Machines

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2nd semester 2018

MechFamily

كُن أنت التغيير..

Notebooks

• Magnetic Field:

*** what?**

This is the field produced by permenant magnet or electromagnetic. "مغناطيس طبيعي"

*** why?**

Because the operation of transformers and electrical machines depend on the existance of magnetic field.

*** How?**

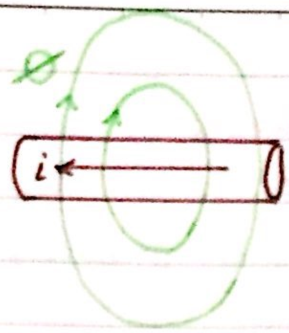
*** principles:**

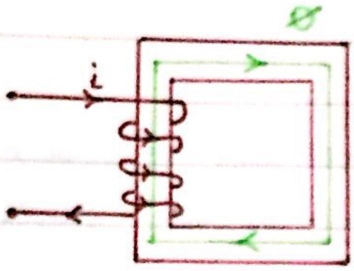
i. Any current (i) generates a magnetic field (ϕ); where ($\phi \propto i$).

i	ϕ
DC	DC
AC	AC

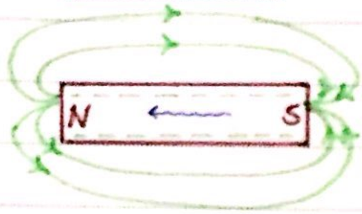
"ϕ" is represented by closed loops whose direction can be found by using "RHR" => Right Hand Rule.

e.g. :



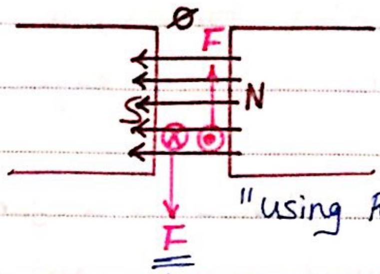


* Inside "S → N"
* Outside "N → S"



ii. A conductor cutting a magnetic field will have a voltage induced in it; whose polarity can be found by using "RHR" ⇒ right hand Rule.

* This is the generator action.



"Voltage is induced"

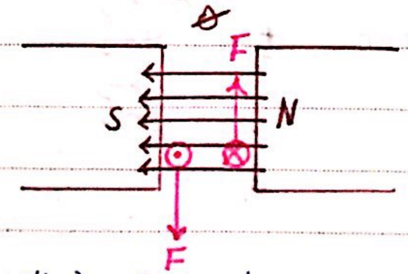
"using RHR"

F → Direction of applied force. (i.e. Motion).

$\odot$ out of the Board. $\otimes$ Into the Board. ⇒ Direction of induced voltage.

iii. A current carrying conductor located in a magnetic field will have a force (F) induced in it; where the direction of (F) can be found by using LHR "Left Hand Rule".

* This is the motor action.



"Force is induced"

$\odot$ $\otimes$ ≡ Direction of applied current.

F ≡ Direction of generated or developed force.

* Motor: gets electrical but gives mechanical.
* Generator: gets mechanical but gives electrical.

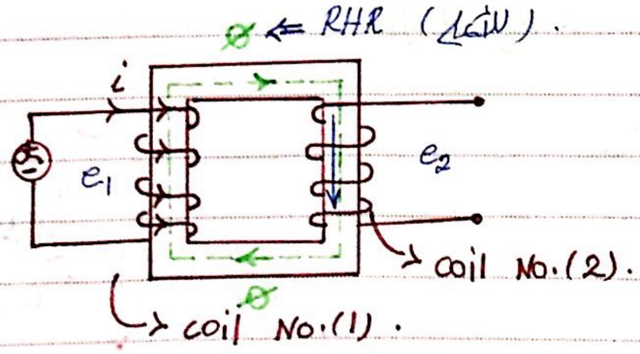
=> Note: Because of the existance of two opposite forces; a torque will be generated. "consequently a torque will be developed".

=> Note: Hence in a generator action; there is a motor action and in a motor action; there is a generator action.

* when we connect a voltage source with a Load; a current will flow then a force will be developed which opposes the applied force.

iv. A time varying flux (Ø) linking (i.e. cutting) a conductor or a coil will induce a voltage (e) in the conductor or coil.

* This is the transformer action.



* If we connected it with a DC-Voltage source; a DC flux will be developed. But, there is no voltage will be induced in the second coil depending on "Faraday's Law".

[If the flux is constant; there is no voltage induced.]

* Ex.:

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} = 10$$

$e_1 = 20$ volt ; $e_2 = ?$ if connected to a DC-source.

$\Rightarrow e_2 = 0$ volt.

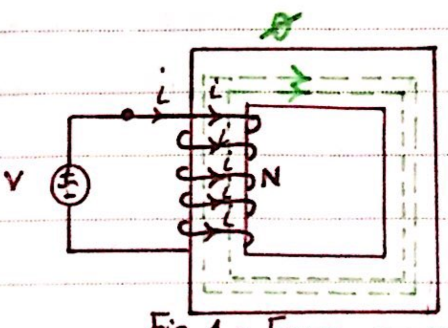
• Basic concepts of magnetic circuits.

* Amper's Law $\Rightarrow \oint H.dL = i$ --- (1) ; where:

↳ Line integral.

$H \equiv$ Magnetic field strength which produced by the current (i).

$L \equiv$ The length of the flux line which encloses i and illustrated as follows:-



$N \equiv$ No. of turns.

قالب حديدي

Fig.1 - Ferro-magnetic field.
core.

NO.

* For (Fig.1) ;

$H l_c = Ni$ --- (1)

(Amp.-turns)

∴ l_c : mean length of flux path.

=> unit of (H) is (A. -turns)/m.

$B = \Phi / A$ --- (2)

B : Flux density. (wb./m^2) or Tesla (T)

A : Cross-sectional area of the core on which (Φ) is perpendicular ⊥ .

* ال (flux) عمودي ع (cross-sectional Area).

$B = \mu H$; $\mu = \mu_0 \mu_r$ ≡ permability.

μ_0: permability of free space ($4\pi * 10^{-7}$).

μ_r: permability "relative" of the core.

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• $Ni = HL = \frac{B}{\mu} L = \frac{\phi}{A} \cdot \frac{L}{\mu}$

$\therefore \underbrace{Ni}_{(mmf)} = \frac{L}{A\mu} \phi$

↳ This is called "Reluctance" $\mathcal{R}$

Γ (mmf) $= \mathcal{R}\phi$; where $\mathcal{R} = \frac{L}{A\mu}$

↳ [Eta; semba].

↳ $\mu = \mu_o \mu_r$; $\mu_r = \frac{\mu}{\mu_o}$

$\phi = \frac{\Gamma}{\mathcal{R}}$; As $\mu \uparrow$ => Then $\mathcal{R} \downarrow$ => Then $\phi \uparrow$

* That is why in transformers and machines ; Ferromagnetic materials (i.e. high μ_r) are used.

* Analogy between electrical and magnetic ccts. :

Electrical ccts.	Magnetic ccts.
emf ; e or V	mmf ; Γ
i	ϕ
R or X or Z (↳ Resistance.)	$\mathcal{R}$ (Reluctance)

* This is the table that can be used to draw the equivelant magnetic circuits for any magnetic structure.

+ consequently one can apply cct. laws to magnetic cct's.

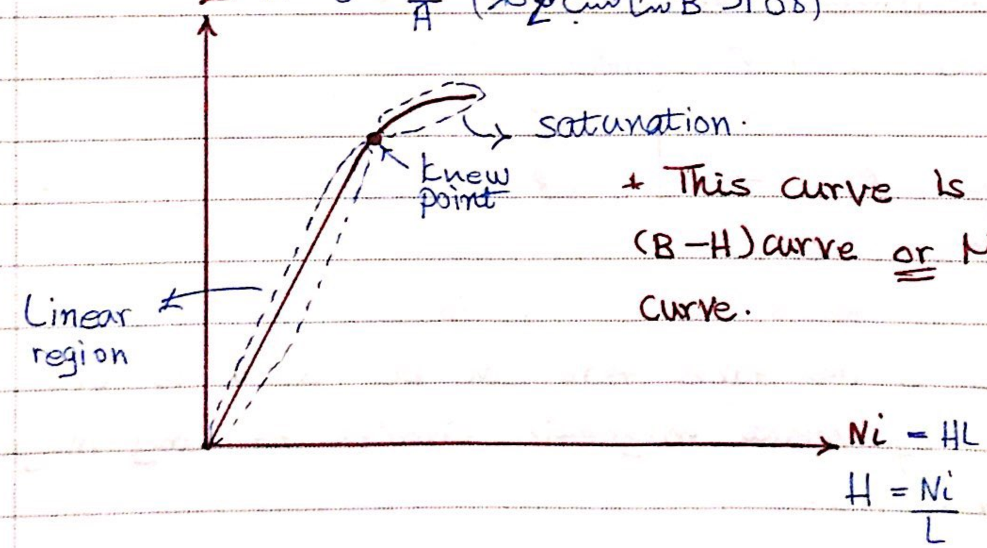
- Ohm's law ⟹ $\Gamma = \mathcal{R}\phi$.
- KVL ⟹ $\sum \Gamma = 0$ around a loop.
- KCL ⟹ $\sum \phi = 0$ at a given junction.

☆ Don't forget parallel and series connection. ☺
The same characteristics can be applied to series and parallel connected elements.

$$B = \mu H.$$

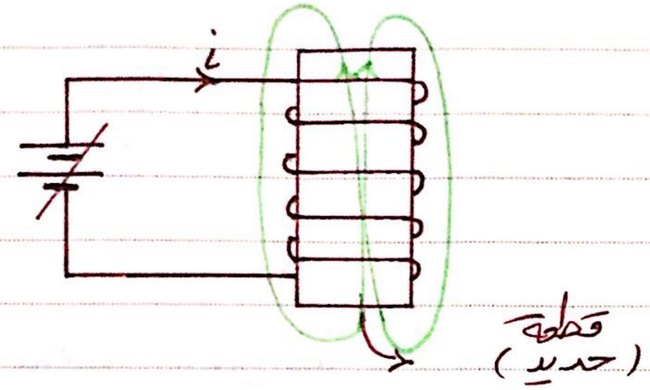
+ Graphical relationship between **B** and **H**.

ϕ or $B = \frac{\phi}{A}$ (لأنّ ال B تناسب مع ϕ)

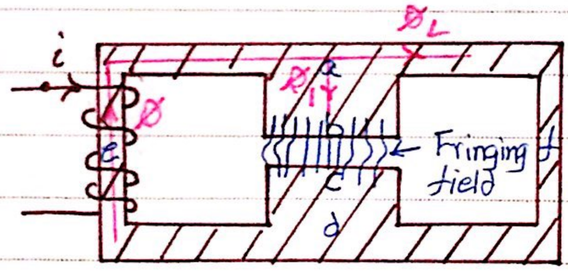


+ This curve is called (B − H) curve **or** Magnetization curve.

* Hence curve is used in the solution of magnetic cct's.
* Each material has it's own (B-H) curve.



* Ex. 1



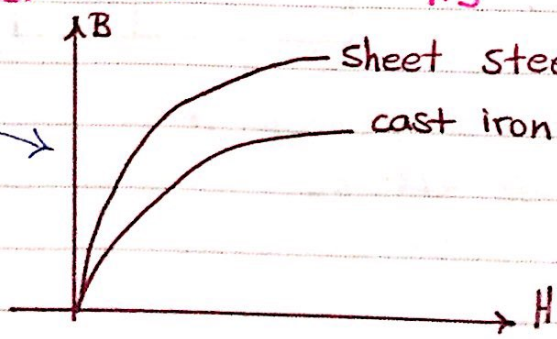
* In this case $A_g > A_c$; in this e.g. (fringing is neglected).

kilo Line or vibers

Path	Material	Length (cm)	Area (cm^2)	Flux (KL)
ab	cast iron	10	10	100
bc	Air-gap	?	10	100
cd	cast iron	10	10	100
dea	sheet steel	60	17.5	225
afd	sheet steel	60	7.5	?

} use the obtained results to find l_{bc} = ?

(given)



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B (kL/cm²)	H (At/cm)	HL	F
10	120	1200	
10	120	1200	
18	150	9000	
16.7	90	5400	

$B = \phi / A$

=> To find (H) use the given curve

(F) By KVL:

$F = F_{dea} + F_{afd}$

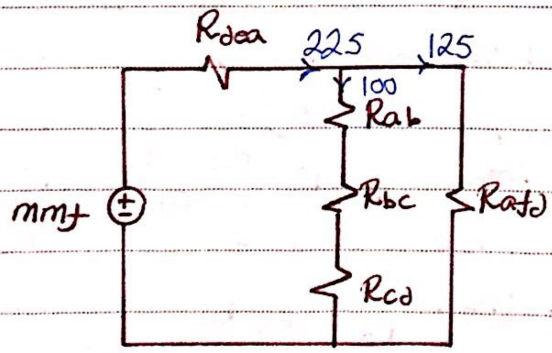
$= 9000 + 5400$

$= 14400$

* mmf (air gap)

mmf (bc)

R (ab, bc, cd) $= R_{afd}$



* $l_{bc} = 0.376$ cm, check it?

Flux (afd) = 125 kL

FIVE APPLE

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• **Losses in magnetic materials:**

1. Eddy current losses; P_e.

* $\phi(t)$ => induces a voltage (e) in the core; since the core is made of conducting material, then a current (i) "This is called eddy current". Due to (e) will circulate within the core in such away to oppose $\phi(t)$.

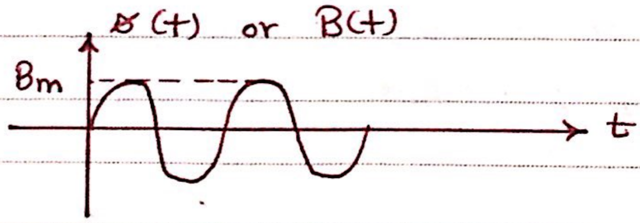
* This is in going to cause losses and heat the core.

* These Losses are called P_e.

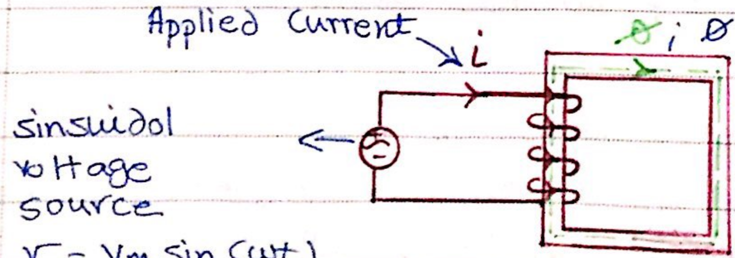
=> It can be found that $P_e = K_e B_m^2 f^2$

$K_e \equiv$ constant depends on the type of ferro-magnetic material.

$B_m \equiv$ Peak or Maximum value of flux density.



$f \equiv$ Frequency of applied voltage or current.



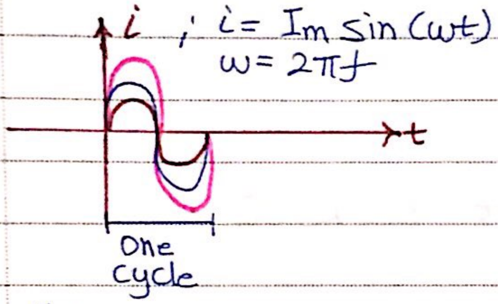
* There is another current inside the core called (eddy current).

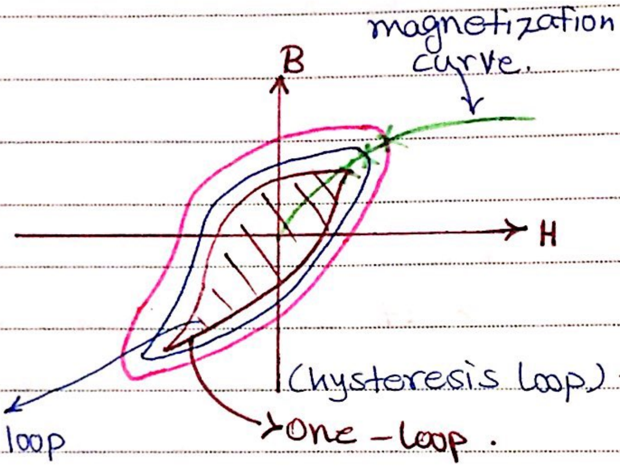
NO.

☆ P_e can be reduced by making the core of شرائح laminations between which there is an insulating material.

* الـ (Laminated core) عبارة عن شرائح بينها مادة عازلة لتخفيض الـ (Eddy-current Losses).

2. Hysteresis Losses:





"Area of the hysteresis loop represents energy density per cycle ; represents the energy supplied or consumed in the processes of of magnetization of (hysteresis loop) magnetic material."

=> As the period of each cycle gets larger ; the area of each loop becomes larger.

* This is called hysteresis losses (P_h).

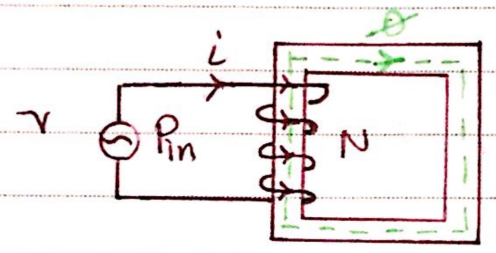
* If we connect the loops tips together ; we will get (Magnetization curve)

=> It can be found that $P_h = k_h B_m^n f$

* $K_h \equiv$ constant "Depends on the type of material"
* $n \equiv$ constant depends on the type of material $(1.5 \leq n \leq 2.5)$.

By definition

* Core losses; $P_c \triangleq P_e + P_h$



P_{in} Losses:

1. To generate flux
2. core losses (Inside the core)
3. Electrical losses (Inside the coil).

* Fill in the blanks:

⇒ $\oint H\,dl = Ni$.

⇒ v ⇒ needs an applied voltage.

⇒ $e \equiv$ Induced voltage due to ϕ.

* By Faraday's Law ⇒ $e \triangleq -N\frac{d\phi}{dt}$ (wL) ↳ to specify the polarity.

[if the flux is DC; there is no induced (e) ⇒ only in AC]

NO.

If $\phi = \phi_m \sin(\omega t)$

→ Derive it

$e = N\phi_m\omega \cos(\omega t)$

$e = E_m \cos(\omega t)$; where $E_m = N\phi_m\omega \equiv$ Peak value.

$$E_{rms} = \frac{E_m}{\sqrt{2}}$$

$E_m = N\phi_m \omega = N\phi_m (2\pi f)$

→ $E_{rms} = 4.44 N\phi_m f$.

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- Comments !

1. There is a rated value for (B_m) in order not to exceed the rated value of (P_e) and (P_h).

2. It was found that $E = 4.44 N f \phi_m$ [rms].

$\therefore \phi_m = \dfrac{E}{4.44 N f}$ $\therefore$ if (f) ↓ ⇒ Then (ϕ_m) ↑ ⇒

In order not to exceed rated value of ϕ_m; then (E) should be decreased ∴ (Derating of the device concerned. Freq. in Jordan 50 Hz
U.S.A 60 Hz

* Transformers *

what ?

It is a device which is used to convert a voltage or a current from one value to another. That is step-up or step-down.

why?

1. It can be used in process of electrical energy transfer, In this case it's called (power Transformer). *

2. It can be used in process of measuring voltage and current, In this case it's called (Instrument Transformer).

NO.

3. It can be used in process of changing the magnitude of impedence, In this case it's called (Impedence matching Transformer). *

How?

Construction and analysis of single phase and three phase transformers (1-ph. ,3-ph.).

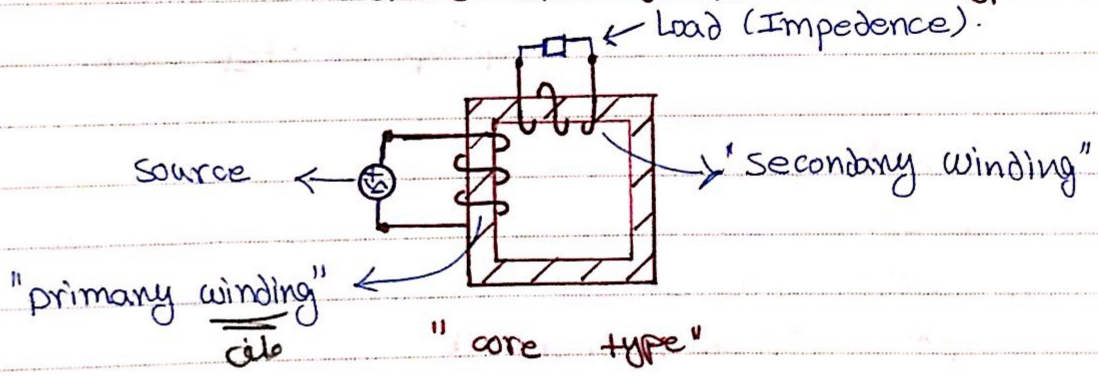
\# 1-ph. Transformer:

=> construction:

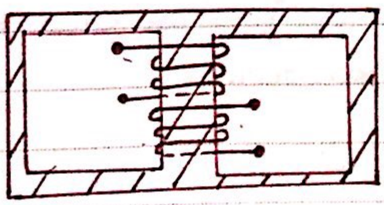
It consists of. :

1. A magnetic core.
2. Two or more coils.

core could be one of two basic types:



" core type"



" shell type"

NO.

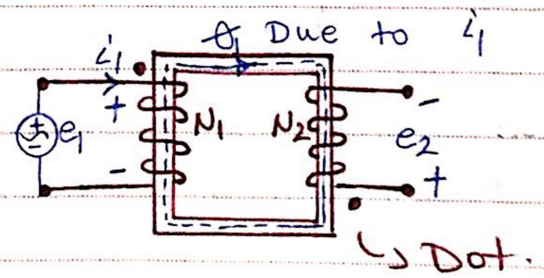
- Primary winding: (P.w.) It is the winding connected to a source.
- Secondary winding: (S.w.) It is the winding connected to a Load.

- Notes:
  - If the transformer is step-up; then the primary is Low voltage (L.v.); secondary is High voltage (H.v.).
  - If the transformer is step-down; then the primary is High voltage (H.v.); secondary is Low voltage (L.v.).

* Ideal 1-ph. Transformer.:

1. A Lossless transformer (No core or electrical losses.)
2. All the flux is within the core.
3. $\mu_r = \infty$

voltage (بنزل) ↑
(current بتعبر ال).



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where;

$V \equiv$ Applied voltage.

$i_1 \equiv$ Applied current.

$N_1; N_2 \equiv$ no. of turns.

$e_1; e_2 \equiv$ Induced voltages due to ϕ_1.

where (as a magnitude):

$e_1 = N_1 \frac{\partial \phi_1}{\partial t}$ ← بدون سالب (لأنها mag. فقط).

$e_2 = N_2 \frac{\partial \phi_1}{\partial t}$

$\therefore \frac{e_1}{e_2} = \frac{N_1}{N_2}$

The voltage direction can be found by knowing the current flow direction (+ve - sign at the current entrance).

*** polarity of e_1 and e_2:**

This is defined by Dot convention (•) which is defined as:

- If a current enters a dotted terminal; it will induce a voltage in the second coil where (+ve) is at it's dotted terminal.

- If a current enters an un-dotted terminal; it will induce a voltage in the second coil where (+ve) is at it's undotted terminal.

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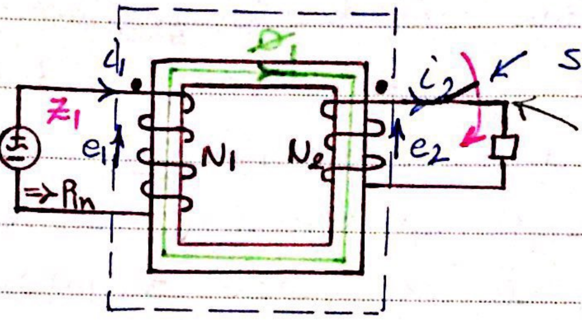
* قيمة ال Flux في ال Transformer دائماً ثابتة.



* في هذه الحالة لا يوجد current لأن الدائرة مفتوحة

* $\frac{e_1}{e_2} = \frac{N_1}{N_2}$

$i_1 = \frac{V - e_1}{Z_1}$

- **Dot concept** is based on Flux Aiding (i.e. if currents enter dotted terminals, they will generate flux in the same direction).

* Note: The previous analysis was based on No-Load condition.

*** Loading conditions:**

close $\underline{\underline{S}}$ "switch" $\Rightarrow i_2$ is going to flow $\Rightarrow i_2$ generates $\phi_2 \Rightarrow \phi_2$ opposses $\phi_1 \Rightarrow$ $\therefore$ Resultant flux in the core $\downarrow$.

$\therefore e_1 \downarrow \Rightarrow \therefore i_1$ is going to increase by an amount say i_1', in order to oppose mmf of i_2. In order to bring the flux in the core to it's original value.

* i_1' is called "Load component of primary Current", when:

$i_1' N_1 = i_2 N_2$ --- (1)

NO.

Summary:

when the switch is open, a current i_1 is induced then ϕ_1 developed in the two coils. Then the switch is closed. so, ϕ_2 is developed opposes ϕ_1. so, $\phi_{tot.}$ is reduced and e_1 is reduced as well. Then an mmf is developed in the opposite direction of secondary's coil mmf to let $\phi_{tot.}$ returns to it's original value.

∴ In general primary i_1 consists of two components:

$$i_1 = i_{1NL} + i_1' \quad \text{--- (2)}$$

NL: No-Load

since:

$$i_1' \gg i_{1NL} \Rightarrow \therefore i_1' \approx i_1 \quad \text{--- (3)}$$

Sub. (3) into (1):

$$i_1 N_1 = i_2 N_2$$

$$\therefore \frac{i_1}{i_2} = \frac{N_2}{N_1}$$

NO.

Fill in the blanks:

what is the function of i_1 (to generate flux ϕ_1)

i_1 (?)

⇒ Small Letters (Time Domain)

capital Letters (phasor Domain)

$$\therefore \frac{e_1}{e_2} = \frac{i_2}{i_1} = \frac{N_1}{N_2} = a$$

$a \equiv$ called "Turns ratio".

* Since $\underline{\underline{a}}$ is a real number then e_1 & e_2 are In phase, also i_1 & i_2 are in phase.

$$\therefore \frac{E_1}{E_2} = \frac{I_2}{I_1} = a \quad ; \quad E, I \equiv \text{Phasors.}$$

For $\underline{\underline{\text{ideal}}}$ transformers $V = E_1$ and $V_2 = E_2$

↳ No resistance or reactance.

$V = E + I_2 V_2$

$$\therefore \frac{V}{V_2} = \frac{I_2}{I_1}$$

$\therefore V I_1 = V_2 I_2$ ⇒ apparent power.

$|V||I_1| = |V_2||I_2|$

NO.

- Apparent power of primary and secondary of HV (and/or) LV sides are equal.

* مقطع السلك الذي بمر فيه تيار أكبر يكون أكبر (سماكة أعلى) وبالتالي
فطاقة أحمل بناءاً على الـ (Apparent power) ⇐ ($V I_1 = V_2 I_2$)

$P_{in} = V I_1 \cos\theta_1$ | since $\theta_1 = \theta_2$

$P_{out} = V_2 I_2 \cos\theta_2$ | $\therefore P_{in} = P_{out}$

$\therefore \eta$ (i.e. efficiency) $= 100\%$ ⇒ IDEAL ($P_{in} = P_{out}$)

Impedance Relationship:

$$Z = \frac{\text{phasor voltage}}{\text{phasor current}}.$$

$$Z \triangleq \frac{V}{I}$$ ⇒ capital (I)

$$Z_1 = \frac{V}{I_1} \quad \text{--- (1)}$$; $Z_1 \equiv$ Impedance of transformer seen from primary side.

$$\Rightarrow \frac{V}{V_2} = \frac{I_2}{I_1} = a \quad \text{--- (2)}$$

Sub. (2) into (1):

$$Z_1 = \frac{aV_2}{I_2 / a} = a^2 \frac{V_2}{I_2} = a^2 Z_2 \Rightarrow \boxed{Z_1 = a^2 Z_2}$$

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

* $Z_1 = \frac{V_1}{I_1} = \frac{aV_2}{I_2/a} = a^2 \frac{V_2}{I_2} = a^2 Z_2$

$Z_1 = a^2 Z_2$ OR $Z_2 = \frac{1}{a^2} Z_1$

∴ To reflect Z_2 (secondary impedence) to (primary side) multiply it by a^2; OR to reflect Z_1 (primary impedence) to (secondary side) divide it by a^2.

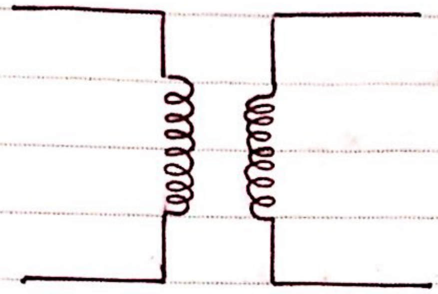
$V_1 = aV_2$ OR $V_2 = \frac{1}{a} V_1$

∴ To reflect V_2 (secondary voltage) to (primary side) multiply it by a; OR to reflect V_1 (primary voltage) to (secondary side) divide it by a.

$I_1 = \frac{1}{a} I_2$ OR $I_2 = a I_1$

∴ To reflect I_2 (secondary current) to (primary side) divide it by a; OR to reflect I_1 (primary current) to (secondary side) multiply it by a.

* This concept of reflection can be used to find a single equivalent circuit of Transformer by reflecting primary to secondary or the other way round. or by reflecting "High voltage" to "Low voltage" or the other way round.



$N_1 : N_2$

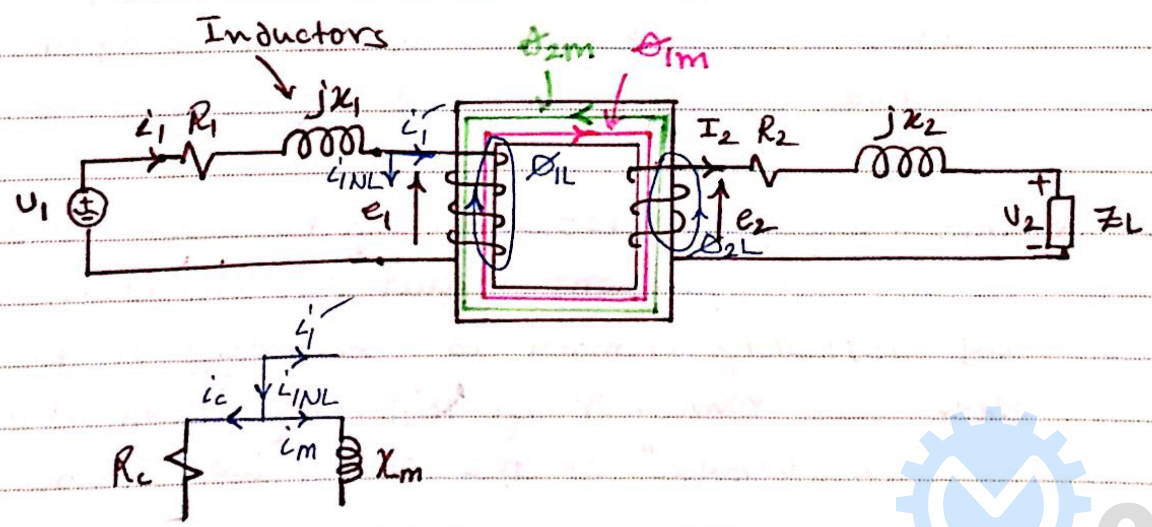
$1 : \frac{N_2}{N_1} = a$ OR $a = \frac{N_1}{N_2} : 1$

- **In general:**

1. To reflect from the "1" side to "a", then multiply "Z" by a^2, multiply "V" by a and divide "I" by a. (primary to secondary).

2. To reflect from the "a" side to "1" side, then divide "Z" by a^2, divide "V" by a, and multiply "I" by a.

*** Practical or Real Transformers:**



NO.

1. Each coil has resistance, R_1 and R_2.
2. ϕ_{1L}, ϕ_{2L} "Leakage flux in the coils", ∴ they are represented by reactances (jx_1) and (jx_2)

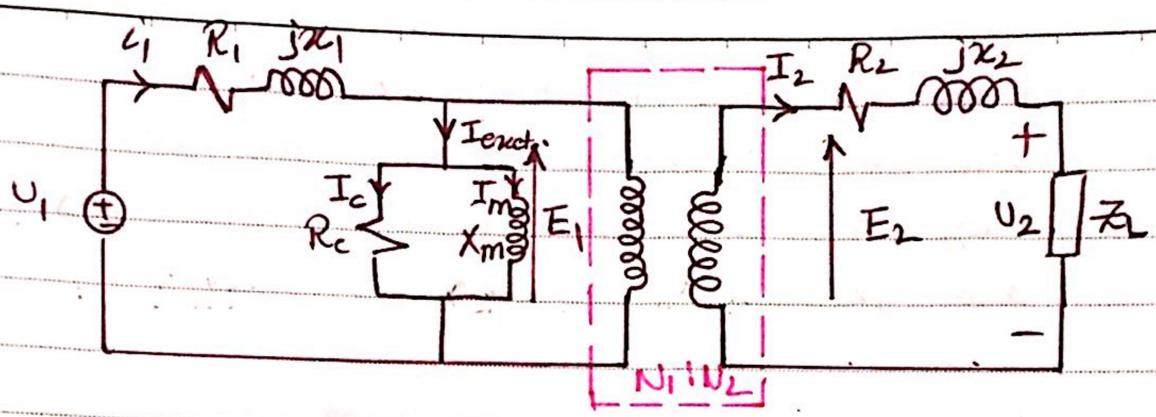
- primary current ≡ two components (Load + No Load).

v_1 ≡ Primary applied voltage.
i_1 ≡ Primary applied current $= i_{1NL} + i_1'$
i_{1NL} ≡ is called excitation current
No Load

$i_{1NL} = i_m$ (magnetizing current) $+ i_c$ (core loss component).
R_c ≡ Resistance to represent current losses.
X_m ≡ To represent mutual flux being generated.
i_1' ≡ Load component of i_1.
e_1, e_2 ≡ Induced voltage.
I_2 ≡ secondary or Load current.
V_2 ≡ secondary "terminal" voltage.

∴ A practical transformer can be represented by an ideal transformer in series with Passive elements on both sides as follows:-

NO.



Practical Transformer.

13. 2. 2018

* Equivalent circuit by using impedance, voltage, and current reflection:

Let $a = \frac{N_1}{N_2}$; let us reflect to the 'a' side

معناه أنو شغلك ال " a – side " بيبقى ثابت.

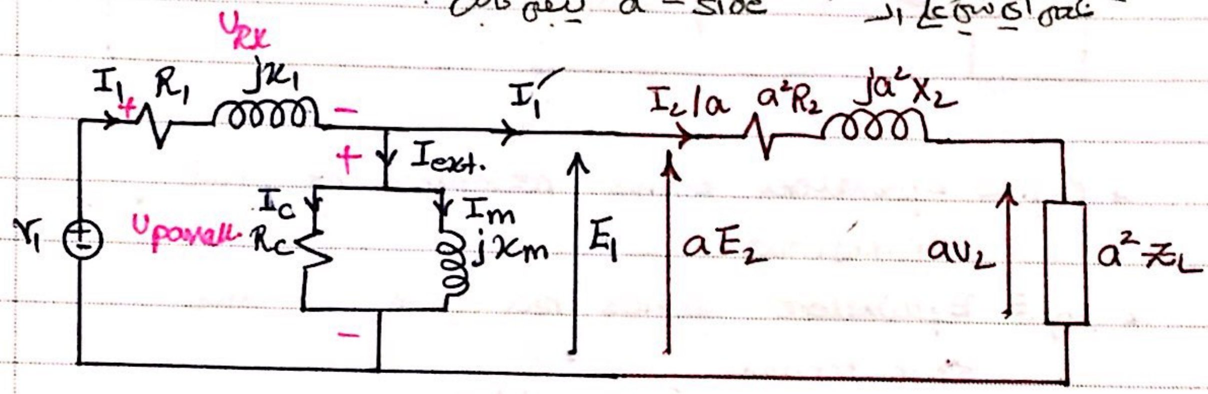


Fig. 1

* Fig. 1 is the exact equivalent cct. of the transformer.

* It can be observed that:

1. $E_1 = aE_2$

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

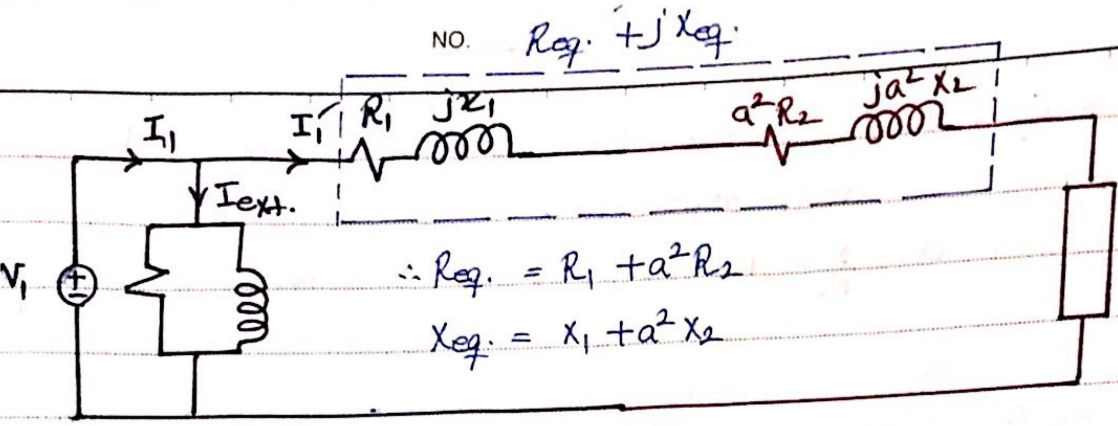
2. $I_1' = \frac{I_2}{a}$

$\therefore \frac{I_1'}{I_2} = \frac{1}{a} = \frac{N_2}{N_1}$

1. Since voltage drop in R_1 and x_1 (V_{Rx}) is very small, then one may say that V_1 appears across branch of $R_c // X_m$ (i.e. $V_1 \cong V_{parallel}$).

$\therefore$ This parallel branch can be shifted to the input.

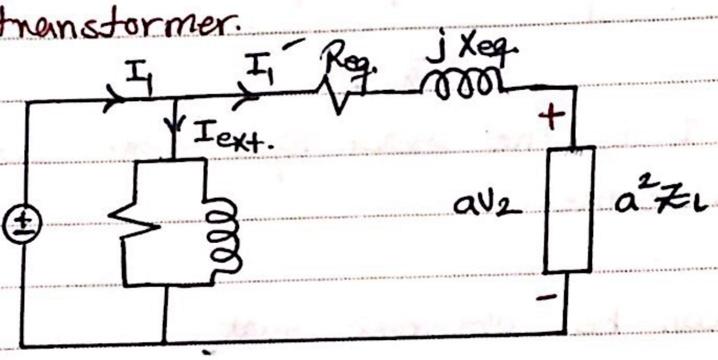
NO.



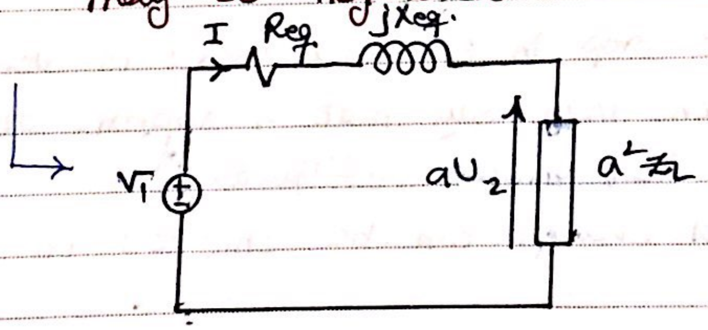
$\therefore R_{eq.} = R_1 + a^2R_2$

$X_{eq.} = X_1 + a^2X_2$

* $R_{eq.} \equiv$ Equivalent series resistance of the transformer.
* $X_{eq.} \equiv$ Equivalent series reactance of the transformer.



2. Since ($I' \gg I_{exct.}$), Then parallel branches may be neglected.



$Z_{eq./a} = R_{eq./a} + jX_{eq./a}$

• **Note:** If the reflection was to "1" side.

$\therefore R_{eq._1} = R_2 + \frac{R_1}{a^2}$ $\quad\quad$ $\therefore R_{eq.a} \neq R_{eq.1}$

$X_{eq_1} = X_2 + \frac{X_1}{a^2}$ $\quad\quad$ $X_{eq.a} \neq X_{eq.1}$

* **Exam:**

Find $Z_{eq.}$ refered to low or high voltage.

انت تقدر تحط الـ a اللي تريدها واللي تناسبك.

=> Try at home $a = \frac{N_2}{N_1}$; reflect once at a and once on 1.

* Tests on the transformers:

* **what?**

In order to determine it's parameters $R_{eq.}$, $X_{eq.}$, R_c and X_m. so, that it's:
voltages, currents, Power
voltage regulation and efficiency can be determined.

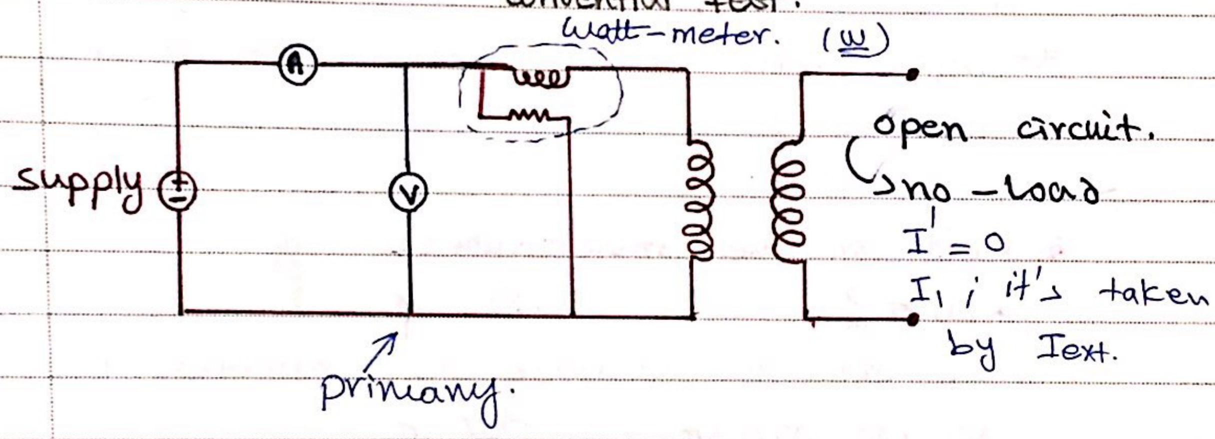
* **How?**

By performing open-circuit (o/c) and short circuit (s/c) tests.

NO.

* (O/C) test.

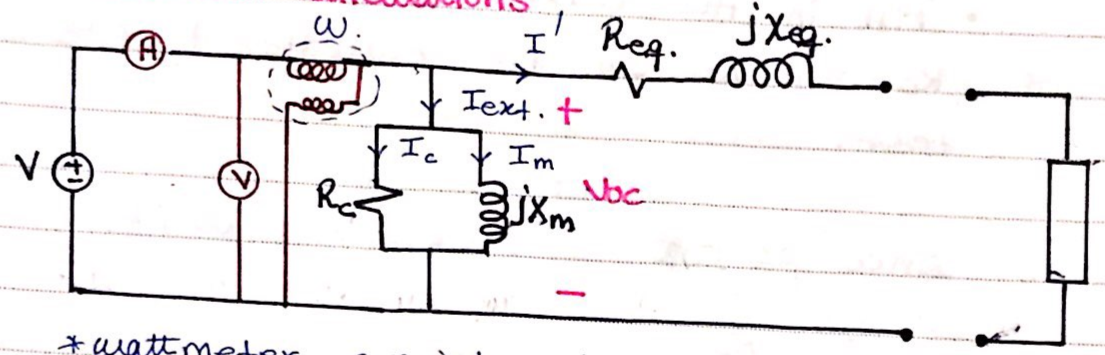
1. Open circuit one of it's sides (i.e. LV or HV); Since it's easier to obtain LV in the Lab, then in convential test HV is made open and rated voltage is applied to LV side.
   ↳ it's up to you to choose weither the HV or LV is open unless it was required to use the "convential test".



2. Take the reading of input current (A), voltage (V) and power (W).

NO. 15. 2. 2018

- (O/C) test calculations



* wattmeter consists of two coils "current coil in series + potential coil".
* $I_{ext.} \equiv$ No load current.

- In red $\equiv$ Measuring instruments
  - Ammeter
  - Voltmeter
  - wattmeter

* $I_1' = 0$

- Ammeter Reading, $I_{oc} = I_{ext.}$ (A)
- Voltmeter Reading, $V_{oc} \equiv V$ across $R_c \,//\, X_m$ (V)
- wattmeter Reading, $P_{oc} \equiv$ Power consumed in the cct (W).

Conventinal Test => low voltage تركب الأجهزة ع ال

∴ In the (O/C) test, the parameters which can be evaluated are R_c and X_m as follows:

* ما هي ال Electrical losses هي ال losses بسبب مرور التيار/ تغير
و هو عبارة عن ال (no − load I) يولد flux ع ال (jXm) وال
core losses ع ال R_c .

FIVE APPLE

NO.

- Fill in the blanks: "Exam"

R_c and X_m can be evaluated by open circuit test.

Since $P \triangleq V^2/R$ $\therefore R_c = V_{oc}^2 / P_{oc}$

$\therefore P_{oc} = \dfrac{V_{oc}^2}{R_c}$

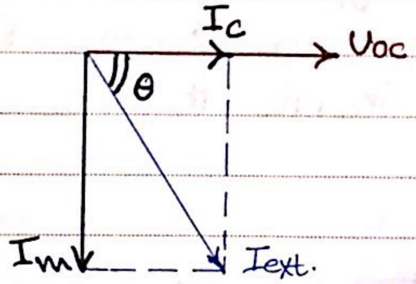
$$R_c = \frac{(\text{voltmeter reading})^2}{\text{wattmeter reading}}$$

$$|I_c| = \frac{V_{oc}}{R_c}$$

$|I_{ext.}| \equiv$ Ammeter reading.

$I_{ext.} = I_m + I_c$ (phasor summation)

I_c and V_{oc} are in phase.



+ which lags and leads:

1. R 2. L 3. C

$I_c = I_{ext.} \cos\theta$

$I_m = I_{ext.} \sin\theta$

$$\therefore |I_{ext.}| = \sqrt{(I_c)^2 + (I_m)^2}$$

$$\therefore |I_m| = \sqrt{|I_{ext.}|^2 - |I_c|^2}$$

$$\therefore X_m = \frac{V_{oc}}{|I_m|}$$

- Resistance => (I and V are in phase).
- Inductor => (I lags V)
- capicator => (I leads V).

Comments:

calculated R_c and X_m are referred to the side at which the readings are taken.

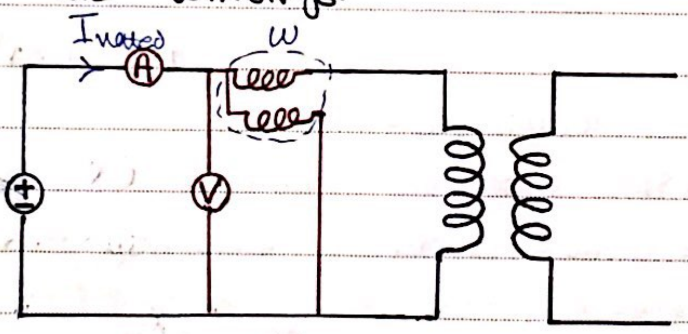
- Referred to low voltage
- Referred to high voltage

ممكن يعطيني القراءات وما يحدد (Referred to what) في هيك الحالة أنا لازم أحدد عن طريق وضع (rating voltage).

- High voltage => low current.
  Low voltage => High current.

• Short circuit test (s/c):

1. short circuit (s/c) the terminals of <u>one</u> of the windings.



short circuit ← Ammeter بدل
open circuit ← voltmeter بدل

2. Apply the rated current to the other winding.

3. Take the reading of the input current, voltage and power.

NO.

Note: Since it's easier to measure low current then high current, [Then in conventinal s/c test; the LV voltage and supply is applied to HV side.

4. calculate the parameters.

• Rated current = $\frac{\text{Rated apparent power, [VA]}}{\text{Rated voltage}}$

Ex.:

Transformer 20 kVA, (240 /110) volt.

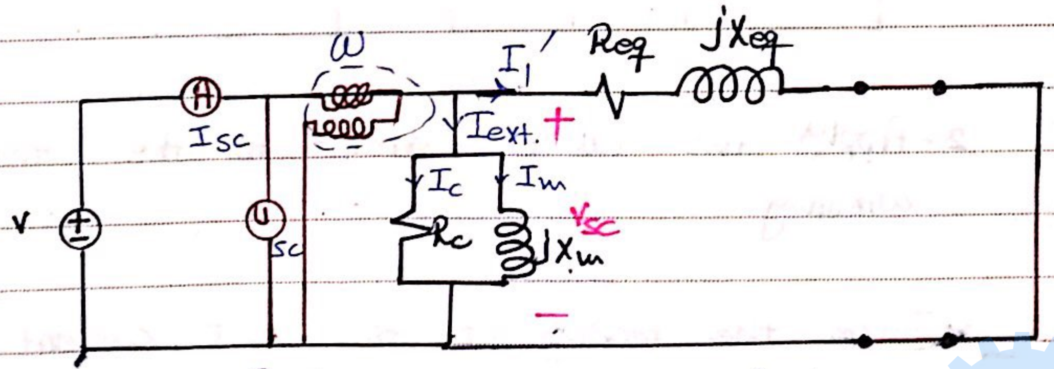
Rated current:

$I_{HV} = \frac{20*10^3}{240}$ $I_{LV} = \frac{240*10^3}{110}$

+ short circuit $Z_L = 0$

in (S/c) test we evaluate (Req. / Xeq.)

P_{sc} ≡ Losses (core + Electrical).

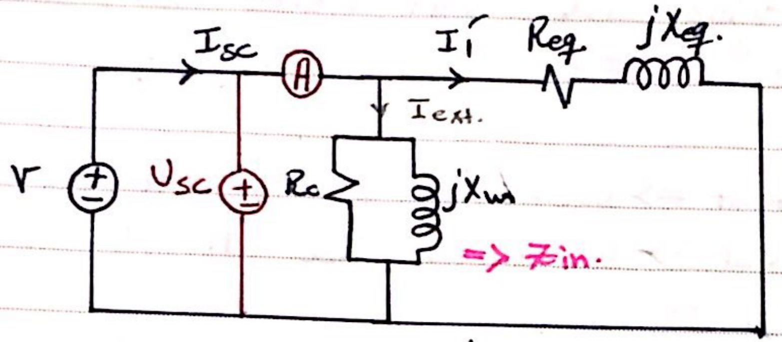


P_{sc} = W - Reading V_{sc} = U - Reading.

I_{sc} = A - Reading

NO. 18. 2. 2018

- Short circuit test:



since $I_{ext.} << I'$

$\therefore I_1' = I_{sc} \equiv$ Amm. Reading.

$\therefore P_{sc} \equiv$ wattmeter Reading $\equiv$ Losses in Req.

$\therefore P_{sc} = I_{sc}^2 R_{eq}$. $\therefore R_{eq.} = \frac{P_{sc}}{I_{sc}^2}$

$\therefore \frac{V_{sc}}{I_{sc}} = |Z_{in}|$ -> magnitude

$= \sqrt{R_{eq}^2 + X_{eq}^2}$ since $Z_{eq.} = R_{eq.} + jX_{eq}$.

$\therefore X_{eq.} = \sqrt{|Z_{in}|^2 - R_{eq.}^2}$.

- The short circuit test, one evaluate X_{eq} and R_{eq}.

=> (O/C) Test ~> we apply rated voltage.

=> (S/C) Test ~> we apply rated current.

NO.

Ex. : A 1380VA, (230/115) V (HV / LV), 50Hz, 1-Ph transformer has been tested with the following results.

* (O/C) test => $V_{oc} = 230V$, $I_{oc} = 0.45A$, $P_{oc} = 30W$
* (S/C) test => $V_{sc} = 13.2V$, $I_{sc} = 6A$, $P_{sc} = 20.1W$

Find the equivalent circuit of the transformer referred to the "LV-side".

=> (O/C) test ~> primary was "High voltage".

• Since in (O/C) test, one apply rated voltage, then in this example the readings were taken on the "HV-side".

∴ The calculated R_o and X_m will be referred to HV side.

∴ Since in (S/C) test, one apply rated current.

$I_{LV,Rated} = \frac{1380}{115} = 12A$

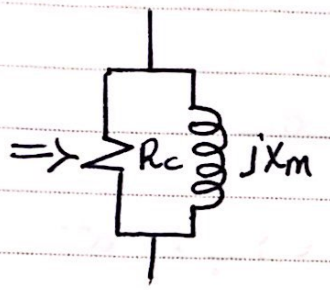
$I_{HV,Rated} = \frac{1380}{230} = \boxed{6A}$ ∴ In this example the readings were taken on the HV side.

∴ The calculated $R_{eq.}$ and $X_{eq.}$ will be referred to the HV side.

NO.

• (O/C)

$P_{oc} = \frac{V_{oc}^2}{R_c}$ $\therefore R_c = \frac{V_{oc}^2}{P_{oc}} = \frac{230^2}{30} = 1763.3\,\Omega = R_{cH}$ --- 1



* $Y = Y_1 + Y_2 = \frac{1}{R_c} + \frac{1}{jX_m} = \frac{1}{R_c} - \frac{j}{X_m}$

$\therefore |Y| = \sqrt{(\frac{1}{R_c})^2 + (\frac{1}{X_m})^2}$ --- 3

but $|Y| = \frac{I_{oc}}{V_{oc}} = \frac{0.45}{230} = 0.001957$ S or ℧ --- 2

sub. (1) and (2) into (3) to find X_m.

$\therefore X_m = 533.9\,\Omega = X_{mH}$

• (S/C)

$P_{sc} = I_{sc}^2 R_{eq}$.

$\therefore R_{eq.} = \frac{P_{sc}}{I_{sc}^2} = \frac{20.1}{(6)^2} = 0.558\,\Omega = R_{eq.H}$ --- (4)

$|Z_{sc}| = \frac{V_{sc}}{I_{sc}} = \frac{13.2}{6} = 2.2\,\Omega$ --- (5)

$X_{eq.} = \sqrt{|Z_{sc}|^2 - R_{eq.}^2}$ --- (6)

NO.

Sub. (4) and (5) into (6).

$\therefore X_{eq.} = 2.128\ \Omega = X_{eq.H}$

=> To refer to "LV-side"; find $\underline{a}$.

(Reflect to $\underline{a}$ side).

Let $a = \frac{N_L}{N_H} = \frac{115}{230} = \frac{1}{2} = 0.5$

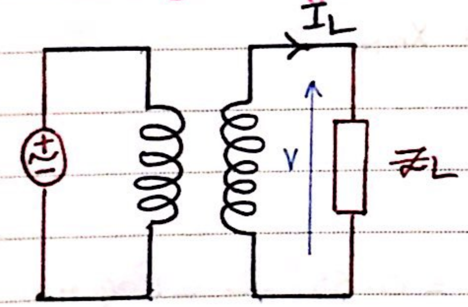
$\therefore R_{eq.L} = R_{eq.H} \cdot a^2$, $X_{eq.L} = X_{eq.H} \cdot a^2$

$\therefore R_{c.L} = R_{c.H} \cdot a^2$, $X_{m.L} = X_{m.H} \cdot a^2$

$R_{eq.L} = 0.139\ \Omega$ $R_{cL} = 440.8\ \Omega$

$X_{eq.L} = 0.532\ \Omega$ $X_{mL} = 133.3\ \Omega$

* Voltage Regulation: VR



$VR \triangleq \frac{|V_{NL}| - |V_{FL}|}{|V_{FL}|} * 100\%$

Magnitudes

NO.

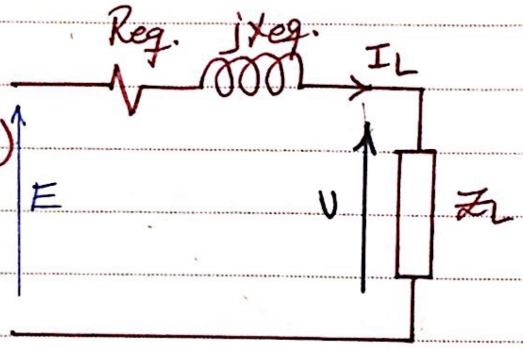
* V_{NL} ≡ No Load voltage.

V_{FL} ≡ Full Load voltage.

I_L ≡ Load current.

To find VR use the equivalent circuit.
↳ referred to the load side (secondary side).

* $E = V + I(R_{eq.} + jX_{eq.})$



• Voltage Regulation:

$$UR = \frac{|V_{NL}| - |V_{FL}|}{|V_{FL}|} = \frac{|E| - |V_{FL}|}{|V_{FL}|}$$

• Efficiency:

$$\eta = \frac{P_{out}}{P_{out} + \text{Losses}} = \frac{P_{out}}{P_{input}}$$

Losses
- Electrical losses (I^2R).
- core Losses
  - Eddey
  - hysteresis

* Example: A 10kVA, (4800/240) V, 50 Hz Transformer was tested with the following results:
(10kVA ↳ Apparent power (rated).)

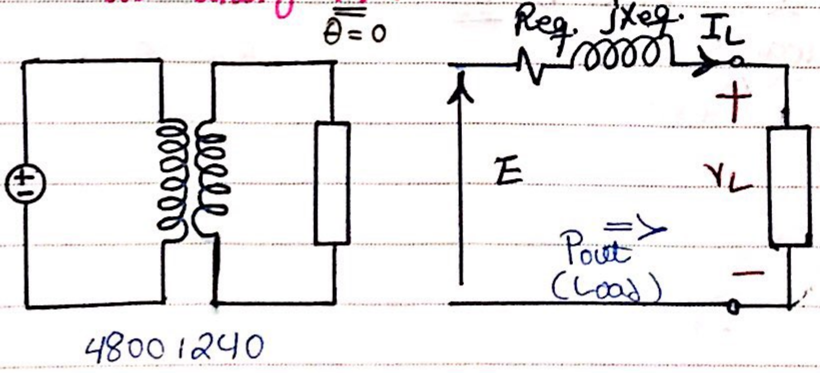
* O/C => 240 V, 1.5A, 60 W

* S/C => 180 V, 2.083A, 180 W

i) Find the voltage regulation if this transformer is used as a step-down to supply a full load at "unity" PF.

$\theta = 0$

Rated current "max. current that can supply!"



$V_L = 240 \angle 0°$

$I_L = \frac{10 \times 10^3}{240} \angle 0°$

+ $Req._L$ and $Xeq._L$ can be evaluated from the given (o/c) and (s/c) results. which it can be found as:-

$Req._L = 0.104\,\Omega$, $Xeq._L = 0.19\,\Omega$

$$*VR = \frac{|E| - |V_L|}{|V_L|}$$

* بالامتحان ممكن يعطيك معلومات زيادة
عشان تخربطك لتحتار.

=> KVL:

$E = V_L + I_L\,(Req. + jXeq.)$

$= 240\angle 0^\circ + 41.67\angle 0^\circ\,(0.104 + j\,0.19)$

$E = 244.3 + j\,(7.93)$

$|E| = \sqrt{(244.3)^2 + (7.93)^2}$

$= 244.4$

$$VR = \frac{244.4 - 240}{240} * 100\% = 1.83\%$$

II) Find η at full load with a PF = 0.9 lagging.

$$\eta = \frac{P_{out}}{P_{out} + \text{Electrical losses} + \text{core losses}}$$

* Full load => multiply it (current) by (1).

$P_{out} = V_L * I_L * \cos(\theta)$

$= (240)(41.67)(0.9)$ OR $(10)(10^3)(0.9)$

9000.72 "Apparent power."

9000

* Half load => *(0.5)

* 0.25 of load => *(0.25)

※ PF = $\cos(\theta)$

NO.

* Electrical losses $= I_L^2 R_{eq.L}$

$= 41.67^2 * 0.104 = 180.5\,w$ **OR**

P_{sc} at full load only (rated current) لأنو بال (S/C) بطبق because I_L is rated

$P_{sc} = 180\,w.$

* core losses:

Core losses $= \dfrac{V_{oc}^2}{R_c} = \dfrac{V_{in\,H}^2}{R_{cH}} = \dfrac{V_{in\,L}^2}{R_{cL}}$ **OR** regulation بنحل at high or low "the same answer"

$= P_{oc} = 60$ watt

at full load or no-load, it doesn't matter since I'm applying rated voltage.

$\eta = 97.4\%$

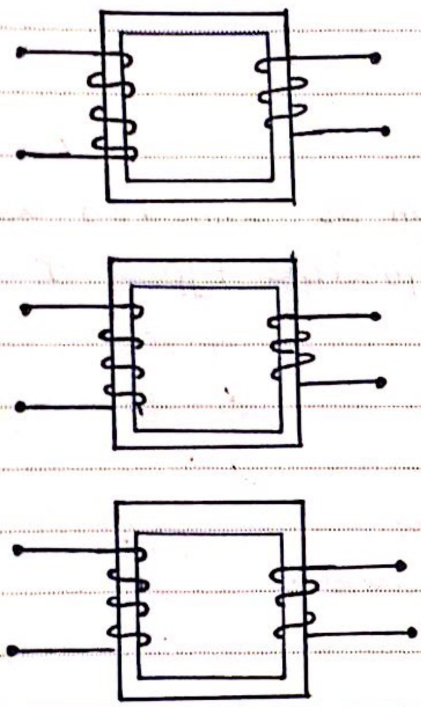
NO. 22 - 2 - 2018

* 3-ph. Transformer:

- Construction:

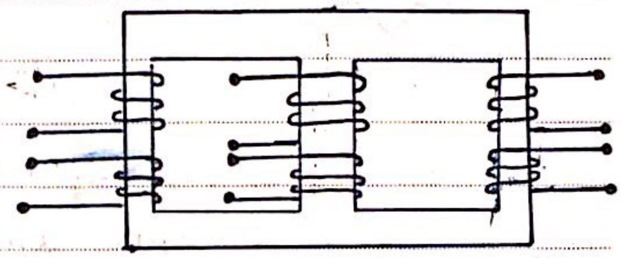
It could be one of two structures:

1. using three 1-ph. transformer, OR
2. A single core with three pairs of windings.



"Bank of 3-ph. transformer"
→ 3 - single phase transformer.

1. more reliable
2. if one 1-ph. transformer fail, then a 3-ph. power can still be supplied but with a reduced input (58%).



This type is more lighter and more economical.

1. It needs less space.
2. It is cheaper.

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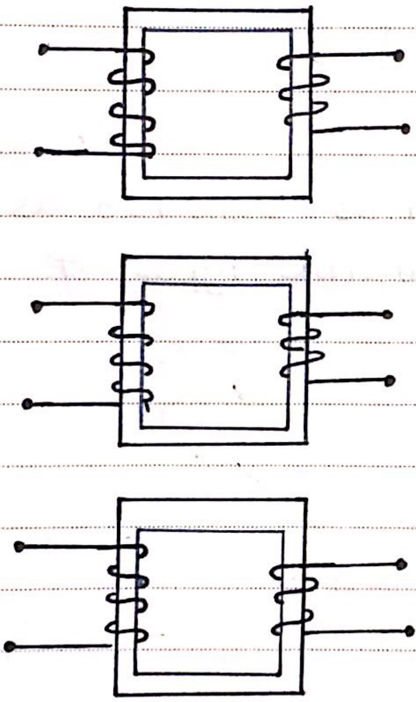

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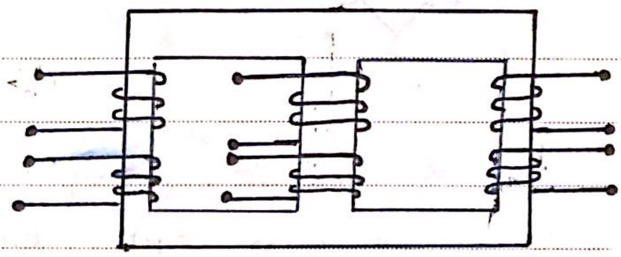

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NO. 22 - 2 - 2018

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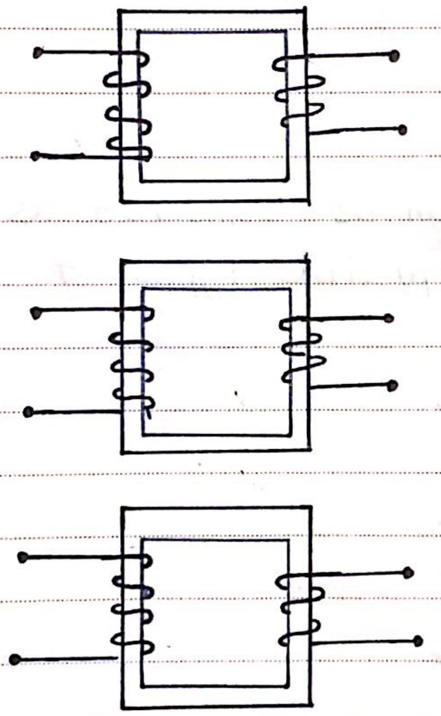

"Bank of 3-ph. trans-former"

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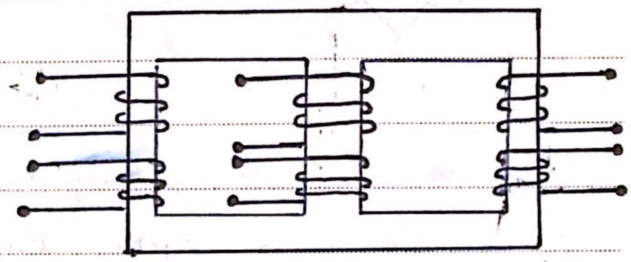
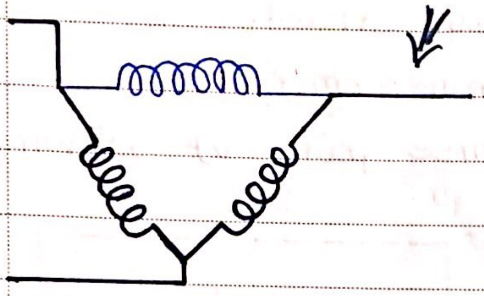


This type is more lighter and more economical.

1. It needs less space.
2. It is cheaper.

NO.

* using the called V- connection.



* Connection types:

since a 3-ph. winding can be connected as Y or Δ then there are 4-possible types of transformers:

1. Y → Δ => Step Down
2. Δ → Y => Step up
3. Δ → Δ => V- connection.
4. Y → Y => Rarely being used.

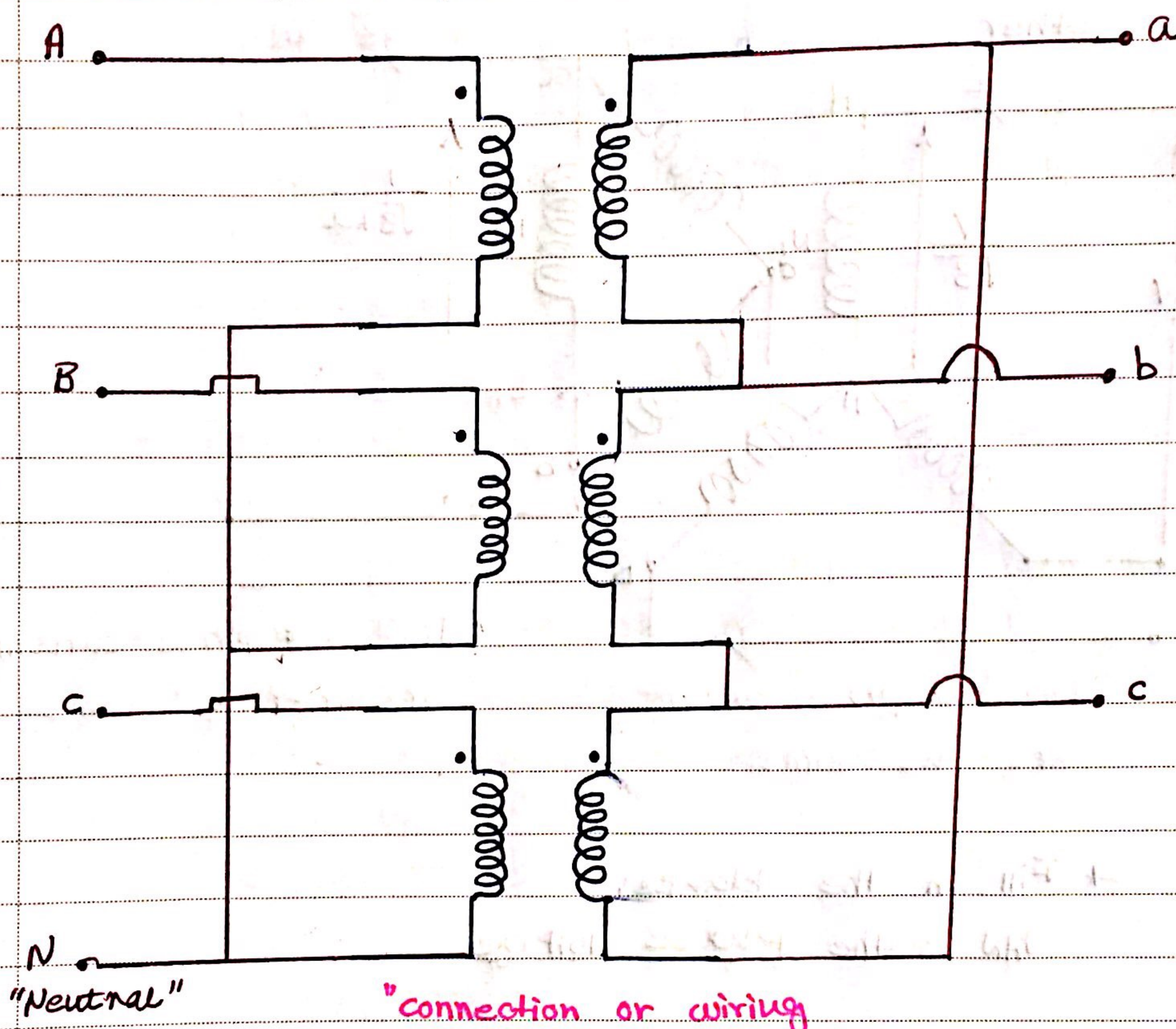
• Markings:

1. usually HV terminals are represented by capital letters (A, B, C)
2. usually LV terminals are represented by small letters (a, b, c).

NO.

Voltage - current relationship:

consider a Y-Δ connection:

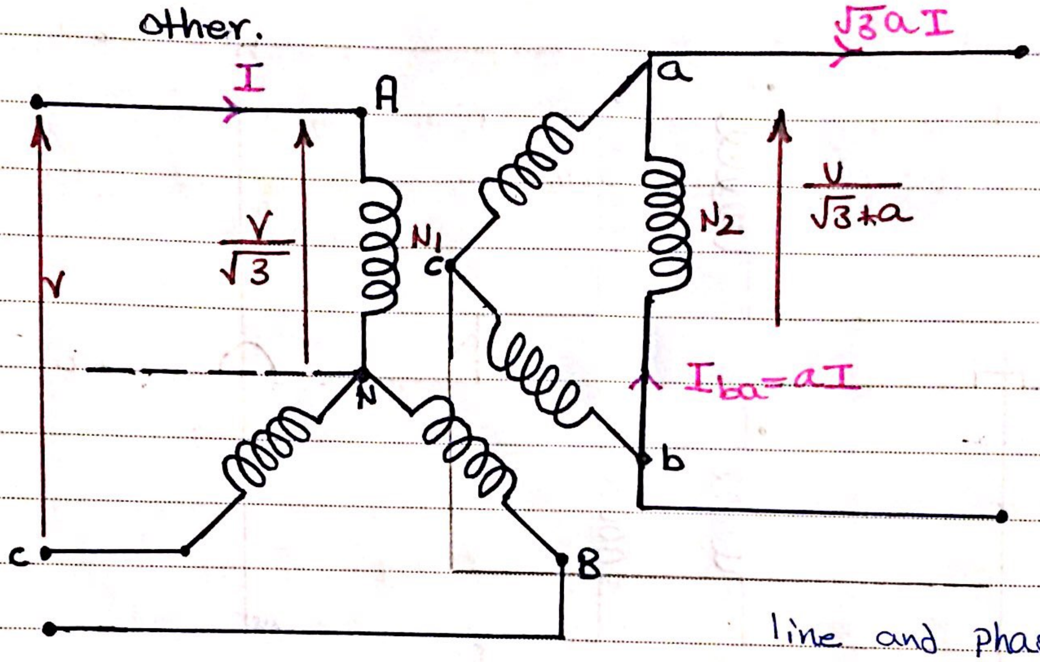


"connection or wiring Diagram."

// => means (parallel).

NO.

*** Schematic Diagram:** Here the winding of each phase are drawn parallel to each other.



line and phase current are the same.

line and phase current are not the same.

* Fill in the blanks:

VAN is the _Phase voltage_ .

N ≡ The common point between the three phases.

N_1, N_2 ≡ No. of turns of HV and LV windings.

Let $a = \frac{N_1}{N_2}$

V ≡ Line voltage.

NO.

* $\frac{|V_{AN}|}{|V_{ab}|} = \frac{N_1}{N_2} = a$

$\therefore |V_{ab}| = \frac{|V_{AN}|}{a} = \frac{V}{\sqrt{3} * a}$ ← magnitude.

* $\frac{I}{I_{ab}} = \frac{N_2}{N_1} = \frac{1}{a}$

$\therefore I_{ab} = aI$

- The same procedure can be repeated to the other connections.

- However the Y−Δ or Δ−Y introduce a phase shift of 30°, as follows:

Assume +ve phase sequence.

let $V_{AN} = V_m \angle\theta°$

$\therefore V_{AB} = \sqrt{2} \angle 30°$

Since ($V_{ab} \parallel V_{AN}$)

$\therefore \angle V_{ab} = \angle V_{AN} = 0°$; Parallel branches have voltages in the same phase.

NO. 25. 2. 2018

• Comments:

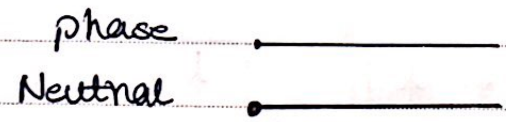
In the case of Y-Δ or Δ-Y transformer:

- The terminal markings are made in such away that HV leads LV by 30° in the (+ve) ph. sequence.

- The terminal markings are made in such away that HV lags LV by 30° in the (-ve) ph. sequence.

* per-phase concept:

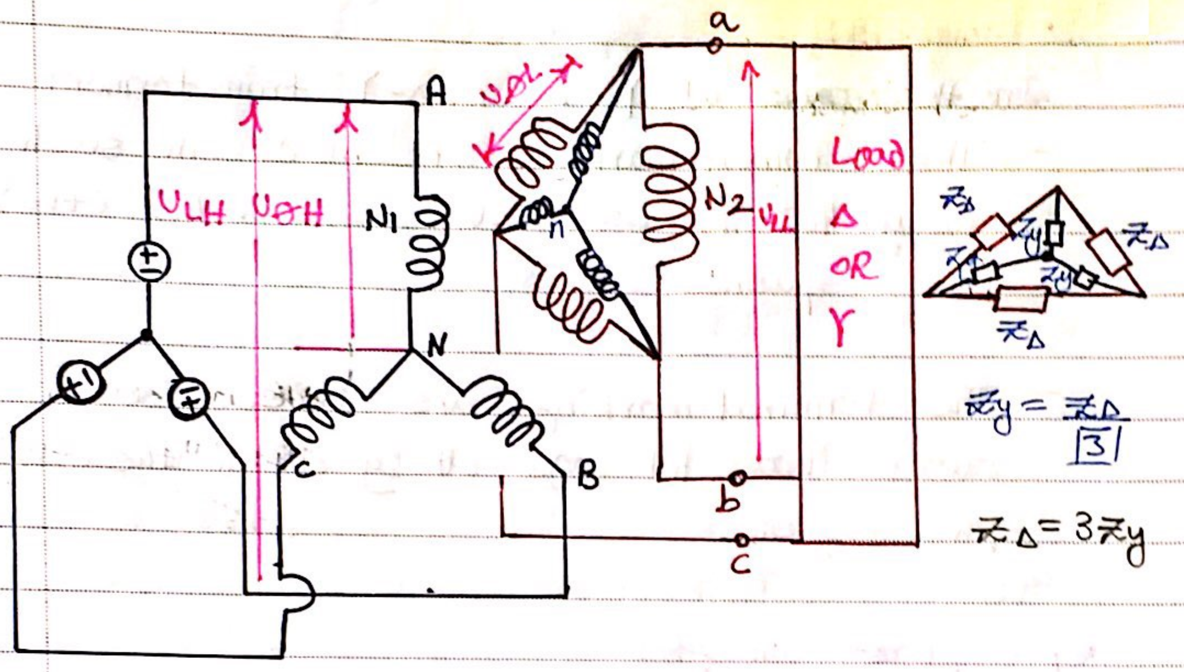
In balanced systems which contain 3-ph. transformers, then the per-phase or single-phase cct. can be used to solve the problem, as follows:



*Note in the case of Δ-connection convert it to it's equivalent Y.

consider the following system.

NO.

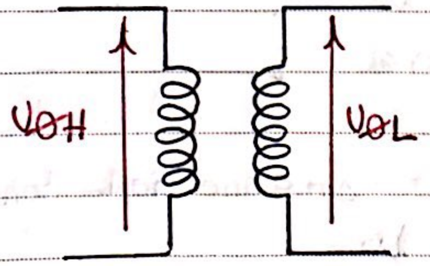


V_{LH} ≡ Line voltage of HV side.

$V_{\phi H}$ ≡ phase voltage of HV side.

V_{LL} ≡ Line voltage of LV side.

$V_{\phi L}$ ≡ phase voltage of LV side.



$N_1 : N_2/\sqrt{3} \Rightarrow N_1/N_2/\sqrt{3} : 1$

a eff. : 1

NO.

* $\frac{V_{LH}}{V_{LL}} = \frac{\sqrt{3}\, V_{\phi H}}{V_{LL}} = \sqrt{3}\,\frac{V_{\phi H}}{V_{LL}} = \sqrt{3}\,\frac{N_1}{N_2} = \sqrt{3}\, a = \frac{N_1}{N_2/\sqrt{3}} = a_{eff}.$

→ magnitudes.

$a \equiv$ Turns ratio $= \frac{N_1}{N_2}$

* Also, $\frac{V_{\phi H}}{V_{\phi L}} = \frac{V_{\phi H}}{V_{LL}/\sqrt{3}} = \frac{N_1}{N_2/\sqrt{3}} = a_{eff} \equiv$ The Effective turns ratio.

→ Ratio between the line voltages $\left(\frac{V_{LH}}{V_{LL}}\right)$.

* In the 4-cases ⇒ the effective turns ratio $\equiv$ line voltage ratio.

- Exam question:

Derive the turns ratio of the phase voltages for Δ-Y ⇒ $\left(\frac{N_1/\sqrt{3}}{N_2}\right)$.

- conclusion:

It can be shown for any type of connection (Y-Y, Δ-Δ, Δ-Y, Y-Δ), that $a_{eff} \triangleq$ Ratio of line voltages.

Make sure of them ?!

→ * Y-Y, Δ-Δ] $\frac{N_1/\sqrt{3}}{N_2/\sqrt{3}} = \frac{N_1}{N_2} = a_{eff}.$

* Δ-Y] $\frac{N_1/\sqrt{3}}{N_2}$

* Y-Δ] $\frac{N_1}{N_2/\sqrt{3}}$

NO.

→ Always line voltages.

\# Ex.: A (13800 / 480) V, Y–Δ transformer Bank consists of three identical single phase 100 KVA, (7967 / 480) V transformers: (HV: 7967, LV: 480)

It is supplied with power directly a large constant supply.

* In the (s/c) test on the HV side of one of the 1-ph. transformer, the following results were obtained:

⇒ $V_{sc} = 560$ V, $I_{sc} = 12.6$ A, $P_{sc} = 3300$ watt.

If this Bank is used as "step-down" to supply rated load at 0.88 PF lagging at rated voltage.

* Find line voltage on the primary side.

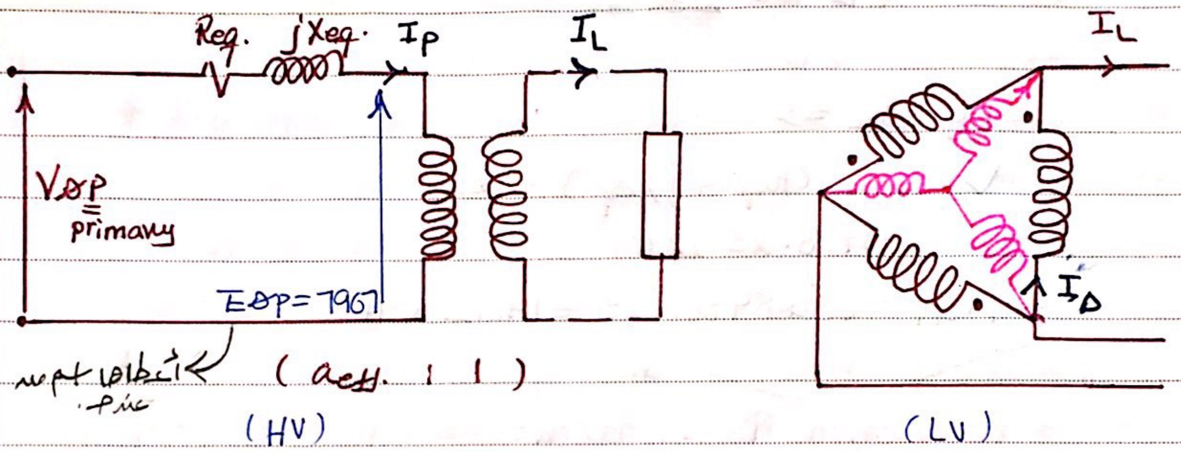
- comment:

It can be deduced that HV side of 1-ph. transformers are connected in Y and LV side of 1-ph. connected in Δ to give the required line voltages (13800 / 480)

NO. 27.2.2018

- Objective: To find the equivalent cct. reflected to HV.

كأنه الشيء الأعاظم :



- $a_{eff.} = \frac{13800}{480} = 28.75$

From the given (s/c) test, it can be found that:

$R_{eq.} = 20.79\ \Omega$

$X_{eq.} = 39.2\ \Omega$

$I_\Delta = \frac{100*10^3}{480} = 208.3\ A$

$\rightarrow I_L = \sqrt{3} * I_\Delta = \sqrt{3} * 208.3 = 360.79 A$

$\therefore \frac{I_P}{I_L} = \frac{1}{a_{eff.}}$

$\therefore I_P = \frac{I_L}{a_{eff.}} = \frac{\sqrt{3}\,(208.3)}{28.75} = 12.55 A$

FIVE APPLE

NO.

$\Rightarrow$ Let $E_{\phi p} = 7967 \angle 0^\circ$

$\therefore I_p = 12.55 \angle -\cos^{-1}(0.88)$

$= 12.55 \angle -28.36$

$\therefore$ By KVL $\Rightarrow$

$V_{\phi p} = I_p (R_{eq.} + jX_{eq.}) + E_{\phi p}$

$= 8436.25 \angle 2.1^\circ$

$\therefore |V_{LP}| = \sqrt{3} * 8436.25 = 14612$ volt.

* Connection Designation:

- These are letters used to represent type of 3-ph. connection.

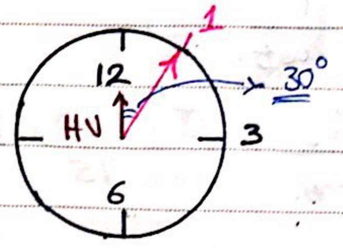
* capital letters for HV ≡ D (Delta) or Y (wye)

* Small letters for LV ≡ d (delta) or y (wye)

* If "neutral line" exist, then use N or n.

- Phase shift between HV and LV represented by the clock arms.

*خلّي الـ HV الـ
reference تبعك
عند الـ 12.



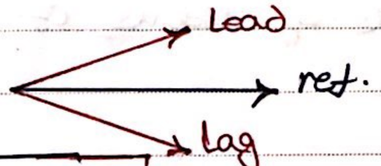
FIVE APPLE

* Hour arm pointing at 12:00 used to represent HV.
* Minutes arm represent LV.
* Designation [HV] [LV] [ph. shift]

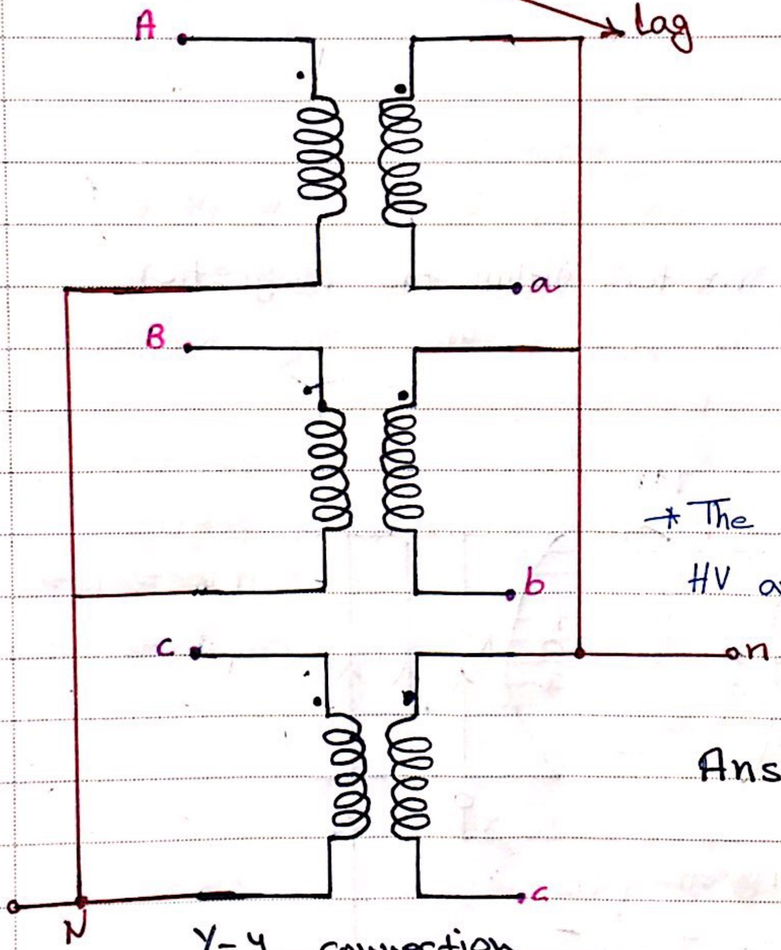
* Illustration:

For example Δ-Y ≡ step up, find connection designation for Δ - Y connection assuming +ve ph. sequence. (Δ → LV, Y → HV)

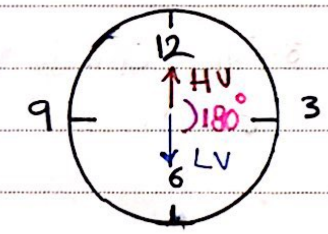
Ans. ≡ YNd1



+ve seq. ⇒ LV Lags HV by 30°.



Y-y connection



* The phase shift between HV and LV is 180°

Ans. ≡ YNyn6

NO.

Electrical Machines (motor or generator)
(AC or DC)

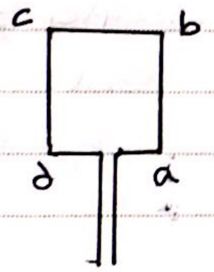
• Basic Fundamentals:

Induced voltage

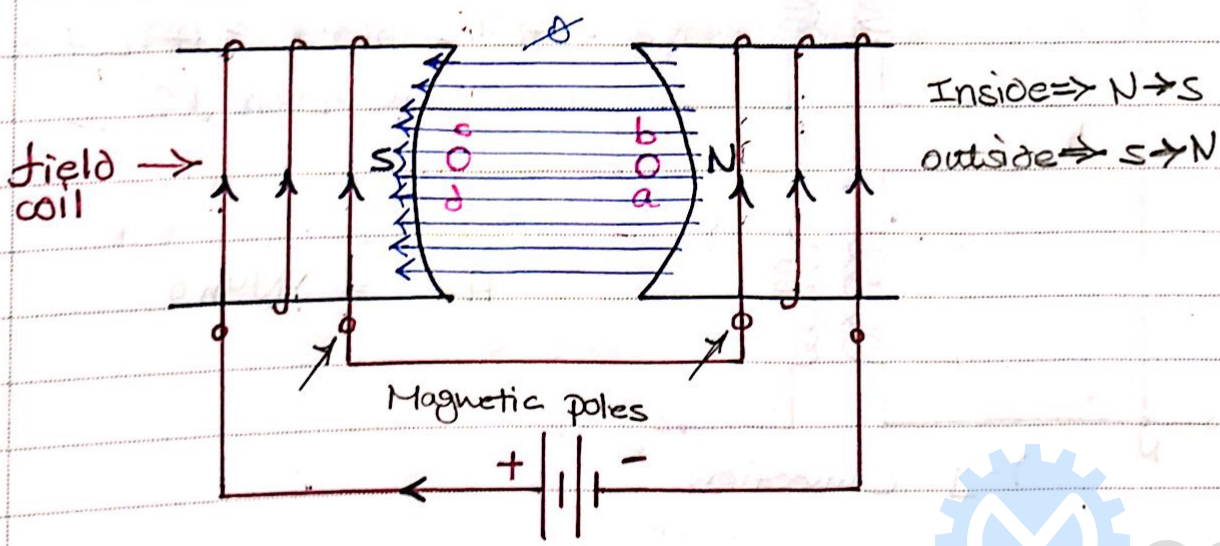
- structure:

1. Magnetic field "stationary" called stator produced by electromagnet to produce ø.

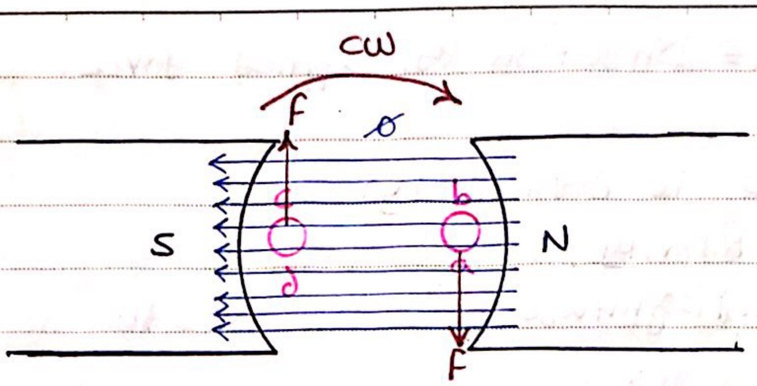
2. conductors by means of coil

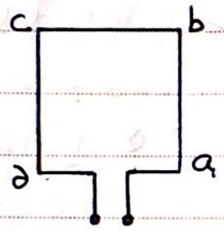


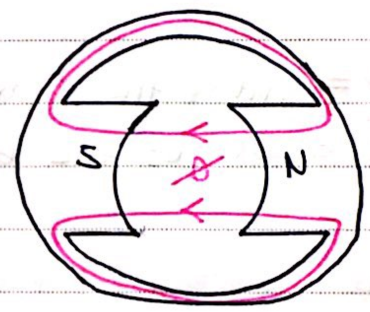
3. The coil is rotated within the magnetic field.



NO. 1.3. 2018







* Field coils ≡ stationary called <u>stator</u>.
* ab, cd ≡ called coil sides.

• Let the coil "abcd" to rotate <u>cw</u> or <u>ccw</u>; it's called <u>Rotor</u>.

- Armature windings: These are the windings in which voltage is induced in the case of "generator" OR windings to which current is applied in the case of "motor".

- Let the Armature to rotate cw. since it's rotating then it will cut θ ⇒ Hence a voltage (e) will be induced in it.

NO.

* f ≡ Direction of applied force.

- e is defined by:
  1. Polarity ; by using RHR
  2. Magnitude; ⊗⊙ ≡ gives direction of induced voltage.

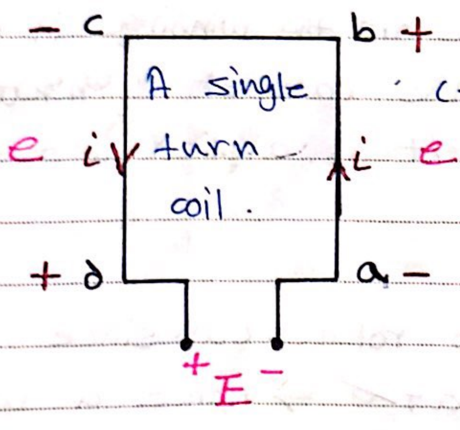
⊗ ≡ Into the board.
⊙ ≡ out of the board.

} السبابة مع اتجاه الـ B والابهام مع
اتجاه الـ f وباقي الأصابع مع
اتجاه التيار , ⊗ ⊙

Dot concept: applied for two mutual couple coils only.

*** Convention:**

If coil abcd is connected to a load, then a current will flow in the same direction of induced voltage.



* التيار بيمشي من الـ (-) إلى الـ (+).

NO.

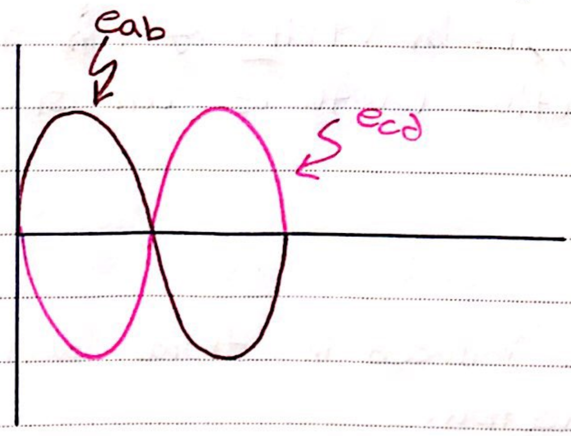
• Since in a source, current flows from (−) to (+)

∴ polarity of induced voltage in each coil side can be determined as shown in fig. 1.

• If ($e \equiv$ voltage induced per coil side)
∴ $E \equiv$ voltage generated by the coil (i.e. voltage at coils terminals) is by KVL:
∴ $E = 2e$

*As the coil rotates one revolution (i.e. one rotation) then the voltage polarity in each coil side reverse every time the side moves from N to S pole.

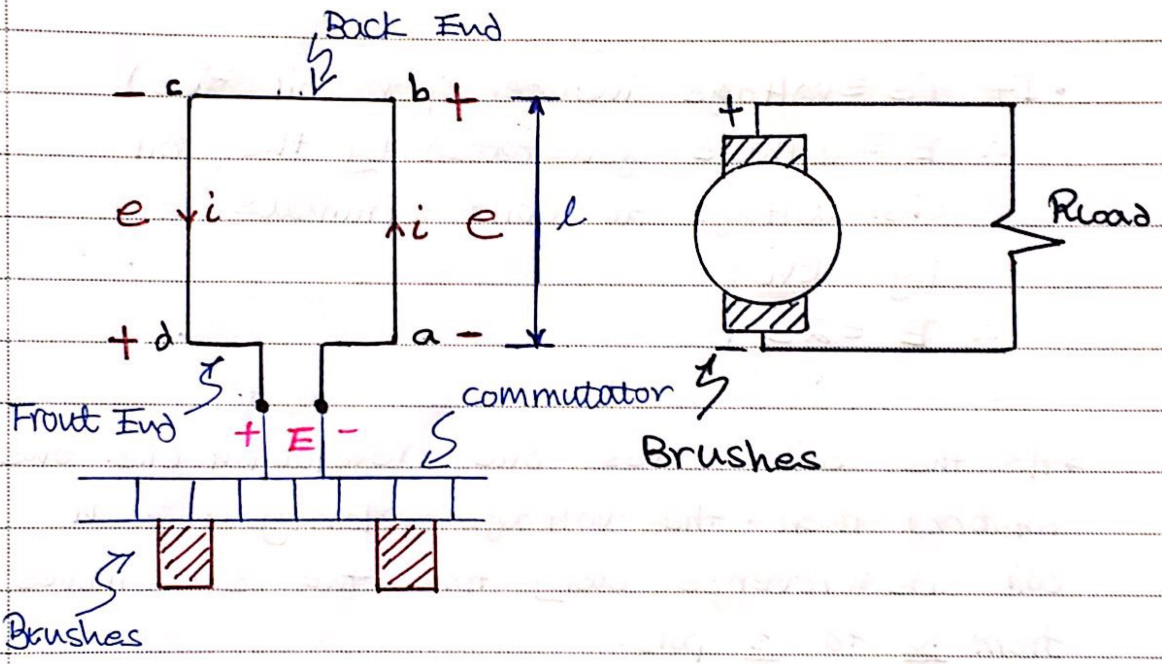
∴ Internal induced voltage is AC.



NO.

But in DC machines this internal AC is converted to dc voltage by using mechanical rectifier which consists of :

1. commutator which is rotating with A.W.
2. Brushes which are stationary but making continous contacts with commutator.



• Magnitude :

$e \triangleq B\,l\,V$

- B → Flux Density (Tesla or $\frac{wb}{m^2}$). "T"
- l → Active Length of coil side.
- V → Linear velocity of coil side.

*No voltage induced in front and back end connection.

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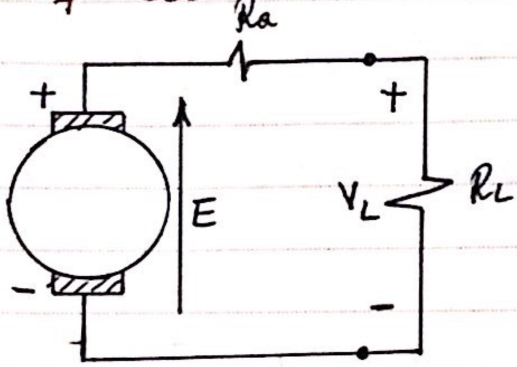
* $E|_{Turn} = 2B\ell V$ (for single turn).

* $E = 2NB\ell V$ => for N turns.

=> Eq. cct.



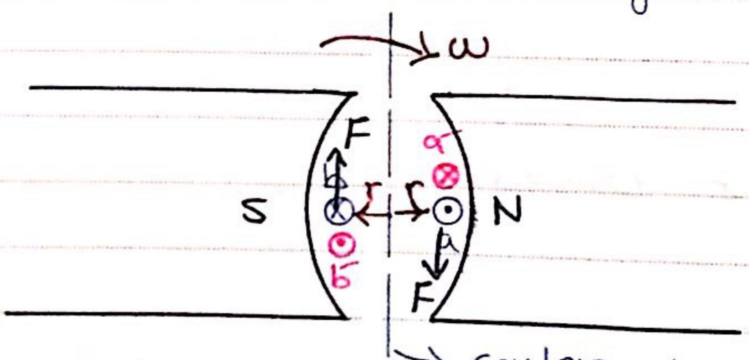
$R_a \equiv$ Internal resistance of armature winding

$R_L \equiv$ Load resistance

$V_L \equiv$ Terminal or Load's voltage.

• Generated or Induced Force and Torque:

If a current is applied to armature windings then a force will be produced on each coil side. It's direction by LHR.



-> center of rotation

*LHR ≡ using 3 fingers

⊙, ⊗ ≡ Direction of applied current (motor Action).

F ≡ Induced or produced force.

$F \triangleq BI\ell$

NO.

$F \triangleq BIl$

- $B \equiv$ Flux Density
- $I \equiv$ Applied Current
- $l \equiv$ Active Length of conductor.

$\omega \equiv$ Direction of produced motion with a radian speed $= \underline{\omega}$.

→ $\tau_1 = BIlr$
→ $\tau_2 = BIlr$
∴ Torque produced, $(\tau = \tau_1 + \tau_2)$
∴ $\tau = 2BIlr$.

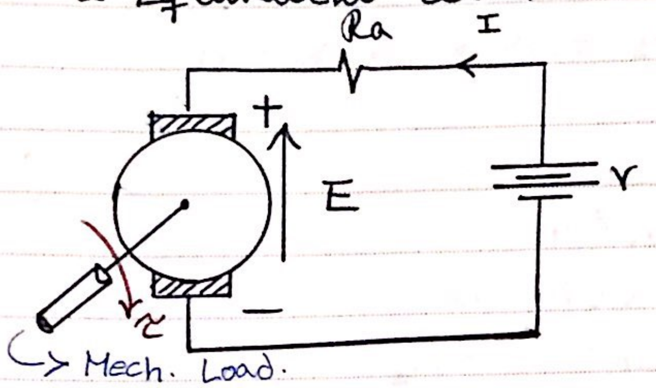
+ Consequently Due to torque (τ) → motor is going to rotate and cutting magnetic field ⇒ Hence a voltage will be induced in these conductors whose direction can be found by RHR as follows:

⊙ ⊗ ≡ Direction of generated voltage (i.e. generator action)   This is called Back emf.

∴ Hence in a motor there is a generator action.

NO

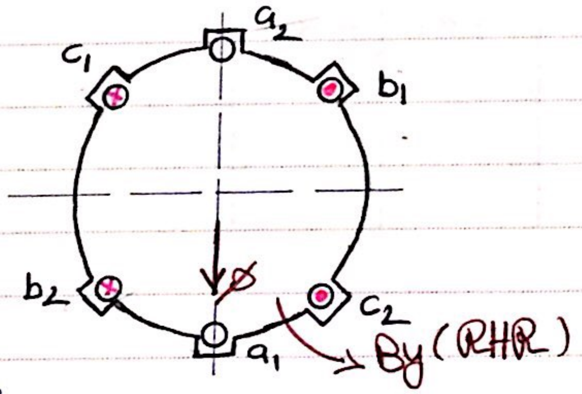
∴ Equivalent cct. :



V ≡ Applied voltage
I ≡ Applied current
E ≡ Back emf

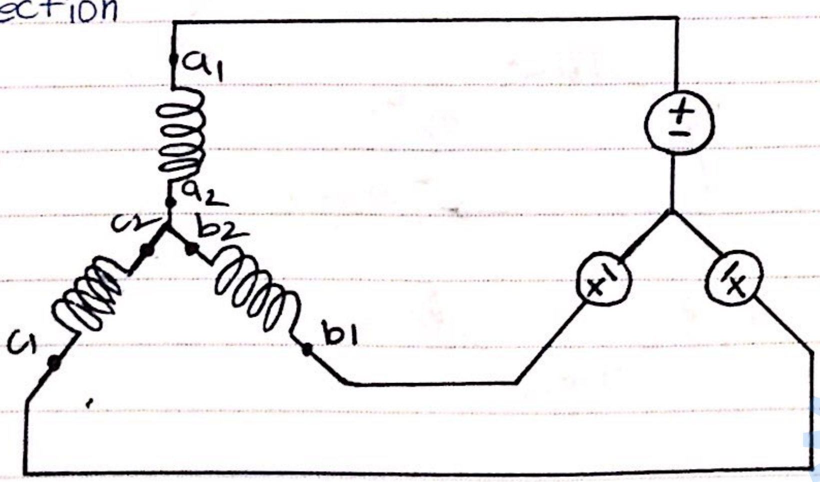
• **Rotating magnetic field:**

If a balanced 3-ph. current is applied to a 3-ph. winding, then a rotating magnetic field is produced within the winding as follows:



1. ωt = 0

Y– connection



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Exam question:
↳ show how its rotating graphically?

Ans.:

1. let $i_{a_1a_2} = I_m \sin(\omega t)$

$i_{b_1b_2} = I_m \sin(\omega t - 120^\circ)$

$i_{c_1c_2} = I_m \sin(\omega t - 240^\circ)$

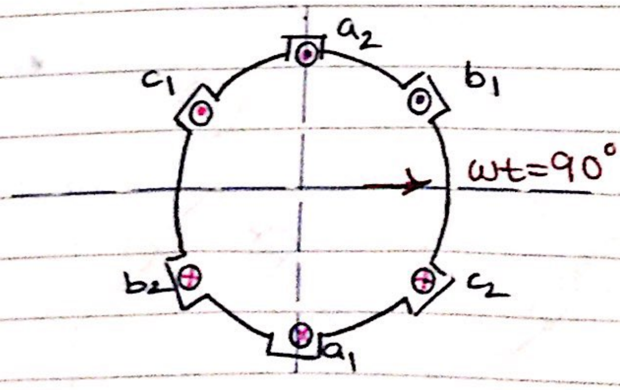
let the current changes over one cycle.}

2.

ωt	$i_{a_1a_2}$	$i_{b_1b_2}$	$i_{c_1c_2}$	$\angle\theta$
0	0	-ve	+ve	-90
90°	+ve	-ve	-ve	0
180°	0	+ve	-ve	
270°				
360°				

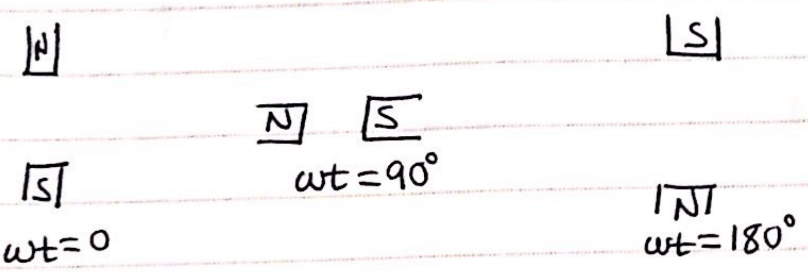
let (+ve) ⇒ ⊗

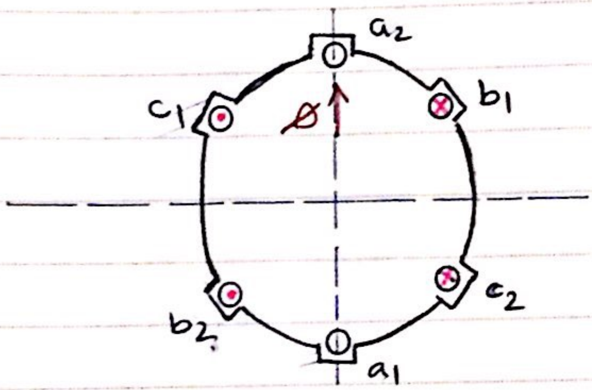
(-ve) ⇒ ⊙



2. $\omega t = 90^\circ$

* Another way of imagination:





$\omega t = 180°$

∴ In one cycle of current, ø makes one mecha. rotation.

NO. 6. 3. 2018

- **Comments:**

I) The 3-ph. windings represent 2 rotating poles.

II) For one cycle of applied current there were one mechanical rotation of s.

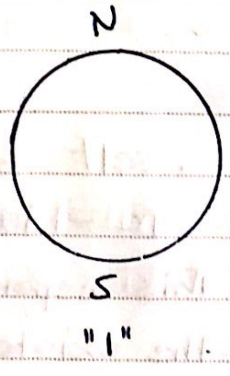
∴ $F_e = F_m$ → Mechanical frequency (r.p.s) "revolution per second".
↳ Electrical frequency (Hz)

III) The three phase winding can be made to have a larger no. of poles.

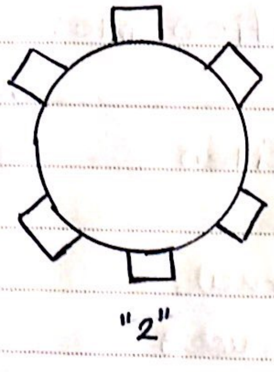
∴ General relationships:

$F_e = P\,F_m$; $P \equiv$ No. of pole pairs "عدد الأزواج"

↳ F_e: frequency of generated voltage
↳ F_m: frequency of rotation of the motor.



"1"



"2"

Rotor types
(الحركة فقط.)

- 2 poles → 1 pair
- 4 poles → 2 pairs

NO.

* DC - Machines:

=> construction:

It consists of:

I) stator: Carrying field windings, which are excited by field current, I_F.

II) Rotor: carry Armature windings.

} As Explained before.

* Fill in the blanks:

Armature windings are: They are windings in which voltage is induced in case of "generator" and in which current is applied in case of "motor" to produce torque.

* classification:

According to the source of I_F, Dc Machines are classified into:

1. Seperately Excited Dc - Machines:
Here an external Dc - source is used to supply I_F.

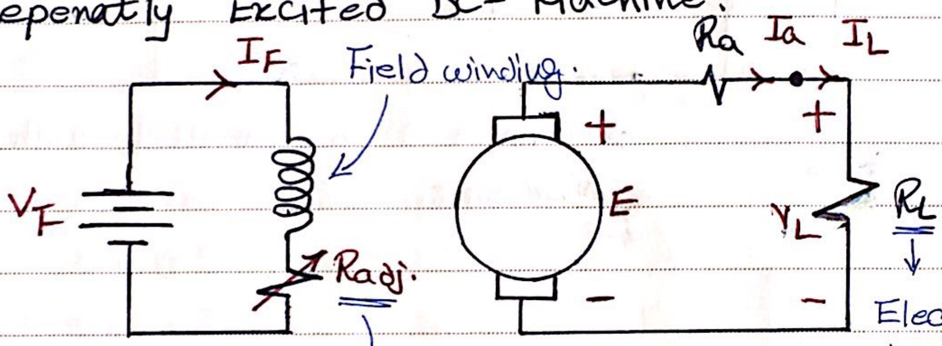
2. self Excited Dc - Machines:
This depends on the existance of residual magnetizim in the poles.

بالتوفيق يا شباب

2. Self Excited DC-Machines:

- Shunt DC machine.
- Series DC machine.
- Compound DC machine

I) Seperatly Excited DC- Machine:



to control the field current

Electrical Load generator.

* Mech. Load (Motor).

$E \equiv$ Generated or induced voltage → (Generator)

$E \equiv$ Back emf → (Motor)

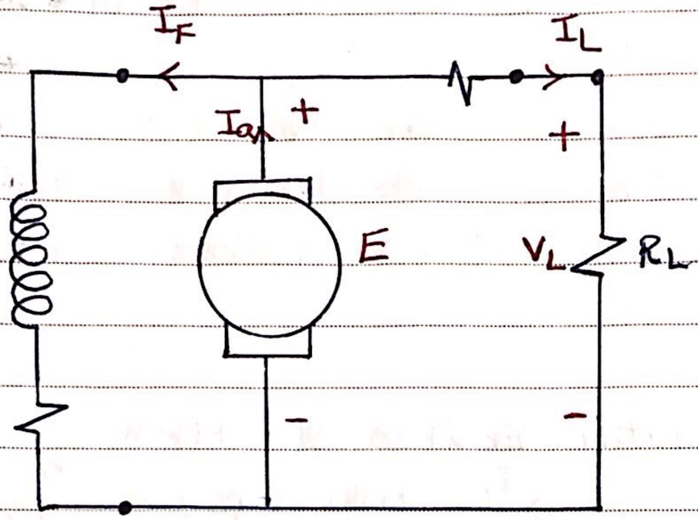
$I_F = \frac{V_F}{R_F}$; $R_F \equiv$ Resistance of the field cct.

$R_F = R_{FW} + R_{adj}$.

$E = V_L + I_a R_a$
→ $E = \ell N B \ell V$

NO.

II) shunt Dc-Machine (self exoited):



↳ connected in parallel with the brushes.

NO. 8. 3. 2018

• Self Excited:

– shunt machines:

* It it is connected with a DC power supply "Motor", with a Load resistance "generator".

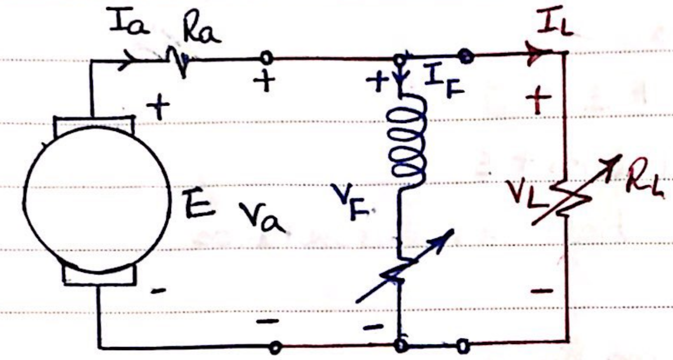


Fig. 1

Fig.1 ≡ DC shunt generator.

$\Rightarrow V_L = V_F = V_a$

$I_a = I_F + I_L$

$E = I_a R_a + V_a$

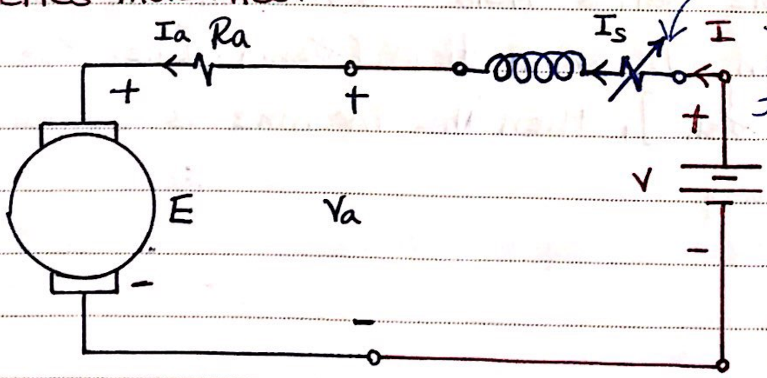
$V_L = I_L R_L$

$I_F = V_F / R_F$

$R_F \equiv$ Field-cct. resistance.

= Field winding (F.W.) resistance $+ R_{adj}$.

– Series machines:



In parallel or series to control the field current.

Fig. 2

NO.

Fig. 2 ≡ DC - series motor.

V, I ≡ Applied voltage and current.

$I = I_s = I_a$

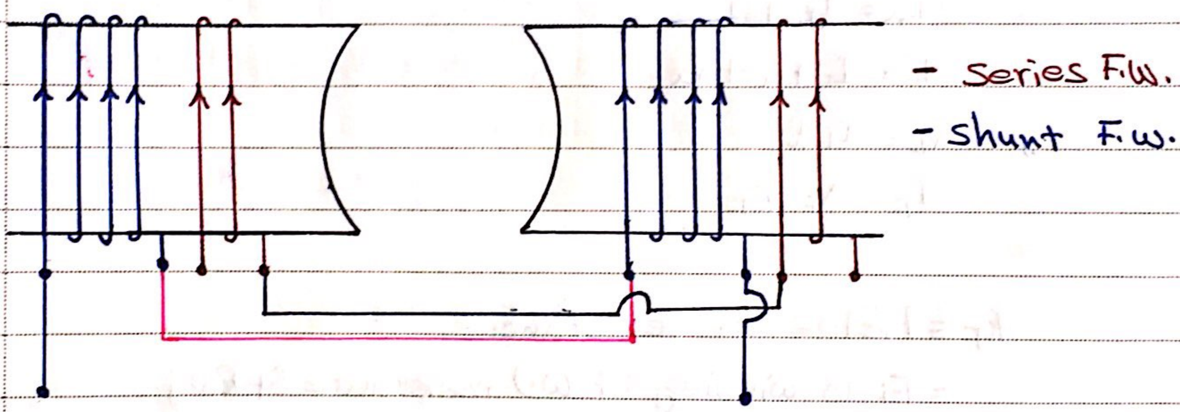
$\therefore V_a = I_a R_a + E$

$V = I_s R_s + I_a R_a + E$

R_s = series field cct. resistance.

- compound machines:

Here there are 2 field windings:
Shunt and series fields.

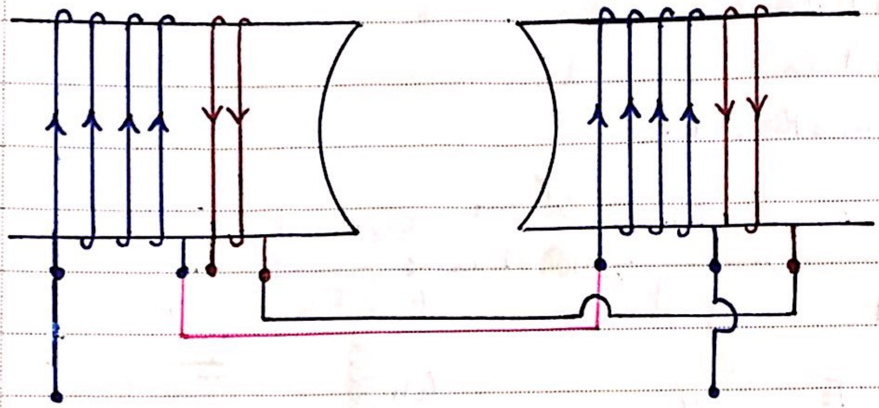


If the series field (ϕ_{se}) is in the same direction of shunt field ($\phi_{sh.}$). [i.e. ϕ_{se} is aiding $\phi_{sh.}$], then the machine is cummulative compound.

مساعد

FIVE APPLE

NO.



If ϕ_{se} opposes [i.e. not aiding] ϕ_{sh}, then the machine is called (Differential compound).

*According to the method of connecting shunt and series fields, there are two types:

1. Long shunt compound machine.
2. Short shunt compound machine.

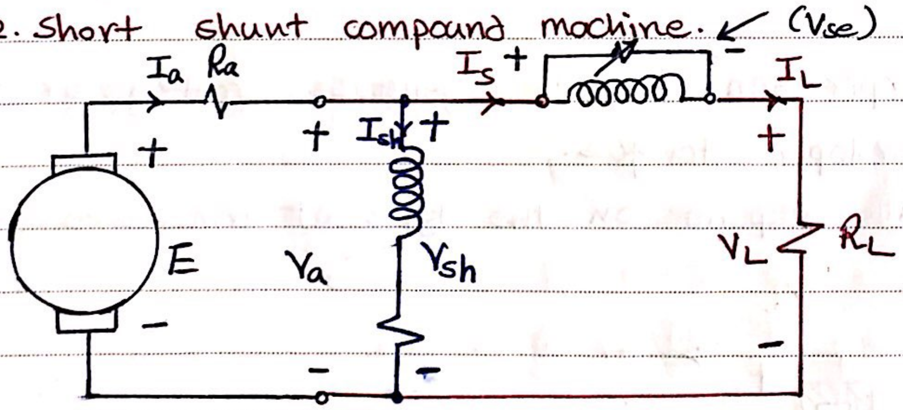


Fig. 3

Fig. 3 ≡ Short shunt compound machine or generator.

NO.

$I_s = I_L$

$I_a = I_{se.} + I_s$

$E = I_a R_a + V_a$

$V_a = V_{sh.} = I_{se} R_{se} + V_L$

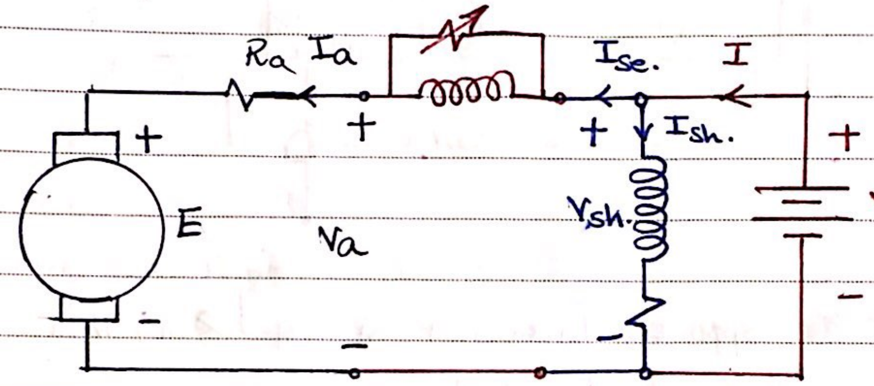


Fig.4

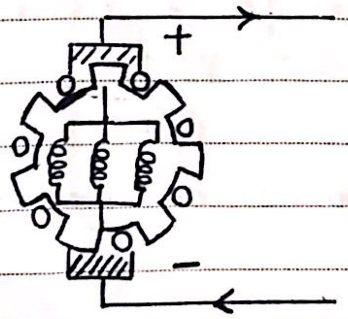
Fig.4 ≡ Long shunt compound DC-motor.

$V = V_{sh.} = I_{se.} R_{se.} + I_a R_a + E$

$I = I_{se.} + I_{sh.}$

- Expression for the generated voltage or developed torque.

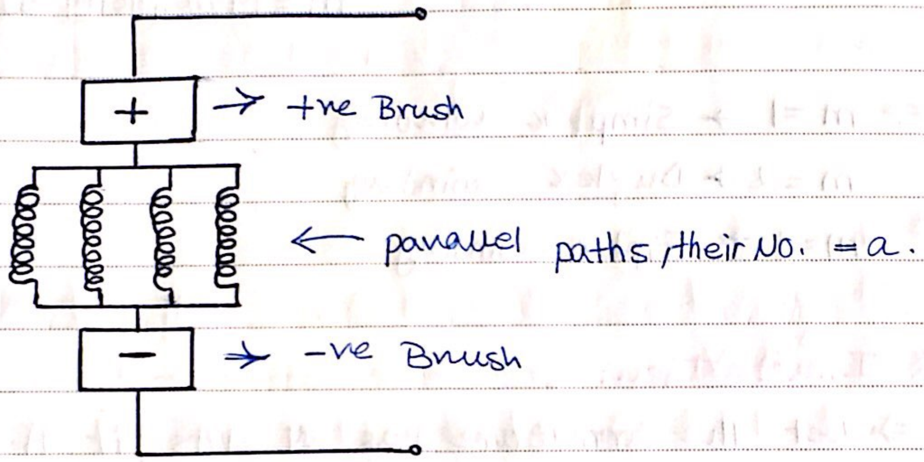
This depends on the type of armature winding.



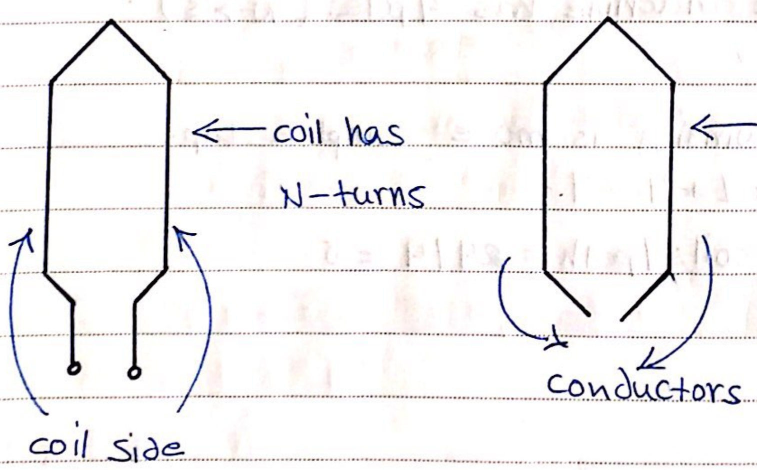
NO. 11. 3. 2018

• Armature windings (A.w.):

A.w. are wound in such away to create a number of parallel paths (a) between the (+ve) and (-ve) brushes.



A.w. ≡ consists of a set of coils, their No. = c. Each coil consist of N turns.



∴ Total No. of turns = cN

∴ Total No. of conductors = Z = 2cN

FIVE APPLE

NO.

- There are types of A.W.:

1. Lap winding , $a = mp$
2. wave winding , $a = 2m$

; where

$P \equiv$ No. of poles

$m \equiv$ Multiplicity of winding

=> $m = 1 \rightarrow$ Simplex winding

$m = 2 \rightarrow$ Duplex winding

$m = 3 \rightarrow$ Triplex winding

※ Illustration:

=> Let the armature has 24 slots , if A.W. consists of 24 coils.

$\therefore c = 24$

=> Let the rated voltage of each coil $= e$

the rated current of each coil $= I$

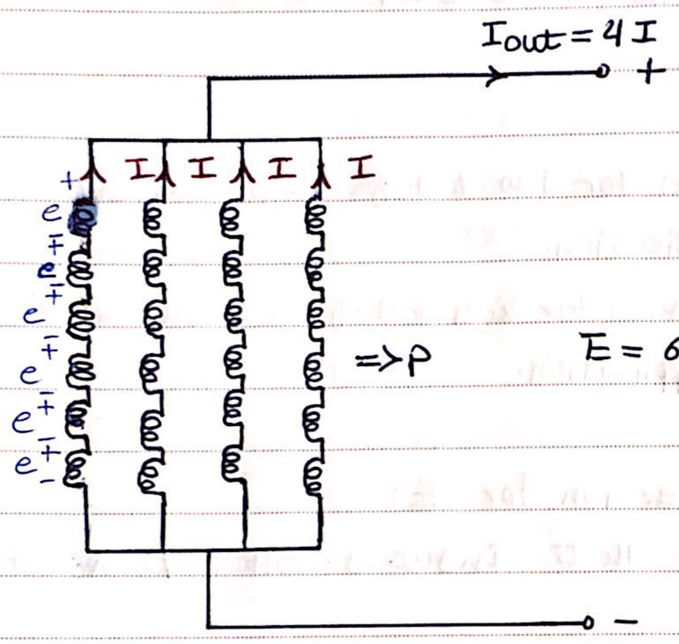
the machine has 4 poles $\left(\begin{smallmatrix} N \rightarrow S \\ N \rightarrow S \end{smallmatrix}\right)$.

If the winding is made simplex Lap.

$\therefore a = mp = 1 * 4 = 4$

$\therefore$ No. of coils / path $= 24 / 4 = 6$

NO.



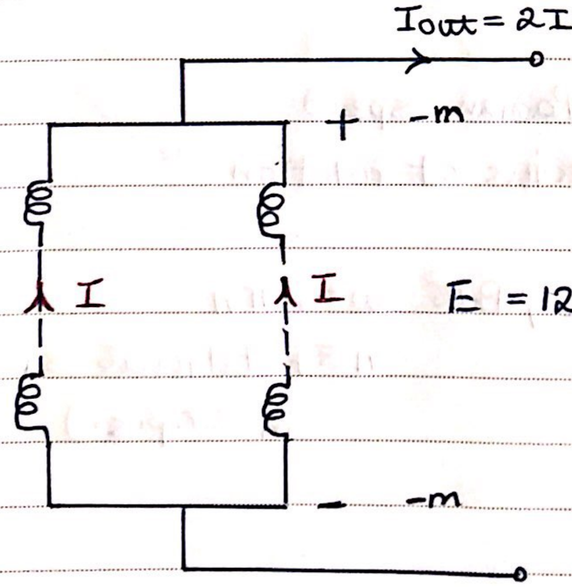
E = 6e

$* P = E * I_{out} = 6e * 4I = 24\, Ie.$

If A.w. is simplex wave.

$\therefore a = 2m = 2*1 = 2$

$\therefore$ No. of coil/path. = 12



E = 12e

NO.

$\therefore P = I_{out} * E = 12e * 2I = 24EI$

* In general:

1- Lap winding: used for low voltage high current application.

2- Wave winding: used for high voltage low current application.

* General Expression for E:

It was found that Induced voltage/conductor

$E_c \triangleq B\ell V$

=> If total No. of conductors $= Z$

If No. of parallel paths $= a$

$\therefore E \equiv$ voltage per path.

$= E_c * \frac{Z}{a}$

$= \frac{B\ell V Z}{a}$

Since $V = \omega r$; $\omega \equiv$ Radian speed

$r \equiv$ Radius of rotation

$\therefore E = \frac{B\ell \omega r Z}{a}$; But $\omega = 2\pi n$

$n \equiv$ Rotational speed in (r.p.s.)

NO.

$$E = \frac{B\ell 2\pi n r Z}{a} \quad --- \ (1)$$

If the No. of poles $= P$

Flux / Pole $= \phi$

$$\therefore B = \frac{P\phi}{2\pi r \ell} \quad --- \ (2)$$

Sub. (2) into (1)

$$E = \frac{P\phi}{2\pi \ell r} * \frac{2\pi \ell r n Z}{a}$$

$$E = \frac{P\phi Z n}{a}.$$

$E = \frac{P \phi Z n}{a}$

* For agiven machine (P, Z, a) constants:

$\therefore E = k \phi n, \quad k = \frac{PZ}{a}$

* General Expression for the torque, τ:

It was found that Torque produced by a conductor,

$\tau_{cond.} \triangleq B I_c l r$

$I_c \equiv$ conductor's current.

$\therefore$ Torque, $\tau = Z \tau_{cond.}$

$= Z B I_c l r$

$\tau = Z * \frac{P\phi}{2\pi L r} * \frac{I}{a} * l r$, since $I_c = \frac{I}{a} \Rightarrow I \equiv$ Applied current to the brushes.

$\tau = \frac{Z P \phi I}{2\pi a}$ [Retarding torque $\Rightarrow$ generator. Generated torque $\Rightarrow$ motor.]

* For a given machine $(P, Z,$ and $a)$ are constants:

$\therefore \tau = k_1 \phi I, \quad k_1 = \frac{Z P}{2\pi a}$.

$\therefore \tau$ can be controlled by means of (ϕ) and (I).

- Example: Two DC-Machines are rated as follows:

Mch. 1 : 120 V, 1500 rpm, 4 poles.
Mch. 2 : 240 V, 1500 rpm, 4 poles.

The avaliable armature coils are rated at 4 V, 5A. For the same number of coils to be used for both machines, Determine:

+ Rating ≡ Max. that the machine could handle.

NO.

I) Type of A.W.   II) Number of coils required
III) kW rating of each machine.

⇒ For <u>HV</u> use wave winding.
⇒ For <u>LV</u> use Lap winding.

*Mch. 2.

I) For machine. 2, use simplex wave winding (S.W.W.)

II) No. of coils / path = $\frac{240}{4}$ = (60 coils)

$a = 2m = 2*1 = 2$

No. of coils required = (2)(60) = 120

III) kW Rating = $E*I$ (Total). = $\frac{240*(5)(2)}{1000}$ = 2.4 kW.

*Mch. 1.

I) For machine. 1, use simplex Lap winding.

II) No. of coils / path = $\frac{120}{4}$ = 30

$a = mb = 1*4 = 4$

Total No. of coils required = 4*30 = 120

III) kW Rating = $E*I$ = $\frac{120*(5)(4)}{1000}$ = $\frac{120*20}{1000}$

= $\frac{2400}{1000}$ = 2.4 kW.

+ بغض النظر عن نوع الـ winding لازم بالنهاية تحقق شرط انه يكون العدد نفسه (No. of coils).

Exam Question:

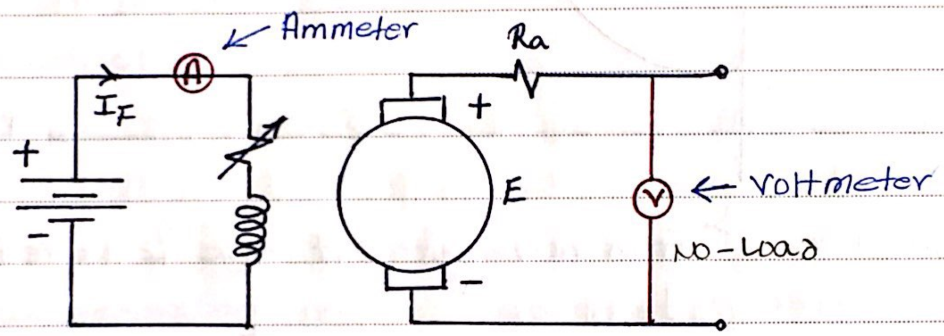
↳ Design a DC-Machine with the following rating.

* Load characterstics of DC-Machines:

DC-generators.

No-Load charactersics:

1. Seperatly Excited Generator:



• Procedure:

I) Run the generator at constant speed (i.e. n = const.)

II) vary I_F

III) Take readings of E.

Input → I_F | E → output

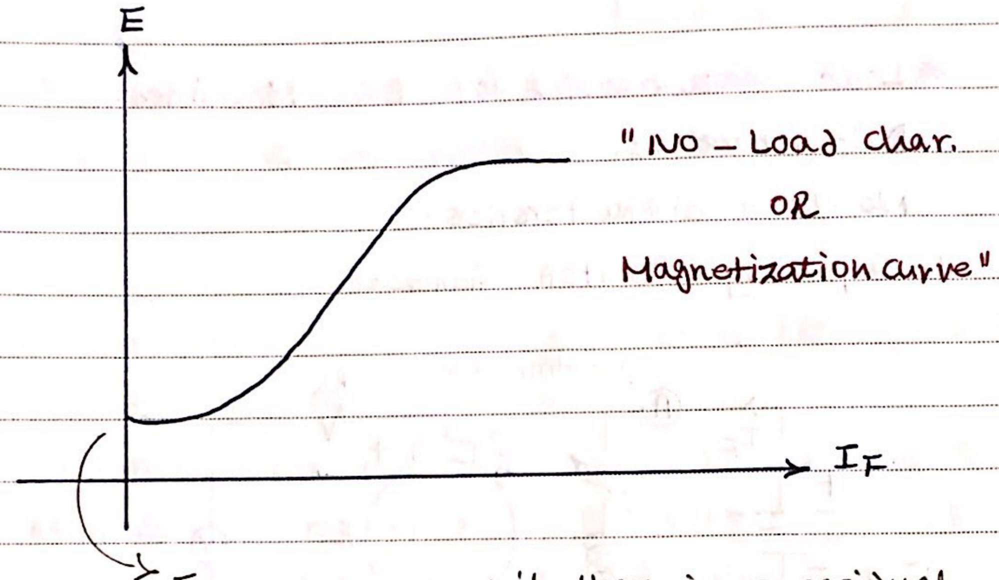
I_F	E
I_1	E_1
I_2	E_2
⋮	⋮
I_n	E_n

IV) Plot E vs. I_F.

NO.

* $E = k\phi n = k'\phi$; $k' = kn$. $\phi\uparrow \Rightarrow E\uparrow$

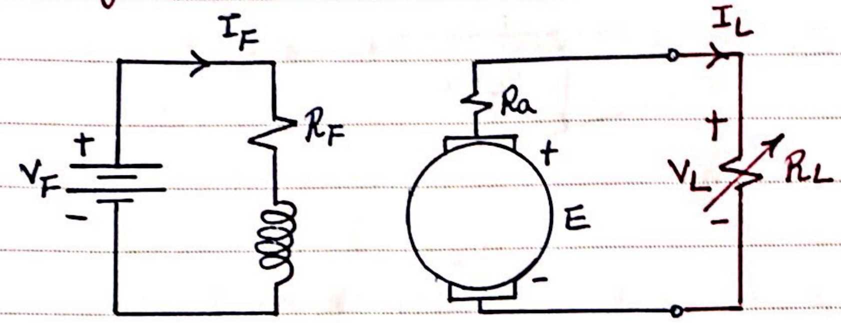
$\phi \propto I_F$



From non-zero; if there is a residual flux.

From zero; if there is no residual flux.

• Load characterastics of s.ext.gen. "Seperatly Excited generator."



• objective:

Find V_L versus I_L.

• procedure:

I) Run generator at constant speed.

II) For given I_F.

Since $E = k\phi n$; E is constant.

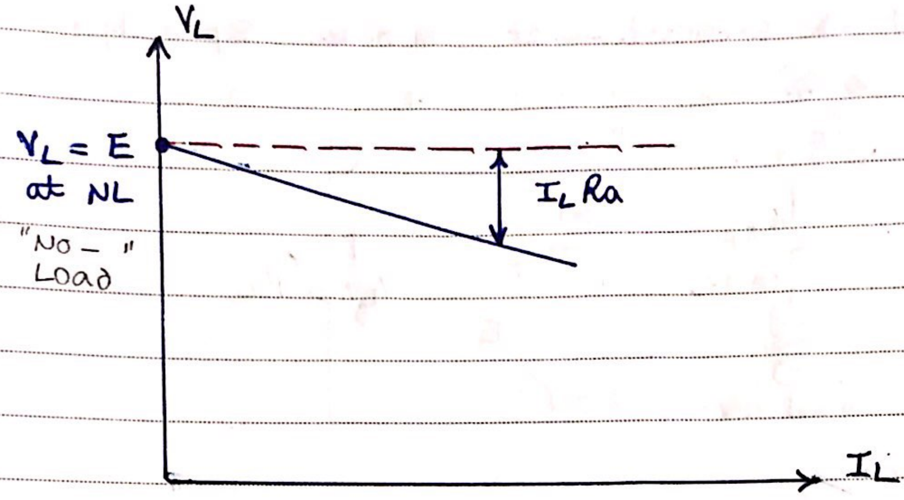
III) vary R_L and take the readings of I_L and R_L.

I_L	V_L
I_1	V_1
I_2	V_2
⋮	⋮
I_n	V_n

IV) plot V_L with I_L.

$V_L = E - I_a R_a = E - I_L R_a$

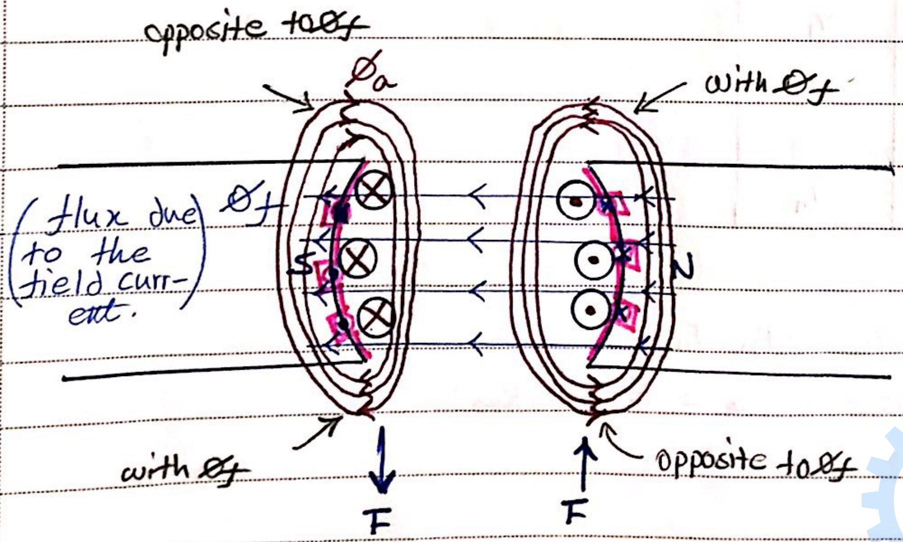
NO.



* Since R_a is usually very small, then up to the rated value of I_a, the drop ($I_L R_a$) is small.

∴ This gen. can be considered as a constant DC-voltage source.

- comment: In addition to the drop of ($I_L R_a$), there is a drop due to armature reaction explained as follows:



NO.

$\phi_F \equiv$ Flux due to I_F

$\phi_a \equiv$ Armature flux due to I_a

⊙ ⊗ ≡ Direction of induced voltages and direction of I_a.

↻ ≡ ϕ_a (RHR)

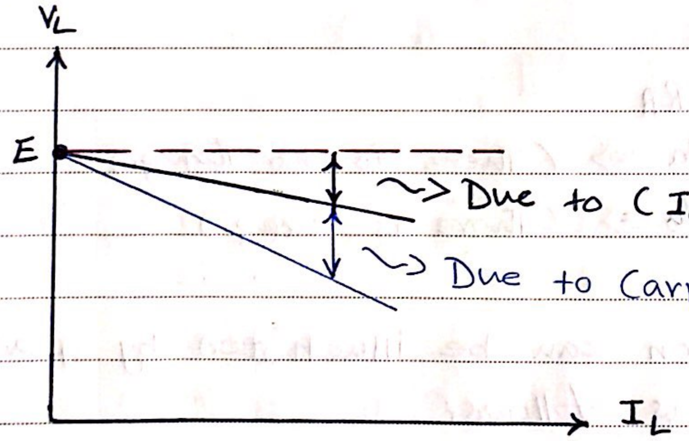
$\phi_a \equiv$ opposes ϕ_F at one pole tip and aid ϕ_F at the other pole tip.

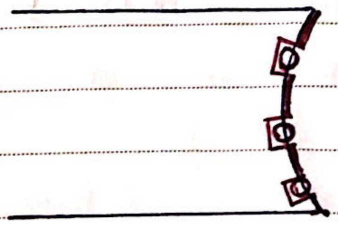
* Due to saturation, the resultant effect of ϕ_a is a reduction in ϕ_F.

- consequently as resultant flux:

$\phi_R = \phi_F + \phi_a \downarrow$ (Decreases)

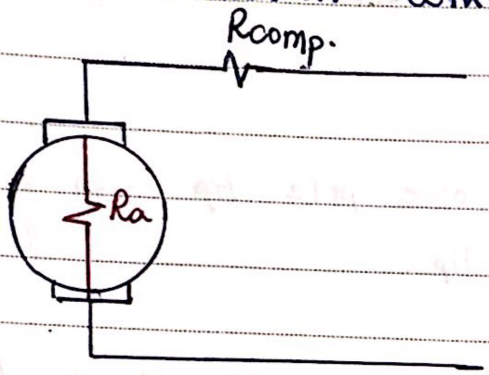
then $E\downarrow \Rightarrow V_L\downarrow$





NO.

• Armature Reaction can be reduced or eliminated by means of compensating windings which are conductors located at the pole faces and connected in series with the armature windings.



(Rcomp. and Ra are in series.).

R_A

∴ Armature cct. resistance, $R_A = R_a + R_{comp.}$

Armature winding resistance

\# Exam Question:

Seperatly Excited gen., Does it have Rcomp.?

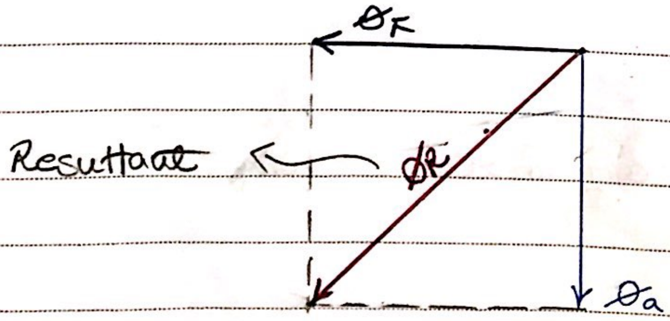
Answer:

calculate R_A

→ If $R_A = R_a$ => (There is no Rcomp.)

→ If $R_A > R_a$ => (There is Rcomp.)

* A reaction can be illustrated by phasors Diagram as follows:



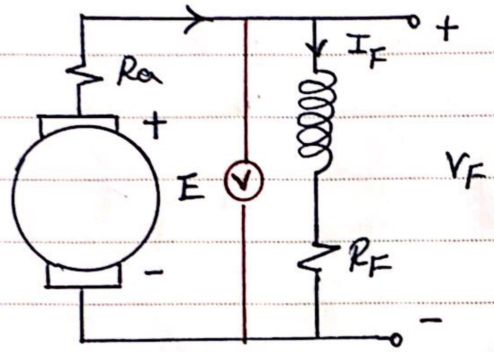
* If No-Load

$I_a = 0 \Rightarrow \phi_a = 0$

FIVE APPLE

* This is based on the existance of residual magnetizim.

Buid up voltage: تزيد الفولطية حتى تصل saturation

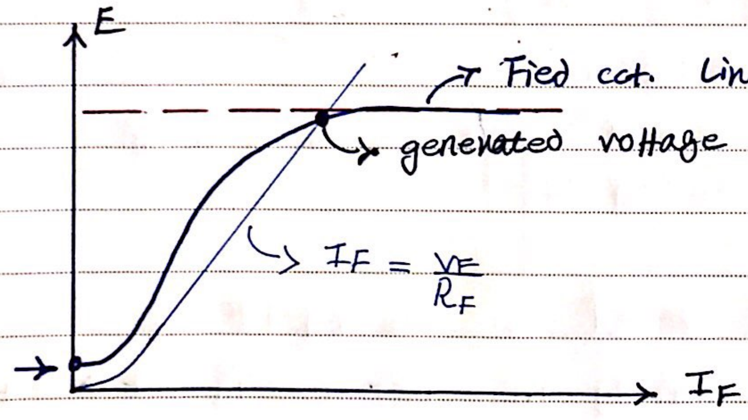


$$I_F = \frac{V_F}{R_F}$$

I) Run the gen. at constant speed.

II) observe the generated voltage $E = K\phi n$ by using the voltmeter Ⓥ.

$I_F \uparrow$ $\phi_F \uparrow$ $E \uparrow$



"Build up of self exciting generator"

*proof ⇒ The Brushes ---- ?

NO. 25. 3. 2018

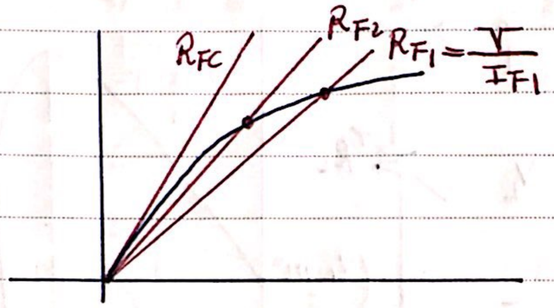
* Causes of Failure to build up:

I) Lack of residual magnetizim.

II) Armature windings are connected in reverse connection w.r.t field windings.

III) o/c in armature windings.

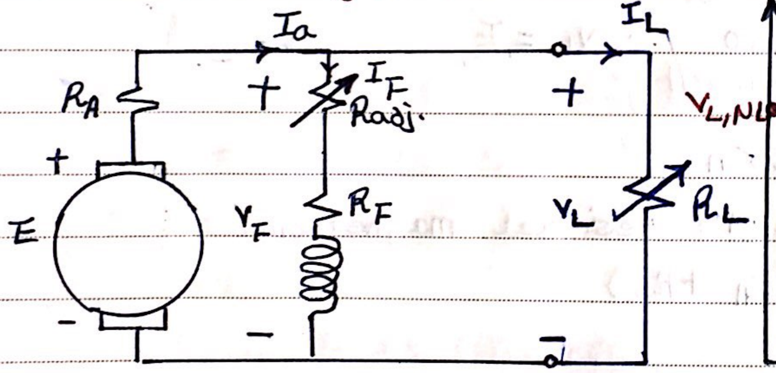
IV) R_F of the field windings is greater (>) than the critical field resistance.

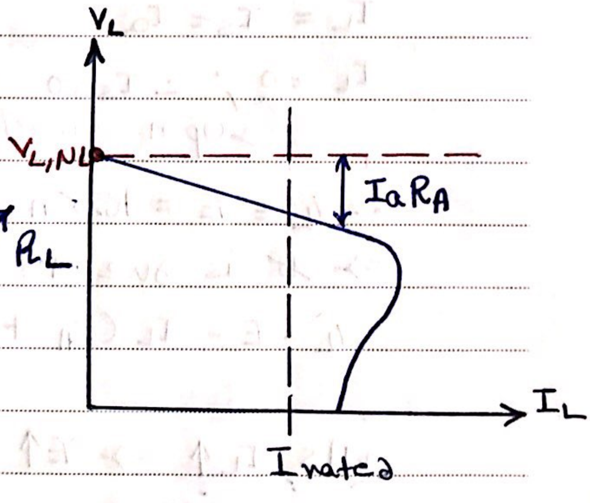


$[R_{F2} > R_{F1}]$.

* Load characterstics of:

- Shunt generator:





$V_L = E - I_a R_A$

$I_a = I_F + I_L$

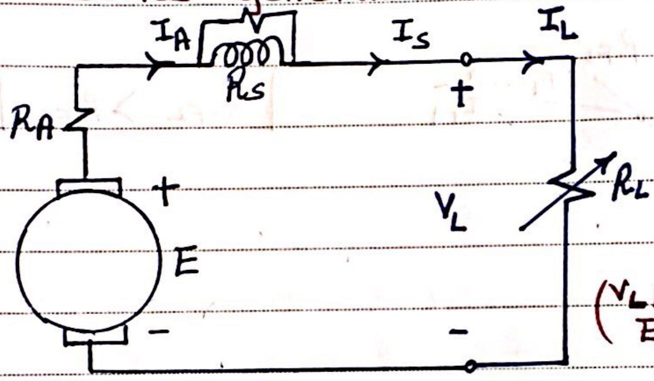
$\therefore$ As $I_L \uparrow \rightarrow I_a \uparrow \rightarrow I_a R_A \uparrow \rightarrow V_L \downarrow$

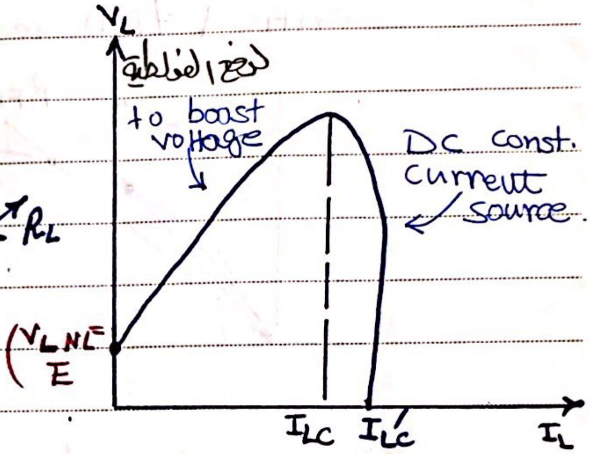
NO.

* since $V_F = V_L$, then as $V_L \downarrow \rightarrow V_F \downarrow \rightarrow I_F = \frac{V_F}{R_F} \downarrow \rightarrow$
$E \propto I_F$. $\therefore E \downarrow$

$\therefore I_L$ is increased after a certain point, then V_L is going to collapse.

- Series generator:





$I_L = I_s = I_a$

$I_L = 0$; $\therefore I_s = 0$ $\therefore V_L = E$
(↳ open circuit.)

$\therefore V_L = E = k\phi n$

=> ϕ is due to residual magnetizim.

$V_L = E - I_L (R_A + R_s)$

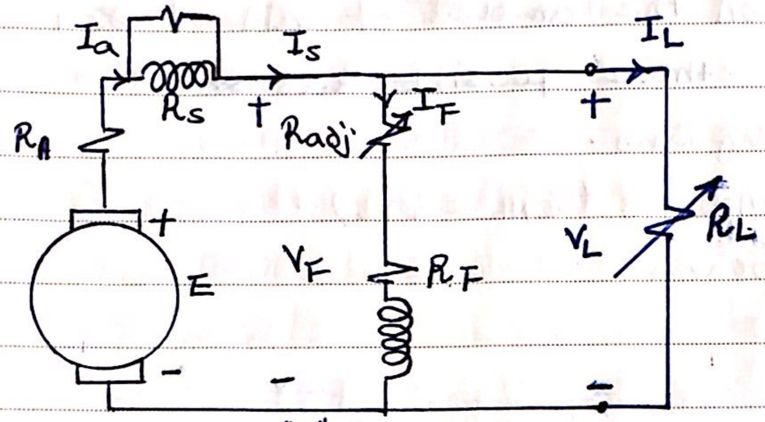
* As $I_L \uparrow \rightarrow E \uparrow$ and $I_L (R_A + R_s) \uparrow$.
However initially the increase in ($E >$ voltage drop of $I_L (R_A + R_s)$ up to the current of I_{LC}.

* After I_{LC}, the situation will be reversed.

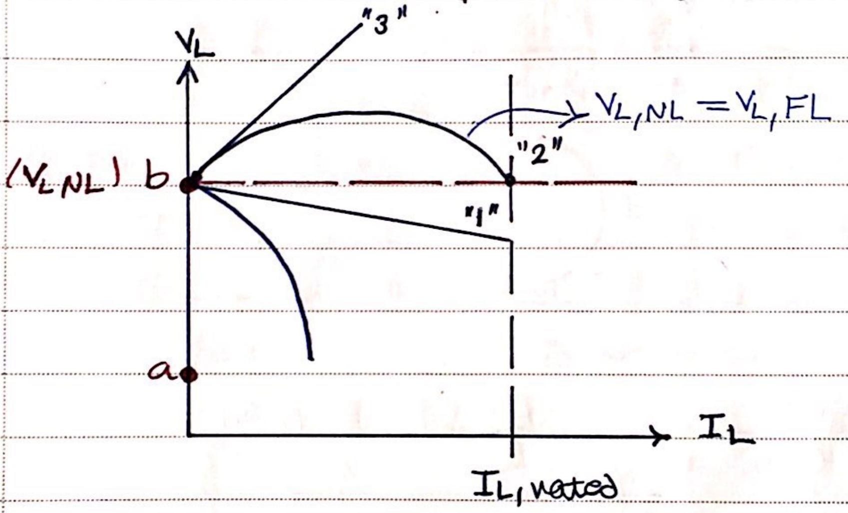
=> consequently (V_L) will drop.

NO.

- compound generator:



Long shunt.



$V_L = E - I_a(R_A + R_s)$

$I_a = I_F + I_L$

$V_L = V_F$

$I_L \uparrow \rightarrow E = k(\phi_{sh} + \phi_{se})n \downarrow$ in differential,
also $I_a(R_A + R_s)\uparrow \rightarrow$ continous drop in V_L.

ϕ_{se} opposes ϕ_{sh}.

NO.

$E = K(\phi_{sh} + \phi_{se})n \uparrow$ in case of cummulative.

→ Depending on the amount of aid of ϕs, there are three possible cases:

1. under compound.
2. Flat compound ($V_{LNL} = V_{LFL}$).
3. Over compound.

* Example: A seperatly excited DC generator with compensating winding is rated at 172 kW, 430 V, 400 A and 1800 rpm.

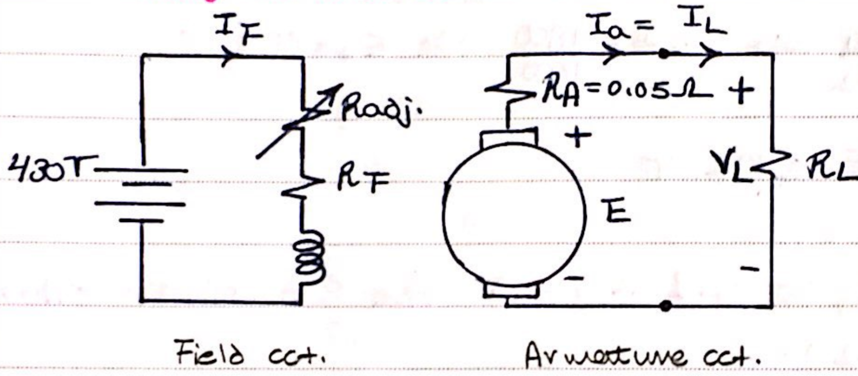
It has the magnetization curve shown in Fig. 1.

The machine has the following data:

$R_a = 0.05\,\Omega$ — $V_F = 430\,V$

$R_F = 20\,\Omega$ — $N_F = 1000$ turns/pole.

$R_{adj.} = 0 \rightarrow 300\,\Omega$



*دايماً بالامتحان لازم ترسمي الرسمات وتحطي عليها كل شي قبل الحل.

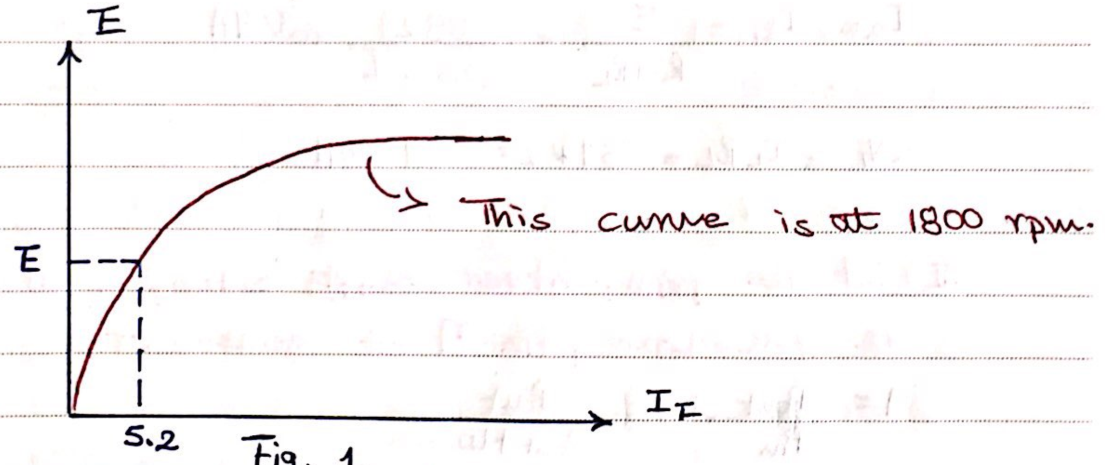


Fig. 1

I) If $R_{adj.}$ is set at 63 Ω and the prime mover driving the generator speed is 1600 rpm. Find No-terminal voltage ($V_{L-NL} = ?$)

NO.

* No Load ≡ open cct.

↳ $V_{L,NL} = E$

$$I_F = \frac{V_F}{R_{adj}+R_F} = \frac{430}{63+20} = 5.2A$$

∴ From Fig. 1, for $I_F = 5.2A$. It can be found that $E = 430\,V$ at 1800 rpm.

($E = k\phi n$)

∴ For same I_F (i.e. ϕ is constant)

$$\therefore \frac{E_1}{E_2} = \frac{n_1}{n_2} \Rightarrow \frac{430}{E_2} = \frac{1800}{1600} \Rightarrow E_2 = 382\,V$$

$\therefore V_{L,NL} = E = 382\,V$.

II) If the Load = 1 Ω, find the terminal voltage ($R_L = 1\,\Omega$).

$$I_a = I_L = \frac{E}{R_a+R_L} = \frac{382}{0.05+1} = 364A$$

$\therefore V_L = I_L R_L = 364 * 1 = 364$ volt.

III) If the prime mover supply a torque of 1000 N.m at full-Load, find η of generator.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+\text{Losses}}$$

$P_{out} = 172$ kW (given)

$$P_{in} = \omega\tau = \frac{(2\pi)(1800)}{60} * 1000 = 60\pi * 10^3$$

$$\eta = \frac{172}{60\pi} \cong 91\,\%$$

NO.

• Note : Read a study about the power flow diagram of DC-machines.

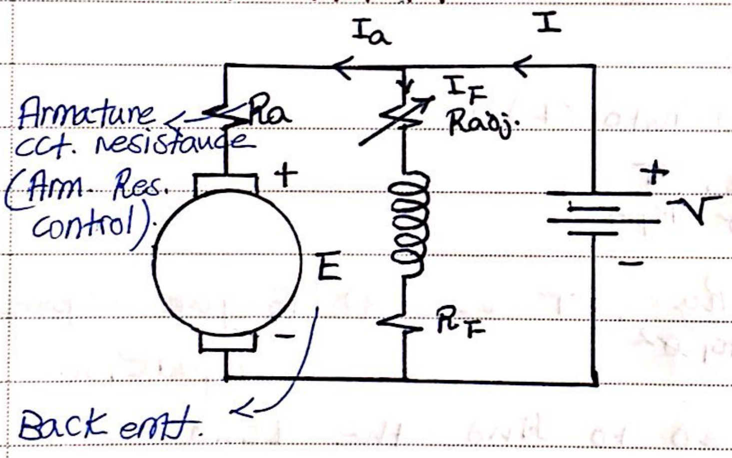
=> Generator gets a mechanical input to move the rotor then produce electrical output.

• **DC-Motors:**

- objectives:

1. voltage - current relationship. => Explained Before.
2. speed equation.
3. speed - Torque relationship.

- Shunt Motor:



* Exam Question:
Derive speed eqn.?
1. Draw the cct.
2. currents directions.
3. write the eqn.'s.

$$E = V - I_a R_a$$

$$K\phi\omega = V - I_a R_a$$

$$\therefore \omega = \frac{V - I_a R_a}{K\phi} \quad \text{--- (1)}$$

Speed equation of DC-motors.

NO.

* Speed equation shows that there are 3 methods to control the speed of the motor:

1. vary V, Armature voltage control.
2. vary R_a, Armature resistance control.
3. vary ϕ, (Field control, i.e. varying (I_F)).

• Comment: If the field cct. is opened suddenly.
$I_F = 0 \rightarrow \phi \downarrow 0 \rightarrow [\omega]$ is going to accelerate reach a very dangerous speed (Never ever open the field cct. suddenly).

* since $T = k_1 \phi I_a$

$\therefore I_a = \frac{T}{k_1 \phi}$ --- (2)

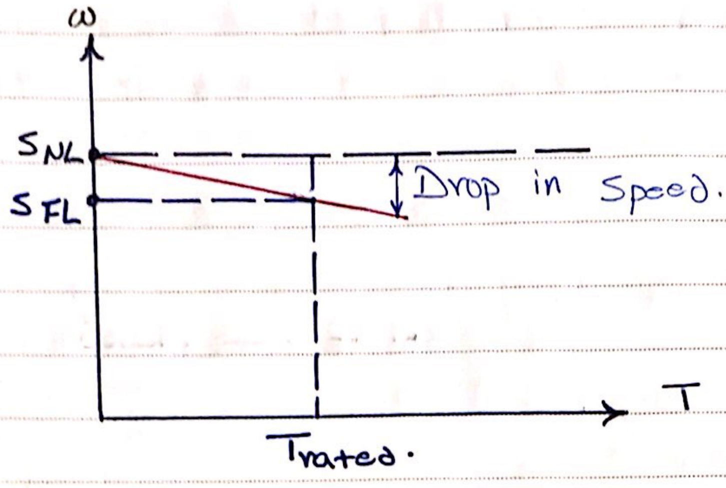
$\Rightarrow$ substitute (2) into (1),

$$\omega = \frac{V}{K\phi} - \frac{R_a}{K\phi} \cdot \frac{T}{k_1 \phi}$$

$$\omega = \frac{V}{K\phi} - \frac{R_a}{K k_1 \phi^2} \cdot T \quad \text{--- (3)}$$ Torque-speed equation.

$\therefore$ (3) can be used to find the Load characteristics (i.e. ω vs. T)

$\therefore$ For a given applied voltage and given R_{adj}.
$\therefore$ V and ϕ are constants.



∴ Speed Regulation = $\frac{S_{NL} - S_{FL}}{S_{FL}}$

∴ If the drop in voltage is very small, then the shunt motor is a "constant speed motor."

NO. 29.3.2018

*Load characteristics:

$E = V - I_a R_a$

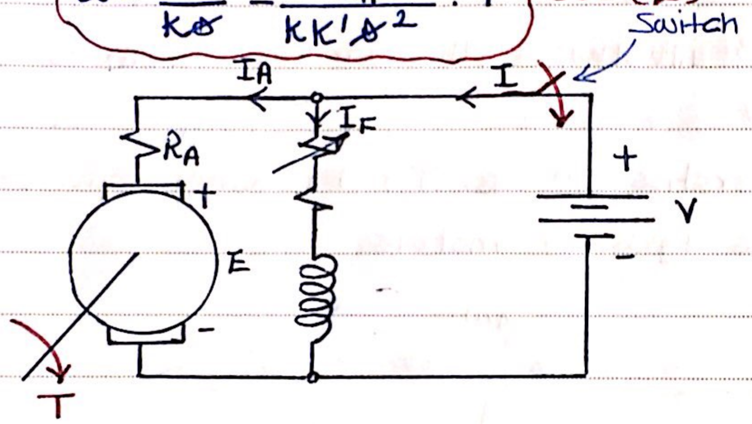
$K\phi\omega = V - I_a R_a$ "The diagram should be given"

$$\omega = \frac{V - I_a R_a}{K\phi} \quad --- (1)$$

$$T = K'\phi I_A$$

$$\therefore \omega = \frac{V}{K\phi} - \frac{R_A}{K\phi} \cdot \frac{T}{K'\phi}$$

$$\omega = \frac{V}{K\phi} - \frac{R_A}{KK'\phi^2} \cdot T \quad --- (2)$$



• For a given torque: by using eqn. (2)

$(T_1 < T_2)$

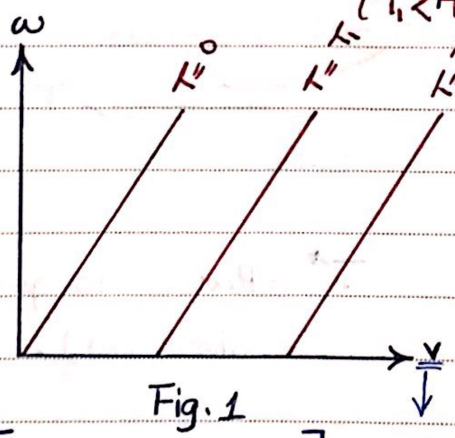


Fig. 1

[RA & ϕ ≡ const.] Armature voltage control

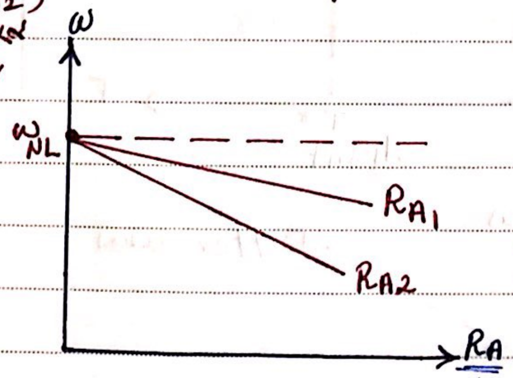


Fig. 2

Armature Resistance control.

NO.

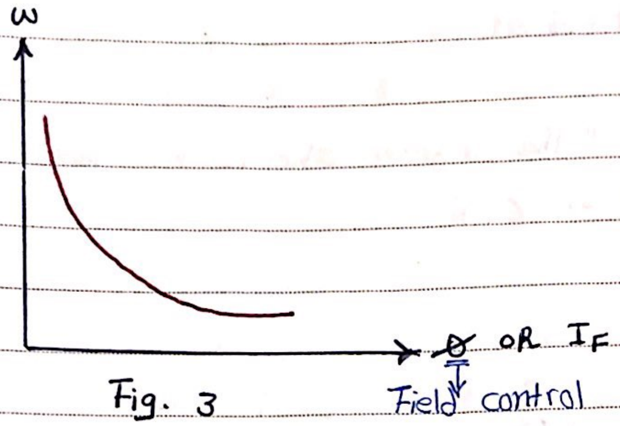
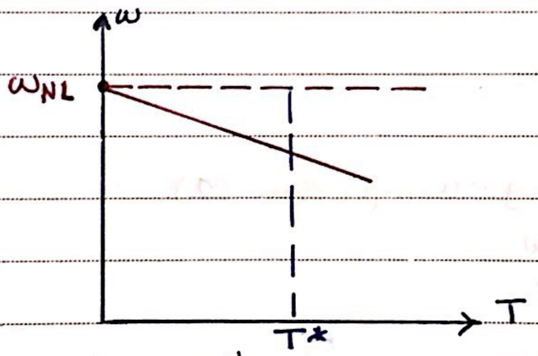


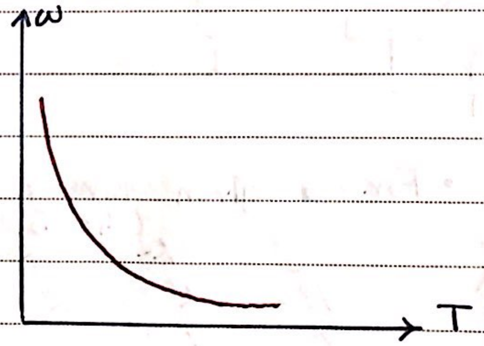
Fig. 3

• comment :

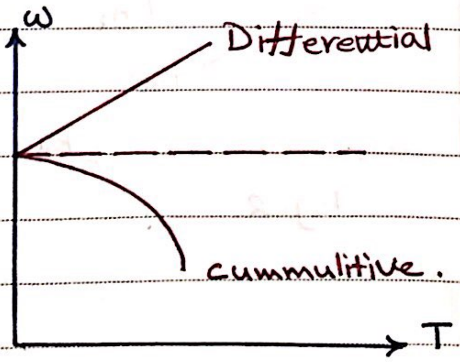
- Fig. 1, 2 and 3 illustrates the various methods of speed control.
- Load characterstics (ω vs. T) by using eqn. (2).
- For the various types of motors.



Shunt



Series



compound

$T^* \equiv$ Rated torque (i.e. Load).

* Depending on Flux type:

1. Differential.
2. cummulitive.

NO.

* when $T\uparrow \rightarrow E\downarrow$

$E = K\phi\omega$

$T = K\phi I_A$

$I_A = \frac{V - E}{R_a}\uparrow$

$I_A = I_s$ (series)$\uparrow \rightarrow \phi\uparrow$

- Starting of Dc-motors:

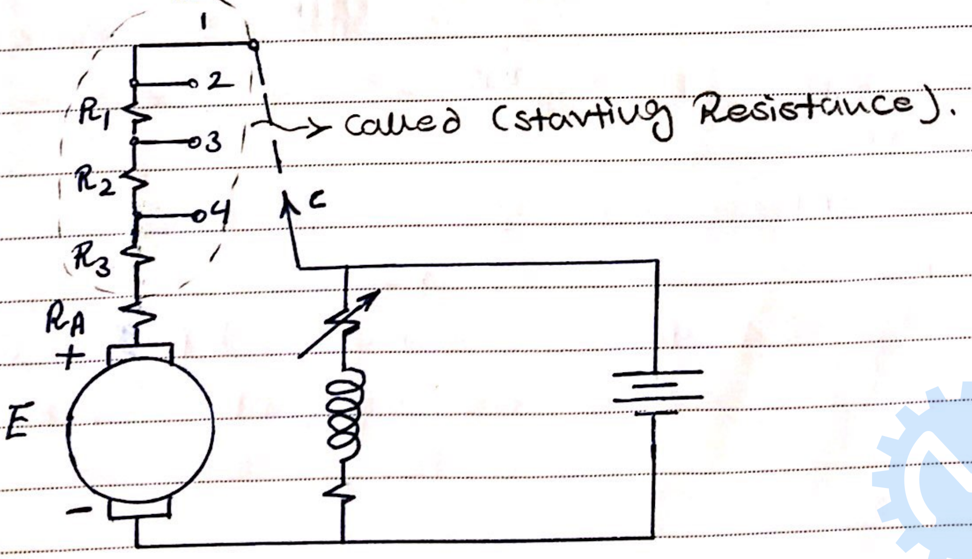
Initially when a voltage (V) is applied to a dc motor, it doesn't rotate due to it's inertia.

$\therefore E = K\phi n = 0;\ n = 0$

$\therefore I_{A_{starting}} = \frac{V - E}{R_a} = \frac{V}{R_a}$

$I_{A_{starting}} \gg I_{A_{rated}}$

$\therefore$ Initially I_A should be limited by using external starting resistance.



NO.

* Initially $\underline{c}$ is at position #1 ⇒ when motor rotated $I_A \downarrow$ → #2 ---- until position #4 is reached.

↳ See the example in the book.

$P_{conv.}$ ⇒ convert (Electrical ⇆ Mechanical)

⇒ consider (shunt Motor):

$(E \triangleq V - I_A R_A) * I_A$

$E I_A = V I_A - I_A^2 R_A$

$= V(I - I_F) - I_A^2 R_A$

$= VI - (V I_F + I_A^2 R_A) = P_{inp.} - \text{Electrical Losses} = P_{conv.}$

VI: P_{input}; $V I_F$: Field Losses; $I_A^2 R_A$: Armature Losses; together: Electrical Losses

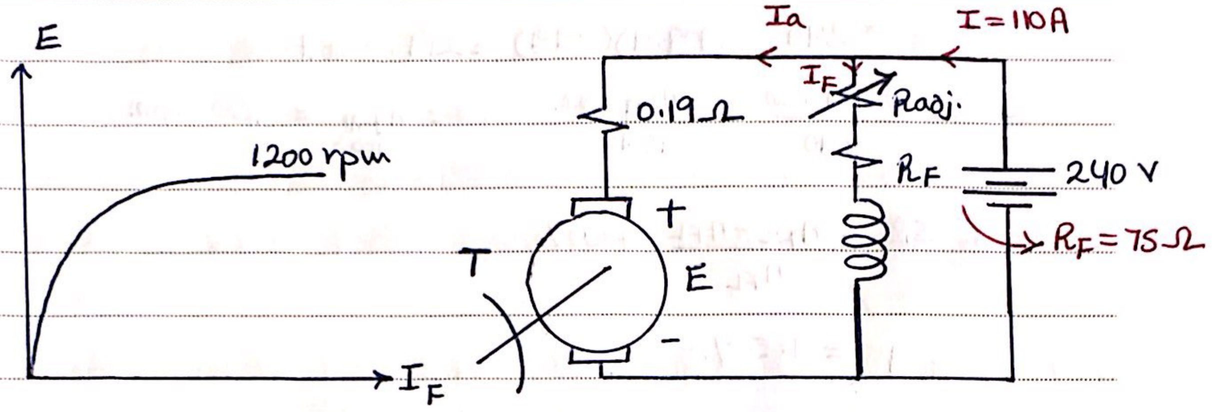
⇒ For shunt.

* solve it for series and compound.

• Note: The same expression of power can be found for all types of (motors).

NO. 1.4. 2018

* Ex. 1 For the given system and magnetization curve, what is the speed at No-Load? given Radj. = 175 Ω.



I.

No-load => T=0

At No-Load (I_a) is very small, assumed to be zero.

∴ E = V = 240 volt

$$I_F = \frac{240}{75+175} = 0.96\,A$$

By using the magnetization curve.

$I_F = 0.96$ => E = 277 volt at 1200 rpm.

=> since $E = k\phi n$

$$\therefore \frac{E_1}{E_2} = \frac{n_1}{n_2} \Rightarrow \frac{277}{240} = \frac{1200}{n_2}$$

∴ $n_2 = 1040$ rpm. (Field control مثال على)

II. Assuming No-armature reaction, what is the speed at full-load, given $I_{full\ load} = 110A$ for the same Radj. !

FIVE APPLE

NO.

$I_A = I - I_F$

$= 110 - 0.96 = 109.4A$

$\therefore E = V - I_A R_A$

$= 240 - (109.4)(0.19) = 219.3$ volt.

$\therefore \frac{E_{full\ load}}{240} = \frac{n_{full\ load}}{1040}$ $\therefore n_{full\ load} = 950$ rpm

$SR = \frac{n_{NL} - n_{FL}}{n_{FL}} * 100\%$

$= 9.5\%$

III . Find $I_{A start}$?

$I_{A start} = \frac{V - 0}{R_A} = \frac{240}{0.19} = 1263A$

If I_{start} is to be limited $[2 I_{A_{rated}}]$, find $R_{ext.}$?

$I_{A\ rated} = 109.04A$

$\therefore 2\ I_{A\ rated} = 109.04 * 2 = \frac{240}{0.19 + R_{A_{ext.}}}$

$\therefore R_{A_{ext.}} = 0.906\ \Omega$

FIVE APPLE

• AC – Machines:

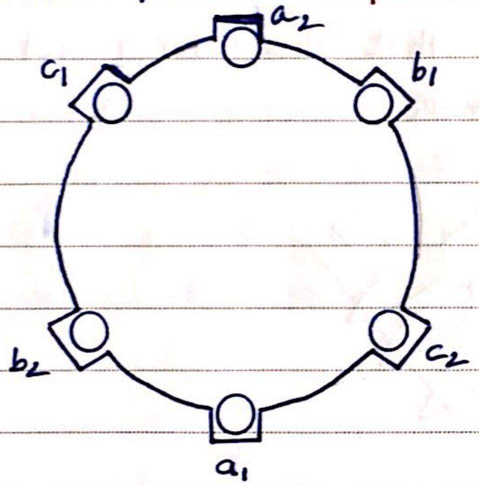
3-ph. induction motor.

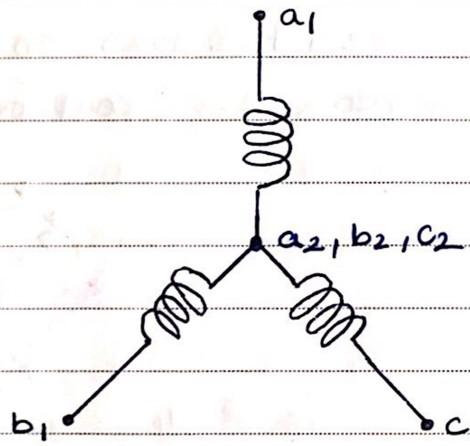
– construction:

It consists of:

1) stator:– which consists of 3-ph. windings into which a balanced 3-ph. voltage is applied. As shown before this produce a rotating magnetic field.

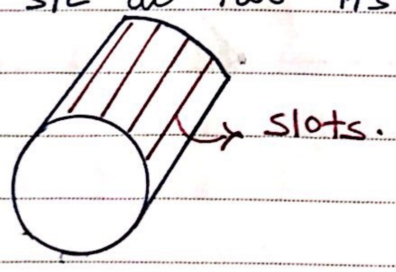
with speed $f = np$





2) Rotor:– There are two types:

a) Squirrel-cage: (قفص السنجاب), Rotor consists of a cylinder at it's surface there are slots. at which conductors are located. These conductors are s/c at two its ends.



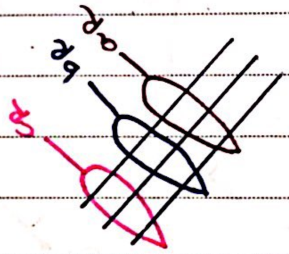
NO.

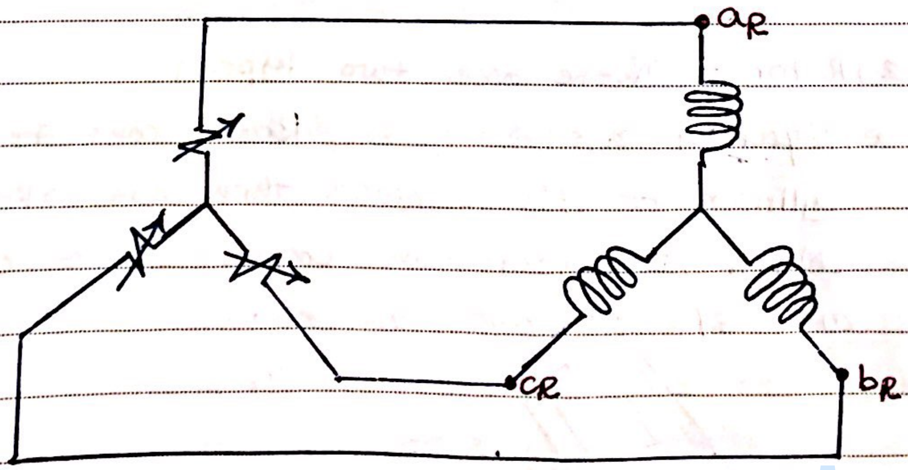
* Hence for this type the motor is called SCIM (squirrel Cage Inductor Motor).

b) Wound-Type: Rotor consists of 3-ph. windings, whose terminals are connected to 3 slip rings.

These rings make contact with 3 stationary brushes.

The brushes are connected to 3-ph. resistive load. so that the rotor resistance can be controlled.





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* operation of Induction Motor:

a 3-ph voltage V_s is applied to stator winding (s.w.)

⇓

current I_s will flow in (s.w.)

⇓

I_s is going to generate Rotating Magnetic Field, B_s.

The speed of $B_s = \frac{F}{P}$; $n_s = \frac{f}{P}$

⇒ $f_s \equiv$ Frequency of V_s ↳ synchronous speed.

$P \equiv$ No. of pairs (pole pairs) of s.w. عدد الأقطاب

⇓

B_s is going to cut Rotor conductors of windings (R.w).

⇓

A voltage E_R will be induced in RW---

⇓

A current I_R due to E_R will flow in the RW.

⇓

I_R will produce a flux B_R.

⇓

Hence, due to I_R and B_s, a torque "T" will be produced OR one can say due to the interaction between B_s and B_R a torque will be produced.

⇒ $T \triangleq K(B_R + B_s)$

⇓

∴ Due to (T), the rotor is going to rotate with a speed n_{motor} (rps) or ω_m (rad/s) ⇒ Mechanical speed

NO.

* $n_s \equiv$ called synchronous Speed ⇒ B_s.
where ($n_m < n_s$), In order to have relative motion between B_s and R.W.

. Induction تولد جهد و تيار I_R

• Comment:

1. Since E_R and I_R are generated by induction effect.
Hence the motor is called Induction motor.

2. Hence the I_M can be considered as a rotating transformer where stator represent primary and rotator represent secondary.

3. slip speed $\triangleq n_s - n_m$

$$slip \triangleq \frac{slip\ speed}{n_s}$$

$$s = \frac{n_s - n_m}{n_s}$$

* If the Rotor is blocked (i.e. $n_m = 0$)
∴ $s = 1$ يعني لما $n_m = 0$ بكون $s=1$

∴ In this case frequency of the induced voltage in RW (f_r) is the same as that of voltage applied to S.W (i.e. f_s)
↳ "$f_r = f_s$"

NO.

* If the Rotor is rotating at speed $= n_s$.

$\therefore s = 0$ "$n_m = n_s$"

*في حالة كانت ($n_m = n_s$) فإن ال (slip) يكون = 0

$\therefore$ In this case $f_r = 0 = f_s$

$\therefore 0 \leqslant \underset{\text{slip}}{s} \nless$

$\therefore$ In general $f_r = s f_s$. تردد ال stator لا يساوي تردد ال Rotor

* Example: A 220 V, 3-ph., 6 pole, 50 Hz, Im is running at a slip of 3.5%.

a. Find the speed of B_s (n_s):

$f = np$

$\therefore n = \frac{f}{p} = \frac{50}{3}$ rps

pairs of poles ← (p)

$= \frac{50}{3} * 60 = 1000$ rpm.

b. n_m

$s = \frac{n_s - n_m}{n_s} \Rightarrow \frac{3.5}{100} = \frac{1000 - n_m}{1000}$

$\therefore n_m = 965$ rpm.

c. slip speed

$= n_s - n_m$

$= 1000 - 965 = 35$ rpm.

NO.

2. Rotor frequency.

$f_r = s f_s$

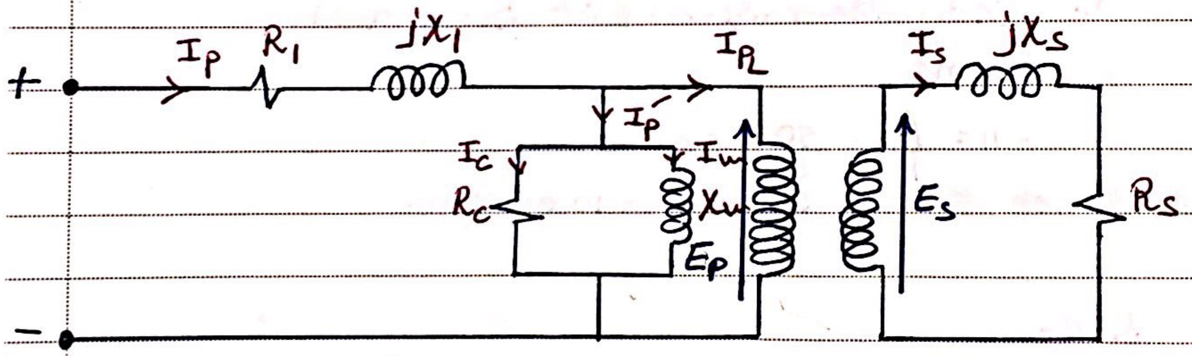
$= \frac{3.5}{100} \times 56 = 1.75 \text{ Hz}$

* Equivalent cct of IM.

This cct. can be used to evaluate the performance of IM.

since IM can be considered as a transformer, then the equivalent cct. of transformer will be used, where: Stator = primary.

Rotor = secondary.



P ≡ Primary (stator) S ≡ Secondary (Rotor)

* V_p ≡ phase voltage applied to stator.

R_1, X_1 ≡ Resistance and Reactance of S.W.

I_p ≡ stator current

I_p' ≡ No-load component of I_p

I_c, I_M ≡ to represent core losses and component of I_p to generate B_s respectively.

I_{PL} ≡ Load component of I_p

NO.

E_P ≡ Induced voltage in stator winding.
(primary)

E_S ≡ Induced voltage in secondary winding.
(secondary)

R_s, jX_s ≡ Resistance and Reactance of Rotor.

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• Equivalent cct. of Rotor:

Let at locked (Blocked) condition (i.e. $n_m = 0$) where $s = 1$, where $f_r = f_e$

* $f_e \equiv$ Electrical frequency of voltage applied to stator.

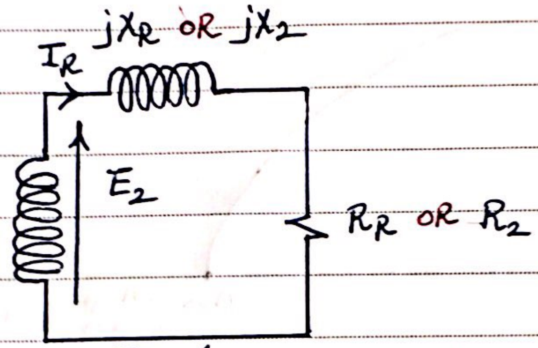


Fig. 1

$\Rightarrow E_2 = E_0$, since in general $f_r = s f_e$

$\therefore$ In general $E_2 = s E_0$

$\Rightarrow X_R = \omega L_R$ *$L_R \equiv$ Inductance of Rotor

$= 2\pi f_r L_R$

$= 2\pi (s f_e) L_R$

$= s\,(2\pi f_e L_R) = s X_0$

$\therefore$ Fig. 1 can be redrawn as follows:

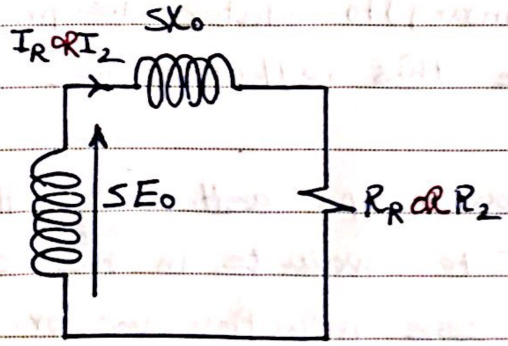
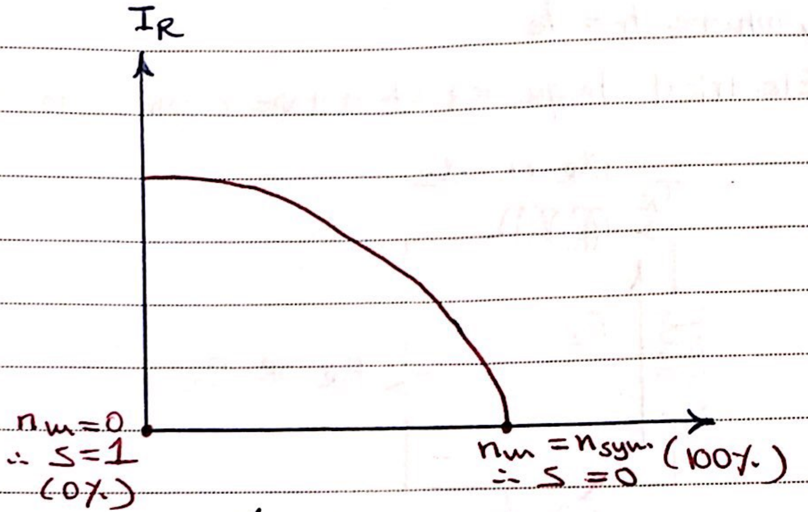


Fig. 2

NO.

$$I_R = \frac{sE_0}{R_2 + jsX_0} = \frac{E_0}{\frac{R_2}{s} + jX_0}$$



% of speed (n_m) w.r.t n_{syn}.

• Comment:

It can be observed that I_R depends on R_2 (i.e. Rotor Resistance). This where the advantage of wound type IM which can be used to control the value of R_2.

• Final Equivalent ckt. of Induction Motor:

This can be obtained by reflecting Rotor (i.e. secondary) to stator (i.e. primary).

* To make this reflection, one should know a_{eff}.

↳ for wound type $a_{eff} = \frac{N_s}{N_R}$. However it is difficult to evaluate in the case of squirrel cage induction motor.

NO.

* Reflect (R → S)

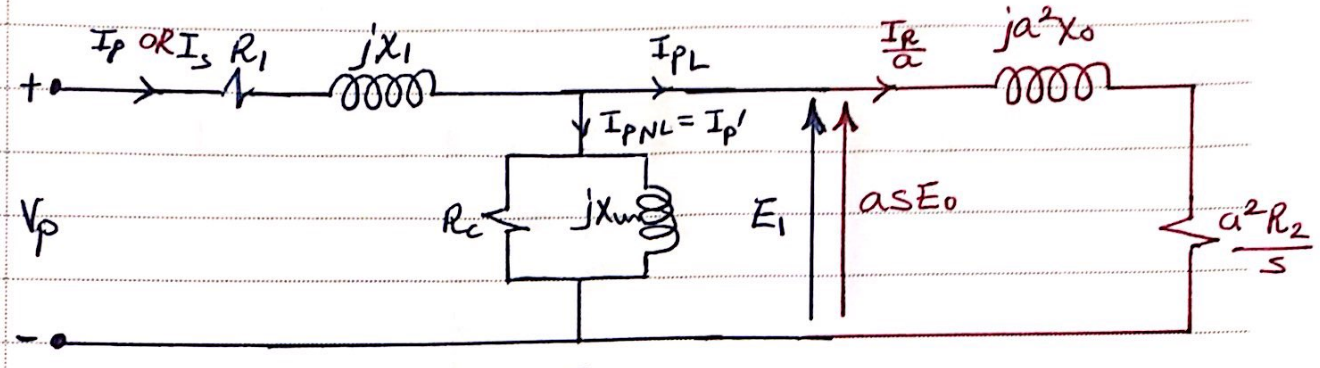


Fig. 3
"per-phase cct."

ja^2X_0 & jX_1
↳ they have the same frequency.

* Reflection when $f_{E_0} = f_{E_1}$

إذا اختلف ال frequency لا نستطيع عمل reflection.

∴ Fig. 3 will be used to find voltage, current, Power, and torque.

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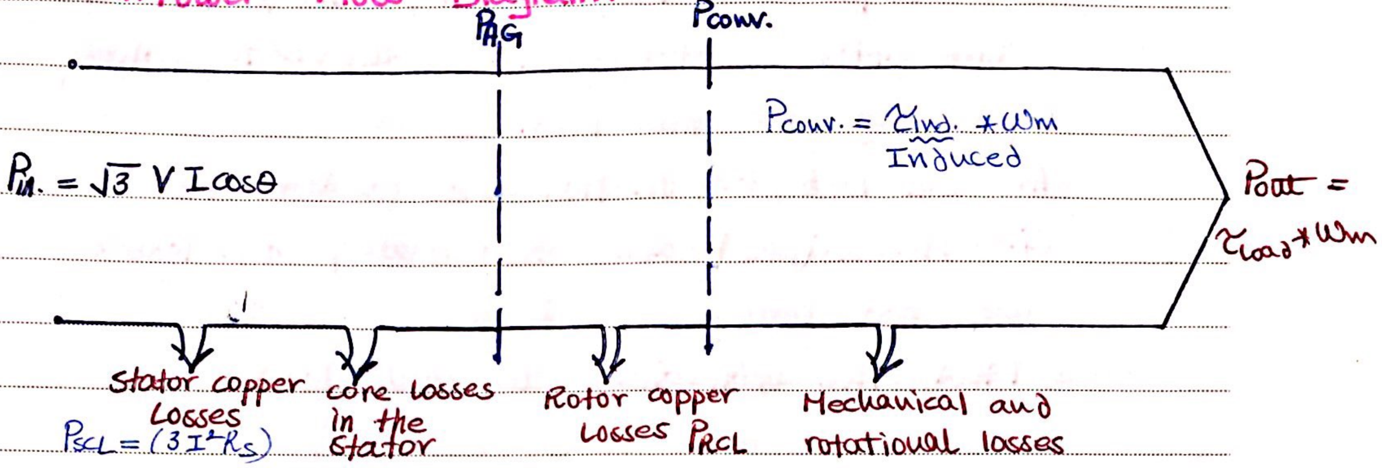
* Power Flow Diagram:



$V, I \equiv$ Applied line voltage & current.

$\theta \equiv$ PF angle

$P_{AG} \equiv$ Power transferred through Air Gap to rotor.

$P_{SCL} \equiv$ Power stator copper losses.

$P_{conv.} \equiv$ Amount of power converted to mechanical power.

∴ Power flow diagram + equ. cct. can be used to find:

1. Relationship between P and T "torque".
2. Relationship between T and ω.

=> Rotor copper losses = $3I^2R$ (in case of wound type only not squirrel cage).

• Note! If core losses is given as a number (i.e. not as R_c) then it is usually combined with the mechanical losses.

NO.

* Example: A 50 kw, 440 volt, 50 Hz, 2 pole I.M. (Induction motor) has a slip = 6%, when operating at full load.
At full load, the friction and windage losses (i.e. Mechanical) are 520 watt, core losses are 500 watt.
Find the followings at full load.

I) P_{out} in watts.

$P_{out} = 50$ kw.

II) Load torque.

$P = \tau \omega_m$ --- (1)

$\omega_m = \omega_{syn.} (1 - s)$ --- (2)

$\omega_{syn.} = 2\pi n_{syn.} = 2\pi \frac{f}{P} = \frac{2\pi (50)}{1}$ --- (3)

↳ No. of pole pairs.

by substitute (2) and (3) into (1)

↳ $\tau_{load} = 169.4$ N.m

III) Find $\tau_{ind.}$

$P_{conv.} = \tau_{ind.} * \omega_m$ --- (4)

$P_{conv} = P_{out} + P_{mech.} + P_{core}$

$= (50 + 0.52 + 0.5)$ kw

$= 51.02$ --- (5)

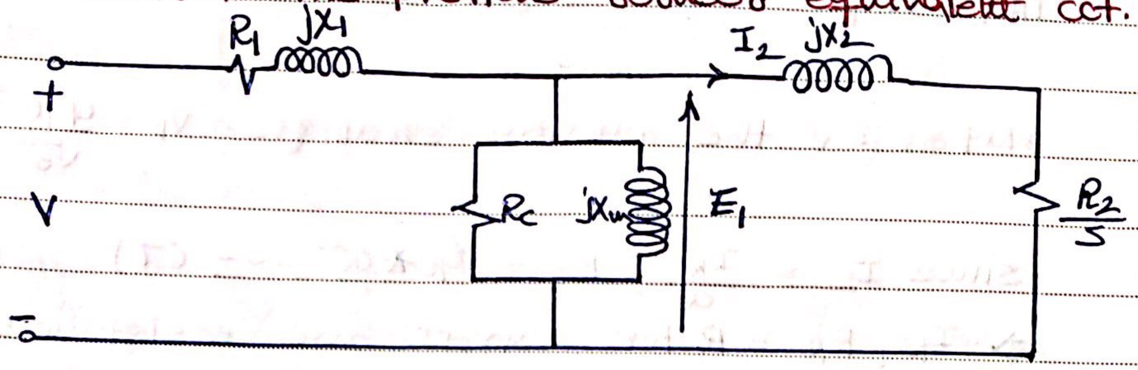
substitute (4) into (5)

$\tau_{ind.} = 172.9$ N.m.

NO.

• **Power and torque relationships:**

Consider the previous deduced equivalent cct.



per phase circuit

$I_2 \equiv$ Secondary (i.e. Rotor) current reflected to primary.

$X_2, R_2 \equiv$ Secondary Resistance and Reactance reflected to primary.

$I_1 \equiv$ Primary current.

$\frac{R_2}{s} \equiv$ Resistance which consumes P_{AG}.

$$\therefore Z_1 = \frac{V_1}{I_1} = R_1 + jX_1 + \cfrac{1}{\frac{1}{R_c} + \frac{1}{jX_m} + \cfrac{1}{\frac{R_2}{s} + jX_2}}$$

$$\therefore I_1 = \frac{V_1}{Z_1} \quad --- (1)$$

*Note: $\theta = \angle Z$, $V_1 \equiv$ Applied phase voltage.

$$Z_1 = Z_{eq}. \quad --- (2)$$

$$P_{SCL} = 3 I_1^2 R_1 \quad --- (3)$$

stator core losses.

$$P_{core} = 3 \frac{E_1^2}{R_c} \quad --- (4)$$

↳ per phase cct.

NO.

$P_{AG} = 3 I_2^2 \frac{R_2}{s}$ --- (5)

$P_{AG} = P_{inp.} - P_{SCL} - P_{core}$ --- (6)

*Note! In the previous example ($V_1 = \frac{440}{\sqrt{3}}$).

since $I_2 = \frac{I_R}{a}$; $R_2 = R_R * a^2$ --- (7)

⇒ I_R, R_R ≡ Rotor current and resistance.

a ≡ Effective turns ratio.

Substitute (7) into (5).

$P_{AG} = 3 \left(\frac{I_R^2}{a^2}\right) * R_R\, a^2 \frac{1}{s}$

$P_{AG} = 3 I_R^2 R_R * \frac{1}{s}$ --- (8)

From these equations, it can be found that

$P_{RCL} = s P_{AG}$ --- (9)

since $P_{conv.} = P_{AG} - P_{RCL}$ --- (10)

substitute (9) into (10).

$P_{conv.} = P_{AG} - s P_{AG}$

$= (1 - s)(P_{AG})$

since $P_{conv.} = \tau_{ind.} * \omega_m$

$\therefore \tau_{ind.} = \frac{P_{conv.}}{\omega_m} = \frac{(1-s) P_{AG}}{\omega_m}$.

- **Conclusion:**

$P_{conv.} = \tau_{ind.} * \omega_m$

$\tau_{ind.} = \dfrac{P_{conv.}}{\omega_m}$

$P_{conv.} = P_{AG} - P_{CRL} = P_{AG} - s\,P_{AG}$

$= P_{AG}(1-s)$

Since $\omega_m = \omega_{syn.}(1-s)$

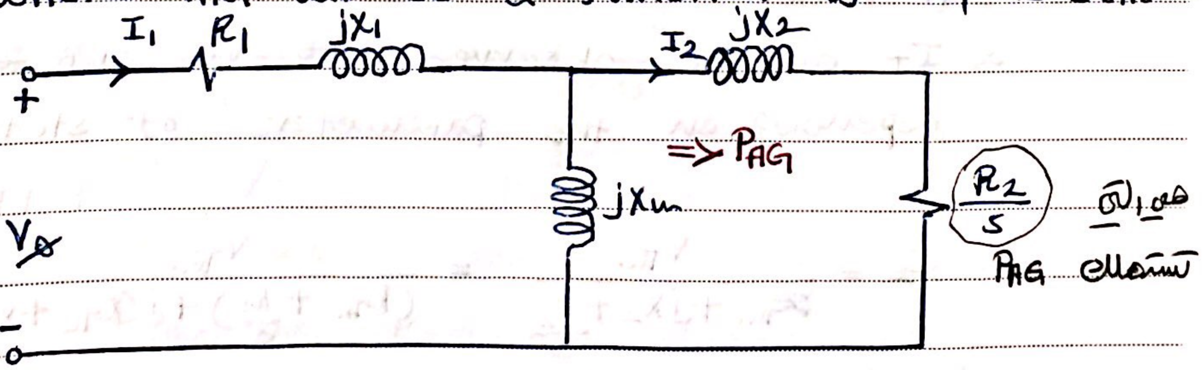
$\therefore \tau_{ind.} = \dfrac{P_{AG}(1-s)}{\omega_{syn.}(1-s)} = \dfrac{P_{AG}}{\omega_{syn.}}$ --- (1)

$\therefore$ Advantage of (1) is that for a given f and No. of poles of stator winding then, $\omega_{syn.}$ is const.

$\therefore \tau_{ind} \propto P_{AG}$

※ Torque vs. ω_m or n_m:

* Since $\tau_{ind.} = \dfrac{P_{AG}}{\omega_{syn.}}$, Then P_{AG} is going to be derived by using a simplified equivalent cct., where P_{AG} will be a function of s, as follows:

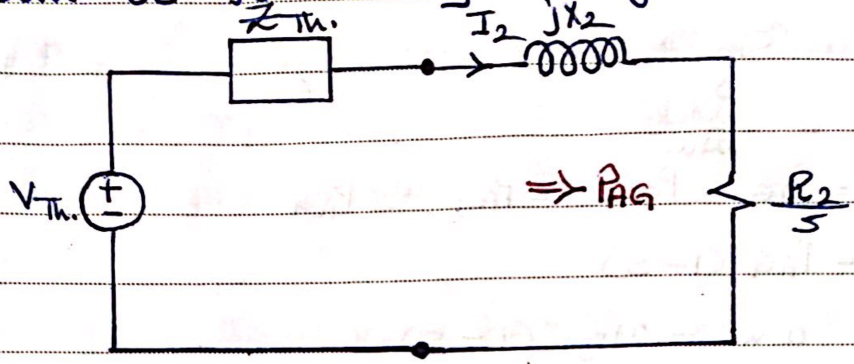


$\tau_{ind.} = \dfrac{P_{AG}}{\omega_{syn.}}$ --- (1)

$P_{AG} = \dfrac{3|I_2|^2 R_2}{s}$ --- (2)

NO.

I_2 can be found by using Thév. equ. cct.



$$* \; V_{Th.} = V_\phi \cdot \frac{jX_m}{R_1 + jX_1 + jX_m} \quad \therefore |V_{Th.}| = \frac{V_\phi X_m}{\sqrt{R_1^2 + (X_1 + X_m)^2}}$$

$$Z_{Th.} = jX_m \parallel (R_1 + jX_1)$$

$$\hookrightarrow Z_{Th.} = R_{Th.} + jX_{Th.}$$

by using the approximation where $X_m > X_1$ and $X_m > R_1$. It will be found that:

$$R_{Th.} \cong R_1 \left(\frac{X_m}{X_1 + X_m}\right)^2$$

$$X_{Th.} \cong X_1$$

$\therefore$ It can be observed that $V_{Th.}$ and $Z_{Th.}$ depending on the parameters of stator cct.

$$\therefore I_2 = \frac{V_{Th.}}{Z_{Th.} + jX_2 + \frac{R_2}{S}} = \frac{V_{Th.}}{(R_{Th.} + \frac{R_2}{S}) + j(X_{Th.} + X_2)}$$

$$\therefore |I_2| = \frac{|V_{Th.}|}{\sqrt{(R_{Th.} + \frac{R_2}{S})^2 + (X_{Th.} + X_2)^2}} \quad --- (3)$$

NO.

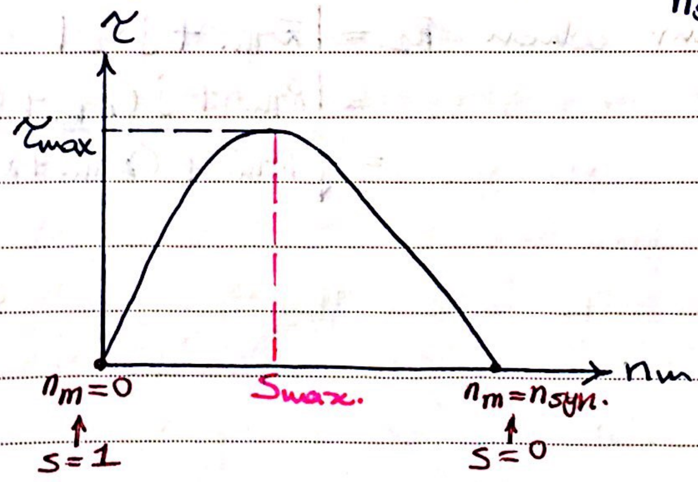
* Sub. (3) into (2) to give P_{AG} as a function of $V_{Th.}$, $R_{Th.}$ and $X_{Th.}$. let this be equation (4).

* Then sub. (4) into (1) to give the following general expression:

$$\therefore \tau_{ind.} = 3 \frac{|V_{Th.}|^2 * \frac{R_2}{s}}{\omega_{syn.}\left[(R_{Th.} + \frac{R_2}{s})^2 + (X_{Th.} + X_2)^2\right]} \quad --- (5)$$

* Comments:

I) equation (5) gives the relationship between $\tau_{ind.}$ vs. n_m or ω_m, since $s = \frac{n_{syn.} - n_m}{n_{syn.}}$.



=> $\tau_{max.}$ ≡ Max. value of torque and it's called (Pull-out torque).

II) One can find variation of torque (τ) as (s) vary.

NO.

III) For a given slip (s), it can be found that τ_{ind}, can be controlled by varying $V_{Th.}$ (i.e. Applied voltage) or Reactance of the motor.

=> $s_{max.} \equiv$ value of (s) when ($\tau = \tau_{max.}$).

IV) Evaluation of $s_{max.}$

Since $\tau_{ind.} = \frac{P_{AG}}{\omega_{syn.}}$

$\therefore$ $\tau_{max.}$ is when P_{AG} is max.

According to the max. power theorem.

This occur when $R_2 = |Z_{Th.} + jX_2|$

$$= |R_{Th.} + j(X_{Th.} + X_2)|$$

$$= \sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2}$$

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* $\tau_{max.}$ => $P_{AG\,max.}$ => when power supplied to $\frac{R_2}{s}$ is max. For max. power $\frac{R_2}{s} = \sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2}$

$$\therefore S_{max.} = \frac{R_2}{\sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2}} \quad --- (1)$$

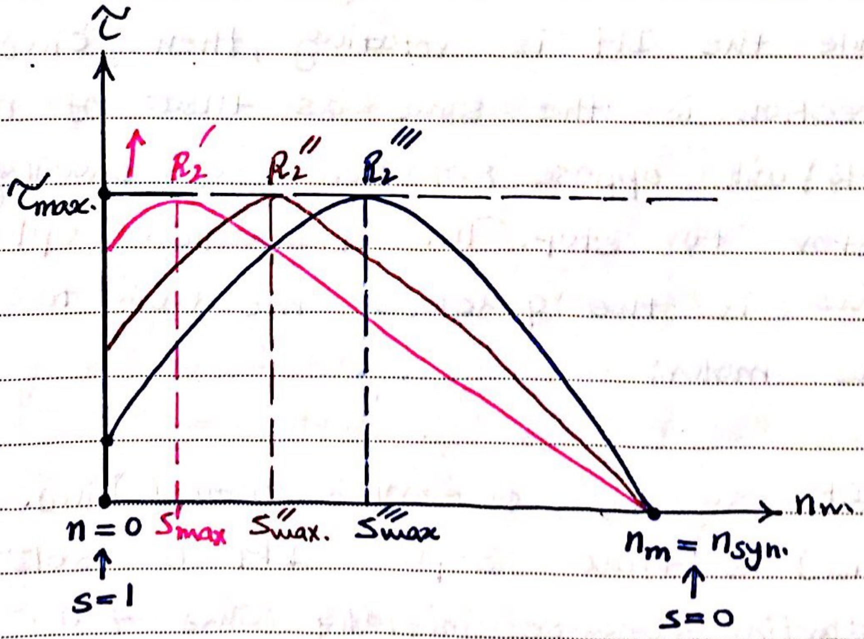
If $S_{max.}$ is substituted in the expression of $\tau_{ind.}$, it can be found:

$$\tau_{max.} = \frac{3V_{Th.}^2}{2\omega_{syn.}\left[\sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2} + R_{Th.}\right]} \quad --- (2)$$

- **Comments:**

I) $S_{max.}$ depends on R_2 but torque $\tau_{max.}$ doesn't depend on R_2.

$\therefore S_{max.}$ can determine the location of $\tau_{max.}$



$\therefore R_2' > R_2'' > R_2'''$

* الرتاك دة من المهم للمشال لأنه في تزيد مع المهم للمسال.

NO.

II) ∴ For a given input voltage and stator parameters, $\tau_{max.}$ is constant.

III) By varying R_2, one can change the location of S_{max}.

IV) This is the advantage of wound type IM. Is that $\tau_{max.}$ can occur at low speed. Therefore the characterstics can be used to derive heavy loads. As the motor rotate then (R_2) is decreased, until n_m reaches near n_{syn}.

V) If the rotation of magnetic field is reversed while the IM is rotating, then $\tau_{ind.}$ (whose direction is the same as that of magnetic field) will oppose Rotation and causing the motor to stop. This is called (plugging). This is the quickest method to stop the motor.

VI) It can be observed from ($\tau_{ind.}$ vs. n_m) is that 3-ph. IM is self starting. Because initially $\tau_{ind.} \neq 0$.

NO.

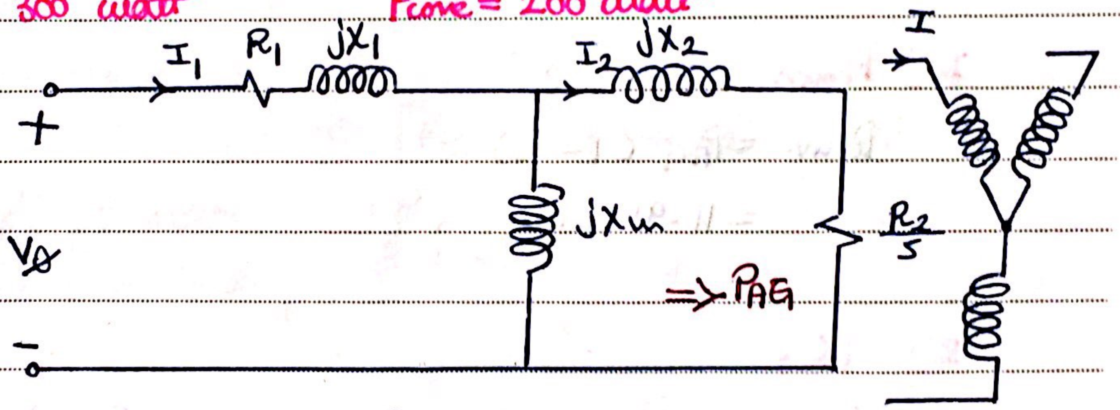
- Squirrel cage: No brushes or slip rings, so, Maintenance cost is very low.
- wound type: It can be used to operate at heavy Loads.

※ Ex.: A 208 V (Line Voltage), 4 poles, 60 Hz, Y connected rotor IM. (→ stator) Rated at 15 hp. Its equivalent cct. has:

$R_1 = 0.22\ \Omega$ $R_2 = 0.127\ \Omega$ $X_m = 15\ \Omega$

$X_1 = 0.43\ \Omega$ $X_2 = 0.43\ \Omega$

$P_{mech.} = 300$ watt $P_{core} = 200$ watt



per phase cct.

For a slip $s = 0.05$, Find the followings:

I) The line current. (stator)

Find $I_1 = ?$

$I_1 = V_\phi / Z_{eq.}$; $V_\phi = \frac{208}{\sqrt{3}} \angle 0^\circ$ (Ref.) زاوية حطن كأنها

$Z_{eq.} = R_1 + jX_1 + (jX_m \,//\, (\frac{R_2}{s} + jX_2))$

$= 2.84 \angle 25.7^\circ\ \Omega$

$I_1 = 42.28 \angle -25.7$ A

NO.

II) P_{SCL}

$$P_{SCL} = 3|I_1|^2 R_1 = 1179.8 \text{ watt}.$$

III) P_{AG}

$$P_{AG} = 3|I_2|^2 \frac{R_2}{s}$$

$$I_2 = I_1 * \frac{jX_m}{jX_m + jX_2 + \frac{R_2}{s}}$$

$$I_2 = 40.65 \angle -16.4 \text{ A}$$

$$P_{AG} = 12.59 \text{ kW}.$$

IV) $P_{conv.}$

$$P_{conv.} = P_{AG}(1-s)$$

$$= 11.91 \text{ kW}.$$

V) $\tau_{ind.}$

$$\tau_{ind.} = \frac{P_{conv.}}{\omega_m} \quad ; \omega_m = \omega_{syn.}(1-s)$$

$$\omega_{syn.} = 2\pi n_s = 2\pi \frac{f}{P} = 2\pi \frac{(60)}{2}$$

$$= 60\pi$$

$$\tau_{ind.} = 66.5 \text{ N.m}.$$

VI) τ_{load}

$$\tau_{load.} = \frac{P_{out}}{\omega_m} \quad ; P_{out} = P_{in} - \text{losses}.$$

$$\eta = \frac{P_{out}}{P_{inp.}}$$

$$P_{in} = 3|V_\phi||I_1| \cos \angle I_1 \rightarrow (I_1 \text{ زاوية})$$

OR

$$P_{out} = P_{conv.} - P_{mech.} - P_{core}$$

$$= 11.41 \text{ kW}; \quad \therefore \tau_{out} = 63.75 \text{ N.m}$$

VII) Find slip at Pull-out torque and the value of this torque ?

$$S_{max.} = \frac{R_2}{\sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2}} \; ; \; R_{Th.} = R_1 \left(\frac{X_m}{X_1 + X_m} \right)^2$$

$$X_{Th.} = X_1$$

* by substitution:

$R_{Th.} = 0.2 \, \Omega$

$X_{Th.} = 0.43 \, \Omega$

$\Rightarrow S_{max.} = 0.144$

$$\tau_{pull\,out} = \tau_{max.} = \frac{3 V_{Th.}^2}{2 \omega_{syn.} \left[R_{Th.} + \sqrt{R_{Th.}^2 + (X_{Th.} + X_2)^2} \right]}$$

* by substitution:

$\Rightarrow \tau_{max.} = 100 \, N \cdot m.$

* Single-phase Induction Motor:

[Industry → 3-ph is supplied.
[Homes → 1-ph is supplied.

Since 1-ph. voltage is distributed to residential section, then most domestic appliances use 1-ph. I.M.

• construction:

As any machine, it consists of:

I) stator.

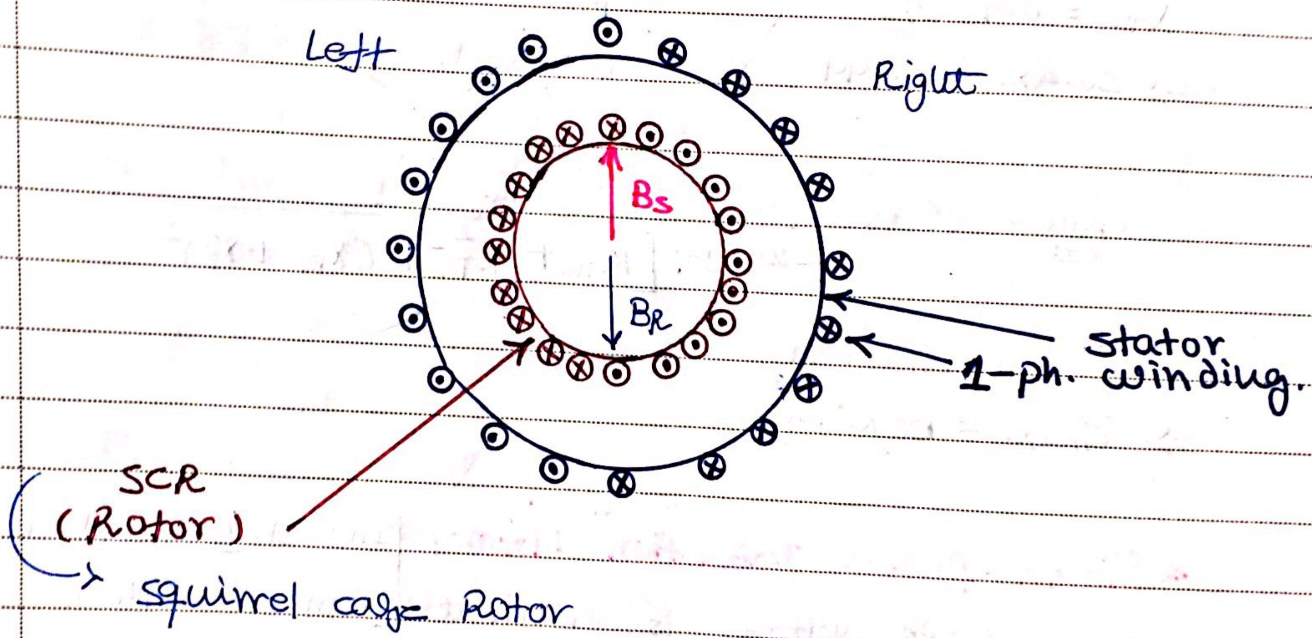
II) Rotor.

I) Stator:

It consists of a distributed 1-ph. winding into which 1-ph. voltage is applied, and consequently a 1-ph. current flow.

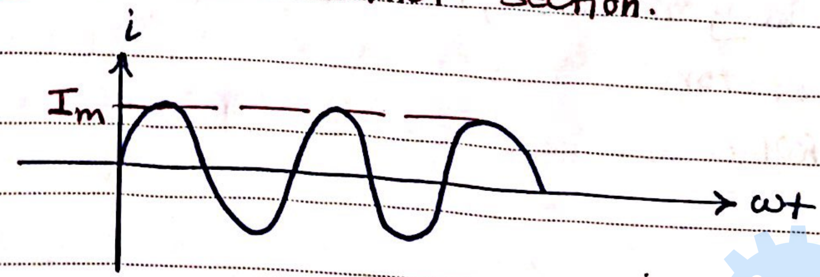
II) Rotor:

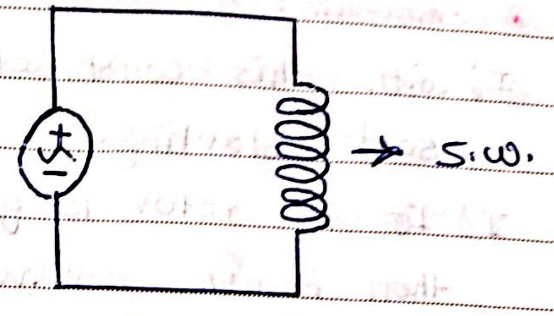
It is a squirrel cage rotor.



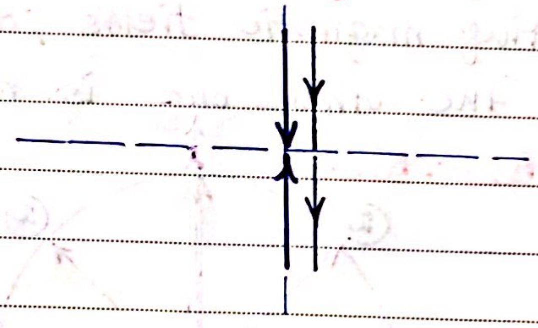
• Operation:

when a current is applied to s.w., Then it will enter from a certain section and leave from the other section.





* i_s is going to generate a flux ϕ_s or B_s, by RHR direction of B_s will be along the vertical axis. It's magnitude vary in sinsuidal manner, since ($B_s \propto i_s$). $\therefore$ B_s is pulsating.



* since ϕ_s is pulsating (i.e. $\frac{d\phi_s}{dt} \neq 0$) then a voltage is going to be induced in the rotor, causing i_R to flow. i_R will generate ϕ_R.

By (Lenz's law) $\Rightarrow$ ϕ_R opposses ϕ_s.

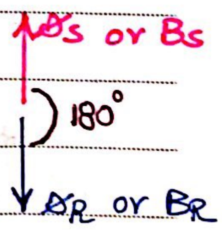
→ Dot product

$\tau_{developed}$ or induced $\triangleq K\,(B_R \cdot B_s)$

$= K\,|B_R|\,|B_s| \sin(\angle B_R - \angle B_s)$

$\sin(180) = 0$

$= \underline{0}$.



NO.

• Comments:

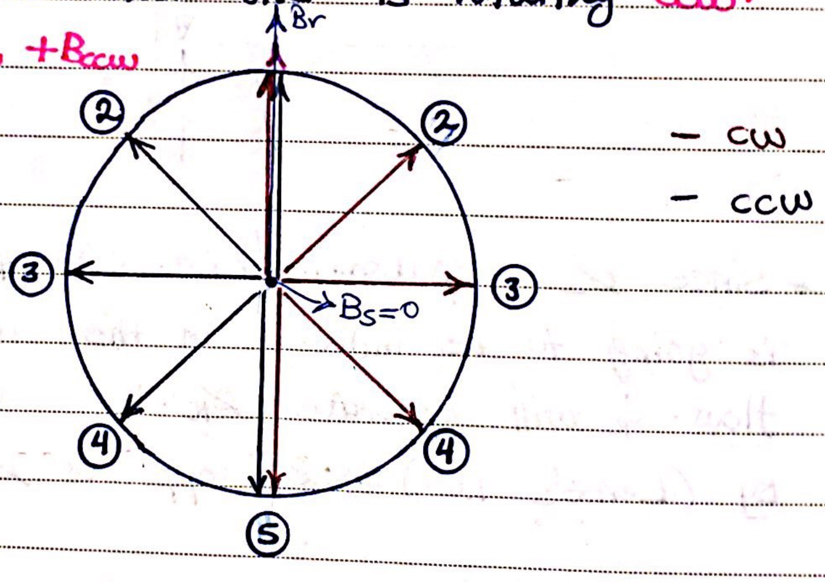
I) with this construction (1-ph. IM) is not a self starting.

II) If the rotor is given an external torque, then it will continue to rotate.

[This will be explained by Two-Revolving field theory.].

III) Pulsating (B_s) can be represented by 2-equal rotating magnetic fields; one is rotating cw and the other one is rotating ccw.

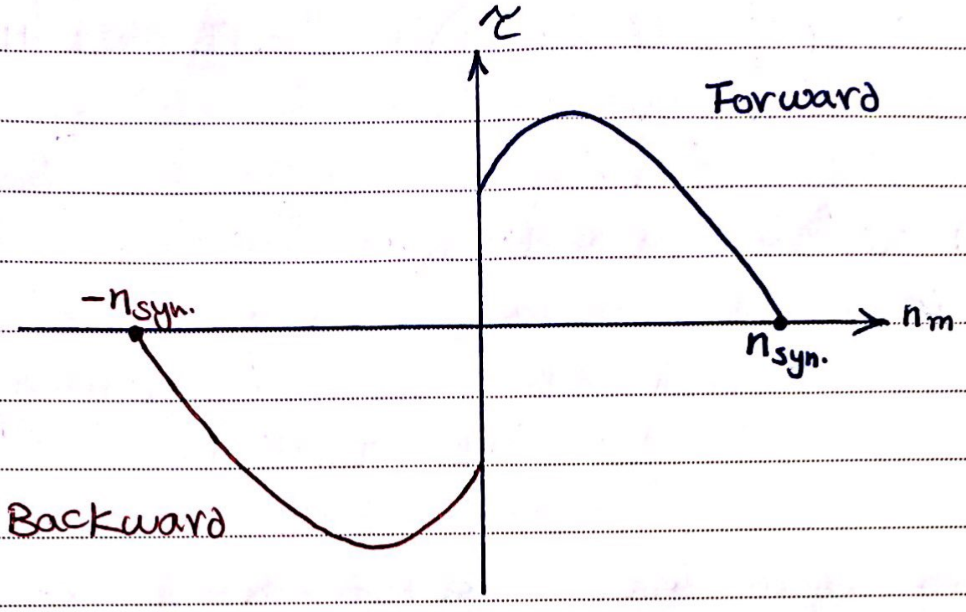
$B_s = B_{cw} + B_{ccw}$



* Hence, when each rotating magnetic field complete one rotation, then B_s complete one cycle (+ve max. → 0 → −ve max → 0).

cw is called forward]
ccw is called Backward]

* Each rotating field produce its tonque the same as the case of the 3-ph. I.M. , as follows:



$$\tau_{1\text{-ph. IM}} = \tau_B + \tau_F$$

* Motor: Device converts from electrical to mechanical.

* Rotor: The rotating part.

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• Comment:

* To find $I_{starting}$ for 3-ph. I.M., then let $s=1$, find Z_{eq} then calculate I_1.

* For the previous example, it can be found that $|Z_{eq.}| = 0.92$

$$\therefore |I_{start.}| = \frac{|V_\phi|}{|Z_{eq.}|} = \frac{208/\sqrt{3}}{0.9}$$

=> It can be found in general, [$I_{start.}$ = (6-8) times $I_{steady\ state}$].

* Starting methods of 1-ph. I.M.:

I) Mechanical method: A rope is used to pull the shaft. This method is usually used to test if there is a defect in the other methods.

II) Electrical method: There are various methods, among which is the so called (split-phase method), explained as follows:

* Rotating field by two-phase system:

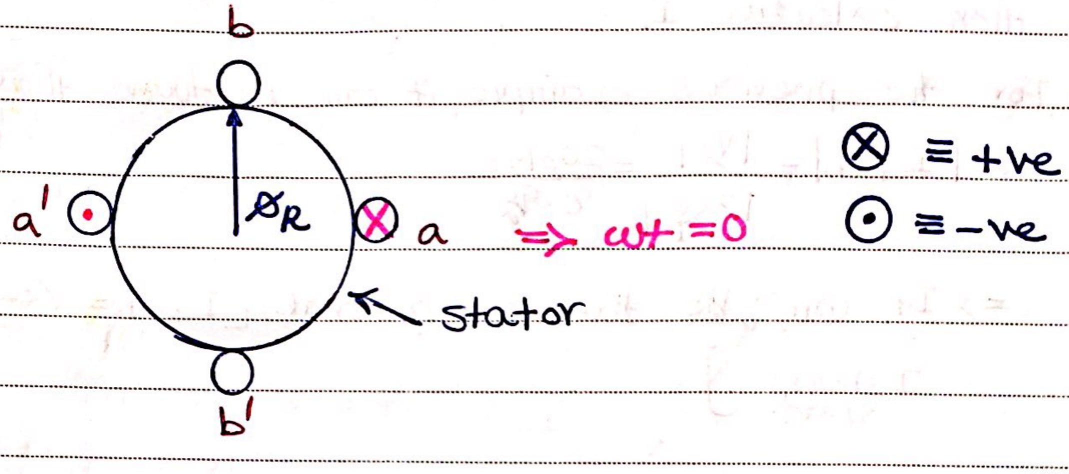
Two coils (a,a') and (b,b') are located on the stator with 90° between them.

They are supplied by currents with 90° phase shift.

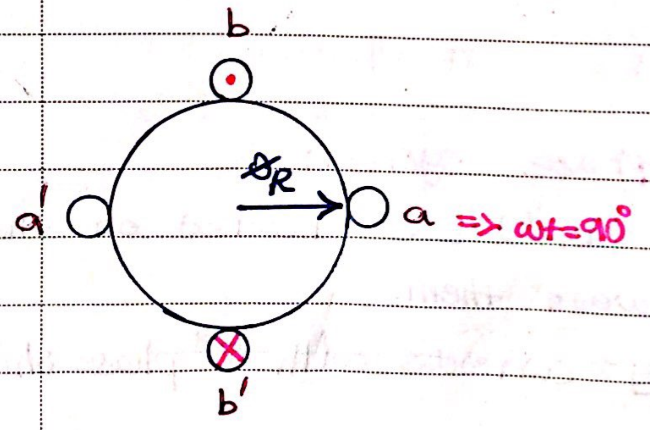
If $i_{aa'} = I_m \cos(\omega t) \Rightarrow I_{aa'} = I_m \angle 0°$

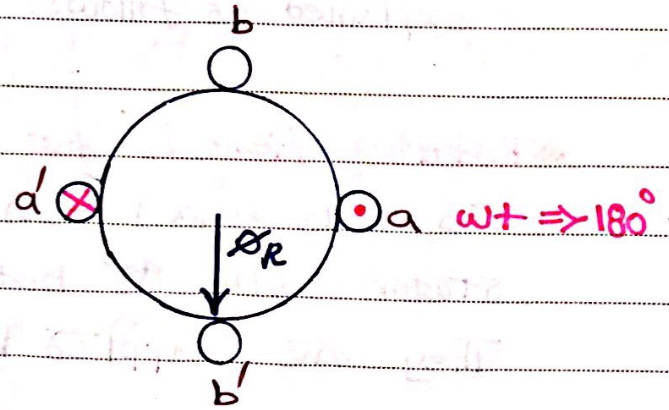
$\therefore i_{bb'} = I_m \cos(\omega t + 90°) \Rightarrow I_{bb'} = I_m \angle 90°$

* Since ($\phi \propto i$), let us see what will happen when (ωt) change over one cycle.



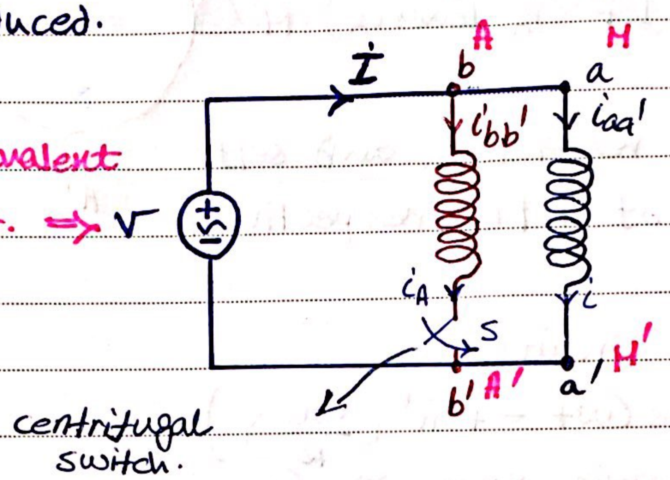
ωt	$i_{aa'}$	$i_{bb'}$	$\phi_R = \phi_{aa'} + \phi_{bb'}$
0	+ve	0	↑
90°	0	−ve	→
180°	−ve	0	↓
270			←
360			↑





1. Hence, with this two phase system, a Rotating magnetic field with constant magnitude is produced.

Equivalent cct. ⇒



2. If the currents are not equal in magnitude and/or phase shift ≠ 90°.
Still a rotating magnetic field is produced but with varying magnitude.

3. with this construction and assumption. ϕ_R rotate cw.
If one of the coils connection is reversed, then the rotation of ϕ_R will be reversed.

*Split-phase method:

Stator: consists of 2 coils:-

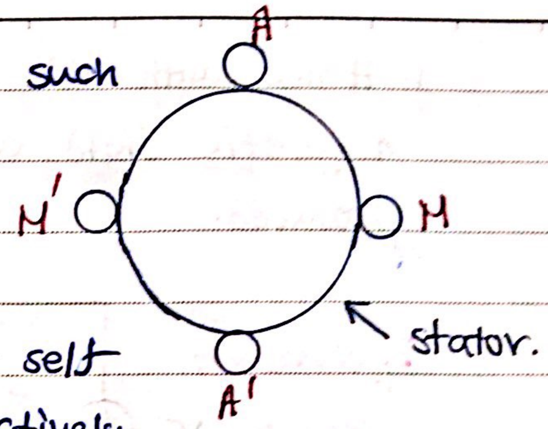
1) one is called Main winding.

2) other is called Auxilliary winding.

A is connected in series with a centrifugal switch (S).

NO.

* The coils are selected in such away that $\frac{R_A}{L_A} > \frac{R_M}{L_M}$ in order to let (i_A leads i_M)



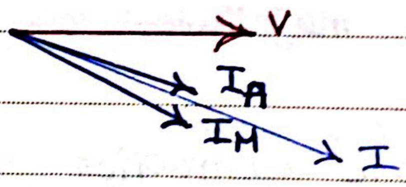
where;
(R & L) are resistance and self inductance of A & M respectively.

=> For RL circuit:

$$i = I_M \cos\left(\omega t - \tan^{-1}\left(\frac{\omega L}{R}\right)\right)$$

* After certain speed => (S) is open and only (M) winding is kept in the cct.

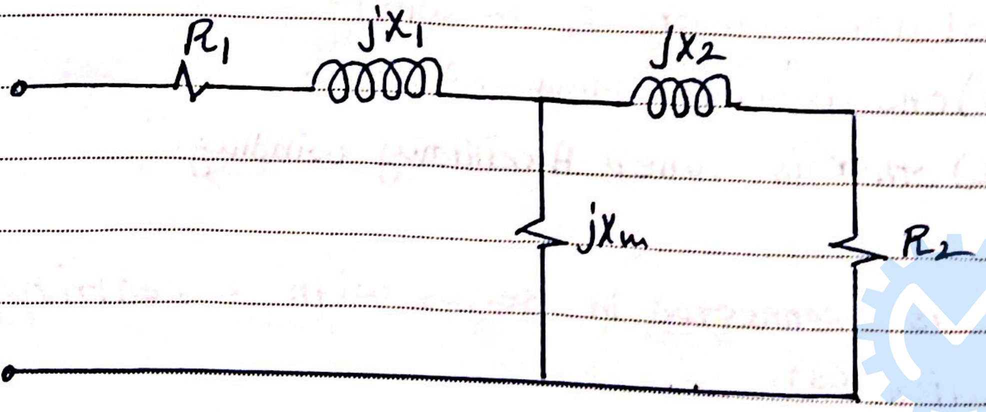
ال switch بكون مغلق بالأول ot.



* Equivalent cct. of 1-ph. induction motor:

let initially the rotor is stalled (i.e. blocked, not rotating).

∴ The motor is ≡ 1-ph. transformer.



NO.

* when a voltage is applied to (M) main winding, then a pulsating field is produced. This field is represented by two opposing rotating fields.

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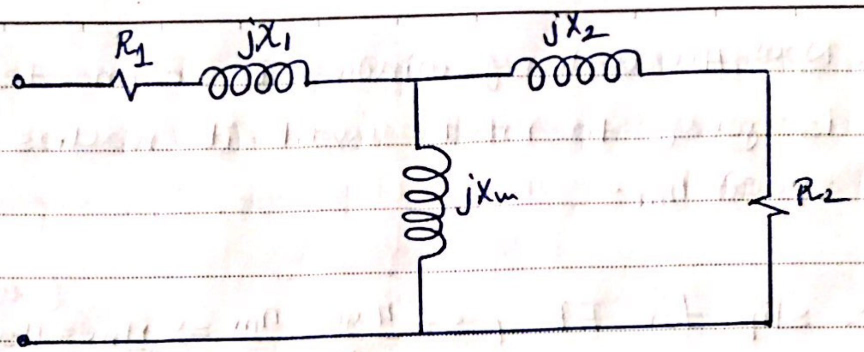

Fig. 1

* Fig. 1 ≡ without AW, V_b is applied to stator → Pulsating field (PF) is produced.

* PF ≡ is represented by 2 revolving magnetic fields (i.e. FF ⇒ Forward field and BF ⇒ Backward field).

* Each FF and BF induces equal voltage in the Rotor cct.

* Hence Fig. 1 is modified as follows as shown in Fig. 2:

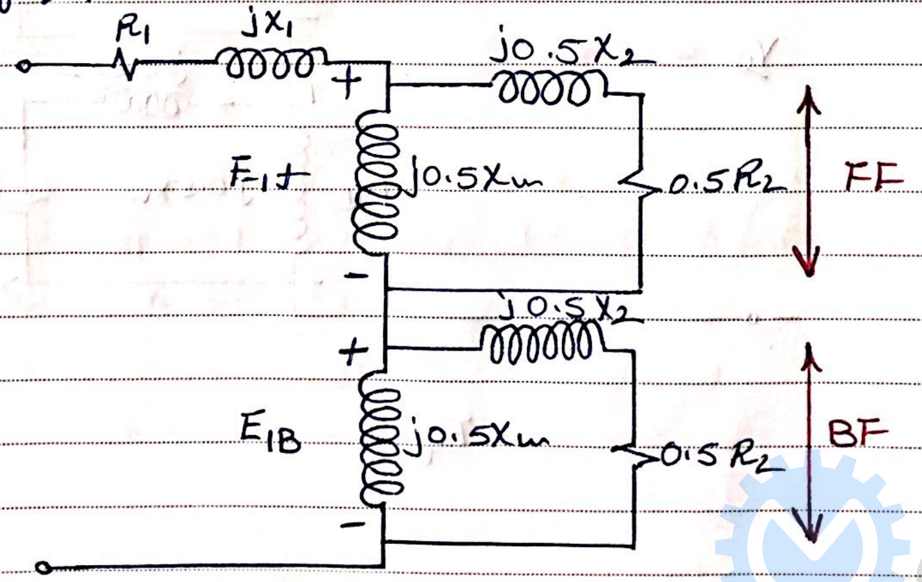

Fig. 2

NO.

* Now, Auxualiary winding is connected => Motor is going to rotate until it reaches certain speed n_m.

$\therefore$ slip for FF, $s = \frac{n_{syn.} - n_m}{n_{syn.}} \Rightarrow n_m = n_{syn.}(1-s)$ ---(1) [CW]

$\therefore$ slip for BF, $s_1 = \frac{-n_{syn.} - n_m}{-n_{syn.}} \Rightarrow \therefore s_1(-n_{syn.}) = -n_{syn.} - n_m$ [CCW]

$n_m = n_{syn.}(s_1 - 1)$ ---(2)

* By equating (1) and (2),

$n_{syn.}(1-s) = n_{syn.}(s_1 - 1)$

$\therefore s_1 = 2 - s$ --- (3)

$\therefore$ Fig. 2 to be modified by introducing slip.

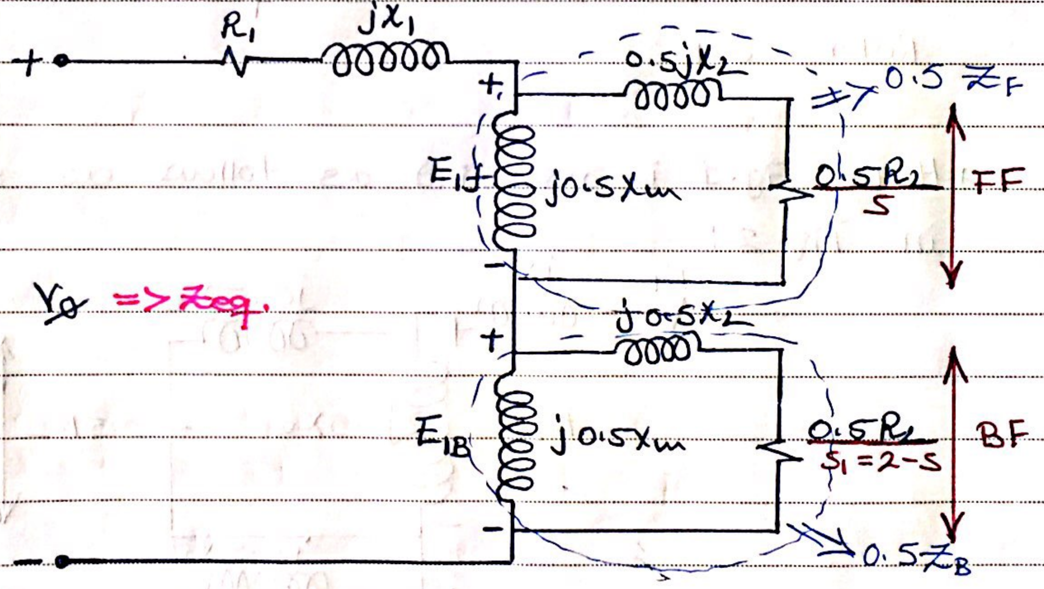

Fig. 3

FIVE APPLE

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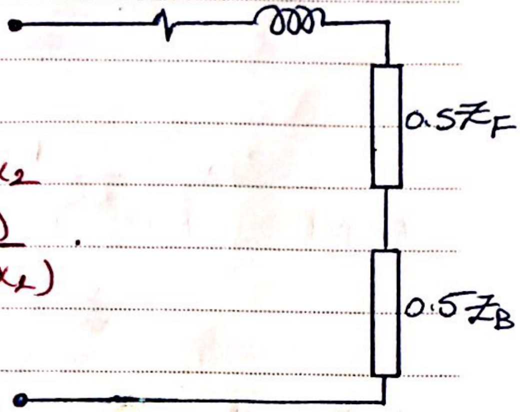
∴ Fig. 3 equivalent cct. of single phase IM.
This cct is used in the analysis of this motor as follows:



$$Z_{eq.} = \frac{V_\phi}{I}$$

$$Z_{eq.} = R_1 + jX_1 + 0.5Z_F + 0.5Z_B$$

$$0.5Z_F = j0.5X_m \parallel \frac{0.5R_2}{s} + j0.5X_2$$

$$= \frac{j0.5X_m\left(\frac{0.5R_2}{s} + j0.5X_2\right)}{j0.5X_m + \left(\frac{0.5R_2}{s} + j0.5X_2\right)}.$$

* similarly Z_B can be found.
∴ where one can write $Z_F = R_F + jX_F$
$Z_B = R_B + jX_B$

* Since, each rotating field (i.e. FF and BF) has its own power flow diagram.

∴ $P_{AG} = P_{AG,FF} - P_{AG,BF}$

$P_{AG,FF}$: Psupplied $\left(\frac{0.5R_2}{s}\right)$; $P_{AG,BF}$: Psupplied $\left(\frac{0.5R_2}{2-s}\right)$.

∴ The rest of variables can be found as in 3-ph. I.M:-

$P_{conv.} = P_{AG}(1-s)$

$P_{conv.} = \tau_{ind.} * \omega_m$.

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※ Ex. 1 A 120 V, $\frac{1}{3}$ hp, 60 Hz, 4 pole, split phase IM has the following parameters:

$R_1 = 2\ \Omega$ $\qquad X_1 = 2.56\ \Omega$ $\qquad X_m = 60.5\ \Omega$

$R_2 = 2.8\ \Omega$ $\qquad X_2 = 2.56\ \Omega$

At slip = 0.05, Rotational mech. losses = 51 watt.

Find the following:

I. Input current:

$$I_1 = \frac{V_\phi}{R_1 + jX_1 + 0.5 Z_f + 0.5 Z_B}$$

by substitution it can be found that:

$$Z_f = \underbrace{28.81}_{R_f} + j28.05\ \Omega$$

$$Z_B = \underbrace{1.32}_{R_B} + j\,2.49\ \Omega$$

$$\therefore I_1 = 4.86 \angle -46.26\ A$$

II. Input power:

$$|V_\phi||I_1| \cos(46.26) = 403.22 \text{ watt.}$$

III. P_{AG}:

$$P_{AG} = P_{AG,F} - P_{AG,B}$$

$$= I_1^2 (0.5 R_f) - I_1^2 (0.5 R_B)$$

$$= 324.65 \text{ watt.}$$

IV. $P_{conv.}$:

$$P_{conv.} = (1 - s) P_{AG} = 308.42 \text{ watt}$$

($s = 0.05$)

NO.

V. P_{out}:

$P_{out} = P_{conv.} - P_{mech.}$

$= 308.42 - 51$

$= 257.42$ watt

VI. $\tau_{ind.}$:

$\tau_{ind.} = \dfrac{P_{conv.}}{\omega_m = \omega_{syn.}(1-s)} = 1.72 \text{ N.m}$

$\dfrac{2\pi(60)}{2}(1-0.05)$

$\omega \equiv$ rad/s

$n \equiv$ rps

$\equiv$ Revolution per sec.

VII. η:

$\eta = \dfrac{P_{out}}{P_{in}} = 63.8\%$

VIII. PF of the load:

$\cos(\angle V - \angle I) = \cos(0 + 46.26)$; standard PF

$= 0.69 < 0.8$ (0.8 – 0.85).

$\uparrow$

*** Synchronous Machines:**

- construction:

I. stator: It consists of 3-ph. windings:

– In the case of generator: 3-ph. voltage is induced in them.

– In the case of motor: 3-ph. current is applied to them.

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NO.

II. Rotor: It consists of two or more poles "Electromagnet poles" into which DC current is applied to its field windings. Through brushes and slip rings

• Introduction to 3-ph. syn. generator:

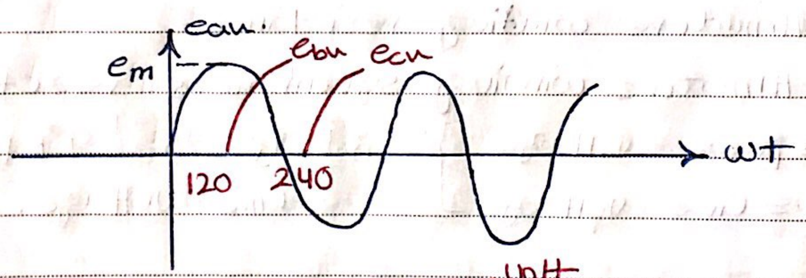
This is the type of generator which is used in conventional power stations (i.e. steam, hydro, gas ---etc.).

• Operation:

Rotor field windings produce sinusoidal flux ~~ϕf~~ => ~~ϕf~~ cut stator windings and induce voltage in them => given by

$$e_{an} = E_m \sin(\omega t)$$
$$e_{bn} = E_m \sin(\omega t - 120)$$
$$e_{cn} = E_m \sin(\omega t - 240)$$

$E_m \equiv$ Peak of induced voltage.



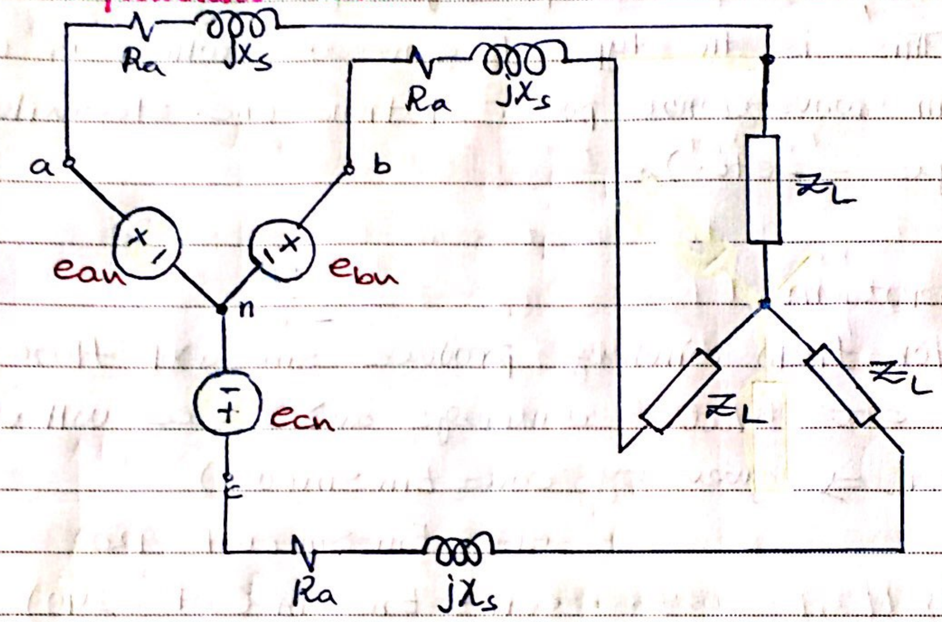
Since $E_{rms.} = \frac{E_m}{\sqrt{2}} \equiv V_{rms.}$ (volt)

NO.

* For this type of generators, it can be found that $E_{rms.} = 4.44 \, f \, N \, \phi \, k_w$ ← winding factor.

frequency ↗ f; ↑ N: No. of turns; ↖ ϕ: Flux per pole

* Equivalent cct. :



$R_a \equiv$ Armature winding resistance.

$X_s \equiv$ Armature winding synchronous reactance.

$V_{an} \equiv$ phase voltage } عادةً المعطى بالسؤال يكون Line voltage.

$V_{ab} \equiv$ Line voltage }

* Commercial generators generate voltage which could be in the range (11 – 25) kv ← Line voltage

NO. 24. 4. 2018

* 3-ph. synch. motor:

• Construction:

1. A balanced 3-ph. voltage is applied to the stator and generating a rotating magnetic field, B_s
2. A DC-current is applied to the rotor windings, producing magnetic field, B_R.

• Operation:

Due to B_R and B_s, a torque is developed or induced:

$\tau_{ind.} \triangleq K(B_R * B_s)$

$= K\,|B_R|\,|B_s| \sin(\angle B_R - \angle B_s)$.

Direction of $\tau_{ind.}$ can be found by using RHR as follows:

Thumb ≡ Direction of B_R. الإبهام

Fore ≡ Direction of B_s. السبابة

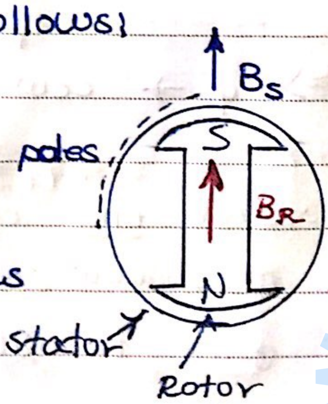
Middle ≡ Direction of $\tau_{ind.}$ الوسطى

* It can be shown that this motor is not self starting as follows:

(1)

⇒ If the stator has two poles windings:

⇒ If the applied voltage has $f = 50\,Hz$.



$t = 0$

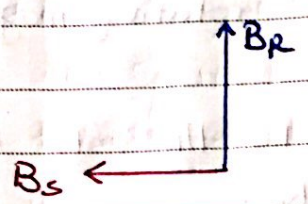
$\theta = 0$

$\therefore \tau_{ind.} = 0$

NO.

$\therefore B_s$ is going to rotate at speed $n = \frac{f}{p} = 50$ rps
$= 2000$ rpm.

(2)



$t = \frac{1}{4} T$ → periodic time.

$\theta = 90^\circ$ (or -90°)

$\therefore \tau_{ind.} \equiv$ ccw ↺

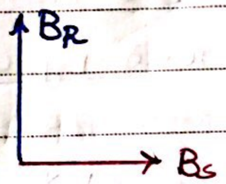
(3)

$t = \frac{1}{2} T$

$\theta = 180^\circ$

$\therefore \tau_{ind.} = 0$

(4)



$t = \frac{3}{4} T$

$\theta = -90^\circ$

$\therefore \tau_{ind.} \equiv$ cw

(5) $t = T$

$\theta = 0^\circ$

$\therefore \tau_{ind.} = 0$

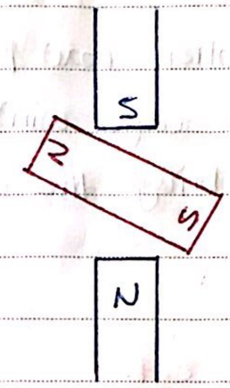
$\Rightarrow$ 0 → ccw → 0 → cw → 0 كف يمين وكف شمال

:)

$\therefore$ over one cycle of rotation of B_s, $\tau_{ind.}$ once ccw and then cw, hence Rotor is going to vibrate.

NO.

∴ Hence a starting mechanisim is needed to start the motor.



* Methods of starting:

1. Use a frequency converter that is apply stator voltage with low frequency, In order to give the rotor the chance to chase B_s.
   * when the motor start to rotate, increase the frequency.

2. Use an external prime mover to rotate rotor, when the rotor reaches near n_{syn}, then switch on DC supply at rotor.

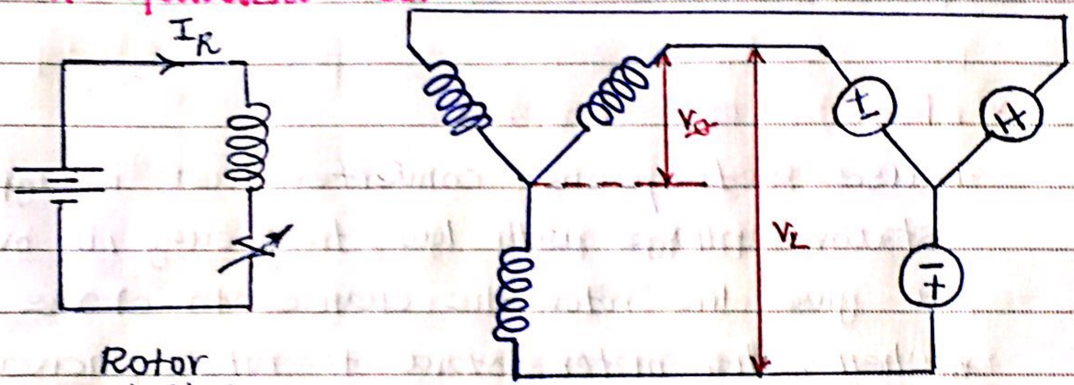
أهم طريقة
3. Start the motor as IM, that is by adding a 3^{rd} winding (i.e. squirrel cage winding) on the shaft of the motor.
   Hence the motor is going to start as IM and the rotor is going to follow B_s, until it reaches the speed at n_{syn}.

FIVE APPLE

∴ Rotor always run at constant speed irrespective of the load.

* For e.g. when load ↑ ⇒ n_r ↓ - current induces in squirrel cage winding and producing additional torque to bring the speed of rotor back to n_{syn}.

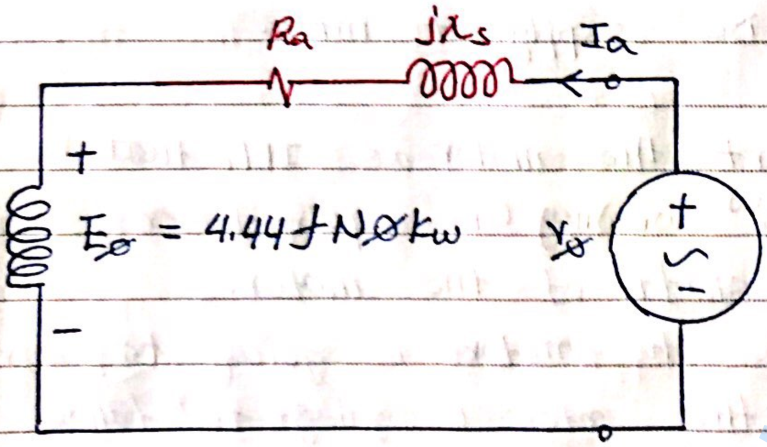
* **Equivalent cct. :**



Rotor winding

Stator winding

* Since the system is balanced then one may use per-phase cct.



Per-phase. cct. "Fig. 1"

NO.

$R_a \equiv$ Armature winding resistance.

$X_s \equiv$ Synchronous reactance

$E_\phi \equiv$ Induced voltage in stator winding.

Note! The equ. cct. for the generator is reversed.

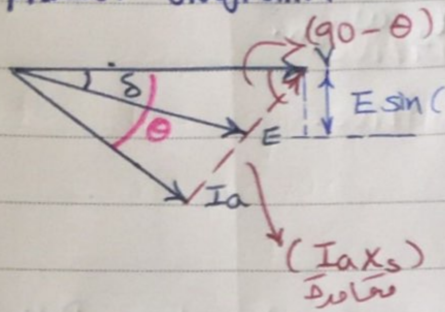
← اتجاه التيار بكون بالعكس ونستبدل V_ϕ بـ Load.

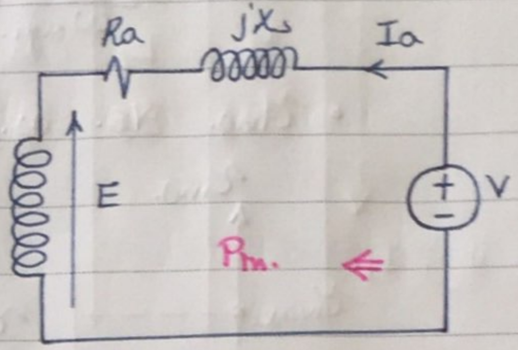
*One may use Fig. 1 to produce the phasor diagram.

NO. 26.4.2018

* Analysis of 3-ph. synch. motor:

This can be presented by means of the following phasor diagram:





$V = E + I_a(R_a + jX_s)$

$\theta \equiv$ PF angle.

$\delta \equiv$ Torque angle.

* If R_a is neglected

$P_{in} = 3 V I_a \cos(\theta)$ --- (1)

* It can be found that:

$\therefore E\sin(\delta) = I_a X_s \sin(90 - \theta)$.

$E\sin(\delta) = I_a X_s \cos(\theta)$ --- (2)

$\therefore I_a \cos(\theta) = \dfrac{E\sin(\delta)}{X_s}$ --- (3)

* Sub. (3) into (1):

$P_{in} = \dfrac{3 V E \sin(\delta)}{X_s}$

$P_{conv.} = P_{in.} - P_{elect.\ losses}$

$(3 I_a^2 R_a = 0)$

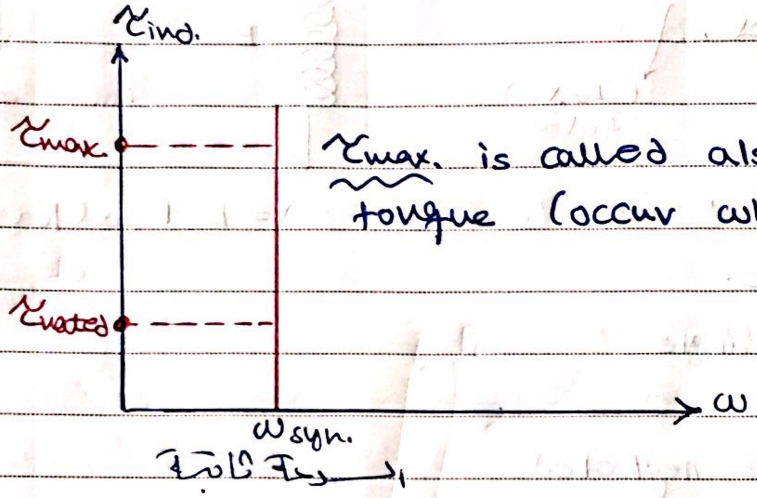
NO.

$\therefore P_{conv.} = P_{in.}$

Since $P_{conv.} = \tau_{ind.} * \omega_{syn.}$

$$\therefore \tau_{ind.} = \frac{P_{conv.}}{\omega_{syn.}} = \frac{3VE\sin(\delta)}{X_s\,\omega_{syn.}}$$

• $\tau_{ind.}$ vs. ω. :



$\tau_{max.}$ is called also Pull-out torque (occur when $\delta = 90^\circ$).

$\therefore$ 3-ph. synch. motor is constant speed drive.

$$\therefore \tau_{max.} = \frac{3VE(1)}{X_s\,\omega_{syn.}} \quad ; \; \delta = 90^\circ \rightarrow \sin(90) = 1$$

※ Effect of field current I_f (i.e. I_R) on the performance of 3-ph. synch. motor:

• problem:

For a given load, what will happen when the field current is increased?

* Since the load doesn't change, the P constant.

* since $P \propto E\sin(\delta) \propto I_a\cos(\theta)$

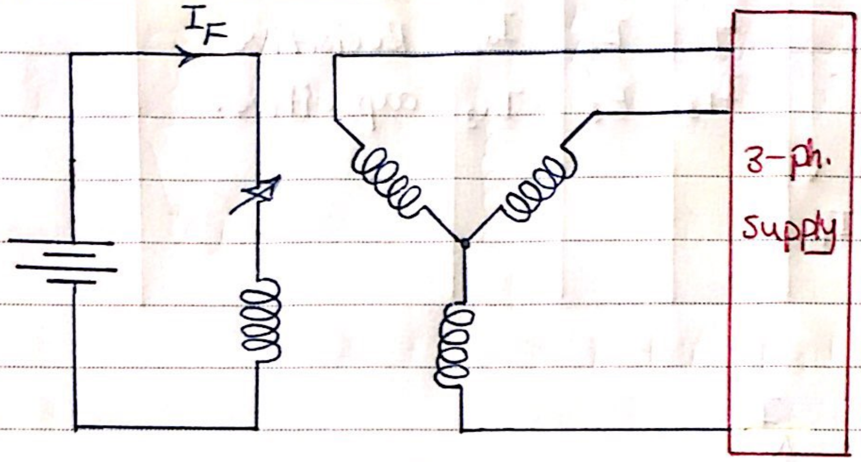
FIVE APPLE

NO.

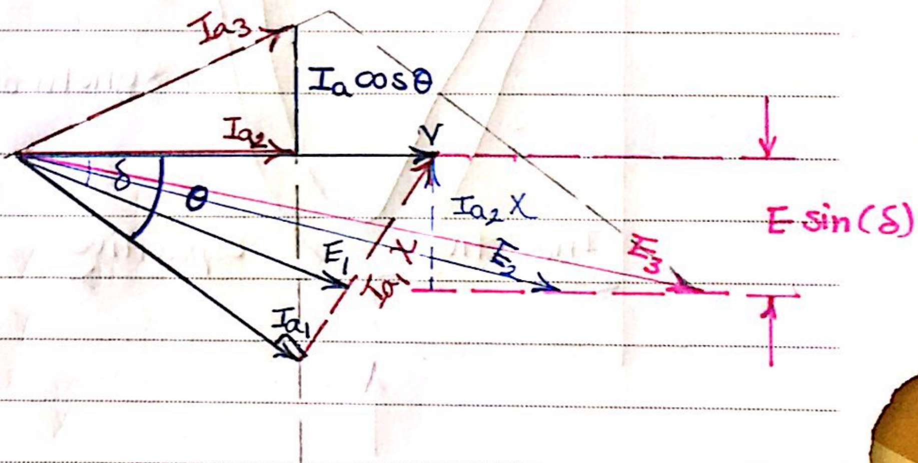
∴ $E\sin(\delta)$ and $I_a\cos(\theta)$ should remain constant.

* since $\{E = k\phi\omega\}$

∴ As $I_F \uparrow \Rightarrow \phi \uparrow \Rightarrow$ ∴ $E\uparrow$



* let us see what will happen on the phasor diagram?

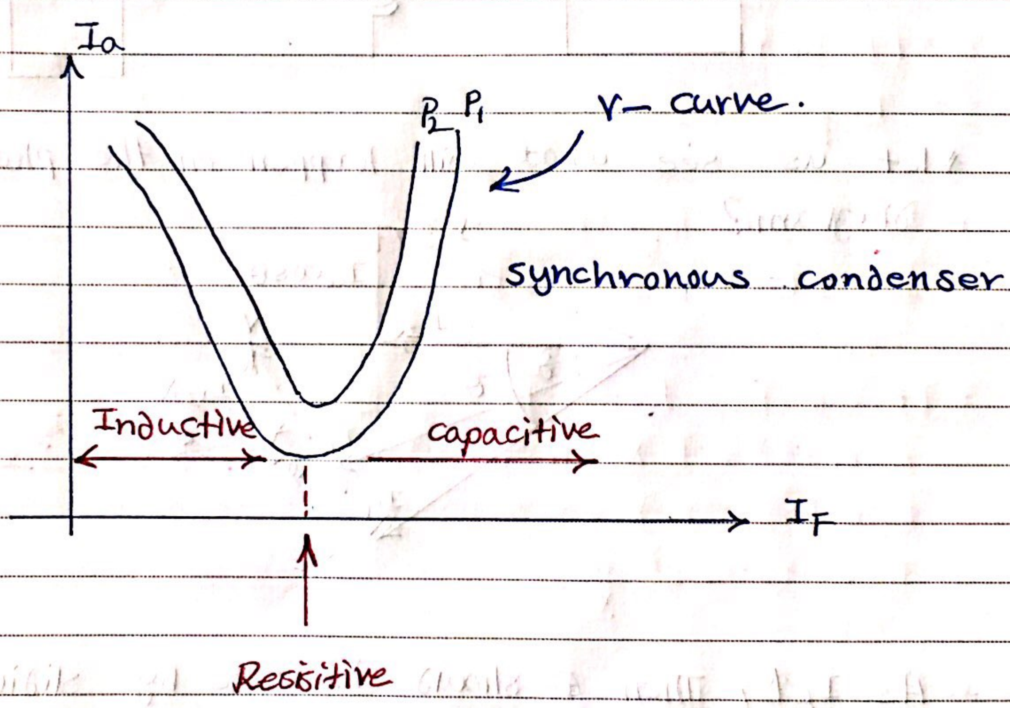


∴ As $I_F\uparrow$, Then E should increase by sliding along the constant line of $(E\sin\delta)$.

NO.

I_F	E	I_a	Type of load
I_{F_1}	E_1	I_{a_1}	Inductive
I_{F_2}	E_2	I_{a_2}	Resisitive
I_{F_3}	E_3	I_{a_3}	capacitive.

I_F تزيد للأسفل



NO. 29. 4. 2018

• Effect of load changes on motor performance:

As the load ↑ ⇒ initially its speed ↓ ⇒ $\tau_{ind.}$ ↑ in order to maintain the speed an n_{syn}.

* Since $E = k\phi\omega$
  if I_F (i.e. ϕ) is kept constant, the E will remain constant.
* Hence, performance can be explained by means of the following phasor diagram.

Knowing that:
$V = E + jX I_a$

* Assume initially that I_a is leading.

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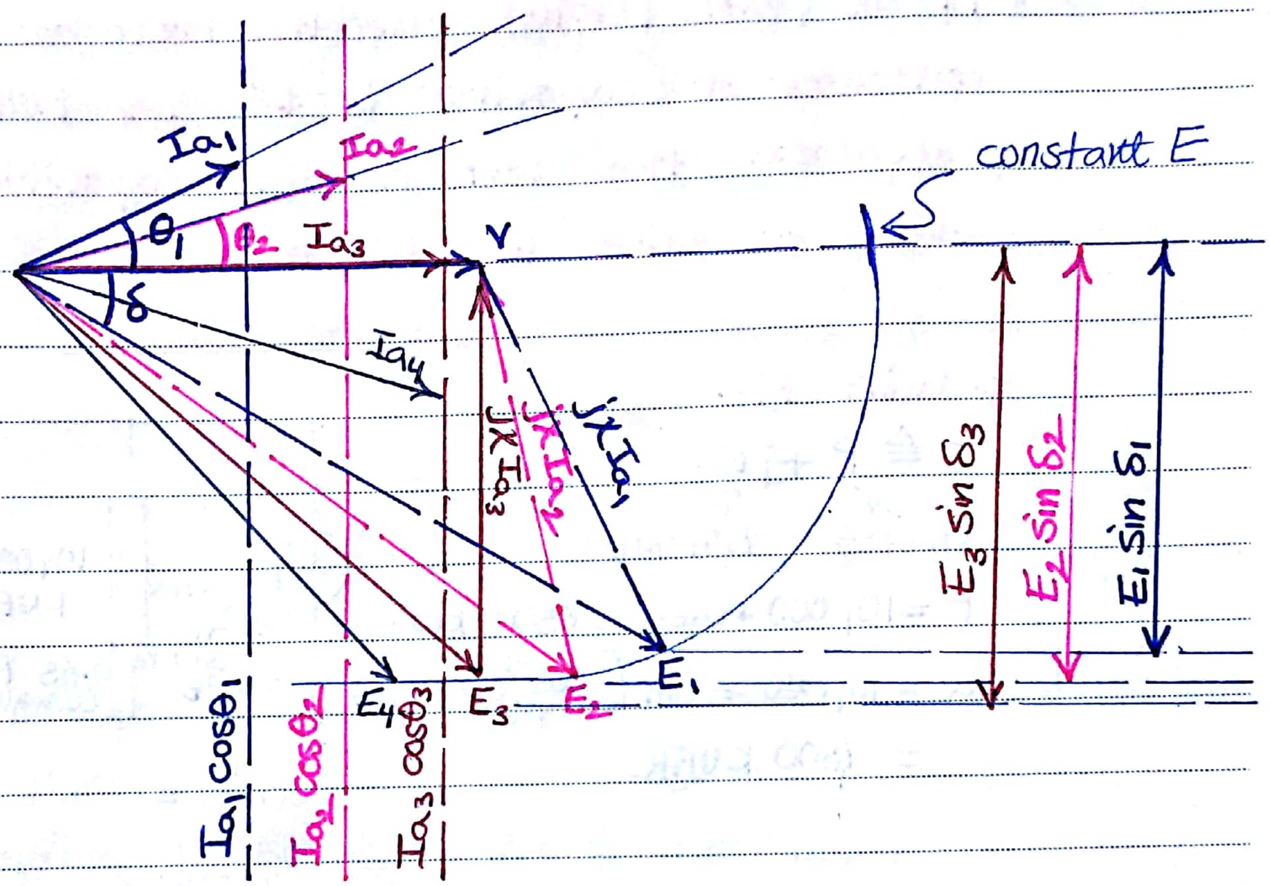


* As the load changes (i.e. $I_a \cos\theta$, and $E \sin\delta$), then E is going to move along a circle.

∴ As the load ↑ ⇒ the PF is going to change from leading ⇒ unity ⇒ lagging.

* Exam Question: show the performance of 3-ph. syn. motor using phasor diagram?
↳ Ans.: Draw the complete figure "Leading ⇒ unity ⇒ lagging.)

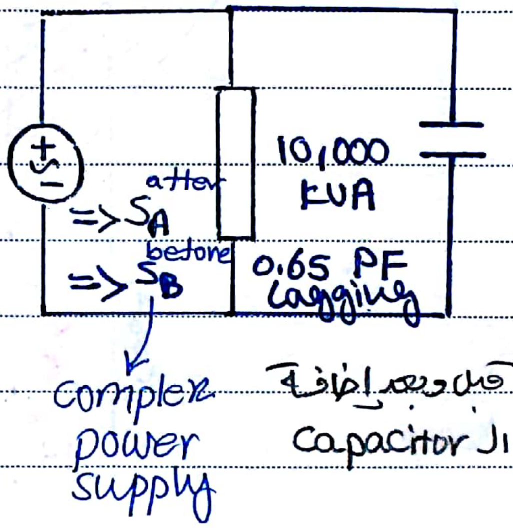
NO.

※ Example: A 10,000 KVA system is operating at PF of 0.65 lagging and the cost of synch. condenser or capacitor is $60 per KVA. Calculate the cost of the capacitor in order to raise the PF to:

a. unity PF.

$S \triangleq P + jQ$

P ← KVA cos θ, Q ← KVA sin θ



$P = 10,000 * 0.65 = 6500$ kw.

$Q = 10,000 * \sin[\cos^{-1} 0.65]$ (49.5)

$= 7600$ KVAR

∴ For unity PF, $S_A = 6500 + j0$

∴ The capacitor should absorb $= -7600$ KVAR

or the capacitor should supply $= 7600$ KVAR

cost $= 7600 * 60 = 456000$ $

PBP (Payback period). $= \frac{456000}{5000}$

b. 0.85 PF.

$\theta = \cos^{-1}(0.85) = 31.8$

$P_B = 6500$ kw $= P_A$

$\therefore Q_A = P_A \tan(31.8) = 4030$ KVAR

$\therefore$ capacitor should supply $= 7600 - 4030 = 3570$ KVAR.

$\therefore$ cost $= 3570 * 60 = 214200$ \$.

※ Example: 480 V, 60 Hz, 6 pole synch. motor takes 80 A from the supply and unity PF and full load. Assume no losses.

I. Find τ_{output}.

$P_{out} = \tau_{out} * \omega_{syn.}$

$P_{out} = P_{in} = \sqrt{3}\ VI\cos\theta = \sqrt{3}(480)(80)(1) = 66.51$ kW.

$\omega_{syn.} = 2\pi n_{syn.} = 2\pi \frac{f}{p} = 2\pi \left(\frac{60}{3}\right)$

by substitution:

$\tau_{out} = 529.5$ N.m

II. what will be the current magnitude if PF is adjusted to 0.8 leading.

$P_{out} = \sqrt{3}\ V_L I_L \cos\theta$

$66.51 = 480\sqrt{3}(I_L)\,0.8$

$\hookrightarrow I_L = 99.98$ A.

NO. 3. 5. 2018

- **Special Motors:**

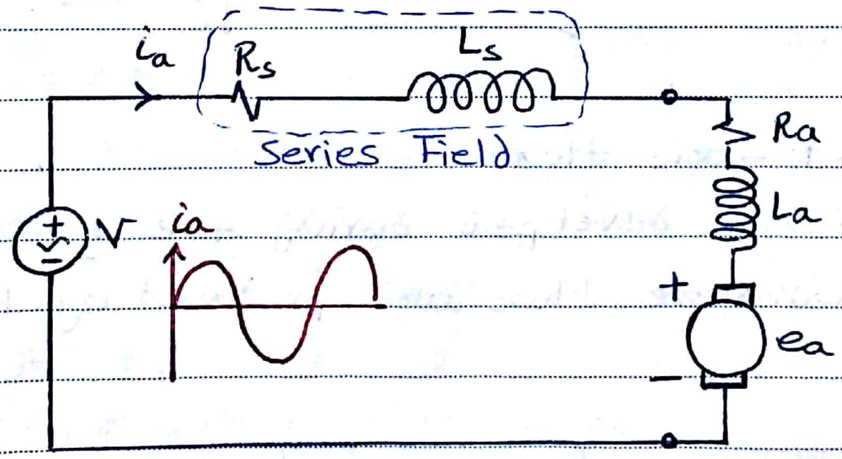
These are fractional hp motors, used mainly in control systems in order to control rotation or linear motion.

=> Among these types:

1. Series motor.
2. Stepper motor.
3. Brushless motor.
4. Reluctance.

1 * Series or universal motors:

It is the same structure as previous DC – series motors:



$R_s, L_s \equiv$ Resistance and self inductance of series field.

$R_a, L_a \equiv$ Resistance and self inductance of armature cct.

$V, e_a \equiv$ Applied voltage and back emf.

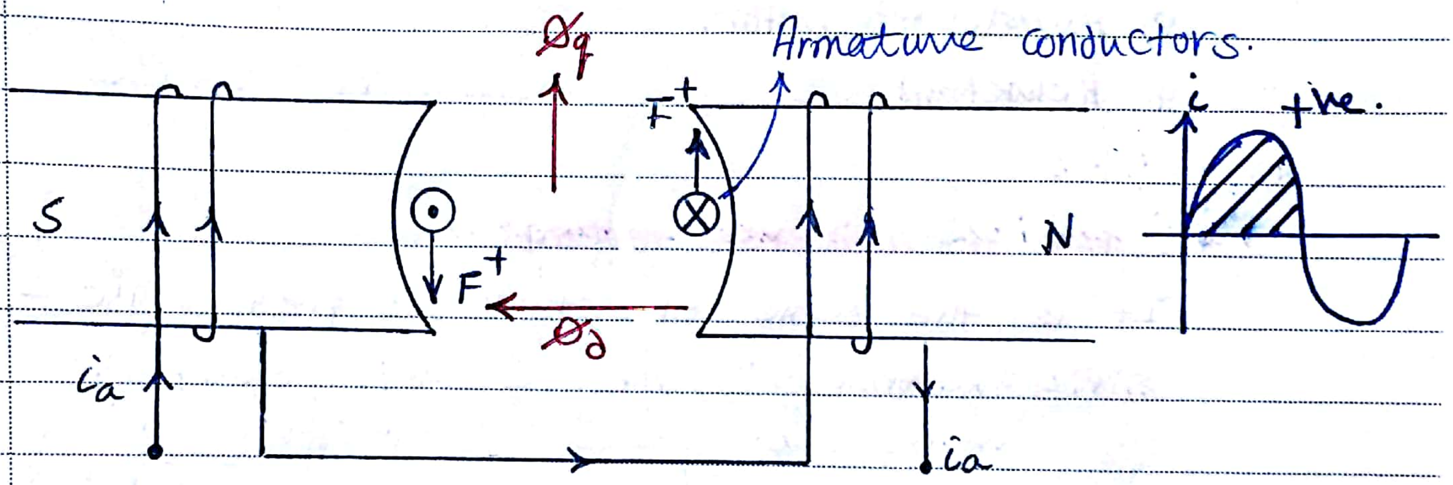
By KVL:

$$V = R_s i_a + L_s \frac{di_a}{dt} + R_a i_a + L_a \frac{di_a}{dt} + e_a.$$

* The performance of this motor, can be explained as follows:

=> Qualitative:

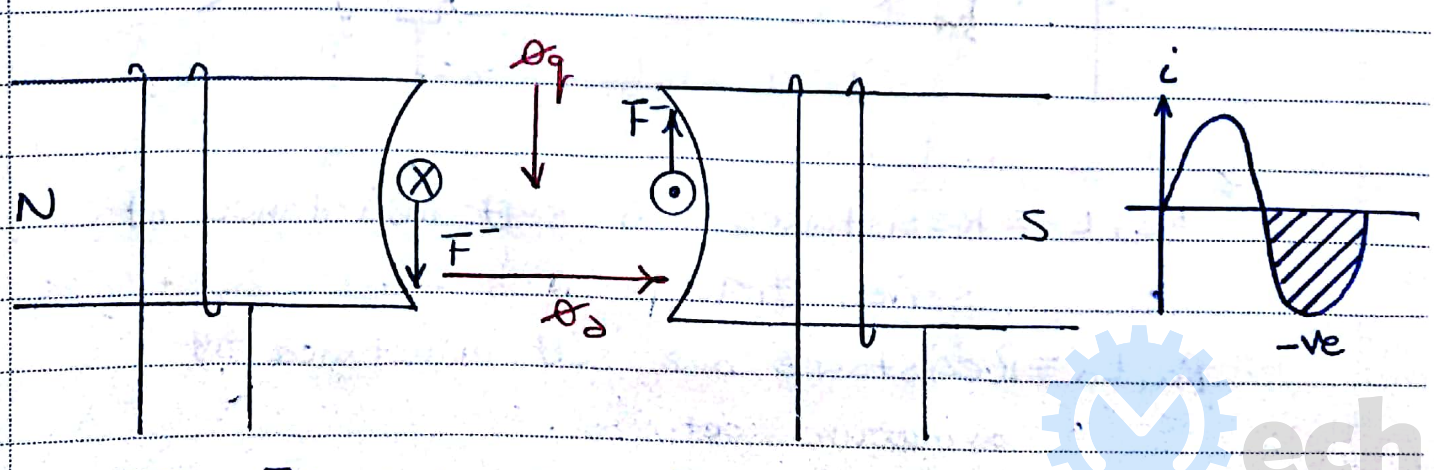
consider the following schematic diagram:



$Ø_d$ ≡ Direct-axis flux.

F^+ ≡ Force developed during +ve $\frac{1}{2}$ cycle.

$Ø_q$ ≡ Quadrature flux and produced by A.W.



F^- ≡ Force developed during −ve $\frac{1}{2}$ cycle.

$F^+ = F^-$; Although current reverses then induced torque always in the same direction.

• Note: In the case of AC series motor, stator and rotor are made of laminated cores.

* Since it is used for DC and AC voltage, then series motor is called "universal".

⇒ Quantitative:

let $i_a = I_m \cos \omega t$.

if $\phi_d \propto i_a$.

$\therefore \phi_d = \phi_{dm} \cos \omega t$, $\omega = 2\pi f$.

$e_a = k \phi_d n = k \phi_d . n \cos \omega t$.

$\therefore i_a, \phi_d$ and e_a are in phase.

But instantenous torque:

$\tau = k \phi_d i_a$

$\tau = k \phi_{dm} \cos \omega t \cdot I_m \cos \omega t$

$= k \phi_{dm} I_m \cos^2 \omega t$.

$\tau = k \phi_{dm} I_m \cdot \frac{1}{2} (1 + \cos 2\omega t)$.

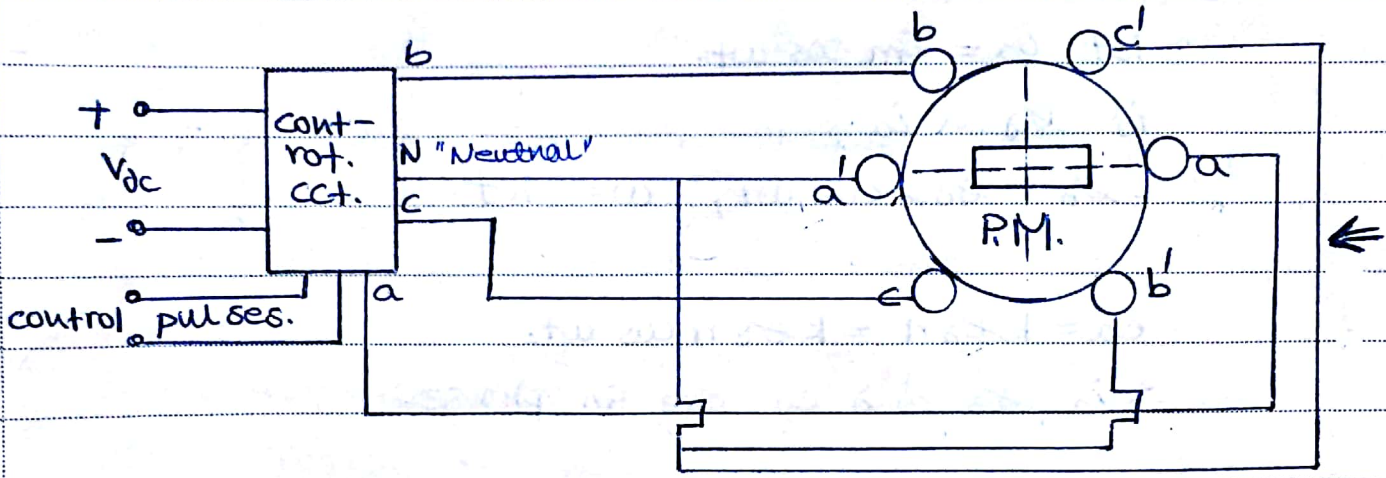
$\therefore$ Average value of $\tau = \tau_{avg.} = \frac{1}{2} k \phi_{dm} I_m$.

$\therefore \tau_{avg.}$ shows always a torque in the same direction is produced.

2 * Stepper motor:

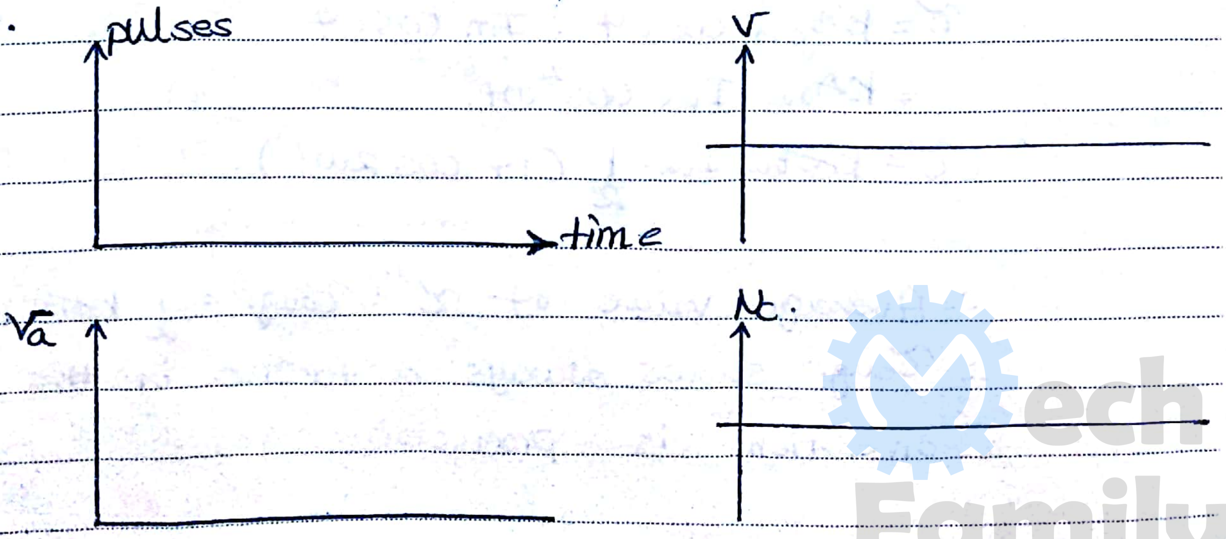
This is a special type of 3-ph. synch. motor.
Its stator consists of 3-ph. winding.
Its rotor is usually a permenant magnet.

* Rotor moves in step every time one phase in excited by DC voltage.
This voltage is controlled by pulses as follows:



2 pole stator winding.

P.M. ≡ Permenant magnet.
* P.M. always align itself with stator field, B_s.



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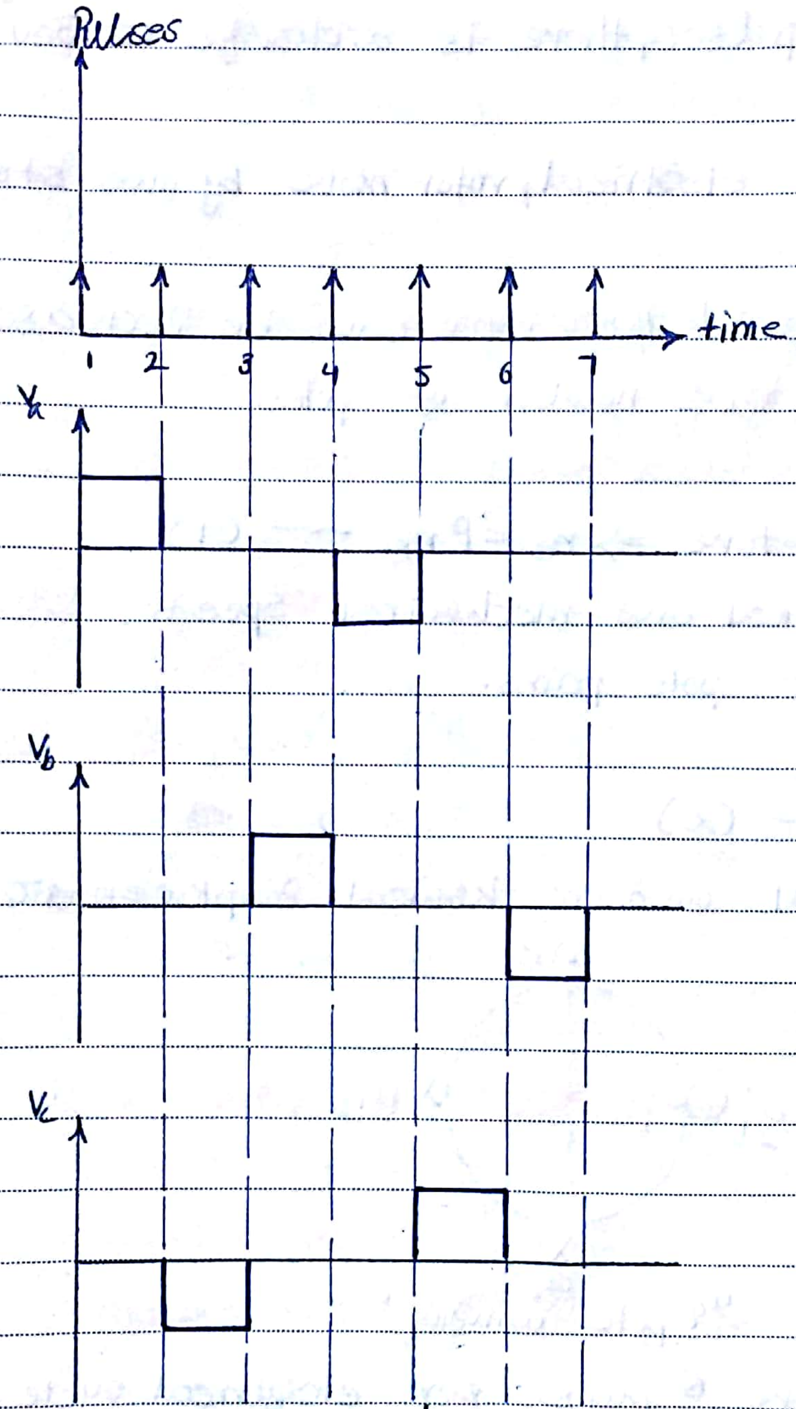
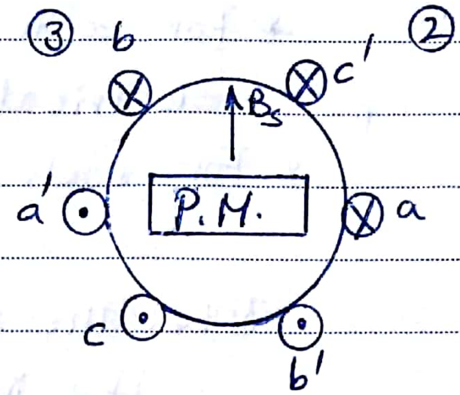




2 pole stator winding.

- P.M. (i.e. Rotor) going to be aligned with B_s.
- For each pulse one DC voltage is applied to one phase causing Deflection of rotor.

Pulse	V_a	V_b	V_c	Position of rotor
1	V	0	0	0°
2	0	0	−V	60°
3	0	V	0	120°
4	−V	0	0	180°
5	0	0	V	240°
6	0	−V	0	300°

* For each 6 pulses, there is a change of 360° electrical.
* For each 60° electrical, rotor move by one step.

• Note: The step of the rotor can be decreased by increasing number of poles.

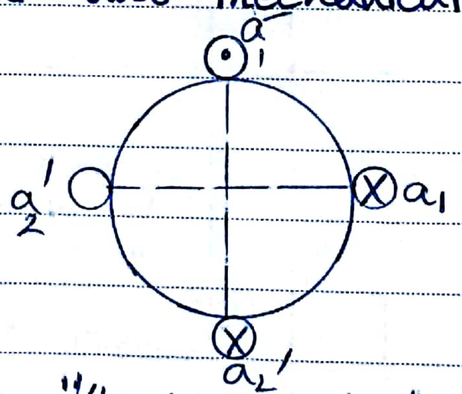
* As found before => $n_e = P n_m$ --- (1)

$n_e, n_m \equiv$ Electrical and mechanical speeds.

$P \equiv$ Number of pole pairs.

$\therefore \theta_e = P\theta_m$ --- (2)

$\theta_e, \theta_m \equiv$ Electrical and mechanical displacement.



"4 pole winding"

* Since there are 6 pulses per electrical cycle.

No. of pulses per second, $n_{pulse} = 6 n_e$

$\therefore n_e = n_{pulse}/6$ --- (3)

Sub. (3) into (1)

$$\frac{n_{pulse}}{6} = P n_m$$

$\therefore n_{pulse} = 6 * P * n_m$ --- (4)

NO.

- one electrical cycle بكون 6-pulses كل * 2
  2 elect. cyc. $\Leftarrow$ 12-pulses

※ Ex.: A 3-ph. P.M. stepper motor required for one particular application must be capable controlling the position of a shaft in steps of 7.5°, and must be capable of running at speed of 300 rpm.

a. How many poles are required for this motor?

since 60° electrical $\Rightarrow$ one mechanical step.

$\theta_e = 60°$, $\theta_m = 7.5°$

from (2) $\Rightarrow P = \frac{\theta_e}{\theta_m} = \frac{60}{7.5} = 8$

$\therefore$ Number of poles $= 2 * 8 = 16$.

b. At what rate must control pulses be received in the motors's control unit if it is to be running at 300 rpm?

$n_{pulse} = 6 * 8 * \frac{300}{60} = 240$ pulses/sec.

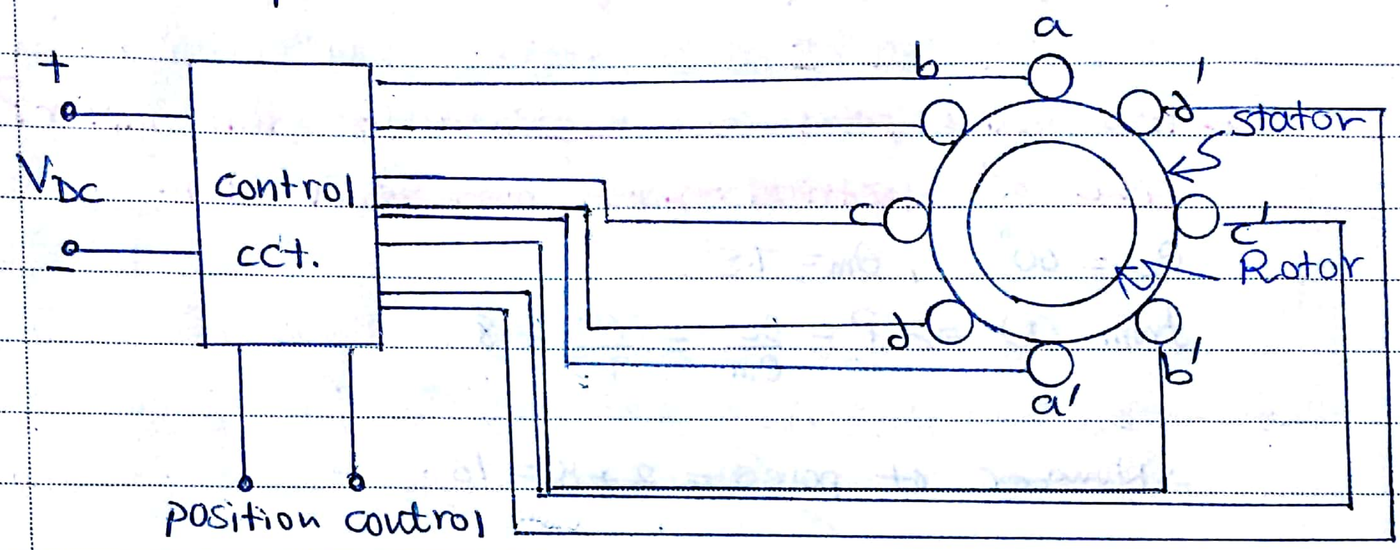
pulses

$\therefore$ No. of electrical cycles $= \frac{240}{60} = 40$ cycle.

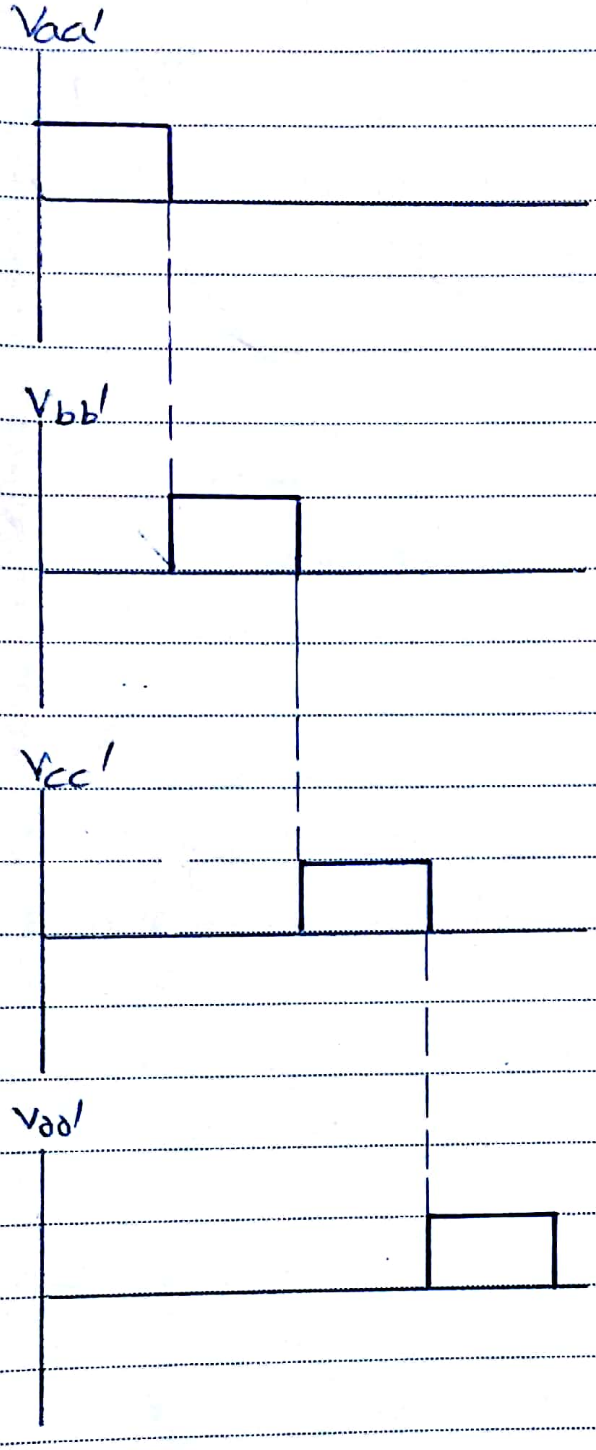
3 * Brushless DC-Motor:

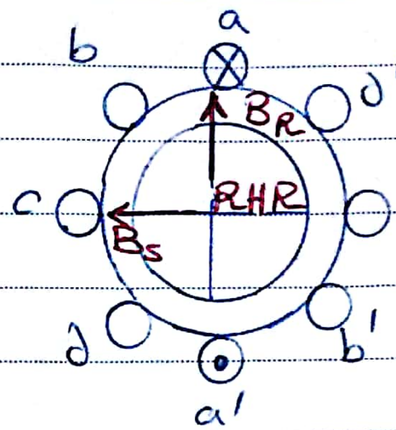
Construction:

1. It consists of stator with 3 or more phases.
2. A cylindrical P.M. rotor.
3. DC-supply.
4. position control unit.



"4-phases stator"





* $\tau = K (B_R * B_s)$

LHR ⇒ Direction of τ

* when B_R is aligned with B_s, then position control changes the voltage from <u>a</u> to <u>b</u>.

4 * Reluctance Motor:

The same of stepper motor, but (P.M. → Electrical magnet.) P.M. ⇒ E.M.