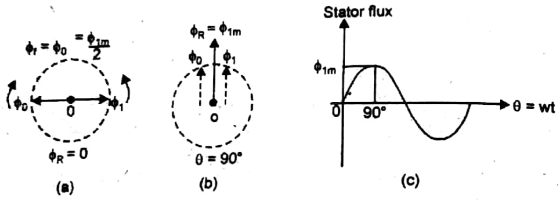
D. Let ϕ_f a is forward component rotating in anticlockwise direction while ϕ_b is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at the instant. So resultant of these two is the original stator flux.

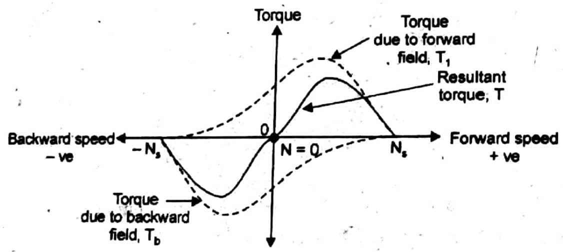
E. The Fig. 1 shows the stator flux and its two components ϕ_f and ϕ_c At start both the components are shown opposite to each other in the Fig.1(a). Thus the resultan ϕ_R = 0. This is nothing but the instantaneous value of the stator flux at start. After 90°, as shown in the Fig. 1(b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant $_R$ is the algebraic sum of the magnitudes of the two components. So $\phi_R = (\phi_{1m}/2) + (\phi_{1m}/2) = \phi_{1m}$. This is nothing but the instantaneous value of the stator flux at $\phi = 90°$ as shown in the Fig 1(c). Thus continuous rotation of the two components gives the original alternating stator flux.

F. At start these two torque are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at start. And hence the single phase induction motors are not self starting.



(b) Torque-speed curve of 1- phase induction motor.

Ans. It can be seen that at start N = 0 and at that point resultant torque is zero. So single phase motors are not self starting.



However if the rotor is given an initial rotation in any direction, the resultant average torque increase in the direction in which rotor initially rotated. And motor starts rotating in that direction. But in practice it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.

Another theory which can also be used to explain why single phase induction motors is not self starting is cross-field theory.

FIRST TERM EXAMINATION [FEB-MARCH-2016]
FOURTH SEMESTER [B.TECH]
ELECTRICAL MACHINES-II [ETEE–202]

Time : 1½ hrs. M.M. : 30

Note: *Attempt Q. No. 1 which is compulsory and any two more from remaining.*

Q.1. (a) A 4-pole induction motor running at 1440 rpm is taking 88 kW as rotor input. Find the copper loss of the rotor. (2)

Ans. No. of poler = 4

$$n_s = \frac{120f}{P} = \frac{120\times 50}{4} = 1500 \text{ rpm}$$

$$\text{Slip} = \frac{1500-1440}{1500} = 0.04$$

$$\text{Rotor copper loss} = \text{Slip} \times \text{power input to rotor per phase}$$

$$= 0.04 \times \frac{88\times 1000}{3}$$

$$= 1173.33 \text{ W}$$

Q.1. (b) What is skewing? Why is the rotor of an induction motor skewed? (2)

Ans. Skewing is slightly twisting the rotor teeth. In this, the rotor bars are skewed.

It is done to prevent cogging. Cogging is magnetic locking. When an induction motor refuses to start even if full voltage is applied to it, this is called cogging. This happens when the rotor slots and stator slots are same in number or they are integer multiple of each other. Due to this, the opposite poles of stator and rotor come in front of each other and get locked. Because of skewing the rotor bars prevent the locking and thus prevents cogging.

Q.1.(c) The rotor resistance and the standstill reactance of a 6-pole, 415 V, 50 Hz, 3-phase slip ring induction motor are 0.5 Ω and 5.0 Ω per phase respectively. Find the value of external resistance to be added per phase to get the maximum starting torque. [2]

Ans.

$$\tau_{ST} = \frac{K(R_2+r)}{(R_2+r)^2 + x_{20}^2}$$

$$\tau_{max} = \frac{K}{2\times 20}$$

$$\tau_{ST} = \tau_{max}$$

$$\Rightarrow \frac{\cancel{K}(R_2+r)}{(R_2+r)^2+X_{20}} = \frac{\cancel{K}}{2\times 20}$$

$$2\times 5\,(0.5+r) = (0.5+r)^2 + 5$$

$$r^2 = 9r + 20.25 = 0$$

$$r = 4.5\ \Omega$$

Q.1.(d) What are the advantages of short pitched winding in synchronous generators? [2]

Ans. (*i*) Shortens the ends of the winding and therefore there is a saving in the conductor material.

(*ii*) Reduces effects of distorting harmonics, and thus the waveform of the generated voltage is improved and making it approach a sine wave.

Q.1.(e) State the conditions to operate 3-phase alternators in parallel. [2]

Ans. (*i*) The phase sequence of the busbar voltage and the incoming machine voltage must be the same.

(*ii*) The busbar voltage and the incoming machine terminal voltage must be in phase.

(*iii*) The terminal voltage of the incoming machine should be equal to that of the alternater with which it is to be run in parallel or with the bus bar voltage.

(*iv*) The frequency of the generated voltage of the incoming machine must be equal to the frequency of the voltage of the live busbar.

Q.2.(a) An 8-pole, 50 Hz, 3-phase induction motor develops a maximum torque of 150 N-m at 650 rpm. The rotor resistance is 0.6 Ω per phase. Find (*i*) standstill rotor reactance per phase and (*ii*) torque at 4% slip. Neglect stator impedance. [5]

Ans.

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

$$N_M = 650 \text{ rpm}$$

$$S_M = \frac{N_S - N_M}{N_S} = \frac{750-650}{750} = \frac{100}{750} = \frac{2}{15}$$

$$x_{20} = \frac{R_2}{S_M} = \frac{R_2}{X_{20}}$$

$$= \frac{0.6 \times 15}{2} = 4.5\ \Omega$$

$$\frac{\tau_S}{\tau_{max}} = \frac{2SS_M}{S^2 + S_m^{\ 2}} = \frac{2 \times \frac{4}{100} \times \frac{2}{15}}{\left(\frac{1}{25}\right)^2 + \left(\frac{2}{15}\right)^2}$$

$$= \frac{60}{109}$$

$$\tau_s = \frac{60}{109} \times 150 = \frac{9000}{109} = 82.57 \text{N.m}$$

Q.2.(b) Name the different methods for starting of an induction motor. Describe any one of them with neat diagram. (5)

Ans. When the supply is connected to the stator of a 3-ϕIM, a rotating magnetic field is produced and the rotor starts rotating. The purpose of a startor is not to start the motor as the name implies. The starter of the motor performs two functions:

(*i*) To reduce the heavy starting current.

(*ii*) To provide overload and under voltage protection.

Starting of cage motors

(*i*) Direct on-line (DOL) starter.

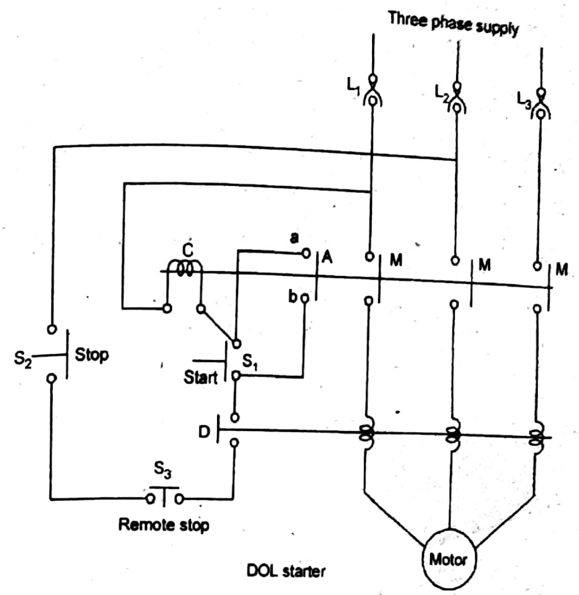
(*ii*) Star-delta starter.

(*iii*) Auto transformer starter.

(*i*) **Direct on-line (DOL) starter:** In DOL starter, the motor is connected by means of a starter across the full supply voltage. It is used for

(*a*) Under voltage protection

(*b*) Over voltage protection.



DOL starter

$C \rightarrow$ Coil operated contactor

S_1 = Push button (normally open)

L_1, L_2, L_3 = Line conductors

M = main contacts

A = Auxilliary contact = Hold contact.

S_2 = Push butter (normally closed)

When S_1 is pressed, C is enersised and the motor starts when S_2 is pressed, C is deenerzised and hence M opens.

3. (a) An 8-pole, 3-phase, double layer winding has 72 coils in 72 slots. The coils are short pitched by two slots. Calculate the winding factor. [5]

Ans.

$$m = \frac{\text{Slots}}{\text{Poles} \times \text{Phases}} = \frac{72}{8 \times 3} = 3.$$

$$\beta = \frac{180° \times \text{Poles}}{\text{Slots}} = \frac{180° \times 8}{72} = 20°$$

$$k_d = \frac{\sin\frac{m\beta}{2}}{m \sin\frac{\beta}{2}} = \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3\sin\left(\frac{20}{2}\right)} = 0.96$$

$$K_C = \cos\frac{\alpha}{2} = \cos 0 = 1$$

$$K_W = K_c K_d$$

$$= 01 \times 0.96 = 0.96.$$

Q.3.(b) What is synchronous reactance? Describe the method for its determination in the laboratory. [5]

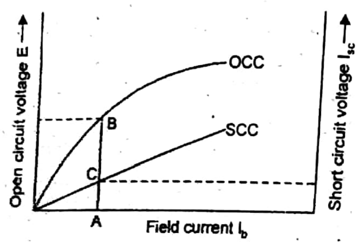
Ans. As synchronous reactance is a combination of armature winding leakage reactance and a reactance used to represent armature reaction. The synchronous machine tests give the induced voltage and the current when armature reaction is greatest, for a range of field current values. This data can be used to approximate the synchronous reactance of the machine. It is important to note that this is only an aproximation of X_s as it is dependent on load condition and phase angle of armature current relative to induced open circuit voltage.

Method for calculation of synchronous reactance

The OCC and SCC are drawn on the same curve sheet.

Determine the value of I_{SC} at the field current that gives rated alternator voltage per phase

$$Z_S = \frac{\text{Open circuit voltage per phase}}{\text{Short circuit armature current}} = \frac{AB}{AC}$$



$$X_S = \sqrt{Z_S^2 - R_a^2}$$

Q.4. (a) What is armature reaction? Describe its effect on an alternator at zero power factor lagging and leading. (5)

Ans. When current flows thorugh the armature winding of an alternator, resulting mmf produces flux. The armature flux reacts with the main pole flux, causing the resulting flux to become either less than or more than the original main field flux. The effect of armature flux on the flux produced by the rotor field poles is called **armature reaction.**

Armature reaction: Unity power factor:

Positive direction of fluxes

$$i_A = I_m \qquad \phi_A = \phi_m$$

$$i_B = -I_m \cos 60 = \frac{-1}{2} I_m \qquad \phi_B = -\frac{1}{2}\phi_m$$

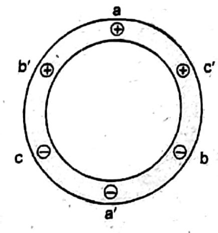
$$i_C = -I_m \cos 60 = -\frac{1}{2} I_m \qquad \phi_C = \frac{-1}{2}\phi_m$$

Resolving in horizontal direction

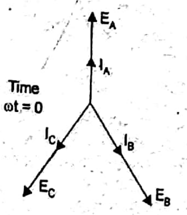
$$\phi_H = \phi_A - \phi_B \cos 60 - \phi_C \cos 60$$

$$= \phi_m - \left(\frac{1}{2}\phi_m\right)\left(\frac{1}{2}\right) - \left(\frac{1}{2}\phi_m\right)\left(\frac{1}{2}\right)$$

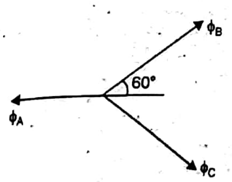
$$= 1.5\phi_m$$

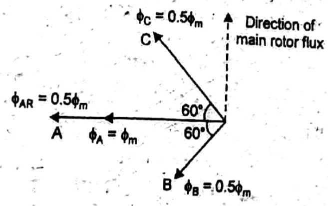


Two-pole alternator



Phasor diagram





Resolving in vertical direction

$$\phi_V = \phi_B \cos 30 + \phi_C \cos 30 = -\frac{1}{2}\phi_m \cos 30 + \frac{1}{2}\phi_m \cos 30 = 0$$

$$\phi_{AR} = \sqrt{\phi_n^2 + \phi_v^2} = 1.5\ \phi_m$$

At lagging power factor:

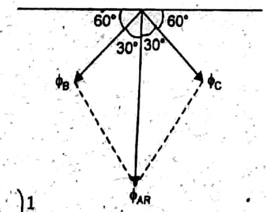
$$i_A = 0 \quad \phi_A = 0$$

$$i_B = I_m \sin(-120°) = -\frac{\sqrt{3}}{2} I_m \qquad \phi_B = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_{AR}^2 = \phi_B^2 + \phi_C^2 + 2\phi_B\phi_C \cos 60$$

$$= \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right)\frac{1}{2}$$

$$Q_{AR} = 1.5\phi_m$$



At leading power factor:

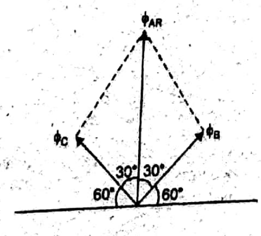
$$i_A = 0 \qquad \phi_A = 0$$

$$i_B = I_m \cos 30 = \frac{\sqrt{3}}{2} I_m \qquad \phi_B = \frac{\sqrt{3}}{2}\phi_m$$

$$I_C = I_m \cos 30 = -\frac{\sqrt{3}}{2} I_m \qquad \phi_c = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_{AR}^2 = \phi_B^2 + \phi_C^2 + 2\phi_B\phi_C \cos 60$$

$$= 2\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right)\cos 60 = 1.5\ \phi_m$$



Following points can be noted about armature reaction:

(i) Armature reaction flux is constant in magnitude and rotates at synchronous speed.

(ii) It is cross-magnetizing when the generator supplies a load at unity power factor.

(iii) When the generator supplies a load at lagging power. The armature reaction is partly demagnetizing and partly cross=magnetizing.

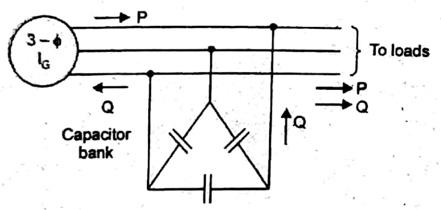
(iv) When the generator supplies a load at leading PF, the armature reaction is partly cross-magnetizing.

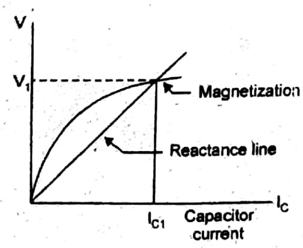
Q.4.(b) How an induction motor operates as an induction generator. Also explain the working of an isolated induction generator with neat diagram. [5]

Ans. An induction generator draws lagging VAr from the main supply. When the speed of the motor is increased above the synchronous speed by an external prime mover in the same direction as the rotating field produced by the stator winding.

Then the induction machine will operate as an induction generator, and will produce a generating torque. This generator torque is opposite to the rotation of the rotor. Under these circumstances, slip is negative and induction generator delivers electrical energy to the supply mains.

Isolated Induction Generator:





An IM can work as a generator even without an external supply system. A 3-ϕ Δ connected capacitor bank is connected across the terminals of the machine to provide necessary excitation.

The presence of residual flux is necessary to provide the initial excitation. In case there is no residual flux, the machine must be momentarily to run as an IM to create residual flux. The motor is run slightly above synchronous speed at no load by a prime mover.

END TERM EXAMINATION [MAY-JUNE–2016]
FOURTH SEMESTER [B.TECH]
ELECTRICAL MACHINES-II [ETEE-202]

Time : 3 hrs. **M.M. : 75**

Note: *Attempt any five questions including Q.no. 1 which is compulsory.*

Q.1.(a) Explain the terms slip, slip frequency, wound rotor and cage rotor. **(3)**

Ans. Slip → The slip speed expressed as a fraction of the synchronous speed is called slip

$$s = \frac{N_s - N_r}{N_s}$$

$$\% \text{ slip} = \frac{N_s - N_r}{N_s} \times 100\%$$

Slip frequency → The rotor frequency $f_2 = s_f$ is called the slip frequency.

Wound rotor → The rotor has a proper 3–ϕ winding with three leads brought out through slip rings and brushes. These leads are normally short circuited when the rotor is running.

Cage rotor → Here the rotor has copper bars embedded in slots which are short circuited at each end. It is a rugged economical construction but develops low starting torque.

Q.1.(b) Why are three phase induction motors commonly used? **(3)**

Ans. (i) It is substantially a constant speed motor with a shunt characteristics.]

(ii) It is a singly fed motor with ac input on stator side.

(iii) The torque developed in this motor has its origin in current induction in the rotor which is only possible at non-synchronous speed; hence the name asynchronous machine.

(iv) Wide range of speed control is possible.

Q.1.(c) What is the basic difference between a synchronous machine and d.c machine? **(3)**

Ans. (i) In dc generators, the field poles are startionary and the armature conductor rotates where as in synchronous machines, the armature is on stator and field is on rotor.

(ii) DC machine can run at different speeds whereas the synchronous machine always runs at synchronous speed.

(iii) voltage generated in the armature is of alternating nature which is conurted to DC voltage in DC machine where as is used is synchronous machines.

Q.1.(d) Define winding factor. Explain their effect on the emf induced in synchronous is machine. **(3)**

Ans. Winding factor is the combination of coil spa factor and distribution factor *i.e.*

$$K_w = K_c \cdot K_d$$

where K_c = coil span factor
k_d = Distribution factor

The actual voltage generated

$$E_p = 2.22\, K_c K_d\, \phi\, Z_p$$
$$= 4.44\, K_c K_d \text{ and } \phi\, T_P$$
$$= 2.22\, K_w\, \phi\, Z_P$$

where ϕ = useful flux perpole

Z_P = Total number of conductors in series per phase

T_P = Total number of coils or turns per phase

f = Frequency of generated voltage.

Q.1.(e) Single phase induction motor is not self starting motor. Give reasons. (3)

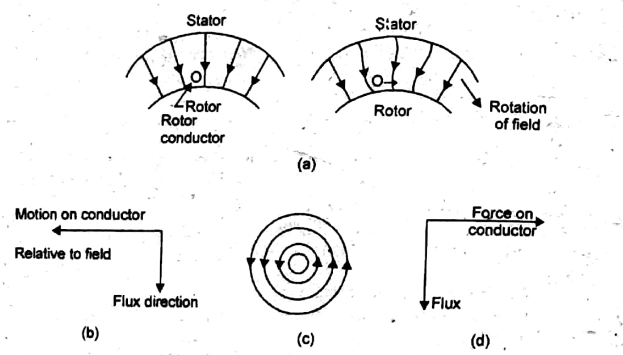
Ans. A $1-\phi$ IM consists of a $1-\phi$ winding mounted on the stator and a case winding on the rotor. When a $1-\phi$ supply is connected on the stator winding a pulsating field is produced.

By pulsating field we mean that the field builds up in one direction, balls to zero and then builds up in the opposite direction. Under these conditions, the rotor does not rotor due to inertia.

Therefore, a $1-\phi$ IM is not a self starting motor.

Q.2. (a) Explain the working principle of 3-phase induction motor. The rotor of induction motor cannot run at synchronous speed. Explain, why? (8)

Ans. Motors work on the principle of Flemings Right hand rule.



We know that when a current carrying conductor is put in a magnetic field, a force is produced on it. Thus, a force is produced on the rotor conductor. The direction of this force can be formed by left hand rule. It is seen that the force a acting on the conductor is in the same direction as the direction of the rotating magnetic field. Since the rotor conductor is in a slation the circumferences of the rotor, this force acts in a trangential direction to the rotor and develops a torque on the rotor. Similar torques are produced on all the rotor conductors. Since the rotor is free to move, it starts rotating in the same direction as the rotating magnetic field. Thus a $3-\phi$ IM is a self starting motor.

An induction motor can not run at synchronous speed. Let us consider for a moment that is rotor is at synchronous speed. Under this condition, there would be no cutting of flux by the rotor conductors and there would be no generated voltage, no current and no torque. The rotor speed is therefore slightly less than the synchronous speed. The induction motor may also be called as 'Asynchronous motor' as it does not run at synchronous speed.

Q.2. (b) The power input to the rotor of a 400 V, 50 Hz, 6 pole 3-phase induction motor is 80 KW. The rotor e.m.f is observed to make 100 complete alteration per minute. Calculation slip, mechanical power developed and rotor copper loss. (7)

Ans.

$$f_1 = 50\,Hz \qquad f_2 = \frac{100}{60}H_2$$

$$f_2 = sf_1 \qquad \Rightarrow s = \frac{f_2}{f_1} = \frac{100}{60\times 50} = 0.033\,pn$$

$$S = \frac{Ns - Nr}{Ns}$$

$$Ns = \frac{120f}{P} = \frac{120\times 50}{6} = 1000\text{ rpm}$$

Mechanical power developed = rotor input – rotor copper loss

rotor copper loss = S × rotor input

$$= \frac{1}{30}\times 80\times 100\text{ W}$$

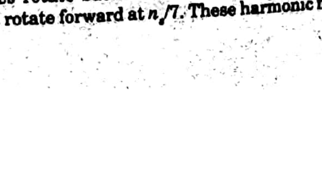
Mechanical power developed $= 80\times 100 - \frac{1}{30}\times 80\times 1000$

$= 77333$W

Rotor copper loss per phase $= \frac{80\times 1000}{30\times 3} = 889$W.

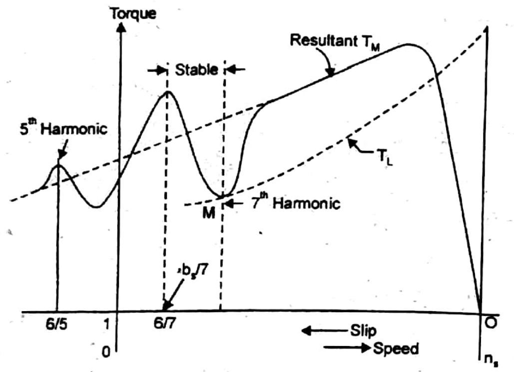
Q.3. (a) Explain the phenomenon of cogging and crawling. (8)

Ans. Sometimes, even where full voltage is applied to the stator winding, the rotor of a 3-phase cage induction motor fails to start. A squirrel-cage rotor may exhibit a peculiar behaviour in starting for certain relationships between the number of poles and the stator and rotor slots. With the number of stator slots S_1 equal to or an integral multiple of rotor slots S_2, the variation of reluctance as a function of space will be quite pronounced resulting in strong alignment forces at the instant of starting. These force may create an aligning torque stronger than the accelerating torque with consequent failure of the motor to start. This phenomenon is known as cogging. Such combination of stator and rotor slots must therefore, be avoided in machine design.



Certain combinations of S_1 and S_2 cause attentuation of certain space harmonics of the mmf wave, *e.g.* fifth and seventh hormonics which corresponce to poles five and seven times that of the fundamental. Since the space-phase difference between fundamental poles of the winding phase is (0°, 120°, 240°), this (space-phase) difference is (0°, 120°, 240°) for the fifth harmonic poles and (0°, 120°, 240°) for the seventh. Hence the fifth harmonic poles rotate backwards with synchronous sheed of $n_s/5$ and the seventh harmonic poles rotate forward at $n_s/7$. These harmonic mmfs produce their own asynchronous (induction) torques of the same general torque slip shape as that of the fundamental figure shows the super imposition of the fundamental.

Fifth and seventh harmonic torque-slip curves. A marked saddle effect is observed with stable region of operation (negative torque-slip slope) around 1/7th normal motor speed (s = 6/7). In figure, the load torque curve intersects the motor torque curve at the point M resulting in stable operation. This phenomenon is known as crawling (running stably at low speed).



Q.3.(b) Why are starters needed to start the induction motor? Explain various starters used for cage and would rotor type induction motor. (7)

Ans. Starting Induction Motor: When the supply is connected to the stator of a three phase induction motor, a rotating magnetic field is produced and the rotor starts rotating. Thus, a three phase induction motor is self-starting. At the time of starting the motor slip is unity and the starting current is very large. The purpose of a stator is not to start the motor as the name implies. The starter of the motor performs 2 actions.

(1) To reduce the heavy starting current.

(2) To provide overload and under-voltage protection.

In general, three phase induction motors may started either by connecting the motor directly to the full voltage of the supply or by applying a reduced voltage to the motor during starting period. The torque of an induction motor is proportional to the square of the applied voltage. Thus a greater torque is exerted by a motor when it is started on full voltage than when it is started on reduced voltage.

Starting of cage motors- The following are the commonly used starters for cage motors:

(i) Direct on-line starters

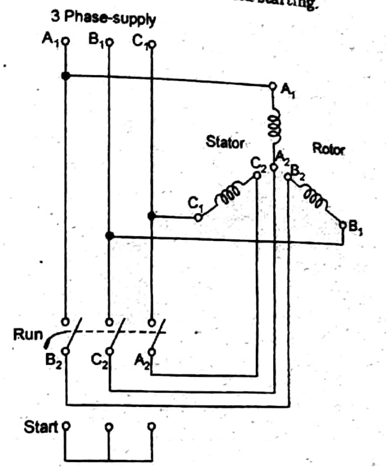
(ii) Star-Delta starter

(iii) Auto transformer starter

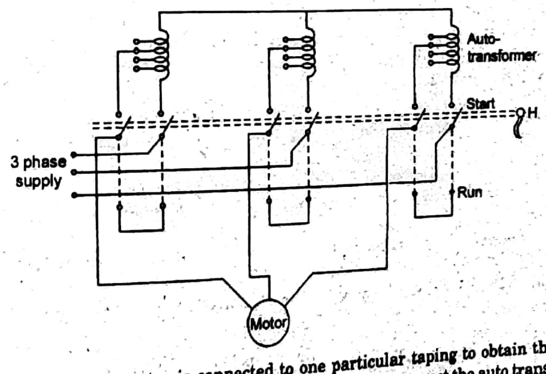
(i) Direct on-line starter: Refer Q.2(b) I First Term 2016.

(ii) Star-Delta starter: This is a very common type of starter and extensively used, compared to the other types of the starters. A star-delta starter is used for a cage motor designed to run normally on delta-connected stator winding.

By connecting the stator windings, first is star and then in delta, the line current drawn by the motor at starting is reduced to one-third as compared to starting current with the windings connceted in delta. At the time of starting when the stator winding are star connected, each stator phase gets a voltage $V_2/\sqrt{3}$, where an induction motor is proportional to the square of the applied voltage star-delta starting reduces the starting torque to one -third that obtainable by direct-delta starting.



Auto-Transformer Starter: An auto transformer starter is suitable for both star, and delta-connected motors. In this method, the starting current is limited by using a three-phase auto-transformer to reduce the initial stator voltage.



In practice, the starter is connected to one particular taping to obtain the most suitable starting voltage. A double throw switch S is used to connect the auto transformer in the circuit for starting. When the hand H of the swich S in the START position, the primary of the auto-transformer is connected to the supply line and the motor is connected to the secondary of the auto transformer. When the motor picks up the speed, say to about 80 percent of its rated value, the handle H is quickly moved to the RUN position. The autotransformer is disconnected from the circuit and the motor is directly connected to the line and gets its full-rated voltage. The handle is held in the RUN position by the under-voltage relay. In case the supply voltage fails or falls below a certain value, the handle is released and returns to the off position. Overload protection is provided by thermal overload relays.

Q.4.(a) Discuss main constructional features of cylindrical rotor and salient pole alternators. (8)

Ans. Salient-pole rotor:

(i) The term salient means 'protruding' or 'projecting'. Thus a salient-pole rotor consists of poles progecting out from the surface of the rotor core.

(ii) Salient-pole rotors are normally used for rotors with four or more poles.

(iii) Since the rotor is subjected to changing magnetic fields, it is made of thin steel laminations to reduce eddy current lossed.

(iv) Poles of identical dimensions are assembled by stacking laminations to the required length and then riveted together.

(v) Salient-pole rotors have concentrated winding on the poles.

(vi) A salient-pole synchronous machine has a non-uniform air gap. The air gap is minimum under the pole centres and it is maximum in between the poles.

(vii) The individual field-pole windings are connected in series to give alternate north and south polarities.

The ends of the field winding are connected to a d.c. source (a d.c. generator or a rectifier) through the brushes on the slip rings.

Cylindrical Rotor

(i) A cyclindrical rotor machine is also called a non-salient pole rotor machine. It has its rotor so constructed that it forms a smooth cylinder.

(ii) The construction is such that there are no physical poles to be seen as in the salient-pole construction.

(iii) In about two-third of the rotor periphery, slots are cut at regular intervals and parallel to the shaft. The d.c. field windings are accommodated in these slots. The winding is of distributed type.

(iv) A cylindrical-rotor machine has a comparatively small diameter and long axial length. Such a construction limits the centrifugal forces. Thus, cylindrical rotors are particularly useful in high speed machines.

(v) The cylindrical rotor type alternator has two or four poles on the rotor. Such a construction provide a greater mechanical strength and permits more accurate dynamic balancing.

(vi) The smooth rotor of the machine makes less windage losses and the operation is less noisy because of uniform air gap.

Q.4.(b) Derive the e.m.f equation for a 3-phase synchronous generator. (7)

Ans. Let

$\phi \rightarrow$ Useful flux per pole in webers (wb)

$P \rightarrow$ Total number of poles

$Z_P \rightarrow$ Total no. of conductors or coil sides in series per phase.

$T_P \rightarrow$ Total number of coils or turns per phase

$n \rightarrow$ Speed of rotation of rotor in revolutions per second (r.p.s)

Since the flux per pole is ϕ, each stator conductor cuts a flux $P\phi$.

The average value of generated voltage per conductor

$$= \frac{\text{Flux cut per revolution in } Wb}{\text{Time taken for one revolution in sec.}}$$

Since revolutions are made in one second, one revolution will be made in 1/n second. Therefore the time for one revolution of the armature is 1/n second. The average voltage generated per conductor

$$E_{av}/\text{conductor} = \frac{P\phi}{1/n} = nP\phi \text{ volts}$$

We know that

$$f = \frac{PN}{120} = \frac{Pn}{2}$$

$$Pn = 2f$$

Substituting the value of Pn,

$$E_{av}/\text{conductor} = 2f\phi$$

Since there are Z_p conductors in series per phase, the average voltage generated per phase is given by

$$\text{all } E_{av}/\text{phase} = 2f\phi Z_p$$

Since one turn or coil has two sides, $Z_p = 2T_p$, and the expression for the average generated voltage per phase can be written as

$$E_{av}/\text{phase} = 4f\phi T_p$$

For the voltage wave, the form factor is given by,

$$K_f = \frac{r.m.s \text{ value}}{\text{Average value}}$$

For a sinusoidal voltage, $K_f = 1.11$, therefore, the r.m.s value of the generated voltage per phase can be writein as

$$\text{r.m.s/phase} = K_f \times E_{av}/\text{phase} = 1.11 \times 4f\phi T_p$$

$$= 4.44\, f\phi T_p$$

The suffix r.m.s. is usually deleted. The r.m.s. value of the generated voltage per phase is given by

$$E_p = 4.44 f\phi T_p$$

Equation has been derived with the following assumption

(a) Coils have got full pitch.

(b) All the conductors are concentrated in one stator slot.

Q.5.(a) A 3-phase 50 Hz, 8 pole alternator has a star connected winding with 120 slots and 3 conductors per slot. The flux per pole is 0.05 wb sinusoidally distributed. Determine the phase and line voltage. (8)

Ans.
$$\alpha = 0°, \quad K_c = \frac{\alpha}{2} = 1$$

$$m = \frac{\text{slots}}{\text{poles} \times \text{phase}} = \frac{120}{8\times 3} = 5$$

$$\beta = \frac{180° \times \text{poles}}{\text{slots}} = \frac{180 \times 8}{120} = 12°$$

$$K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin\frac{5\times 12}{2}}{5\sin\frac{12}{2}}$$

$$= \frac{\sin 30}{5\sin 6} = 0.9567$$

Total Number of conductors
$$S = 120 \times 3 = 360$$

$$Z_p = \frac{360}{3} = 120$$

$$E_p = 2.22\, K_c K_d f \phi Z_p$$
$$= 2.22 \times 1 \times 0.9567 \times 50 \times .05 \times 120$$
$$= 637.1622 \text{ V}$$

$$E_L = \sqrt{3} \times E_p$$
$$= \sqrt{3} \times 637.1622$$
$$= 1103.56\text{V}$$

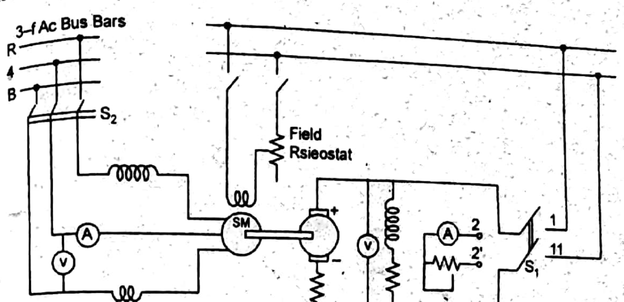
Q.5.(b) Explain constructional features of salient pole alternator. (7)

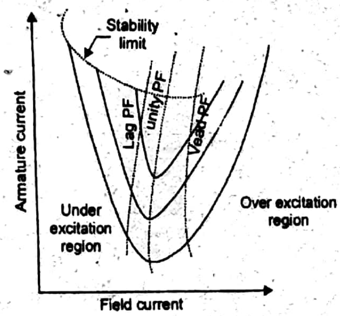
Ans. Refer Q. 4 (a) of End Term 2016.

Q.6. What are V-curves of a synchronous motor? Explain how a synchronous motor operates as synchronous condenser and mention its applications. (15)

Ans. In case of synchronous motor driving a constant mechanical load, variation in field or dc excitation current will not only effect the power factor but also the current drawn by the motor. Except for the change in copper losses due to variation in armature current and a slight change in core loss due to variation in flux, the power input to the motor is almost constant for a constant load.

The power drawn by a 3-phase synchronous motor is given by, $P = \sqrt{3} V_L I_L \cos\phi$ where V_L is line voltage I_L is the armature current and $\cos\phi$ is the power factor. Since input power P and supply voltage V is constant, so decrease in power factor causes increase in armature current and vice-versa.





The V-curves of a synchronous motor give relation between armature current and field current for different power inputs.

First of all synchronous motor is started by the dc shunt motor and brought to its rated speed. Resistances R_1 and R_f are employed respectively for the purpose of starting and controlling the field current to dc shunt machine during starting field control resistance R_f is kept zero.

When the synchronous motor attains nearly the synchronous speed, its field is energised and voltage of the machine is built up to the bus- bar voltage (ac) Now the synchronous motor is synchronised with the bus-bars, and dc supply to the dc/Shunt machine is interrupted by opening the switch S_1. Now the synchronous motor is running on no load and it can drive the dc shunt machine working as a dc shunt generator. DC shunt machine is made to operate as a dc shunt generator by making resistance R_1 in the armature circuit as zero and exciting it and then loading it.

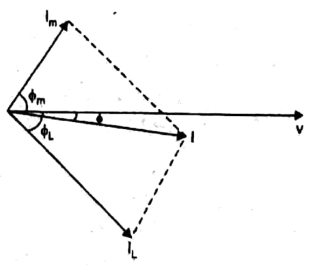
Keeping the syncronous motor on no load, take the readings of ammeter, voltmeter and wattmeter on a.c. side for different value of excitation.

By the aid of *V*-curves, the power factor for any value of armature current I and given input power can be determined from the relation power factor, $\cos\phi = \frac{I_{min}}{I}$ where I_{min} is the minimum current drawn by the motor at given load.

From *V*-curves for different power inputs it is observed that with low value of field current, the armature current is large and lagging. As the field current is increased the power factor increases and armature current decreases untill it reaches its minimum value. When the armature current is minimum, the power factor is unity and the corresponding field current is known as normal field current or excitation of the motor for that particular load. The point at which unity power factor occurs is shown by dotted curve.

The lines drawn through points of equal power factor at different loads are known as compounding curves. The region in which field current is less than its normal value is known as region of underexcitation or region of lag. If the field current is further increased, the power factor becomes leading and begins to decrease, so armature current begins to increase. This region in which field current is more than normal value of field current or armature current leads, is known as region of over excitation or region of lead.

Synchronous condenser



An over excited synchronous motor running on no load is called the synchronous condenser and behaves like a capacitor, the capacitive reactance of which depends upon the motor excitation. Power factor can be improved by using synchronous condensers like shunt capacitors connected across the supply.

In large industrial plants, which have a low lagging power factor load, it is often found economical to install a synchronous motor, even through the motor is not required to drive a load. The motor is operated over-excited at no load so that the current drawn by it leads the voltage by nearly 90°. A synchronous motor used in this way is said to float on the line because it has no mechanical output. Since the motor operating at no load acts in the same manner as a static capacitor and when operated in this manner, it is called synchronous condenser.

Advantages:

(*i*) A finer control can be obtained by variation of field.

(*ii*) Inherent characteristics of synchronous condensers of stabilizing variations in the line voltage and there by automatically aid in regulation.

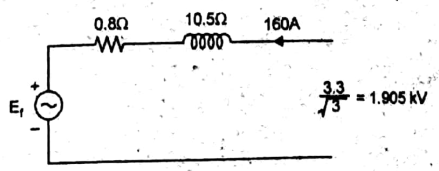
(*iii*) Possibility of overloading a synchronous condenser for short periods.

(*iv*) Improvement in the system stability and reduction of the effect of sudden changes in load owing to incertia of synchronous condenser.

Synchronous condensers are largely employed by utilities at large substations for improving the power factor and voltage regulation. Machines up to 100 MVAR rating or even higher have been used. The excitation current is regulated automatically to give a desired voltage level.

Q.7. The full load current of 3.3 KV star connected synchronous motor is 160A at 0.8 pf lagging. The resistance and synchronous reactance of the motor are 0.8 Ω and 10.5 Ω per phase respectively. Calculate the excitation e.m.f, torque angle, efficiency and shaft output of the motor. Assume mechanical loss to be 30 KW. (15)

Ans.



$$E = \frac{3.3}{\sqrt{3}} = 1.905 \text{ kV}$$

$$X_s = 0.8 + j10.5 = 10.53 \tan^{-1}(13.125) = 10.53 < 85.64$$

$$E_f = 1.905 - X_s \times 0.16 < -36.9$$

$$= 1.905 - (0.8 + j10.5) \times 0.16 \times (0.8\text{-}j0.6)$$

$$= 1.4957 < -5791$$

$$P_{mech} = 3 \times 1.4957 \text{ and } 160 \cos(-36.9 + 57.91)$$

$$= 381.40\text{kW}$$

$$\text{Shaft output} = 381.40\text{-}30$$

$$= 351.40\text{kW}$$

$$= -57.91$$

$$\text{Torque angle} = -57.91^{\circ}$$

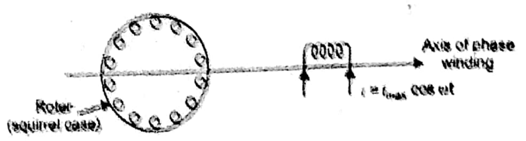
$$\text{Power input} = \sqrt{3} \times 3.3 \times 160 \times 0.8$$

$$= 731.5 \text{ kW}$$

$$\eta = \frac{351.40}{731.5} \times 100 = 48.04\%$$

Q.8. Explain the principle of operation of a single phase induction motor using double revolving field theory. Discuss the method to produce the starting torque. (15)

Ans. A $1-\phi$ *IM* comprises of a $1-\phi$ distributed winding on the stator and normal squirrel cage rotor. There are two important methods of analyzing this motor viz. cross field theory and rotating field theory.



Double revolving field theory:

The winding is distributed in space so that the space fundamental of mmf is the most dominant component of the actual mmf distribution. The space harmonics of mmf, as in case of $3-\phi IM$, would then be ignored.

$$F = F_{peak}\cos\theta$$

F = mmf at any angle θ

θ = angle measured from winding axis.

$$F_{peak} = F_{max}\cos\omega t$$

$$F = F_{max}\cos\omega t\cos\theta$$

$$= \frac{1}{2}F_{max}\cos(\theta-\omega t)+\frac{1}{2}F_{max}\cos(\theta+\omega t)$$

$\frac{1}{2}F_{max}\cos(\theta-\omega t)$ = Forward rotating field F_f

$\frac{1}{2}F_{max}\cos(\theta-\omega t)$ = Backward rotating field F_b

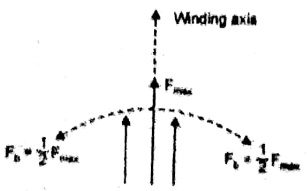
$$\Rightarrow \qquad F = F_f + F_b$$

Both these fields have an amplitude equal to $\frac{1}{2}F_{max}$. The splitting of single pulsating field into two rotating fields rotating in opposite directions.

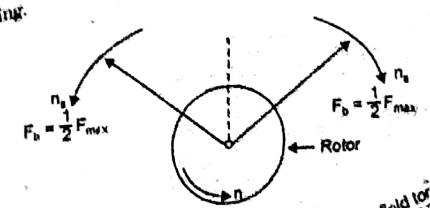
The slip of rotor wrt forward rotating field F_b is then

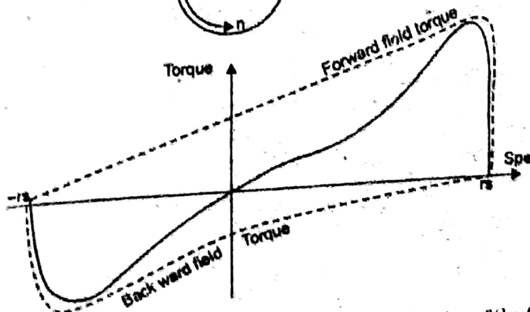
$$S_f = \frac{n_s - n}{n_s} = s$$

$$S_b = \frac{n_s(-n)}{n_s} = \frac{2n_s-(n_s-n)}{n_s} = (2-s)$$



Qualitative treatment : Under stationary rotor condition (n = 0 i.e. s = 1) the two rotating fields slip past the rotor at the same slip s = 1, inducing equal currents in the squirrel cage rotor. The two rotating fields have the same strength and produce equal and opposite torques resulting in net starting torque of zero value. The single winding $1-\phi IM$ is thus non-self starting. Further, the two rotating fields induce a resultant emf in the stator which balances the applied voltage assuming low leakage impedance of the stator winding.





If however, the rotor is made to run at speed n in the direction of the forward field, the two slips are now S $(2-S)$ for normal operation $(2-S) >> S$ and as a consequence the backward field induced rotor currents are much larger than at stand still and have a lower power factor. The corresponding opposing rotor mmf, in presence of stator impedances, causes the backward field to be greatly reduced in strength. On the other hand, the low slip forward rotating field induces smaller current of a higher power factor in the rotor than at standstil. This leads to great enhencement in the forward flux wave. This reduction in the backward field and strengthening of the forward field is slip-dependent and the difference increases as slip s reduces or the rotor speed in the forward direction becomes close to the synchronous speed. In fact, at near about the synchronous speed, the forward field may be several times the backward field. As a result there is a net running torque which drives the rotor of the motor.

Q.8. A 175 W, 220 V, 50 Hz single-phase capacitor start motor has main winding resistance of 4.5 Ω and inductive reactance of 3.7 Ω. It has auxiliary winding resistance of 9.5 Ω and inductive reactance of 3.5 Ω. Find the value of starting capacitor which will give rise to the maximum starting torque. **(15)**

Ans.

$$Z_m = 4.5 + j\,3.7$$

$$= 5.826 < 39.43$$

$$Z_0 = 9.5 + j3.5$$

$$Z_a = 9.5 + j3.5 - j \times c$$

$$= 9.5 + j(3.5 - X_c)$$

$$\tan\phi_a = \frac{3.5 - X_c}{9.5}$$

$$\tan(-90 + 39.43) = \frac{3.5 - X_c}{9.5}$$

$$X_c = \frac{3.5 - 9.5\tan(-50.57)}{9.5}$$

$$= 15.05\ \Omega$$

Capacitance of the capacitor $= \frac{1}{2\pi fC} = X_c$

$$15.05 = \frac{1}{2\times\frac{22}{7}\times 50\times C}$$

$$C = \frac{7}{2\times 22\times 50\times 15.05}$$

$$= 0.211\ \text{mF}$$

$$= 211.42\ \mu\text{F}$$

FIRST TERM EXAMINATION [FEB. 2017]
FOURTH SEMESTER [B.TECH]
ELECTRICAL MACHINES–II [ETEE–202]

Time : 1.5 Hrs. **M.M. : 30**

Note: Q.No 1. is compulsory and attempt any two more questions from the remaining.

Q.1. (a) State the advantages of squirel cage and wound rotor induction motors. **(2)**

Ans. Squirrel-cage Induction Motor Advantages:

- Squirrel-cage Induction motors are simple and rugged in construction.
- Squirrel-cage Induction motors are cheaper in cost due to the absence of brushes, commutators, and slip rings
- They are maintenance free motors unlike dc motors due to the absence of brushes, commutators and slip rings.
- Squirrel-cage Induction motors can be operated in polluted and explosive environments as they do not have brushes which can cause spark

Wound Rotor Induction Motors-Advantages:

1. High starting torque.
2. High over-load capacity.
3. Nearly constant speed.
4. Low starting current (in comparison with squirrel cage motor).

Q.1. (b) The frequency of the EMF in the stator of a 4-pole induction motor in 50Hz and that in the rotor is 2Hz what is the slip and at what speed is the motor running? **(2)**

Ans.
$$P = 4, f = 50\text{ Hz}, f_r = 2\text{Hz}$$
$$f_r = sf$$
$$s = \frac{2}{50} = 0.04 = 4\%$$
$$N_s = \frac{120f}{P} = \frac{120\times 50}{4} = 1500\,\text{rpm}$$
$$N = (1-s)N_s = 1440\text{ rpm}$$

Q.1. (c) State the advantages of short pitched and distributed winding. **(2)**

Ans. The advantages of short pitch winding are:

1. Waveform of induced EMF can be approximately made into a sine wave and losses due to harmonics can be totally reduced or eliminated.
2. Conductor material copper is saved in the back and in the front due to less copper span.
3. Fractional slot winding or fractional coils can /be used which in turn reduces losses due to the tooth ripple.
4. Mechanical strength of the coil is increased.

The advantages of distributed winding are:

1. It also reduces harmonic emf and so wave/form is improved.
2. It also diminishes armature reaction.
3. Even distribution of conductors, helps for better cooling.
4. The core is fully utilized as the conductors are distributed over the slots on the armature periphery.

Q.1. (d) Define the synchronous reactance of an alternator? (2)

Ans. The Synchronous Reactance (X_S) is the imaginary reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and by the change in the air gap flux caused by the armature reaction.

Q.1. (e) State the need and advantages of parallel operation of alternators? (2)

Ans. When a large number of alternators or synchronous generators are connected in parallel to an infinite bus bar system having a constant terminal voltage, constant bus bar frequency and very small synchronous impedance, then this kind of connection is known as parallel operation of alternators.

Parallel operation of alternators is often called as synchronizing. In this post we shall be discussing some of the advantages of the parallel operation of alternators.

Advantages of Parallel Operating Alternators

- When there is maintenance or an inspection, one machine can be taken out from service and the other alternators can keep up for the continuity of supply.
- Load supply can be increased.
- During light loads, more than one alternator can be shut down while the other will operate in nearly full load.
- High efficiency.
- The operating cost is reduced.
- Ensures the protection of supply and enables cost-effective generation.
- The generation cost is reduced.
- Breaking down of a generator does not cause any interruption in the supply.
- Reliability of the whole power system increases.

Q.2. (a) Describe the working principle of an induction motor and explain why the speed of this motor can not be equal to the synchronous speed. (5)

Ans. The stator of the motor consists of overlapping winding offset by an electrical angle of 120°. When the primary winding or the stator is connected to a 3 phase AC source, it establishes a rotating magnetic field which rotates at the synchronous speed.

According to Faraday's law, an emf induced in any circuit is due to the rate of change of magnetic flux linkage through the circuit. As the rotor winding in an induction motor are either closed through an external resistance or directly shorted by end ring, and cut the stator rotating magnetic field, an emf is induced in the rotor copper bar and due to this emf a current flows through the rotor conductor.

Here the relative speed between the rotating flux and static rotor conductor is the cause of current generation; hence as per Lenz's law the rotor will rotate in the same direction to reduce the cause i.e. the relative velocity.

From the working principle of three phase induction motor it may observed that the rotor speed should not reach the synchronous speed produced by the stator. If the speeds are equals, there would be no such relative speed, so no emf induced in the rotor, and no current would be flowing, and therefore no torque would be generated. Consequently the rotor can not reach the synchronous speed. The difference between the stator (synchronous speed) and rotor speeds is called the slip.

Q.2. (b) A-3 phase 8-pole 50Hz induction motor has a full load slip of 1.5%. The rotor resistance is 0.001Ω per phase and the standstill reactance is 0.005W per phase. Calculate the ratio of the maximum to full load torque and the speed at which the maximum torque occurs. (5)

Ans. Slip at which maximum torque occurs $= \frac{R_2}{X_2} = S = \frac{0.001}{0.005} = 0.2$

Rotor speed at maximum torque $= (1 - S) N_S$

$= (1 - 0.2)\, 750 = 600$ rpm

$$\frac{T_m}{T_f} = \frac{a^2 + s^2}{2as} = \frac{0.2^2 + 0.15^2}{2 \times 0.2 \times 0.15} = 1.04$$

Q.3. (a) What is the armature reaction in a synchronous generator? Describe its effect at unity power factor and zero power factor lagging? (5)

Ans. As soon as current starts flowing through the armature conductor there is one reverse effect of this current on the main field flux of the alternator (or synchronous generator). This reverse effect is referred as **armature reaction in alternator or synchronous generator**. In other words the effect of armature (stator) flux on the flux produced by the rotor field poles is called armature reaction.

Armature Reaction of Alternator at Unity Power Factor

At unity power factor, the angle between armature current I and induced emf E, is zero. That means, armature current and induced emf are in same phase. But we know theoretically that emf induced in the armature is due to changing main field flux, linked with the armature conductor.

The main field flux of the alternator in respect of armature can be represented as

$\phi_f = \phi_{fm} \sin \omega t$ ....(1)

Then induced emf E across the armature is proportional to, $\frac{d\phi_f}{dt}$

Now $\frac{d\phi_f}{dt} = -\omega\phi_{fm} \cos \omega t$ ....(2)

the angle between, ϕ_f and induced emf E is 90°.

Now, armature flux ϕ_a is proportional to armature current I. Hence, armature flux ϕ_a is in phase with armature current I.

Again at unity electrical power factor, I and E are in same phase. So at unity pf, ϕ_a is phase with E. So at this condition, armature flux is in phase with induced emf E and field flux is in quadrature with E. Hence, armature flux ϕ_a is in quadrature with main field flux ϕ_f.

As this two fluxes are perpendicular to each other, the **armature reaction of alternator at unity power factor** is purely distorting or cross-magnetizing type.

Armature Reaction of Alternator at Lagging Zero Power Factor

At lagging zero electrical power factor, the armature current lags by 90° to induced emf in the armature.

As the emf induced in the armature coil due to main field flux thus the emf leads the main field flux by 90°. From equation (1) we get, the field flux,

$\phi_f = \phi_{fm} \sin \omega t$

Therefore induced emf $E \propto -\frac{d\phi_f}{dt}$

$\Rightarrow E \propto -\omega\phi_{fm} \cos \omega t$

Hence, at ωt = 0, E is maximum and ϕ_f is zero.

At ωt = 90°, E is zero and ϕ_f has maximum value.

At ωt = 180°, E is maximum and ϕ_f zero.

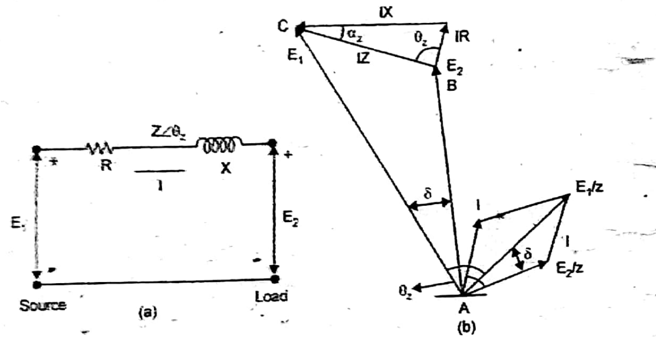
At $\omega t = 270°$, E is zero and ϕ_f has negative maximum value.

Here, ϕ_f got maximum value 90° before E. Hence ϕ_f leads E by 90°.

Therefore, armature flux and field flux act directly opposite to each other. Thus, armature reaction of alternator at lagging zero power factor is purely demagnetizing type. That means, armature flux directly weakens main field flux.

Q.3. (b) Derive the expressions for power developed by a cylindrical rotor synchronous generator. (5)

Ans. The circuit diagram shown below consists of voltage source E_1, voltage source E_2 and load which consists of one resistor in series with an inductor. Now if we assume that the voltage source E_1 is greater than the voltage source E_2 then the voltage equation for this circuit is given by the equation,



Where, Z is R + jX as shown in the above circuit diagram.

From the above expression we write the expression of current as

$$I = \frac{E_1}{Z} - \frac{E_2}{Z}$$

Component of current in phase with the voltage source E_1 is

$$\frac{E_1}{Z}\cos\theta_z - \frac{E_2}{Z}\sin(\theta_z + \delta)$$

On substituting this expression in the above equation we have

$$P_1 = E_1 \times \left[\frac{E_1}{Z}\cos\theta_z - \frac{E_2}{Z}\sin(\theta_z + \delta)\right]$$

$$\Rightarrow P_1 = E_1 \times \frac{E_1}{Z}\cos\theta_z - E_1 \times \frac{E_2}{Z}\sin(\theta_z - \delta)$$

From the phasor diagram, we have

$\theta_z = 90° - \alpha z$.

On substituting the value of the angle θ_z in the above expression we have

$$P_1 = E_1 \times \frac{E_1}{Z} - E_1 \times \frac{E_2}{Z}\sin(\delta - \alpha_z) \quad ...(1)$$

This is the required expression for the power supplied by the source E_1.

Let the power supplied by the source E_2 be P_2.

$P_2 = E_2 \times$ (component of current I in phase with the voltage source E_2)

Component of current in phase with the voltage source E_2 is

$$\frac{E_1}{Z}\cos(\theta_z - \delta) - E_1 \times \frac{E_2}{Z}\sin\theta_z$$

On substituting this expression in the above equation we have

$$P_2 = E_2 \times \left[\frac{E_1}{Z}\cos(\theta_z - \delta) - \frac{E_2}{Z}\sin\theta_z\right]$$

$$\Rightarrow P_2 = E_2 \times \frac{E_1}{Z}\cos(\theta_z - \delta) - E_2 \times \frac{E_2}{Z}\sin\theta_z$$

From the phasor diagram, we have $\theta_z = 90° - \alpha z$.

$$P_2 = -E_2 \times \frac{E_2}{Z} + E_1 \frac{E_2}{Z}\sin(\delta + \alpha_z) \quad ...(2)$$

This is the required expression for the power supplied by the source E_2.

Now let us substitute

voltage source E_1 = excitation voltage (E_f), voltage source E_2 = terminal voltage (V_t), and

$Z_s = r_a + jX_s$.

Power input to the generator (P_{ig}). So,

$$P_{ig} = P_1 = E_f \times r_a \times \frac{E_f}{Z_s} - E_f \times \frac{V_t}{Z_s}\sin(\delta - \alpha_z)$$

similarly we have output of the generator

$$P_{og} = P_2 = -V_t \times r_a \times \frac{V_t}{Z_s} - E_f \times \frac{V_t}{Z_s}\sin(\delta + \alpha_z)$$

$$P_{ig} - P_{og} = \left[E_f \times r_a \times \frac{E_f}{Z_s} - E_f \times \frac{V_t}{Z_s}\sin(\delta - \alpha_z)\right]$$

$$-\left[-V_t \times r_a \times \frac{V_t}{Z_s} - E_f \times \frac{V_t}{Z_s}\sin(\delta + \alpha_z)\right]$$

$$P_{ig} = P_{og} = \frac{E_f \times V_t}{X_s}\sin\delta$$

Q.4. (a) What are the synchronizing power and synchronizing torque in alternators? Derive the expression for both. (5)

Ans. Synchronizing Power is defined as the varying of the synchronous power P on varying in the load angle δ. It is also called **Stiffness of Coupling, Stability** or **Rigidity factor**. It is represented as P_{syn}. A synchronous machine, whether a generator or a motor, when synchronised to infinite Busbars has an inherent tendency to remain in **Synchronism**.

Synchronising Power Coefficient.

$$P_{syn} \triangleq \frac{dp}{d\delta}$$

Power output per phase of the cylindrical rotor generator

$$P = \frac{V}{Z_s}\left[E_f \cos(\theta_z - \delta) - V\cos\theta_z\right]$$

$$P_{syn} = \frac{dP}{d\delta} = \frac{VE_f}{Z_s}\sin(\theta_z - \delta)$$

The synchronising torque coefficient

$$\tau_{syn} \triangleq \frac{d\tau}{d\delta} = \frac{1}{2\pi n_s}\frac{dP}{d\delta}$$

$$\tau_{syn} = \frac{VE_f}{2\pi n_s Z_s}\sin(\theta_z - \delta)$$

Synchronising Torque Coefficient gives rise to the synchronising torque coefficient at synchronous speed. That is, the Synchronizing Torque is the torque which at synchronous speed gives the synchronising power. If τ syn is the synchronising torque coefficient than the equation is given as shown below.

$$\tau_{syn} = \frac{1}{\omega_s} m \frac{dP}{d\delta} \text{ Nm/elect.radian or}$$

$$\tau_{syn} = \left(\frac{1}{\omega_s} m \frac{dP}{d\delta}\right)\frac{p\pi}{180} \text{ Nm/mech.radian}$$

Where,

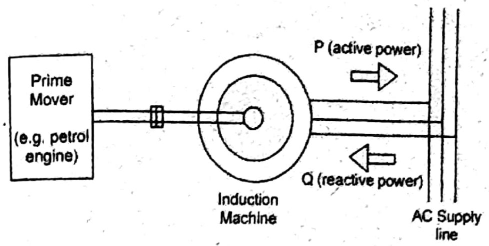
- m is the number of phases of the machine
- $\omega_s = 2\pi n_s$
- n_s is the synchronous speed in revolution per second

$$\tau_{syn} = \frac{P_{syn}}{\omega_s} = \frac{P_{syn}}{2\pi n_s}$$

Q.4. (b) Write short note on Induction Generator. **(5)**

Ans.

- Consider, an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the stator pulls the rotor to run behind it (the machine is acting as a motor).
- Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.
- If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field.
- This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).



Induction generator is not a self-excited machine. Therefore, when running as a generator, the machine takes reactive power from the AC power line and supplies active power back into the line. Reactive power is needed for producing rotating magnetic field. The active power supplied back in the line is proportional to slip above the synchronous speed.

Applications of induction generators: Induction generators produce useful power even at varying rotor speeds. Hence, they are suitable in wind turbines.

Advantages: Induction or asynchronous generators are more rugged and require no commutator and brush arrangement.

One of the major disadvantage of induction generators is that they take quite large amount of reactive power.

END TERM EXAMINATION [MAY-JUNE 2017]
FOURTH SEMESTER [B.TECH]
ELECTRICAL MACHINES-II [ETEE–202]

Time : 3 Hrs. **M.M. : 75**

Note: *Q.No 1 is compulsory and attempt any five more questions from the remaining.*

Q.1. Write short, up to the point and clear answer of the following

(a) Why does an induction motor not develop torque at synchronous speed? **(2.5)**

Ans. If rotor runs at the synchronous speed, then it will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed.

Q.1. (b) What is the frequency of the rotor current of a 415 V, 50 Hz, 4 pole induction motor running at 1440 rpm? **(2.5)**

Ans. (a) Synchronous speed, $n_s = \frac{f}{p} = \frac{50}{\frac{4}{2}} = 25$ rev/s or $25 \times 60 = 1500$ rev/min

(b) Slip,
$$s = \left(\frac{n_s - n_r}{n_s}\right) \times 100\% \quad \text{where } n_r = \frac{1440}{60} = 24 \text{ rev/s}$$

i.e.
$$\text{slip, } s = \left(\frac{25-24}{25}\right) \times 100\% = \frac{100}{25} = 4\%$$

(c) $n = \frac{f}{p}$ or frequency of the rotor current, $f = n \times p = (25 - 24)\left(\frac{4}{2}\right) = 2$ Hz

Q.1. (c) What are cogging, and crawling in squirrel cage induction motors? How can their effect be minimized? **(2.5)**

Ans. Crawling of Induction Motor

It has been observed that squirrel cage type induction motor has a tendency to run at very low speed compared to its synchronous speed, this phenomenon is known as crawling. The resultant speed is nearly 1/7th of its synchronous speed. Now the question arises why this happens? This action is due to the fact that harmonics fluxes produced in the gap of the stator winding of odd harmonics like 3rd, 5th, 7th etc. These harmonics create additional torque fields in addition to the synchronous torque. The torque produced by these harmonics rotates in the forward or backward direction at $N_s/3$, $N_s/5$, $N_s/7$ speed respectively. Here we consider only 5th and 7th harmonics and rest are neglected. The torque produced by the 5th harmonic rotates in the backward direction.

Cogging of Induction Motor

This characteristic of induction motor comes into picture when motor refuses to start at all. Sometimes it happens because of low supply voltage. But the main reason for starting problem in the motor is because of cogging in which the slots of the stator get locked up with the rotor slots. As we know that there is series of slots in the stator and rotor of the induction motor. When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this

stage the reluctance of the magnetic path is minimum and motor refuse to start. This **characteristic of the induction motor** is called cogging.

Methods to overcome cogging

This problem can be easily solved by adopting several measures. These solutions are as follows:

- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

Q.1. (d) What are the advantages of rotating field and stationary armature of synchronous generator? **(2.5)**

Ans. Advantages of Rotating Field with Stationary Armature

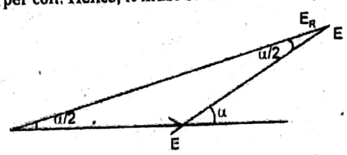
1. Rotating field is comparatively light and can run with high speed.
2. High voltage can be generate due to high speed and there is very little difficulty in providing high voltage on a stationary part than a moving part.
3. It is easier to insulate armature coils for high pressure usually generated (6.6 to 11 kV). Since the stator is outside the rotor, so more space is available for greater insulation required for armature winding.
4. Very little difficulty is experience in supplying the field magnet current as it is very low in comparison with the armature current.

Q1 (e) Define pitch factor and distribution factor of a synchronous machine. **(2.5)**

Ans. Pitch Factor

In short pitched coil, the induced emf of two coil sides is vectorically added to get, resultant emf of the coil. In short pitched coil, the phase angle between the emfs induced in two opposite coil sides is less than 180°(electrical). But we known that, in full pitched coil, the phase angle between the emfs induced in two coil sides is exactly 180° (electrical). Hence, the resultant emf of a full pitched coil is just arithmetic sum of the emfs induced on both sides of the loop. We well know that vector sum or phasor sum of two quantities is always less than their arithmetic sum. Pitch factor is the measure of resultant emf of a short pitched coil in comparison with resultant emf of a full pitched coil.

Hence, it must be the ratio of phasor sum of induced emf's per coil to the arithmetic sum of induced emfs per coil. Hence, it must be less than unity.



$$E_R = 2E\cos\frac{\alpha}{2}$$

$$K_p = \frac{\text{Resultant emf of } \ldots \text{ pitched coil}}{\text{Resultant emf of } \ldots \text{ pitched coil}}$$

$$= \frac{\text{Phasor sum of coil side emf}}{\text{Arithmetic sum of coil side emf's}}$$

$$\Rightarrow K_p = \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$

Distribution Factor

Distribution factor is measure of resultant emf of a distributed winding in compared to a concentrated winding.

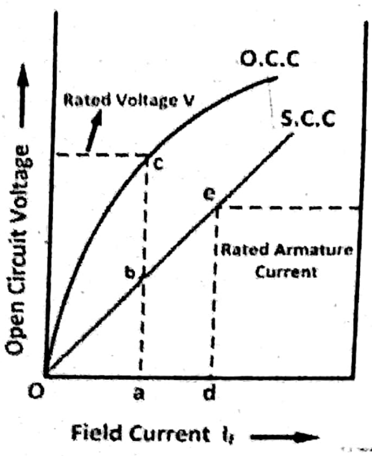
It is expressed as ratio of the phasor sum of the emfs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the emfs induced. Distribution factor is,

$$K_d = \frac{\text{EMF induced in distributed winding}}{\text{EMF induced if the winding would have been concentrated}}$$

$$= \frac{\text{Phasor sum of component emfs}}{\text{Arithmetic sum of component emfs}}$$

Q.1. (f) What is short circuit ratio (SCR) of synchronous generartor and what advantages are of high value of SCR? (2.5)

Ans. The **Short Circuit Ratio (SCR)** of a synchronous machine is defined as the ratio of the field current required to generate rated voltage on an open circuit to the field current required to circulate rated armature current on short circuit. The short circuit ratio can be calculated from the **open circuit characteristic (O.C.C)** at rated speed and the **short circuit characteristic(S.C.C)** of a three-phase synchronous machine



$$SCR = \frac{I_f \text{ for rated O.C. voltage}}{I_f \text{ for rated S.C. current}} = \frac{Oa}{Od} \quad ...(1)$$

A synchronous machine with the high value of SCR had a better voltage regulation and improved steady state stability limit, but the short circuit fault current in the armature is high. It also affects the size and cost of the machine.

Q.1. (g) Why speed of single phase induction motor is not reversed if connection of supply terminal are interchanged, but is reversed, if terminals of either main winding or auxillary winding are interchanged. (2.5)

Ans. The speed of single phase induction motor is not reversed if the connection of supply terminals are interchanged because in this case, the auxilliary winding will start behaving as main winding and the main winding will start behaving as auxilliary winding. This will not affect the direction of rotation of rotating magnetic field. Whereas it is reversed if the terminals of the main winding or the auxilliary winding are reversed, the direction of rotation of rotating magnetic field is changed and hence the motor will start running in reverse direction.

Q.1. (h) What improvements should be made to run single phase ac series motor satisfactorily? (2.5)

Ans. 1.The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.

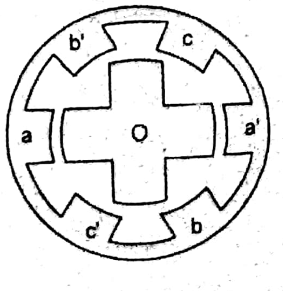
2.The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.

3.The number of armature conductors is increased in order to get the required torque with the low flux.

4.In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used.

Q.1. (i) State the principle of working of a reluctance motor. (2.5)

Ans. Reluctance motors operate on the principle that forces are established that tend to cause iron poles carrying a magnetic flux to align with each. One form of reluctance motor is shown in cross section. The rotor consists of four iron poles with no electrical windings. The stator has six poles each with a current-carrying coil. In the condition represented in the figure, current has just been passed through coils a and a', producing a torque on the rotor aligning two of its poles with those of the a-a' stator. The current is now switched off in coils a and a' and switched on to coils b and b'. This produces a counterclockwise torque on the rotor aligning two rotor poles with stator poles b and b'. This process is then repeated with stator coils c and c' and then with coils a and a'. The torque is dependent on the magnitude of the coil currents but is independent of its polarity. The direction of rotation can be changed by changing the order in which the coils are energized. Reluctance motors can have other pole configurations, such as eight stator poles and six rotor poles.



Q.1. (j) What are the pull in torque and pull out torque of synchronous motors? (2.5)

Ans. Pull in torque: **Pull-in torque** (or **pull in torque**) - such a value of torque which allows a synchronous motor to transit or "pull into" from induction (asynchronous) to synchronous operation.

The value of pull-in torque is always lower than that of pull-out torque.

Pull out torque: In synchronous motors the value of **pull-orut torque** is a maximum value of torque which allows a synchronous motor to remain in synchronism without "pulling out" of step or synchronism.

The value of pull-out torque is always higher than value of pull-in torque and can be between 1.25 - 3.5 of the nominal full-load torque.

Typically, during normal operation the torque of the load should not exceed the value of the pull-out torque.

UNIT–I

Q.2. Name the different methods of speed control of 3 phase inductions motors and describe the Kramer system of speed control with neat diagram. Also state its merits and demerits. (3+5.5+4=12.5)

Ans. The speed control of three phase induction motor from stator side are further classified as :

1.V / f control or frequency control.

2.Changing the number of stator poles.

3.Controlling supply voltage.

4.Adding rheostate in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

1.Adding external resistance on rotor side.

2.Cascade control method (Kramer speed control)

3.Injecting slip frequency emf into rotor side.

Kramer system of speed control

It consists of main induction motor M, the speed of which is to be controlled. The two additional equipments are, d.c. motor and a rotary converter. The slip rings of the main motor are connected to the a.c. side of a rotary converter. The d.c. side of rotary converter feeds a d.c. shunt motor commutator, which is directly connected to the shaft of the main motor. A separate d.c. supply is required to excite the field winding of d.c. motor and exciting winding of a rotary converter. The variable resistance is introuced in the filed circuit of a d.c. motor which acts as a field regulator.

The speed of the set is controlled by varying the field of the d.c. motor with the rheostate R. When the field resistance is changed, the back e.m.f. of motor changes. Thus the d.c. voltage at the commutator changes. This changes the d.c. voltage on the d.c. side of a rotary converter. Now rotary converter has a fixed ratio between its a.c. side and d.c. side voltages. Thus voltage on its a.c. side also changes. This a.c. voltage is given to the slip rings of the main motor. So the voltage injected in the rotor of main motor changes which produces the required speed control

Advantages of Kramer drive are

The main advantage of this method is that any speed, within the working range,

1. Can be obtained instead of only two or three, as with other methods of speed control. If the rotor converter is over excited, it will take a leading current which

2. Compensates for the lagging current drawn by SRIM & hence improves the power factor of the system.

Disadvantages are

1.The slip power can flow in one direction

2.This is applicable for below synchronous speed operation

Q.3. What is slip in induction motors? Derive relation between strip, rotor copper loss and rotor input power. A 3 phase 2 pole, 50 Hz induction motor is running at 2800 rpm with an input power of 15 kW and a terminal current of 22A. The stator resistance is 0.20 per phase calculate copper loss of rotor. (12.5)

Ans. Slip is defined as the difference between the synchronous speed and the rotor speed.

$$S = \frac{N_s - N_r}{N_s} \times 100\%$$

where N_s = synchronous speed (rpm)

N_r = Rotor speed (rpm)

Note: Slip increases with increase in load.

Relationship between slip, rotor copper loss and rotor input power:

net τ_d = developed torque

n_s = synchronous speed (rps)

n_r = rotor speed (rps)

Power transferred from stator to rotor = air gap power P_g

$$P_g = \omega_s \tau_d = 2\pi n_s \tau_d = \text{input power to rotor}$$

Total mechanical power developed by the rotor

$$P_{md} = \omega_r \tau_d = 2\pi n_r \tau_d \text{ W.}$$

Total I^2R loss in rotor = (Power transferred from stator to rotor)– (Total mechanical power developed by rotor)

$$P_{rc} = P_g - P_{md} = 2p(n_s - n_r)\tau_d$$

$$\frac{\text{Total } I^2R \text{ loss in rotor}}{\text{Input power to rotor}} = \frac{2\pi(n_s - n_r)\tau_d}{2\pi n_s \tau_d} = s$$

$\therefore$ rotor copper loss = s. rotor input

$$P_{rc} = sP_g = sP_{ir}$$

$$P_{ir} = P_{md} + P_{rc}$$

$$P_{rc} = s(P_{md} + P_{rc})$$

$$P_{rc}(1-s) = s\,P_{md}$$

$$P_{rc} = \frac{s}{1-s} P_{md}$$

Rotor copper loss = $\frac{s}{1-s}$ × mechanical power developed by the rotor

$$P_g : P_{rc} : P_{md} = 1 : s : (1-s)$$

$$P_{rc} = s\,Pg$$

$$P_{md} = (1-s)\,Pg$$

$$\boxed{\tau_d = \frac{P_g}{\omega_s}}$$

No of poles = 2 = P

$$f = 50 \text{ Hz}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

$$N_r = 2800 \text{ rpm}$$

$$S = \frac{N_s - N_r}{N_s} \times 100\% = \frac{1}{15}\%$$

$R_1 = 0.2\Omega$

Input power = 15 kW = 15000 W

Terminal current (I_1) = 22A

Stator losses = $I_1^2 R_1 = (22)^2 \times 0.2 = 96.8$ W

Stator output = Rotor input = 15000 − 3 × 96.8

= 14709.6 W

Total rotor copper losses = s × Rotor input

$$= \frac{1}{15} \times 14709.6 = 980.64W$$

UNIT-II

Q.4. Describe two reactance theory for synchronous machines. Explain why it is not applicable for cylindrical rotor machines. Also explain and draw neat phasor diagram of an alternator based on it. (12.5)

Ans. Two reaction theory: The theory proposes to resolve the given armature mmfs into two mutually perpandicular components, with one located along the axis of the rotor salient pole. It is known as the direct axis component. The other component is placed, perpendicular to the axis of rotor salient pole. It is known as quadrature axis component. The d-axis component of armature mmf F_a is denoted by F_d and q-axis is denoted by F_q. The component F_d is either magnetizing or de-magnetizing. The component F_q results in a cross-magnetizing effect If ψ is the angle between armature current I_a and excitation voltage E_f and F_a is the amplitude of armature mmf, then

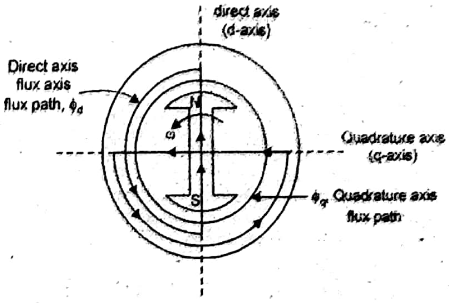
$$F_d = F_a \sin\psi$$

$$F_q = F_a \cos\psi$$

The two reaction theory of synchronous machines is not applicable to cylinderical rotor as the cylinderical rotor has uniform air gap. Because of the uniform air gap, the reactance is uniform in cylinderical rotor. Whereas in salient rotor, the air gap is non-uniform and hence it is not possible to different in between the axis.

Hence in order to simplify the problem, two reaction theory is applied.

Two reaction theory applied to salient pole synchronous machine:



A 2-pole salient-pole rotor rotating in anticlock wise direction within a 2-pole stator

ϕ_d = Direct axis flux

ϕ_q = Quadrature axis flux

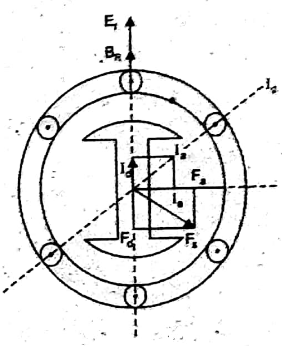
R_d = reluctance

$$\phi_d = \frac{F_d}{R_d}$$

$$\phi_q = \frac{F_q}{R_q}$$

$$E_{ad} = -j\,X_{ad}\,I_d$$

$$E_{aq} = -j\,X_{aq}\,I_q$$



where E_{ad} = d-axis component of armature reaction voltage.

E_{aq} = q-axis component

x_{ad} = armature reaction reatance (d-axis)

x_{aq} = armature reaction reactance (q-axis)

$E' = E_f + E_{ad} + E_{aq}$

$= E_f - j\,X_{ad}\,I_d - j\,X_{aq}\,I_q$

$I_a = I_d + I_q$

$E' = V + I_a R_a + jI_a X_l$

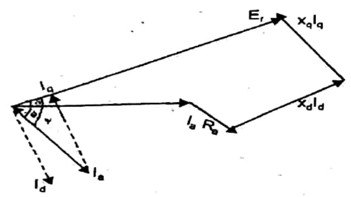
$E_f = V + I_a R_a + jI_a X_l + j\,X_{ad}\,I_d + jX_{aq}\,I_q$

$= V + R_a(I_d + I_q) + j(X_l + X_{ad})\,I_d + j(X_l + X_{aq})\,I_q$

let $X_d = X_e + X_{ad}$

$X_q = X_l + X_{aq}$

$E_f = V + I_a R_a + j X_d I_d + j X_q I_q$



Phasor diagram (simplified)

Q.5. What is synchronous reactance? How is it determined from OCC and SCC of an alternator? Calculate the saturated synchronous reactance of a 85 kVA synchronous machine which achives its rated open circuit voltage of 460 V at a field current 8.7A and which achieves the rated short circuit current at field current of 11.2 A. (3+4+5.5=12.5)

Ans. The net reactance of the armature circuit due to the combined effect of leakage reactance and the fictitious reactance due to armature reaction effect is known as synchronous reactance, since it is caused in synchronous speed. It is denoted by the symbol $X_s = \sqrt{Z_s^2 - R_r^2}$, where Z_s is the synchronous impedance. Its unit is ohm.

The synchronous reactance varies inversely with the degree of saturation of the magnetic circuit.

With the assumption of a linear magnetic circuit, the circuit model (per phase) of a synchronous machine. If R_a is neglected, it then follows that

$$\bar{E}_f = \bar{V}_t + j\bar{I}_a X_s$$

It is immediately seen from Eq. above that for a given field current under short-circuit condition.

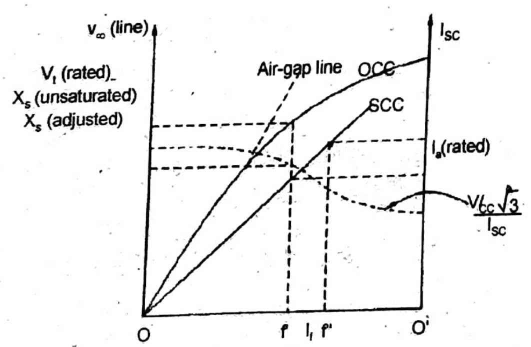


Fig. Open-circuit and short-circuit characteristics

$$X_s = \frac{E_f}{I_{SC}}$$

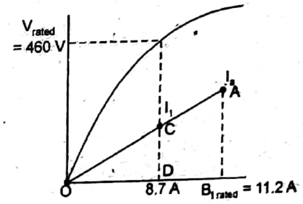
But $E_f = V_{oc}$ (open-circuit voltage, i.e. $I_a = 0$ with the same field current). Then with the linearity assumption.

$$X_s = \left.\frac{V_{OC}}{I_{SC}}\right|_{I_{f a\, const}}$$

where V_{oc} = open circuit voltage

and I_{sc} = short-circuit current on a per phase basis with the same field current.

Since the magnetization characteristic of the machine is nonlinear, it is necessary to determine the complete open-circuit characteristic (OCC) of the machine (V_{oc} /f relationship). However, it will soon be shown that it is sufficient to determine one point on the short-circuit characteristic (SCC) of the machine ('SC - If relationship) as it is linear in the range of interest (for /sc up to 150% of the rated current)



$$I_a = \frac{85kVA}{\sqrt{3} \times v_{rated}} = \frac{85 \times 1000}{\sqrt{3} \times 460} = 106.7A$$

$$\frac{I_1}{8.7} = \frac{I_a}{11.2}$$

$$I_1 = \frac{I_a \times 8.7}{11.2} = \frac{106.7 \times 8.7}{11.2} = 82.9A$$

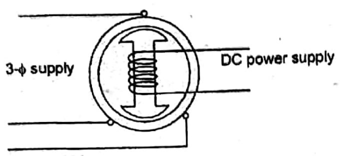
$$Z_s \approx X_s = \frac{V_{rated}}{\sqrt{3} I_1}$$

$$= \frac{460}{\sqrt{3} \times 82.9} \approx 3.21\Omega$$

Q.6. State the principle of working of synchronous motor and explain why it is not self-starting. Describe any two method of its starting. (12.5)

Ans. Working principle of a synchronous motor:

Consider a 2-pole synchronous motor, when a 3-ϕ AC supply is given to stator winding, a rotating magnetic field is produced in the air gap. The stator field rotates at synchronous speed.



The field current of the motor produces a steady- state magnetic field. Therefore, there are two magnetic fields present in the machine. The rotor will tend to align with the stator field just as two bar magnets will tend to align if placed near each other. Since the stator magnetic field is rotating, the rotor magnetic field and the rotor will tend to rotate with the rotating field of the stator. In order to develop a continuous torque. Two fields must be stationary w.r.t each other. This is possible only when the rotor also rotates at synchronous speed. The basic principle of synchronous motor operation is that the rotor chases the stator magnetic field.

Why synchronous motor is not self starting: Let us assume that the rotor is stationary. When a pair of rotating stator poles sweeps across the stationary rotor poles at synchronous speed, the stator poles will tend to rotate the rotor in one direction and then in the other direction. However, because of the rotor inertia the stator field slides by so fast that the rotor can not follow it, consequently, the rotor does not move and we say that the starting torque is zero, In other words, a synchronous motor is not self starting

Methods of starting

(1) Starting with the help of external prime mover.

(2) Starting with the help of damper winding.

(1) With the help of external prime mover: In this method an external motor drives the synchronous motor and brings it to synchronous speed. The synchronous machine is then synchromized with the bus bar as a synchronous generator. The prime mover is then disconnected. Once in parallel, the synchronous machine will work as a motor. Now the load can be connected to a synchronous motor before synchronising, the starting motor has to overcome the inertia of synchronous motor at no load. Therefore the rating of the starting motor is much smaller than the rating of synchronous motor.

(2) With the help of damper windings: Today the most widely used method of starting a synchronous motor is to use damper windings. A damper winding consist of heavy copper bars inserted in slots of the pole faces of the rotor. These bars are short circuited by end rings at both ends of the rotor. Thus these short circuited bars form a squirrel-cage winding. When a 3-φ supply is connected to the stator, the synchronous motor with damper winding will start as a 3-φ induction motor. As the motor approaches synchronous speed DC excitation is applied to field windings. The rotor will pull into step with stator magnetic field.

Q.7. Explain and draw the neat phasor diagram of a synchronous motor at Lagging power factor. Also derive the expressions for the power developed by synchronous motor. (12.5)

Ans. Phasor diagram of a synchronous motor

Voltage equation is

$V = E_f + R_a I_a + jI_d X_d + jI_q X_q$

where E_f = field voltage

R_a = Armature resistance

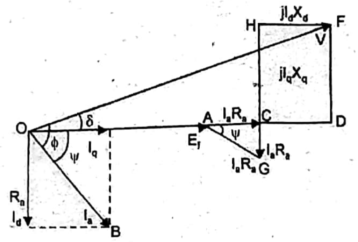
I_a = Armature current

I_d = Direct axis current

I_q = Quadrature axis current

X_d = Direct axis reactance

X_q = Quadrature axis reactance.



$OA = E_f, AG = I_a R_a, GH = I_q X_q$

$HF = I_d X_d, OF = V$

$OD = OA + AC + CD$

$V\cos\delta = E_f + I_a R_a + I_d X_d$

$GH = GC + CH$

$I_q = I_a \cos\psi = I_a \cos(\phi - \delta)$

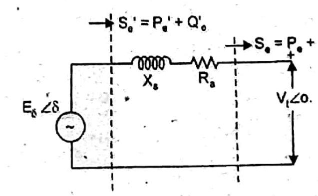
$I_a X_q \cos(\phi - \delta) = I_a R_a \sin(\phi - \delta) + V\sin\delta$

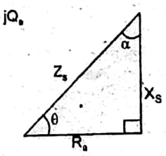
$\Rightarrow I_q X_q (\cos\phi\cos\delta + \sin\phi\sin\delta) = I_a R_a (\sin\phi\cos\delta - \cos\phi\sin\delta) + V\sin\delta$

$(V - I_a R_a \cos\phi - I_a X_q \sin\phi)\sin\delta = (I_a X_q \cos\phi - I_a R_a \sin\phi)\cos\delta$

$$\tan\delta = \frac{I_a X_q \cos\phi - I_a R_a \sin\phi}{V - I_a X_q \sin\phi - I_a R_a \cos\phi}$$

Expression for power developed by synchronous motor:





$$\bar{Z}_s = R_a + jX_s = Z_S\angle\theta$$

$$\theta = \tan^{-1}\frac{X_s}{R_a}$$

$$\alpha = 90 - \theta = \tan^{-1}\frac{R_a}{X_s}$$

$$\bar{I}_a = \frac{E_f\angle\delta - V_t\angle 0}{Z_s\angle\theta}$$

$$S_o = P_o + jQ_o = V_t\angle 0 . \bar{I}_a^*$$

$$\text{Power factor} = \cos\left(\tan^{-1}\frac{Q}{P}\right)$$

$$P_o + jQ_o = V_t\angle 0\left(\frac{E_f\angle\delta - V_t\angle 0}{Z_s\angle\theta}\right)$$

$$= \frac{V_tE_f}{Z_s}\angle(\theta-\delta) - \frac{V_t^2}{Z_s}\angle\theta$$

$$P_o\,(\text{out}) = \frac{V_t^2}{Z_s}\cos\theta + \frac{V_tE_f}{Z_s}\cos(\theta-\delta)$$

$$Q_o\,(\text{out}) = -\frac{V_t^2}{Z_s}\sin\theta + \frac{V_tE_f}{Z_s}\sin(\theta-\delta)$$

Q.8. What is double-revolving-field theory? On its basis draw torque-slip characteristics, explain the working of single-phase induction motor and state why single-phase induction motors are not self-starting. (12)

Ans. Double Revolving Field Theroy

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating quantity.

In case of single phase induction motors, the stator winding produces an alternating magnetic field having maximum magnitude of Φ_{1m}.

According to double revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e. $(\Phi_{1m}/2)$. Both these components are rotating in opposite directions at the synchronous speed N_s which is dependent on frequency and stator poles.

Let Φ_f is forward component rotating in anticlockwise direction while Φ_b is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at the instant. So resultant of these two is the original stator flux.

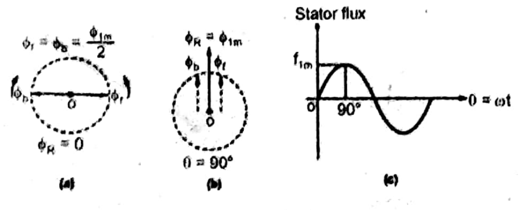


Fig. 1 Stator flux and its two components

The Fig. 1 shows the stator flux and its two components Φ_f and Φ_b. At start both the components are shown opposite to each other in the Fig.1(a). Thus the resultant $\Phi_R = 0$. This is nothing but the instantaneous value of the stator flux at start. After 90°, as shown in the Fig. 1(b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant Φ_R is the algebraic sum of the magnitudes of the two components. So $\Phi_R = (\Phi_{1m}/2) + (\Phi_{1m}/2) = \Phi_{1m}$. This is nothing but the instantaneous value of the stator flux at $\theta = 90°$ as shown in the Fig 1(c). Thus continuous rotation of the two components gives the original alternating stator flux.

Both the components are rotating and hence get cut by the motor conductors. Due to cutting of flux, e.m.f. gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component Φ_f to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component Φ_b to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative.

At start these two torque are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at start. And hence the single phase induction motors are not self starting.

Torque speed characteristics

The two oppsitely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics. It is shown in the Fig.2.

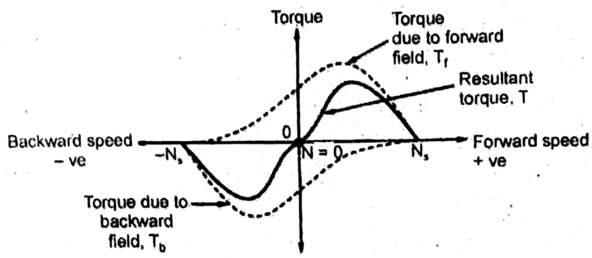


Fig. 2 Torque-speed characteristic

It can be seen that at start N = 0 and at that point resultant torque is zero. So single phase motors are not self starting.

However if the rotor is given an initial rotation in any direction, the resultant average torque increase in the direction in which rotor initially rotated. And motor starts rotating in that direction. But in practice it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.

Working of single phase induction motor

When single phase AC supply is given to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors. According to the Faraday's law of electromagnetic induction, emf gets induced in the rotor. As the rotor circuit is closed so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its own flux called rotor flux. Since this flux is produced due to induction principle so, the motor working on this principle got its name as induction motor. Now there are two fluxes one is main flux and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

Why Single Phase Induction Motor is not Self Starting?

According to double field revolving theory, any alternating quantity can be resolved into two components, each component have magnitude equal to the half of the maximum magnitude of the alternating quantity and both these component rotates in opposite direction to each other. For example - a flux, ϕ can be resolved into two components

$$\frac{\Phi_m}{2} \text{ and } -\frac{\Phi_m}{2}$$

Each of these components rotates in opposite direction i. e if one $\phi_m / 2$ is rotating in clockwise direction then the other $\phi_m / 2$ rotates in anticlockwise direction.

When a single phase AC supply is given to the stator winding of single phase induction motor, it produces its flux of magnitude, ϕ_m. According to the double field revolving theory, this alternating flux, ϕ_m is divided into two components of magnitude ϕ_m /2. Each of these components will rotate in opposite direction, with the synchronous speed, N_s. Let us call these two components of flux as forward component of flux, ϕ_f and backward component of flux, φ_b. The resultant of these two component of flux at any instant of time, gives the value of instantaneous stator flux at that particular instant.

i.e. $$\phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \text{ or } \phi_r = \phi_f + \phi_b$$

Now at starting, both the forward and backward components of flux are exactly opposite to each other. Also both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at starting is zero. So, the single phase induction motors are not self starting motors.

Q.9. Write short notes on:

(a) Stepper motor. **(6.5)**

Ans. A stepper motor is an electromechanical device. It converts electrical power into mechanical power. Also it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps. The motor's position can be controlled accurately without any feedback mechanism, as long as the motor is carefully sized to the application. Stepper motors are similar to switched reluctance motors.

Stepper motors operate differently from DC brush motors, which rotate when voltage is applied to their terminals. Stepper motors, on the other hand, effectively have multiple

toothed electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external control circuit, for example a microcontroller.

There are three main types of stepper motors, they are:

1.Permanent magnet stepper
2.Hybrid synchronous stepper
3.Variable reluctance stepper

Advantages of Stepper Motor:

1.The rotation angle of the motor is proportional to the input pulse.

2.The motor has full torque at standstill.

3.Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next.

4.Excellent response to starting, stopping and reversing.

5.Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependant on the life of the bearing.

6.The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.

Limitations of servo motor

- Low Efficiency
- Limited High Speed Torque
- No Feedback

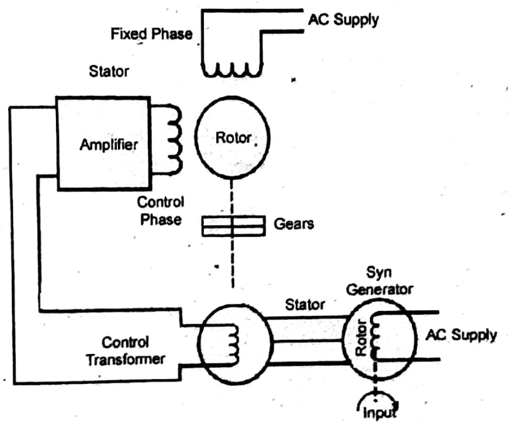
Applications

- Positioning
- Speed Control
- Low Speed Torque

Q.9. (b) AC Servo Motors **(6)**

Ans. AC Servo Motors

AC servo motors are basically two-phase squirrel cage induction motors and are used for low power applications. Nowadays, three phase squirrel cage induction motors have been modified such that they can be used in high power servo systems.



The main difference between a standard split-phase induction motor and AC motor is that the squirrel cage rotor of a servo motor has made with thinner conducting bars, so that the motor resistance is higher.

Based on the construction there are two distinct types of AC servo motors,

1. Synchronous type AC servo motor
2. Induction type AC servo motor.

In this, the reference input at which the motor shaft has to maintain at a certain position is given to the rotor of synchro generator as mechanical input theta. This rotor is connected to the electrical input at rated voltage at a fixed frequency.

The three stator terminals of a synchro generator are connected correspondingly to the terminals of control transformer. The angular position of the two-phase motor is transmitted to the rotor of control transformer through gear train arrangement and it represents the control condition alpha.

Initially, there exist a difference between the synchro generator shaft position and control transformer shaft position. This error is reflected as the voltage across the control transformer. This error voltage is applied to the servo amplifier and then to the control phase of the motor.

With the control voltage, the rotor of the motor rotates in required direction till the error becomes zero. This is how the desired shaft position is ensured in AC servo motors.