SNS COLLEGE OF ENGINEERING

Kurumbapalayam (Po), Coimbatore – 641 107

AN AUTONOMOUS INSTITUTION

Approved by AICTE, New Delhi and Affiliated to Anna University, Chennai

INTERNAL ASSESSMENT EXAMINATION – I ANSKER KEY

IV Semester

B.E – Electrical and Electronics Engineering

23EEB203 – Synchronous and Induction Machines

Regulations 2023

Duration : 1 Hour 30 Minutes

Date : 07.03.2025 Session: FN Maximum: 50 Marks

Answer ALL questions

	PART A - (5 X 2 = 10 marks)
Q.No	**Question**
1.	**State any four advantages of rotating field and stationary armature.** Easier insulation of high-voltage windings, simpler maintenance due to fewer slip rings, greater flexibility in rotor speed, and more efficient cooling.
2.	**Calculate the distribution factor for a 36 slots, 4 pole, single layer three phase winding of an alternator.** Step 1: Compute Slots per Pole $\text{Slots per pole} = \frac{\text{Total slots}}{\text{Poles}} = \frac{36}{4} = 9$ Step 2: Compute Slots per Pole per Phase $m = \frac{\text{Slots per pole}}{\text{Phases}} = \frac{9}{3} = 3$ Step 3: Compute Slot Angle β $\beta = \frac{180^\circ}{\text{Slots per pole}} = \frac{180^\circ}{9} = 20^\circ$ Step 4: Compute Distribution Factor K_d $K_d = \frac{\sin\left(\frac{3\times 20^\circ}{2}\right)}{3\sin\left(\frac{20^\circ}{2}\right)}$ $K_d = \frac{\sin(30^\circ)}{3\sin(10^\circ)}$ $K_d = \frac{0.5}{3\times 0.1736} = \frac{0.5}{0.5208} \approx 0.96$
3.	**Why alternators are rated in kVA and not in kW?** The kVA rating represents the apparent power, which takes into account both the voltage and current, and is a better indicator of the maximum capacity of the alternator regardless of the load's power factor, while kW only measures the real power which depends on the load connected to it.

4.	**Why a synchronous motor is called as constant speed motor?** Its rotor is designed to rotate at precisely the same speed as the rotating magnetic field generated by the stator, known as the synchronous speed, regardless of the load.
5.	**How the synchronous motor made self-starting?** Synchronous motors are inherently not self-starting, but a damper or squirrel-cage winding embedded in the rotor poles allows them to start as an induction motor, enabling them to "pull into synchronism" once reaching near synchronous speed.

PART B - (2 X 13 = 26 marks)

6. (a) **Two identical 2000 kVA alternators operate in parallel. The governor of the prime mover of first machine is such that the frequency drops uniformly from 50 Hz on load to 48 Hz on full load. The corresponding uniform speed drop of the second machine is 50 Hz to 47.5 Hz. Find (i) How will the two machines share a load of 3000 kW? (ii) What is the maximum load of unity p.f. that can be delivered without overloading either machine?**

Line PQ is drawn for machine 1 while line PR is drawn for machine 2. At any load the frequency of the two machines must be same. A line AB is drawn at a frequency x measured from point P. Total load at this frequency is given as 3000 kW.

$$\therefore \quad AC + CB = 3000$$

Using the similarly of the triangles PAC and PQS

$$\frac{AC}{QC} = \frac{PC}{PS} \quad \text{i.e.} \quad \frac{AC}{2000} = \frac{x}{2.5} \quad \text{i.e} \quad AC = \frac{2000\,x}{2.5} = 800\,x$$

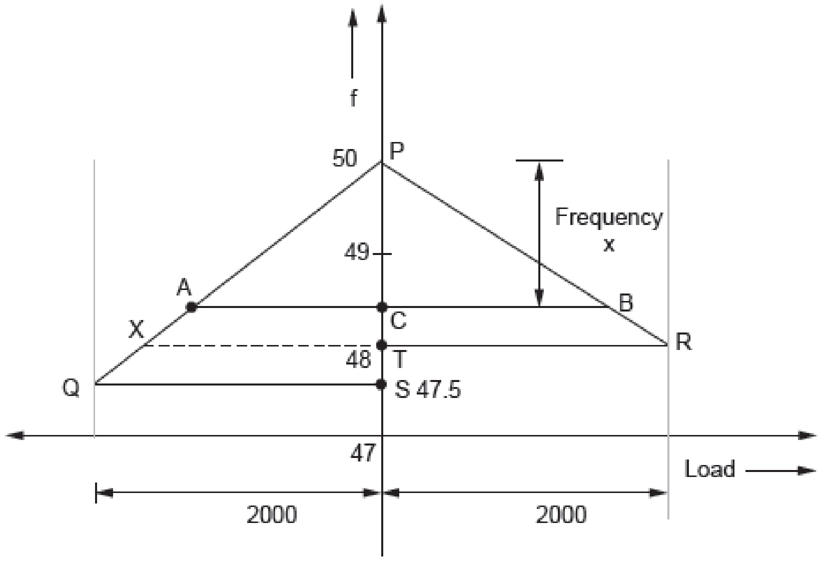


Fig. 3.15.6

Similarly using the similarity of the triangles PCB and PTR

$$\frac{CB}{TR} = \frac{PC}{PT} \quad \text{i.e} \quad \frac{CB}{2000} = \frac{x}{2} \quad \text{i.e.} \quad CB = \frac{2000\,x}{2} = 1000\,x$$

Using $\quad AC + CB = 3000 \quad$ i.e. $\quad 800x + 1000x = 3000 \quad$ i.e. $\quad x = 1.66$ Hz

$\therefore \quad$ Frequency $= 50 - x = 50 - 1.66 = 48.33$ Hz

i) Assuming load to be of unity p.f.

Load shared by machine 1 $= AC = 800\,x = 800 \times 1.666 = \approx 1333$ kW

Load shared by machine 2 $= BC = 1000\,x = 1000 \times 1.666 \approx$ **1667 kW**

ii) For finding the maximum load line RT is extended to cut PQ at point X. So maximum load is RX.

Using similarity of triangles PQS and PXT

$$\frac{XT}{QS} = \frac{PT}{PS}$$

$$XT = QS \cdot \frac{PT}{PS} = 2000 \ \frac{2}{2.5} = 1600 \text{ kW}$$

$$\text{Maximum load} = RX = RT + XT = 2000 + 1600 = \mathbf{3600\ kW}$$

OR

(b) **Explain the construction and working principle of synchronous generator with neat diagram. Also derive the EMF equation.**

- A synchronous generator is a synchronous machine which converts mechanical power into AC electric power through the process of electromagnetic induction.
- Synchronous generators are also referred to as alternators or AC generators.
- The term "alternator" is used since it produces AC power.
- It is called synchronous generator because it must be driven at synchronous speed to produce AC power of the desired frequency.
- A synchronous generator can be either single-phase or poly-phase (generally 3phase).

Construction:

As alternator consists of two main parts viz.

- **Stator** − The stator is the stationary part of the alternator. It carries the armature winding in which the voltage is generated. The output of the alternator is taken form the stator.
- **Rotor** − The rotor is the rotating part of the alternator. The rotor produces the main field flux.

(a) Stator:

The stator of the alternator includes several parts, viz. the frame, stator core, stator or armature windings, and cooling arrangement.

- The stator frame may be made up of cast iron for small-size machines and of welded steel for large-size machines.
- The stator core is assembled with high-grade silicon content steel laminations. These silicon steel laminations reduce the hysteresis and eddy-current losses in the stator core.
- The slots are cut on the inner periphery of the stator core. A 3-phase armature winding is put in these slots.
- The armature winding of the alternator is star connected. The winding of each phase is distributed over several slots. When current flows through the distributed armature winding, it produces an essential sinusoidal space distribution of EMF.

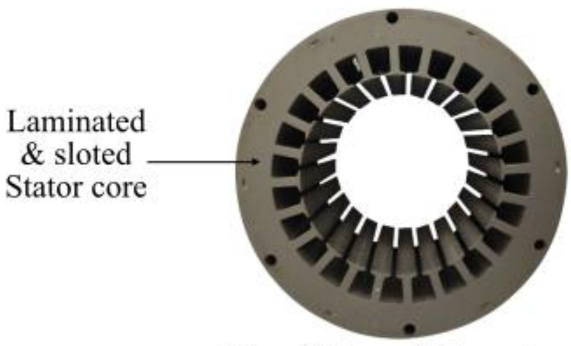


Fig. - Stator of Alternator

(b) Rotor:

- The rotor of the alternator carries the field winding which is supplied with direct current through two slip rings by a separate DC source (also called exciter).
- The exciter is generally a small DC shunt generator mounted on the shaft of the alternator.
- For the alternator, there are two types of rotor constructions are used viz. **the salient-pole type** and **the cylindrical rotor type**.

(i) Salient Pole Rotor:

- The term salient means projecting.
- Hence, a salient pole rotor consists of poles projecting out from the surface of the rotor core.
- This whole arrangement is fixed to the shaft of the alternator.
- The individual field pole windings are connected in series such that when the field winding is energised by the DC exciter, the adjacent poles have opposite polarities.

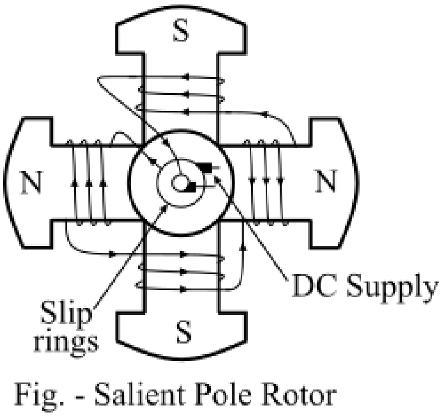


Fig. - Salient Pole Rotor

The salient pole type rotor is used in the low and medium speed (from 120 to 400 RPM) alternators such as those driven by the diesel engines or water turbines because of the following reasons −

- The construction of salient pole type rotor cannot be made b enough to withstand the mechanical stresses to which they may be subjected at higher speed.
- If the salient field pole type rotor is driven at high speed, then it would cause windage

loss and would tend to produce noise.

Low speed rotors of the alternators possess a large diameter to provide the necessary space for the poles. As a result, the salient pole type rotors have large diameter and short axial length.

(ii) Cylindrical Rotor:

The cylindrical rotors are made from solid forgings of high-grade nickel-chrome-molybdenum steel.

- The construction of the cylindrical rotor is such that there are no-physical poles to be seen as in the salient pole rotor.
- In about two-third of the outer periphery of the cylindrical rotor, slots are cut at regular intervals and parallel to the rotor shaft.
- The field windings are placed in these slots and is excited by DC supply. The field winding is of **distributed type**.
- The unslotted portion of the rotor forms the pole faces.
- It is clear from the figure of the cylindrical rotor that the poles formed are non-salient, i.e., they do not project out from the rotor surface.

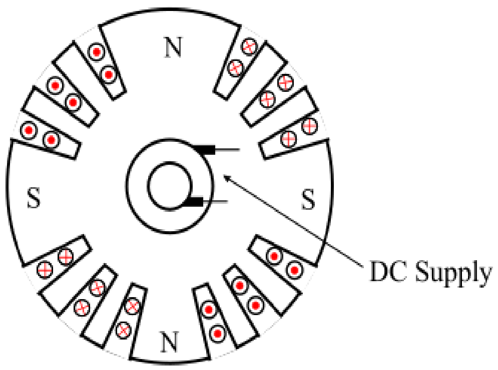


Fig. - Cylindrical Rotor

The cylindrical type rotor construction is used in the high-speed (1500 to 3000 RPM) alternators such as those driven by steam turbines because of the following reasons −

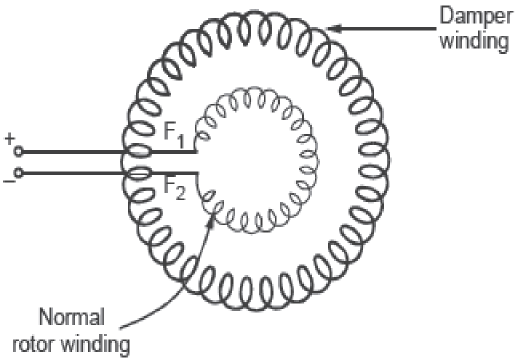
- The cylindrical type rotor construction provides a greater mechanical strength and permits more accurate dynamic balancing.
- It gives noiseless operation at high speeds because of the uniform air gap.
- The flux distribution around the periphery of the rotor is nearly a sine wave and hence a better EMF waveform is obtained.

A cylindrical rotor alternator has a comparatively small diameter and long axial length. The cylindrical rotor alternators are called **turbo-alternators** or **turbo-generators**. The alternator with cylindrical rotor have always horizontal configuration installation.

Working Principle and Operation:

- An alternator or synchronous generator works on the principle of electromagnetic induction, i.e., when the flux linking a conductor changes, an EMF is induced in the conductor.

		➢ When the armature winding of alternator subjected to the rotating magnetic field, the voltage will be generated in the armature winding. ➢ When the rotor field winding of the alternator is energised from the DC exciter, the alternate N and S poles are developed on the rotor. ➢ When the rotor is rotated in the anticlockwise direction by a prime mover, the armature conductors placed on the stator are cut by the magnetic field of the rotor poles. ➢ As a result, the EMF is induced in the armature conductors due to electromagnetic induction. ➢ This induced EMF is alternating one because the N and S poles of the rotor pass the armature conductors alternatively. ➢ The direction of the generated EMF can be determined by the Fleming's right rule and the frequency of it is given by, $f = \frac{N_s P}{120}$ ➢ The magnitude of the generated voltage depends upon the speed of rotation of the rotor and the DC field excitation current. ➢ For the balanced condition, the generated voltage in each phase of the winding is the same but differ in phase by 120° electrical.
7.	(a)	**List the various starting methods of a synchronous motor and explain in detail.** ➢ Synchronous Motor is Not self Starting. ➢ It is necessary to rotate the rotor at a speed very near to synchronous speed. ➢ This is possible by various methods in practice. The various methods to start the synchronous motor are, **(i) Using Pony motors** ➢ In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. ➢ Such an external device is called 'Pony Motor'. ➢ Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. ➢ Once the synchronism is established pony motor is decoupled. ➢ The motor then continues to rotate as a synchronous motor. **(ii) Using Damper Winding** ➢ In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. ➢ The bars are short circuited with the help of end rings. ➢ Such an additional winding on the rotor is called damper winding. ➢ This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor.



- Once the stator is excited by a three phase supply, the motor starts rotating as an induction motor at sub synchronous speed.
- Then d.c. supply is given to the field winding.
- At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed.
- As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero.
- Hence when motor is running as synchronous motor, there cannot be any induced e.m.f. in the damper winding.
- So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit.
- As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

(iii) As a Slip ring induction motor

- The above method of starting synchronous motor as a squirrel cage induction motor.
- A squirrel cage induction motor does not provide high starting torque.
- So to achieve this, instead of shorting the damper winding, it is designed to a from a three phase star or delta connected winding.
- The three ends of this winding are brought out through slip rings.
- An external rheostat then can be introduced in series with the rotor circuit.
- So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque.
- The resistance is then gradually cut off, as motor gathers speed.
- When motor attains speed near synchronous. d.c. excitation is provided to the rotor, then motors gets pulled into synchronism and starts rotating at synchronous speed.
- The damper winding is shorted by shorting the slip rings.
- The initial resistance added in the rotor not only provides high starting torque but also limits high in rush of starting current.
- Hence it acts as a motor resistance starter.

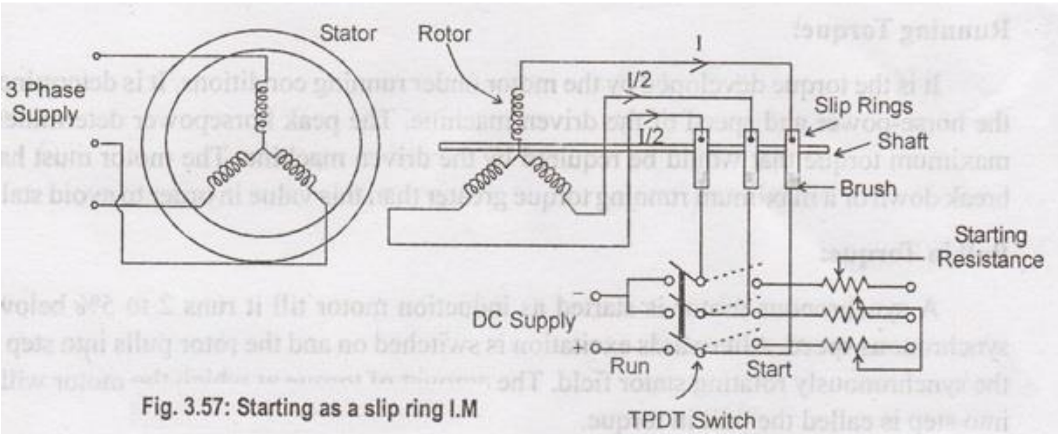


Fig. 3.57: Starting as a slip ring I.M

(iv) Using small dc machines coupled to it

- Many a times, a large synchronous motor are provided with a coupled d.c. machine.
- This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed.
- Then the excitation to the rotor is provided.
- Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter.
- The field of the synchronous motor is then excited by this exciter itself.

OR

(b) **Describe the effect of changing field current excitation at constant load and following variable excitation. (i) Under excitation (ii) Normal excitation (iii) Over Excitation.**

(i) Under excitation

When the excitation is adjusted in such a way that the magnitude of induced e.m.f. is less than the applied voltage ($E_b < V$) the excitation is called Under excitation.

Due to this, E_R increases in magnitude. This means for constant Z_s, current drawn by the motor increases. But E_R phase shifts in such a way that, phasor I_a also shifts (as $E_R \wedge I_a = \theta$) to keep $I_a \cos\phi$ component constant. This is shown in the Fig. 4.10.1 (b). So in under excited condition, current drawn by the motor increases. The p.f. $\cos\phi$ decreases and becomes more and more lagging in nature.

(ii) Over excitation

The excitation to the field winding for which the induced e.m.f. becomes greater than applied voltage ($E_b > V$), is called over excitation.

Due to increased magnitude of E_b, E_R also increases in magnitude. But the phase of E_R also changes. Now $E_R \wedge I_a = \theta$ is constant, hence I_a also changes its phase. So ϕ changes. The I_a increases to keep $I_a \cos\phi$ constant as shown in Fig. 4.10.1 (c). The phase of E_R changes so that I_a becomes leading with respect to V_{ph} in over excited condition. So power factor of the motor becomes leading in nature. So overexcited synchronous motor works on leading power factor. So power factor decreases as over excitation increases but it becomes more and more leading in nature.

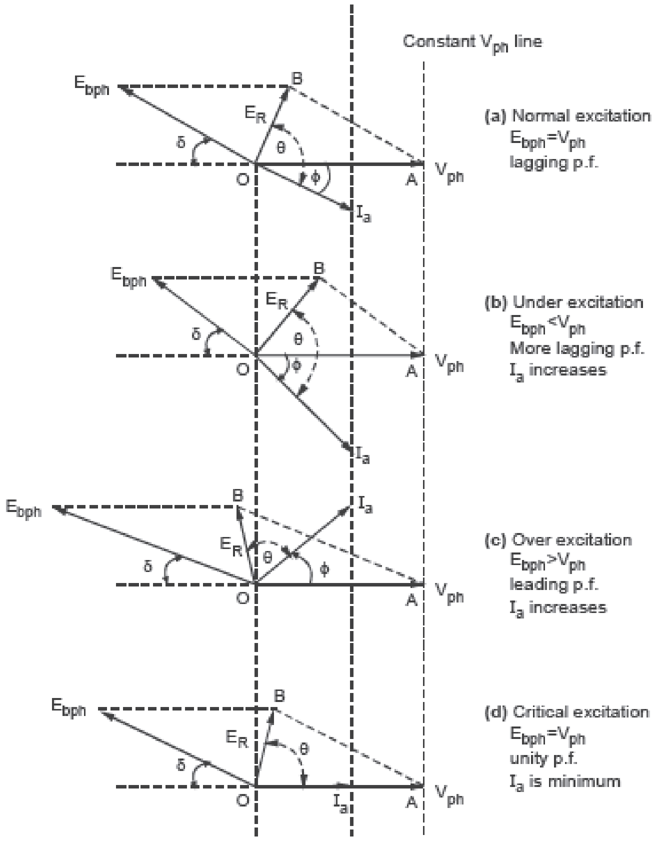


Fig. 4.10.1 Constant load variable excitation operation

		(iii) Normal Excitation

When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity ($\cos \phi = 1$) is called critical excitation. Then I_{aph} is in phase with V_{ph}. Now $I_a \cos \phi$ must be constant, $\cos \phi = 1$ is at its maximum hence motor has to draw minimum current from supply for unity power factor condition.

So for critical excitation, $\cos \phi = 1$ and current drawn by the motor is minimum compared to current drawn by the motor for various excitation conditions. This is shown in the Fig. 4.10.1 (d).

Under excitation	Lagging p.f.	$E_b < V$
Over excitation	Leading p.f.	$E_b > V$
Critical excitation	Unity p.f.	$E_b \cong V$
Normal excitation	Lagging	$E_b = V$

PART C –(1 x 14 = 14 Marks)

8. (a) **The open and short circuit test readings for a 3 phase star connected, 1000 kVA, 2000 V, 50 Hz synchronous generator are**

Open Circuit terminal Voltage $(V_{oc})_{line}$ Volts	800	1500	1760	2000	2350	2600
Short circuit I_{sc} (A)	-	200	250	300	-	-
Field amps (I_f)	10	20	25	30	40	50

The armature effective resistance is 0.2 Ω per phase. Draw the characteristics curves and estimate full load percentage regulation (a) 0.8 p.f. lagging (b) 0.8 p.f. leading. Use M.M.F Method.

Field current I_F (A)	10	20	25	30	40	50
Open circuit terminal voltage (V)	461.88	866.02	1016.13	1154.70	1356.77	1501.11
Short circuit I_{sc} (A)	–	200	250	300	–	–

Now, $$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{2000}{\sqrt{3}} = 1154.70 \text{ V}$$

$R_a = 0.2\,\Omega, \quad \cos\phi = 0.8, \quad \sin\phi = 0.6$

As R_a is given, F_O is field current to obtain the voltage equal to $V_{ph} + I_{aph} R_a \cos\phi$.

where I_{aph} = Full load armature current per phase

$$kVA = \sqrt{3} \times V_L \times I_L$$

$$\therefore \quad 1000 \times 10^3 = \sqrt{3} \times 2000 \times I_L$$

$$\therefore \quad I_L = 288.67 \text{ A}$$

$$I_{aph} = I_L = 288.67 \text{ A} \quad \text{...As star connection}$$

$$\therefore V_{ph} + I_{aph} R_a \cos\phi = 1154.70 + (288.67)(0.2)(0.8) = 1200.8872 \text{ volts}$$

Find F_O corresponding to voltage of 1200.88 V from O.C.C.

So $F_O = 32.5$ A

While F_{AR} is field current required to circulate full load short circuit current of 288.67 so obtain it from S.C.C.

$\therefore \quad F_{AR} = 29.5$ A

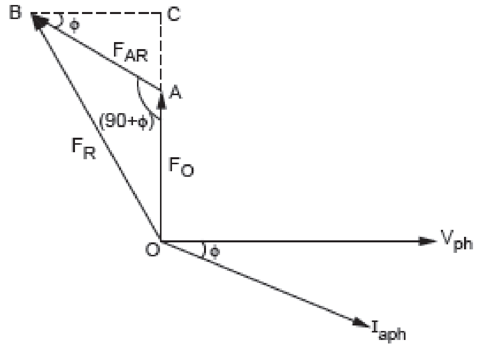


Fig. 2.14.9

For lagging power factor the phasor diagram is shown in Fig. 2.14.9.

From triangle OCB,

$$(F_R)^2 = (F_O + F_{AR}\sin\phi)^2 + (F_{AR}\cos\phi)^2$$

$$= (32.5 + 29.5 \times 0.6)^2 + (29.5 \times 0.8)^2 = (2520.04) + (556.96)$$

$$= 3077$$

$$\therefore \quad F_R = 55.47 \text{ A}$$

Now obtain E_{ph} corresponding to F_R = 55.47 A of field current from O.C.C.

For F_R = 55.47, E_{ph} = 1560 V from graph shown in the Fig. 2.14.11.

$$\therefore \quad \%\text{ Reg.} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$= \frac{1560 - 1154.70}{1154.70} \times 100$$

$$= \mathbf{35.10\ \%}$$

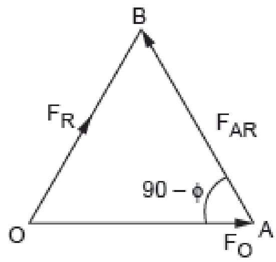
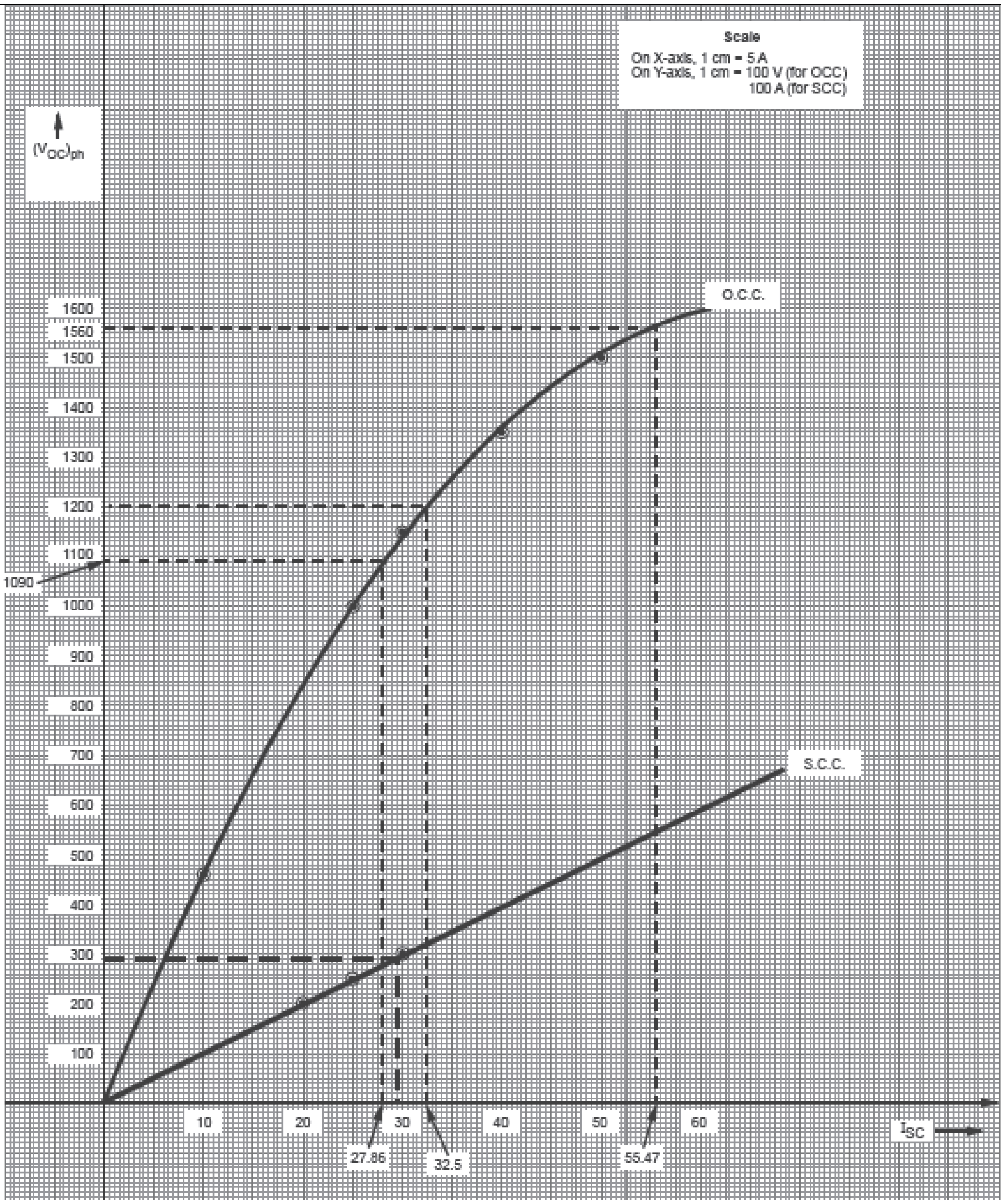


Fig. 2.14.10

For 0.8 p.f. leading, F_R can be obtained as follows.

$$\cos\phi = 0.8, \quad \phi = 36.86°$$



$$90 - \phi = 90 - 36.86 = 53.14°$$

Using cosine rule to triangle OAB

$$F_R^2 = F_O^2 + F_{AR}^2 - 2F_O F_{AR} \cos(53.14°)$$

$$= (32.5)^2 + (29.5)^2 - 2(32.5)(29.5)(0.6)$$

$\therefore$ $F_R = 27.86$ A

For $F_R = 27.86$ A, $E_{ph} = 1090$ V from graph

Refer Fig. 2.14.11.

$$\% \text{ Reg} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100 = \frac{1090 - 1154.70}{1154.70} \times 100$$

$\therefore$ Reg = **– 5.6031 %**

OR		
	(b)	**A salient pole alternator has direct axis and quadrature axis reactance of 0.8 p.u. and 0.5 p.u. respectively. The effective resistance is 0.02 p.u. Compute percentage regulation when the generator is delivering rated at 0.8 p.f. lag and lead. Assume rated voltage and rated current as one per unit.**

Solution : $X_d = 0.8$ p.u., $X_q = 0.5$ p.u., $R_a = 0.02$ p.u.

Case 1) $\cos\phi = 0.8$ lag, $\phi = 36.86°$

$V_t = 1$ p.u. and I_a full load $= 1$ p.u.

$$\tan\psi = \frac{V_t \sin\phi + I_a X_q}{V_t \cos\phi + I_a R_a} = \frac{1\times 0.6 + 1\times 0.5}{1\times 0.8 + 1\times 0.02} = 1.3414 \quad \text{i.e.} \quad \psi = 53.29°$$

$\therefore \quad \delta = \psi - \phi = 53.29 - 36.86 = 16.44°$

and $\quad I_d = I_a \sin\psi = 1\times\sin(53.29°) = 0.8016$

$I_q = I_a \cos\psi = 1\times\cos(53.29°) = 0.5977$

Now $\quad E_f = V_t\cos\delta + I_d X_d + I_q R_a$

$= 1\times\cos(16.44) + 0.8016\times 0.8 + 0.5977\times 0.02 = \mathbf{1.6123}$ p.u.

This is open circuit voltage required.

$$\%R = \frac{E_f - V_t}{V_t}\times 100 = \frac{1.6123-1}{1}\times 100 = \mathbf{61.23\ \%}$$

Case 2) $\cos\phi = 0.8$ lead , $\phi = -36.86°$

The ϕ is negative for leading p.f.

$$\therefore \quad \tan\psi = \frac{1\times\sin(-36.86°)+1\times 0.5}{1\times\cos(-36.86°)+1\times 0.02} = -0.1217$$

$\therefore \quad \psi = -6.94°, \ \delta = \psi - \phi = -6.94° - (-36.86°) = 29.92°$

$I_d = I_a\sin\psi = 1\times\sin(-6.94°) = -0.1208$

$I_q = I_a\cos\psi = 1\times\cos(-6.94°) = 0.9926$

Now $\quad E_f = V_t\cos\delta + I_d X_d + I_q R_a$

$= 1\times\cos(29.92) + (-0.1208)(0.8) + (0.9926)\times 0.02 = \mathbf{0.7899}$

This is open circuit voltage required.

$$\therefore \quad \%R = \frac{E_f - V_t}{V_t}\times 100 = \frac{0.7899-1}{1}\times 100 = -\mathbf{21\ \%}$$