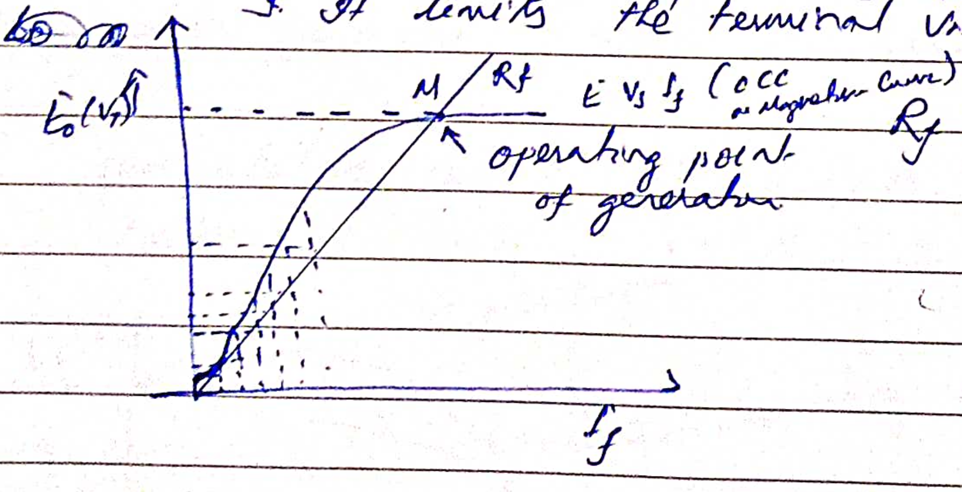
$\hookrightarrow I_f = \frac{V_t}{R_f}$

$\hookrightarrow \phi \uparrow$

Loop

(E_o is almost equal to V_t)
open ckt. or No load

* flux will increase up to its saturation point & It limits the terminal voltage.



$R_f = \frac{V_T}{I_f}$ (linear graph) as $E_O \simeq V_T$

E_o & I_f increases simultaneously steady state.

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Why no voltage build up in shunt gen.

1) There may be no residual flux.

Ans → Connecting the field to an external dc circuit (It is called as flashing of field)

(2) The direction of rotation might be reversed. or field connection could have been reversed.

$\leftarrow \phi_{res}$

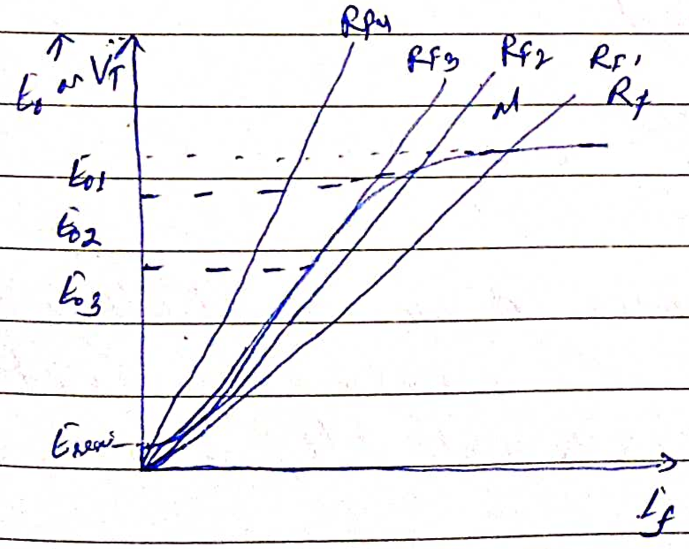
$\overrightarrow{\phi_{field}}$

Ans → Either reverse the direction and check again or reverse the field connection.

(3) The field resistance (R_f) might be more than the critical field resistance ($R_{f\,critical}$) [$R_f > R_{f\,critical}$]

Ans →

Operating point is the intersection between magnetisation curve & field resistance line (R_f line)



$R_{f3} > R_{f2} > R_{f1}$

$E_{03} < E_{02} < E_{01}$

At R_{f3} the value of E_0 changes significantly with change in R_f or I_f

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If R_f is increased beyond R_{f_3} then the voltage is only residual one & no voltage build up occurs.

* We concluded that for any value of $R_f > R_{f_3}$ (critical field resistance) voltage will not build up because the operating point is just at residual voltage.

Voltage Regulation

Change in the terminal voltage of a generator between full and no load (at const. speed) is called the voltage regulation, usually expressed in % of the voltage at full load.

$$\% VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where V_{NL} = Terminal voltage of generator at no-load
V_{FL} = Terminal voltage at full load.

* Lesser the V.R the generator's V.R is good and more V.R indicates the poor voltage stability

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⇒ Series DC Generator is having poor voltage generator i.e
% V.R is more.

⇒

V.R = V.R can be defined as the change in terminal voltage from no load to full load expressed in term of full load at const. speed.

1) Over Comp. DC generator $V_{FL} > V_{NL}$
2) Under Comp. " $V_{FL} < V_{NL}$
3) level or flat " $V_{FL} = V_{NL}$

Sequence of V.R :-

Series > Differential > Over Comp. > Shunt > Separately > Under > flat or level
↓ +ve poorest V.R, -ve, +ve, +ve, +ve, Zero
-ve poorest V.R (As characteristics is rising i.e V increases with load)

Parallel operation of DC Generator

Why or Benefits of parallel operations.

a) Efficiency is increased :- DC generator perform best or very well at full load or near to full load. When load increases, ~~At light load~~ various dc gen. are connected in parallel in order to improve efficiency (η)

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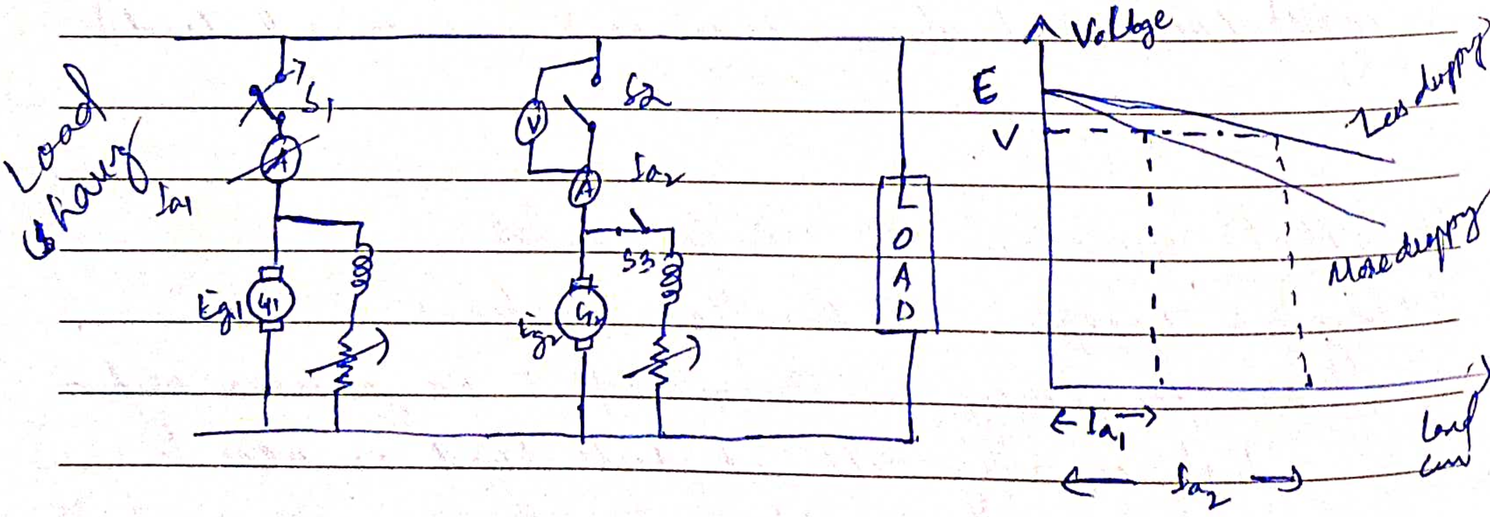
b) Maintenance & Repairs :- Maintenance is very essential for any m/c so inorder to avoid interruption, the maintenance & repair of m/c can be performed.

c) Reliability or continuity of supply :- continuity of power supply can be maintained.

d) Addition demand can be fullfilled according to requirement by connecting Generator in parallel

* ~~condition of parallel~~

Parallel operation of DC shunt Generator.



→ The generator having more drooping charateristic will share less loading & vice versa.

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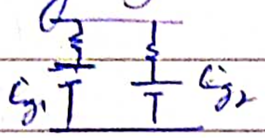
* Condition for parallel operation

1) The terminal voltage of both the generator must be equal. To make equal voltage we need to vary the field current.
If voltmeter reads zero reading, both the generator are at same potential.

2) The polarity of incoming gen. must be same as the polarity of existing gen.

3) 

In case of shunt DC gen

1) The prime mover of G_2 is brought to the rated speed.
2) ~~Close the~~ field excitation is varied or adjusted to get voltage as G_1 (I_f changed) (by S_3)
3) Then close the switch S_2
4) Gradually increase I_f of G_2 till it supplies the required load. $I_2 = \frac{E_2 - V}{R_2}$

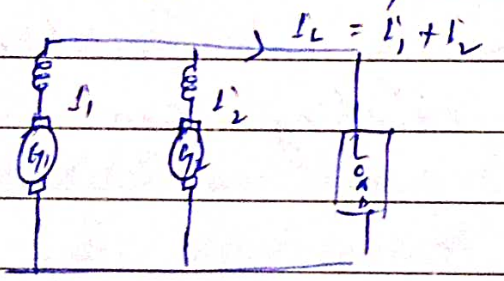
* To increase the load sharing of any generator we have to increase the field of that particular generator.

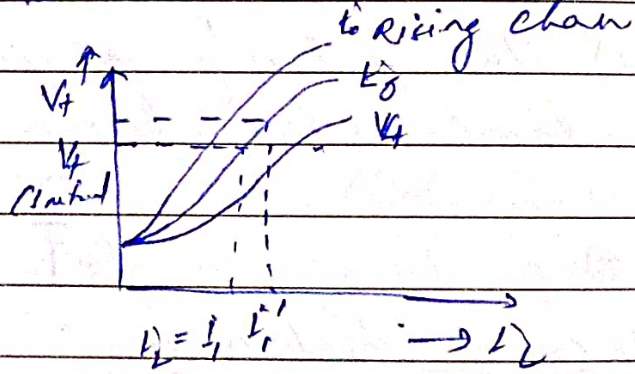
* Decrease field current of generator which has to share less load.

⇒ Shunt & Comp. Generators are used for power supply

* Series DC Generator

→ Used in railway for regenerative braking or to stop the train.





$N_1 = N_2$

$E_{g1} = E_{g2}$

$I_1 = I_2$

Suppose the load increases & $E_{g1} > E_{g2}$ (Rise) then

$I_1 > I_2$ so as I_2 decreases $E_{g2} \downarrow$

$I_{f1} > I_{f2} \downarrow$ & $E_{g1} \uparrow > E_{g2} \downarrow$

Because of this the generator may spoil or damaged

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DC MOTORS

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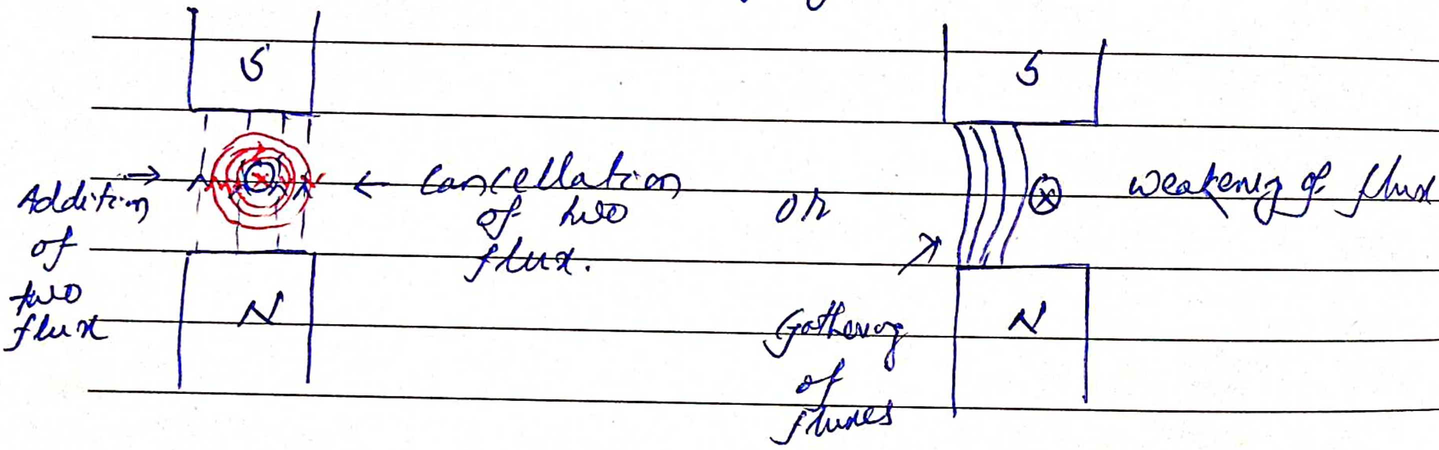
Working Principle :-

When a current carrying conductor is placed in a magnetic field, it experiences a mechanical force.

- flux is created by a field winding.
- Armature winding plays a role of current carrying conductor.



* Force is experienced from high flux density to low flux density.

Direction of Rotation of Motor.

Magnitude of the force experienced by conductor (armature) is given as

$F = BLI$ Newton

Where B = Mag. flux density produced by field winding

L = Active length of conductor

I = Mag. of current carried by conductor

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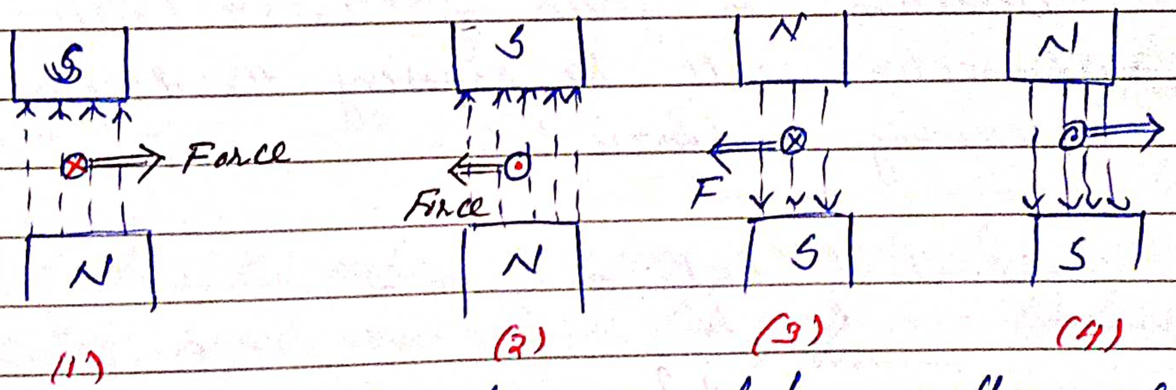
This force is a vector quantity & its direction is determined by Fleming's left hand Rule (LHR)

Fleming's left hand Rule (LHR) :-

The rule states that, out stretch the three finger of the left hand namely the first finger/point finger, middle finger & thumb such that they are mutually perpendicular to each other. Now the point finger in the direction of magnetic field and the middle finger in the direction of current then the thumb gives the direction of the force experienced by the conductor.



To reverse the direction of rotation either of main field produced by the winding is reversed (case 1, 3) or direction of the current passing through armature is reversed (case 1, 2)

Back EMF (E_b)

Once motor starts rotating its conductor will cut the magnetic flux produced by field winding. So by Faradays law of electromagnetic induction emf is induced in the armature coil of dc motor just like in case of dc generator and called as back emf

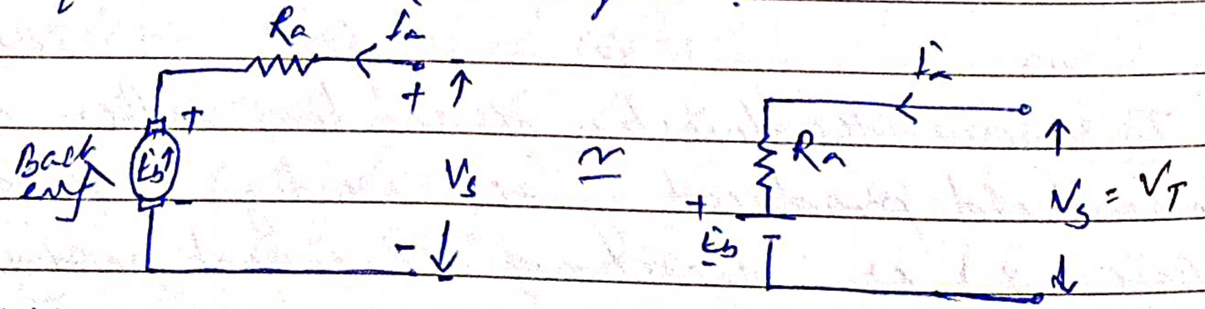
* Back emf is generated by the generating action (moving conductors cutting the magnetic flux)

i.e $\boxed{E_b = \dfrac{Z P \phi N}{60 A}}$. Emf eq^n of motor.

Direction is given by Lenz's Law.

⇒ Direction will be opposing the supply voltage according to Lenz's Law.

Equivalent ckt. diagram :-



Voltage Eq^n

$$V_T = I_a R_a + E_b + V_{brush}$$

V_T = Supply voltage I_a = Armature current

R_a = Armature resistance E_b = back emf V_{brush} = Brush drop

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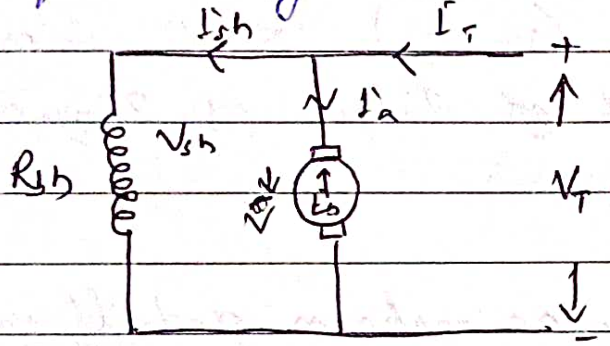
$$I_a = \frac{V_T - E_b}{R_a}$$ V_T & R_a are constant. (V_S or V_T)

Significance of back emf

* DC m/c is a self regulating machine because of back emf.
* It enables the dc motor to draw as much armature current as is sufficient to develop the torque required by the load.



V_T = supply voltage.
R_{sh} = shunt field resistance
I_{sh} = shunt current

(DC shunt motor)

Now

$$I_a = \frac{V_T - E_b}{R_a}$$ or $I_a \propto E_b$ {As V_T & R_a are const/Fixed}

Case I (When DC motor is running on no-load)

* The torque required is less. [Torque depends upon I_a]

$$I_a = \frac{V_T - E_b \uparrow (1st)}{R_a}$$ As m/c is running at no load the machine starts rotating freely or at high speed so E_b increases. Hence $(V_T - E_b)$ decreases & I_a decreases. finally torque decreases or adjusted to required torque.

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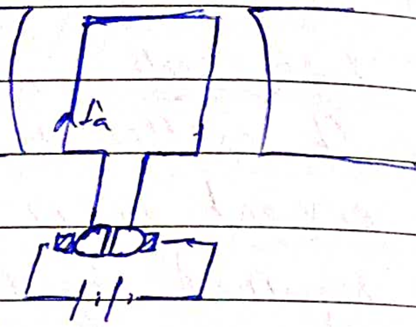
Case-2 (When a DC motor is suddenly loaded)
*Torque required to drive load increases.



If load increases then speed of rotation decreases then E_b reduces

$$i_a = \frac{V_T - E_b \downarrow (1st)}{R_a}$$

This results decrease in $(V_T - E_b)$ & i_a increases and results in increase of Torque as Torque depends on i_a

Case-3 When the load on DC motor is gradually reduces [~~Full load to~~ Torque required will decreases gradually.

$$I_a = \frac{V_T - E_b}{R_a}$$

i) Speed gradually decrease as load decreases gradually so $E_b \uparrow$

As $E_b \uparrow$ the term $(V_T - E_b)$ decreases & I_a decreases and results gradual decrease in torque.

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Condition for max power Developed / output in DC Machine

Gen * The dc generator will delever maximum power when the terminal voltage (V_T) is half of the emf.

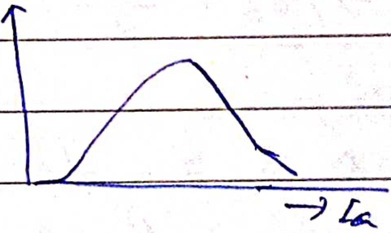
Generator

$$I_a = \frac{E_a}{2R_a}$$

$$V_T = E_a - I_a R_a = E_a - \frac{E_a}{2R_a} R_a$$

$$\boxed{V_T = \frac{E_a}{2}}$$

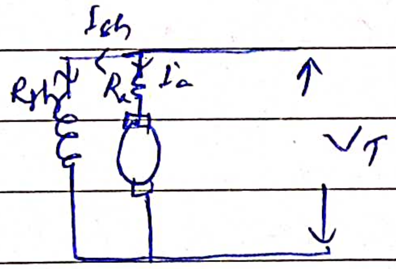
* $$\eta = \frac{P_{out}}{P_{in}} = \frac{V_T I_a}{E_a I_a} = \frac{V_T}{E_a} = \frac{V_T}{2V_T} = \frac{1}{2} = 50\%$$



* If all conditions are taken (losses) the η will be less than 50%.

DC Motor

$$E_b = V_T - I_a R_a \quad \text{— (1)}$$



$$P_{dev} = E_b I_a \quad \text{— (2)}$$

i.e. $E_b I_a = V_T I_a - I_a^2 R_a$ — (3)

Cond For maximum power delevered, $\frac{d}{dI_a}(P_{dev}) = 0$

$$\Rightarrow \frac{d}{dI_a}(P_{dev}) = \frac{d}{dI_a}(V_T I_a - I_a^2 R_a)$$

$$\Rightarrow 0 = V_T - 2I_a R_a$$

$$\Rightarrow \boxed{I_a = \frac{V_T}{2I_a}} \quad \text{— (4)}$$

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Putting the value of I_a from eq(4) in eq(1)

$$E_b = V_T - \frac{V_T}{2R_a} R_a$$

$$\Rightarrow E_b = V_T - \frac{V_T}{2}$$

$$\Rightarrow \boxed{E_b = \frac{V_T}{2}} \quad \text{or} \quad E = \frac{V}{2}$$

* In a dc motor power developed is maximum when the Back EMF (E_b) is half of the supply or terminal voltage.
* $\eta < 50\%$
* $I_a = \frac{V_T}{2R_a}$

Torque Equation of DC motor :-

⇒ The turning or twisting force acting on a body about an axis is termed as Torque (T_o)

or

⇒ Torque is a qualitative measure of tendency of a force to cause rotational motion in a machine

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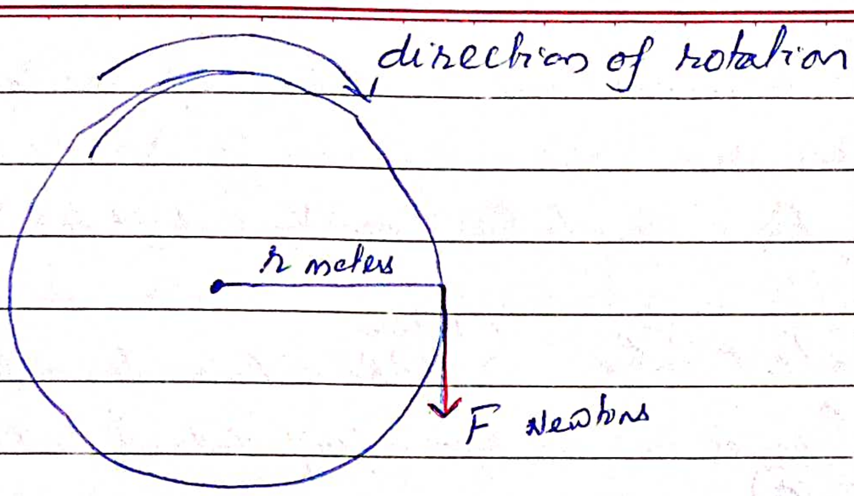

Let us assume that a motor is running in clock wise direction as shown above with an angular velocity of ω rad/sec

Where $\omega = 2\pi f$

Where
f = frequency & $f = \frac{1}{T}$
N = rpm ∴ 60 sec → N revolution
Time for 1 revolution = $\frac{60}{N}$
i.e $T = 60/N$
& $f = \frac{N}{60}$

Now we can say

$\omega = \frac{2\pi . N}{60}$

We know that the torque produced in a given machine can be given as $\tau = F \times r$ —— eqn (3) Nm force x displacement

or work done in one revolution $W = $ Force × distance covered

$W = F \times 2\pi r$ (Circumference

The mechanical power developed by the motor is given by

$P_{out} = \frac{\text{work done}}{\text{time}} = \frac{F \times 2\pi r}{60/N}$

$= F.r \times \frac{2\pi N}{60}$ or $\tau_a \times \omega$

$$P_{out} = \tau_a \times \frac{2\pi N}{60}$$ —— eqn (4)

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~~For~~ Now the electrical input power of DC machine can be given as

We know $E_b = V_T - I_a R_a$ or $V_T = E_b + I_a R_a$

$\Rightarrow V_T I_a = E_b I_a + I_a^2 R_a$ { Where $I_a^2 R_a$ = Power loss in form of heat

↑ power in armature [Neglected as ideal case]

$P_{in} = E_b I_a$ — (B)

{ or $P = VI$ & Voltage in armature is E_b & I in I_a

$\therefore$ Eqn (A) = Eq (B)

Power in Armature = Gross armature torque × ω

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

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

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

$$\Rightarrow \boxed{T_a \propto \phi I_a}$$ As Z, P, A & 2π are const.

$$\Rightarrow \boxed{T_a = 0.159 \times \frac{\phi Z P I_a}{A}}$$ Nm. Armature torque developed in a dc motor.

Imp

* Practically the mechanical power developed in the armature is transmitted to the load through the shaft of the motor.

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* It is impossible to transmit the entire power developed by the armature to the load because while transmitting the power through shaft, the power losses occurses due to friction, windage and iron core or iron loss.

* The torque required to overcome this loss is called as loss torque (T_L) or called as stray loss of the motor.

⇒ The torque available at the shaft for doing the useful work is known as load torque or shaft torque & denoted as T_{sh} or T_{sh}

$\therefore T_a = T_L + T_{sh}$ or $T_a = T_L + T_{sh}$

Hence $T_{sh} \times$ Angular Speed (ω) = Power available at shaft of motor.

or $T_{sh} = \frac{\text{output}}{\omega}$

$\Rightarrow T_{sh} = \frac{\text{output}}{2\pi N/60}$

$\Rightarrow T_{sh} = 9.55 \times \frac{\text{output}}{N}$

1) N Vs. I_a
2) T Vs. I_a } Electrical characteristic
3) N Vs T } Mechanical

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Characteristics of DC Series Motor.

(a) Speed ~ Armature current (N Vs. I_a)

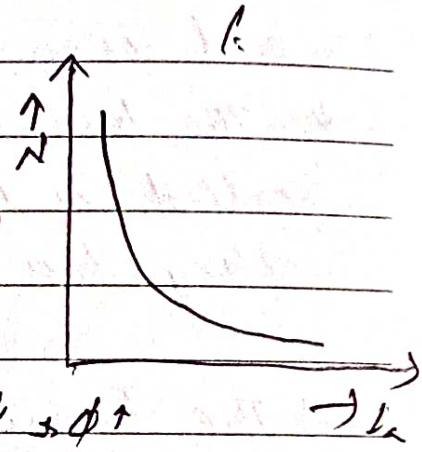
As we know $E_b = \frac{2\phi N}{60} \times \frac{P}{A}$

or $E_b = K\phi N$

* $I_a R_a$ drop is neglected. So E_b is cost.

So $N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$

$\therefore N \propto \frac{E_b}{\phi}$ — (1)

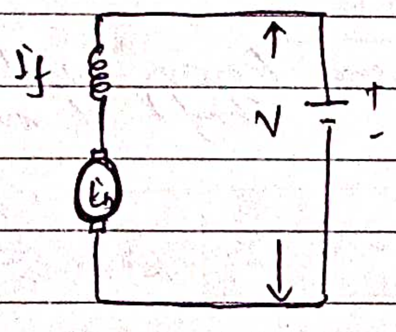


Again & $E_b = V - I_a R_a$

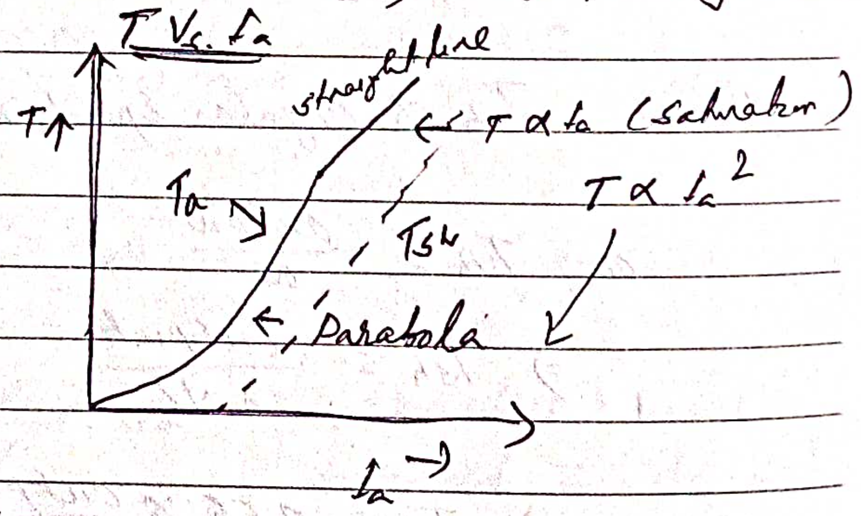
$Power_{o/p} = \frac{2\pi NT}{60}$ $E_b\downarrow$ & $\phi\uparrow$

$\Rightarrow T = 0.159\,\phi Z I_a \frac{P}{A}$ — (3)

$\Rightarrow T \propto \phi I_a$ — (2)   & $\phi \propto I_f$



(b) T Vs. I_a



As $T_{sh} = T_a - loss.$

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~~(B) Speed Vs I_a~~

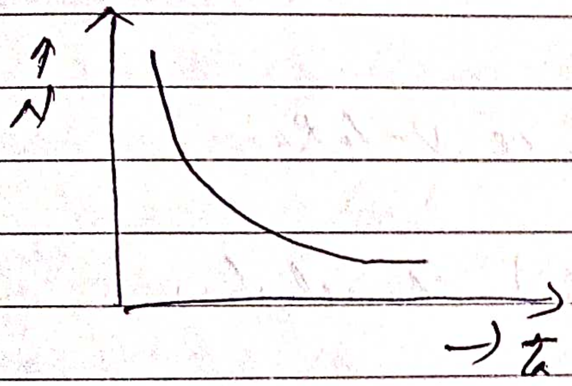
(c) Speed Vs. Torque

As we know $N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$ — (A)

And $T \propto \phi I_a$ or $T \propto I_a^2$ — (B)

∴ from A & (B) we can write

$N \propto \frac{1}{\sqrt{T_a}}$



observation

⇒ When ~~speed~~ torque is less speed is extremely high. Because of this reason the series motor shouldn't be operated under no-load.

⇒ $T \propto I_a^2$: $N \propto \frac{1}{I_a}$ & $P \propto NT$

Amount of extra power required to start with high torque is very less i.e. size in power is less.

Application :- High starting torque (locomotive or train)

Hoist, electric trains, cranes etc.

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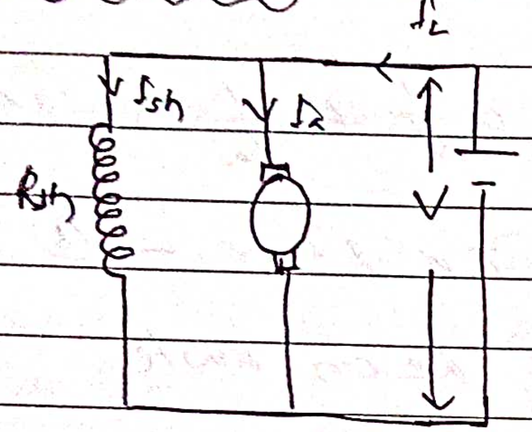
shunt motor.



$I_{sh} = \frac{V}{R_{sh}}$ ← cst (V), ← cst (R_{sh})

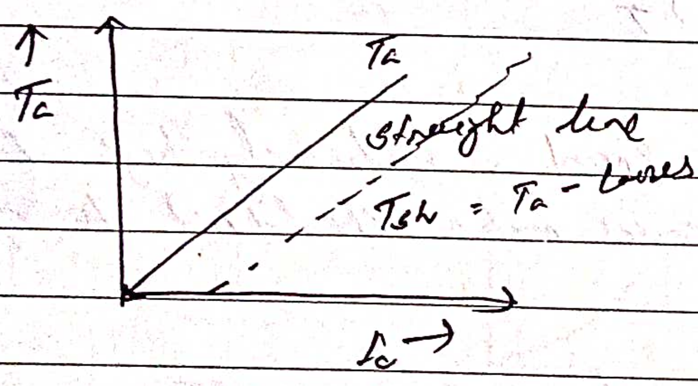
i.e ϕ is constant

I_a will vary.

$T_a \propto \phi I_a \Rightarrow T_a \propto I_a$

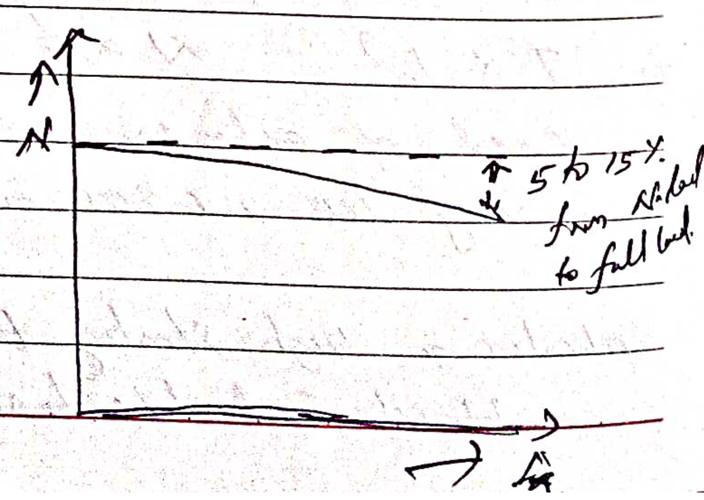
$N \propto \frac{E_b}{\phi} \Rightarrow N \propto E_b$ i.e $V - I_a R_a$

a) Torque (T) & Armature (I_a) characteristics



b) speed (N) Vs I_a

$N \propto E_b$ or $V - I_a R_a$



✓ Const speed motor

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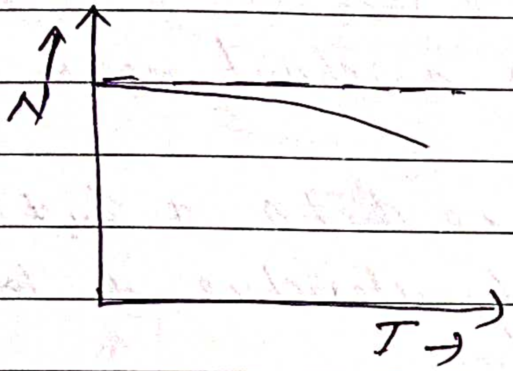
c) Torque (T) Vs Speed (N)

As $T \propto I_a$ so we can replace I_a by T_a



observation :-

1) Speed regulation is very less. / M/C can operate at No-Load condition.

application

Machine tools, lathe machine, wood working m/c

Reciprocating pump. fans. { Const speed (Approximately) can be used upto 1.5 FL

blowers & fans { Uses- Lathe M/c, Centrifugal Pumps, machine tools

Disadvantages :- $T \propto I_c$ (Series motor produces more torque)

Compound motor.

→ Cummulative = $\phi_{se} + \phi_{sh}$

→ Differential = $\phi_{sh} - \phi_{se}$

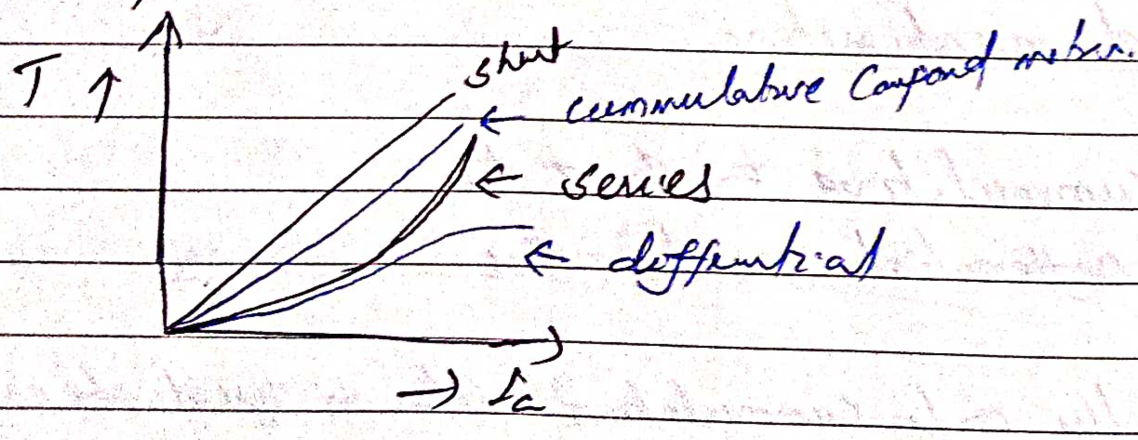
Practically only cummulative motor is used because it has the characteristics of both series & shunt motor.

(c) cummulative C motor ($\Phi_{sh} + \Phi_{se}$)

* At no-load $I_a = 0$ i.e $\Phi_{se} = 0$ & $\Phi_{sh} \neq 0$
  ∴ works as a shunt motor.

* ~~For~~ Full load $I_a \neq 0$ i.e $\Phi_{se} \neq 0$ & $\Phi_{sh} \neq 0$
  It combines the characteristics of both series & shunt motor.
  1) As load increases then the series field will starts dominating the ~~field~~ shunt field as $\Phi_{se} \propto I_a$

Application :- 1
Where there is so much fluctuation in there in the load. ~~Eg~~
2) Used in Electric shovels, Metal-stamping etc compressor etc.



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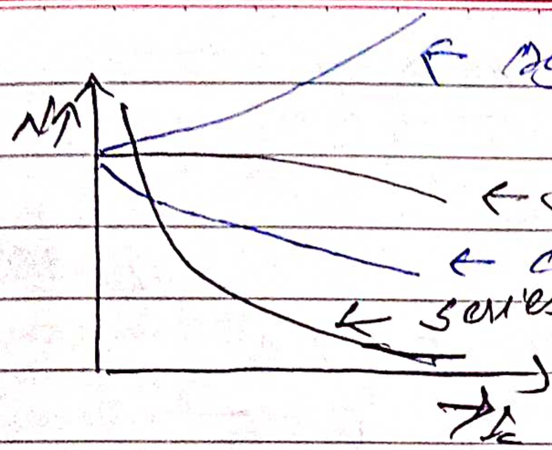

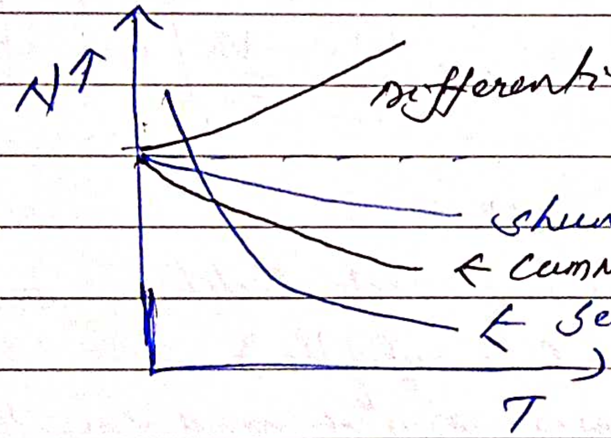

Uses

Differential C. motor is used for experimental purpose in laboratory to get constant speed drive.

		Use
Shunt	Approximately Const. speed [Can be used upto 1.5 time of FL]	Lathe m/c, centrifugal pump, machine tools, Blowers & Fan, Reciprocating pumps, Trolley
Series	Variable speed, High starting torque	Traction, Trolleys cars, Cranes, hoist etc. conveyer.
Compound (cummulative)	Variable speed & High starting torque (intermittent load)	Intermittently where high starting torque is used & operate at no load also. E.g. shears, elevators, Rolling mills, Ice machine, Printing press, air compressor, Punching m/c, shears, etc.

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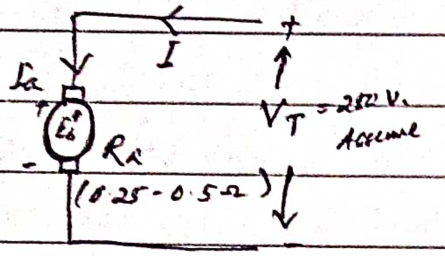
Starting methods of DC motor :-

Need of starter in DC motor



(Basic model of Motor)

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

$V_T = E_b + I_a R_a$

$\Rightarrow I_a = \frac{V_T - E_b}{R_a}$ [$E_b \approx 0$ As motor is at rest]

i.e. $I_a = \frac{V_T}{R_a}$

$I_a = \frac{250}{0.25} = 100$ A   OR

When motor is started from rest condition in such case $I_a \simeq V_T$ (When R_a is negligible)

Because of this 1) M/c may be damaged. (armature winding)

2) Voltage drop in system (As it draws huge current) (Connected in series)

$T_a \propto \phi I_a$

To avoid all these undesired condition we need Starter where we add external resistance in series with the armature resistance.

Starter :- a) 3-point starter. → shunt motor

b) 4- Point starter. → Compound Motor.

(2-point Sr → Series motor)

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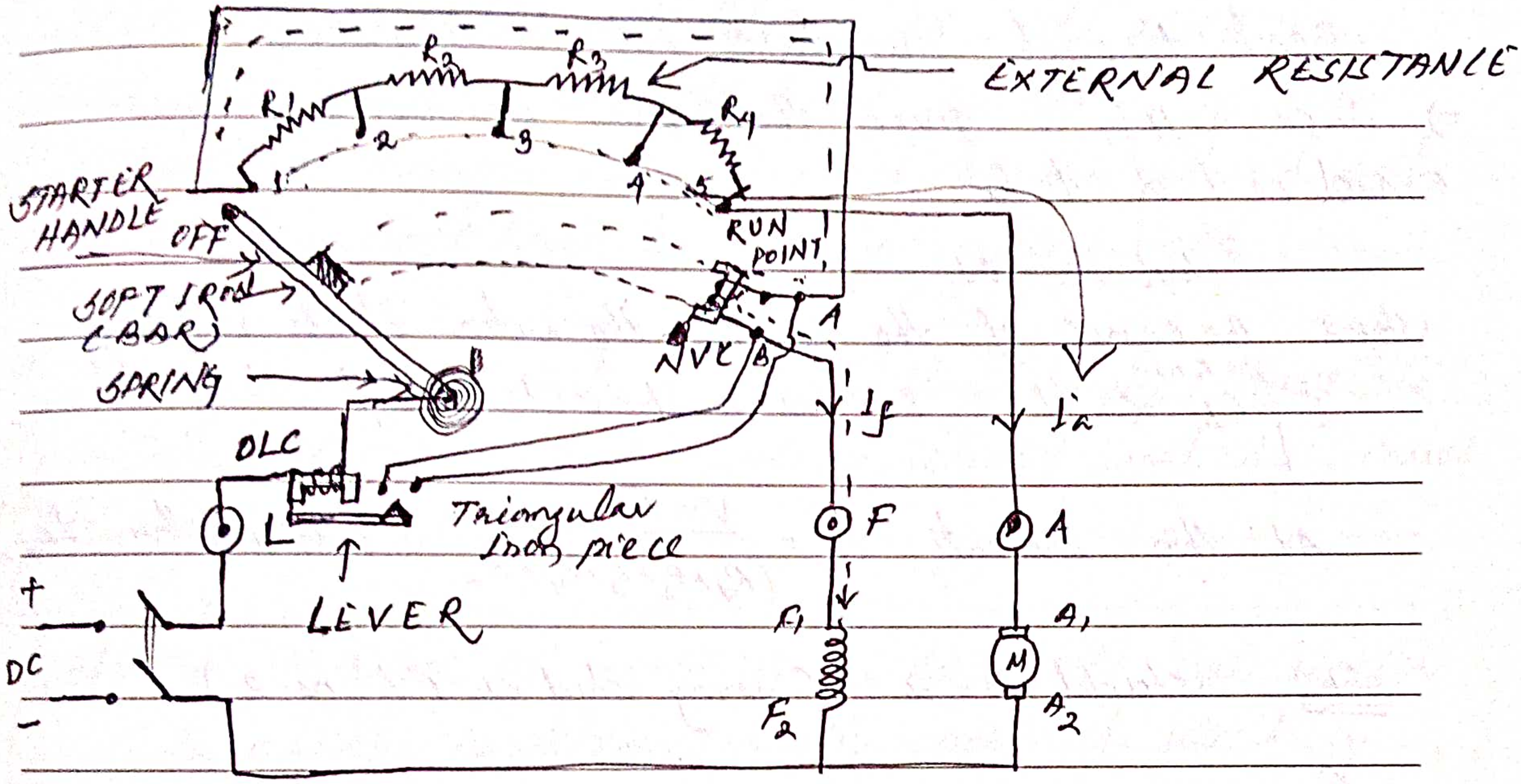

(3- POINT STARTER)

OLC = over load coil

NVC = No voltage coil.

field circuit

* R_{NVC} is connected in series with the field resistance. As value of R_{NVC} is very small it doesn't affect field flux. R_{NVC} ↓↓ ⇒ $\phi = \phi_{rated}$

Armature circuit

step 1 $$I_{a_0} = \frac{V}{R_1 + R_2 + R_3 + R_4 + R_a}$$

Because of this extra resistance $(R_1 + R_2 + R_3 + R_4)$ the

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current through armature can be limitted.

=) Once supply is given the motor produces torque.
~~STARt~~ i.e $T \propto \phi I_a$

~~start no - 01~~
step 2 Because of the torque the motor starts rotating & (we know) $E_b \propto N$ so as speed (N) ↑ → E_b ↑

At this instant $I_{a_1} = \frac{V - E_b}{(R_1 + R_2 + R_3 + R_4) + R_a}$ (is less than I_{a_0})

step 3 stadd no - 2 (moving stud no 1 to no - 2)

{ Torque initially is increased with the help of field flux as $T \propto \phi I_a$. Once torque is established the motor starts accelerating & speed (N) increases.
Because of this E_b increases ($E_b \propto N$) & results in reduce of armature current (As $I_a = \frac{V - E_b}{R_{extn} + R_a}$.

To increase the armature current we move the stud to next point to cut off the external resistance in phase wise manner.

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Once it reaches stud no-05, the NVC is carrying the current to the field circuit. As current is passing through it, it will be magnetized and hold the soft iron bar from going back.

Spring is provided for controlling torque. Once the power goes the NCV is demagnetized and bar comes to original position.

NVC – Purpose of NVC is to hold the bar under running condition under normal working condition.
If for some reason the current is zero/Power goes then automatically the current passing through NVC is zero & then bar will return to original position

OLC :- It is connected in series with armature & field coil. i.e total or line current is passing through OLC.
Under normal operating condition it will operate as usual but whenever load crosses some limit (permissible) of motor. It will get magnetized. Once magnetized the bar of lever will be attracted & Triangular Iron piece will

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short circuit the two terminal A & B. Because of this the current through NVC will be bypassed & demagnetized and will release the Bar and handle will come to off position.

Field current

Once starter handle moves forward the extra resistance will be added to field circuit

$$I_f = \frac{V}{R_f + R_{NVC} + R_{external}}$$

* As R_{NVC} & $R_{external}$ is very less compared to R_f so current will be not affected

OR Initially at stud no. 1 the flux produced is more and finally stud no. 05 the flux produced is equal to rated value of flux. ($T \propto \phi I_a$)

Disadvantages

1) Field control of motor can't be done (above rated speed) As I_f ↓↓ and NVC is demagnetized & may trip

To overcome this problem we go for Four point starter. (To make NVC independent of I_f)

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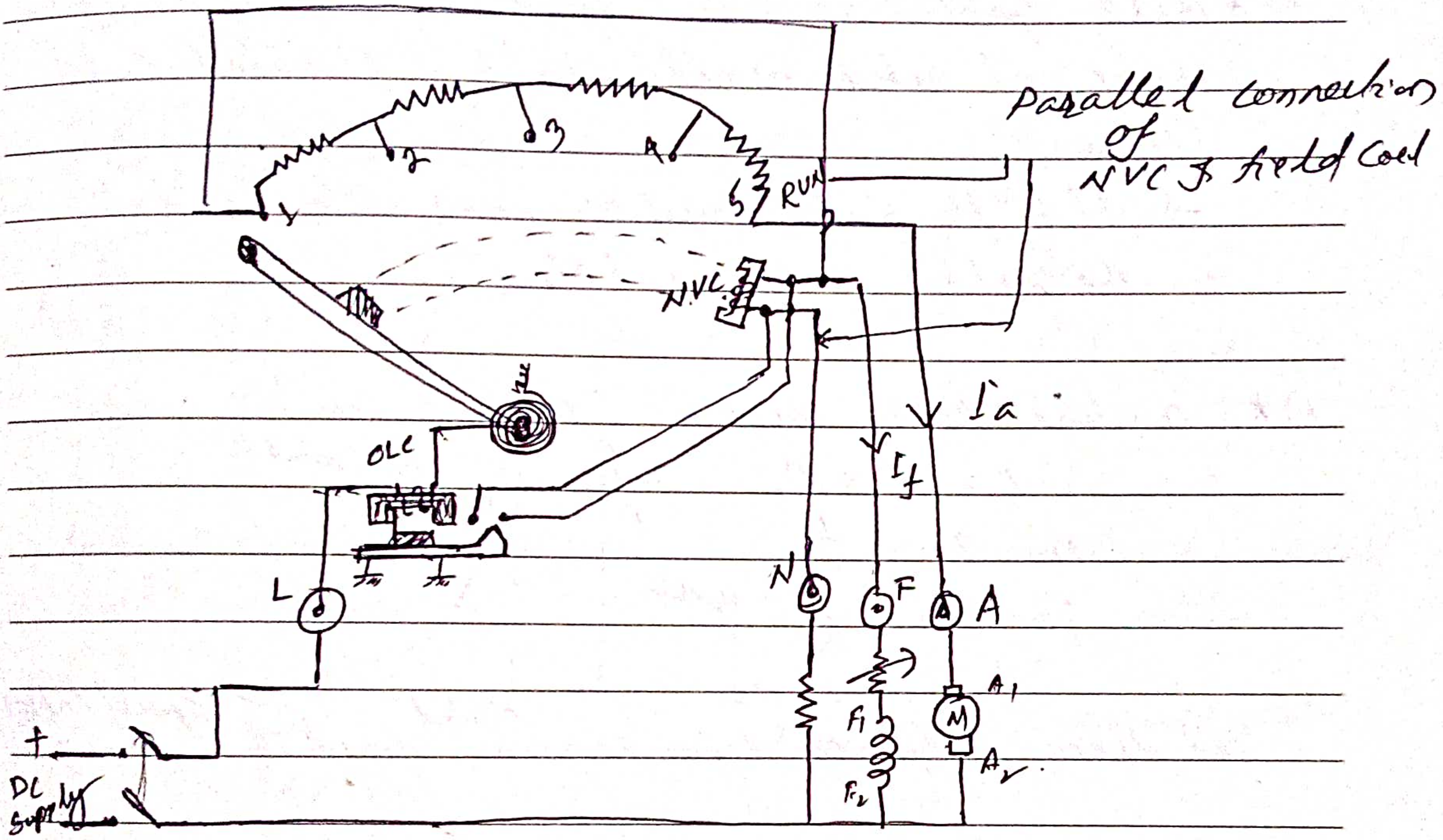
4- Point starter.



(4- Point starter.)

Speed control of DC shunt Motor

a) * Base Speed : It is the speed at which the motor runs at rated armature voltage & rated field current.

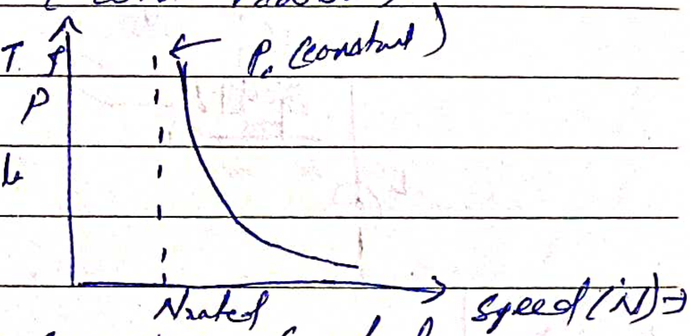
→ It is the rated speed or name plate speed of the motor (N_{rated} / N_{base})

b) * Constant Power Drive :- (Const. Power)

$P = T \times \omega_m$

or $T \propto \frac{1}{\omega_m}$

$\therefore T \propto \frac{1}{N}$ Hyperbola

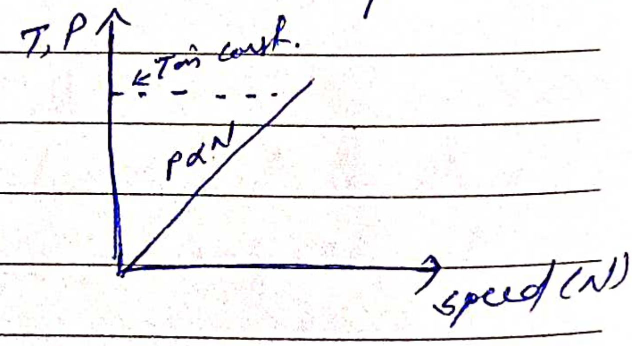


The drive in which power remains constant.

c) Constant Torque drive (Drive in which Torque is const)

power → $P = T\omega_m$ (T const.)

$\Rightarrow P \propto \omega_m$ or $P \propto N$



Speed can be controlled by

✓ ① Field flux control method / Field weakening / flux weakening / field resistance method

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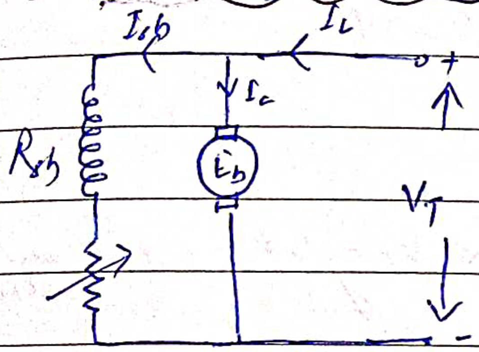
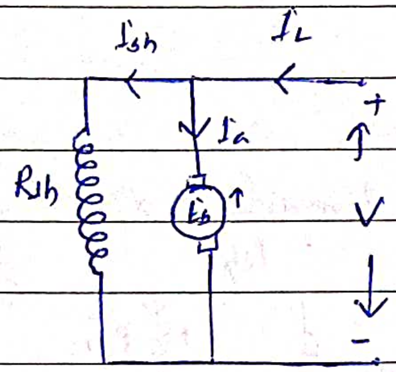
2) Armature resistance control method.
3) Armature voltage control method.

1) Field flux control method (1st)





External R_f is connected in series with field winding

[DC shunt motor under Normal condition]

⇒ $I_{sh} = \frac{V}{(R_{sh} + R_f\uparrow)}$

⇒ $I_{sh} = \frac{V}{R_{sh}}$ Normal condn.

⇒ As $I_{sh}\downarrow$ ~~then~~ $\phi\downarrow$

& We know $N \propto \frac{E_b}{\phi} \propto \frac{V_t - I_a R_a}{\phi\downarrow\downarrow}$

Then speed will increase with decrease of flux ϕ and speed increases above rated speed (N_{rated})

⇒ flux can't be increased above rated value.

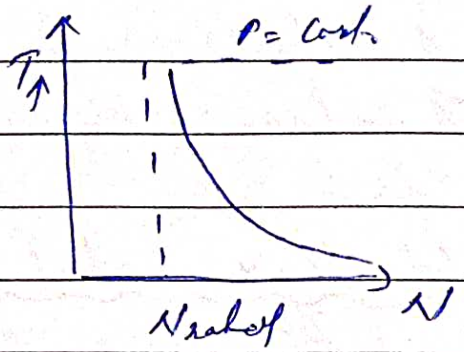
Features of method :-

* N (Speed) above rated speed can be obtained

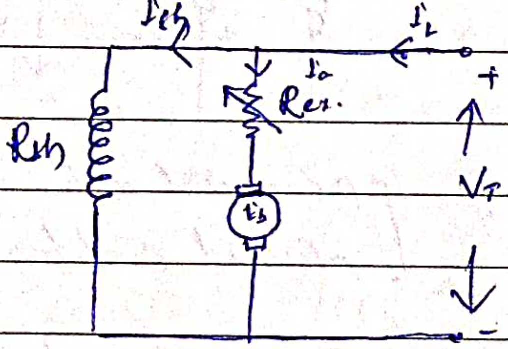
Date / /

* Constant Power drive

* Variable Torque drive.



(2) Armature Resistance Method



i) $N \propto \frac{V_T - I_a R_a}{\phi}$ [Normal Condition]

ii) $N \propto \frac{V_T - I_a (R_a + R_{ex})}{\phi}$

iii) $\downarrow\downarrow E_b = V_T - I_a (R_a + R_{ex})^{\uparrow\uparrow}$

iv) $I_a = \frac{V_T - E_b}{R_a}$ [Normal] $\quad I_a = \frac{(V_T - E_b^{\downarrow\downarrow})^{\uparrow\uparrow}}{R_a + R_{ex}\uparrow\uparrow}$

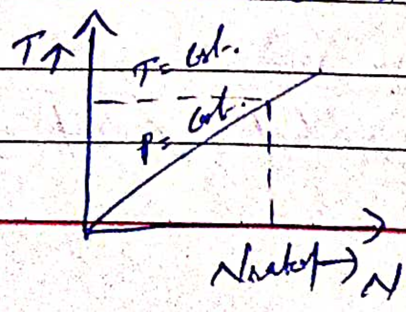
i.e I_a is constant & ϕ = Const (for dc shunt m/c)

Feature.

As we know $T \propto \phi I_a$ or $T \propto I_a$

① ∴ Torque is almost Const. in this method.

② Speed is below rated speed as $E_b \Downarrow$ with external resistance at armature.



③ Variable Power drive

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(2) Voltage drop occurs due to external Resistance.
Then ⇒ I^2R (Power loss) occurred. & unnecessary heating of machine occures.

(3) Armature Voltage control method.
(Not applied to small M/C Practically)

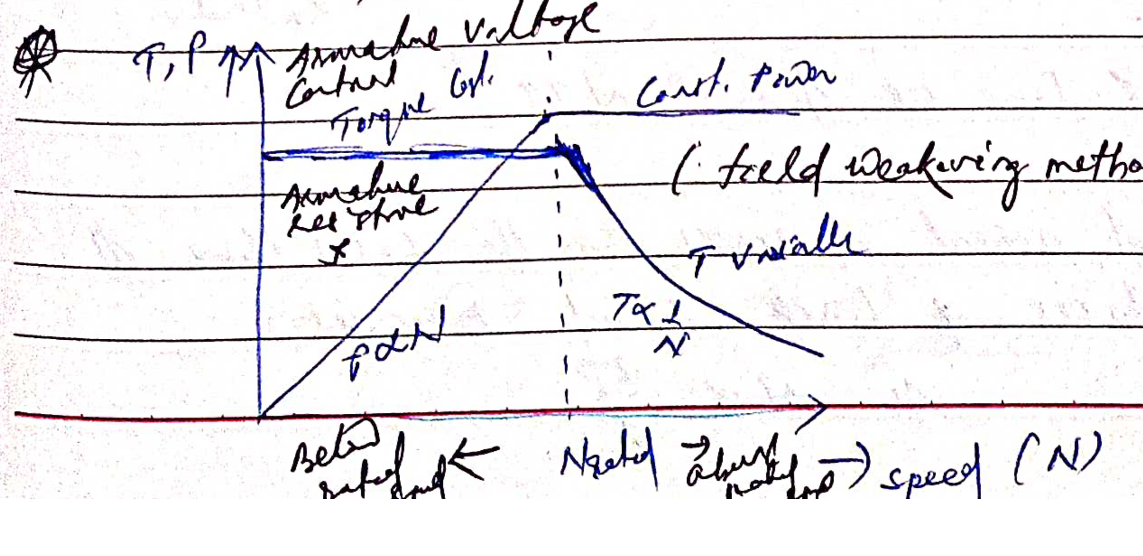
⇒ It is applicable to large method because it is an expensive.

As $N \propto V$ If V is increased there is a chance of insulation failure in the winding.
as insulation ∝ voltage.

⇒ This method is generally applied to DC separately excited motor. Generally not prefered for DC shunt motor.

Feature :-

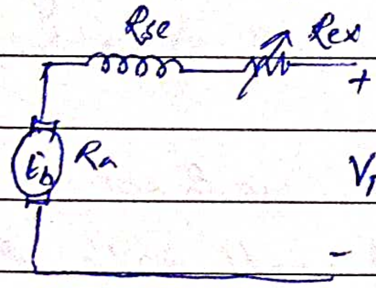
i) Constant Torque drive.
ii) speed below base speed.

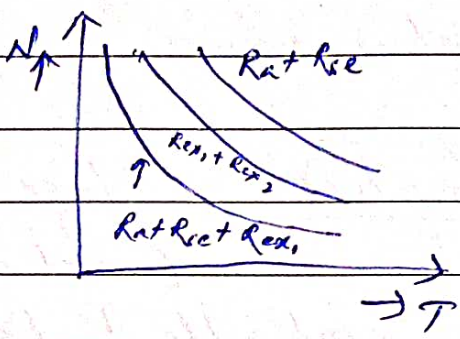


Speed control of DC series motor :-

① Armature Resistance Control $N \propto \frac{1}{\sqrt{T}}$

Armature side





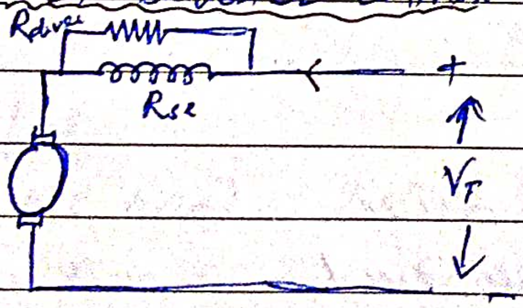
Field side

(2) Field Diverter Control

(3) Tapped field Control

(4) Series-Parallel Control

(3) Field Diverter control :-



* under normal condition

$I_a = I_{se}$

* With diverter $I_{div} = I_a \times \frac{R_{se}}{R_{se}+R_{div}}$

& $I_{se} = I_a \times \frac{R_{div}}{R_{se}+R_{div}}$.

$I_{se} < I_a$ i.e $\phi \downarrow$ & $N \uparrow\uparrow$

As field current decreases then the field flux ϕ reduces & hence speed Increases

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

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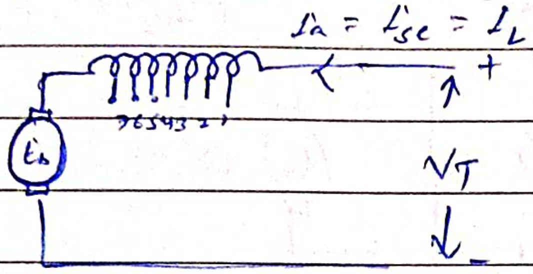
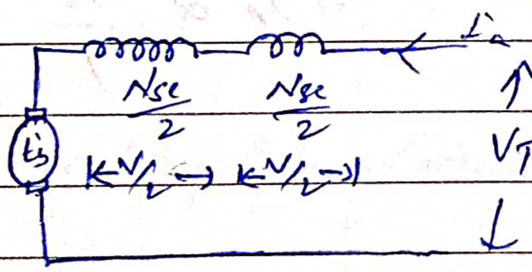
(3) Tapped field control.

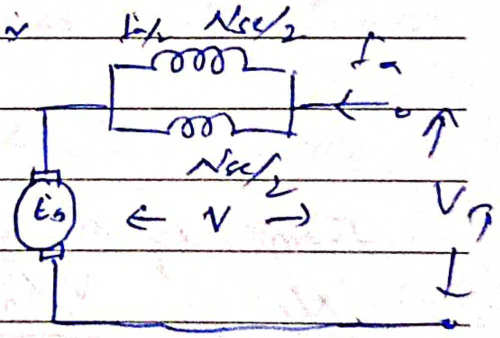


* Tapping is provided in the field winding.
* Generally used in electric traction.
* When all turns are connected → Lowest Speed as flux ~~increases~~ is maximum.

When turns are cut-out → slowly speed will lowered.

※ Series - Parallel Connection :





AT = current × Turns

$\frac{I_a N_{se}}{2} + \frac{I_a N_{se}}{2}$

$= I_a N_{se}$

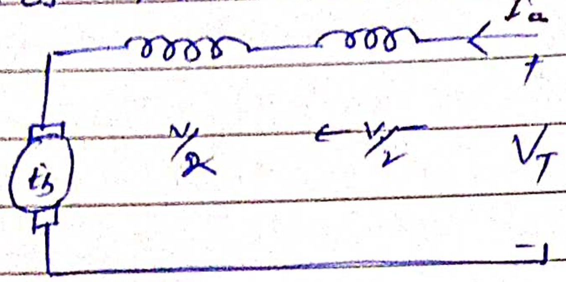
$AT = \frac{I_a}{2} \times \frac{N_{se}}{2} + \frac{N_{se} I_a}{2 \cdot 2}$

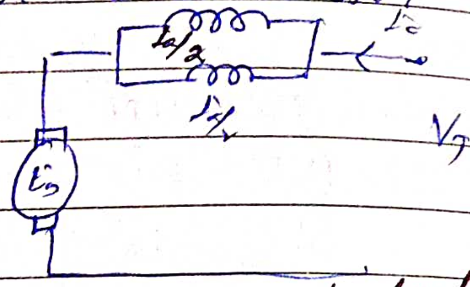
$= \frac{I_a N_{se}}{2}$

ie $(AT)_{Series} = 2(AT)_{parallel}$

N is the no of turns

(4) Series - Parallel Control of DC Series Motor:





$N_s \propto \frac{V}{\phi}$ N_s = Speed in series

$\Rightarrow N_s \propto \frac{V/2}{I_a}$ (as $\phi \propto I_a$)

$\Rightarrow N_s \propto \frac{V}{2I_a}$ — (1)

$T_s \propto \phi I_a$

$\Rightarrow T_s \propto I_a^2$ — (2)

$N_p \propto \frac{V}{\phi}$ N_p = Speed in parallel.

$N_p \propto \frac{V}{I_a/2}$ ($\phi \propto I_a$ & parallel ckt current is $I_a/2$)

$\Rightarrow N_p \propto \frac{2V}{I_a}$ — (3)

$T_p \propto \phi I_a \Rightarrow T_p \propto I_a^2$

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

$\Rightarrow T_p \propto \frac{I_a^2}{4}$ — Eq (4)

From Eq (1) & (3)

$\frac{N_s}{N_p} = \frac{V/2I_a}{2V/I_a} =$

$\Rightarrow \frac{N_s}{N_p} = \frac{1}{4}$ $\therefore$ $\boxed{N_p = 4N_s}$

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From Eq (2) & (4)

$$\frac{T_s}{T_p} = \frac{I_a^2}{I_a^2/4}$$

T_s = Torque in series connection
T_p = Torque in parallel connection.

$$\Rightarrow \frac{T_s}{T_p} = 4 \Rightarrow \boxed{T_s = 4 T_p}$$

Testing of DC machine -

a) Losses

b) Efficiency $= \frac{P_{out}}{P_{out} + Losses} \times 100$

(c) Voltage Regulation in case of generator $= \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$

i.e. $\frac{E_g - V}{V} \times 100$

(d) Speed regulation of Motor $= \frac{N_0 - N_{FL}}{N_{FL}} \times 100$

(e) Temperature rise (Must be within its permissible limit otherwise may damage insulation)

(f) Vibration

(g) Humming / sound etc.

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Methods of Testing of DC Machine.

1) Direct Method - Brake test.
2) Indirect method - Swinburne's test
3) Regenerative method - Hopkinson's test.

① Brake Test.

→ Each machine is designed to operate within certain specified limits.

→ The name plate of M/c shows these details or specifications. It indicates the safe operating limits for that machine.

→ If these limits are exceeded for considerably long time / ~~because of that~~ then this may cause excessively temperature rise and because of this it may cause damage to one or more part of the machine.

* Rated Power :- Max output power of motor or generator.
Specified in SI system of measurement i.e KWatt
Eg. 3.7 KWatt

* Duty :- operating hours of M/c   continuous duty
S_1 · 365 × 24 hours.
If duty is 15 minute

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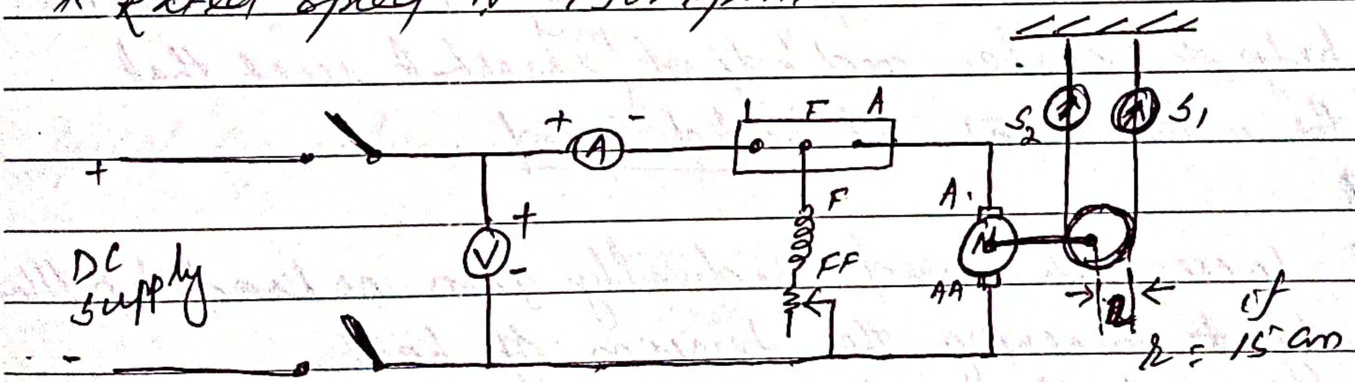
* Rated armature voltage :- Permissible voltage across armature.
* Rated Armature current :- Full load current of the m/c
  Eg. 40A. Generally it can be overloaded upto 120%.
  i.e upto 48 A (short time period)

* Rated field Voltage :- Max. Voltage can be applied across field winding.
* Rated field current :- Eg. 0.87A. Max.

* Rated Speed :- 1500 rpm.



Efficiency can be calculated directly by measuring the input & output power by loading the machine upto Full load.

⇒ The machine is loaded by mechanical brake so that the output power is totally wasted

This method is for Small m/c only as all power is wasted.

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⇒ A ~~rop~~ belt is wound around the pulley and its two ends are attached to the two spring balances S_1 & S_2

⇒ The load on motor can be increased by increasing the tension of the rope.

Procedure :-

* Note down name plate
* connect the ckt as shown in ckt diagram.
* Switch on the supply & start the motor with the help of starter and adjust field rheostat such that the motor runs at rated speed..
*
* Increase the load gradually from no load to full load by ~~to~~ increasing the tension of belt.
  Record the reading in observation table at each steps.
*

Observation Table

Sl no	Supply Voltage in Volt	Load current I_L (in Amp)	S_1 W_1 (Kg)	S_2 W_2 Kg	Speed N (Rpm)
1					
2	230	5	6	2	1480
3					
⋮					

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* After this gradually reduce the load by loosening the belt & switch off the supply.

Eg Power Input = $V \times I_L$ = 230 × 5 = 1150 watt

Shaft Torque (T_{sh}) = $9.81 (S_1 - S_2) R$ = $9.81 (6-2) \times 0.15$

= 5.886 Nm.

$$P_{out} = \frac{2\pi N T_{sh}}{60} = \frac{2 \times \pi \times 1480 \times 5.886}{60} = 912.24 \text{ watt.}$$

* Efficiency (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{912.24}{1150} \times 100 = 79.33\%$$

$$\text{Speed Regulation} = \frac{N_{OL} - N_{FL}}{N_{FL}} \times 100$$

$$= \frac{1500 - 1480}{1480} \times 100$$

Adv.

① All actual loading conditions can be checked.

② This gives most accurate results.

③ Any type of m/c can be tested.

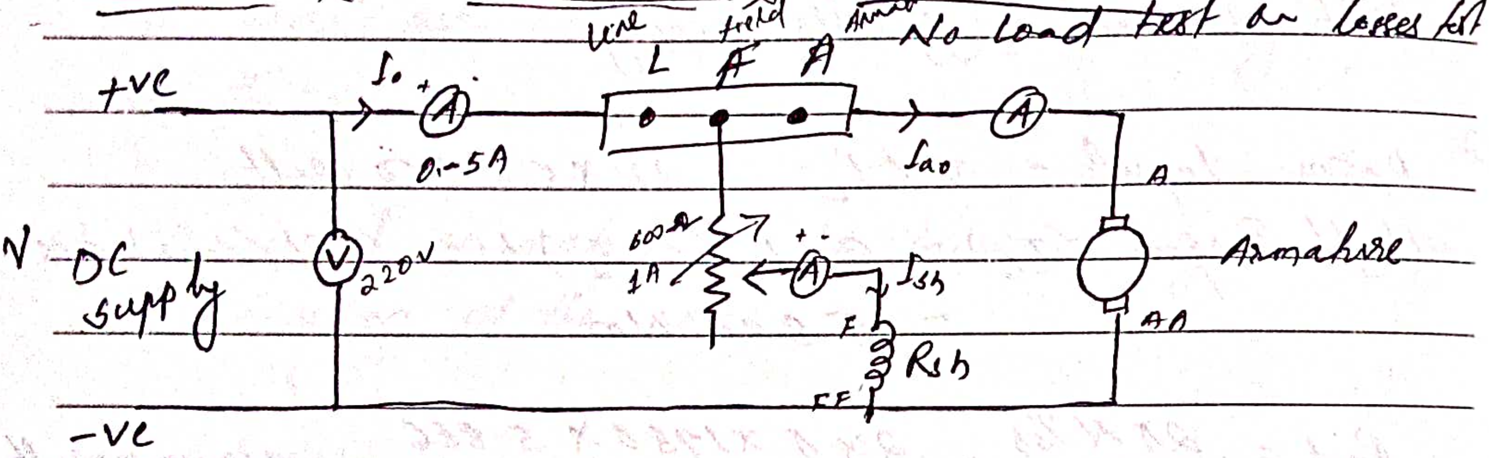
Dis Adv.

① Entire input power is wasted during testing.

(2) Suitable for small dc machine only.

Indirect Method (Swinburne's Test)

No load test or losses test



* operated under no load condition to determine loss
* Power required to very loss. (cu loss + const loss)

Let V = supply voltage to the motor.
I_o = No load current
I_{ao} = No load armature current
I_{sh} = Current of the shunt field.
R_{sh} = Resistance of the shunt field.
R_a = Resistance of the armature winding
R_{ao} = Armature resistance at No-load.

At no load $I_{ao} = I_o - I_{sh}$ — ①

& No load power $(P_i)_{no\ load} = VI_o$ — ②

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This total power is used to supply certain losses.

(1) Iron losses in core. (depend on B_{max})

(2) friction losses in bearing & commutator.

(3) windage losses. (depend on speed — almost const.)

(4) Armature copper losses at no load.

(5) loss in field = $V I_{sh} = I_{sh}^2 R_{sh}$ (As no load so const)

So: Stray load loss = Iron loss + friction loss + windage loss.
or Stray loss

∴ Stray loss (P_s) = Input power at no load − Armature copper loss at no load − Field copper loss

$P_s = P_i(\text{no load}) - P_{a0} - P_f$

where

P_s = Stray load loss

P_{a0} = No load Armature loss.

P_f = field copper loss.

∴ $P_s + P_f = V I_0 - P_{a0}$

But $P_s + P_f$ = constant loss

Hence we can write

$$P_c = V I_0 - P_{a0} \quad \text{— (B)}$$

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For motor

Let I = value of motor current at which efficiency is to be calculated.

Motor Input = VI — (4)

∴ Armature copper losses $= I_a^2 R_a$

$= (I - I_{sh})^2 R_a$ (for dc shunt motor)

Constant losses $(P_c) = P_c + V I_{sh}$ or $P_c + P_f$

Hence Total losses of motor = Armature Cu. loss + Constant loss

$= (I - I_{sh})^2 R_a + P_c$ — (6)

$$\text{Efficiency}(\eta) = \frac{\text{Output Power}}{\text{Input Power}} \times 100$$

or $$\frac{\text{Input} - \text{Losses}}{\text{Input}} \times 100$$

$$= \frac{VI - [(I - I_{sh})^2 R_a + P_c]}{VI} \times 100$$

~~For Generator~~ $$\frac{\text{Output}}{\text{Output} + \text{Loss}} \times 100$$

$$= \frac{VI}{VI + (I + I_{sh})^2 R_a + P_c} \times 100$$

Date / /

* Adv :-

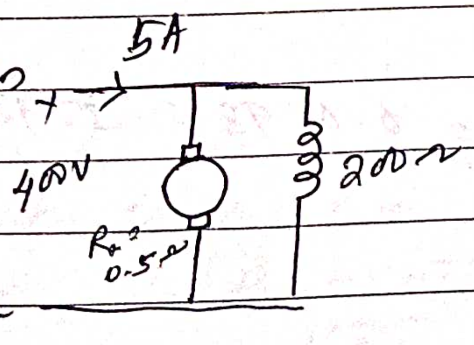
* Very less amount of power is required to test very large dc machine

* The test is conducted at no-load hence the permissible temperature rise cannot be determined by this method.

* Only suitable of DC shunt motor not suitable for dc series motor

Q.1. When running on no-load a 400 V shunt motor takes 5A, armature resistance is 0.5 Ω and field resistance is 200 Ω. Find the output of the motor & η when running on full load taking a current of 50A. Also find % change in speed from no load to full load.

Ans Given,



$I_{fL} = 50A$

Input Power = 400 × 5 = 2000 Watt

$I_{sh} = \frac{400}{200} = 2A$

$\therefore I_a = 5 - 2 = 3A$

No load copper loss = $I_{a_0}^2 R_a = 3^2 \times 0.5 = 4.5$ Watt

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Total constant losses = 2000 − 4.5 = 1995.5 Watt

P_c = 1995.5 Watt

Again at full load I = 50A I_f = 2A (Const)

I_a = 50 − 2 = 48 A

Input = VI = 400 × 50 = 20,000 Watt

Armature Cu. loss = $I_a^2 R_a$ = $48^2 \times 0.5$ = 1152

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{loss}}{400 \times 50} = \frac{20000 - 1152 - 1995.5}{20000}$$

= 84.26 %

for shunt m/c $\frac{N_1}{N_2} = \frac{E_{b_1}}{E_{b_2}} = \frac{400 - (I_{a_1} \times R_a)}{400 - I_{a_2} \times 0.5}$ (No load / full load)

$$\Rightarrow \frac{N_1}{N_2} = \frac{400 - 3 \times 0.5}{400 - 48 \times 0.5} = \frac{398.5}{376}$$

$$\therefore \frac{N_1 - N_2}{N_2} = \frac{22.5}{376} = 0.0598 = 5.98\%$$

Losses & Efficiency

Losses in case of motor is same to that of generator. Basically there are 3 types of losses.

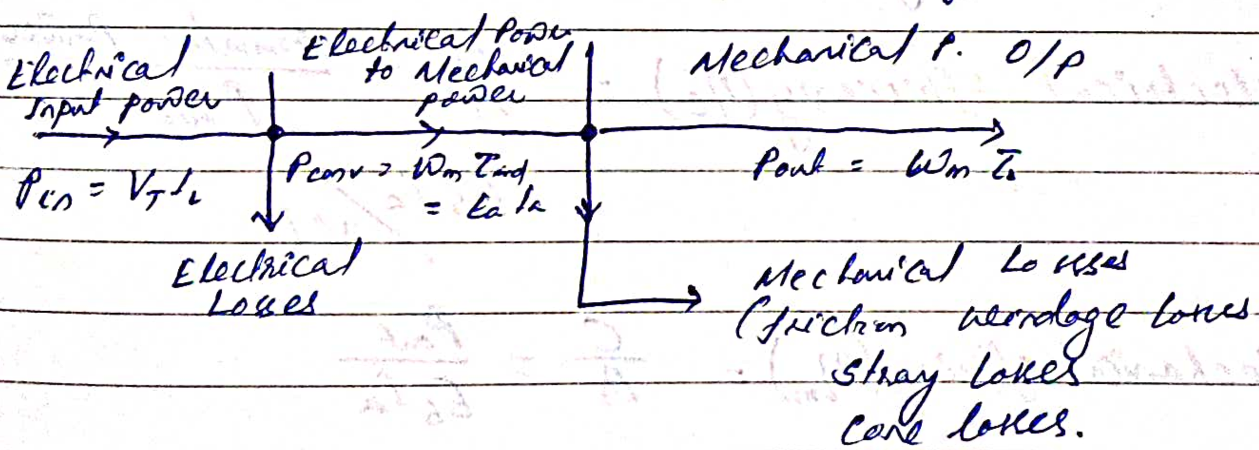
(a) Copper losses

(b) Magnetic losses / Iron losses

(c) Mechanical losses — bearing friction, windage loss (commutator) — { (i) Brush loss, (ii) Stray load losses.

The condition for maximum power developed by the motor is $I_a R_a = V/2$

~~So the condition for max. efficiency is that the~~



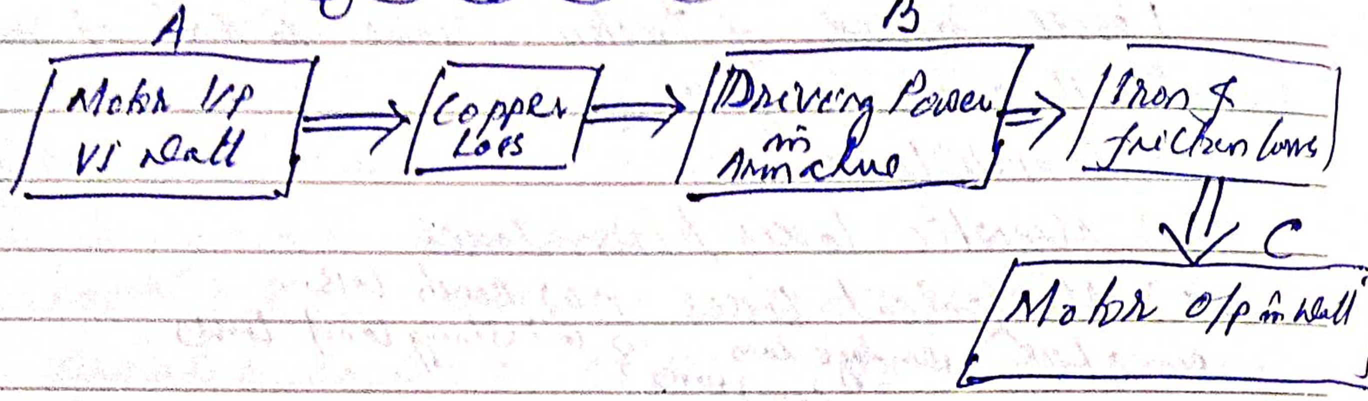
Condition for maximum efficiency is that the armature copper loss is equal to constant losses (W_c)

i.e. $I_a^2 R_a = W_c$

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

Date / /

Power Stages of DC Motor



* Overall efficiency / commercial Efficiency $(\eta_c) = \frac{C}{A} = \frac{P_{o/p}}{P_{i/p}}$

* Electrical Efficiency $(\eta_e) = \frac{B}{A} = \frac{\text{Armature Power}}{P_{i/p}}$

$= E_b I_a / VI$

* Mechanical Efficiency $(\eta_m) = \frac{C}{B} = \frac{P_{out}}{E_b I_a}$

Use of D.C motor

DC motors are used in both high & low power drive, for fixed and variable speed electric drive etc. (i) Electric traction. (ii) Electric footing (iii) Cranes (iv) Lift (v) Air Compressor (vi) Elevator.

Instrument Transformer

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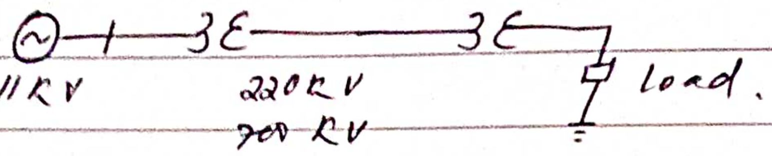

Direct measuring method is not possible as these are too high in value.

* In power systems current & voltage handled are very high and hence direct measurement with conventional instrument is not possible without compromising the operator safety.

→ Solution for this is to stepdown these current & voltages with the help of instrument transformers so that instrument of moderate rating can be used for measurement.

{ The transformer used for measurement of current is called current Transformer
& The T/F used for measurement of voltage is called potential T/F

Instrument Transformer : The transformer used in conjunction with measurement instrument for the measurement purpose is called instrument.

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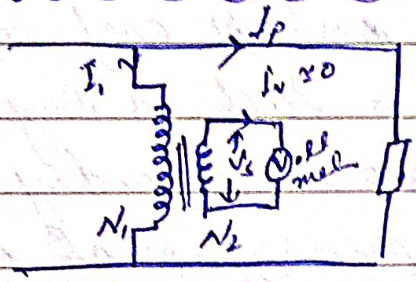
∴ The instrument transformer are used to
(i) Extend the range of measuring instrument
(ii) Isolate the measuring instrument from a high voltage line

Operation

Potential Transformer (PT)



Similar to power T/F but rating is very less.

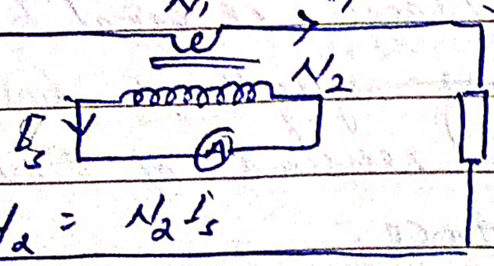
$I_v \approx 0$ so the power required is very less so the size of T/F required will reduced drastically

∴ The T/F will transfer V_p to a lesser value in secondary side

i.e $\frac{N_1}{N_2} = \frac{V_p}{V_s}$ or $V_s = V_p\left(\frac{N_2}{N_1}\right)$

* Primary Voltage is fixed.

Current Transformer



$mmf_1 = N_1 I_p$

$mmf_2 = N_2 I_s$

*CT should be such that it must not be super imposed any extra burden.

* So the ckt. Characteristics is not changed.

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* Let N_1 & N_2 be the number of turn in primary & secondary side of current transformer.

* I_p & I_s be be current in primary & secondary of C.T.

mmf produced in primary side (mmf_1) = $N_1 I_p$

So according to Lenz's law ~~mmf~~ emf induced in secondary side should be in a such a way that it will produces ~~opposes~~ the mmf pro in secondary which opposes the ~~secondary~~ primary mmf i.e mmf_1

i.e $mmf_1 = mmf_2$

$\Rightarrow N_1 I_p = N_2 I_s$

$$\Rightarrow \boxed{I_s = I_p \left(\frac{N_1}{N_2} \right)}$$

* T/F work on the principle of mmf balance so current in secondary is not infinite even it is short circuited.

* Primary current can't change i.e equal to I_p & in secondary side is ~~having negligible~~ i.e burden is nearly equal to zero as resistance of Ammeter is negligible or very less resistance.

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→ The voltage and current of PT & CT standardised at 110V & 5A therefore it is safe for operator & equipment in the switchyard or metering room.

→ There are very less power loss in CT & PT compared to shunt and series for extending the range of instrument

* shunt for increasing the current limit.
series for " voltmeter limit.

⇒ several instrument can be operated from single instrument transformer.

Ratios of Instrument Transformer

$$\text{Transformation Ratio (R)} = \frac{|\text{Primary phasor}|}{|\text{Secondary Phasor}|}$$

$$R = \frac{\text{Primary winding current}}{\text{Secondary winding current}} \leftarrow CT$$

$$R = \frac{\text{Primary winding Voltage}}{\text{Secondary winding Voltage}} \leftarrow PT$$

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$$\text{Nominal Ratio } (n) = \frac{\text{No of turn of Secondary winding}}{\text{No. of turns of primary winding}} \quad CT$$

$$n = \frac{\text{No of turn of Primary winding}}{\text{No of turns of Secondary winding}} \leftarrow PT$$

Imp*

* The ratio mentioned on name plate of instrument transformer is nominal ratio.

* Transformation Ratio (R) = Nominal Ratio (n) x Ratio correction factor (RCF)

$$RCF = \frac{R}{n}$$