A.C. MACHINES

* Synchronous Machines :

* A 3ϕ Ac system is inherently used in the generation, transmission & distribution of Electrical power.
* In A.C Electrical power System, 3ϕ synchronous Machine play important role.
* Basically these Machines are rotating Electrical Machines.

* Definition of Synchronous Machine :

* A Synchronous Machine is defined as an A.C Electromagnetic rotating Machine which bears a fixed relationship of its Speed, with number of poles & supply frequency.

* In short a Synchronous Machine runs at a Constant speed "N_s" which is given by the relation.

$$N_s = \frac{120 f}{P}$$

* Where N_s : Synchronous Speed in rpm
  f : Supply freq: in Hz
  P : No. of poles of Machine.

* The Synchronous Machine convert the rotary Mechanical power into A.C Electrical power.

* Types of Synchronous Machines :

the Synchronous Machines are Classified into Various ways as follows.

1) Types according to the number of phases :

* Single phase Synchronous Machine
* three phase Synchronous Machine.

* the use of Single phase Synchronous Machines are limited, Where as three phase Machines are used in power plants & industrial sector.

2) Types According to the function of Conversion :

* Synchronous generator (alternator)
* Synchronous Motor

* a Synchronous generator Converts rotary Mechanical power into A.C Electrical power.
* Where as a Synchronous motor Converts Ac Electrical power into the rotary Mechanical power.
* Basically both the functions are reversible & therefore the Same synchronous machine Can function as a Synchronous generator or a synchronous motor.

3) Types according to the particular winding on the rotating part :

* Rotating armature type
* Rotating field.

* In rotating armature type synchronous machine, the armature winding is placed on the rotor while in rotating field type synchronous Machine, the field winding is placed on the rotor.

4) Types according to the type of rotor for rotating field type synchronous Machine:

* Salient pople type synchronous Machine
* NON- Salient pole (or) cylindrical rotor type

* Basic concepts:

the generating action & motoring action of the synchronous machine can be well understood by the following fundamental principles.

* generating action:

A synchronous machine works as synchronous generator or alternator when its rotor is driven by some prime-mover to give Mechanical Energy input. it Converts this Energy into A.C Electrical Energy output.

the generating action can be Explained as follows:

* Law of Electromagnetic induction:

the faraday's law of Electromagnetic induction states that an Emf is induced in the conductor or winding when it Cut's the Magnetic field during its motion.

* generator Emf :-

* a field winding of synchronous generator produces main magnetic field.

* An Emf is induced in the armature winding when it Cuts this magnetic flux due to the relative motion.

* when the Armature ckt is closed, the armature Current flows and produces its own magnetic field.

* this armature flux interacts with the main field flux & develops a force on armature conductors to oppose the relative motion.

* So the mechanical Energy must be Supplied to maintain the relative motion between the Armature conductors & Main field.

* thus this mechanical Energy is Converted into the Electrical Energy in the form of generator Emf & Current.

* Motoring action:

* A Synchronous machine works as a synchronous motor when A.c Electric Supply given to its armature.

* it Converts this Energy into Mechanical Energy output in the rotary form.

* this motoring action is based on following principle.

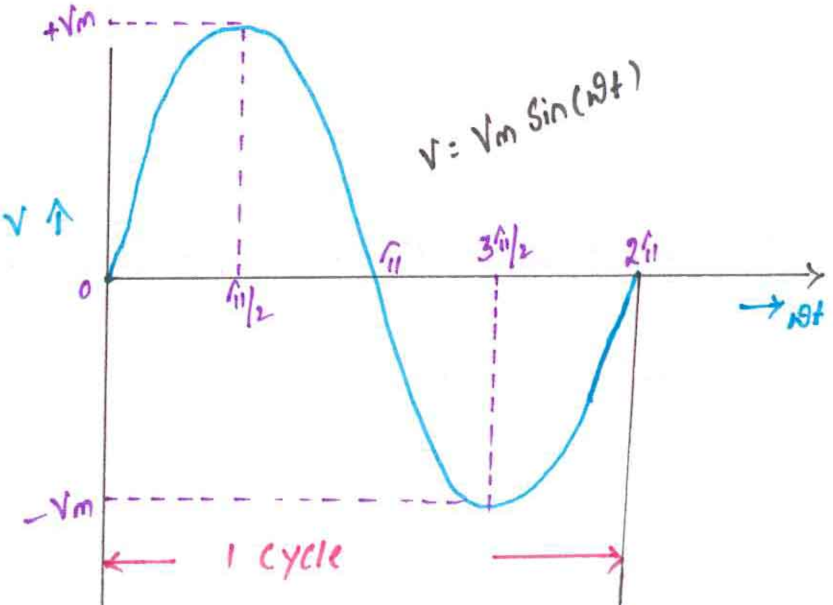
* Law of interaction:- this law states that when a Current Carrying Conductor is placed in the magnetic field, a force is Excerted on the Conductor due to the interaction between the field produced by Conductor Current

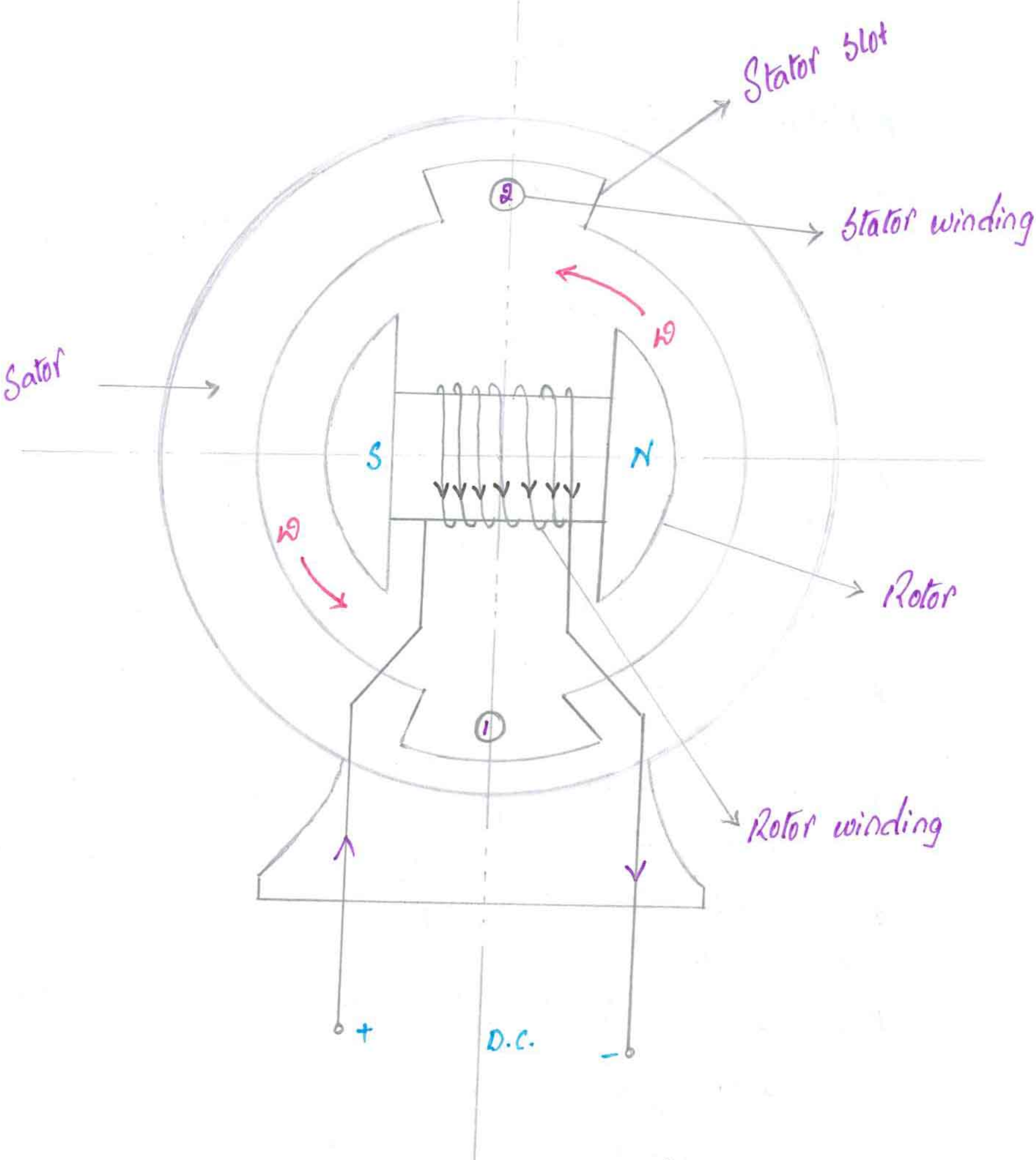
& the main magnetic field. this force can develop a torque for the rotation.

* **Motor rotation:**

* the field winding of Synchronous motor produces main magnetic field.
* the A.C Electric Supply is given to the Armature winding which produces Current. this Armature Current produces Armature flux.
* the interaction between the armature flux & the main field flux gives rise to the force & corresponding torque which produces the relative motion between Armature & Main field.
* the relative motion induces Emf in the armature. this back Emf opposes the armature Current.
* So the Electric supply voltage should be given to the motor to maintain the Armature Current.
* In doing so, this Electric Energy is Converted into the mechanical Energy Output.

* **principle of operation of rotating field type 1ϕ alternator:**





ELEMENTARY ROTATING FIELD TYPE SINGLE PHASE ALTERNATOR

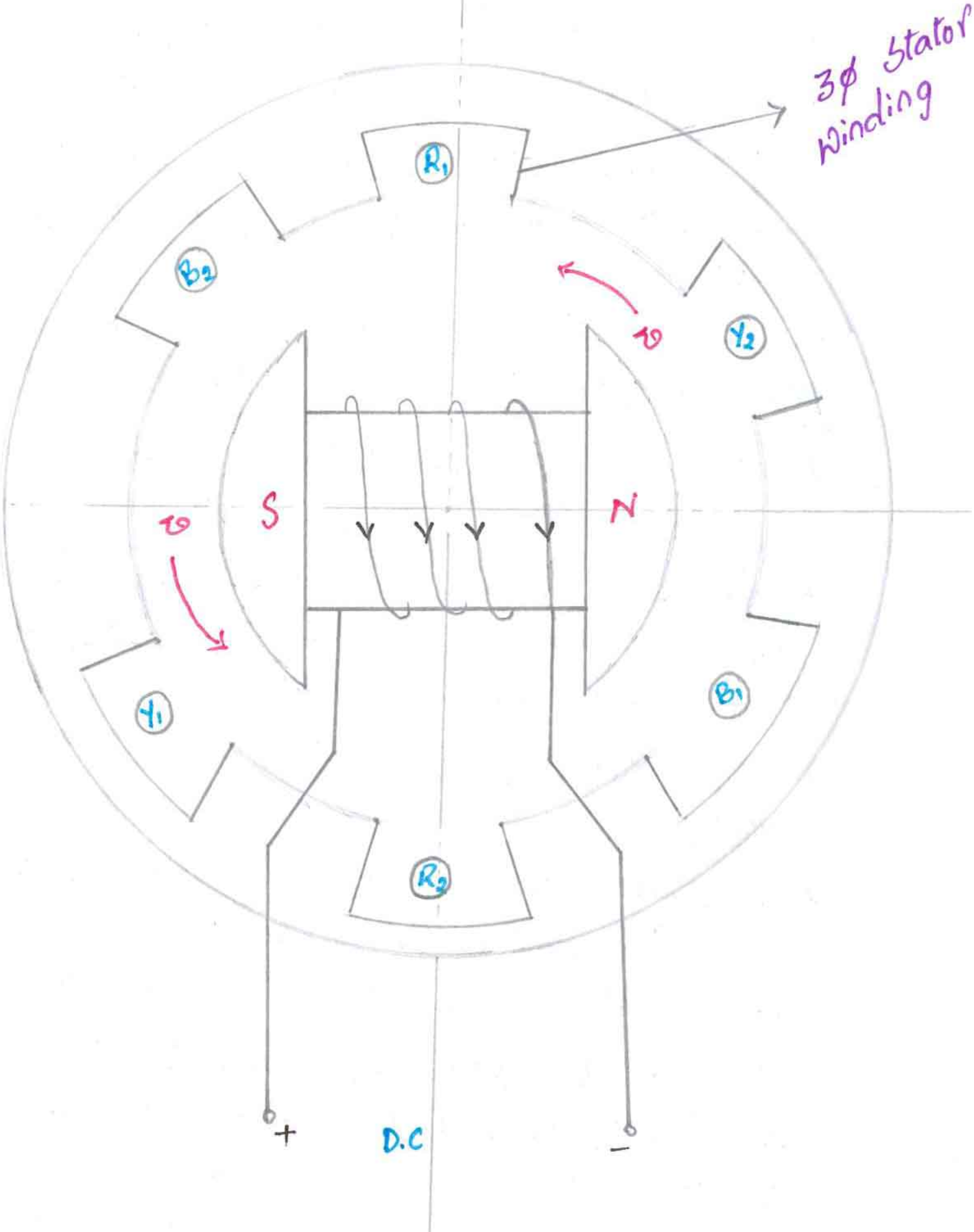
* An Elementary 1ϕ rotating field type alternator is shown in fig.
* it Essentially Consists of two parts 1) Stationary part (stator) 2) rotating part (rotor).
* In stator slots there is a 1ϕ stator winding (Armature) & rotor has a rotor winding (field winding).
* A D.C Supply is taken from the Exciter to the rotor winding.
* this rotor winding produces magnetic poles N & S as shown in fig.
* the rotor is rotated in an anticlockwise direction at a constant angular speed of "ω" radians per second by some prime mover.
* thus magnetic poles & magnetic field are rotated while the stator winding conductors 1 & 2 are stationary.
* so the rotor magnetic field or flux is cut by the stator conductors & Emf is induced in them according to faraday's law of Electromagnetic induction.
* this Emf is known as dynamically or motionally induced Emf.
* the magnitude of this Emf is proportional to the rate of Cutting the flux & its direction depends on the polarity of the magnetic field Cut by the Conductor.
* the rate of Cutting the flux varies according to the sine of the rotor angle w.r.t positive x-axis.
* $\therefore$ the instantaneous value of the Emf or Voltage generated in the stator winding is given by $v = V_m \sin \omega t$

where "V_m" is the maximum Emf induced when the rotor angle is 90° or $\pi/2$ radians.

* At this position, rotor pole axis is in line with the stator conductors 1 and 2 & so maximum flux is cut.
* when rotor is horizontal, rotor angle ωt is zero. so no flux is cut & hence voltage induced is zero.
* the variations of the voltage are plotted against angle "ωt" in fig:.
* this graph is known as a sinusoidal waveform or wave shape.
* In one revolution of the rotor i.e, for $\omega t = 2\pi$ radians, one set of variations is completed.
* This set is repeated again & again. this alternating voltage is known as a sinusoidal voltages.
* Similarly the alternating current is also sinusoidal.

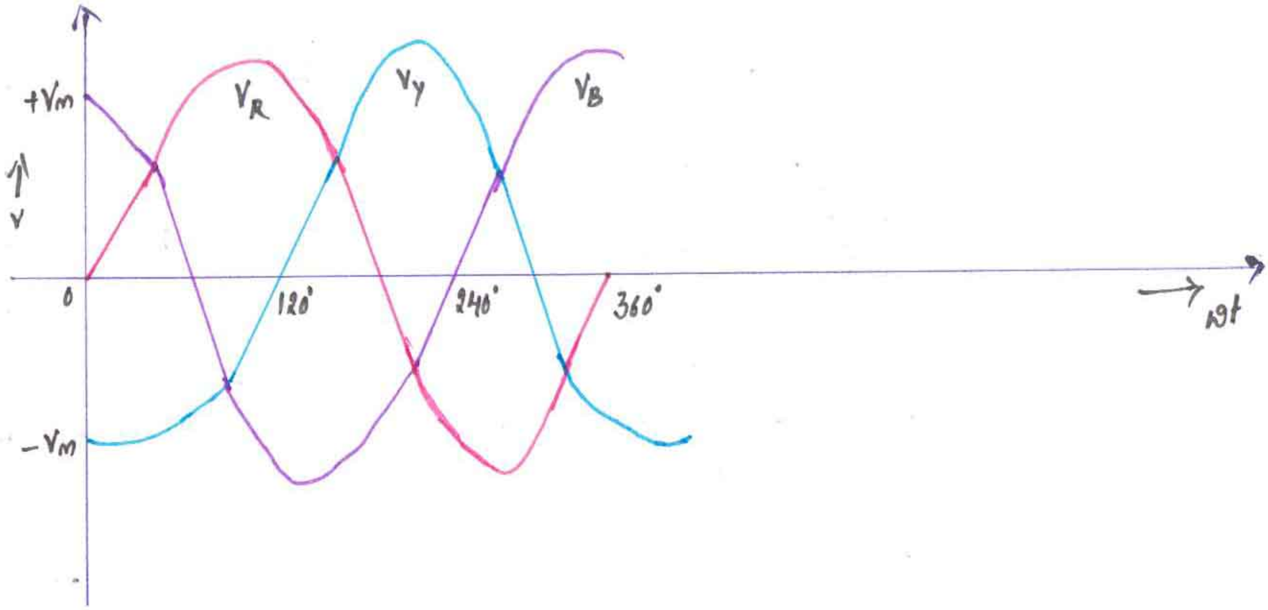
* principle of operation of Rotating field type 3-phase Alternator:

* A 3ϕ alternator converts rotary mechanical power into a 3ϕ Electric power.
* A rotating field type 3ϕ alternator is shown in fig.
* Constructionally it is similar to a single phase alternator.
* the only difference is that a 3ϕ stator winding is used instead of a single phase winding.
* A 3ϕ winding is uniformly distributed in stator slots as shown in the fig.



ELEMENTARY ROTATING FIELD TYPE 3 PHASE ALTERNATOR

* Conductors $R_1 R_2$ form R phase, Conductors $Y_1 Y_2$ form Y phase & Conductors B_1, B_2 form B phase.
* the space angle between any two phase windings is 120°.
* thus angle between R_1 and Y_1 is 120°, that between Y_1 & B_1 is 120° & that between B_1 and R_1 is also 120°.
* the two Conductors of Each phase are placed diametrically opposite.
* when dc supply is taken from Exciter to the rotor winding magnetic poles N and S are produced.
* when the rotor is rotated in anticlockwise direction at a constant angular velocity "ω" rad/sec.
* the flux is Cut by conductors "R_1" & "R_2" of "R" phase & Emf is induced in "R" phase winding just similar to that of the single phase alternator.
* this voltage "V_R" is varying Sinusoidally & is shown by a wave form in fig:-
* R-phase voltage is given by $V_R = V_m \sin \omega t$. Similarly the same rotor flux is Cut by the other two phases "Y" and "B" & the Sinusoidal Emfs are induced in them.
* Due to the Space displacement of 120° between any two phases, the flux is Cut first by R phase, then after 120° of rotation of rotor, the same flux is Cut by Y phase & after additional rotation of 120°, the same flux is Cut by B phase.
* So the Emfs of R, Y and B phases are of the Same magnitude but they have a phase difference of 120° i.e, Emf V_Y lags V_R by 120°, V_B lags V_Y by 120° or V_B leads V_R by 120°. the Equations of the instantaneous Values of the 3ϕ voltage are.

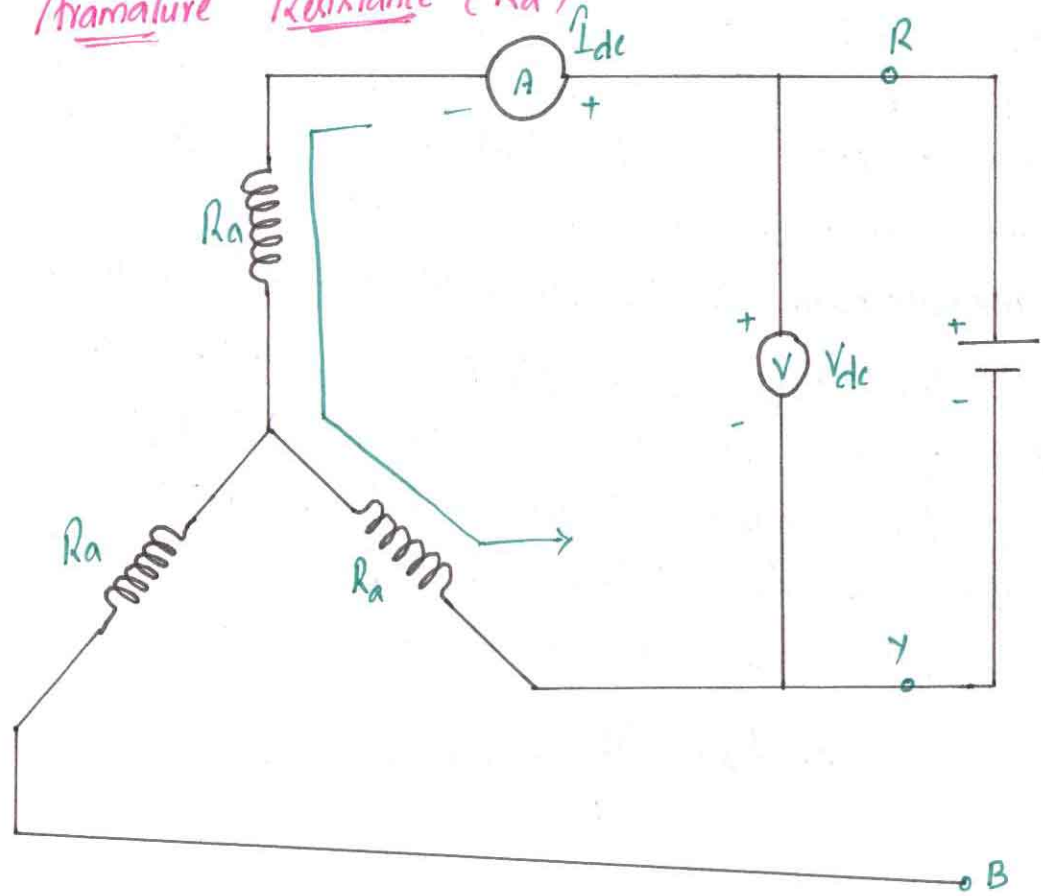


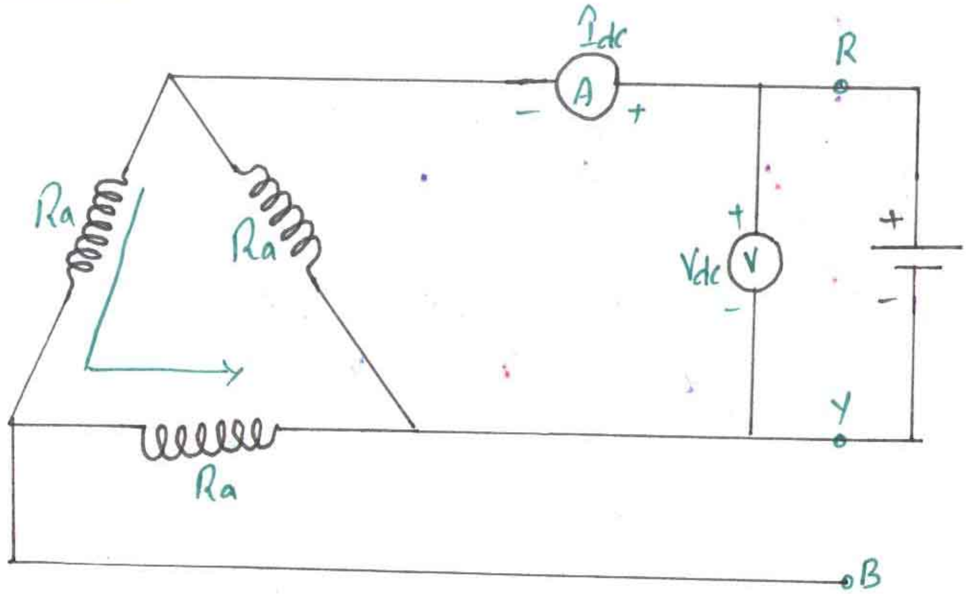
* $V_R = V_m \sin\omega t$ * $V_y = V_m \sin(\omega t - 120°)$

* $V_B = V_m \sin(\omega t - 240°)$ * $V_B = V_m \sin(\omega t + 120°)$

* the sinusoidal waveform of 3 phase voltages are shown in fig.

* **Aramature Resistance (R_a)**





* the armature winding of a 3ϕ alternator is Connected Either in star or in delta.
* it offers a resistance "R_a" per phase to the flow alternating Current "I" & produces a voltage drop "IR_a" in it.
* the aramature resistance "R_a" Can be determined by DC measurements using voltmeter & ammeter.
* this D.c value is further modified by 1.25 to 1.75 times to account for increase in resistance due temperature rise and skin Effect of alternating Current.

* **measurement of "R_a" for star Connected winding:-**

* A low voltage d.c supply is given between the two terminals R-Y of the star Connected aramature winding as shown in fig.
* If the armature resistance is "R_a" per phase, the resistance R_{RY} between the line terminals "R" & "Y" is given by the ratio of voltmeter readings to the armature reading.

$$\therefore R_{RY} = \frac{V_{DC}}{I_{DC}} = R_a + R_a = 2R_a$$

$$\therefore R_a = \frac{R_{RY}}{2}$$

$$\boxed{R_a = \frac{1}{2}\frac{V_{DC}}{I_{DC}}}$$

* measurement of "R_a" for delta Connected winding :-

* for delta Connected winding as shown in fig. R_{RY} is given as the $\parallel^{le}$ combination of "R_a" and (R_a+R_a).

$$\therefore R_{RY} = \frac{V_{DC}}{I_{DC}} = \frac{R_a(R_a+R_a)}{R_a+(R_a+R_a)}$$

$$= \frac{2R_a^2}{3R_a} = \frac{2}{3}R_a$$

$$\boxed{\therefore R_a = 3/2\, R_{RY}}$$

* Voltage Regulation :-

* the voltage regulation of alternator is defined as the change in its terminal voltage expressed as a fraction or percentange of its rated terminal voltage, when the load is removed, keeping its speed and field excitation constant.

At full load condition,

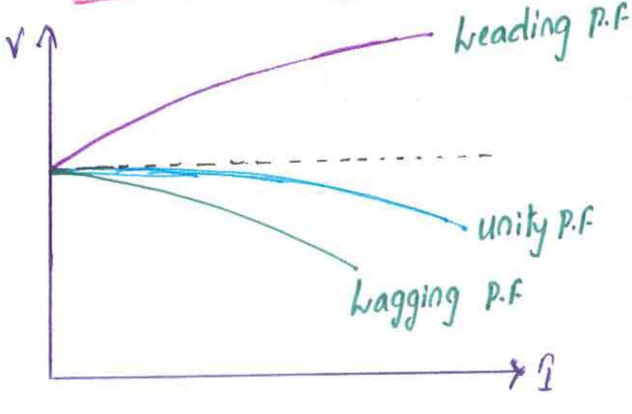
V = Rated or F.L terminal voltage per phase and

E_0 = No load induced emf per phase.

$$\therefore \text{Regulation} = \frac{E_0 - V}{V}$$

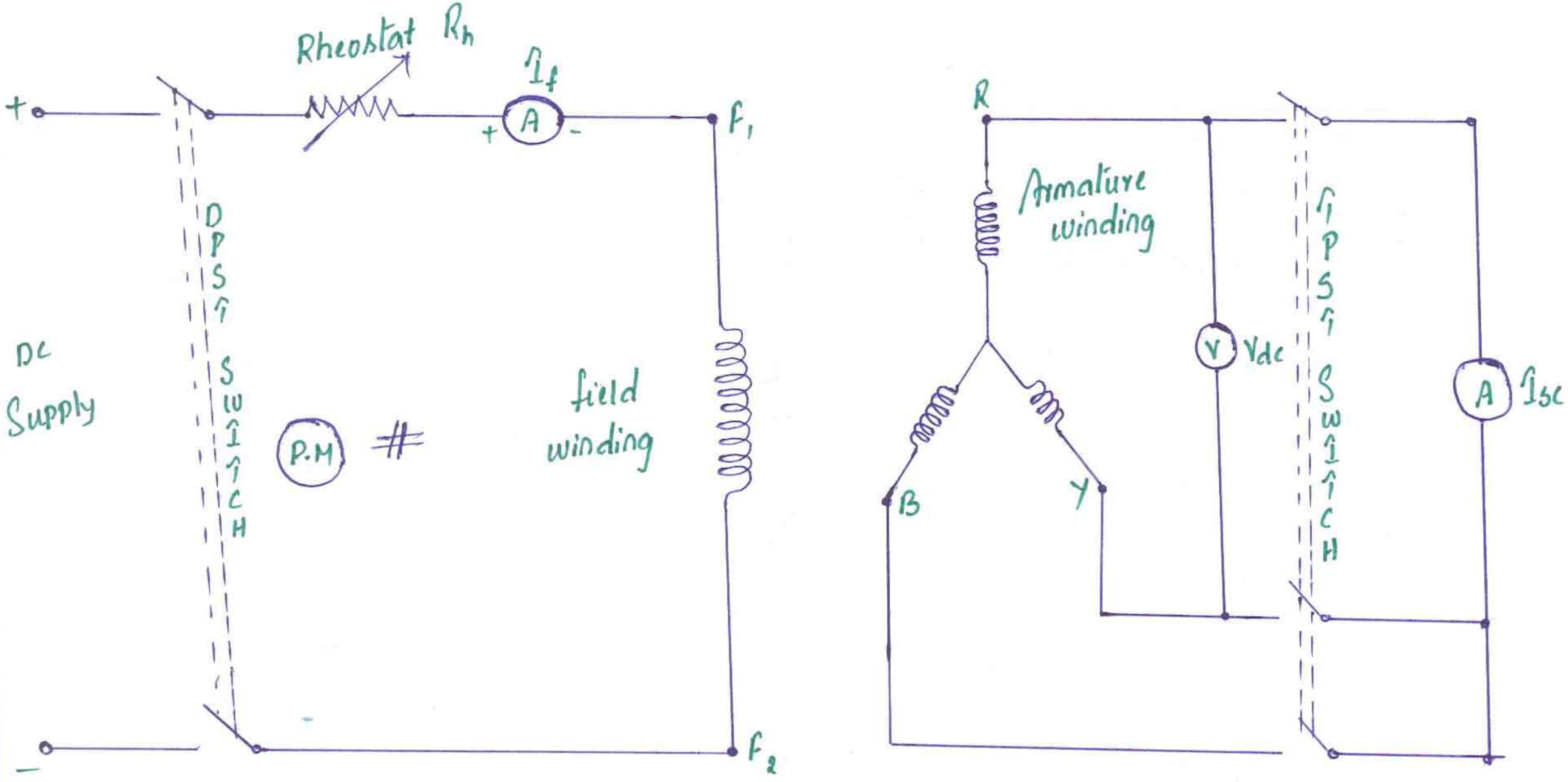
$$\%\ \text{Regulation} = \frac{E_0 - V}{V} \times 100$$

* Load Characteristics of an alternator :-



* It is seen that there is a change in the terminal voltage "V" of alternator with the variations in the load current "I".
* this change in "V" also depends on the load power factor.
* A graph of "V" versus "I" is called load characteristic.
* Different load characteristics can be drawn for different power factors as shown in fig.
* for different load power factors, the nature of load characteristics are as follows
* for lagging power factor, "V" reduces rapidly with increase of load (I) i.e, $V < E_0$
* for unity p.f load, "V" reduces slowly with increase of load (I) i.e, $V < E_0$
* for leading p.f load, "V" increases above "E_0" value as the load current (I) is increased i.e, $V > E_0$
* ∴ the voltage regulation is positive for lagging and unity p.f loads but it is negative for leading p.f loads.

* Regulation By Synchronous impedance method (E.m.f Method)
  * In case of large alternator, its voltage regulation can be determined by synchronous impedance method or Emf Method.
  * the method involves the determination of armature resistance "R_a" per phase & synchronous reactance "X_s" per phase.
* for this purpose, the following tests are conducted on the alternator.



circuit diagram for O.C & S.C Test

* determination of Armature resistance "R_a" per phase by using D.C Measurements i.e, voltmeter & Ammeter method.
* determination of synchronous impedance by performing open-circuit test and short circuit test on the Alternator.
* the above fig: shows the circuit diagram for conducting open circuit & short circuit test.
* the alternator is driven by the prime mover at a synchronous speed.
* its field winding is connected to a D.C supply through a DPST (double pole single throw) switch.
* the field current "I_f" is varied by the series field rheostat & it is measured by D.C. Ammeter.
* the 3ϕ star connected winding is connected to the terminals on one side of a triple pole single throw (TPST) switch.
* A voltmeter is connected across the line terminals of the Armature to measure the open circuit voltage "V_{oc}".
* The terminals on the other side of the TPST switch are short circuited through an ammeter.
* this ammeter measures a short circuit current "I_{sc}" when the TPST switch is closed.

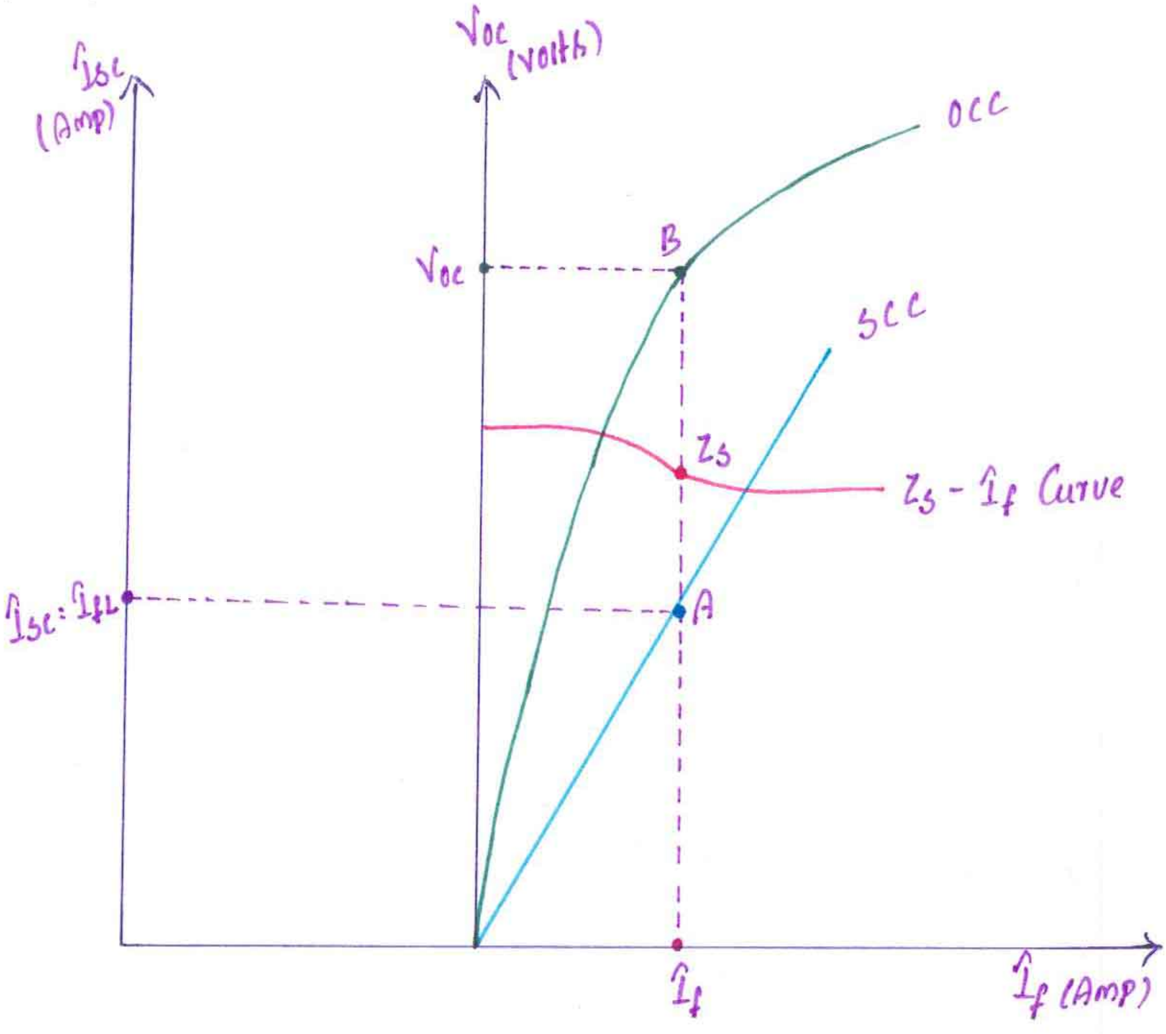
* **Open Circuit test and O.C Characteristics :-**

* Keep DPST & TPST Switches open and drive the alternator at the synchronous speed by its prime mover.
* Keep maximum rheostat "R_h" in the field circuit & close DPST switch, to switch on DC Supply.
* Keeping TPST Switch open, decrease field rheostat "R_h" gradually to increase the field Current "I_f".
* Note down corresponding values of field Current "I_f" & the open circuit armature line voltage "V_{oc}" using ammeter and voltmeter.
* plot the Variations of "V_{oc}" aganist "I_f". this Emf V_{oc} increases with "I_f" due to increase in the flux.
* this Characteristics is Known as open circuit Characteristics
* it is a Curve Similar to B-H Curve as Shown in figure.

* **Short Circuit test and S.C Test Characteristics:**

* Increase field rheostat "R_h" to the Maximum Value at the End of O.C Test & Close TPST Switch.
* Now Voltmeter reading "V_{oc}" will be zero due to Short Circuit the D.C Ammeter reads S.C Current.
* Now reduce rheostat "R_h" to increase field Current "I_f".
* it increases the flux & induced Emf which, in turn is used to increase the Short Circuit Current "I_{sc}".
* Adjust "R_h" Such that $I_{sc} = I_{fL}$ for the Alternator.
* plot the Variations of ammeter reading "I_{sc}" aganist the field Current "I_f" as Shown in fig.
* this Characteristics is Known as Short Circuit Characteristics

* this Characteristics is a stright line passing through origin. so only one reading corresponding to $I_{sc} = I_{FL}$ is sufficient.



* Synchronous impedance Z_s versus I_f curve :-

* during open circuit test the field current "I_f" induces emf or o.c voltage V_{oc} in the Armature.
* during short circuit test, the same field current "I_f" induces emf "V_{oc}" which is utilised to circulate s.c current "I_{sc}" through the synchronous impedance "Z_s" of the Armature.

* thus on per phase basis

$$Z_s = \frac{\text{O.C Emf/ph}}{\text{S.C Current/ph}}$$ for Same field Current

$$\therefore \ Z_s = \frac{(V_{oc})_{ph}}{(I_{sc})_{ph}}$$ for same "I_f"

* In this way by using O.C.C & S.C.C the Synchronous impedance "Z_s" can be determined for various values of "I_f".
* the graph of Z_s versus I_f can be plotted in fig.
* for determination of "Z_s" in full load condition "I_{fL}" take $I_{sc} = I_{f.L}$ on SCC & obtain the corresponding "I_f"
* Now obtain "V_{oc}" Corresponding to this "I_f" on O.C.C.
* then the value of Z_s at full load is given by

$$Z_s = \frac{(V_{oc})_{ph}}{(I_{sc})_{ph}}$$ for Same "I_f" to get $I_{sc} = I_{fL}$

* Determination Of Regulation from Z_S :-

* Armature resistance "R_a" per phase is obtained by Voltmeter - Ammeter Method.

* Synchronous impedance "Z_S" per phase is obtained at the required load condition from O.C.C & S.C.C i.e, from O.C test & S.C test.

* then the Synchronous reactance "X_S" per phase is given by

$$X_S = \sqrt{Z_S^2 - R_a^2} \quad \ldots\ \Omega/ph$$

* No load induced Emf per phase (E_0) is given by

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi \pm IX_S)^2} \quad \ldots \text{ per phase}$$

where all Quantities are per phase Values

* The Voltage regulation is given by

$$\%\ \text{Regulation} = \frac{E_0 - V}{V} \times 100$$

where E_0 and V are per phase Values.