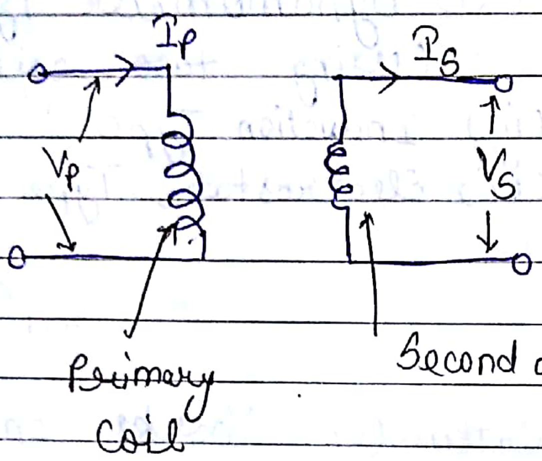
Transformers :-

Converts Voltages from one value to another. It can also be designed to convert currents too.

Construction - Two coils of Conducting wire would upon the same 'core'



N_p → No. of turns in primary Coil

N_S → No. of turns in Secondary Coil

Turns ratio

$$a = \frac{N_p}{N_S} \quad \text{— (1)}$$

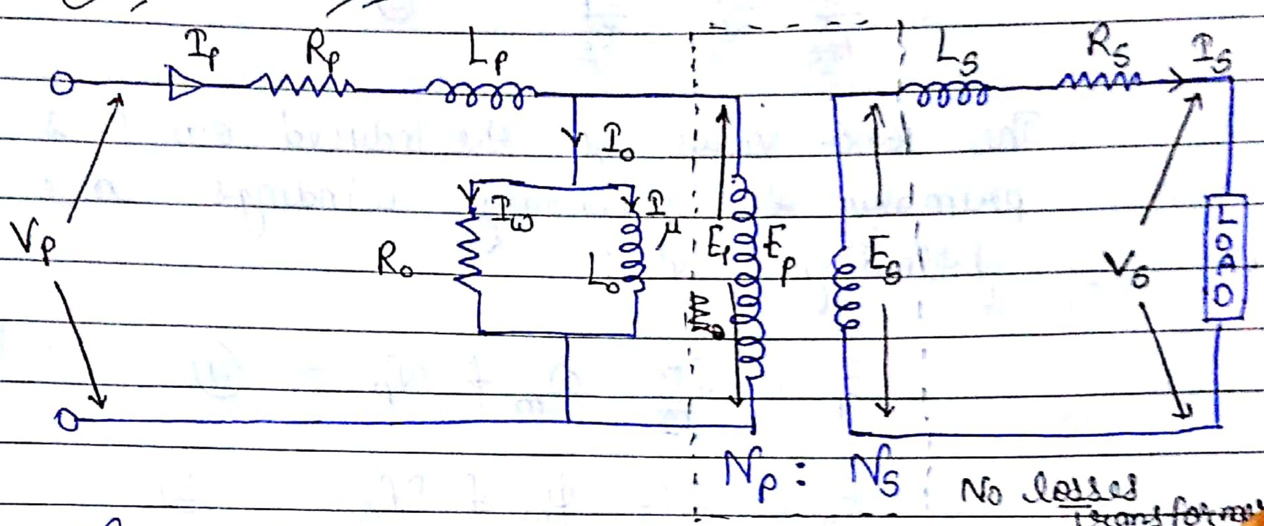
$$= \frac{V_p}{V_S} = \frac{I_S}{I_p} \quad \text{— (2)}$$

Efficiency →

Output Power = Input Power − Losses

$$\eta = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Input Power} - \text{Losses}}{\text{Input Power}}$$

★ An approximate equivalent circuit of a Transformer :-



(i) V_p = Voltage applied to the terminals of the primary winding.

(ii) V_s = Voltage available from the terminals of the secondary winding.

(iii) I_p = Primary Current (iv) I_s = Secondary Current

(v) N_p = No. of Turns in Primary Winding
(vi) N_s = No. of Turns in secondary Winding

(vii) I_o = No load Current
(viii) R_p, L_p = Resistance & inductance of Primary Welding
(ix) R_s, L_s = Resistance & inductance of Secondary winding

$$\text{Turns ratio } a \triangleq \frac{N_p}{N_s} \quad — (1)$$

$$I_o = I_\omega + I_\mu \quad — (2)$$

I_ω = Working Current ; I_μ = Magnetising Current

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$$a \triangleq \frac{N_p}{N_s}$$

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} \quad — ③$$

The R.M.S. value of the induced e.m.f.'s in primary & secondary windings are given by following eq^n :

$$E_p = \frac{2\pi}{\sqrt{2}} \phi_m f N_p \quad — ④ \qquad f = \text{Frequency}$$

$$E_s = \frac{2\pi}{\sqrt{2}} \phi_m f N_s \quad — ⑤$$

Where ϕ_m (in Webers) is the Maximum Magnetic flux produced in the core of the transformer.

$$\text{Since } \frac{2\pi}{\sqrt{2}} \simeq 4.443 \quad — ⑥$$

We can write
$$E_p \simeq 4.443\, \phi_m f N_p \quad — ⑦$$
$$E_s \simeq 4.443\, \phi_m f N_s \quad — ⑧$$

We can define magnetic flux density as-

$$\text{Maximum (Peak Value)} \rightarrow B_m = \frac{\phi_m}{A} \quad — ⑨$$

Where 'A' is area of cross-section of core.

Then, we can write-

$$E_p \simeq 4.443\, B_m f N_p A \quad — ⑩$$
$$E_s \simeq 4.443\, B_m f N_s A \quad — ⑪$$

$E_p, E_s \rightarrow$ r.m.s. values

Efficiency of a Transformer:→

$$\eta = \frac{\text{Output Power}}{\text{Input power}} \quad — ①$$

$$= \frac{\text{Input Power} - \text{Loss}}{\text{Input Power}}$$

$$= 1 - \frac{\text{Loss}}{\text{Input power}} \quad — ②$$

$$\text{Loss} = \underset{\text{Loss}}{\text{Iron}}\ (\omega_i) + \underset{\text{Loss}}{\text{Copper}} \quad — ③$$

Iron Loss ↓ doesn't depend much on load

Copper Loss → (I^2R Loss) ↓ Load dependent

$$\therefore \eta = 1 - \frac{\omega_i + I_p^2 R_p + I_s^2 R_s}{V_p I_p \cos\phi_p} \quad — ④$$

[Note that V_p, I_p are not peak values, but r.m.s.]

For Max. η → $I_S^2 R_S \simeq 0$

$$\frac{d\eta}{dI_p} = 0 \quad — ⑤$$

⇒ we should get

$$\omega_i = I_p^2 R_p \quad — ⑥$$

⇒ Iron Loss = Copper Loss — ⑦

Q1. A step-down transformer has a turn ratio of 4 to 1 or 4. If transformer's secondary voltage is 120 V, determine the primary voltage.

Ans

$$a = \frac{N_P}{N_S} = \frac{E_P}{E_S}$$

$$\Rightarrow E_P = E_S \times a$$

$$= 120 \times 4 = 480\ V$$

Q2. A single-phase transformer with a 2-KVA rating has a 480 V primary, and a 120-V secondary. Determine primary & secondary full load currents of the transformer.

Ans

Apparent Power (S) = 2-KVA

= 2000 VA

Since we assume no loss transformer

∴ Power in Primary = Power in Secondary

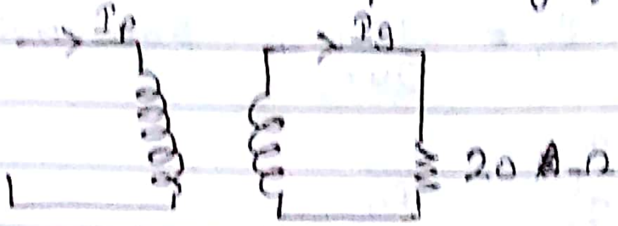
$$\therefore 2000 = 480\ I_P$$

$$\Rightarrow I_P = \frac{2000}{480}\ A$$

$$\& \quad 2000 = 120\ I_S$$

$$\Rightarrow I_S = \frac{2000}{120}\ A$$

Q3. For the transformer in problem 1, if a load resistance of 20 Ω is connected to the secondary, how much current would flow in the primary?



Ans

$$I_S = \frac{V_S}{R} = \frac{120}{20} = 6\ A$$

$$\frac{I_S}{I_P} = a$$

$$\Rightarrow I_P = \frac{I_S}{4}$$

$$= \frac{6}{4} = 1.5\ A$$

Q4. A Voltage transformer has primary Voltage of 480 Volt and secondary Voltage of 120 Volts. If primary winding has 700 turns, how many turns are there in secondary winding?

Ans

$$\cancel{\frac{N_S}{N_S} = \frac{E_P}{E_S}} \qquad \frac{N_P}{N_S} = \frac{E_P}{E_S}$$

$$\Rightarrow N_S = N_P \times \frac{E_S}{E_P}$$

$$= 700 \times \frac{120}{480} = 175$$

Q5 For the transformer in Prob 4, If a purely-resistive load of 240 Ω is connected across the two terminals of the secondary winding, Calculate the resulting currents in the

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two windings. Also calculate the power factor of load and the Values of Power P, Q, & S.

Ans)

$$I_S = \frac{120}{240} = 500\ mA$$

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$\Rightarrow I_P = I_S \times \frac{N_S}{N_P}$$

$$= 500 \times \frac{175}{700}$$

$$= 125\ mA$$

P. F. of load → 1 (purely - resistive)

Q 6. A single - phase transformer has $N_P = 1000$ & $N_S = 200$. The max. Value of the magnetic flux density in the core is 1.1 Tesla, when 2200 V, 50 Hz is applied to the primary. Calculate the area of cross-section of the core.

Ans

$$E_P \simeq 4.443\ B_m A f N_P$$

$$E_S \simeq 4.443\ B_m A f N_S$$

In ideal case,

$E_P = 2200$ V (assuming no loss)

$$2200 \simeq 4.443\ B_m A f N_P$$

$$\Rightarrow 2200 \simeq 4.443 \times 1.1 \times A \times 50 \times 1000$$

$A =$

Q 7. Consider a 440/110 V transformer with the following parameters:

(i) Resistance R_p of primary winding $= 10\ \Omega$

(ii) Resistance R_S of secondary winding $= 2\ \Omega$

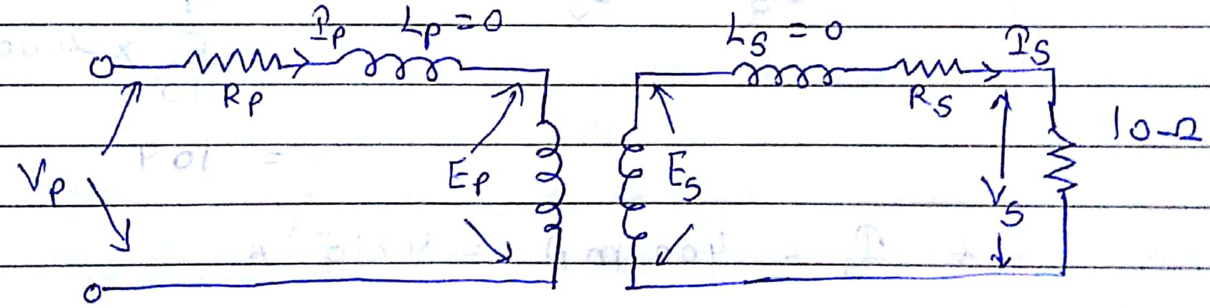
(iii) Negligible core losses

(iv) Negligible inductances in two windings

If the secondary is connected to a 10-Ω load, how much current would flow in primary. ~~Assume $V_p = 440$ Volts~~
~~$a = 4$.~~

Ans Assume $V_p = 440$ & $a = 4$

$\therefore \quad V_S = \frac{V_p}{a} = \frac{440}{4} = 110V$



$$V_p - I_p R_p = E_p \quad — (1)$$
$$E_S - I_S R_S = V_S \quad — (2)$$

$$a = \frac{E_p}{E_S} \Rightarrow E_p = a E_S$$
$$= 4 E_S \quad — (3)$$

$$V_S = 10 \times I_S \quad — (4)$$

Q 8: A doorbell requires 400 mA at 6 V. The doorbell is connected to a transformer whose primary contains 2000 turns and is connected to a 110 V household outlet. How many turns should be there in the secondary? What is the current in the primary? How many Watts does the bell require from the transformer?

Ans

$V_p = 110\text{ V}$

Assuming the whole Voltage ~~is~~ comes across ~~into~~ primary winding. (No losses)

$\therefore V_p \simeq E_p = 110\text{ V}$

$V_s = E_s = 6\text{ Volts}$

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} \Rightarrow N_s = \frac{E_s}{E_p} \times N_p$$

$$= \frac{6}{110} \times 2000$$

$$= 109$$

& $I_s = 400\text{ mA} = 4 \times 10^{-3}\text{ A}$

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} = \frac{E_s}{E_p} \Rightarrow I_p = I_s \times \frac{N_s}{N_p}$$

$$= 4 \times 10^{-3} \times \frac{6}{110}$$

$$\simeq 22\text{ mA}$$

$$\text{Power} = I_s E_s = I_p E_p$$

$$= 400 \times 6$$

$$= 2400\text{ mV} = 2.4\text{ V}$$

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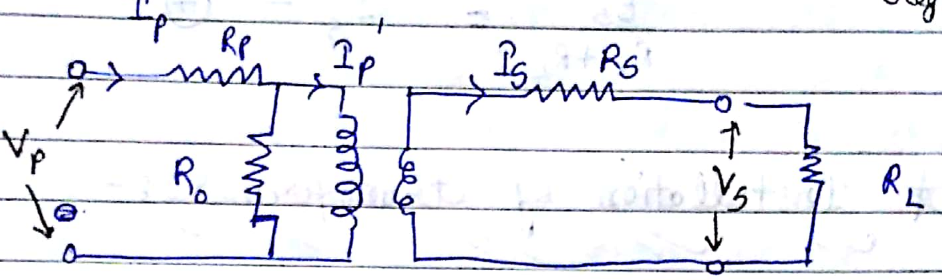
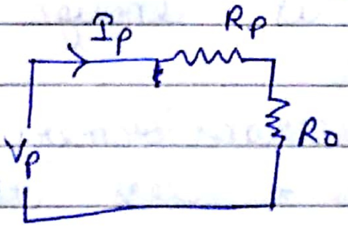
Q 9. ~~For~~ Consider a single-phase transformer with turns ratio $a = 10$, applied primary Voltage $V_p = 100\,V$, primary winding resistance $R_p = 2\,\Omega$, secondary winding resistance $R_S = 0.2\,\Omega$ under no-load conditions, the primary current is $100\,mA$. How much primary current would flow when a 50-Ω resistance load is connected to secondary? Calculate Voltage regulation.

Ans



(a) When Load $(R_L) = 0 \rightarrow I_S = 0$ & $I_p' = 0$

$I_p = 100\,mA$



$$100 \times 10^{-3} = \frac{V_p}{R_p + R_o}$$

$$0.1 = \frac{100}{2 + R_o}$$

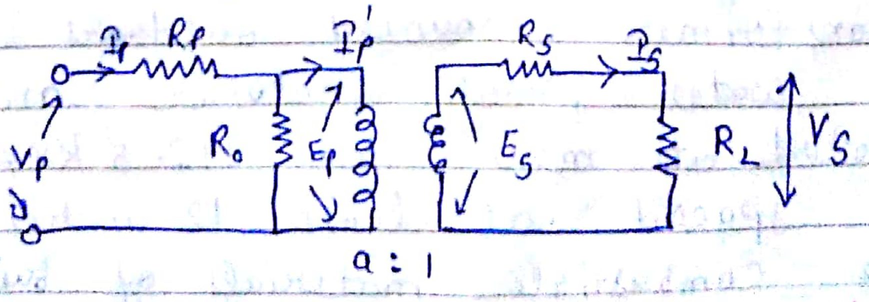
$$\Rightarrow 0.2 + 0.1 R_o = 100$$

$$\Rightarrow 0.2\ R_o \simeq 100$$

$$R_o \simeq \frac{1000}{1}$$

$$\simeq 1000\,\Omega$$

(b) When $R_L = 50\,\Omega$



$$\frac{E_p}{E_s} = 10 \quad — ②$$

$$\frac{I'_p}{I_s} = \frac{1}{10} \quad — ③$$

$$V_s = R_L I_s = 50 I_s \quad — ④$$

$$V_p - I_p R_p = E_p \quad — ⑤$$

$$(I_p - I'_p) R_o = E_p \quad — ⑥$$

$$\frac{E_s}{R_s + R_L} = I_s \quad — ⑦$$

✯ Installation of transformers :-

(i) Transformers must be installed in an area that will minimize the possibility of physical damage and in an area where there is enough free circulation of air.

(ii) Dry-type transformers rated at less than 600 V & less than 112.5 KVA should be mounted on fire-retardant material.

(iii) Transformers rated at more than 112.5 KVA should be installed in a transformer room of fire-retardant construction.

(iv) Transformers mounted outdoors should have a water-proof enclosure and, if rated at more than 112.5 KVA, should be spaced at least 12 inches from the combustible materials of buildings.

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Protection of transformers:-
Use relays & fuses

Grounding of a Transformer:-
Detailed applicable documents must be consulted naturally available grounds, e.g. effectively-grounded metal water pipes, effectively-grounded metal in the nearby structure etc. can be used (via an electrode) to provide sufficient grounding to a transformer.

Q How do we decide the diameter of the 'Cu' wires used in primary & secondary windings?

Ans There are two standards used to specify wire-diameter:
(i) American Wire Gauge (AWG)
(ii) Standard Wire Gauge (SWG)

Q A 500 KVA, single-phase, 13.8/4.160 KV, 60 HZ transformer has primary resistance = 0.8 Ω and secondary resistance = 0.04 Ω. The iron loss (i.e. core loss) = 3000 watts. Calculate the copper loss & efficiency at full-load.

Ans
$$\eta = \frac{\text{Output Power}}{\text{Input Power}}$$

$$= \frac{\text{Input Power} - \text{Cu loss} - \text{Iron loss}}{\text{Input power}}$$

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Cu loss → $I_p^2 R_p + I_S^2 R_S$ (Because These are generating both hence wire loss)

Assume $[\cos\phi = 1]$

$V_p I_p = V_S I_S = \text{Power}$

$\Rightarrow 13.8 \times I_p = 500 = 4.160 \times I_S$

$I_p = \frac{500}{13.8}$ & $I_S = \frac{500}{4.160}$

$\Rightarrow I_p \simeq 36.23\ A$ $I_S = 120.19\ A$

Cu loss $= 1626$ Watt

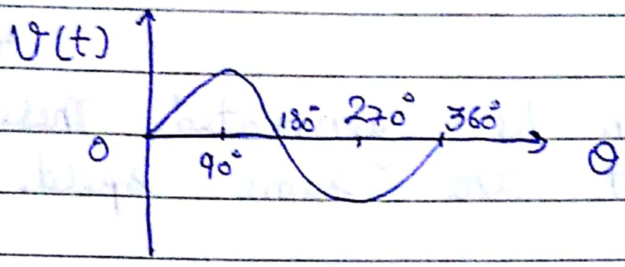
$\eta = 1 - \frac{(3000 + 1626)}{500 \times 10^3}$

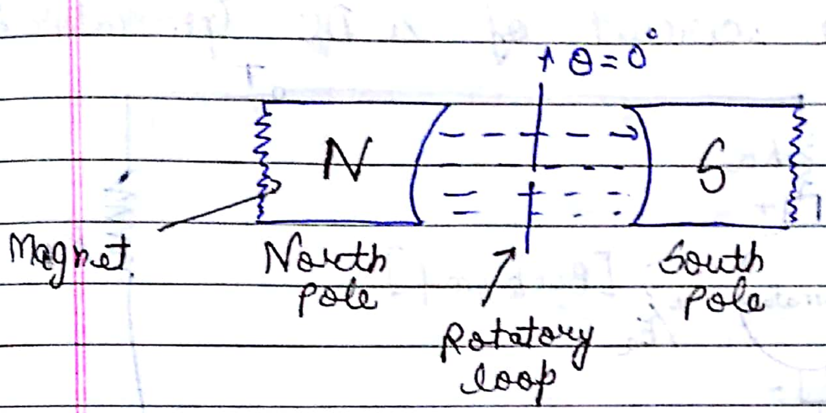
$\simeq 99.3\ \%$

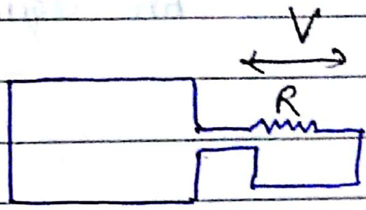
★ DC Machines :-

DC machines can be either DC Generators or DC motors. In the case of a DC Generator, the input power is mechanical (rotatory input) and the output power is electrical (DC power). In the case of a DC motor, the input power is electrical (DC power) and the output power is mechanical (rotatory output). The same DC machine can work, at least in principle, both as DC Generator & DC motor.

Principle of operation of a DC Generator -



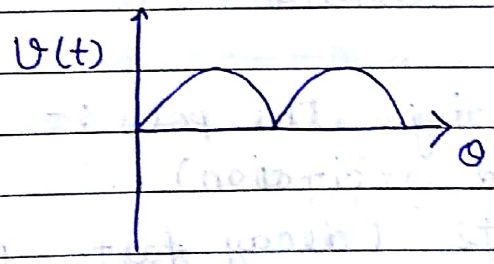




Side View

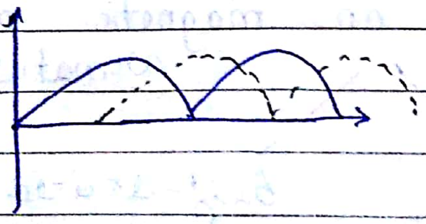
Front View

After Commutator,

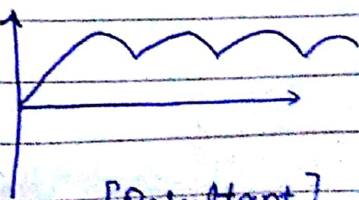


In case we increase the no. of loops (with some phase shift)

Two loops →



⇒

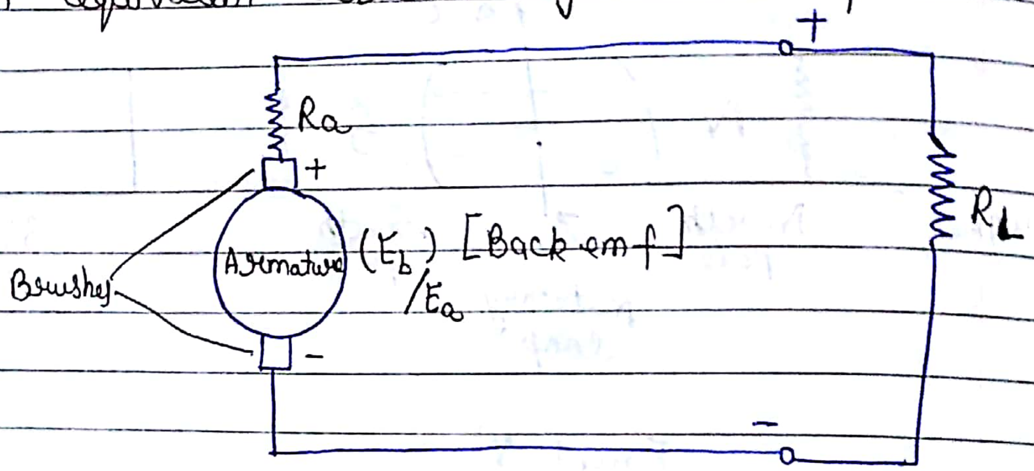


[Resultant]

→ with large number of loops (with progressive angles with each other to create phase shift)

DC can be generated. These all loops move at the same speed.

An equivalent circuit of a DC Generator :-



R_a → Armature resistance
E_b / E_a → Voltages across brushes
R_L → Load resistance

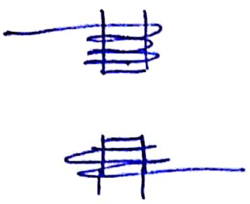
Methods of exciting the poles :-
(Field excitation)

(i) Permanent Magnets (decay fast, not too strong etc.)

(ii) using Field windings
(Windings on magnetic poles, ~~not~~ not on armature)

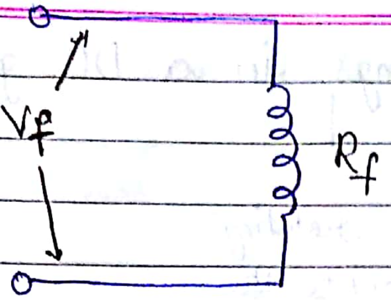
Separately excited
(external Voltage is applied)

Self-excited
↓
Voltage ~~generated~~ generated from Armature can be utilized.

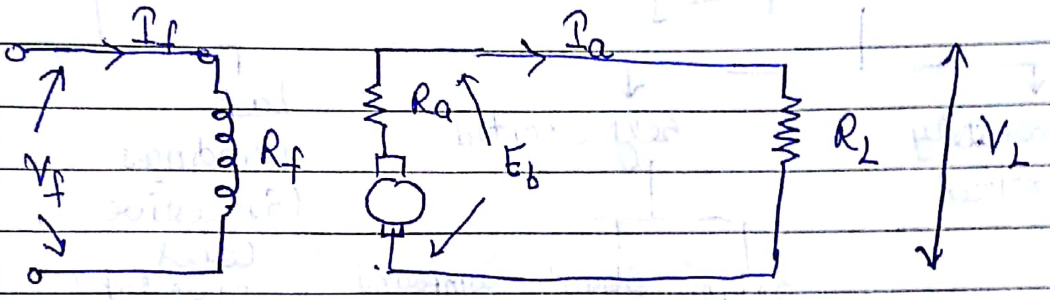


Fields windings :-
[Magnetization generated due to current + Magnetization due to magnet]

Seperately → excited



R_f → Field resistance



$$I_a = \frac{E_b}{R_a + R_L} \quad — \text{①}$$

Armature current

$$I_f = \frac{V_f}{R_f} \quad — \text{②}$$

Self-excitation

- Shunt wound (fields windings in parallel to armature)
- Series wound (field windings in series to armature)
- Compound wound (some in series, some in parallel)

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Windings in a DC generator

- Field windings (non-rotating) [necessary to excite the poles]
  - Separately Excited
  - Self-excited
    - Series Wound
    - Shunt Wound
    - Compound wound
- Armature Windings (rotating)
  - Lap windings (Successive coils overlap)
  - Wave Winding (No overlapping of coils)

Mathematical Expression for the "back emf" E_b developed in armature:-

$$E_b = \frac{\phi Z N P}{60 A} \quad \text{—} \quad (1)$$

where, ϕ = Magnetic Flux produced in stator per pole (wb). wb → weber

Z = Total number of conductors on the Armature

N = RPM at which the rotator is being driven by the Prime Mover (e.g.- a turbine)

P = Number of magnetic poles in the stator (has to be an even number)

A = Number of parallel electrical paths between the two brushes

= P for lap-wound armature

= 2 for wave-wound armature

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Q An 8-pole, lap wound DC generator has 960 conductors on Armature. The stator is produced a flux/pole = 0.02wb. Calculate the emf generated in the armature when the armature is driven at 500 RPM.

Ans Back e.m.f. $E_b = \frac{\phi Z N P}{60 A}$

$P = A = 8$

$\phi = 0.02$ wb

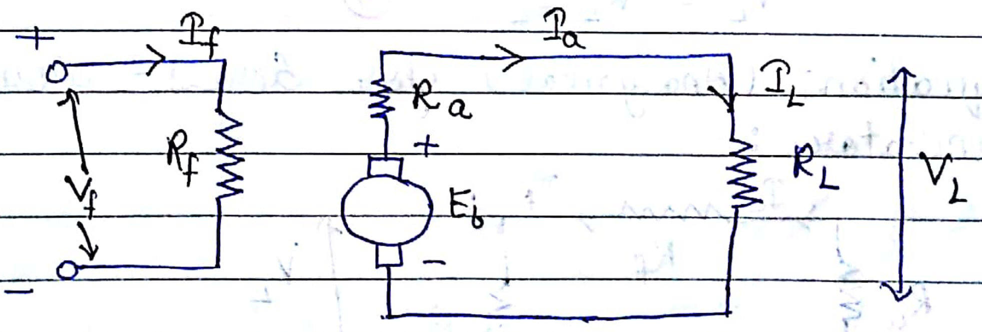
$Z = 960$

$N = 500$

$\therefore \quad E_b = \frac{0.02 \times 960 \times 500}{60}$

$= 160$ Volts

Analytical equations for a separately excited DC generator :-



f → field windings
a → armature circuit
L → load
b → back

$I_a = I_L$ — ①

$E_b - I_a R_a = V_L$ — ②

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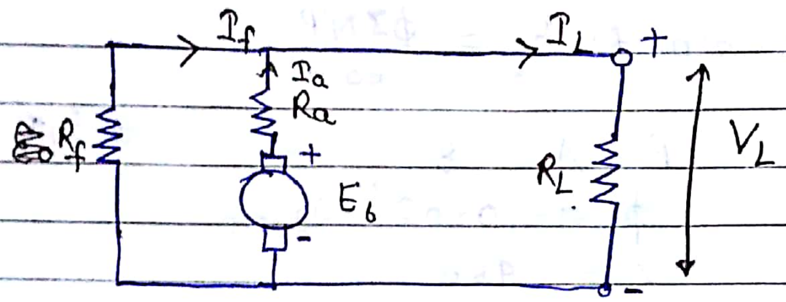
$$V_L = R_L I_L \quad — (3)$$

$$I_f = \frac{V_f}{R_f} \quad — (4)$$

Equations for Shunt wound DC generator :-



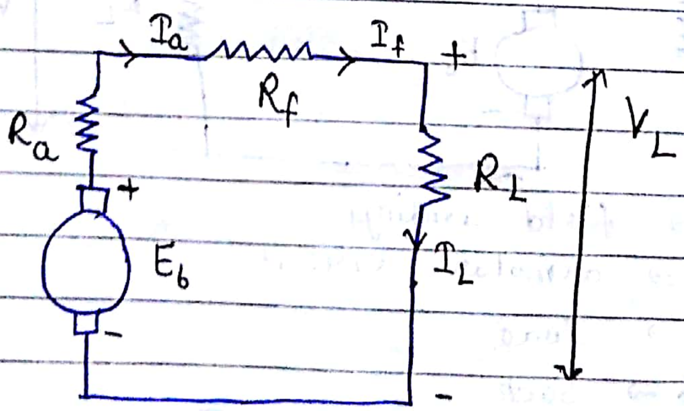
$$I_a = I_f + I_L \quad — (1)$$

$$I_f = \frac{V_L}{R_f} \quad — (2)$$

$$E_b - I_a R_a = V_L \quad — (3)$$

$$V_L = R_L I_L \quad — (4)$$

Equations (Analytical) for Series - Wound DC generator :-

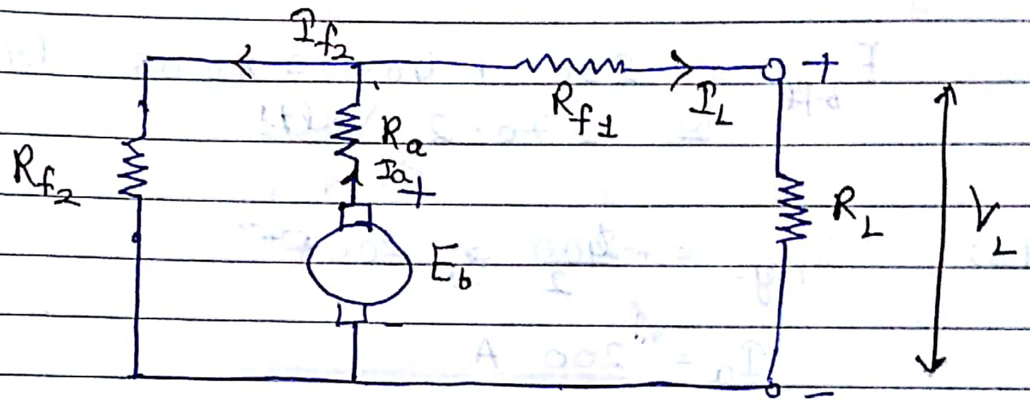


$$V_L = I_L R_L \quad — (1)$$
$$= I_a R_L \quad — (2)$$
$$= I_f R_L \quad — (3)$$

$$I_L = I_a = I_f \quad — (4)$$

$$E_b - R_a I_a - R_f I_f = V_L \quad — (5)$$

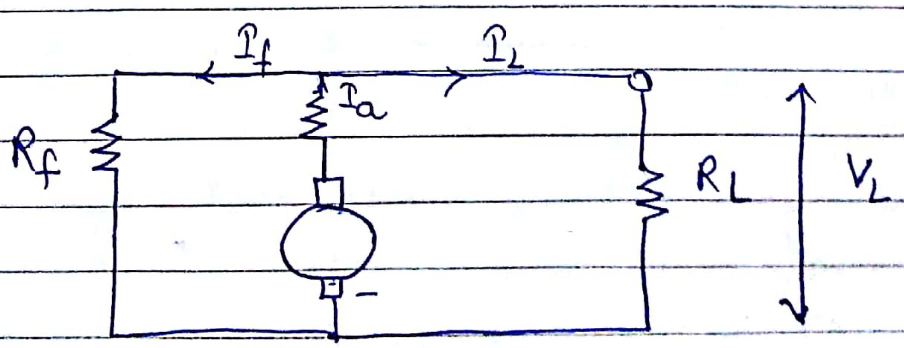
Equations for Compound wound DC generator :-



Q. A 100-KW, 250-V DC shunt generator has an armature resistance of 0.05 Ω and field circuit resistance of 60 Ω. With the generator operating at rated Voltage, determine the induced Voltage at
a) full-load
b) half-full load

Ans

a) $I_{full} = \dfrac{100,000}{250} = 400\ A = I_L$



$$E_b - I_a R_a = V_L \quad — (1)$$

$$I_L = I_a - I_f \quad — (2)$$

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$$I_f = \frac{V_L'}{R_f} = \frac{250}{60}$$

$$\simeq 4.17\ A$$

$$\therefore\ I_a = 400 + 4.17\ A$$

$$= 404.17\ A \quad \text{(from ①)}$$

$$E_{bfl} = 250 + 404.17 \times 0.05 \quad \text{(from ②)}$$

$$\simeq 270.2\ \text{Volts}$$

(b) $I_{half} = \frac{400}{2} = 200$

$$I_a = 200\ A$$

$$I_f \simeq 4.17\ A$$

$$\therefore\ I_L = 204.17\ A$$

$$E_{b\,half} = 250 + 204.17 \times 0.05$$

$$= 260.2\ A$$

Mech

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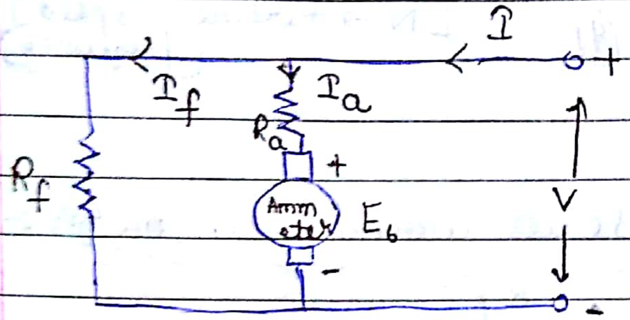
☆ Analysis of a Shunt-wound DC motor :-



$$I = I_a + I_f \quad — (1)$$

$$I_f = \frac{V}{R_f} \quad — (2)$$

$$E_b = V - I_a R_a \quad — (3)$$

V = External DC Voltage applied to the two terminals of the motor

I = Current Drawn by the Motor

I_a = Alternative Current

I_f = Field Current

E_b = Back e.m.f. = $\frac{\phi Z N P}{60 A}$

"No load" is required since ~~rotor~~ output is mechanical.

Input Power

$$P_I = VI \quad — (4)$$

The electrical power generated in the armature = $E_b I_a$ — (5)

If we decide to ignore (core loss + mechanical loss + stray loss),

we get the output mechanical power as-

$$P_o = E_b I_a \quad — (6)$$

$$= \omega_m T_m \quad — (7)$$

[m → Mechanical]

[For Accuracy →
$P_o = E_b I_a$ − mech loss − core loss − stray loss]

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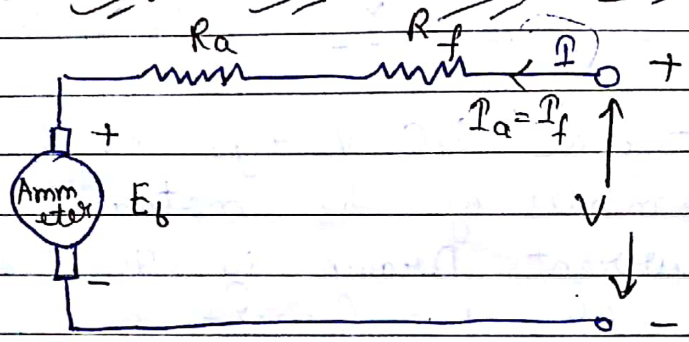
$$= \frac{2\pi N}{60} T_m \quad \text{— (8)}$$

$$\eta = \frac{P_o}{P_I} \quad \text{— (9)}$$

[$N \to$ turbine speed]
(frequency)

✯ Analysis of a series-wound DC motor :-



$$I = I_f = I_a \quad \text{— (1)}$$

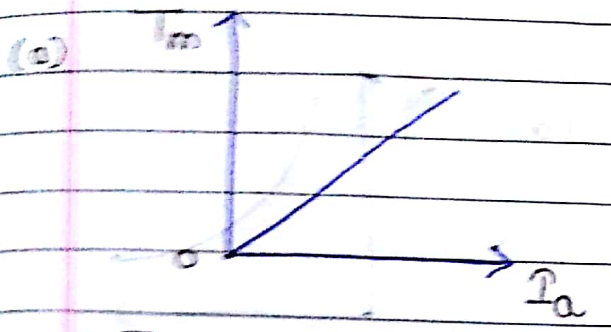
$$I = \frac{V - E_b}{R_a + R_f} \quad \text{— (2)}$$

$$E_b = V - I(R_a + R_f) \quad \text{— (3)}$$

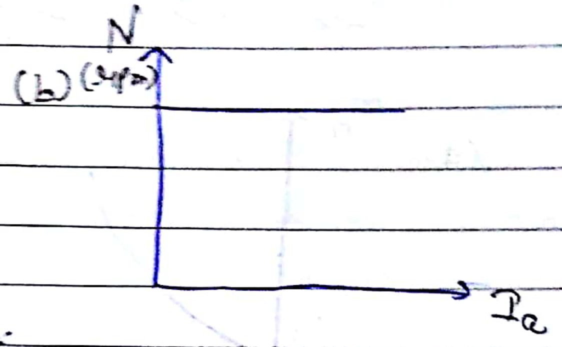
✯ Performance Parameters of a DC motor :-

(i) Losses
(ii) Efficiency
(iii) Torque produced V/S Armature Current
(iv) Speed produced V/S Armature Current
(v) Torque V/S Speed

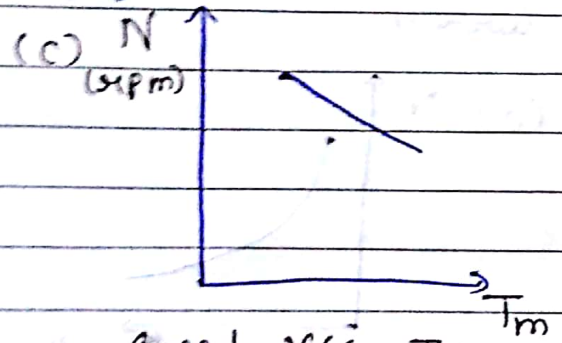
For a shunt-wound DC motor -



Torque V/S Armature Current



Speed V/S Armature current



Speed V/S Torque

From ⑥ & ⑦

$$\omega_m T_m = E_b I_a$$

$$\Rightarrow T_m = \frac{E_b I_a}{\omega_m} = \frac{E_b I_a}{2\pi N} \times 60$$

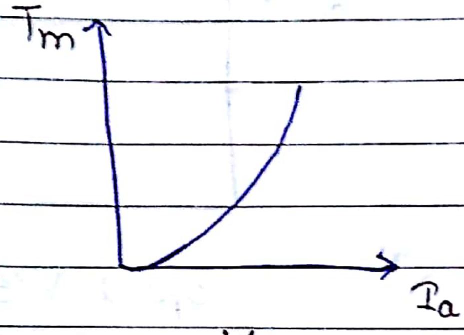
$$\& \quad E_b = \frac{\phi Z N P}{60 \times A}$$

Speed Regulation →

$$= \left(\frac{\text{No-load speed} - \text{Full-load speed}}{\text{Full-load speed}}\right) \times 100$$

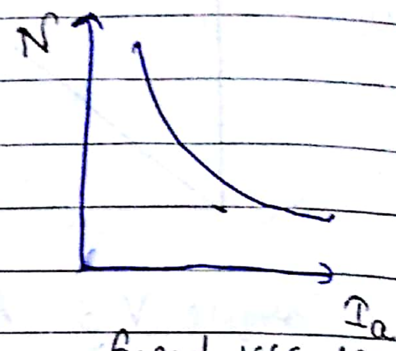
For a series-wound DC motor :-

(a)



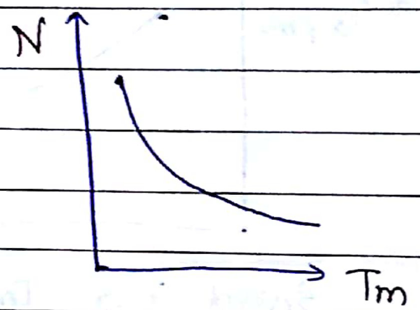
Torque V/S Armature current

(b)



Speed V/S ~~Arme~~ Armature Current

(c)



Motor Speed VS Torque

$$\phi \propto I_f \quad \Rightarrow \phi \propto I_a$$

$$E_b = \frac{\phi Z N P}{60 A} \quad \left[\Rightarrow E_b \propto I_a \right]$$

$$\omega_m T_m = E_b I_a$$

$$T_m \propto \frac{E_b I_a}{\omega_m}$$

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

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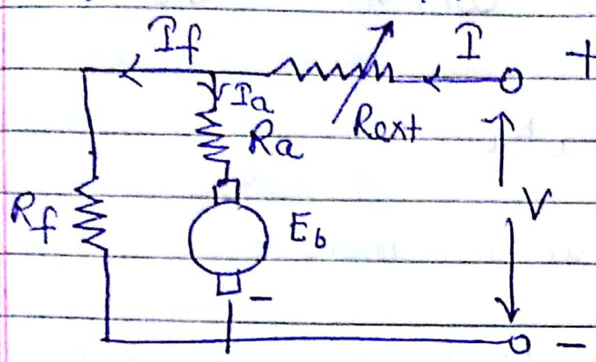
★ The need for starter in a DC motor :-



When we apply an external Voltage 'V' to the motor, initially the motor speed $N = 0$.

Hence $E_b = \frac{\phi Z N P}{60 A} = 0$

Hence, the armature current $I_a = \frac{V - E_b}{R_a}$ is quite large (since the armature resistance R_a is generally small). This will damage the motor. We use "starter" to to avoid this problem. Starter is nothing but a variable resistant R_{ext} put in series with the motor. Initially, we make $R_{ext.}$ quite high. As motor starts picking speed, we generally reduce R_{ext} and make it almost zero by the time the motor has picked up the full-speed.

Speed Control →

Speed $(N) \propto \frac{E_b}{\phi}$

(i) By changing ϕ : $\phi \propto I_f$

(Field or flux control method) $\Rightarrow \phi = K I_f$

[K → constant of prop.]

Teacher's Signature

(ii) By Change E_b :
(Armature control method)

$$E_b = V - I_a R_a$$

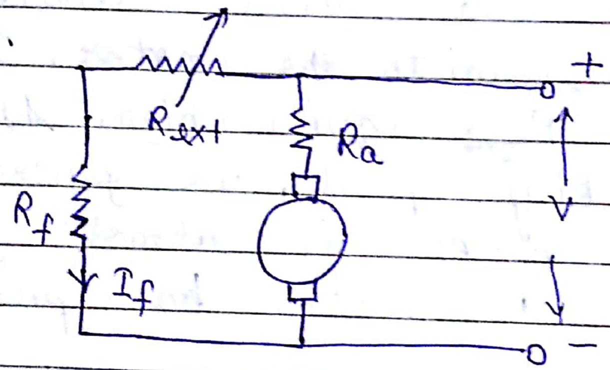
Speed Control of a DC motor :-

Since, $N \propto \frac{E_b}{\phi}$ — ①

We can change N by "Armature control" method or "Field (flux) Control" method.

(a) Shunt Wound motor =>

(i) Flux Control method :->



I_f changes with R_{ext}.

& Since $\phi \propto I_f$

$\therefore$ ϕ changes with R_{ext}.

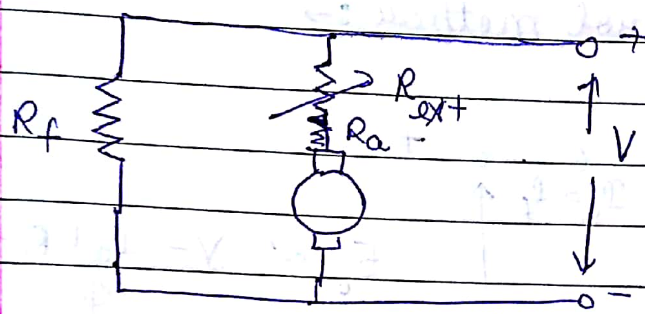
Field current (I_f) is given by –

$$I_f = \frac{V}{R_f + R_{ext}} \quad — ①$$

$$\phi = K I_f \quad — ②$$

$$\because N \propto \frac{1}{\phi} \Rightarrow N \propto \frac{1}{I_f} \Rightarrow N \propto R_{ext.}$$

(ii) Armature Control method :→



$$N \propto \cancel{\frac{V - I_a R_a}{\phi}} \quad — \cancel{①}$$

$$N \propto \frac{V - I_a(R_a + R_{ext})}{\phi} \quad — ①$$

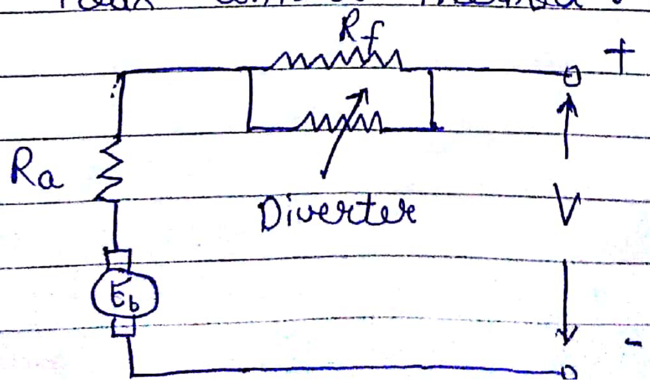
$\phi \rightarrow$ Constant

(iii) Voltage Control method :-

external Voltage is ~~cont~~ provided to control I_f.

(b) Series-Wound DC motor ⇒

(i) Flux-Control method :→

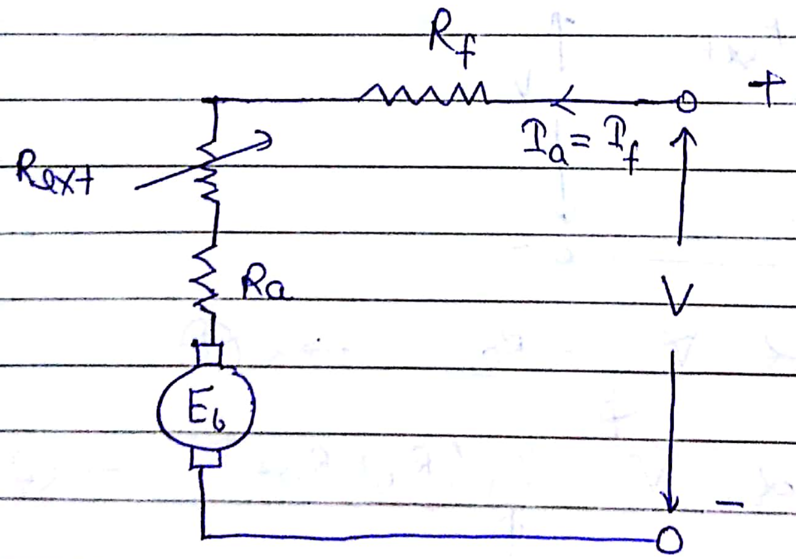


Diverter → R_{ext}

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

Diverter can have varied resistance per "continuous control" or "tapped-control" ('Discrete values)

(ii) Armature Control method :→



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