Course Code	Course Title						Core / Elective
PC402EE	**ELECTRICAL MACHINES - I**						Core
Prerequisite	Contact Hours per Week				CIE	SEE	Credits
	L	T	D	P			
NIL	3	1	-	-	30	70	3

Course Objectives

- To learn and understand electromechanical energy conversion devices.
- To be able to understand in detail about DC machines. Construction, principle, performance characteristics and testing.

Course Outcomes

- Understand construction, operating principle and characteristics of different types of DC motors and generators
- Test and calculate performance parameters of DC motors and generators
- Select appropriate DC machines for a specific application

UNIT I

Electromechanical energy conversion: Principle of energy conversion, Flow of energy in electromechanical devices, Coupling-field reaction, Singly excited magnetic system – Electric energy input, Magnetic field energy stored, Mechanical work done – with slow, instantaneous and transient movement of armature, Calculation of mechanical force, Doubly excited magnetic systems, electromagnetic and reluctance torques.

UNIT II

DC Machines: Simple loop generator, Essential parts of DC machine, Details of Lap winding & Wave winding, EMF equation, Armature reaction — Remedies, Ampere turns, Commutation — reactance voltage, Methods of improving commutation — High resistance brushes, shifting of brushes, Interpoles, Compensating winding.

UNIT III

DC Generators; Classification & types of DC generators, Open circuit, Internal & External characteristics — Critical resistance & critical speed, Voltage regulation, Conditions for self excitation, Causes of failure of voltage buildup, Parallel operation Series, Shunt and Compound generators, Applications.

UNIT IV

DC Motors: Classification & Types of DC motors, Back emf, Speed regulation, Armature torque, Armature reaction, Operating characteristics, Performance curves, Basic speed control methods Shunt and Series motors, Three & four-point starters, Calculation of step resistances, Applications.

UNIT V

Testing, Losses and Efficiency: Power losses — Copper losses and Rotational losses, Power flow, Efficiency, Testing - Brake Test and Swinburne's test, Hopkinson's test, Field's test, Retardation test, Heat run test.

Suggested Reading:

1. D.P. Kothari, I.J. Nagrath, **Electric Machines**, Tata McGraw Hill, 4th Edition, 2010
2. Bhimbra P.S., **Electrical Machinery**, Khanna Publications, 2000
3. Gupta J.B., **Theory and Performance of Electrical Machines**, S.K. Kataria & Sons, Delhi, 2005.
4. AE Clayton and NN Hancock, **The Performance and Design of Direct Current Machines**, 3rd edition, 1959.

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UNIT - I

ElectroMechanical Energy Conversion

1. Principles of Energy Conversion
2. Flow of energy in electromechanical Devices
3. Coupling Field reaction
4. Singly excited Magnetic System

Electrical energy input — Magnetic Field energy stored — Mechanical work do

with slow, instantaneous and transient movement of armature

Calculation of mechanical force,

5. Doubly excited magnetic System,

electromagnetic torque

Reluctance torque.

Basics

a) Magnetic field → the space around the poles of a magnet in which the effect of magnetic force is felt.

b) the invisible lines of force surrounding the magnet is called the magnetic flux.

c) the force of attraction or repulsion, exerted by one magnet on the other is the magnetic force.

d) Coulomb's law → $F \propto \frac{m_1 m_2}{d^2}$ m_1, m_2 → pole strength, d = distance of seperation

or $F = \frac{m_1 m_2}{4\pi \mu_0 \mu_r d^2}$ N. m_1, m_2 in webers. d in meters. F in Newtons

e) Relative permeability 'μ_r'

the ratio of force of attraction or repulsion, between two poles m_1 & m_2 placed at a distance 'd' in a ~~medium~~ air and of relative permeability μ_r and to that of force at same distance of seperation, ~~in~~ ~~air~~

$$F_{air} = \frac{m_1 m_2}{4\pi \mu_0 d^2}$$

in Medium $F_{\mu r} = \frac{m_1 m_2}{4\pi \mu_0 \mu_r d^2}$

$$\mu_r = \frac{F_{air}}{F_{medium}}$$

f) magnetic field strength :-

Force experienced per unit strength is magnetic field intensity.

$$F = \frac{m_1 m_2}{4\pi \mu_0 \mu_r d^2}$$

$$H = F/m_1 = \frac{m_2}{4\pi \mu_0 \mu_r d^2}$$ where $m_1 = 1$ and $m_2 = m$.

then $$H = \frac{m}{4\pi \mu_0 \mu_r d^2} \; N/Wb.$$

g) magnetic flux density $B = \frac{\phi}{a}$ (Wb/m^2) Scalar quantity

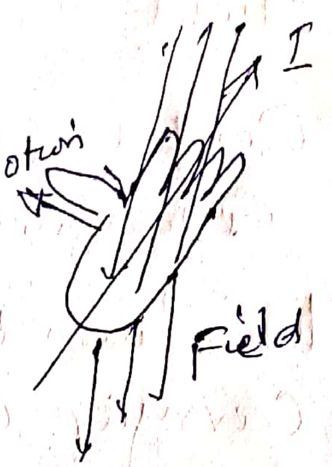
$1\ Wb/m^2 = 1$ Tesla.

h) B and H are directly proportional (assumption)

$B = \mu_0 H$. μ_0 = Permittivity of free space $= 4\pi \times 10^{-7}$

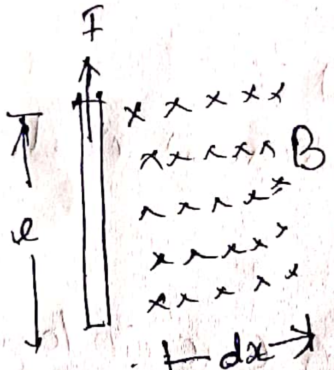
(l) Force on a current carrying conductor, in a magnetic field.

$F = BIl$ since N.



<u>Fleming's left hand rule</u>

m) Force on a conductor of length 'l' carrying current I, in a field of flux density B.



$F = BIl$ N.

If work is done by moving the conductor against the force over a distance dx

the work $= F \times dx = BIl \times dx$

$= BI(l \times dx)$ Joules $= BI\Phi$ Joules

Since $l \times dx = A$

and $B \cdot A = \Phi$.

i) Current Carrying Conductor & Magnetic Field.

Oersted discovered the effect of Current on a magnetic field.

the lines of force encircle a current carrying Conductor and their direction is given by —

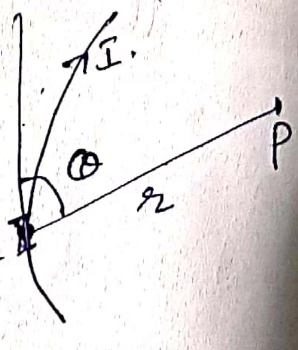
(i) Cork screw rule, (ii) Right hand rule

(iii)

(j) Amperes' circuit law : the magnetic field intensity vector H when summed up on a current carrying surface, gives the current enclosed.

$$\oint H \cdot dl = I.$$

(k) Biot-Savart's law.



Flux density dB at a point P, at a distance 'r' from the element 'dl' carrying current I is given by

$$dB \propto \frac{I\,dl\,\sin\theta}{r^2}$$

or $$dB = K\frac{I\,dl\,\sin\theta}{r^2} \qquad K = \frac{\mu_0 \mu_r}{4\pi}$$

(ii) <u>Magnetostriction</u>. The change in dimensions of the magnetic material, in the direction of magnetic field, i.e. either expanding or contracting, of the order of 10^{-6} is called <u>magnetostriction</u>.

<u>Magnetic circuits</u> → the closed path followed by magnetic flux is called the magnetic circuit.

Magneto motive force 'mmf' → the product of No of turns N and the current I flowing through it is called mmf. MMF = NI. ampere turn

<u>Reluctance</u> "S" in a magnetic circuit is analogous to Resistance in electric circuit

$$S = \frac{l}{\mu a} \quad \text{amp-turn/wb.}$$

Similar to current I, flux in a magnetic circuit

$$\phi = \frac{mmf}{S} = \frac{AT}{l/\mu a} = \frac{AT}{l/\mu_0\mu_r a}.$$

$$AT = \frac{\phi \cdot l}{\mu_0\mu_r \cdot a} = \left(\frac{\phi}{a}\right) \cdot \frac{l}{\mu_0\mu_r} = \frac{B \cdot l}{\mu_0\mu_r} = H \cdot l \text{ amp Turns}$$

9n) Magnetic material

a) Para magnetic material having a small positive relative permeability. eg: Aluminium, tin, manganese

b) Diamagnetic material : relative permeability less than 1. eg Bismuth, Copper,

c) Ferromagnetic material. very high relative permeability. eg: Iron, Cobalt, Nickel.

(i) Soft ferromagnetic — easily magnetized and demagnetised

(ii) Hard ferromagnetic — difficult to magnetize and demagnetize

d) Ferrites → intermediate to ferromagnetic and non magnetic material.

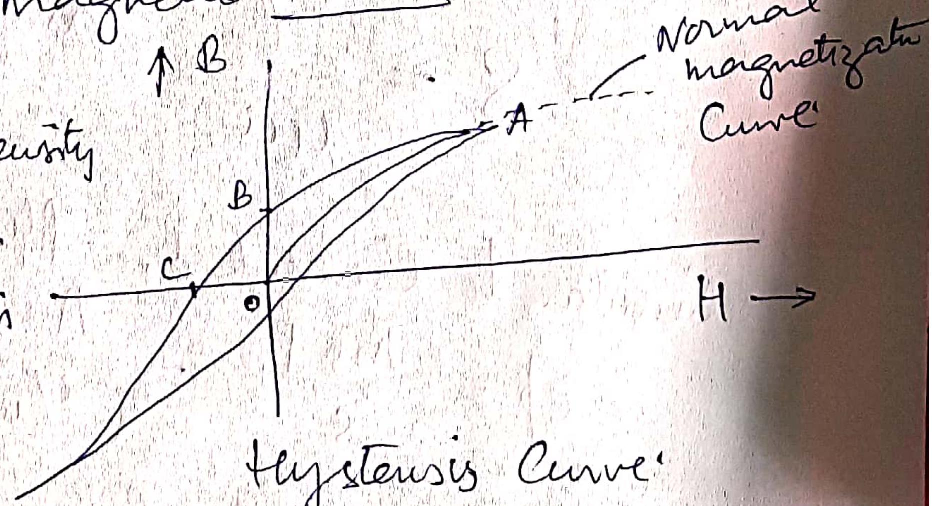
(i) Soft ferrites (ii) Hard ferrites

o) Properties of magnetic materials

(i)

OB = Residual flux density

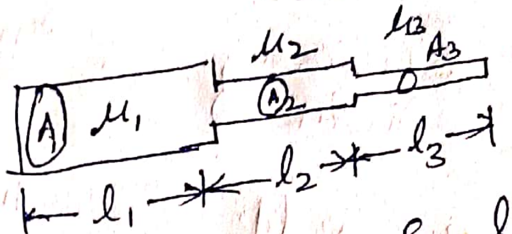
OC = Coercive force for demagnetization



Hysteresis Curve

Composite magnetic circuit

$S_2 = \frac{l_2}{\mu_0 \mu_2 A_2}$



Total reluctance

$S = S_1 + S_2 + S_3$

$S_1 = \frac{l_1}{\mu_0 \mu_1 A_1}$ $S_3 = \frac{l_3}{\mu_0 \mu_3 A_3}$

Total mmf $= \phi \cdot S$

$= \phi (S_1 + S_2 + S_3)$

$= \phi \left(\frac{l_1}{\mu_0 \mu_1 A_1} + \frac{l_2}{\mu_0 \mu_2 A_2} + \frac{l_3}{\mu_0 \mu_3 A_3} \right)$

$= \left(\frac{\phi}{A_1}\right) \cdot \frac{l_1}{\mu_0 \mu_1} + \left(\frac{\phi}{A_2}\right) \frac{l_2}{\mu_0 \mu_2} + \left(\frac{\phi}{A_3}\right) \frac{l_3}{\mu_0 \mu_3}$

$= \left(\frac{B_1}{\mu_0 \mu_1}\right) \cdot l_1 + \left(\frac{B_2}{\mu_0 \mu_2}\right) l_2 + \left(\frac{B_3}{\mu_0 \mu_3}\right) l_3$

$= H_1 \cdot l_1 + H_2 \cdot l_2 + H_3 \cdot l_3$

i.e. Total mmf = Sum of ampere turns of each part.

Magnetic leakage $\rightarrow \frac{\text{Total flux}}{\text{Useful flux}}$

leakage factor $= \frac{\text{Flux in iron path}}{\text{Flux in air gap}}$

Flux in air gap = useful flux $\rightarrow$ used for various applications

Induced emf.

- Statically induced
- Dynamically induced

Dynamically induced: moving Conductor in a magnetic field

$e = Bl v \sin\theta$ Volts.

Direction of Dynamically induced emf by Flemings Right hand Rule

Statically induced:

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

- Self induced EMF
- Mutually Induced EMF

Self induced EMF:

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

$$= -N\frac{d}{dt}\left(\frac{Ni}{l/\mu_0\mu_r a}\right)$$

$$= -\frac{N^2\mu_0\mu_r a}{l}\cdot\frac{di}{dt}$$

$$= -L\frac{di}{dt}$$

L = Inductance

$$= \frac{N^2\mu_0\mu_r a}{l}$$

Mutually Induced EMF:

Current induced in Coil B due to change in Current in Coil A because of change in flux linkage

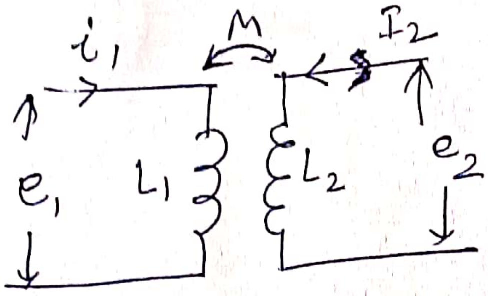
e_m = − Rate of change of flux in Coil B

$= -N_2$ rate of change of flux in Coil A

$$= -N_2\cdot\frac{d}{dt}\left[\frac{N_1 i_1}{l/\mu_0\mu_r a_1}\right]$$

$$= -\frac{N_1N_2\mu_0\mu_r a}{l}\cdot\frac{di_1}{dt}$$

$$= -M_{12}\frac{di_1}{dt}$$



$$e_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$

$$e_2 = L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

Coefficient of Coupling:

Flux in one Coil links with the other Coil, a fraction th. Let this factor be K.

Then $\phi_1 = \frac{N_1 i_1}{l/\mu_0 \mu_r a}$ Wb. Flux created by i_1 in N_1 turns.

Let this link by a factor K with Coil 'B'

Then $\phi_2 = K \cdot \phi_1 = \frac{K N_1 i_1}{l/\mu_0 \mu_r a}$ Wb.

Mutual inductance $M_{12} = \frac{N_2 \phi_2}{i_1} = \frac{K N_1 N_2}{l/\mu_0 \mu_r a}$.

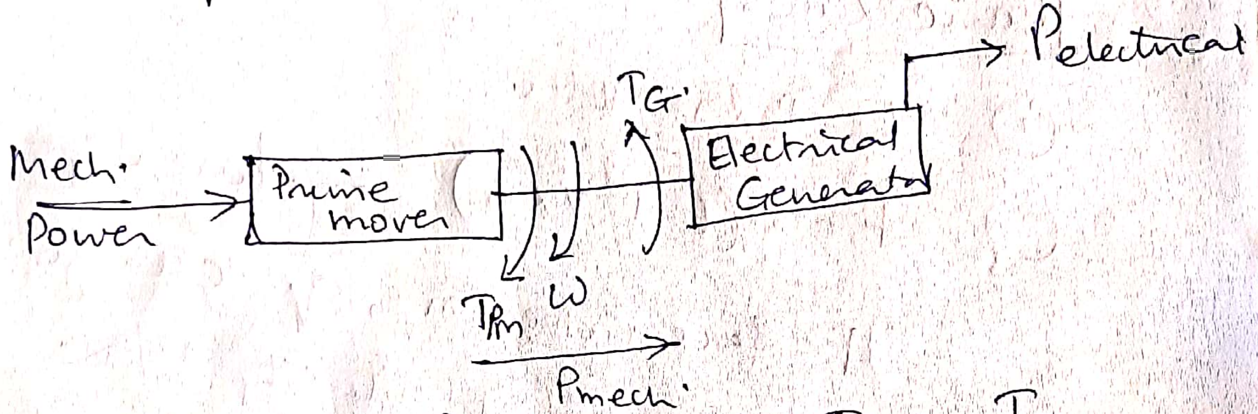
Coefficient of self inductance $L_1 = \frac{N_1 \phi_1}{i_1} = \frac{N_1^2 \cdot i_1}{l/\mu_0 \mu_r a}$

" " $L_2 = N_2^2$

Principles of Electro Mechanical Energy Conversion EMEC

EMEC devices

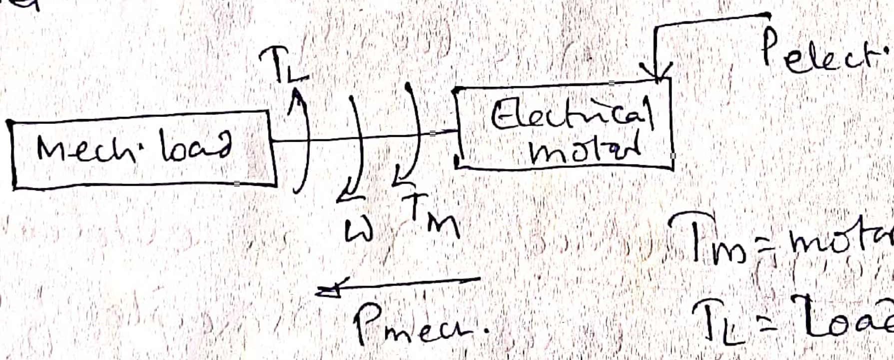
- Transducers: measurement & control purposes.
- Force producing: Solenoids, Relays.
- Continuous energy generation / Consumption: Dynamo / motors



$T_{pm} \rightarrow$ Torque Prime mover

$T_G \rightarrow$ Generator Torque

$T_{pm} = T_G$



T_m = motor torque

T_L = Load torque

$T_m = T_L$

EMEC device is a link between Electrical and mechanical systems.

All these devices make use of either or all

1) Force experienced on a current carrying conductor in a magnetic field

2) Force of attraction or repulsion of a ferro-magnetic material

3) Electrostatic force on the charged plate of the capacitors

4)

Basic laws

① $E = Blv$ Volts.

② $F = q(E + v \times B)$ — Lorentz equation

F = force in Newton, q = charge in Coulombs

E = Electric field intensity V/m.

V = velocity of particle in m/s.

B = Flux density in Tesla.

Energy balance In an electromagnetic energy conversion device, the principle of conservation of energy is applied between the stages of conversion.

Energy input from Electrical Source

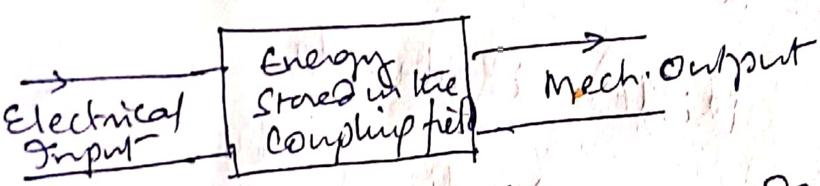
= Energy output in mechanical form + Energy converted to heat + increase in stored energy in magnetic field. (MOTOR action)

Similarly for Generator action

Mechanical Energy input
= Electrical energy output + energy converted to heat + change in stored magnetic field.

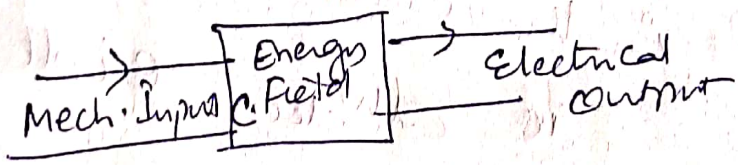
Coupling Field Reaction

(MOTOR)

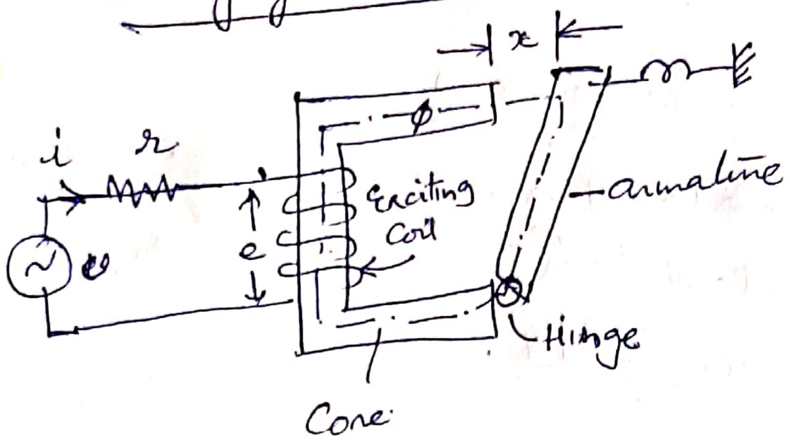


When the coupling field losses are zero, i.e the coupling field is lossless then entire energy input is converted to proportional output.

(GENERATOR)



Singly excited Magnetic System



$$v = ir + e = ir + \frac{d\psi}{dt}$$

or $vi = i^2 r + ei = i^2 r + i\frac{d\psi}{dt}$

or $vi\,dt = i^2 r\,dt + i\,d\psi$

ie $(v - ir)\,i\,dt = i\,d\psi$

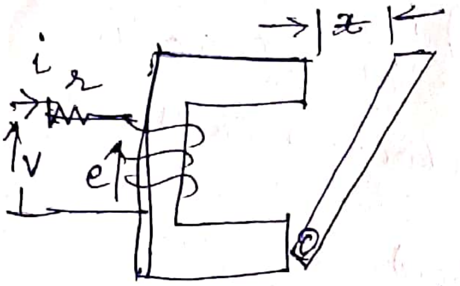
or $\boxed{e\,i\,dt = i\,d\psi}$

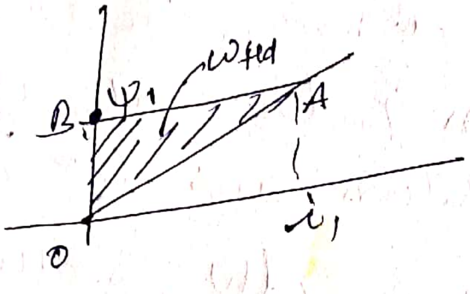
the electrical energy input to the coil is reflected in the change in flux linkages.

ie $dW_{elec} = e\,i\,dt = i\,d\psi$.

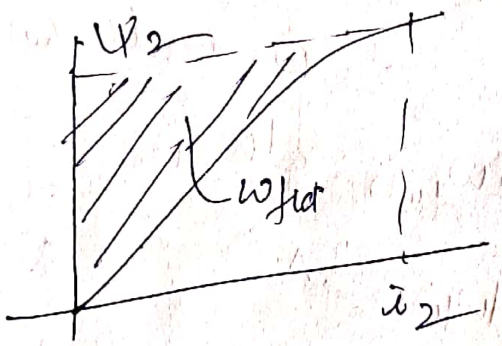
In a toroidal Core, all the flux links with the turns then $i\,d\psi = i\,N\,d\phi = (mmf)\cdot d\phi$

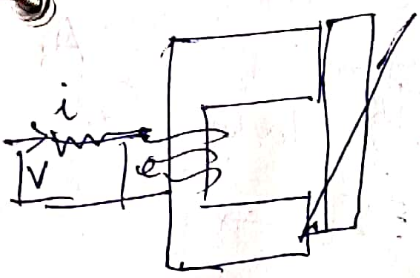
When mechanical work done-





armature held



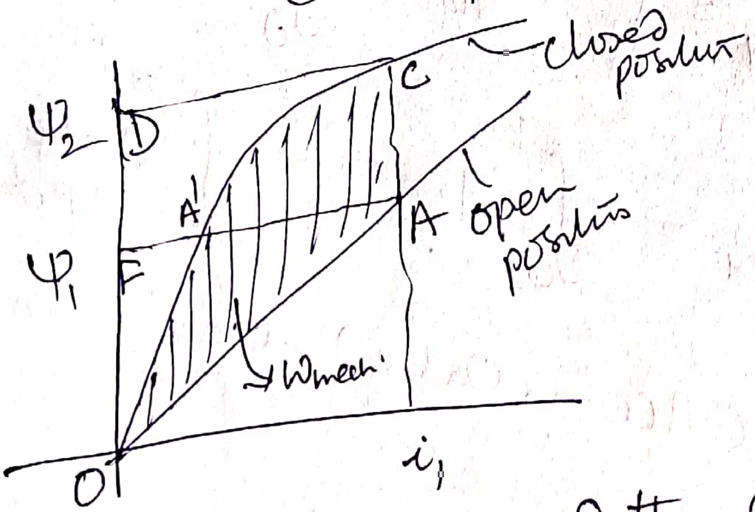


$\psi_2 > \psi_1$

Slow movement

open position $\rightarrow$ ψ_1 & i_1

Closed position $\rightarrow$ ψ_2 & i_2.



the slow movement of the armature is done such that the rate of change of flux linkages $\frac{\psi_2 - \psi_1}{time}$ is negligible

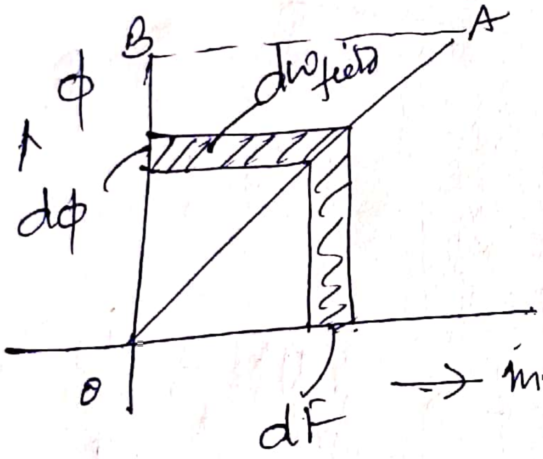
Magnetic field is stored, when the mechanical work done is zero.

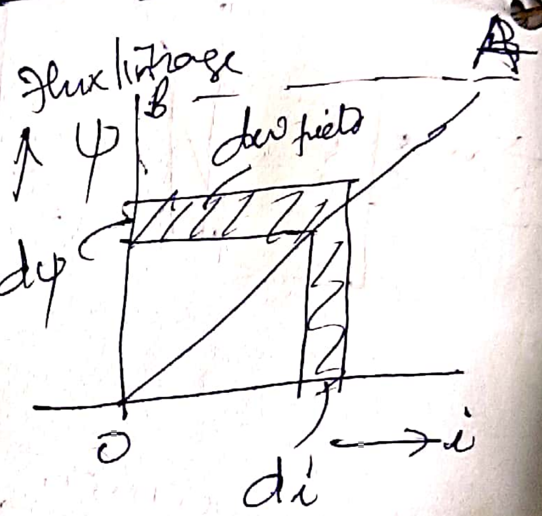
frea: in a magnetic relay, on the energisation of the coil, if armature is held in position and not allowed to move

then $dW_{elec} = dW_{work} + dW_{field}$

$= 0 + dW_{field}$

or $dW_{field} = dW_{elec}$ — Stored energy





$$OABO = W_{fld} = \int_0^{\phi_1} dW_{fld} = \int_0^{\phi_1} F \cdot d\phi$$

$$OACO = \int dW'_{fld} = \int_0^{F_1} \phi \, dF = \int_0^{i} \psi \, di$$

Area OACO is called area of Co energy

Hence the operating point 'A' reaches 'C' along AC.

Change in Stored energy from open to closed position

$= W_{fld} =$ Energy in closed − Energy in open position

= area $OA'CDFO - OAA'FO$.

Electrical energy input $= \int_{\psi_1}^{\psi_2} i\,d\psi$ = area $ACDFA'A$

Since $W_{elec} = W_{fld} + W_{mech}$.

$W_{mech} = W_{elec} - W_{fld}$

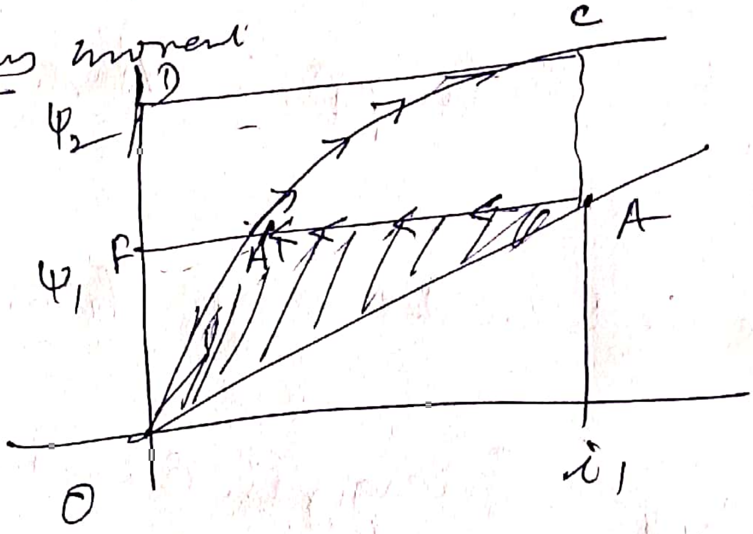
$= ACDFA'A - (OA'CDFO - OAA'FO)$

$= ACDFA'A - OA'CDFO + OAA'FO$

= Area $OACA'O$.

Ignoring Saturation, half of electrical input is Stored as magnetic field and other as mech. output during slow motion of armature.

Instantaneous movement



for instantaneous movent ψ_1 is not changed and the operating point travels from A to A' and from A' to C'.

3rd Unit III

Shunt Generator

Characteristics

① Magnetizing Characteristics or saturation or open ckt or no load } E_a Vs I_f, N = Const

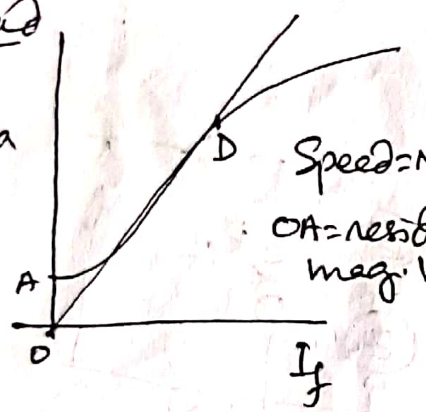
② Internal characteristics

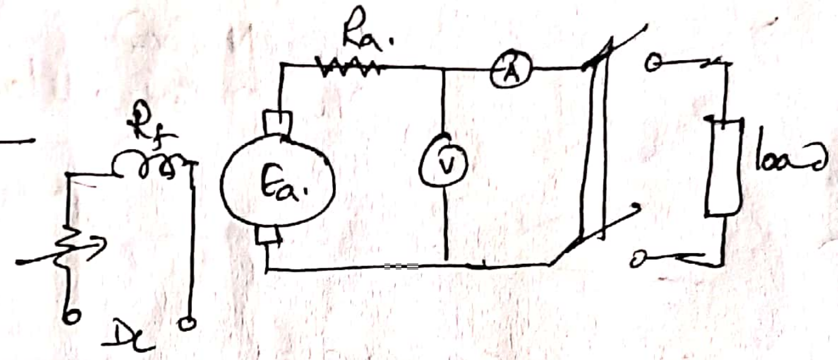
③ External characteristics — V_t Vs I_L : I_f & N Const

④ Load characteristics or load magnetization Curve — V_t Vs I_f : I_a, N Const

For Seperately excited

① No load





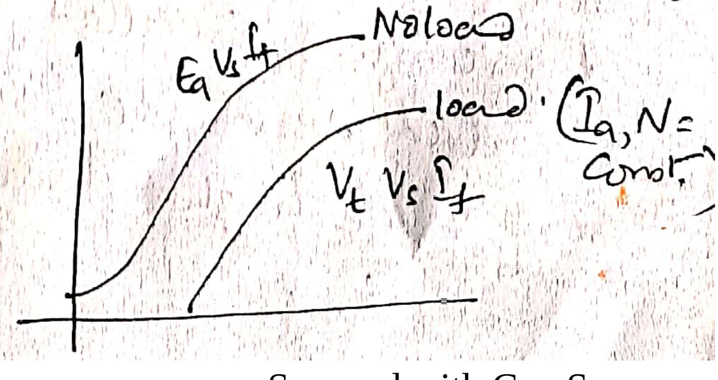
I_f is increased in steps till $E_a' = 1.1 E_a$.

I_f is retraced, Curve plotted is higher, because of hysteresis

② load — V_t & I_f for I_a, N Const

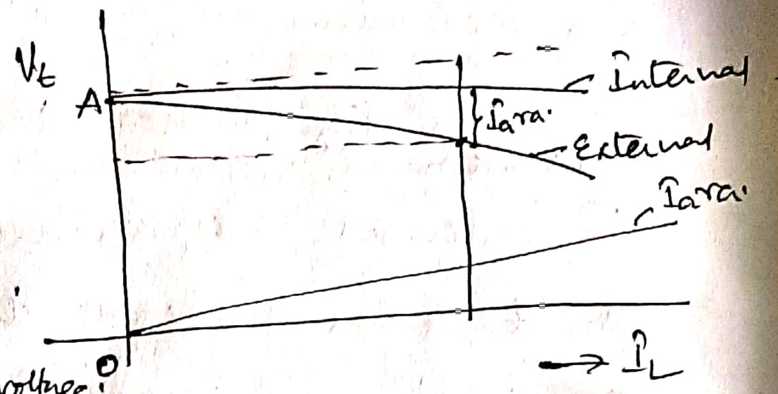
Adjust I_f to get rated arm. Current I_a and maintain N Constant.

Vary load and field Current to maintain I_a, N Const. take the readings of V_t & I_f.



(3) External V_t & I_L. for I_f, N = Constant

Rated speed,
fieldwinding adjusted to give rated V_t.
Load resistance is varied and V_t and I_L noted.



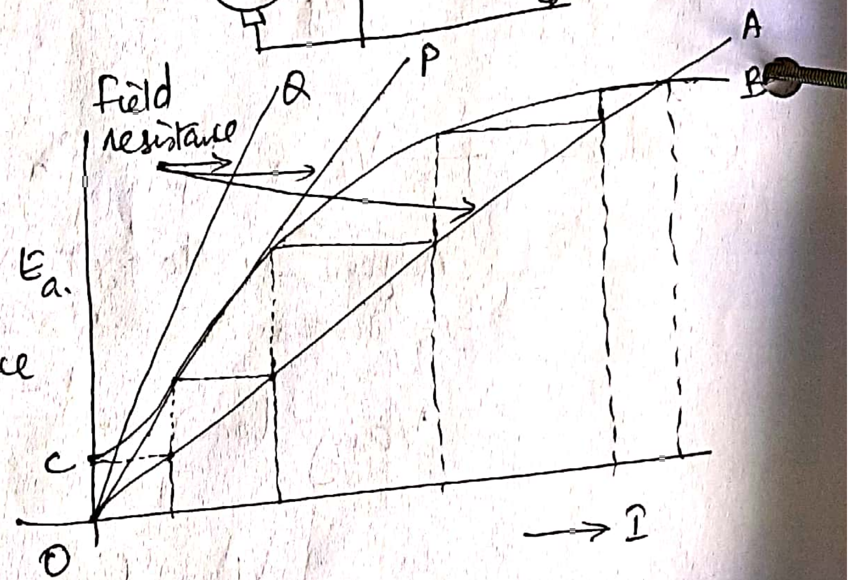
OA = no load terminal voltage.

$$\text{Voltage regulation} = \frac{E_0 - V_r}{V_r} \times 100$$

E_0 = No load
V_r = rated full load voltage.

Shunt generator

Voltage built up



The value of field resistance (line tangent to OC curve from origin) is called Critical resistance.
Any value higher than this, m/c will not generate.

Failure to build up voltage in a Shunt M/c.

① No residual magnetism — excite field winding from a seperate source.

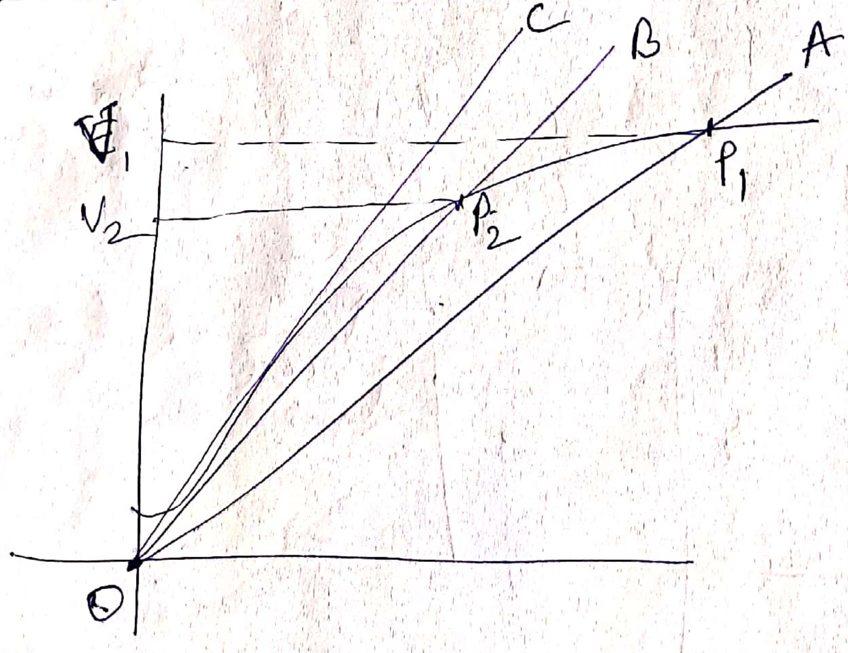
② Field Connections are reversed.

③ High field resistance → In this case the field resistance is greater than Critical resistance.

reasons → open ckt in field, dirty Commutator or large external resistance

④ Speed less than Critical speed → Increase Primemover Speed.

OP represents the Critical field resistance R_c
$R_2 = OQ$ is greater than OP. Hence no built up of voltage.



OA → field resistance R_1 for which corresponding ~~emf~~ voltage is V_1.

OB is increased field R_2, corresponding to V_2. OC is R_3 ~~for which emf is built up~~ is called Critical resistance

Determination of

① Critical resistance from OCC

a) Draw the OCC from data induced emf and I_f.

b) draw tangent from origin to OCC.

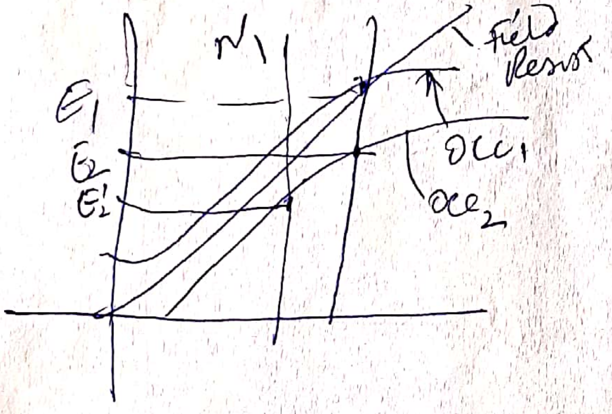
c) find the slope of the tangent to obtain critical resistance

② OCC at different speed

a) plot OCC at given speed.

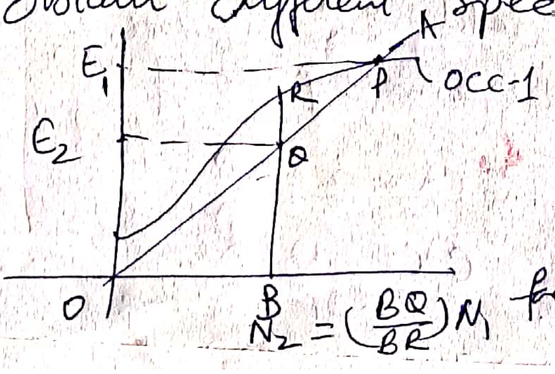
Since $E \propto \phi N_1$ or $E_1 \propto N_1$, $E_2 \propto N_2$

or $\frac{E_1}{E_2} = \frac{N_1}{N_2}$ Given any 3 values the other can be found



$E_2 = \left(\frac{N_2}{N_1}\right) E_1$

③ To obtain different speed for a given new emf.



Draw OCC-1
Draw OA – field resis line
P gives the operating point for E_1.

$N_2 = \left(\frac{BQ}{BR}\right) N_1$ for any E_2

or $N_2 = \left(\frac{E_2}{E_1}\right) N_1$

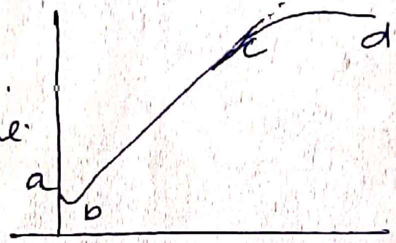
Operating Characteristics

1). Magnetization Curve.

$$E = \frac{\phi Z N}{60} \cdot \frac{P}{A} \text{ volts.} = \left(\frac{ZP}{60A}\right)(\phi N) \text{ volts}$$

ie $E \propto \phi N$. for a given m/c.

When speed is maintained constant, $E \propto \phi$.



$E \propto \phi \rightarrow N$ constant $\longrightarrow$ field Ampereturns.

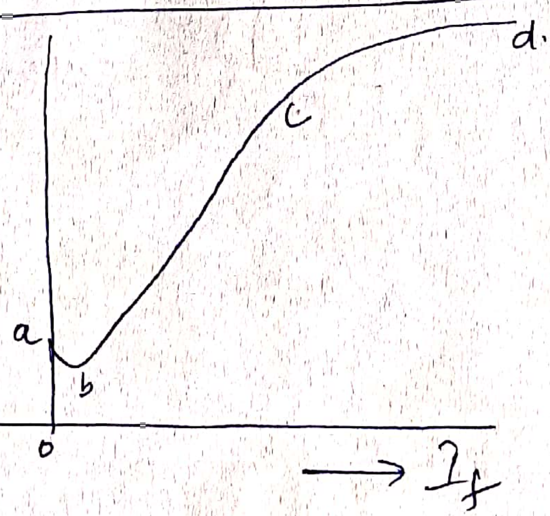
ϕ (per pole) $\propto$ field ampere turns

$\propto I_f \cdot$ turns

or ϕ (per pole $\propto I_f$ since turns are fixed and hence constant

$\therefore E \propto I_f$.

the graph between E & I_f is called the open circuit characteristics $\rightarrow$ OCC or magnetic characteristic



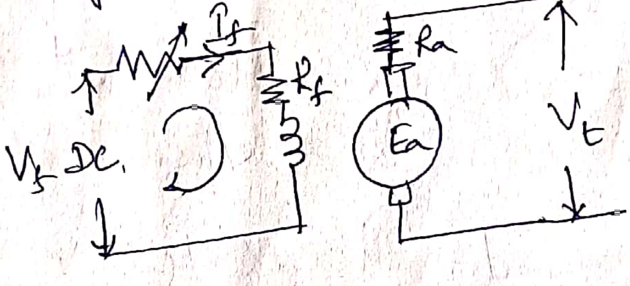
Oa represents the residual magnetism.. 'bc' is the

Straight line portion and C the saturation starting point known as "knee" of the curve.

Experimentally determination:—

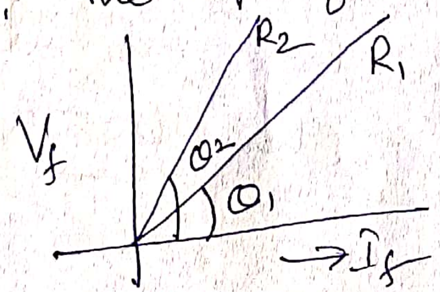
the field of series or shunt m/c is disconnected and connected through (A) of a source via a rheostat. m/c run at constant speed rated speed and on NO LOAD.

Vary rheostat to get different readings of I_f and the corresponding E_a.



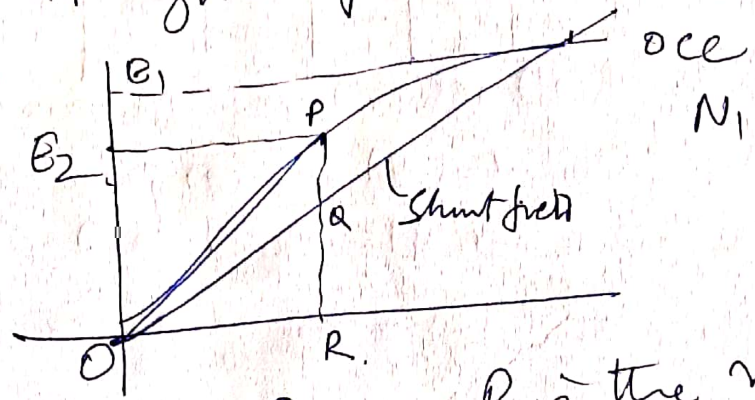
On No load
$\therefore V_t = E_a$.

→ field resistance line is a graph between V_f and I_f. the slope of the line $\frac{V_f}{I_f}$ gives R_f



$R_2 > R_1$
$\theta_2 > \theta_1$

(4) to reduce shunt resistance, to obtain reduced emf at given speed

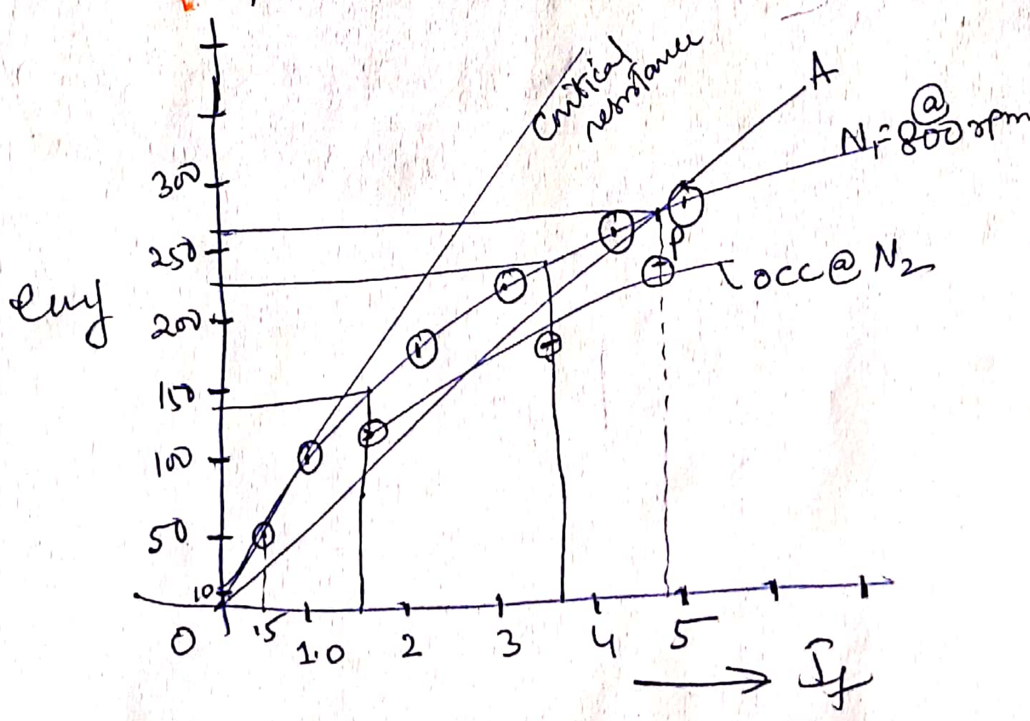


Corresponding to E2, P is the new operating point. the slope of OP ie $\frac{PR}{OR}$ represents the new resistance of shunt field ckt

— x —

@800 rpm

I_f	0	0.5	1.0	2.0	3.0	4.0	5.0
Induced emf (volts)	10	50	100	175	220	245	262



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

$$E_2 = \left(\frac{N_2}{N_1}\right) E_1 .$$

I_f	0	0.5	0.9	1.35	1.6	2.10	2.5	2.8	3.0
E_0	7	65	140	180	210	233	245	265	275

@ 1500 rpm (8)

find a) for a field resist 150Ω The no load emf
b) the critical field at 1500 rpm
c) the OCC for 1150 rpm, and critical resistance
d) for ~~critical~~ field resistance of 100Ω the OC voltage.

4P, Shunt gen, Lap connection $R_f = 50\Omega$ $R_a = 0.4\Omega$ supplies 60nos 40W @ 100V. Cal. Ia per path and gen. emf. Assume 1V drop per brush

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4P, Shunt, $R_f = 100\Omega$, $R_a = 1\Omega$, $Z = 378$, wave connection $\phi = 0.02$ wb, $R_L = 10\Omega$, $N = 1000$ rpm.
Cal. power absorbed by load

4P, $\phi = 0.07$ wb, 400 lap conductors, each of resistance 0.002 $N = 900$. $I_a = 50$ A Calculate V_t.

[Arm resistance = $\frac{\text{Resist of Conductor} \times (\text{no of Cond/path})}{\text{No of parallel path}}$

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

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the field of Shunt m/c or compound m/c should not be opened excepting when shunted through resistance called field break Switch

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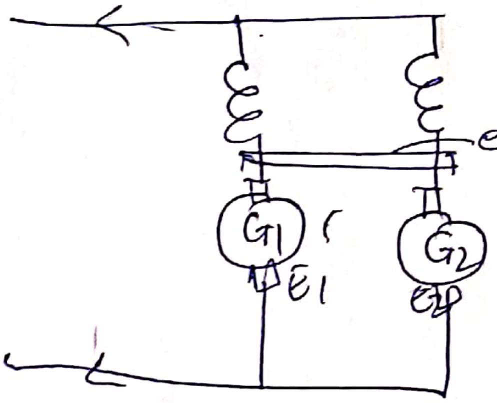
Parallel operation of Gen

→ Load fluctuates
→ To supply varying loads, fixed value generator is not economical and efficient.
→ To increase reliability
→ to take care of maintenance / repair
→ power plant can be augmented.

Parallel operation of Series Gen



Two m/c of Resistance R
E_1 & E_2.
for $E_1 = E_2$ → load shared is equal
in case $E_1 > E_2$, circulating currents will flow $\frac{E_1 - E_2}{2R} = i$
current $= I + i$ and $I - i$.
↑ I_1 causes ↑ E_1 thereby increasing I

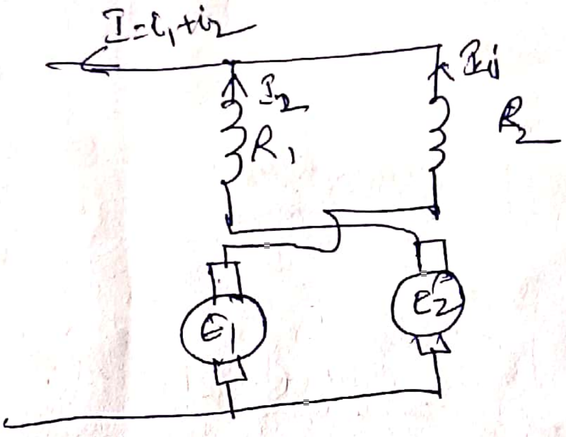
a Stage will Come when E_2 reverses its direction

hence $E_1 - (-E_2) = E_1 + E_2$ is the net voltage.

the Current would be $\frac{E_1 + E_2}{2R}$, $\Rightarrow$ high Current nearly Short ckt.

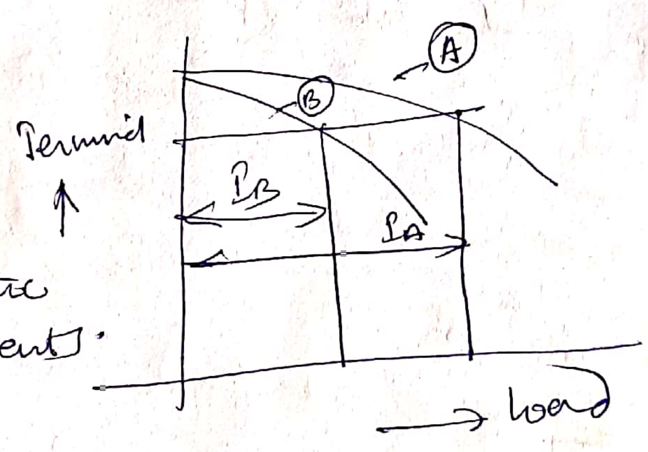
Hence equalizer bar is connected

alternative arrangement $\Rightarrow$ Cross Connection



Shunt gen

Generator with more drooping characteristic carries lesser currents.



Conditions:

(1) Same polarity (2) Equal terminal voltage

(3)