MODULE - 4

I . THREE PHASE CIRCUITS :

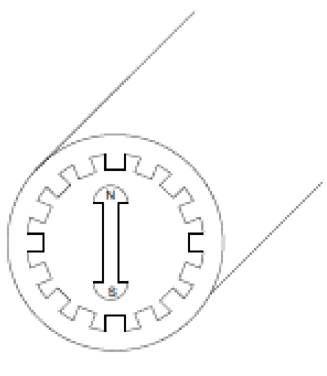
Syllabus : *Necessity and advantages of 3 phase systems, generation of three phase power. Definition of phase sequence, balanced supply & balanced load. Relationship between line & phase values of balanced star & delta connections. Power in balanced three-phase circuits, measurement of power by two-wattmeter method. Determination of power factor using wattmeter readings. Illustrative examples.*

Advantages of three-phase systems :

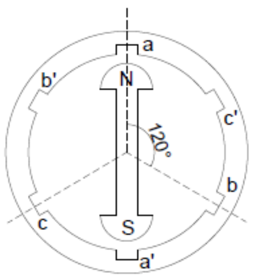
1. Three phase transmission lines require much less conductor material. The return conductor is replaced by single neutral conductor of small size.
2. Three phase machine gives higher output than a single phase machine.
3. Three phase motor develops uniform torque whereas single phase motor develops pulsating torque.
4. Three phase can generate rotating magnetic field & hence three phase induction motors are self starting.
5. Three phase system can be used to supply domestic & industrial power.
6. Voltage regulation is better in three phase system compared to single phase supply.
7. Three phase system is more efficient & less expensive compared to single phase system.

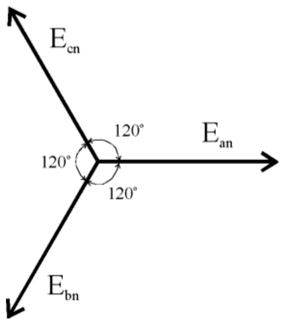
Generation of three phase power :

Three phase power is generated using alternator. Alternator contains stator (stationary part) and rotor (rotating part). The stator is cylindrical in shape and has slots in its inner periphery as shown in the figure below. The conductors are placed in the slots. They are connected either in star or delta. Rotor is a magnet with two poles 'N & S'.

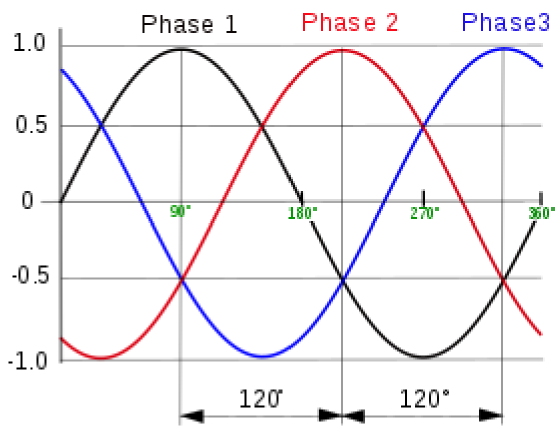


Generation of three phase emf :





Stator conductors aa' , bb' and cc' are mutually displaced by 120^0. As the rotor rotates , the stator conductor cuts the flux and hence emf is induced in all 3 conductors.



$e_A = E_m \sin wt$

$e_B = E_m \sin(wt-120)$

$e_C = E_m \sin(wt-240)$

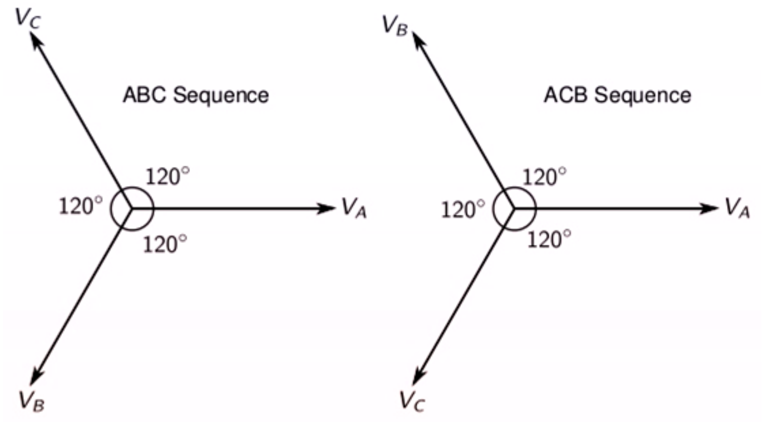
Phase sequence :

Phase sequence is the order in which the 3 phase voltages reach their maximum. It is either 'abc' or 'acb' .

'abc' sequence -- waveform 'a' reaches the peak first , followed by 'b' and 'c' .

'acb' sequence -- waveform 'a' reaches the peak first , followed by 'c' and 'b' .

In the figure , phase1 reaches the peak first , followed by 'phase 2' and 'phase 3' .



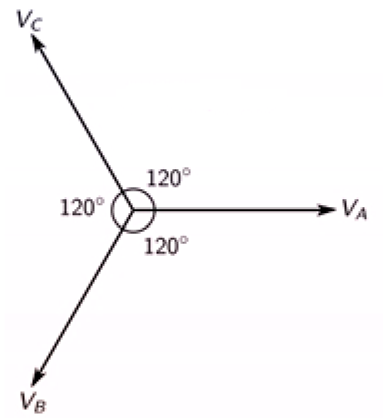
<u>Importance of phase sequence</u> **:**

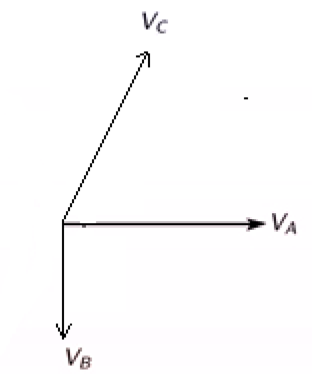
- 3 phase supply of a particular sequence is given to <u>3 phase load (static load)</u>. If the **phase sequence** is changed then the direction of current flow will also change.
- If the 3 phase supply is given to 3 phase induction motor , and if phase sequence is changed then the **direction of current flow will reverse and also the direction of rotation changes**.

<u>Balanced supply and balanced load</u> **:**

Balanced supply :

If the magnitude of 3 phases are same and are displaced by 120^0 it is said to be balanced supply.





$V_A = V_B = V_C$

All 3 vectors are displaced by 120^0

$V_A \neq V_B \neq V_C$

All 3 vectors are displaced by different angles

Balanced load : If the impedances in all the three phases are equal in magnitude then the load is said to be balanced .

Relation between line & phase values of balanced star connections :

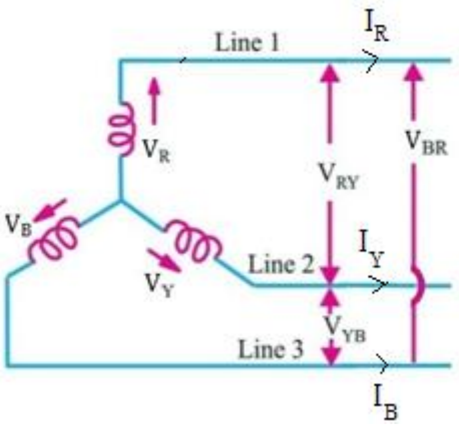
Let I_R, I_Y, I_B → Line Currents

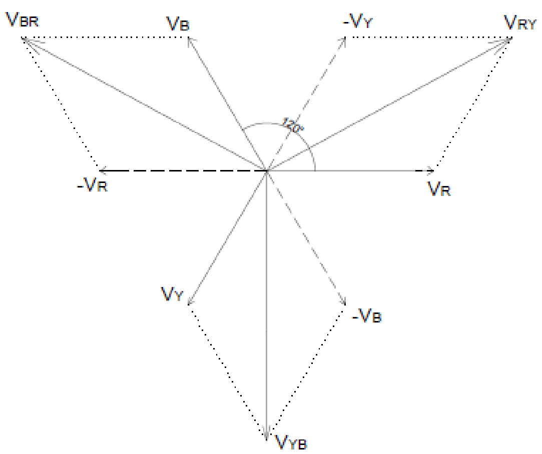
V_{RY}, V_{YB}, V_{BR} → Line Voltages

V_R, V_Y, V_B → Phase Voltages

Phase voltage is the voltage between line & neutral

Line voltage is the voltage between any two lines





3Ø system is a balanced system :

$|V_R| = |V_Y| = |V_B| = V_{ph}$

$V_R = V_{ph} \angle 0^0$

$V_Y = V_{ph} \angle -120^0$ (here V_Y lags V_R by 120^0)

$V_B = V_{ph} \angle -240^0$ (here V_B lags V_R by 240^0)

$\boxed{V_{RY} = V_R - V_Y}$

$= V_{ph} \angle 0^0 - V_{ph} \angle -120^0$

$= V_{ph} \angle 0^0 - [V_{ph} \{\cos(-120^0) + j\sin(-120^0)\}]$

$= V_{ph} \angle 0^0 - [V_{ph}(\cos 120^0) - j\sin 120^0]$

$= V_{ph} \angle 0^0 - [V_{ph} (-½ - j.\sqrt{3}/2)]$

$= V_{ph} [1 + ½ + j\sqrt{\mathbf{3}}/2]$

$V_{RY} = V_{ph} [3/2 + j\sqrt{\mathbf{3}}/2]$

$|V_{RY}| = \sqrt{(3/2)^2 + (\sqrt{\mathbf{3}}/2)^2} * V_{ph}$

$$\boxed{|V_{RY}| = \sqrt{\mathbf{3}}\ V_{ph}}$$

Similarly,

$|V_{YB}| = \sqrt{\mathbf{3}} V_{ph}$ & $|V_{BR}| = \sqrt{\mathbf{3}}\ V_{ph}$

Therefore, $\boxed{\begin{matrix} V_L = \sqrt{\mathbf{3}} V_{ph} \\ I_L = I_{PH} \end{matrix}}$

Power consumed by 3 phase circuit is given by ,

P = 3 x Power in each phase

$P = 3\ V_{ph} I_{ph} * \cos Ø$

$P = 3 \left(\frac{V_L}{\sqrt{\mathbf{3}}}\right) I_L * \cos Ø$

$$\boxed{P = \sqrt{\mathbf{3}}\ V_L I_L * \cos Ø}$$

<u>Relation between line & phase values of balanced delta connections</u> :

Let $I_R, I_Y, I_B \rightarrow$ Line currents

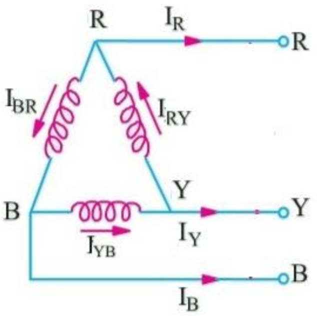
$I_{RY}, I_{YB}, I_{BR} \rightarrow$ Phase Currents

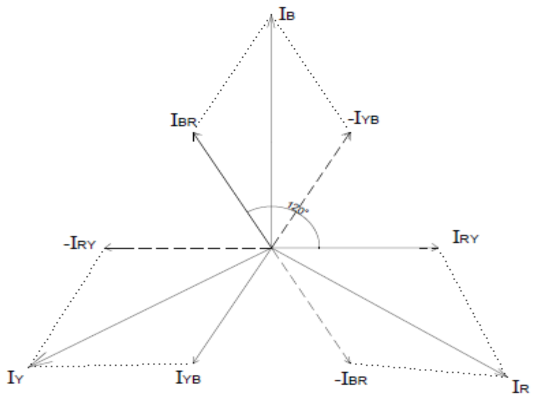
$$|I_{RY}| = |I_{YB}| = |I_{BR}| = I_{ph}$$

$$I_{RY} = I_{ph} \angle 0^0$$

$$I_{YB} = I_{ph} \angle -120^0$$

$$I_{BR} = I_{ph} \angle -240^0$$





Apply KCL @ R ,

$$I_{RY} = I_{BR} + I_R$$

$$I_{RY} - I_{BR} = I_R$$

$$I_{ph} \angle 0^0 - I_{ph} \angle -240^0 = I_R$$

$$I_R = I_{ph} \angle 0^0 - I_{ph} \angle -240^0$$

$$I_R = I_{ph} \angle 0^0 - [\, I_{ph} \{\cos(-240^0) + j\sin(-240^0)\}]$$

$$I_R = I_{ph} \angle 0^0 - [\, I_{ph} \{-½ + j\sqrt{3}/2\}]$$

$$I_R = I_{ph} [\, 1 + ½ \sqrt{3}/2\, j \,]$$

$$I_R = I_{ph} [3/2 - j\sqrt{3}/2 \,]$$

$$|I_R| = I_{ph} \sqrt{(3/2)^2 + (\sqrt{3}/2)^2} = I_{ph}\sqrt{3}$$

$$|I_R| = |I_Y| = |I_B| = I_L$$

Therefore, $I_L = \sqrt{3}\, I_{ph}$

$$\mathbf{V_L = V_{ph}}$$

Power consumed by 3Ø circuit is given by,

$$P = 3\, V_{ph}\; I_{ph} \cos Ø$$

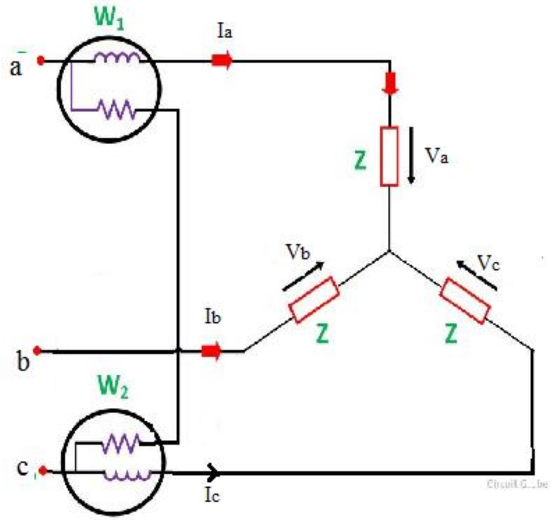
$$P = \sqrt{3}\, V_L\, (I_L / \sqrt{3}\,) \cos Ø$$

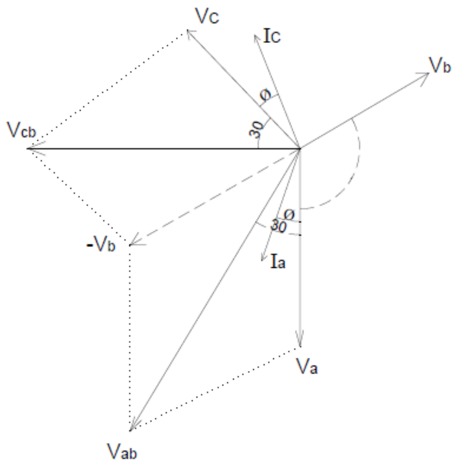
$$\boxed{P = \sqrt{3}\, V_L\, I_L \cos Ø}$$

Measurement of Power by two wattmeter method :

Here load and supply are balanced

Power can be measured using two wattmeters.





V_a, V_b, V_c → Phase Voltages

V_{ab}, V_{bc}, V_{ca} → Line Voltages

I_c lags V_c by Ø

I_a lags V_a by Ø

<u>Reading of Wattmeter W_1</u> :

W_1 = <u>Voltage across potential coil</u> x <u>Current through CC</u> x <u>cos angle between V & I</u>

$$W_1 = V_{ab}\, I_a \cos(\angle V_{ab} - \angle I_a)$$

$$W_1 = V_{ab}\, I_a \cos(30^0 - Ø)$$

$$\boxed{W_1 = V_L\, I_L \cos(30^0 - Ø)} \quad \rightarrow (1)$$

Reading of Wattmeter W_2 :

$W_2 = V_{cb}\, I_c \cos(30^0 + Ø)$

$W_2 = V_L\, I_L \cos(30^0 + Ø) \quad \rightarrow (2)$

By adding both the equations (1) and (2),

We get,

$W_1 + W_2 = [\, V_L I_L \cos(30^0 - Ø)\,] + [\, V_L I_L \cos(30^0 + Ø)\,]$

$W_1 + W_2 = V_L I_L\, [\cos(30^0 - Ø) + \cos(30^0 + Ø)\,]$

$W_1 + W_2 = V_L I_L\; 2\cos 30^0 \cos Ø$

Therefore, $\boxed{W_1 + W_2 = \sqrt{3} V_L I_L \cos Ø}$ = Three Phase Power

Two wattmeter's are sufficient to measure 3Ø power.

Determination of power factor from wattmeter's readings–

$W_1 - W_2 = V_L I_L \cos(30^0 - Ø) - V_L I_L \cos(30^0 + Ø)$

$W_1 - W_2 = V_L I_L\, [\cos(30^0 - Ø) - \cos(30^0 + Ø)\,]$

$W_1 - W_2 = V_L I_L\; 2\sin 30^0 \sin Ø$

Therefore, $W_1 - W_2 = V_L I_L \sin Ø$

Take ratio,

$$\left(\frac{W_1 - W_2}{W_1 + W_2}\right) = \left(\frac{V_L I_L \sin Ø}{\sqrt{3}\, V_L I_L \cos Ø}\right) = \left(\frac{\tan Ø}{\sqrt{3}}\right)$$

Therefore, $\tan Ø = \sqrt{3} \left(\frac{W_1 - W_2}{W_1 + W_2}\right)$

$$\text{Ø} = \tan^{-1} \sqrt{3} \left(\frac{(W_1 - W_2)}{(W_1 + W_2)} \right)$$

$$\boxed{\cos\text{Ø} = \cos \left(\tan^{-1} \left\{ \frac{\sqrt{3}\,(W_1 - W_2)}{(W_1 + W_2)} \right\} \right)}$$

II . THREE PHASE SYNCHRONOUS GENERATORS :

Syllabus : *Principle of operation , types and constructional features, advantages of rotating field type alternator, synchronous speed, frequency of generated voltage, emf equation. Concept of winding factor (excluding the derivation of distribution & pitch factors). Illustrative examples on calculation of distribution factor, pitch factor and emf equation.*

Principle: Whenever a coil is rotated in a magnetic field an EMF will be induced in the coil. This is called the dynamically induced EMF.

- Alternators are also called as Synchronous Generators due to the reason that under normal conditions the generator is to be rotated at a definite speed called "SYNCHRONOUS SPEED", Ns R.P.M. in order to have a fixed frequency in the output EMF wave.
- Ns is related with the frequency as Ns = 120f / P, where f is the frequency and P is the total number of poles.

The following table gives the idea of the various synchronous speeds for various numbers of poles for the fixed frequency of 50 Hz.

P	2	4	6	8	10	12	16	....
Ns rpm	3000	1500	1000	750	600	500	375	....

TYPES AND THEIR CONSTRUCTION:

Their two basic parts in an alternator: (i) Stator, (ii) Rotor.

- Stator is the stationary part and Rotor is the revolving part.

- There are two possibilities that (i) The armature can be the stator and the field system can be the rotor, and (ii) The armature can be the rotor and the field system be the stator.
- In practice large alternators are of the first type where in the stator is the armature and the rotor is the field system. And this type is called the “REVOLVING FIELD TYPE”.

Revolving field types are preferred due to the following reasons:

(i) More conductors can be easily accommodated and with these high voltage and higher power capacity can be achieved.
(ii) Armature conductors can be easily braced over a rigid frame.
(iii) It is easier to insulate a stationary system.
(iv) Cooling of the conductors will be very effective with proper cooling ducts / vents in the stationary part.
(v) Power can be tapped easily without any risk from the stationary part through terminal bushings.
(vi) The armature conductors are totally free from any centrifugal force action which tends to drag the conductors out of the slots.

CONSTRUCTION:

Revolving field type alternators are further classified into two types:

(i) Salient pole type, (ii) Non-salient pole type or cylindrical rotor type.
Figs. (a), (b) and (c) shows the constructional features of the Alternator. Fig. (a) represents the stator, the core of which is made of steel laminations with slots cut in its inner periphery and all the stator stampings are pressed together and are fixed to the stator frame.

- Three phase windings are accommodated in these slots. These coils are identical to each other and are physically distributed such that they are displaced from each other by 120 degrees as shown in fig. (d).

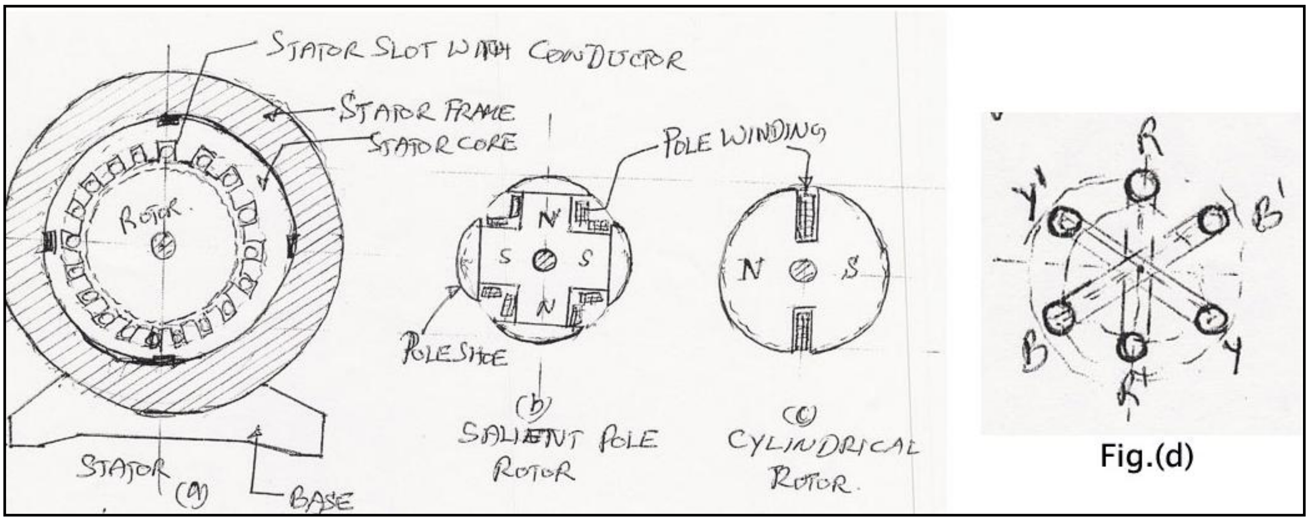


Fig.(d)

Fig. (b) represents the structure of a salient pole rotor where the poles are of projected type and are mounted on a spider and the field or the pole windings are wound over the pole core as shown.

- This type is preferred where the running speeds are low. Fig.(c) represents the structure of a non-salient pole rotor where the overall structure is like a cylinder having 2 or 4 poles.
- This type is preferred where the running speeds are very high.
- The armature windings in the stator are made of copper and are normally arranged in two layers and are wound for lap or wave depending on the requirements and are usually connected in star with the neutral terminal brought out.

EMF Equation:

- Let P be the total number of poles, Ns be the synchronous speed, f be the frequency of the induced EMF and the flux Φ considered to be sinusoid ally distributed.
- As we know that the induced emf is due to the rate of change of flux cut by coils, the average induced emf in Tph number of turns is

$$E_{avg} = T_{ph}\, d\Phi / dt \text{ volts.}$$

For a flux change from Φm to Φm is $d\Phi = 2\,\Phi m$ in time $dt = T / 2$ seconds,

The average induced Emf $= T_{ph}.\ 2\,\Phi m / (T/2) = 4\, T_{ph}.f.\ m$ volts.

For a sine wave we know that the form factor is of value $1.11 = E_{rms} / E_{avg}$.

Therefore, $E_{rms} = 1.11.E_{avg}$.

$$E_{rms} = 4.44\, f\, \Phi m\, T_{ph} \text{ volts per phase.} \quad \ldots\ldots\ldots\ldots (1)$$

If the armature windings are connected in star the line emf is El = 3 $E_{phase.}$

If the armature windings are connected in delta the line emf is the phase emf itself.

QUESTION BANK

1. Obtain the relationship between the phase & line values of voltages & currents in a balanced star connected system.(Jan 2015,9M)(Jan 2014,8M)(June 2015,8M)
2. With relevant vector diagram, show that two wattmeter are sufficient to measure three phase power.(Jan 2013,10M)(Jan 2012,8M)
3. Obtain the relationship between line currents & phase currents in a balanced 3ф delta connected system.(Jan 2012,8M)
4. State the advantages of three-phase system over a single-phase system.(Jan 2010,6M)
5. With a help of connection diagram & phasor diagram show that the two wattmeters are sufficient to measure the active power in a three phase three wire system with a balanced star connected load.(Jan 2011,8M)(Jan 2012,7M)(June 2014,8M)
6. A 3ф, 400V, motor takes an input of 40kW at 0.45 p.f. lag. Find the reading of each of the two single phase wattmeters connected to measure the input.(Jan 2010,4M)
7. A 3 phase 230V supply is given to balanced load which is connected in delta. Impedance in each phase of the load is (8+j6) ohm. Determine the phase current & total power power consumed.(Jan 2014,6M)(Jan 2012,6M)(June 2014,6M)
8. A 3 phase delta connected load consumes a power of 60kW taking a lagging current of 200A at a line voltage of 400V, 50Hz. Find the parameters of each phase. What would be the power consumed if the load were connected in star?(Jan 2010,7M)
9. Three identical coils, each having resistance of 10 ohm & a reactance of 10 ohm are connected in delta, across 400V, 3 phase supply. Find the line current & the readings on the two wattmeters connected to measure the power.(Jan 2013,7M)(June 2014,8M)(Jan 2010,8M)
10. Three similar impedances are connected in delta across a 3 phase supply. The two wattmeters connected to measure the input power indicate 12kW & 7kW. Calculate power input & power factor of the load.(Jan 2014,4M)(Jan 2010,5M)(June 2012,6M)(Jan 2012,6M)
11. Three similar coils each having resistance of10 ohm & a reactance of 8 ohms are connected in star across a 400V, 3 phase supply. Determine the line current, total power &

readings of each of the two wattmeters connected to measure the power.(Jan 2012,8M)(Jan 2011,7M)(June 2014,7M)

12. A balanced three phase star connected system draws power from 440V supply. The two wattmeters connected indicate W_1 = 5kW & W_2 = 1.2kW .calculate power, power factor & current in the circuit.(Jan 2015,5M)(June 2014,6M)(Jan 2010,6M)

4 (b) Synchronous generators

1. Derive an expression for emf equation of an alternator. What is the necessity of considering pitch factor & distribution factor for emf equation.(Jan 2012,6M)(June 2010,5M)(June 2014,6M)(Jan 2014,6M)(June 2015,6M)
2. With the help of sketches, explain the different parts of an alternator. Mention their salient features(Jan 2014,8M)(Jan 2015,8M)(Jan 2009,7M)
3. Enumerate the advantages of having stationary armature & rotating field system in large size alternator.(Jan 2010,6M)(June 2014,6M)
4. With a neat diagram, explain the constructional features of a 3 phase alternator.(Jan 2011,8M)
5. Explain the essential difference between cylindrical & salient pole rotors.(Jan 2013,4M)
6. Sketch the two types of rotors used in alternators.(Jan 2013,4M)(June 2014,4M)
7. A 2 pole, 3 phase alternator is running at 3000 rpm has armature slots with 2 conductors in each slot. Calculate the flux/pole required to generate a line voltage of 230V. distribution factor is 0.952 & pitch factor is 0.956(Jan 2015,6M)(June 2014,6M)(Jan 2011,6M)
8. A 12 pole 500 rpm star connected alternator has 48 slots with 15 conductors/slot. The flux/pole is 0.02Wb & is distributed sinusoidally. The winding factor is 0.97 & pitch factor 0.98. Calculate the line emf(Jan 2014,6M)(Jan 2012,6M)(June 2014,6M)
9. A 3 phase, 6 pole, Y connected A.C generator revolves at 1000 rpm. The stator has 90 slots &8 conductors/slot. The flux/pole is 0.05Wb. Calculate the generated line voltage by the machine if the winding factor is 0.96(Jan 2011,7M)(Jan 2012,8M)
10. A 3 phase, 16 pole, Y connected alternator has 144 slots on the armature periphery. Each slot contains 10 conductors. It is driven at 375 rpm. The line voltage available across the terminals is 2.657kV. Find the frequency of the induced emf & flux/pole.(Jan 2014,8M)
11. A 6 pole, 3 phase Y connected alternator has 90 slots & 8 conductors/slot & rotates at 1000 rpm. The flux/pole is 50mWb. Find the induced emf across the line. Take K_d = 0.97 & K_c = 0.96(Jan 2013,7M)(Jan 2010,6M)(June 2014,6M)

12. A 3 phase, 50 Hz, 16 pole alternator with star connected winding has 144 slots with 10 conductors/slot. The flux/pole is 24.8mWb is sinusoidally distributed, the coils are full pitched. Find the speed, the line emf. Assume winding factor is 0.96(Jan 2009,5M)
13. A 12 pole, 500 rpm, Y connected alternator has 60 slots, with 20 conductors/slot. The flux/pole is 0.02Wb & is distributed sinusoidaly. The winding factor is 0.97. Calculate frequency, phase emf & line emf.(June 2012,8M)