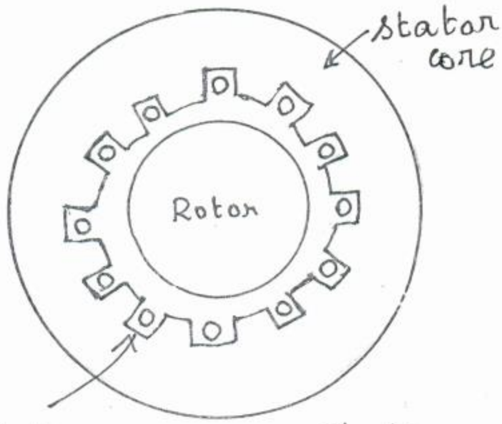
UNIT-I

SYNCHRONOUS GENERATORS

→ Stationary Armature, Rotating Field

→ Stationary Field, Rotating Armature

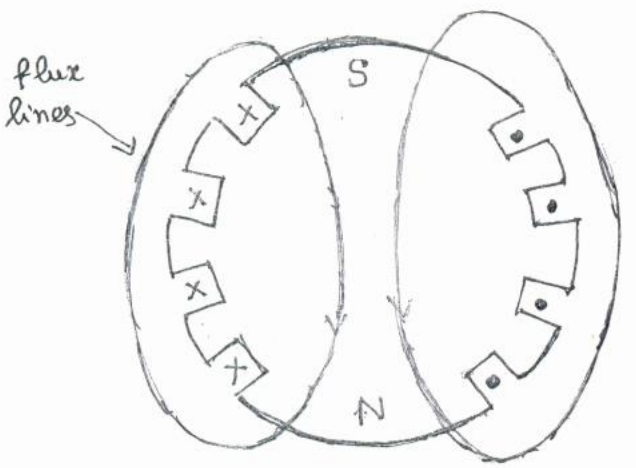
(See page 14 bottom for definition of Synchronous Condenser (This should come unit-2))



- Stationary Armature & Rotating Field -

The stator core is made of silicon steel laminations. The armature conductors are housed in slots. Two conductors form a turn. A coil may consist of one or more turns.

The coils on the stator are connected to form a 3-phase winding. The 3-phase winding can be connected in Y or Δ. The rotor can be a non-salient pole or salient pole construction

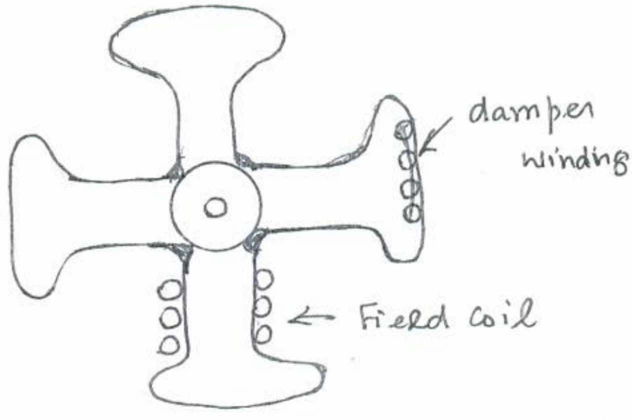


2-pole Non-Salient pole rotor (cylindrical)

Field coils are shown in rotor slots. The poles are not projecting out. The unslotted portions act as poles.

Used in Thermal and Nuclear Stations as <u>turbo alternators</u>.

Large axial length and short diameter since these machines are used with 2 or 4-poles high speed alternators



4-pole salient pole rotor

Field coil and damper winding will be on all the four poles.

Salient pole rotors may have large number of poles suitable for hydro alternators (slow speed) driven by water turbines.

Large diameter and short axial length for machines with large number of poles.

Advantages of stationary Armature Rotating Field over Rotating Armature Stationary Field :-

i) It permits sturdy mechanical bracing of the armature coils and better insulation is possible if the armature conductors are on the stator.

ii) The armature conductors and insulation are not subjected to centrifugal stresses and mechanical vibration.

iii) The high armature voltage in the order of 13 kV and high current can be brought to external circuit through fixed contacts without the need for slip-rings and brush. The low dc voltage of the order of 110 V 230V can be fed to the field winding on the rotor through slip rings and brushes.

EMF Equation

$E = 4.44 \, f \, \phi \, T_{ph} \, K_d \, K_p$

(Learn the derivation of EMF equation)

T_{ph} = Turns in series per phase $= \dfrac{(\text{No. of Conductors per slot} \times \text{No. of slots})}{2 \times 3}$

For example, if the number of slots = 36

conductors / slot = 10

$$T_{ph} = \frac{10 \times 36}{2 \times 3} = 60.$$

K_p: Pitch factor (This is concerning the span of a coil)

Full coil span = 180° $\left(\text{or } \dfrac{\text{number of slots}}{\text{number of poles}}\right)$

For example. For a 36-slot, 4-pole alternator

full span $= \dfrac{36}{4} = 9$ slots $= 180^\circ$

definition: K_p : $\dfrac{\text{Vector sum of the two EMFs in the two sides of a coil}}{\text{Their arithmetic sum}}$

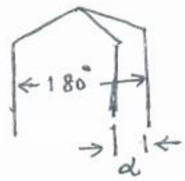
The slot angle, $\beta = \dfrac{180 \times \text{Poles}}{\text{no. of slots}} = \dfrac{180 \times 4}{36} = 20^\circ$

or $\beta = \dfrac{180}{(\text{no. of slot})/\text{pole}} = \dfrac{180}{(36/4)} = 20^\circ$

If the coil span is 6 slots (3 slots less than full pitch)

Actual coil span $= 6 \times 20^\circ = 120^\circ$

$K_p = \sin\left(\dfrac{120}{2}\right) = 0.866$



Learn the derivation

OR

Angle of short pitch $= 3 \times 20^\circ = 60^\circ = \alpha$

$K_p = \cos\left(\dfrac{\alpha}{2}\right) = \cos\left(\dfrac{60}{2}\right) = 0.866$

OR

$K_p = \cos\dfrac{(180 - \text{actual span})}{2} = \cos\left(\dfrac{180-120}{2}\right) = 0.866$

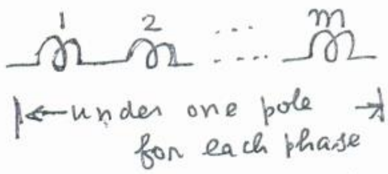
defition: $K_d = \dfrac{\text{Vector sum of 'm' EMFs of the adjacent coils of a phase under each pole}}{\text{Their Arithmetic sum}}$

K_d: distribution factor

This factor is to account the phase difference the induced EMFs of adjacent coil sides of the various coils of one phase under one pole.

m = No. of coils per pole per phase

$K_d = \dfrac{\sin(m\,\beta/2)}{m \sin \beta/2}$ Learn the derivation



Ex:

For a 72 slot 4-pole 3-phase alternator.

$m = \dfrac{72}{4 \times 3} = 6$

$\beta = \dfrac{180 \times 4}{72} = 10^\circ$ (or) $\beta = \dfrac{180}{(72/4)} = 10^\circ$

Example in EMF Calculation

A 3-phase, 8-pole alternator has 72 slots on the armature (stator). Each slot contains 14 conductors. It is driven at 750 RPM. The flux per pole is 29.73 mWb. Calculate the phase and line induced EMFs if i) alternator is star connected ii) delta connected. Assume the coil span = 7 slots.

Soln: $f = \frac{PN_s}{120} = \frac{8 \times 750}{120} = 50$ Hz

The slot angle $\beta = \frac{P \times 180}{\text{No. of slots}} = \frac{8 \times 180}{72} = 20^\circ$

Coil span $= 7 \times 20^\circ = 140^\circ$

$\therefore k_p = \sin\left(\frac{140}{2}\right) = \underline{0.94}$ (or) $\cos\frac{(180-140)}{2} = 0.94$

$m = \frac{\text{No. of slots}}{P \times \text{No. of phases}} = \frac{72}{8 \times 3} = 3$

$k_d = \frac{\sin(m\beta/2)}{m \sin\beta/2} = \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3\sin\left(\frac{20}{2}\right)} = \underline{0.9596}$

T_{ph} = Turns in series per phase $= \frac{(\text{No. of conductors/slot}) \times \text{No. of slots}}{2 \times 3}$

$= \frac{14 \times 72}{6} = 168$

$\phi = 29.73$ mWb $= 29.73 \times 10^{-3} = 0.02973$ Wb

Phase voltage

$E_p = 4.44 f \phi T_{ph} k_d k_p$

$= 4.44 \times 50 \times 0.02973 \times 168 \times 0.9596 \times 0.94$

$= 1000$ V /phase

i) If the alternator is star connected

$$E_L = \text{Line Voltage} = \sqrt{3}\, E_p = \sqrt{3} \times 1000 = 1732 \text{ V}$$

ii) If the alternator is delta connected

$$E_L = E_p = 1000 \text{ V}$$

Harmonics

The induced EMF in the alternator will be sinusoidal only if the field flux distribution in the air gap is sinusoidal. If the space flux distribution is not sinusoidal, corresponding induced EMF will also be non-sinusoidal, will contain harmonics. For example in a 4-pole, 1500 rpm alternator ($f = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50$ Hz), if there is a 3rd harmonic flux density, then the induced EMF will have a $3 \times 50 = 150$ Hz component.

The distribution of coils reduces this EMF harmonic component. The coil pitch can also be chosen to reduce or eliminate a harmonic EMF.

The distribution of coils also gives a lower leakage reactance for the winding and better distribution of heat in the armature coils leading to better cooling effect.

Armature Leakage Reactance

Flux linking only armature conductors (due to load current or armature current) and not linking the field winding causes Armature leakage reactance:

The components of armature leakage reactance are:

i) Slot leakage reactance (X_s)

ii) End winding or overhang leakage reactance (X_e)

iii) Tooth tip reactance (X_t)

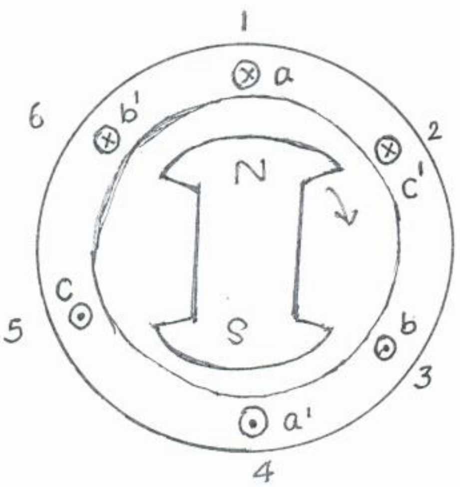
$$X_\ell = X_s + X_e + X_t$$

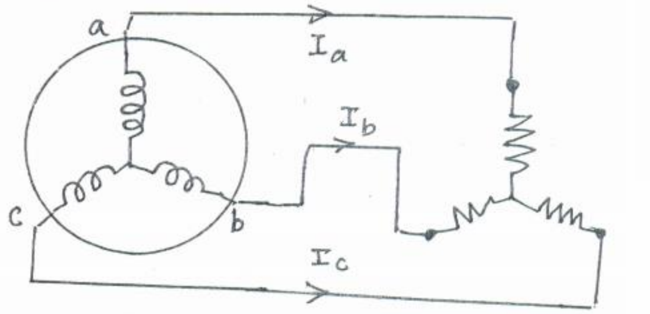
X_ℓ causes a voltage drop, when the alternator is loaded.

Read your assignment Note book

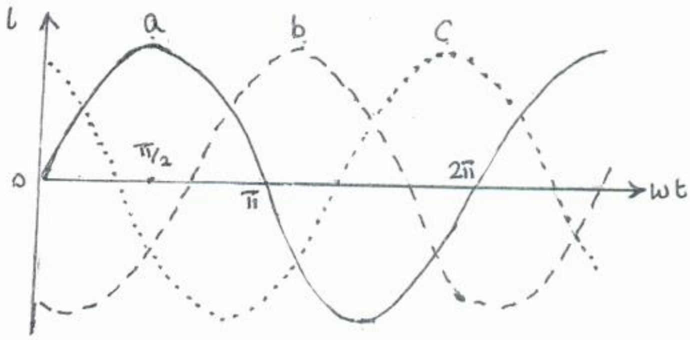
Armature Reaction in 3-phase Alternators

Armature reaction is the MMF (Magnetomotive force) produced by the armature current flowing in the armature conductors. Let us assume for the sake of simplicity, a 3-phase, 2-pole winding in a minimum number of 6 stator slots.





alternator supplying UPF load



3-phase current wave form

At the instant of the poles shown, (t_1) a-phase EMF will be maximum.

$i_a = I_m \sin \omega t$

$i_b = I_m \sin(\omega t - 120^\circ)$

$i_c = I_m \sin(\omega t - 240^\circ)$

Let us first assume

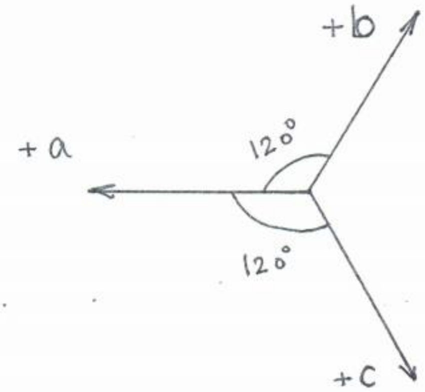
UPF Load

For UPF load when EMF is maximum, the corresponding a-phase current will be maximum, i.e., $i_a = I_m$ and $\omega t = 90^\circ$. Starting from this, let us consider $\omega t = 180^\circ, 270^\circ, 360^\circ$. At each of these instants, the instantaneous values of the 3-phase currents will be as follows:

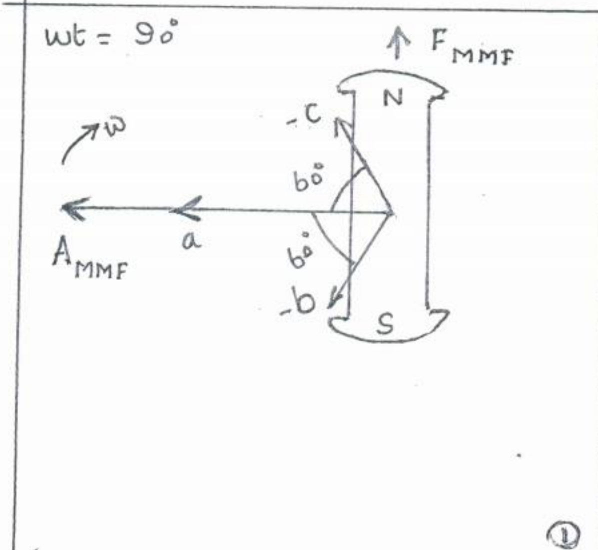
ωt	i_a	i_b	i_c	ωt	i_a	i_b	i_c
90°	I_m	$-\frac{I_m}{2}$	$-\frac{I_m}{2}$	270°	$-I_m$	$\frac{I_m}{2}$	$\frac{I_m}{2}$
180°	0	$\frac{\sqrt{3}}{2} I_m$	$-\frac{\sqrt{3}}{2} I_m$	360°	0	$-\frac{\sqrt{3}}{2} I_m$	$\frac{\sqrt{3}}{2} I_m$

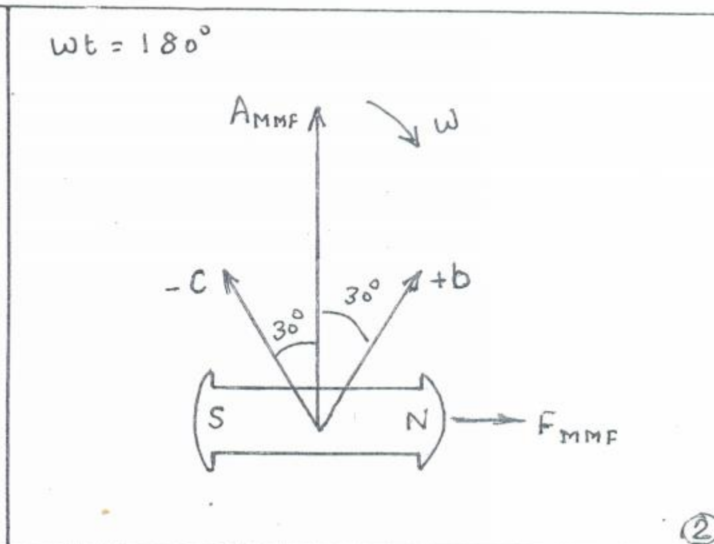
The cycle then repeats

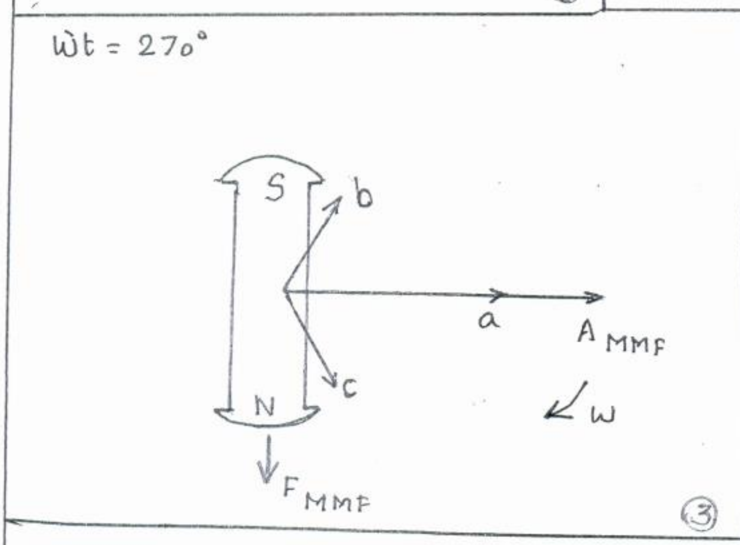
Each phase carrying the sinusoidal current produces a pulsating MMF along its own axis, the magnitude of the MMF being proportional to current. At any instant, the resultant of all the three-phase MMFs should be taken. The positive directions of a, b, c phase MMFs are shown below:

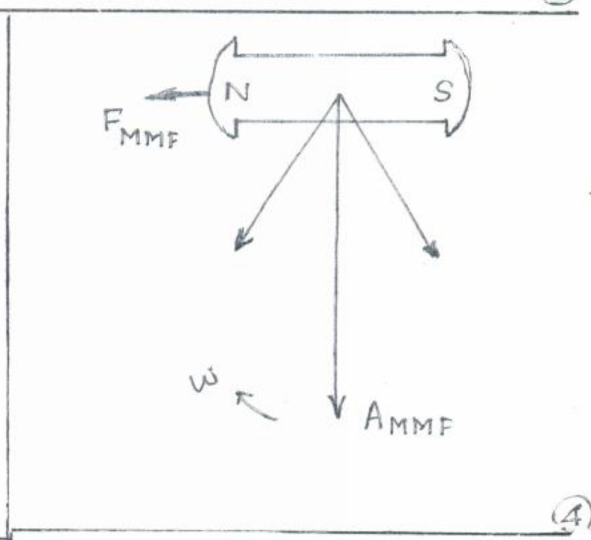


During the negative half cycle of the phase current, the corresponding MMF will be in the opposite direction. Thus at ωt = 90, 180, 270 & 360, the a, b and c phase MMFs and their resultant are shown below for UPF:









Each phase MMF at any instant = Corresponding instantaneous current $\times T_{ph}$

Thus we note two points :-

i) The resultant Armature MMF (A_{MMF}) of all the three phases = $1.5\ I_m T_{ph}$

ii) A_{MMF} rotates at synchronous speed (same speed as the rotor.

For UPF A_{MMF} is behind the Field MMF (F_{MMF}) by 90°

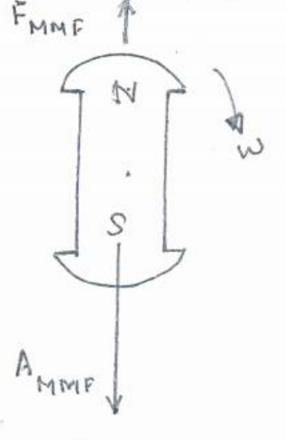
So A_{MMF} has a cross magnetising effect.

For 0 lag PF the current will lag by 90°, and so the A_{MMF} will be behind by 90° with respect to UPF position

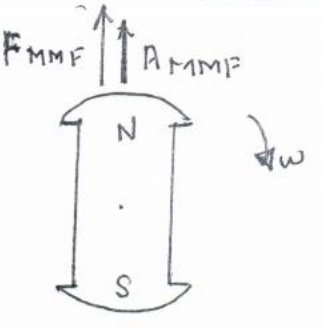
So A_{MMF} is demagnetising, the Field MMF

For 0 lead PF the current will lead by 90° and so the A_{MMF} will be ahead by 90° with respect to UPF position

So A_{MMF} will be magnetising, the Field MMF



0 lag PF



0 lead PF

For any other lag PF (Ex: 0.8 lag), A_{MMF} will be partly demagnetising and partly cross magnetising

For any other lead PF (Ex 0.8 lead), A_{MMF} will be partly magnetising and partly cross magnetising

So with lagging PF loads, the field current has to be increased to maintain the rated terminal voltage and with leading PF loads, the field current may have to be decreased to maintain the rated terminal voltage.

The nature of armature reaction is such that it produces changes in terminal voltage very much similar to that produced by leakage reactance. So the armature reaction is represented by an equivalent fictious reactance (X_a) and combined with X_ℓ. and called Synchronous Reactance X_s; in non-salient pole machines.

Thus $X_s = (X_a + X_\ell)$.

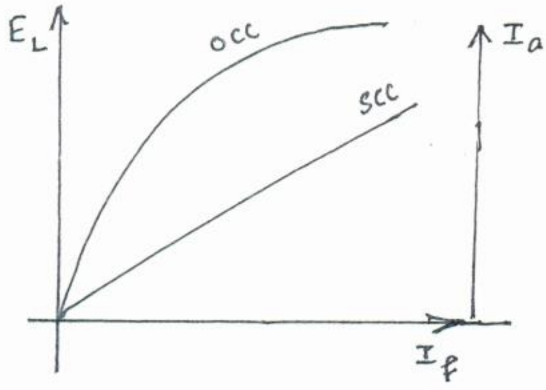
Regulation of Alternators

Regulation of alternator is defined as the change in terminal voltage, when a given load (current magnitude and Power factor to be specified) is thrown off. The given load should have been supplied at rated voltage and frequency.

$$\% \text{ Reg} = \frac{E - V}{V} \times 100$$

Both E and V should be phase voltages or both Line voltages

Voltage Regulation by Synchronous Impedance Method.



$$Z_s = \frac{\text{open circuit Voltage per phase}}{\text{Corresponding short circuit current}}$$

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

Example: A 100 KVA, 3000 V, 50 Hz, 3-phase star connected alternator has $R_a = 0.5\ \Omega$. A field current of 50 A produces a short circuit current of 30 A and an open circuit EMF of 1300 V (line value).

Calculate the full load voltage regulation at 0.8 PF lag and 0.8 PF lead. Draw the phasor diagram.
(Ans: 11.2 %, −8.54 %)

Soln:

$$Z_s = \frac{\text{OC Voltage/phase}}{\text{SC current/phase}} = \frac{1300/\sqrt{3}}{50} = \underline{15.0\ \Omega}$$

$$X_s = \sqrt{15^2 - 0.5^2} = \underline{14.99\ \Omega}$$

$$I_{a\ \text{full load}} = \frac{\text{KVA} \times 10^3}{\sqrt{3}\ V_L} = \frac{100 \times 10^3}{\sqrt{3} \times 3000} = \underline{19.24\ \text{A}}$$

V = Rated phase voltage

0.8 lag

$$E_p = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$$

$$= \sqrt{\left(\frac{3000}{\sqrt{3}} \times 0.8 + 19.24 \times 0.5\right)^2 + \left(\frac{3000}{\sqrt{3}} \times 0.6 + 19.24 \times 14.99\right)^2}$$

$$= \underline{1926\ \text{V}}$$

OR

$$E_p = V\angle 0 + I_a \angle{-\phi}\ (R_a + jX_s)$$

$$= \frac{3000}{\sqrt{3}}\angle 0 + 19.24\angle{-36.87}\ (15.0\angle 88.1)$$

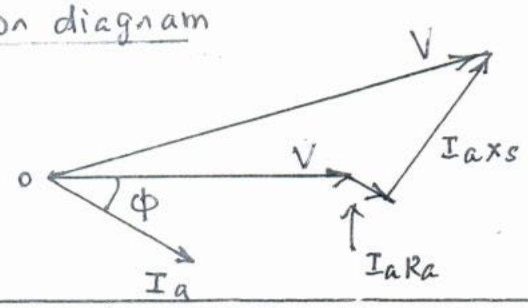
$$= 1732\angle 0 + 288.6\angle 51.23 = 1912.7 + j225$$

$$= \underline{1926\angle 6.71^\circ}\ \text{V}, \quad E_L = \sqrt{3} \times 1926 = 3336\ \text{V}$$

$$\text{Regulation} = \frac{E-V}{V} \times 100 = \frac{E_p - V}{V} \times 100 = \frac{1926 - 1732}{1732} \times 100$$

$$= \underline{11.20\ \%}$$

Phasor diagram



Similar calculations can be made for 0.8 lead PF.