UNIT 7 SYNCHRONOUS MOTOR

Structure

7.1 INTRODUCTION

A synchronous machine can be used as a generator as well as motor without change in construction. The synchronous motor has same construction as alternator which was discussed in last unit Section 6.2. In this unit, we will turn our attention to the working principle and starting methods of synchronous motor. In three phase system, induction and synchronous motors are used. So we discuss the various similarities and dissimilarities of these motors. In power system, the over exited synchronous motor is used as a synchronous condenser. So, we discuss the effect of excitation and *V* curves before discussing synchronous condenser. Finally, you will consider hunting or surging in synchronous machines.

Objectives

After studying this unit, you should be able to

- explain working principle and starting methods,
- give a comparison of synchronous motor and induction motor,
- describe effect of excitation on motor current and power factor,
- explain the V curves,
- give a qualitative account of the performance of synchronous condenser, and
- explain hunting and damper winding.

7.2 SYNCHRONOUS MOTOR

A Synchronous Motor can run only at synchronous speed, $N_s = \frac{120f}{P}$. When the stator of motor is connected to a three-phase supply and driven up to its rated speed, it continues to run at the constant speed, converting the electrical energy into mechanical energy. The constructional features of a synchronous motor are same as that of synchronous generator. Rather, the Alternator can itself be made to run as a synchronous motor.

A synchronous motor works on the principle of magnetic inter-locking between stator and rotor poles and maintains a constant speed for all loads within its rated capacity. If such a motor is over-loaded to such an extent that it can no longer continue to maintain its synchronous speed, then it loses its synchronism and torque at which motor fails to run is called pull-out torque.

A synchronous motor is not a self-starting motor and there are various methods of starting the synchronous motor. They are :

(a) Starting as an Alternator, synchronizing it to the Infinite Bus Bar and then prime-mover is taken off. It starts running as synchronous motor, drawing power from the 3-phase supply of the Infinite Bus Bar.

(b) Starting it with a D.C. Shunt Motor and energizing the stator field winding by three-phase supply at synchronous speed.

(c) Constructional features incorporating additional damper windings.

7.2.1 Working Principle

Why is a synchronous motor not 'self-starting'?

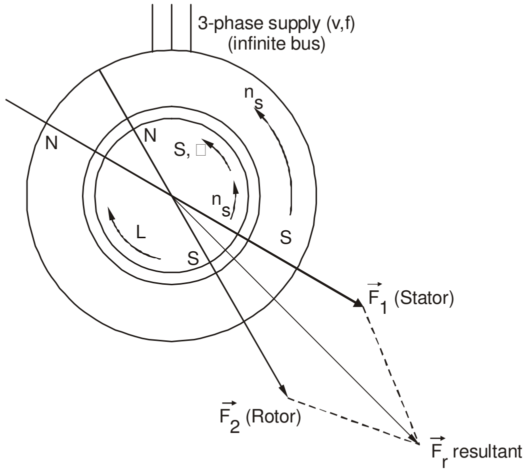


Figure 7.1 : Synchronous Machine with Round Rotor

Figure 7.1 shows a synchronous machine with a round rotor. The rotor is initially stationary with fixed North and South poles created by DC excitation.

Let the three phase winding of the stator be connected to a 3-phase supply of fixed voltage V (line) and fixed frequency f (This is known as the infinite bus.) As a result, three-phase currents flow in the stator winding creating a rotating magnetic field rotating at synchronous speed N_s in the counter-clockwise direction. Since the rotor is stationary and cannot pick-up speed instantaneously because of inertia of rotor, so the two fields move relative to each other, thereby resulting in zero starting torque and hence the motor is not self-starting.

By auxiliary means, if the rotor is brought upto a speed close to synchronous speed in the direction of rotation of field, the two fields interlock with each other and the relative speed of the rotor field with respect to stator field will become zero and then motor runs exactly at synchronous speed.

Alternator used as a Motor

If two alternators are running in parallel and the driving force of one is suddenly removed, then the machine continues to run as a motor, taking the electrical power necessary to drive it from the other machine, which is thereby loaded to a certain extent on this account. The supply of direct current to the field system of the motor must be maintained throughout. In addition, as is seen later, the motor must be brought up to the speed of synchronism and synchronized before the motoring action takes place.

Consider the case of the elementary two-pole, single-phase synchronous motor represented in Figure 7.2. This machine is supposed to be exactly the same as the corresponding alternator, and may have a stationary field system and a rotating armature, or vice versa, the current being led into the rotating element by means of slip rings. Consider the conductor arriving at *A* at the moment when the current is zero. The instantaneous value of the torque due to this conductor is also zero, since it is proportional to the product of the field strength and the armature current.

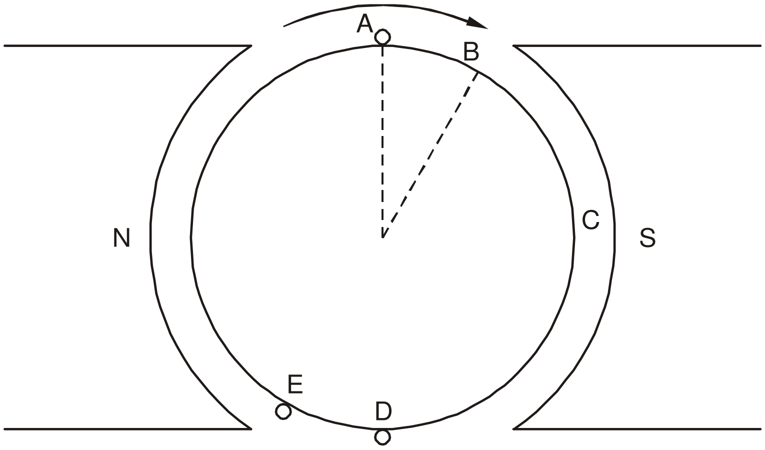
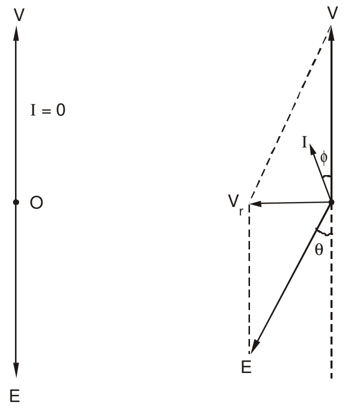


Figure 7.2 : Action of Synchronous Motor

The field strength is assumed to be constant throughout. A moment later the conductor arrives at *B*, the armature having rotated through an angle θ. Since the speed is assumed to be that of synchronism, the current has also advanced in phase by the same angle θ, this current being supposed to be flowing away from the observer. A torque is produced in a clockwise direction, which rotates the rotor in same direction. When the conductor reaches *C* the current has reached its maximum value, and by the time the conductor reaches *D* the current has died down to zero. Throughout the whole of this *half-revolution*, which has taken places while the current has advanced through half a cycle, the torque has been in the same direction. A little later the conductor arrives at *E*, but the current has now started to grow in the reverse direction. However, since this reverse current is cutting the magnetic flux in the reverse direction, the torque still tends to produce rotation in a clockwise direction. By the time the armature has completed one whole revolution the current has advanced through one whole period. This is the essential condition for the continuance of rotation, the armature must rotate synchronously with the current, and hence the machine is called a synchronous motor. The currents in the other armature conductors produce torques which aid one another. During the first half-period of the current they are cutting the field in one direction, and during the second half-period, when the current reverses, they are cutting the field in the other direction. The same principle operates in the case of three-phase synchronous motors.

7.2.2 No Load Conditions

When a synchronous motor is run up to synchronous speed and synchronized with an alternator the two machines act as generators in parallel. Considering the local circuit formed by the two armatures, these may be regarded as being in series with each other, but with their emfs in opposition. The armature of the motor, which is beginning run by prime mover and acting as generator, may therefore be considered as setting up a back emf equal to and opposite in phase with the applied emf, as shown in Figure 7.3(a). The resultant voltage in this circuit is zero, and so no current is supplied to the motor armature. Since the latter receives no power in an electrical form from the supply, it immediately commences to slow down when the mechanical driving power is removed.



(a) Ideal Conditions for Synchronizing (b) Actual Condition for Running

Figure 7.3

But as soon as the motor armature falls behind the position, that it should occupy if it maintained an absolutely synchronous speed, the back emf and the applied emf no longer neutralize each other, for, notwithstanding the fact that they are equal, no two voltage can completely neutralize each other unless they are in exact phase opposition. These conditions are shown in Figure 7.3(b), E now lagging behind V by an angle ($180° + \theta$). The applied and the back emfs now produce a resultant voltage V_r that causes a current I to flow through the motor armature, supplying it with a certain amount of power. If this power is sufficient to maintain the rotation, the motor continues to rotate synchronously, but always lagging by a constant small space angle θ. If the power supplied to the armature in this manner is not sufficient to overcome the losses at this speed, the armature is further retarded and lags behind by a larger angle. The effect of this is to increase the resultant voltage and the armature current, and the power supplied to the motor is thereby increased. This retarding action continues until the lag of the motor is sufficient to cause the required power to be supplied to the motor.

7.2.3 Effect of Load on Motor

When a load is put upon the shaft of the motor, the first tendency is to retard the rotation, but as soon as the armature commences to drop behind, the back emf lags by a rather larger angle than before. An increase in the angle of lag of the back emf causes an increase in the resultant voltage acting on the circuit, and this in turn causes an increased current to flow, with the result that the motor takes more power from the supply. The motor armature thus drops behind until its position, relative to that of the driving alternator, is such as to produce sufficient power to maintain the rotation.

An increase of load results in a further increase in the angle θ. This retards the back emf a little more and further increases V_r. The current is increased and more power is taken from the supply. Hence, θ is called power/load/toque angle.

During the transient period that the induced back emf is falling behind in phase the speed is momentarily less than that of synchronism, but when steady-state conditions are re-established the speed reverts to its former constant (synchronous) value.

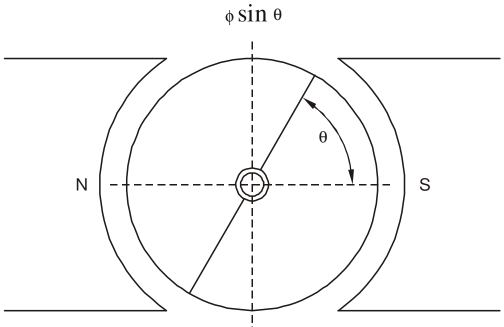


Figure 7.4 : Hypothetical Armature Flux

If by chance, the motor drop too far behind, the power that it takes from the supply will be greater than the required power and then armature will accelerate until it reaches the correct relative position and it may even get ahead of its correct relative position. If it happens like that it will again get retarded and the action is repeated. Some motors are subject to this overshooting of the mark, when a motor is constantly retarded and accelerated in this manner, the effect is called hunting or phase-swinging.

If the load is excessive, the momentary reduction in speed may be such as to bring the torque down to zero, or even to cause it to reverse in direction. The synchronous motor then falls out of synchronism and comes to rest.

A change in the excitation causes a change in the induced e.m.f., E. If the excitation is reduced the induced e.m.f., E, is also reduced as shown in Figure 7.5. This causes the resultant voltage V_r to be retarded in phase, and since the current I lags behind V_r by a constant angle α, as α is decided by armature circuit parameters, the current is also retarded in phase.

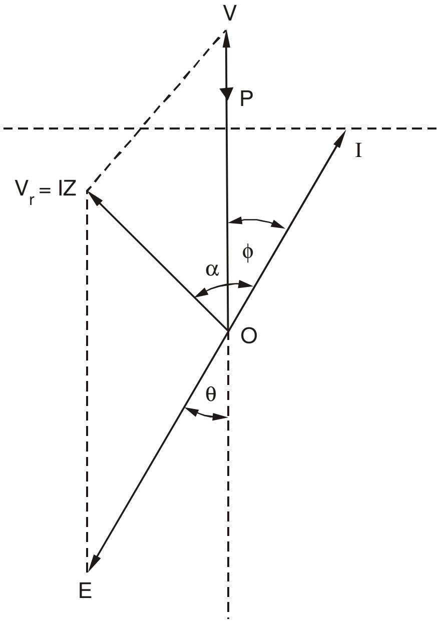


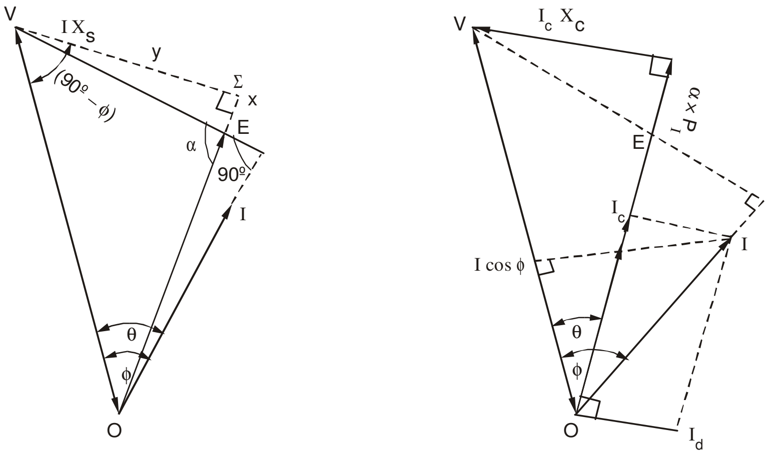
Figure 7.5 : Weakened Excitation

With a weak field current (under-excited) the armature current lags and the motor operates at a lagging power-factor. Similarly, with a strong field current (over-excited) the motor operates on a *leading power-factor*.

7.3 POWER OUTPUT

The vector diagrams shown in Figure 7.6(a), by neglecting all losses and reversing E so that V_r becomes the difference between V and E instead of the sum. This diagram is now applicable to a cylindrical rotor synchronous motor where the synchronous reactance does not vary when the position of the rotor is changed with respect to position of the stator. With a lagging current, the electrical power developed per phase is now $-EI \cos (\phi - \theta)$ so that the mechanical power output per phase is $+ EI \cos (\phi - \theta)$ and, if all losses be neglected, this is equal to the power input per phase, $VI \cos \phi$. Assume the synchronous reactance to be constant and equal to X_s. Since armature resistance is to be neglected, the current I must be in quadrature with $I X_s$. The angle θ is determined by the load, and the value of E by the excitation.

For a particular load and a constant applied voltage V, therefore, the triangle OEV is defined, so that $I X_s$ is fixed in magnitude and phase. This, in turn, determines the magnitude and phase of the current I, since X_s is assumed to be constant.



(a) Cylindrical Rotor **(b) Salient Pole**

Figure 7.6 : Vector Diagram of Synchronous Motor Neglected Losses

Consider the triangle *MEV*, $x = V \sin \theta$, $y = V \cos \theta - E$

$$(I\,X_s)^2 = V^2 + E^2 - 2\,VE \cos \theta .$$

$$(I\,X_s)^2 = x^2 + y^2$$

$$= V^2 \sin^2 \theta + (V \cos \theta - E)^2$$

$$= V^2 \sin^2 \theta + V^2 \cos^2 \theta + E^2 - 2VE \cos \theta$$

$$= V^2 (\sin^2 \theta + \cos^2 \theta) + E^2 - 2VE \cos \theta$$

Also,

$$\frac{IX_s}{\sin \theta} = \frac{E}{\sin (90° - \phi)} = \frac{E}{\cos \phi}$$

$$\cos \phi = \frac{E \sin \theta}{IX_s} = \frac{E \sin \theta}{\sqrt{V^2 + E^2 - 2VE \cos \theta}}$$

and

$$I = \frac{\sqrt{V^2 + E^2 - 2VE \cos \theta}}{X_s}$$

Again, it follows that the power input per phase = power output per phase (neglecting losses) = $VI \cos \phi$

$$= V \times \frac{\sqrt{V^2 + E^2 - 2VE \cos \theta}}{X_s} \times \frac{E \sin \theta}{\sqrt{V^2 + E^2 - 2VE \cos \theta}}$$

$$= \frac{VE \sin \theta}{X_s}$$

With constant, applied voltage and excitation, therefore, $\sin\theta$ is proportional to the load, although when losses are taken into consideration this proportionality, while still approximately true, is no longer mathematically correct.

On no-load and neglected losses, $\theta = 0°$, $\phi = 90°$ and $I = \frac{V - E}{X_s}$, but allowing for losses, θ becomes slightly greater than 0°, ϕ slightly less than 90° and I slightly greater than $\frac{V - E}{X_s}$.

Under condition of constant load, θ varies slightly for different values of I and $\cos\phi$.

For a salient-pole synchronous motor, the vector diagram may be modified as shown in Figure 7.6(b) which makes use of the double-reaction theory. Still neglecting losses the electrical power input per phase (= mechanical power output per phase) is again $P = VI\cos\phi = V(I_c\cos\theta - I_d\sin\theta)$. Also from the vector diagram,

$$I_d X_d = V\cos\theta - E,$$

so

$$I_d = \frac{V\cos\theta - E}{X_d}$$

and

$$I_c X_c = V\sin\theta,$$

so

$$I_c = \frac{V\sin\theta}{X_c}$$

Therefore

$$P = V\left(\frac{V\sin\theta\cos\theta}{X_c} - \frac{V\sin\theta\cos\theta - E\sin\theta}{X_d}\right)$$

$$= \frac{VE}{X_d}\sin\theta + \frac{V^2}{X_c}\sin\theta\cos\theta - \frac{V^2}{X_d}\sin\theta\cos\theta$$

$$= \frac{VE}{X_d}\sin\theta + \frac{V^2}{2}\left(\frac{1}{X_c} - \frac{1}{X_d}\right)\sin 2\theta$$

The same formula shall be applicable for a salient pole alternator, but while E is usually larger than V in an alternator, the reverse is the case in a synchronous motor.

7.4 STARTING OF SYNCHRONOUS MOTOR

A synchronous motor is not self-starting, so it is necessary to start it by some auxiliary means. There are two methods generally in use, those being:

(a) by means of an auto-transformer through tap starting or damping winding starting, and

(b) by means of an auxiliary direct coupled induction motor.

Tap Starting

A three-phase synchronous motor is here provided with a special cage winding fitted to the field system. This consists of a number of bars fitted into slots or holes in the pole shoes where salient poles are employed, all the bars being joined at each end by a stout copper end ring. This cage winding is thus seen to be a development of the system of damping grids. In a cylindrical rotor the cage conductors are placed in the rotor slots above the main field winding, a short-circuiting ring being fitted at each end as before.

The stator currents set up a rotating magnetic flux that cuts the cage winding on the field system and induces currents in it. A torque is developed and the motor runs up to a speed a little less than that of synchronism, as an induction motor. The DC exciting current, if obtained from a separate source, is now switched on, and sets up definite poles on the rotor (the field system), these poles slowly slipping past the poles due to the rotating flux set up by the stator (armature) currents. The relative speed of the two sets of poles is due to slip, and decreases as slip reduces. As the DC field strength is gradually increased, the two sets of pole suddenly lock with each other, the motor thus pulling into synchronism automatically. If the synchronous motor has its own exciter, this develops very little emf in the early stages, but suddenly excites when a certain speed is reached, and thereafter the action proceeds as before.

No synchronizing gear is required, and in addition the cage winding acts as a damper winding when running, thus serving to prevent hunting.

On account of the large starting current required by this method, it is usual to start on a reduced voltage, as with a cage-type induction motor. This reduced voltage at starting is derived from tappings on an auto transformer, and the method is known as tap-starting.

Starting by Auxiliary Motor

An alternative method of starting is to use a small auxiliary direct-coupled induction motor, the stator windings of which are connected in series with the stator windings of the main synchronous motor. All six ends of the stator windings of the starting induction motor are brought out, the three front ends being connected to the supply and the three rear ends to the synchronous motor stator terminals, as shown in Figure 7.7. The rotor of the starting motor is of the short-circuited type, and is frequently made of a solid steel cylinder without any slots or winding at all. The eddy currents induced in this rotor set up sufficient torque to enable the motor to start.

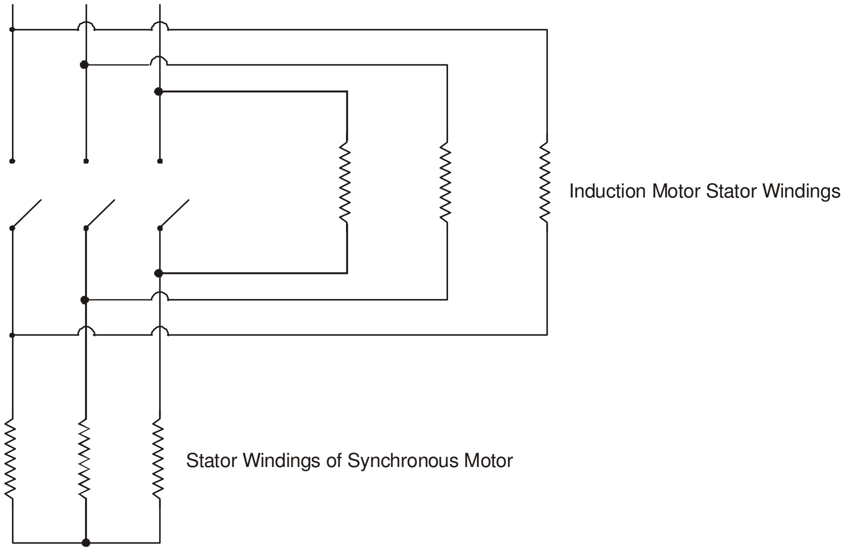


Figure 7.7 : Starting with Auxiliary Motor

When first switched in, the greater part of the voltage appears across the starting motor on account of the lower impedance of the synchronous motor stator windings. As the speed rises, however, these conditions are changed gradually and automatically, until when near synchronism nearly all the voltage is across the main synchronous motor. The exciter, which is permanently connected to the synchronous motor field winding, builds up a considerable voltage when near full speed, and the DC excitation, increasing automatically, suffices to pull the synchronous motor into synchronism. The auxiliary starting motor now has its stator windings short circuited, thus cutting it out of circuit and throwing the whole of the supply voltage on to the synchronous motor.

V-Curves

If the excitation is varied, the armature current will vary for constant load. When armature curve is plotted against exciting current, the resulting curve takes the shape of word *V*, as shown in Figure 7.8, and is known as a *V*-curve. With one particular excitation the armature current is a minimum for unity power-factor. For smaller exciting currents, the armature mmf, F_a is made to lag, since the flux, ϕ, and the resultant m.m.f., F_r are the same as before. A lagging armature mmf, F_a, is only brought about by a lagging armature current, *I* and motor operates as lagging *PF* load. For larger exciting currents, the armature mmf, F_a, is made to lead, in order that F_r shall again remain unaltered and motor operates as leading *PF* load. This effect can be seen more clearly from the approximate vector diagram given in Figure 7.5. A low excitation here corresponds to a reduced back emf, giving rise to a resultant voltage that leads the applied voltage by a relatively small angle, thus causing the current to lag by a considerable angle. Since the power-factor is low, the current is relatively large. As the exciting current is increased, the back e.m.f. is also increased, thus swinging the resultant voltage vector round and advancing it in phase. The current is also advanced in phase, its magnitude decreasing since the power-factor is increasing. When the current becomes in phase with the applied voltage it reaches a minimum value, the power-factor being unity. A further increase in exciting current causes an increase in the armature current, which is now a leading one.

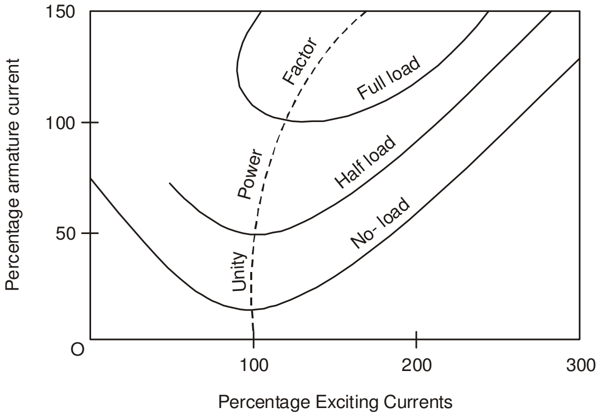


Figure 7.8 : *V*-Curves

The excitation corresponding to unity power-factor and minimum current is called the normal exciting current for that particular load.

A smaller exciting current (under-excitation) results in a lagging armature current and a larger exciting current (over-excitation) in a leading armature current, due to the reduction and increase in the induced back e.m.f. respectively.

The excitation necessary for unit power-factor goes up as the load increases. On no-load the point on the *V*-curve is sharply accentuated, but if the machine is loaded the tendency is to round off the point, this effect being more marked at the higher loads.

7.5 HUNTING AND DAMPER WINDING

Sudden changes of load on synchronous motors sometimes set up oscillations that are superimposed upon the normal rotation, giving rise to periodic variations of a very low frequency in speed. This effect is known as hunting or phase-swinging. Occasionally, the trouble is aggravated by the motor having a natural period of oscillation approximating to the hunting period, when it is possible for the motor to phase-swing into the unstable region, thus causing it to fall out of synchronism.

Damper Winding

The tendency to hunt can be minimized by the addition of a mechanical flywheel, but this practice is rarely adopted, the use of a damper winding being preferred.

Assuming that the speed of rotation of the magnetic flux is constant, there is no relative movement between the flux and the damper bars if the rotation of the field system is also absolutely uniform. No emfs are induced in the damper bars and no current flows in the damper winding, which is not operative. Whenever any irregularity takes place in the speed of rotation, however, the polar flux moves from side to side of the pole, this movement causing the flux to move backwards and forwards across the damper bars. Emfs are induced in the damper bars forwards across the damper winding. These tend to damp out the superimposed oscillatory motion by absorbing its energy.

The damper winding, thus, has no effect upon the normal average speed, it merely tends to damp out the irregularities in the speed, thus, acting as a kind of electrical flywheel.

In the case of a three-phase synchronous motor the stator currents set up a rotating mmf rotating at uniform speed (except for certain minor harmonic effects), and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars.

7.6 SYNCHRONOUS CONDENSER

We know that over excited synchronous motor operates at unity or leading power factor. Generally, in large industrial plants the load power factor is lagging. The specially designed synchronous motor which runs at zero load takes leading current approximately near to 90° leading. When it is connected in parallel with inductive loads to improve power factor, it is known as synchronous condenser.

Compared to static capacitor the power factor can improve easily by variation of field excitation of motor. Phasor diagram of a synchronous condenser connected in parallel with an inductive load is given below.

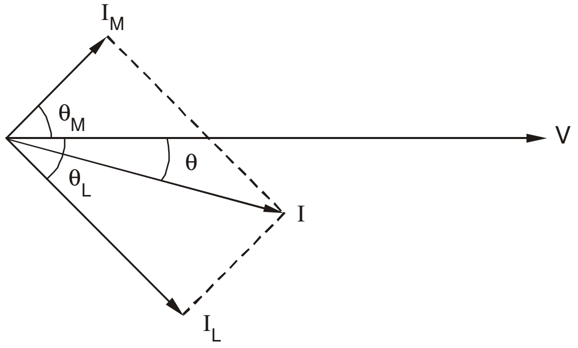


Figure 7.9 : Phasor Diagram

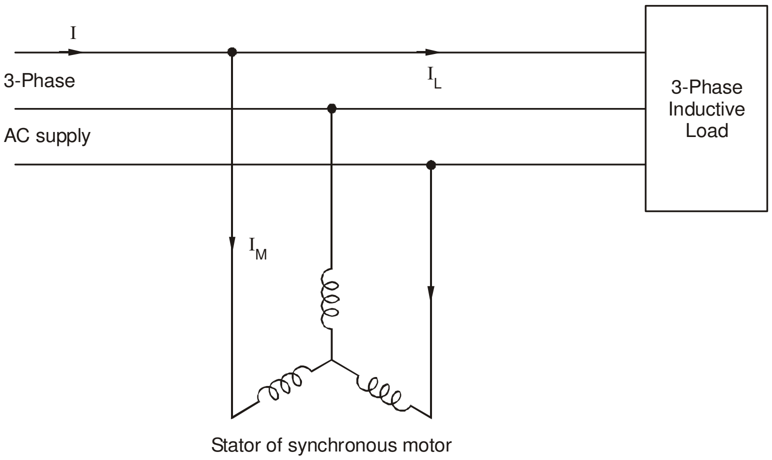


Figure 7.10 : Connection of Synchronous Motor with Connected Load

7.7 COMPARISON OF INDUCTION AND SYNCHRONOUS MOTOR

Sl. No.	Induction Motor	Synchronous Motor
1.	It does not need dc excitation and is singly-excited machine	It's a doubly-excited machine and requires dc and ac both
2.	It possesses inherent starting torque	Its requires external means for starting
3.	Its speed decreases with increase in load and never runs at N_S	It operates at synchronous speed
4.	Speed control is, therefore, possible	Speed control is not possible
5.	It can supply only mechanical loads	It can supply mechanical loads and can be used for improving system power factor
6.	It operates only at lagging P.F.	It can operate for both leading and lagging P.F.
7.	Its maximum torque is proportional to square of the supply voltage	Its maximum torque is proportional to the supply voltage
8.	Induction motor with speeds above 500 RPM and rating below 120 KW are cheaper than synchronous motors	Synchronous motors with speed below 500 RPM and ratings more than 40 KW or with medium speeds from 500-1000 rpm and ratings above about 500 KW are costly, i.e. than induction motor

Example 7.1

A 10 kW, 400 volt, 3-phase, star connected synchronous motor has a synchronous impedance of 0.3 + j 2.5. Find the voltage to which the motor must be excited to give a full load output at 0.866 leading pf. Assume the armature efficiency of 90%. Also calculate the total mechanical power developed, losses in armature winding and iron plus excitation cases.

Solution

$$\text{Input to the motor } = \frac{\text{Output}}{\text{Efficiency}} = \frac{10}{0.9}\text{kW } = 11.11 \text{ kW}$$

$$\text{Applied voltage per phase } V = \frac{400}{\sqrt{3}}\text{volts} = 230.94 \text{ Volts}$$

$$\text{Input current } I_a = \frac{10\times 10^3}{0.9\times\sqrt{3}\times 400\times 0.866}$$

$$= 18.52 \text{ Amp}$$

$$Z_s = \sqrt{(0.3)^2 + (2.5)^2} = 2.52\ \Omega$$

$$IZ_s = 18.52\times 2.52 = 46.67 = E_R$$

In the phasor diagram shown in Figure 7.11.

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

$$\alpha = \tan^{-1}\frac{2.5}{0.3} = 83.157$$

$$\phi = \cos^{-1} 0.866 = 30°$$

$$\alpha + \phi = 113.157°$$

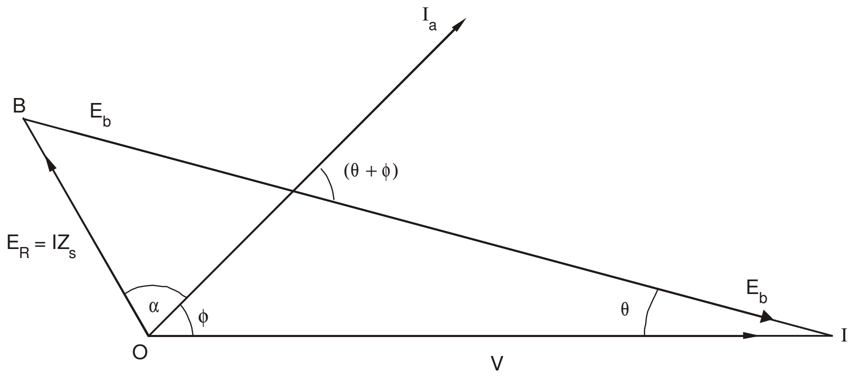


Figure 7.11

In triangle *OAB* of Figure 7.11.

$$= [I\,Z_s \cos\,(\theta + \phi - 90°)]^2 + [V + I\,Z_s \cos\,\{80^o - (\phi + \theta)\}]^2$$

$$= (Z\,Z_s)^2 \sin^2\,(\theta + \phi) + [V + I\,Z_s \cos\,(\theta + \phi)]^2$$

$$= (I\,Z_s)^2 \sin^2\,(\theta + \phi) + V^2 + (I\,Z_s)^2 \cos^2\,(\theta + \phi)$$

$$- 2V\,(I\,Z_s) \cos\,(\theta + \phi)$$

$$= V^2 + (I\,Z_s)^2 - 2V\,(I\,Z_s) \cos\,(\alpha + \phi)$$

$$E_b^2 = (230.94)^2 + (46.67)^2 - 2 \times 230.94 \times 46.67 \cos 113.157$$

or $E_b = 252.96$ Volts

Line value of induced emf. = $\sqrt{3} \times 252.96 = 438.14$ Volts

Also $\dfrac{E_R}{\sin\alpha} = \dfrac{E_b}{\sin(\theta + \phi)}$

or $\sin\alpha = \dfrac{E_R}{E_b} \sin(\theta + \phi)$

or $\sin\alpha = \dfrac{46.67}{252.96} \sin(113.157)$

or $\alpha = 9.766$

$$= \frac{E_b V}{Z_s} \cos(\theta - \alpha) - \frac{E_b^2}{Z_s} \cos\theta$$

Mechanical power developed per phase can also be found by the relation.

∴ Mechanical power developed phase

$$= \frac{252.96 \times 230.94}{2.52} \cos\,(83.157^o - 9.766^o)$$

$$= \frac{-\,252.962 \times \cos\,3.157^o}{2.52} = 3.6 \text{ kW}$$

$I^2\,R_a$ loss in armature windings

$$= 3 \times 18.52^2 \times 0.3 = 0.31 \text{ kW}$$

∴ Iron and excitation losses

$$= P_m - P_0$$

$$= 10.8 - 1.0 = 0.8 \text{ kW}$$

Also, mechanical power developed

$$P_m = P_m - \text{armature copper loss}$$

$$= 11.11 - 0.31 = 10.8 \text{ kW}$$

SAQ 1

The full load current of a 6600 volt, 3-phase star connected synchronous motor is 80 amperes at 0.83 power factor leading. The resistance and synchronous reactance of the motor are 3 ohms and 22 ohms per phase respectively. Calculate the phase and line value of emf induced, the efficiency and the bhp of the motor. The stray losses are equal to 35 kW.

Example 7.2

The line current of 11 KV, three phase, star connected synchronous motor is 60 amperes at a power factor of 0.8 leading. The effective resistance and synchronous reactance per phase are respectively 1 ohm and 30 ohms. Find the phase and the line value of the induced emf and also the power input of the motor.

Solution

Power input to the motor $= \sqrt{3}\, V_L I_L \cos\phi$

$$= \sqrt{3} \times 11000 \times 60 \times 0.8 \text{ watts} = 914523 \text{ watts}$$

$$= 914.52 \text{ kW}$$

Applied voltage per phase $= \dfrac{11000}{\sqrt{3}} = 6350.853 \text{ volts}$

or $V_{ph} = 6350.853 \text{ volts}$

Induced emf per phase = $V_{ph} - I_{ph} Z_s$

$$I_L = 60\underline{\angle \cos^{-1} 0.8} = 60\,(0.8 + j\,0.6) = 60 \angle 36.87^{\circ}$$

For star connection $I_{ph} = I_L = 60\,(0.8 + j\,0.6) = 60 \angle 36.87^{\circ}$

$$Z_s = (1 + j\,30) = 30.017 \angle 88.09^{\circ}$$

∴ Induced emf per phase $E_{ph} = 6350.853 - I_{ph} Z_s$

or $E_{ph} = 6350.853 - 60\underline{\angle 36.87^{\circ}} \times 30.017\underline{\angle 88.09^{\circ}}$

$$= 6350.853 - 1801.02\underline{\angle 124.96^{\circ}}$$

$$= 6350.853 - 1801.02\,(-0.573 + j\,0.8195)$$

$$= 7382.84 - j\,1475.94$$

$$= 7528.92\underline{\angle -11.3^{\circ}} \text{ Volts.}$$

Line value of induced emf $E_L = \sqrt{3}\, E_{ph}$

$$= \sqrt{3} \times 7528.92 = 13040.47 \text{ Volts}$$

Example 7.3

The load in a factory is 800 kVA at 0.85 power factor lagging and in addition there is a synchronous motor having an input of 200 KW. Determine the input to the synchronous motor in kVA and the power factor at which it must operate, if the power factor of the combined load should be 0.95 lagging.

Solution

Here, $\cos \phi_1 = 0.85$, $\phi_1 = \cos^{-1} 0.85 = 31.788^{\circ}$, $\sin \phi_1 = 0.52678$

Active power drawn by the factory

$$W_1 = \text{kVA} \cos \phi_1 = 800 \times 0.85 = 680 \text{ kW}$$

Reactive power drawn by the factory

$$Q_1 = \text{kVA} \sin \phi_1 = 800 \times 0.52678 = 421.43 \text{ KVAR (lagging)}$$

Active power drawn by the synchronous motor

$$W_2 = 200 \text{ kW}$$

Total active power drawn = $W_1 + W_2 = 680 + 200 = 880$ kW

Power factor of the combined load = $\cos \phi = 0.95$ (lagging),
$\phi = \cos^{-1} 0.95 = 18.1949^{\circ}$

$$\therefore \quad \tan \phi = 0.32868$$

$$\text{But} \quad \tan\phi = \frac{\text{Total reactive load}}{\text{Total active load}}$$

$$\therefore \quad \text{Total reactive load} = \text{Total active load} \times \tan \phi$$

$$= 880 \times 0.32868$$

$$= 289.242 \text{ KVAR (lagging)}$$

Reactive power supplied by the motor

$$= 289.242 - 421.43 = - 132.188 \text{ KVAR}$$

Here −ve sign indicates leading reactive power

$$\text{KVA rating of the motor} = \sqrt{(\text{kW})^2 + (\text{KVAR})^2}$$

$$= \sqrt{(200)^2 + (132.188)^2} = 239.737 \text{ kVA}$$

$$\text{Power factor of the motor } \cos \phi_2 = \frac{\text{Active power}}{\text{kVA rating}}$$

$$= \frac{200}{239.737} = 0.834 \text{ (leading)}$$

SAQ 2

(a) The load on a factory is 1200 kVA at 0.8 power factor lagging. An addition synchronous motor is to be installed taking an input power of 164 kW and excited so that the power factor of the combined load is 0.95 lagging. Determine the kVA rating of the motor and the power factor at which it operates.

(b) A 230 V, 3-phase, 60 Hz star connected cylindrical rotor synchronous motor has a synchronous reactance of 11 ohms per phase. When it delivers 200 hp the efficiency is found to be 90 percent exclusive of field loss, and the power angle is 15 electrical degree as measured by a stroboscope. Neglect ohmic resistance and determine :

(i) The induced excitation voltage per phase,

(ii) The line current, and

(iii) The power factor.

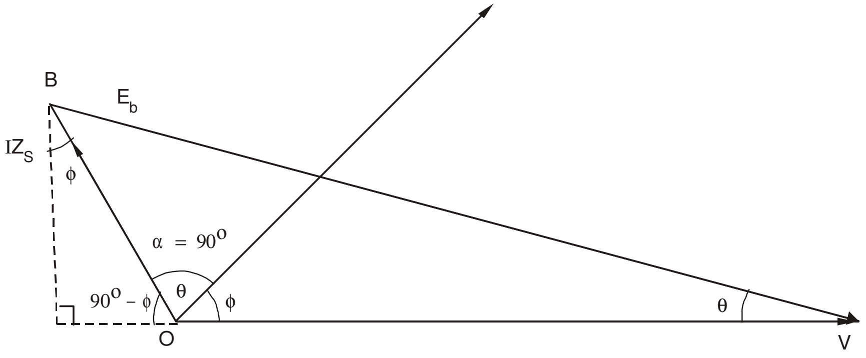


Figure 7.12

7.8 SUMMARY

In Section 7.2 after a brief consideration of working principle of synchronous motor you learnt how to start a synchronous motor. You were than introduced the effect of excitation on motor current and power factor in next section. You also learnt about V curves and hunting. Finally, the application of synchronous motor as condenser for power factor improvement was considered.

7.9 ANSWERS TO SAQs

SAQ 1

The phasor diagram for the motor is shown in Figure 7.13.

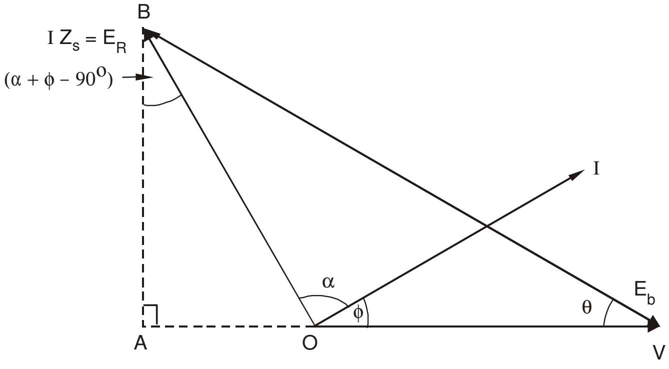


Figure 7.13

Voltage per phase $V = \dfrac{6600}{\sqrt{3}}$ Volts.

or $V = 3810.5$ volts

$R = 3\Omega s,\quad X_s = 22\Omega s$

$Z_s = \sqrt{R^2 + X_s^2} = \sqrt{(3)^2 + (22)^2} = 22.2\ \Omega$

$IZ_s = 80 \times 22.2 = 1776$ volts

$\tan\alpha = \dfrac{X_s}{R} = \dfrac{22}{3} = 7.33 \qquad \therefore\ \alpha = 82.235$

$\cos\phi = 0.83$ leading $\qquad \therefore\ \phi = 33.901$

The angle $\alpha + \phi = 116.136$

$\cos(\alpha + \phi) = -0.44$

From the phasor diagram,

$$E_b^2 = V^2 + (IZ_s)^2 - 2V(IZ_s)\cos(\alpha + \phi)$$

or $E_b^2 = (3810.5)^2 + (1776)^2 - 2(3810.5)(1776)(-0.44)$

$\therefore$ $E_b = 4861$ volts

$\therefore$ Line value of induced emf $= \sqrt{3} \times 4861$

$= 8419.5$ volts

Total input to the motor $= \sqrt{3}\, V_L I_L \cos\phi$

$= \sqrt{3} \times 6600 \times 80 \times 0.83$

$= 759053.94$ watts

I^2R losses $= 3 \times (80)^2 \times 3$

$= 57600$ watts

Stray losses = 35000 watts

Total losses = 92600 watts

Output = input − losses = 666453.94

$\therefore$ Efficiency $= \dfrac{\text{output}}{\text{input}} \times 100$

$= \dfrac{666453.94}{759053.94} \times 100 = 87.8\%$

BHP of the motor $= \dfrac{\text{Output}}{746}$

$= \dfrac{666453.94}{746}$

$= 893.37$ BHP

SAQ 2

(a) $\cos \phi_1 = 0.8$, $\phi_1 = 36.87^{\circ}$, $\sin \phi_1 = 0.6$

Active power drawn by the factory

$$W_1 = \text{kVA} \cos \phi_1 = 1200 \times 0.8 = 960 \text{ kW}$$

Reactive power drawn by the factory

$$Q_1 = \text{kVA} \sin \phi_1 = 1200 \times 0.6 = 720 \text{ KVAR lagging}$$

Active power drawn by the motor

$$W_2 = 164 \text{ kW}$$

Total active power drawn = $W_1 + W_2 = 960 + 164 = 1124$ kW

Power factor of the combined load,

$$\cos \phi = 0.95 \text{ lagging}$$

$$\therefore \quad \tan \phi = 0.3287$$

But $\tan\phi = \dfrac{\text{Total reactive power}}{\text{Total active power}}$

$$\therefore \quad \text{Total reactive power} = 0.3287 \times 1124 \; KVAR$$

$$= 369.46 \text{ KVAR (lagging)}$$

Reactive power supplied by motor = 369.46 − 720

$$= -\,350.54 \text{ KVAR}$$

Here −ve sign indicates leading reactive power

KVA rating of the motor = $\sqrt{(\text{kW})^2 + (\text{KVAR})^2}$

$$= \sqrt{(164)^2 + (350.54)^2} = 387 \text{ kVA}$$

Power factor of the motor $\cos \phi_2 = \dfrac{\text{Active power}}{\text{kVA rating}}$

$$= \frac{164}{387} = 0.424 \text{ (leading)}$$

(b) Applied voltage per phase $V = \dfrac{2300}{\sqrt{3}}$

$$= 1327.9 \text{ Volts}$$

Input to the motor $= \dfrac{200 \times 746}{0.9}$ Watts = 165.78 kW

Line current $= I = \dfrac{200 \times 746}{0.9 \times \sqrt{3} \times 2300 \cos \phi}$

or $\quad I \cos \phi = 41.61$ or $I = \dfrac{41.61}{\cos \phi}$

Since resistance is neglected

$$\alpha = \tan^{-1} \frac{X_s}{R} = \tan^{-1} \frac{11}{0} = 90^{\circ}$$

$$E_R = \text{Reactance drop} = I \, X_s$$

$$= 11 I = 11 \times \frac{41.61}{\cos \phi}$$

From the voltage triangle we can write

$$\frac{E_R}{\sin\,\theta} = \frac{E_b}{\sin\,(\alpha + \phi)}$$

or
$$\frac{11 \times 41.61}{\cos\,\phi\,\sin\,15^{o}} = \frac{E_b}{\sin\,(90^{o} + \phi)} = \frac{E_b}{\cos\,\phi}$$

or
$$E_b = \frac{11 \times 41.61}{\sin\,15^{o}} = 1768.45 \text{ Volts per phase}$$

$$\tan\,\phi = \frac{AO}{AB} = \frac{E_b \cos\,\theta - V}{E_b \sin\,\theta}$$

or
$$\tan\,\phi = \frac{1768.45\,\cos\,15 - 1327.9}{1768.45\,\sin\,15^{o}} = 0.8308$$

$$\phi = \tan^{-1}\,0.8308 = 39.71^{o}$$

∴
$$\cos\,\phi = 0.769$$

$$\text{Line current } = \frac{41.61}{\cos\phi} = \frac{41.61}{0.769} = 54.11\,\text{amp.}$$

FURTHER READING

Cotton H. (1996), *Advanced Electrical Technology*, Wheeler Publishing.

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Wadera (2004), *Network Theory*, New Age International.

Mittal (2001), *Basic Electrical Engineering*, G. K. Publication.

Ashfaq Hussain (2001), *Fundamentals of Electrical Engineering*, Dhanpath Rai Publicaton.

Naidu Kamakshaiah (2001), *Introduction to Electrical Engineering*, Tata McGraw-Hill.

Schuler, Fowler (1993), *Electric Circuit Analysis*, Macmillan/McGraw-Hill.

ELECTRICAL TECHNOLOGY

You will be introduced to Electrical Technology in this course. The Electrical Technology course is designed for the basic knowledge for the repair, installation and maintenance of electrical systems. The curriculum will be a blend of both fundamental electrical systems in the electrical technology field. Diploma holders have to play the role as supervisor in Electrical Technology areas and also to assist in carrying out the analysis and investigation work. This subject finds utility in understanding the concepts in other electrical subjects such as electrical power system, electrical measurement and instrumentation and electrical machines, etc.

There are seven units in this course.

Unit 1 deals with Circuits and Networks. Electrical circuits and networks subject is categorised under engineering science group. Mainly this subject includes the concept and principles of circuits and circuit analysis. You will be able to know that define the basic elements; electric circuit terminology, energy source used in electric circuit and also AC waveform and its various quantities.

Networks theorems have been discussed in Unit 2. In electrical network analysis, the fundamental rules are Ohm's law and Kirchhoff's laws. While these humble laws may be applied to analyse just about any circuit configuration.

Unit 3 deals with DC machines. DC machine is an industrial design and machining centre that designs and manufacturers close tolerance components. From prototype to full production runs, DC machine can help you from the earliest stages of concept development to the finished, assembled product.

In Unit 4, you will be introduced to Transformer. A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors – the transformer's coils. Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundred of tone used to interconnect portions of national power grids. All operate with the same basic principles, although the range of designs is wide. Transformers are essential for high voltage power transmission, which makes long distance transmission economically practical.

Induction Motors have been discussed in Unit 5. An induction motor (or asynchronous motor or squirrel-cage motor) is a type of alternating current motor where power is supplied to the rotor by means of electromagnetic induction. These motors are probably the simplest and most rugged of all electric motors. They consists of two basic electrical assemblies : the wound stator and the rotor assembly.

Unit 6 deals with Alternator (Synchronous Generator). An alternator is an electromechanical device that converts mechanical energy to electrical energy in the form of alternating current. Most alternators use a rotating magnetic field but linear alternators are occasionally used. In principle, any AC electrical generator can be called an alternator, but usually the word refers to small rotating machines driven by automatic and other internal combustion engines.

We had discussed Synchronous Motor in Unit 7. A synchronous electric motor is an AC motor distinguished by a rotor spinning with coils passing magnets at the same rate as the alternating current and resulting magnetic field which drives it. A synchronous and brushes are used to conduct current to the rotor. The rotor poles connect to each other and move at the same speed – hence the name synchronous motor. We hope that the knowledge, information and experience given in the course would help you to enhance your practical as well as theoretical knowledge of Electrical Technology.