LECTURE NOTES

ON

AC MACHINES

2017 – 2018

IV Semester (IARE-R16)

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UNIT-I

Poly Phase Induction Machines

Introduction

The induction machine was invented by NIKOLA TESLA in 1888. Right from its incep-tion its ease of manufacture and its robustness have made it a very strong candidate for electromechanical energy conversion. It is available from fractional horsepower ratings to megawatt levels. It finds very wide usage in all various application areas. The induction machine is an AC electromechanical energy conversion device. The machine interfaces with the external world through two connections (ports) one mechanical and one electrical. The mechanical port is in the form of a rotating shaft and the electrical port is in the form of terminals where AC supply is connected. There are machines available to operate from three phase or single phase electrical input. In this module we will be discussing the three phase induction machine. Single phase machines are restricted to small power levels.

The Rotating Magnetic Field

The principle of operation of the induction machine is based on the generation of a rotating magnetic field. Let us understand this idea better.

Click on the following steps in sequence to get a graphical picture. It is suggested that the reader read the text before clicking the link.

- Consider a cosine wave from 0 to 360°. This sine wave is plotted with unit amplitude.

- Now allow the amplitude of the sine wave to vary with respect to time in a simisoidal fashion with a frequency of 50Hz.Let the maximum value of the amplitude is, say, 10 units. This waveform is a pulsating sine wave.

  $$i_{apk} = I_m \cos 2\pi.50.t \qquad (1)$$

- Now consider a second sine wave, which is displaced by 120° from the first

- (lagging). . .
- And allow its amplitude to vary in a similar manner, but with a 120°time lag.

$$i_{bpk} = I_m \cos(2\pi.50.t - 120^\circ) \qquad (2)$$

- Similarly consider a third sine wave, which is at 240° lag. . .
- And allow its amplitude to change as well with a 240° time lag. Now we have three pulsating sine waves.

$$i_{cpk} = I_m \cos(2\pi.50.t - 240^\circ) \qquad (3)$$

Let us see what happens if we sum up the values of these three sine waves at every angle. The result really speaks about Tesla's genius. What we get is a constant amplitude travelling sine wave!

In a three phase induction machine, there are three sets of windings — phase A winding, phase B and phase C windings. These are excited by a balanced three-phase voltage supply. This would result in a balanced three phase current. Equations 1 — 3 represent the currents that flow in the three phase windings. Note that they have a 120° time lag between them.

Further, in an induction machine, the windings are not all located in the same place. They are distributed in the machine 120° away from each other (more about this in the section on alternators). The correct terminology would be to say that the windings have their axes separated in space by 120°. This is the reason for using the phase A, B and C since waves separated in space as well by 120°.

When currents flow through the coils, they generate mmfs. Since mmf is proportional to current, these waveforms also represent the mmf generated by the coils and the total mmf. Further, due to magnetic material in the machine (iron), these mmfs generate magnetic flux, which is proportional to the mmf (we may assume that iron is infinitely permeable and non-linear effects such as hysterisis are neglected). Thus the waveforms seen above would also represent the flux generated within the machine. The net result as we have seen is a travelling flux wave. The x-axis would represent the space angle in the machine as one travels around the air gap. The first pulsating waveform seen earlier would then represent the a-phase flux, the second represents the b-phase flux and the third represents the c-phase.

This may be better visualized in a polar plot. The angles of the polar plot represent the space angle in the machine, i.e., angle as one travels around the stator bore of the machine. Click on the links below to see the development on a polar axes.

- This plot shows the pulsating wave at the zero degree axes. The amplitude is maximum at zero degree axes and is zero at 90° axis. Positive parts of the waveform are shown in red while negative in blue. Note that the waveform is pulsating at the $0 - 180^\circ$ axis and red and blue alternate in any given side. This corresponds to the sinewave current

  changing polarity. Note that the maximum amplitude of the sinewave is reached only along the $0 - 180^\circ$ axis. At all other angles, the amplitude does not reach a maximum of this value. It however reaches a maximum value which is less than that of the peak occuring at the $0 - 180^\circ$ axis. More exactly, the maximum reached at any space angle θ would be equal to $\cos\theta$ times the peak at the $0 - 180^\circ$ axis. Further, at any space angle θ, the time variation is sinusoidal with the frequency and phase lag being that of the excitation, and amplitude being that corresponding to the space angle.

- This plot shows the pulsating waveforms of all three cosines. Note that the first is pulsating about the $0 - 180^\circ$ axis, the second about the$120^\circ - 300^\circ$axis and the third at $240^\circ - 360^\circ$axis.

- This plot shows the travelling wave in a circular trajectory. Note that while individual pulsating waves have maximum amplitude of 10, the resultant has amplitude of 15.

If f_1 is the amplitude of the flux waveform in each phase, the travelling wave can then be represented as

$$\begin{aligned} f(t) &= f_1 \cos\omega t \cos\theta + f_1 \cos(\omega t - \frac{2\pi}{3}) \cos(\theta - \frac{2\pi}{3}) + f_1 \cos(\omega t - \frac{4\pi}{3}) \cos(\theta - \frac{4\pi}{3}) \\ &= \frac{3}{2} f_1 \cos(\omega t - \theta) \end{aligned} \tag{4}$$

Principles of Torque Production

In the earlier section, we saw how a rotating flux is produced. Now let us consider a rotor, which is placed in this field. Let the rotor have a coil such that the coil sides are placed diametrically opposite each other. This is shown in the fig. 1. Since the flux generated by the stator rotates flux linked by this rotor coil also changes.

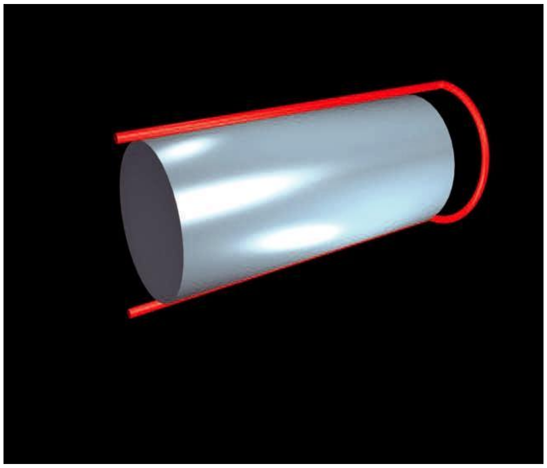


Figure 1: A Coil on the rotor

Since the flux pattern is varying sinusoidally in space, as the flux waveform rotates, the flux linkage varies sinusoidally. The rate of variation of this flux linkage will then be equal to the speed of rotation of the air gap flux produced. This sinusoidal variation of the flux linkage produces a sinusoidal induced emf in the rotor coil. If the coil is short circuited, this induced emf will cause a current flow in the coil as per Lenz's law.

Now imagine a second coil on the rotor whose axis is 120° away from the first. This is shown in fig. 2. The flux linkage in this coil will also vary sinusoidally with respect to time and therefore cause an induced voltage varying sinusoidally with time. However the flux linkages in these two coils will have a phase difference of 120° (the rotating flux wave will have to travel 120° in order to cause a similar flux linkage variation as in the first coil), and hence the time varying voltages induced in the coils will also have a 120° phase difference.

A third coil placed a further 120° away is shown in fig. 3. This will have a time varying induced emf lagging 240° in time with respect to the first.

When these three coils are shorted upon themselves currents flow in them as per Lenz's law. The mechanism by which torque is produced may now be understood as follows. The diagram in fig. 4 shows a view of the rotor seen from one end. Positive current is said to

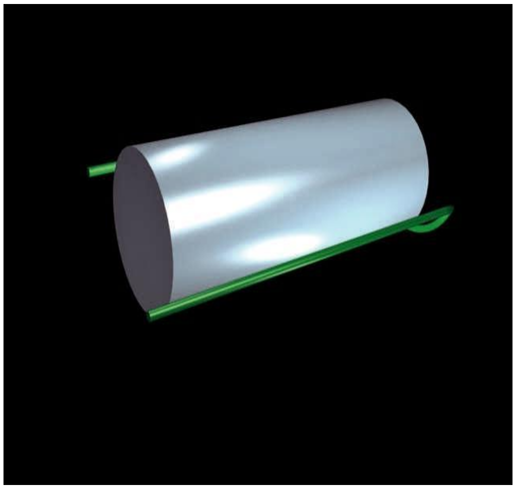


Figure 2: A coil displaced 120° from the first

flow in these coils when current flows out of the page in a, b, c conductors and into a', b' and c' respectively.

If we look at the voltage induced in these coils as phasors, the diagram looks as shown in fig. 5. The main flux is taken as the reference phasor. Considering that the induced emf is $-d\psi/dt$ where ψ is the flux linkage, the diagram is drawn as shown.

As usual, the horizontal component of these phasors gives the instantaneous values of the induced emf in these coils.

Let these coils be purely resistive. Then these emf phasors also represent the currents flowing in these coils. If we consider the instant t = 0, it can be seen that

1. The field flux is along 0° axis.
2. The current in a phase coil is zero.
3. The current in c phase coil is $+\frac{\sqrt{3}}{2}$ units.

These currents act to produce mmf and flux along the axes of the respective coils. Let us consider the space around b' and c coil sides. The situation is shown in fig. 6.

The resulting flux pattern causes a tendency to move in the anticlockwise direction. This is easy to see through the so called whiplash rule. Alternatively, since the force on a current carrying conductor is F = q(v X B), it can be seen that the torque produced tends to rotate the rotor counter-clockwise. The magnitude of the torque would increase with the current magnitude in the coils. This current is in turn dependent on the magnitude of the main field flux and its speed of rotation. Therefore one may say that motion of the main field tends to drag the rotor along with it.

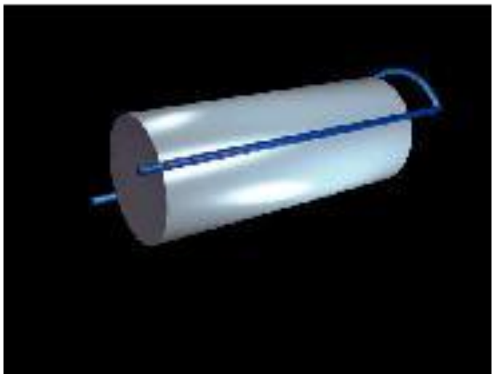


Figure 3: A coil displaced 240° from the first

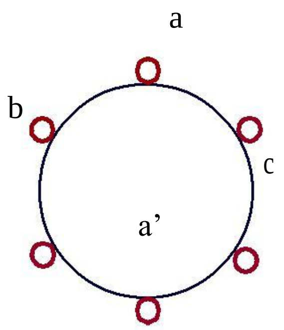


Figure 4: Coils on the rotor

When the rotor is free to move and begins moving, the motion reduces the relative speed between the main field and the rotor coils. Less emf would therefore be induced and the torque would come down. Depending on the torque requirement for the load, the difference in speed between the rotor and the main field settles down at some particular value.

From the foregoing, the following may be noted.

1. The torque produced depends on a non-zero relative speed between the field and the rotor.

2. It is therefore not possible for the rotor to run continuously at the same speed

of the field. This is so because in such a condition, no emf would be induced in the rotor and hence no rotor current, no torque.

3. The frequency of currents induced in the rotor coils and their magnitude depends on this difference in speed.

These are important conclusions. The speed of the main field is known as the synchronous speed, n_s. If the actual speed of the rotor is n_r then the ratio is known as slip and is frequently expressed as a percentage. Typically induction machines are designed to operate at about less than 4 percent slip at full load.

$$s = \frac{n_s - n_r}{n_s} \qquad (5)$$

It is instructive to see the situation if the rotor resistance is neglected and is considered to be purely inductive. The phasor diagram of voltages and the currents would then look as shown in fig. 7.

At t = 0, one can see that current in a phase coil is at negative maximum, while b and c phases have positive current of 0.5 units. Now if we consider the current flux profiles at coil sides a, b', c, the picture that emerges is shown in fig. 8.

Since main flux at the a coil side is close to zero, there is very little torque produced from there. There is a tendency to move due to the b' and c coil sides, but they are in opposite directions however. Hence there is no net torque on the rotor. This brings up another important conclusion — the resistance of the rotor is an important part of torque production in the induction machine. While a high resistance rotor is better suited for torque production, it would also be lossy.

Construction

In actual practice, the three coils form three windings distributed over several slots. These windings may be connected in star or delta and three terminations are brought out. These are conventional three phase windings which are discussed in greater detail in the chapters on alternators. Such windings are present n the stator as well as rotor. A photograph of

Figure 9: stator of an induction machine

the stator of an induction machine is shown in fig. 9. A close up of the windings is shown in fig. 10.the several turns that makeup a coil are seen in this picture. The three terminations are connected to rings on which three brushes make a sliding contact. As the rotor rotates the brushes slip over the rings and provide means of connecting stationary external circuit elements to the rotating windings. A schematic of these arrangements is shown in fig. 13. A photograph of a wound rotor for an induction machine is shown in fig. 11. Fig. 12 shows a close up of the slip ring portion. Brushes are not shown in this picture.

Induction machines, which have these kinds of windings and terminals that are brought out, are called slip ring machines. The reader may note that in order that torque is produced current must flow in the rotor. To achieve that, the stationary brush terminals must either be shorted, or connected to a circuit allowing current flow. Sometimes a star connected resistor bank is connected so that the developed starting torque is higher. There are also other forms of power electronic circuitry that may be connected to the rotor terminals to achieve various functions.

The popularity of the induction machine however, stems from another variety of rotor

Figure 10: Coils in the stator

Figure 11: A wound rotor with slip rings

Figure 12: slip rings

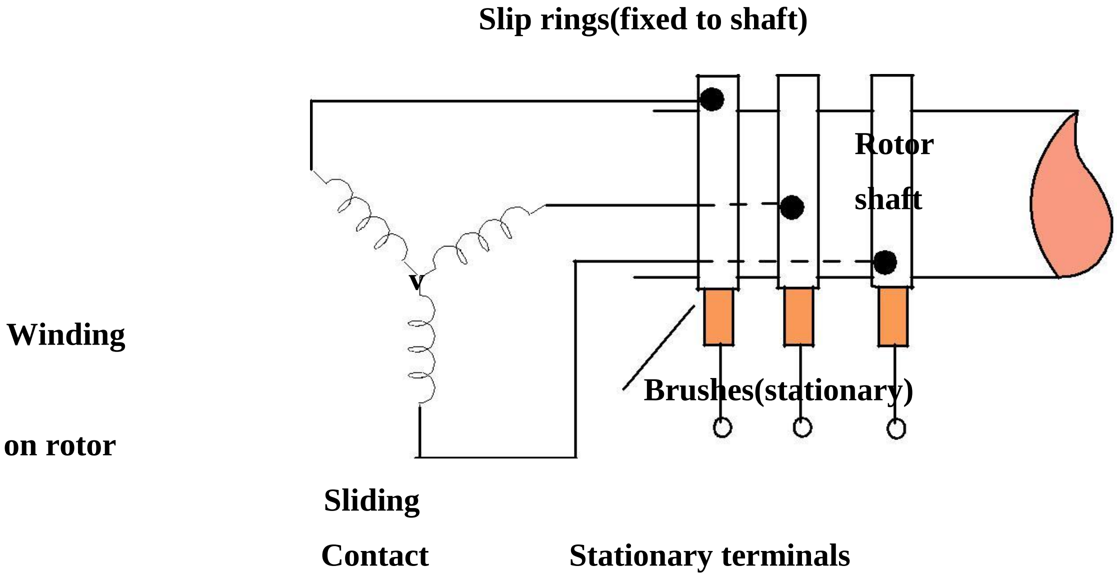


Figure 13: Slip rings and brushes in induction machines — a schematic

That is used. This rotor has slots into which copper or aluminum bars are inserted. These bars are then shorted by rings that are brazed on to each of the rotor ends. Figure 14 shows a simple schematic.

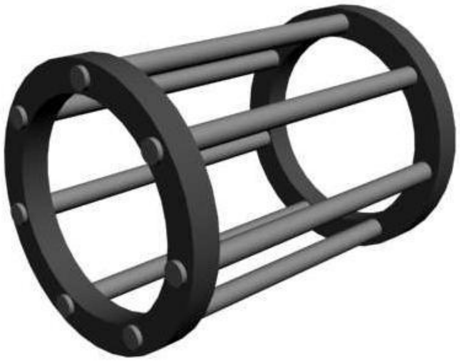


Figure 14: Squirrel cage rotor — a schematic

Such a rotor is called squirrel cage rotor. This rotor behaves like a short-circuited winding and hence the machine is able to perform electromechanical energy conversion. This type of rotor is easy to manufacture, has no sliding contacts and is very robust. It is this feature that makes induction machine suitable for use even in hazardous environments and reliable operation is achieved. The disadvantage of this type of rotor is that the motor behavior cannot be altered by connecting anything to the rotor — there are no rotor terminals.

Fig. 15 shows a photograph of a squirrel cage rotor. The rotor also has a fan attached to it. This is for cooling purposes. The bars (white lines on the surface) are embedded in the rotor iron which forms the magnetic circuit. The white lines correspond to the visible portion of the rotor bar.

Sometimes two rotor bars are used per slot to achieve some degree of variability in the starting and running performances. It is to make use of the fact that while high rotor

Figure 15: squirrel cage rotor

resistance is desirable from the point of view of starting torque, low rotor resistance is desirable from efficiency considerations while the machine is running. Such rotors are called double cage rotors or deep-bar rotors.

To summarize the salient features discussed so far,

1. The stator of the 3 - phase induction machine consists of normal distributed AC wind-ings.

2. Balanced three phase voltages impressed on the stator, cause balanced three phase currents to flow in the stator.

3. These stator currents cause a rotating flux pattern (the pattern is a flux distribution which is sinusoidal with respect to the space angle) in the air gap.

4. The rotating flux pattern causes three phase induced e.m.f.s in rotor windings (again normal ac windings). These windings, if shorted, carry three phase-balanced currents. Torque is produced as a result of interaction of the currents and the air gap flux.

5. The rotor may also take the form of a squirrel cage arrangement, which behaves in a manner similar to the short-circuited three phase windings.

Equivalent Circuit

It is often required to make quantitative predictions about the behavior of the induction machine, under various operating conditions. For this purpose, it is convenient to represent the machine as an equivalent circuit under sinusoidal steady state operating conditions. Since the operation is balanced, a single-phase equivalent circuit is sufficient for most purposes.

In order to derive the equivalent circuit, let us consider a machine with an open circuited rotor. Since no current can flow and as a consequence no torque can be produced, the situation is like a transformer open-circuited on the secondary (rotor). The equivalent circuit under this condition can be drawn as shown in fig. 16.

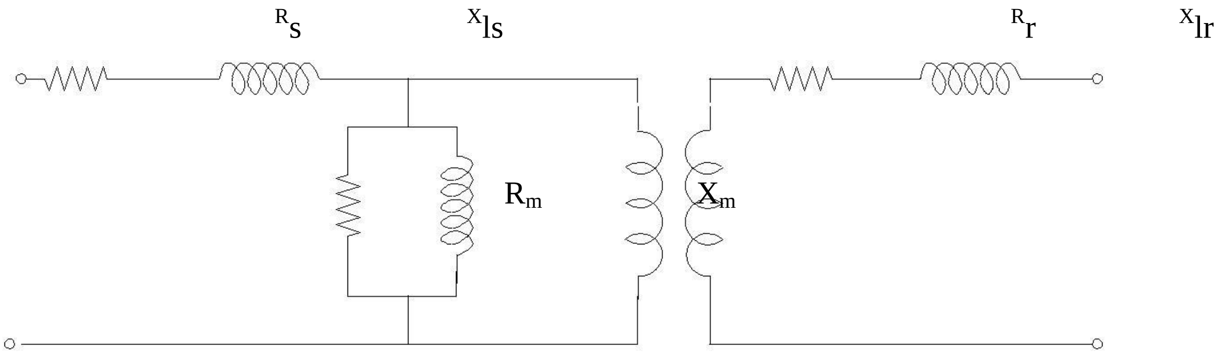


Figure 16: Induction machine with the rotor open

This is just the normal transformer equivalent circuit (why?). Measurements aregenerally made on the stator side and the rotor, in most circumstances, is shorted (if required, through some external circuitry). Since most of the electrical interaction is from the stator, it makes sense to refer all parameters to the stator.

Let us consider the rotor to be shorted. Let the steady speed attained by the rotor be ω_r and the synchronous speed be ω_s. The induced voltage on the rotor is now proportional to the slip i.e., slip times the induced voltage under open circuit (why?). Further, the voltage induced and the current that flows in the rotor is at a frequency equal to slip times the stator excitation frequency (why?). The equivalent circuit can be made to represent this by shorting the secondary side and is shown in fig. 17.

R_r' and X_{lr}' refer to the rotor resistance and leakage resistance referred to the stator side (using the square of the turns ratio, as is done in transformer). The secondary side loop is excited by a voltage sE_1 , which is also at a frequency sf_1 . This is the reason why the rotor

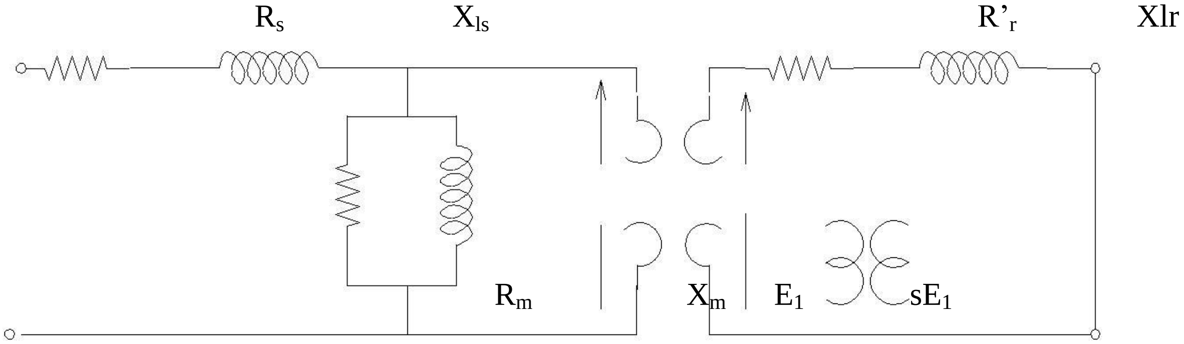


Figure 17: Equivalent circuit : rotor at its own frequency

leakage is sX_{lr}' now . The current amplitude in the rotor side would therefore be

This expression can be modified as follows (dividing numerator and denominator by s)

Equation 7 tells us that the rotor current is the same as the current flowing in a circuit with a load impedance consisting of a resistance R_r' /s and inductive reactance X_{lr}' . This current would also now be at the frequency of E_1 (stator frequency). Note that the slip no longer multiplies the leakage reactance. Further this current is now caused by a voltage of E_1 itself (no multiplying factor of s). Hence the transformer in fig. 17 can also be removed.

Since, with this, the conversion to slip frequency is no longer there, the equivalent circuit can be represented as in fig. 18.

This is then the per-phase equivalent circuit of the induction machine, also called as exact equivalent circuit. Note that the voltage coming across the magnetizing branch is the applied stator voltage, reduced by the stator impedance drop. Generally the stator impedance drop is only a small fraction of the applied voltage. This fact is taken to advantage and the magnetizing branch is shifted to be directly across the input terminals and is shown in fig. 19.

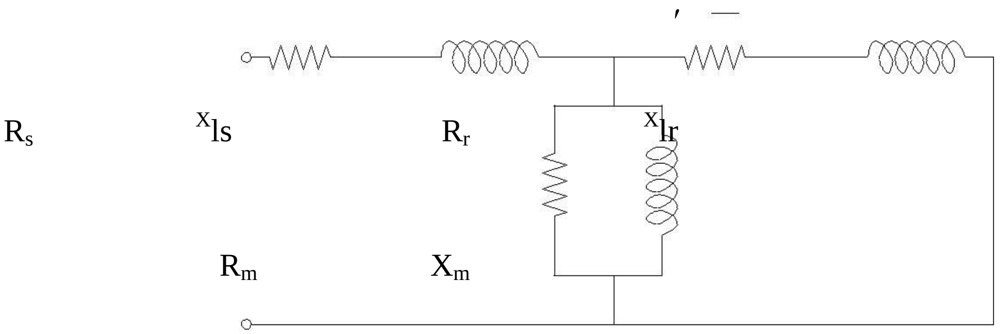


Figure 18: The Exact equivalent circuit

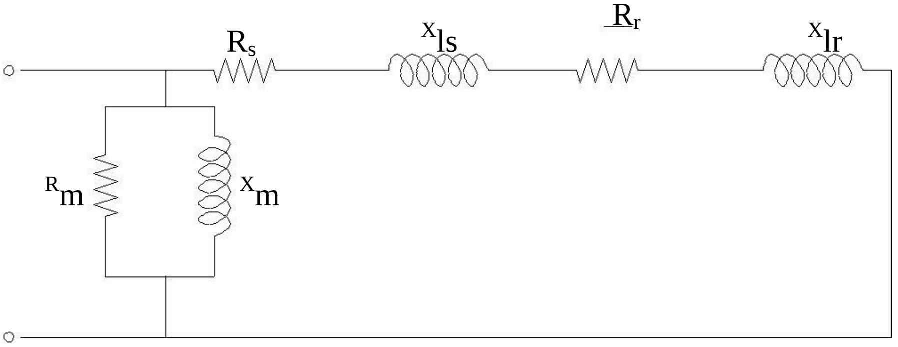


Figure 19: The approximate equivalent circuit

This circuit, called the approximate equivalent circuit, is simple to use for quick calcula-tions. With this equation the equivalent circuit can be modified as shown in fig. 20.

Dividing the equation for the rotor current by s and merging the two sides of the trans-former is not just a mathematical jugglery. The power dissipated in the rotor resistance (per phase) is obviously $I_2^{'2}R_r^{'}$. From the equivalent circuit of fig. 20 one can see that the rotor current (referred to stator of course) flows through a resistance $R_r^{'}/s$ which has a component $R_r^{'}(1 - s)/s$ in addition to $R_r^{'}$, which also dissipates power. What does this represent?

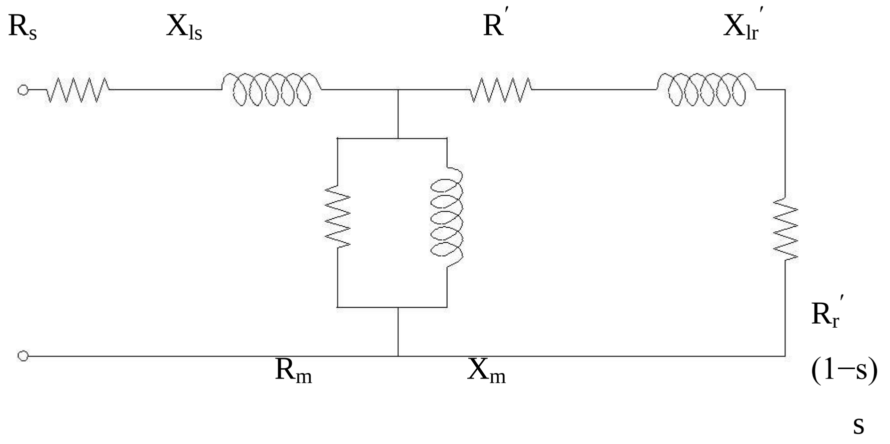


Figure 20: The exact equivalent circuit - separation of rotor resistance

From the equivalent circuit, one can see that the dissipation in R_s represents the stator loss, and dissipation in R_m represents the iron loss. Therefore, the power absorption indicated by the rotor part of the circuit must represent all other means of power consumption - the actual mechanical output, friction and windage loss components and the rotor copper loss components. Since the dissipation in R_r' is rotor copper loss, the power dissipation in $R_r'(1-s)/s$ is the sum total of the remaining. In standard terminology, dissipation in

- R_r'/s is called the air gap power.
- R_r' is the rotor copper loss.
- $R_r'(1-s)/s$ is the mechanical output.

In an ideal case where there are no mechanical losses, the last term would represent the actual output available at the shaft. Out of the power P_g Transferred at the air gap, a fraction s is dissipated in the rotor and $(1-s)$ is delivered as output at the shaft. If there are no mechanical losses like friction and windage, this represents the power available to the load.

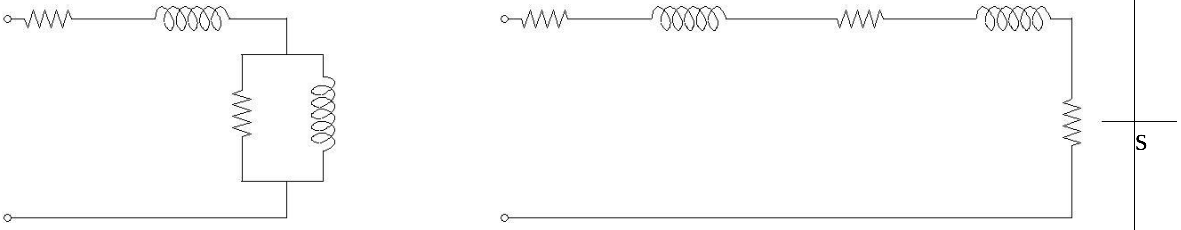
Determination of Circuit Parameters

In order to find values for the various elements of the equivalent circuit, tests must be conducted on a particular machine, which is to be represented by the equivalent circuit. In order to do this, we note the following.

1. When the machine is run on no-load, there is very little torque developed by it. In an ideal case where there is no mechanical losses, there is no mechanical power deveoped at no-load. Recalling the explanations in the section on torque production, the flow of current in the rotor is indicative of the torque that is produced. If no torque is produced, one may conclude that no current would be flowing in the rotor either. The rotor branch acts like an open circuit. This conclusion may also be reached by reasoning that when there is no load, an ideal machine will run up to its synchronous speed where the slip is zero resulting in an infinite impedance in the rotor branch.

2. When the machine is prevented from rotation, and supply is given, the slip remains at unity. The elements representing the magnetizing branch R_m &X_m are high impedances much larger than $R_r^{'}$ & $X_{lr}^{'}$ in series. Thus, in the exact equivalent circuit of the induction machine, the magnetizing branch may be neglected.

From these considerations, we may reduce the induction machine exact equivalent circuit of fig.18 to those shown in fig. 21



(a) No-load equivalent equivalent

(b) Blocked rotor

Figure 21: Reduced equivalent circuits

These two observations and the reduced equivalent circuits are used as the basis for the two most commonly used tests to find out the equivalent circuit parameters — the blocked rotor test and no load test. They are also referred to as the short circuit test and open circuit test respectively in conceptual analogy to the transformer.

The no-load test

The behaviour of the machine may be judged from the equivalent circuit of fig. 21(a). The current drawn by the machine causes a stator-impedance drop and the balance voltage is applied across the magnetizing branch. However, since the magnetizing branch impedance is large, the current drawn is small and hence the stator impedance drop is small compared to the applied voltage (rated value). This drop and the power dissipated in the stator resistance are therefore neglected and the total power drawn is assumed to be consumed entirely as core loss. This can also be seen from the approximate equivalent circuit, the use of which is justified by the foregoing arguments. This test therefore enables us to compute the resistance and inductance of the magnetizing branch in the following manner.

Let applied voltage = V_s. Then current drawn is given by

$$I_s = \frac{V_s}{R_m} + \frac{V_s}{jX_m} \qquad (9)$$

The power drawn is given by

$$P_s = \frac{V_s^2}{R_m} \Rightarrow R_m = \frac{V_s^2}{P_s} \qquad (10)$$

V_s, I_s and P_s are measured with appropriate meters. With R_m known from eqn. 10, X_m can be found from eqn. 9. The current drawn is at low power factor and hence a suitable wattmeter should be used.

Blocked-rotor Test

In this test the rotor is prevented from rotation by mechanical means and hence the name. Since there is no rotation, slip of operation is unity, s = 1. The equivalent circuit valid under these conditions is shown in fig. 21(b). Since the current drawn is decided by the resistance and leakage impedances alone, the magnitude can be very high when rated voltage is applied. Therefore in this test, only small voltages are applied — just enough to cause rated current to flow. While the current magnitude depends on the resistance and the reactance, the power drawn depends on the resistances.

The parameters may then be determined as follows. The source current and power drawn may be written as

$$I_s = \frac{V_s}{(R_s + R_r') + j(X_s + X_r')} \qquad (11)$$

$$P_s = |I_s|^2(R_s + R_r') \qquad (12)$$

In the test V_s, I_s and P_s are measured with appropriate meters. Equation 12 enables us to compute$(R_s + R_r')$. Once this is known, $(X_s + X_r')$ may be computed from the eqn. 11.

Note that this test only enables us to determine the series combination of the resistance and the reactance only and not the individual values. Generally, the individual values are assumed to be equal; the assumption $R_s = R_r'$, and$X_s = X_r'$suffices for most purposes. In practice, there are differences. If more accurate estimates are required IEEE guidelines may be followed which depend on the size of the machine.

Note that these two tests determine the equivalent circuit parameters in a ‘Stator-referred’ sense, i.e., the rotor resistance and leakage inductance are not the actual values but what they ’appear to be’ when looked at from the stator. This is sufficient for most purposes as interconnections to the external world are generally done at the stator terminals.

Deducing the machine performance

From the equivalent circuit, many aspects of the steady state behavior of the machine can be deduced. We will begin by looking at the speed-torque characteristic of the machine. We will consider the approximate equivalent circuit of the machine. We have reasoned earlier that the power consumed by the ’rotor-portion’ of the equivalent circuit is the power transferred across the air-gap. Out of that quantity the amount dissipated in R_r' is the rotor copper loss and the quantity consumed by R_r' $(1 - s)/s$ is the mechanical power developed. Neglecting mechanical losses, this is the power available at the shaft. The torque available can be obtained by dividing this number by the shaft speed.

The complete torque-speed characteristics

In order to estimate the speed torque characteristic let us suppose that a sinusoidal voltage is impressed on the machine. Recalling that the equivalent circuit is the per-

$$I_s = \frac{V_s}{(R_s + \frac{R_r'}{s}) + j(X_{ls} + X_{lr}')} \qquad (14)$$

where V_s is the phase voltage phasor and I_s is the current phasor. The magnetizing phase represen-tation of the machine, the current drawn by the circuit is give by current is neglected. Since this current is flowing through $\frac{R_r}{s}$, the air-gap power is given by The mechanical power output was shown to be $(1 - s)P_g$ (power dissipated in R_r'/s). The torque is obtained by dividing this by the shaft speed ω_m.Thus we have,

$$\frac{P_g(1-s)}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = |I_s|^2 \frac{R_r'}{s\omega_s} \qquad (16)$$

where ω_s is the synchronous speed in radians per second and s is the slip. Further, this is the torque produced per phase. Hence the overall torque is given by

$$T_e = \frac{3}{\omega_s} \cdot \frac{V_s^2}{\left(R_s + \frac{R_2}{s}\right)^2 + \left(X_{ls} + X_{lr}'\right)} \cdot \frac{R_r'}{s}$$

The torque may be plotted as a function of ‘s’ and is called the torque-slip (or torque-speed, since slip indicates speed) characteristic — a very important characteristic of the induction machine. Eqn. 17 is valid for a two-pole (one pole pair) machine. In general, this expression should be multiplied by p, the number of pole-pairs. A typical torque-speed characteristic is shown in fig. 22. This plot corresponds to a 3 kW, 4 pole, 60 Hz machine. The rated operating speed is 1780 rpm.

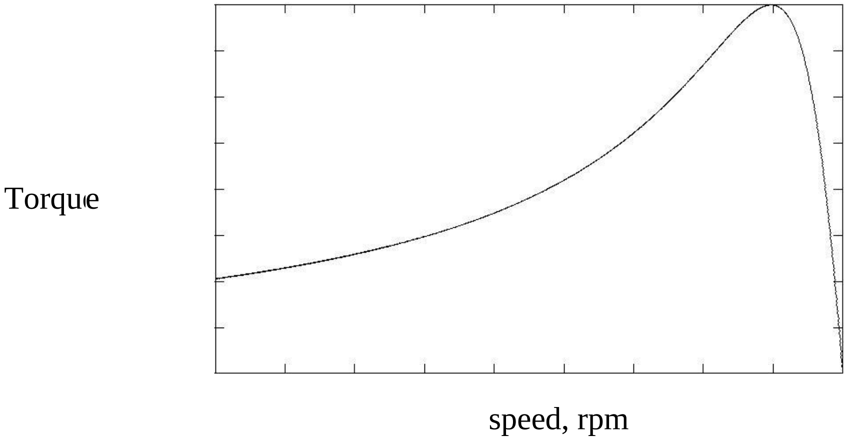


Figure 22: Induction machine speed-torque characteristic

We must note that the approximate equivalent circuit was used in deriving this relation. Readers with access to MATLAB or suitable equivalents (octave, scilab available free under GNU at the time of this writing) may find out the difference caused by using the 'exact' equivalent circuit by using the script found here. A comparison between the two is found in the plot of fig. 23. The plots correspond to a 3 kW, 4 pole, 50 Hz machine, with a rated speed of 1440 rpm. It can be seen that the approximate equivalent circuit is a good approximation in the operating speed range of the machine. Comparing fig. 22 with fig. 23, we can see that the slope and shape of the characteristics are dependent intimately on the machine parameters.

Further, this curve is obtained by varying slip with the applied voltage being held constant. Coupled with the fact that this is an equivalent circuit valid under steady state, it implies that if this characteristic is to be measured experimentally, we need to look at the torque for a given speed after all transients have died down. One cannot, for example, try to obtain this curve by directly starting the motor with full voltage applied to the terminals

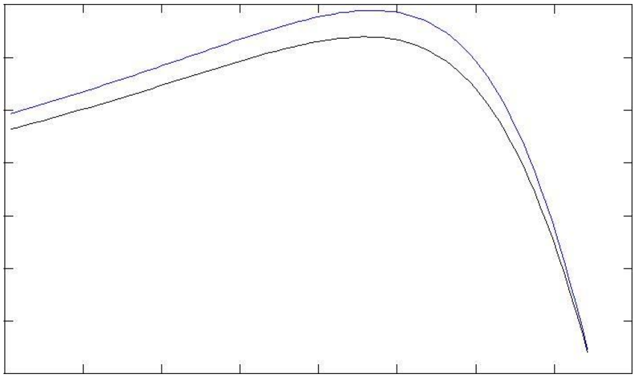


Figure 23: Comparison of exact and approximate circuit predictions

and measuring the torque and speed dynamically as it runs up to steady speed.
Another point to note is that the equivalent circuit and the values of torque predicted is valid when the applied voltage waveform is sinusoidal. With non-sinusoidal voltage wave-forms, the procedure is not as straightforward.

With respect to the direction of rotation of the air-gap flux, the rotor maybe driven to higher speeds by a prime mover or may also be rotated in the reverse direction. The torque-speed relation for the machine under the entire speed range is called the complete speed-torque characteristic. A typical curve is shown in fig. 7.1 for a four-pole machine, the synchronous speed being 1500 rpm. Note that negative speeds correspond to slip values greater than 1, and speeds greater than 1500 rpm correspond to negative slip. The plot also shows the operating modes of the induction machine in various regions. The slip axis is also shown for convenience.

Restricting ourselves to positive values of slip, we see that the curve has a peak point. This is the maximum torque that the machine can produce, and is called as stalling torque. If the load torque is more than this value, the machine stops rotating or stalls. It occurs at a slip sˆ, which for the machine of fig. 7.1 is 0.38. At values of slip lower than sˆ, the curve falls steeply down to zero at s = 0. The torque at synchronous speed is therefore zero. At values of slip higher than s = sˆ, the curve falls slowly to a minimum value at s = 1. The torque at s = 1 (speed = 0) is called the starting torque.

The value of the stalling torque may be obtained by differentiating the expression for torque with respect to zero and setting it to zero to find the value of sˆ. Using this method

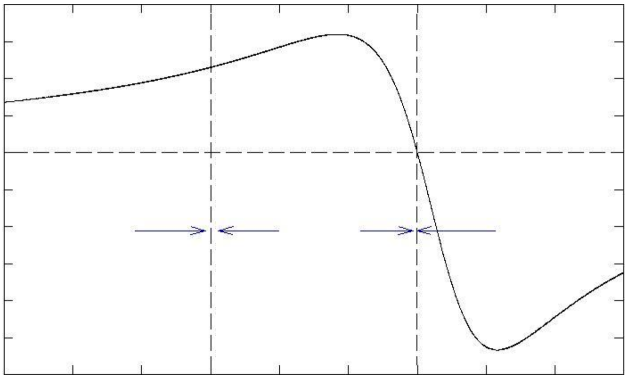


Figure 24: Complete speed-torque characteristic

This fact can be made use of conveniently to alter sˆ. If it is possible to change R_r' , then we can get a whole series of torque-speed characteristics, the maximum torque remaining constant all the while. But this is a subject to be discussed later.

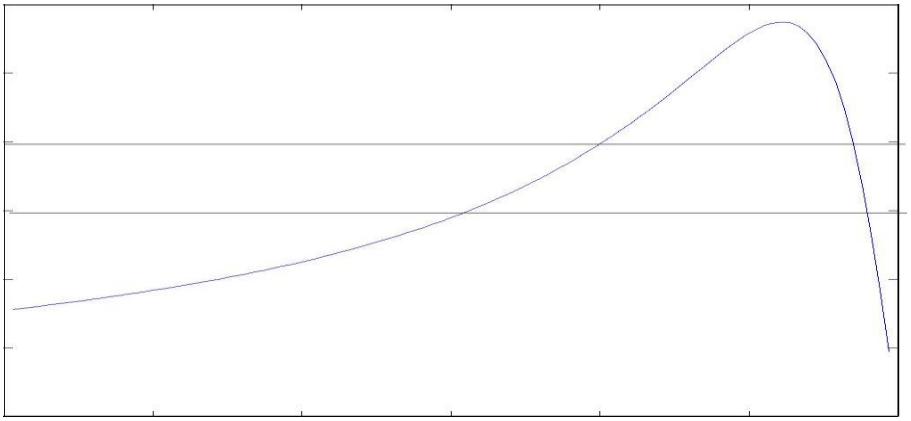
While considering the negative slip range, (generator mode) we note that the maximum torque is higher than in the positive slip region (motoring mode)

Operating Point

Consider a speed torque characteristic shown in fig. 25 for an induction machine, having the load characteristic also superimposed on it. The load is a constant torque load i.e.,the torque required for operation is fixed irrespective of speed.

The system consisting of the motor and load will operate at a point where the two characteristics meet. From the above plot, we note that there are two such points. We therefore need to find out which of these is the actual operating point.

To answer this we must note that, in practice, the characteristics are never fixed; they change slightly with time. It would be appropriate to consider a small band around the curve drawn where the actual points of the characteristic will lie. This being the case let us considers that the system is operating at point 1, and the load torque demand increases slightly. This is shown in fig. 26, where the change is exaggerated for clarity. This would shift the point of operation to a point $1'$ at which the slip would be less and the developed torque higher.



Speed, rpm

Figure 26: Stability of operating point

The difference in torque developed ΔT_e, being positive will accelerate the machine. Any overshoot in speed as it approaches the point $1'$ will cause it to further accelerate since the developed torque is increasing. Similar arguments may be used to show that if for some reason the developed torque becomes smaller the speed would drop and the effect is cumulative. Therefore we may conclude that 1 is not a stable operating point.

Let us consider the point 2. If this point shifts to $2'$, the slip is now higher (speed is lower) and the positive difference in torque will accelerate the machine. This behavior will tend to bring the operating point towards 2 once again. In other words, disturbances at point 2 will not cause a runaway effect. Similar arguments may be given for the case where the load characteristic shifts down. Therefore we conclude that point 2 is a stable operating point.

From the foregoing discussions, we can say that the entire region of the speed-torque characteristic from $s = 0$ to $s = \hat{s}$ is an unstable region, while the region from $s = \hat{s}$ to $s = 0$ is a stable region. Therefore the machine will always operate between $s = 0$ and $s = \hat{s}$

Modes of Operation

The reader is referred to fig. 7.1 which shows the complete speed-torque characteristic of the induction machine along with the various regions of operation.

Let us consider a situation where the machine has just been excited with three phase supply and the rotor has not yet started moving. A little reflection on the definition of the slip indicates that we are at the point s = 1. When the rotating magnetic field is set up due to stator currents, it is the induced emf that causes current in the rotor, and the interaction between the two causes torque. It has already been pointed out that it is the presence of the non-zero slip that causes a torque to be developed. Thus the region of the curve between s = 0 and s = 1 is the region where the machine produces torque to rotate a passive load and hence is called the motoring region. Note further that the direction of rotation of the rotor is the same as that of the air gap flux.

Suppose when the rotor is rotating, we change the phase sequence of excitation to the machine. This would cause the rotating stator field to reverse its direction — the rotating stator mmf and the rotor are now moving in opposite directions. If we adopt the convention that positive direction is the direction of the air gap flux, the rotor speed would then be a negative quantity. The slip would be a number greater than unity. Further, the rotor as we know should be ”dragged along” by the stator field. Since the rotor is rotating in the opposite direction to that of the field, it would now tend to slow down, and reach zero speed. Therefore this region (s > 1) is called the braking region. (What would happen if the supply is not cut-off when the speed reaches zero?)

There is yet another situation. Consider a situation where the induction machine is operating from mains and is driving an active load (a load capable of producing rotation by itself). A typical example is that of a windmill, where the fan like blades of the wind mill are connected to the shaft of the induction machine. Rotation of the blades may be caused by the motoring action of the machine, or by wind blowing. Further suppose that both acting independently cause rotation in the same direction. Now when both grid and wind act, a strong wind may cause the rotor to rotate faster than the mmf produced by the stator excitation. A little reflection shows that slip is then negative. Further, the wind is rotating the rotor to a speed higher than what the electrical supply alone would cause. In order to do this it has to contend with an opposing torque generated by the machine preventing the speed build up. The torque generated is therefore negative. It is this action of the wind against the torque of the machine that enables wind-energy generation. The region of slip $s > 1$ is the generating mode of operation. Indeed this is at present the most commonly used approach in wind-energy generation. It may be noted from the torque expression of eqn. 17 that torque is negative for negative values of slip.

Speed control of Induction Machines

We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque at synchronous speed to the stall torque at a value of slip $s = \hat{s}$. Normally $\hat{s}$ may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite stiff with respect to load changes. The entire speed variation is only in the range n_s to $(1 - \hat{s})n_s$, n_s being dependent on supply frequency and number of poles.

The foregoing discussion shows that the induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However,the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

UNIT-II

Speed control by changing applied voltage

From the torque equation of the induction machine given in eqn.17, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in fig. 27. These curves show that the slip at maximum torque $\hat{s}$ remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

Figure 27 also shows a load torque characteristic — one that is typical of a fan type of load. In a fan (blower) type of load,the variation of torque with speed is such that $T \propto \omega^2$. Here one can see that it may be possible to run the motor to lower speeds within the range n_s to $(1 - \hat{s})n_s$. Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads.

One may note that if the applied voltage is reduced, the voltage across the magnetising branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production

Stator voltage variation

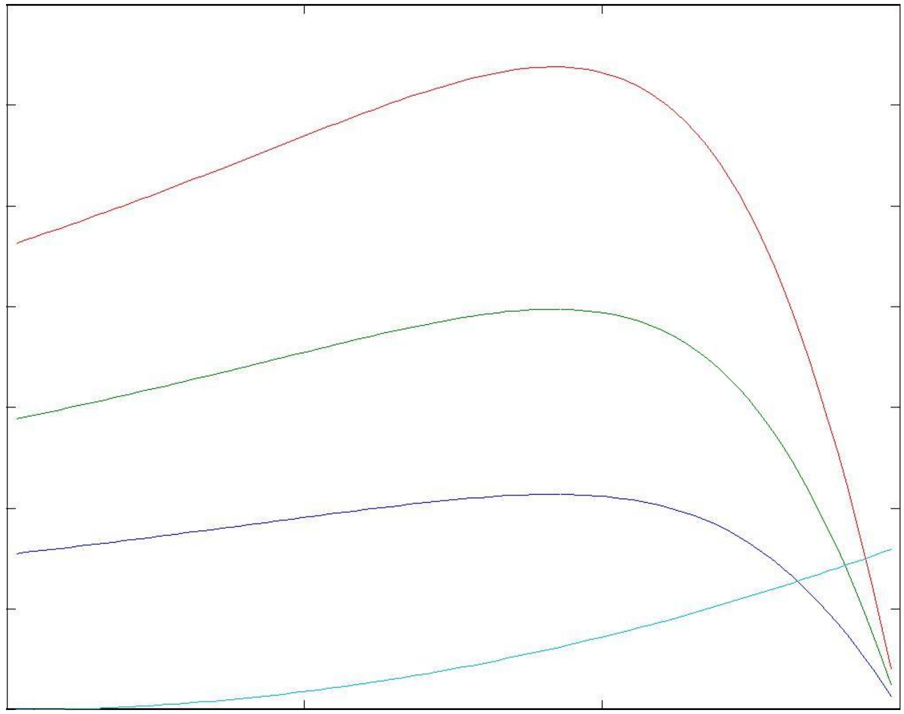


Figure 27: Speed-torque curves: voltage variation

(recall explantions on torque production), which is primarily the explanation for fig. 27. If, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such conditions, reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved.

Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper. Another use of voltage control is in the so-called ‘soft-start’ of the machine. This is discussed in the section on starting methods.

Rotor resistance control

The reader may recall from eqn.17 the expression for the torque of the induction machine. Clearly, it is dependent on the rotor resistance. Further, eqn.19 shows that the maximum value is independent of the rotor resistance. The slip at maximum torque eqn.18 is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Figure 28 shows a family of torque-speed characteristic obtained by changing the rotor resistance.

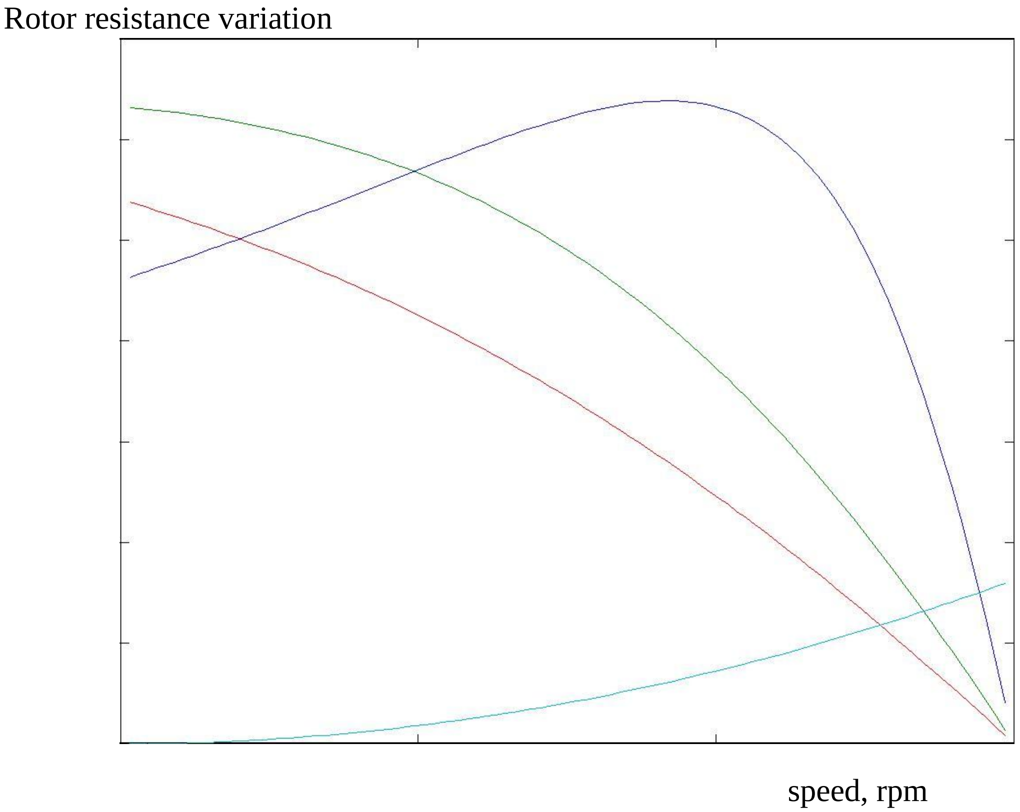


Figure 28: Speed-torque curves : rotor resistance variation

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

The resistors connected to the slip-ring brushes should have good power dissipation ca-pability. Water based rheostats may be used for this. A ‘solid-state’ alternative to a rheostat is a chopper controlled resistance where the duty ratio control of of the chopper presents a variable resistance load to the rotor of the induction machine.

Cascade control

The power drawn from the rotor terminals could be spent more usefully. Apart from using the heat generated in meaning full ways, the slip ring output could be connected to another induction machine. The stator of the second machine would carry slip frequency currents of the first machine which would generate some useful mechanical power. A still better option would be to mechanically couple the shafts of the two machines together. This sort of a connection is called cascade connection and it gives some measure of speed control as shown below.

Let the frequency of supply given to the first machine be f_1 , its number poles be p_1, and its slip of operation be s_1 . Let f_2, p_2 and s_2 be the corresponding quantities for the second machine. The frequency of currents flowing in the rotor of the first machine and hence in the stator of the second machine is s_1f_1. Therefore $f_2 = s_1f_1$. Since the machines are coupled at the shaft, the speed of the rotor is common for both. Hence, if n is the speed of the rotor

in radians,

$$n = \frac{f_1}{p_1}(1 - s_1) = \pm \frac{s_1 f_1}{p_2}(1 - s_2). \tag{20}$$

Note that while giving the rotor output of the first machine to the stator of the second, the resultant stator mmf of the second machine may set up an air-gap flux which rotates in the same direction as that of the rotor, or opposes it. this results in values for speed as

$$n = \frac{f_1}{p_1 + p_2} \quad \text{or} \quad n = \frac{f_1}{p_1 - p_2} \quad (s_2 \text{ negligible}) \tag{21}$$

The latter expression is for the case where the second machine is connected in opposite phase sequence to the first. The cascade connected system can therefore run at two possible speeds

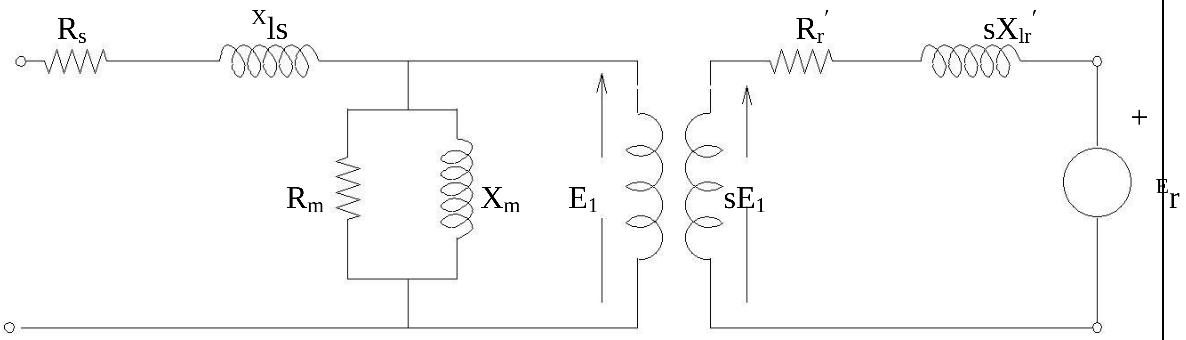


Figure 29: Generalized rotor control

Speed control through rotor terminals can be considered in a much more general way. Consider the induction machine equivalent circuit of fig. 29, where the rotor circuit has been terminated with a voltage source E_r .

If the rotor terminals are shorted, it behaves like a normal induction machine. This is equivalent to saying that across the rotor terminals a voltage source of zero magnitude is connected. Different situations could then be considered if this voltage source E_r had a non-zero magnitude. Let the power consumed by that source be P_r . Then considering the rotor side circuit power dissipation per phase

$$sE_1I_2^{'} \cos \varphi_2 = I_2^{'} R_2^{'} + P_r . \qquad (22)$$

Clearly now, the value of s can be changed by the value of P_r . For $P_r = 0$, the machine is like a normal machine with a short circuited rotor. As P_r becomes positive, for all other circuit conditions remaining constant, s increases or in the other words, speed reduces. As P_r becomes negative,the right hand side of the equation and hence the slip decreases. The physical interpretation is that we now have an active source connected on the rotor side which is able to supply part of the rotor copper losses. When $P_r = -I_2^{'2}R_2$ the entire copper loss is supplied by the external source. The RHS and hence the slip is zero. This corresponds to operation at synchronous speed. In general the circuitry connected to the rotor may not be a simple resistor or a machine but a power electronic circuit which can process this power requirement. This circuit may drive a machine or recover power back to the mains. Such circuits are called static kramer drives.

Pole changing schemes

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by $n_s = f_s/p$ (in rev./s) where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps.

If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four pole faces A, B, C, D as shown in fig. 30.

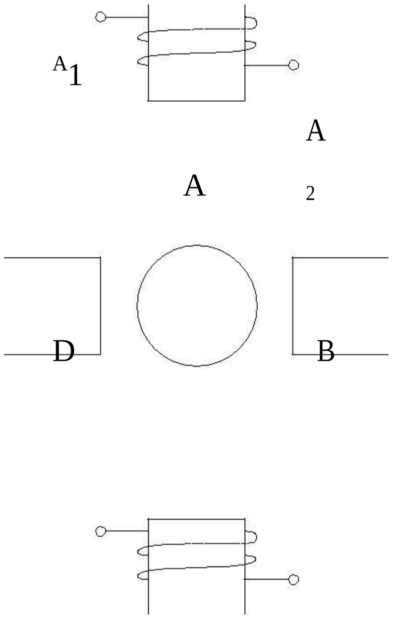


Figure 30: Pole arrangement

Harmonics in Induction Machines

In attempting to understand the performance of an induction machine, we consider that the air-gap flux wave is purely sinusoidal. It is from that assumption the analysis of induced emf, sinusoidal currents, the expressions for generated torque etc. proceed. In practice, there are deviations from this idealistic picture.

Time Harmonic

The first non-ideality is the presence of harmonics in the input supply given to the three phase machine. The source may contain 3rd, 5th, 7th. . . harmonics. Note that due to the symmetry of the waveform (f (t) = −f (t + T /2), where T is the period of the supply sine waveform, even ordered harmonics cannot exist. Let the R phase supply voltage be given by the expression

$$v_R = V_{1m} \sin(\omega_1 t + \varphi_1) + V_{3m} \sin(3\omega_1 t + \varphi_3)$$
$$+V_{5m} \sin(5\omega_1 t + \varphi_5) + V_{7m} \sin(7\omega_1 t + \varphi_7) + - - - \quad (25)$$

Being a balanced three phase supply, we know that the waveforms of v_Y and v_B are 120° and 240° shifted from v_R respectively. It is further well known that if a waveform is shifted by φ degrees, its harmonics are shifted by nφ degrees, where n is the order of the harmonic.

If we consider the third harmonic components of the three phase waveforms, and if $v_{x3}(t)$ is the third harmonic of phase x, we can see that

$$Vr = V_{3m} \sin(3\omega_1 t + \varphi_3)$$
$$Vy = V_{3m} \sin(3\omega_1 t + \varphi_3)$$
$$Vb = V_{3m} \sin(3\omega_1 t + \varphi_3) \quad (28)$$

Therefore, all the three third harmonics are in phase. In a STAR connected system with isolated neutral, these voltages cannot cause any current flow since all three terminals are equal in potential. If the neutral point is connected to some point, then then current can flow through the neutral connection. Such a connection is however rare in induction machines. The machine is therefore an open circuit to third harmonics. In fact, one can see that any harmonic whose order is a multiple of three, i.e., the triplen harmonics, as they are called, will face an identical situation. Since the machine is an open circuit to triplen harmonics in the excitation voltage, these do not have effect on the machine.

Let us now consider the fifth harmonic. From the equations above, one can see that

$$vRS = V_{5m} \sin(5\omega_1 t + \varphi_5)$$
$$vYS = V_{5m} \sin\left(5\omega_1 t + \varphi_5 - 5.\frac{2\pi}{3}\right)$$
$$= V_{5m} \sin\left(5\omega_1 t + \varphi_5 - \frac{4\pi}{\;}\right)$$

3

$$vBS = V_{5m}\sin(5\omega_1 t + \varphi_5 - 5.\frac{4\pi}{3})$$

$$= V_{5m}\sin(5\omega_1 t + \varphi_5 - \frac{2\pi}{3}) \qquad (29)$$

UNIT-III

SYNCHRONOUS MACHINES & CHARACTERISTICS

Introduction

Synchronous machines are principally used as alternating current generators. They supply the electric power used by all sectors of modern society. Synchronous machine is an important electromechanical energy converter. Synchronous generators usually operate in parallel forming a large power system supplying electrical power to consumers or loads. For these applications the synchronous generators are built in large units, their rating ranging from tens to hundreds of Megawatts. These synchronous machines can also be run as synchronous motors.

Synchronous machines are AC machines that have a field circuit supplied by an external DC source. Synchronous machines are having two major parts namely stationary part stator and a rotating field system called rotor.

In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then driven by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

Types of synchronous machines

According to the arrangement of armature and field winding, the synchronous machines are classified as rotating armature type or rotating field type.

In rotating armature type the armature winding is on the rotor and the field winding is on the stator. The generated emf or current is brought to the load via the slip rings. These type of generators are built only in small units.

In case of rotating field type generators field windings are on the rotor and the armature windings are on the stator. Here the field current is supplied through a pair of slip rings and the induced emf or current is supplied to the load via the stationary terminals.

Based on the type of the prime movers employed the synchronous generators are classified as

1. Hydrogenerators : The generators which are driven by hydraulic turbines are called hydrogenerators. These are run at lower speeds less than 1000 rpm.

2. Turbogenerators: These are the generators driven by steam turbines. These generators are run at very high speed of 1500rpm or above.

3. Engine driven Generators: These are driven by IC engines. These are run at aspeed less than 1500 rpm.

Construction of synchronous machines

1. Salient pole Machines: These type of machines have salient pole or projecting poles with concentrated field windings. This type of construction is for the machines which are driven by hydraulic turbines or Diesel engines.

2. Nonsalient pole or Cylindrical rotor or Round rotor Machines: These machines are having

cylindrical smooth rotor construction with distributed field winding in slots. This type of rotor construction is employed for the machine driven by steam turbines.

Stator core:

The stator is the outer stationary part of the machine, which consists of

- The outer cylindrical frame called yoke**,** which is made either of welded sheet steel, cast iron.
- The magnetic path**,** which comprises a set of slotted steel laminations called stator core pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, reducing losses and heating. CRGO laminations of 0.5 mm thickness are used to reduce the iron losses.

A set of insulated electrical windings are placed inside the slots of the laminated stator. The cross-sectional area of these windings must be large enough for the power rating of the machine. For a 3-phase generator, 3 sets of windings are required, one for each phase connected in star. Fig. 1 shows one stator lamination of a synchronous generator. In case of generators where the diameter is too large stator lamination can not be punched in on circular piece. In such cases the laminations are punched in segments. A number of segments are assembled together to form one circular laminations. All the laminations are insulated from each other by a thin layer of varnish.

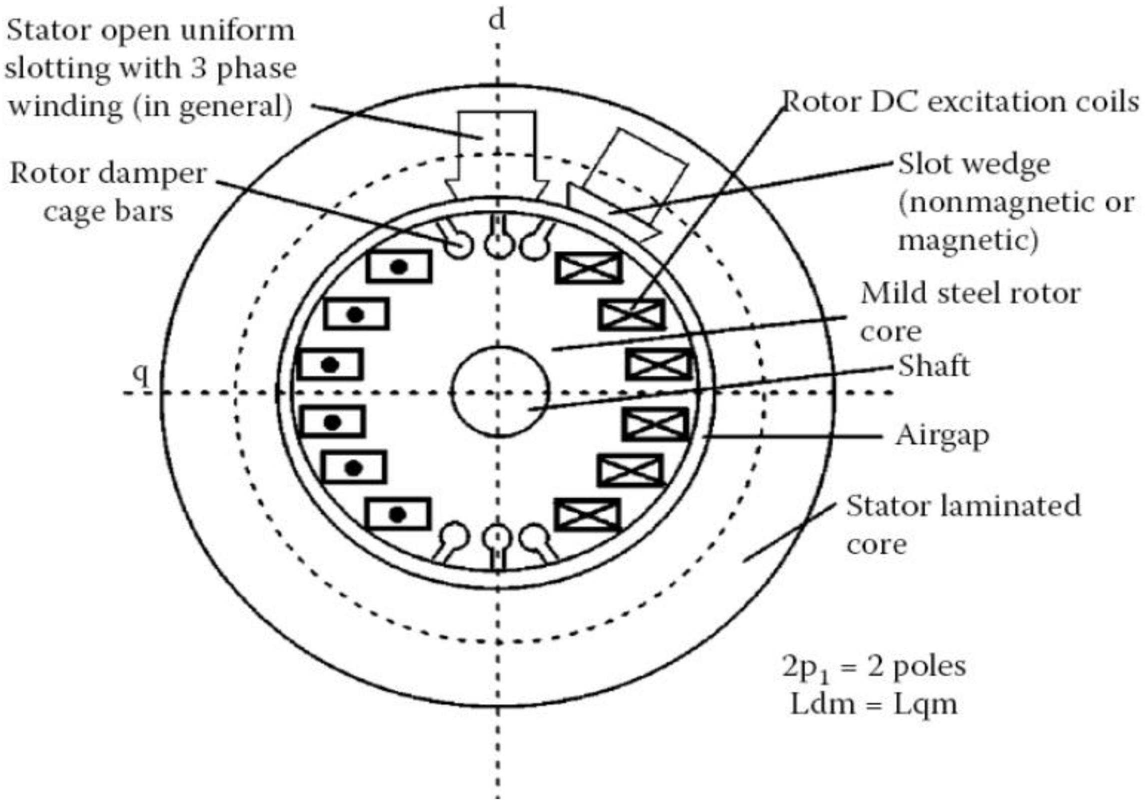


Figure 3.1. Non Salient pole generator

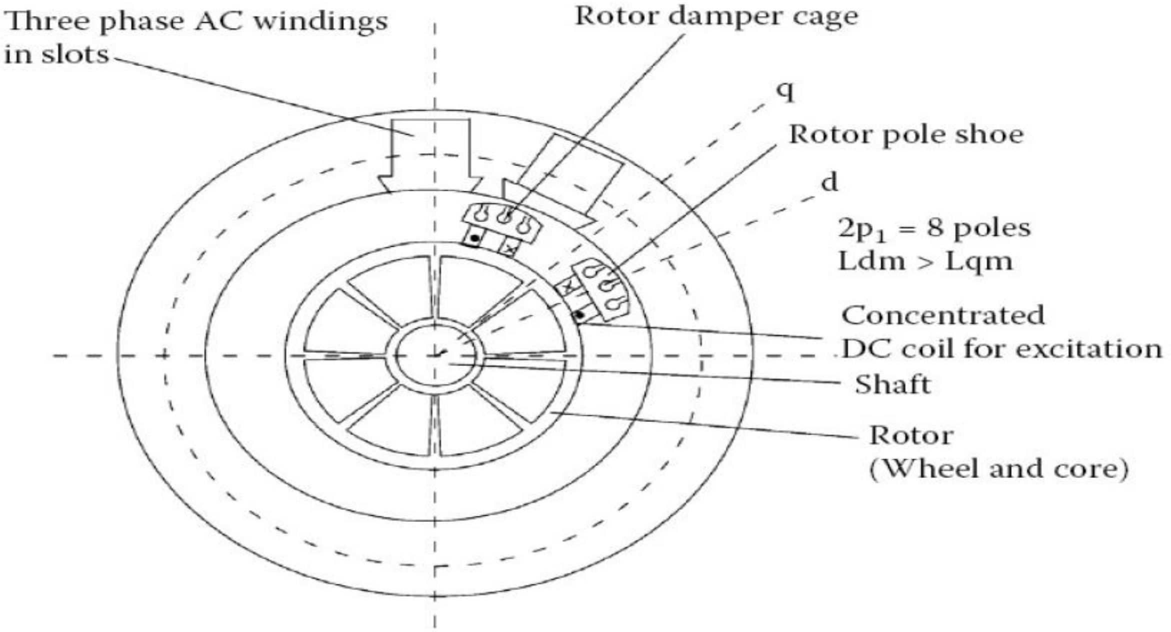


Figure: 3.2. Salient pole generator.

Rotor of water wheel generator consists of salient poles. Poles are built with thin silicon steel laminations of 0.5mm to 0.8 mm thickness to reduce eddy current laminations. The laminations are clamped by heavy end plates and secured by studs or rivets. For low speed rotors poles have the bolted on construction for the machines with little higher peripheral speed poles have dove tailed construction as shown in Figs. Generally rectangular or round pole constructions are used for such type of alternators. However the round poles have the advantages over rectangular poles.

Generators driven by water wheel turbines are of either horizontal or vertical shaft type. Generators with fairly higher speeds are built with horizontal shaft and the generators with higher power ratings and low speeds are built with vertical shaft design. Vertical shaft generators are of two types of designs (i) Umbrella type where in the bearing is mounted below the rotor. (ii) Suspended type where in the bearing is mounted above the rotor.

In case of turbo alternator the rotors are manufactured form solid steel forging. The rotor is slotted to accommodate the field winding. Normally two third of the rotor periphery is slotted to accommodate the winding and the remaining one third unslotted portion acts as the pole. Rectangular slots with tapering teeth are milled in the rotor. Generally rectangular aluminum or copper strips are employed for filed windings. The field windings and the overhangs of the field windings are secured in place by steel retaining rings to protect against high centrifugal forces. Hard composition insulation materials are used in the slots which can with stand high forces, stresses and temperatures. Perfect balancing of the rotor is done for such type of rotors.

Damper windings are provided in the pole faces of salient pole alternators. Damper windings are nothing but the copper or aluminium bars housed in the slots of the pole faces. The ends of the damper bars are short circuited at the ends by short circuiting rings similar to end rings as in the case of squirrel cage rotors. These damper windings are serving the function of providing mechanical balance; provide damping effect, reduce the effect of over voltages and damp out hunting in case of alternators. In case of synchronous motors they act as rotor bars and help in self starting of the motor.

Relation between Speed and Frequency:

In the previous course on induction motors it is established that the relation between speed and frequency and number of poles is given by

Frequency f = P x N /120 Hz

Windings in Alternators: In case of three phase alternators the following types of windings are employed.

- Lap winding,
- wave winding and
- Mush winding.

Based on pitch of the coil

- full pitched
- short pitched windings

Based on number of layers

- Single layer
- Double layer

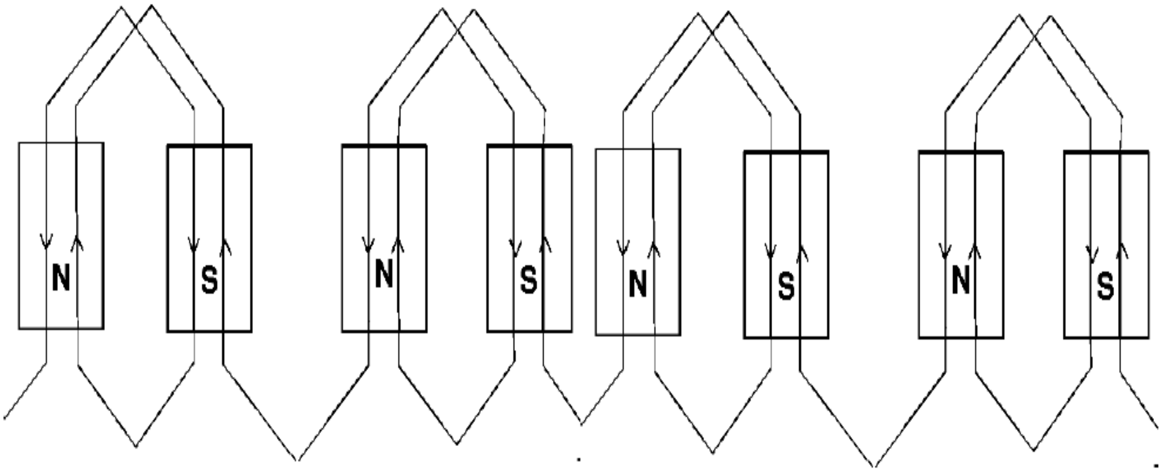


Figure: 3.3. Single layer winding

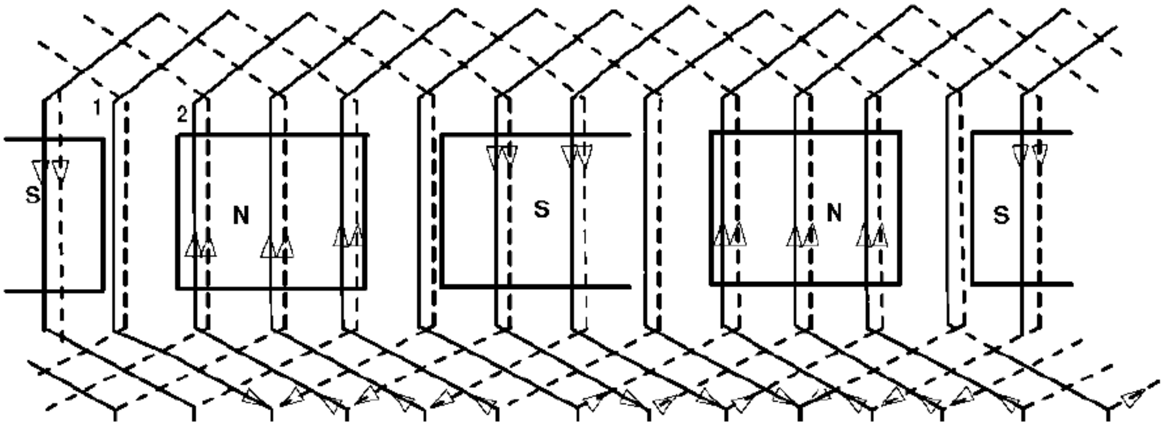


Figure: 3.4. Double layer winding

EMF Equation of an alternator:

Consider the following Φ = flux per pole in wb

P = Number of poles

N_s = Synchronous speed in rpm

f = frequency of induced emf in Hz
Z = total number of stator conductors

Z_{ph} = conductors per phase connected in series T_{ph}
= Number of turns per phase

Assuming concentrated winding, considering one conductor placed in a slot
According to Faradays Law electromagnetic induction,

The average value of emf induced per conductor in one revolution
e_{avg} = d /dt e_{avg} = Change of Flux in one revolution/ Time taken for one revolution

Change of Flux in one revolution = p x
Time taken for one revolution = $60/N_s$ seconds

Hence e_{avg} = (p x) / ($60/N_s$) = p x x N_s / 60 We
know f = PN_s /120
hence PN_s /60 = 2f

Hence e_{avg} = 2 f volts
Hence average emf per turn = 2 x 2 f volts = 4 f volts
If there are $T_{ph,}$ number of turns per phase connected in series, then average emf induced in T_{ph} turns is

$E_{ph,\ avg}$ = T_{ph} x e_{avg} = 4 f ø T_{ph} volts
Hence RMS value of emf induced E = 1.11 x $E_{ph,\ avg}$
= 1.11 x 4 f ø T_{ph} volts

= 4.44 f ø T_{ph} volts
This is the general emf equation for the machine having concentrated and full pitched winding.

In practice, alternators will have short pitched winding and hence coil span will not be 180^0, but on or two slots short than the full pitch.

Pitch Factor:

Pitch factor K_p= emf induced in a short pitched coil/ emf induced in a full pitched coil =
(2E cos α/2)/ 2E
K_p = cos α/2
where α is called chording angle.

Distribution Factor: Even though we assumed concentrated winding in deriving emf equation, in practice an attempt is made to distribute the winding in all the slots coming under a pole. Such a winding is called distributed winding.

In concentrated winding the emf induced in all the coil sides will be same in magnitude and in phase with each other. In case of distributed winding the magnitude of emf will be same but the emfs induced in each coil side will not be in phase with each other as they are distributed in the slots under a pole. Hence the total emf will not be same as that in concentrated winding but will be equal to the vector sum of the emfs induced. Hence it will be less than that in the concentrated winding. Now the factor by which the emf induced in a distributed winding gets reduced is called distribution factor and defined as the ratio of emf induced in a distributed winding to emf induced in a concentrated winding.

Distribution factor K_d = emf induced in a distributed winding/ emf induced in a concentrated winding = vector sum of the emf/ arithmetic sum of the emf

Let
E = emf induced per coil side

m = number of slots per pole per phase, n = number of slots per pole
β = slot angle = 180/n

The emf induced in concentrated winding with m slots per pole per phase = mE volts.

Fig below shows the method of calculating the vector sum of the voltages in a distributed winding having a mutual phase difference of β. When m is large curve ACEN will form the arc of a circle of radius r.

From the figure below AC = 2 x r x sin $\beta/2$
Hence arithmetic sum = m x 2r sin$\beta/2$
Now the vector sum of the emfs is AN as shown in figure below = 2 x r x sin m$\beta/2$

Hence the distribution factor K_d = vector sum of the emf / arithmetic sum of the emf =

$$(2r \sin m\beta/2) / (m \times 2r \sin \beta/2)$$

$$K_d = (\sin m\beta/2) / (m \sin \beta/2)$$

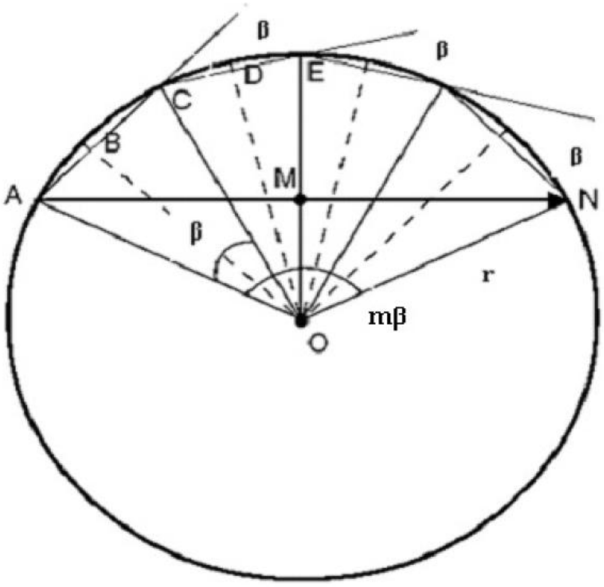


Figure: 3.5. Calculation of vector sum

In practical machines the windings will be generally short pitched and distributed over the periphery of the machine. Hence in deducing the emf equation both pitch factor and distribution factor has to be considered. Hence the general emf equation including pitch factor and distribution factor can be given as EMF induced per phase = 4.44 f T_{ph} x K_pK_d volts

$E_{ph} = 4.44\ K_pK_d\ f\ \ T_{ph}$ vlolts

Hence the line Voltage $E_L = \sqrt{3}$ x phase voltage = $\sqrt{3}\ E_{ph}$

Harmonics: When the uniformly sinusoidal distributed air gap flux is cut by either the stationary or rotating armature sinusoidal emf is induced in the alternator. Hence the nature of the waveform of induced emf and current is sinusoidal. But when the alternator is loaded waveform will not continue to be sinusoidal or becomes non sinusoidal. Such non sinusoidal wave form is called complex wave form. By using Fourier series representation it is possible to represent complex non sinusoidal waveform in terms of series of sinusoidal components called harmonics, whose frequencies are integral multiples of fundamental wave. The fundamental wave form is one which is having the frequency same as that of complex wave.

The waveform, which is of the frequency twice that of the fundamental is called second harmonic. The one which is having the frequency three times that of the fundamental is called third harmonic and so on. These harmonic components can be represented as follows.

Fundamental: $e_1 = E_{m1}$ Sin $(\omega t \pm \theta_1)$
2nd Harmonic $e_2 = E_{m2}$ Sin $(2\omega t \pm \theta_2)$
3rd Harmonic $e_3 = E_{m3}$ Sin $(3\omega t \pm \theta_3)$
5th Harmonic $e_5 = E_{m5}$ Sin $(5\omega t \pm \theta_5)$ etc.

In case of alternators as the field system and the stator coils are symmetrical the induced emf will also be symmetrical and hence the generated emf in an alternator will not contain any even harmonics.

Slot Harmonics: As the armature or stator of an alternator is slotted, some harmonics are induced into the emf which is called slot harmonics. The presence of slot in the stator makes the air gap reluctance at the surface of the stator non uniform. Since in case of alternators the poles are moving or there is a relative motion between the stator and rotor, the slots and the teeth alternately occupy any point in the air gap. Due to this the reluctance or the air gap will be continuously varying. Due to this variation of reluctance ripples will be formed in the air gap between the rotor and stator slots and teeth. This ripple formed in the air gap will induce ripple emf called slot harmonics.

Minimization of Harmonics: To minimize the harmonics in the induced waveforms following methods are employed:

1. Distribution of stator winding.
2. Short Chording
3. Fractional slot winding
4. Skewing
5. Larger air gap length.

Effect of Harmonics on induced emf:

The harmonics will affect both pitch factor and distribution factor and hence the induced emf. In a well designed alternator the air gap flux density distribution will be symmetrical and hence can be represented in Fourier series as follows.

$B = B_{m1}\sin \omega t + B_{m3} \sin 3\omega t + B_{m5}\sin 5\omega t + \ldots\ldots\ldots\ldots$

The emf induced by the above flux density distribution is given by

$e = E_{m1}\sin \omega t + E_{m3} \sin 3\omega t + E_{m5}\sin 5\omega t + \ldots\ldots\ldots\ldots$

The RMS value of the resultant voltage induced can be given as
$E_{ph} = \sqrt{[(E_1)^2 + (E_3)^2 + (E_5)^2 + \ldots\ldots\ldots\ldots\ldots (E_n)^2]}$
And line voltage $E_{Line} = \sqrt{3} \times E_{ph}$

Effect of Harmonics of pitch and distribution Factor:

The pitch factor is given by $K_p = \cos \alpha/2$, where α is the chording angle.
For any harmonic say nth harmonic the pitch factor is given by $K_{pn} = \cos n\alpha/2$

The distribution factor is given by $K_d = (\sin m\beta/2) / (m \sin \beta/2)$
For any harmonic say nth harmonic the distribution factor is given by $K_{dn} = (\sin m\, n\beta/2) / (m \sin n\beta/2)$

Operation of Alternators:

Similar to the case of DC generator, the behavior of a Synchronous generator connected to an external load is different than that at no-load. In order to understand the performance of the Synchronous generator when it is loaded, consider the flux distributions in the machine when the armature also carries a current. Unlike in the DC machine in alternators the emf peak and the current peak will not occur in the same coil due to the effect of the power factor of the load. The current and the induced emf will be at their peaks in the same coil only for upf loads. For zero power factor lagging loads, the current reaches its peak in a coil which falls behind that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. Likewise for zero power factor leading loads, the current reaches its peak in a coil which is ahead of that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. For simplicity, assume the resistance and leakage reactance of the stator windings to be negligible. Also assume the magnetic circuit to be linear i.e. the flux in the magnetic circuit is deemed to be proportional to the resultant ampere-turns - in other words the machine is operating in the linear portion of the magnetization characteristics. Thus the emf induced is the same as the terminal voltage, and the phase-angle between current and emf is determined only by the power factor (pf) of the external load connected to the synchronous generator.

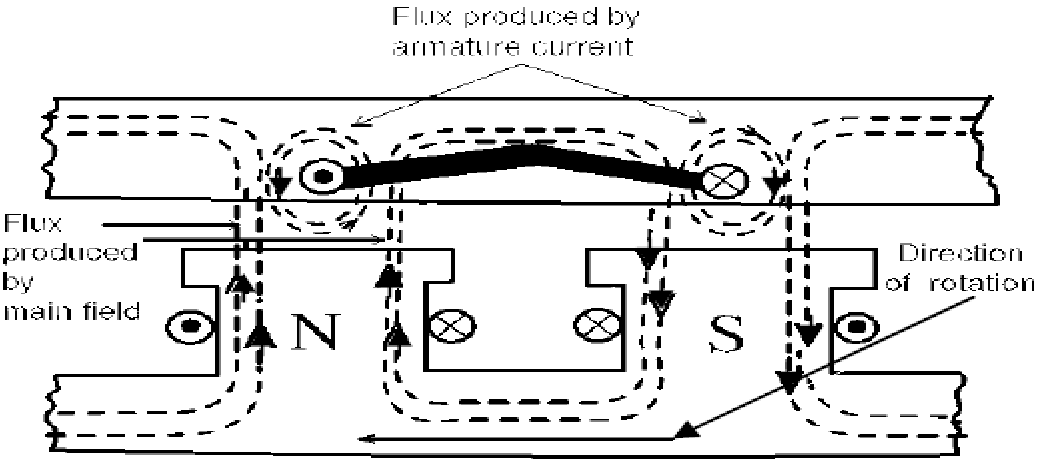
Armature Reaction:
Magnetic fluxes in alternators

There are three main fluxes associated with an alternator:

- i) Main useful flux linked with both field & armature winding.
- ii) Leakage flux linked only with armature winding.
- iii) Leakage flux linked only with field winding.

The useful flux which links with both windings is due to combined mmf of the armature winding and field winding. When the armature winding of an alternator carries current then an mmf sets in armature. This armature mmf reacts with field mmf producing the resultant flux, which differs from flux of field winding alone. The effect of armature reaction depends on nature of load (power factor of load). At no load condition, the armature has no reaction due to absence of armature flux. When armature delivers current at unity power factor load, then the resultant flux is displaced along the air gap towards the trailing pole tip. Under this condition, armature reaction has distorting effect on mmf wave as shown in Figure. At zero lagging power factor loads the armature current is lagging by 90° with armature voltage. Under this condition, the position of armature conductor when inducing maximum emf is the centre line of field mmf. Since there is no distortion but the two mmf are in opposition, the armature reaction is now purely demagnetizing as shown in Figure. Now at zero power factors leading, the armature current leads armature voltage by 90°. Under this condition, the mmf of armature as well as the field winding is in same phase and additive. The armature mmf has magnetizing effect due to leading armature current as shown in Figure.

(a) Unity Power Factor



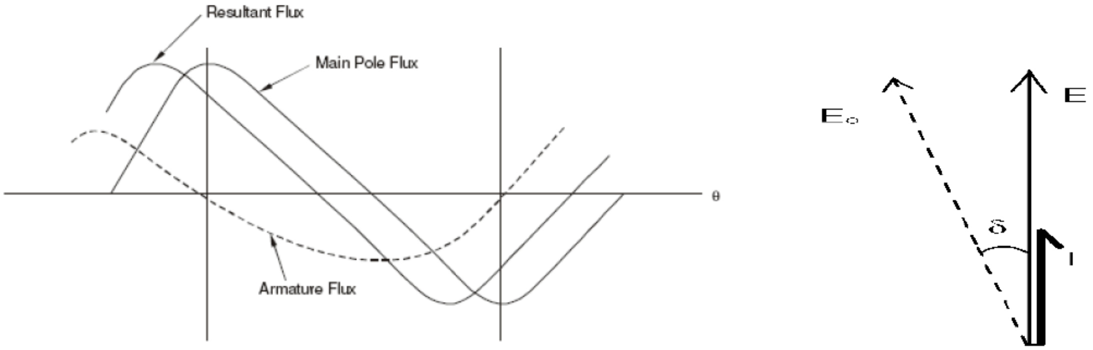
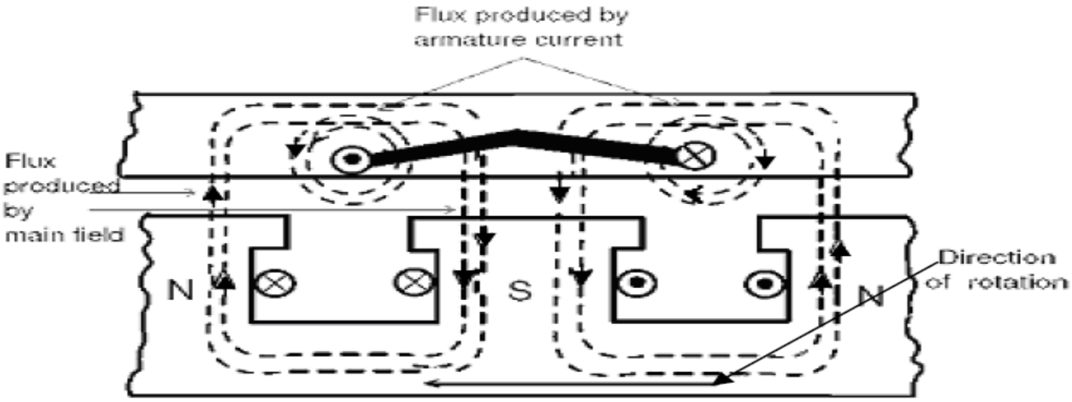


Figure: 3.6. Distorting effect of armature reaction

(b) Zero Power Factor Lagging



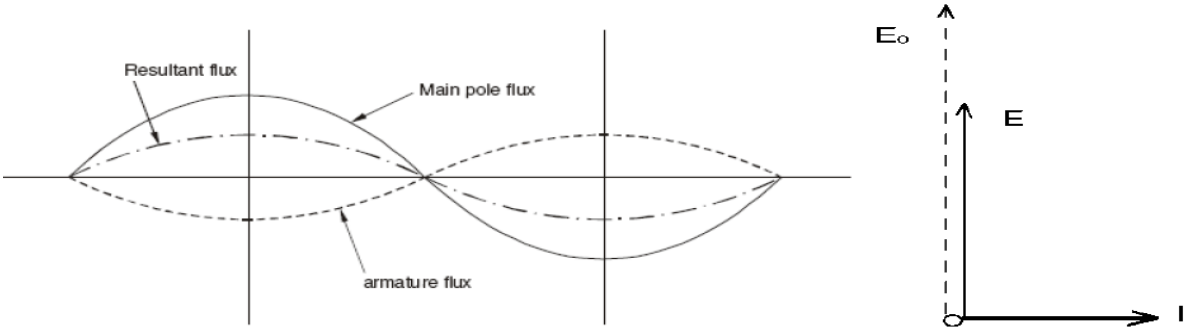


Figure3.7. Demagnetizing effect of armature reaction

(c) Zero Power Factor Leading

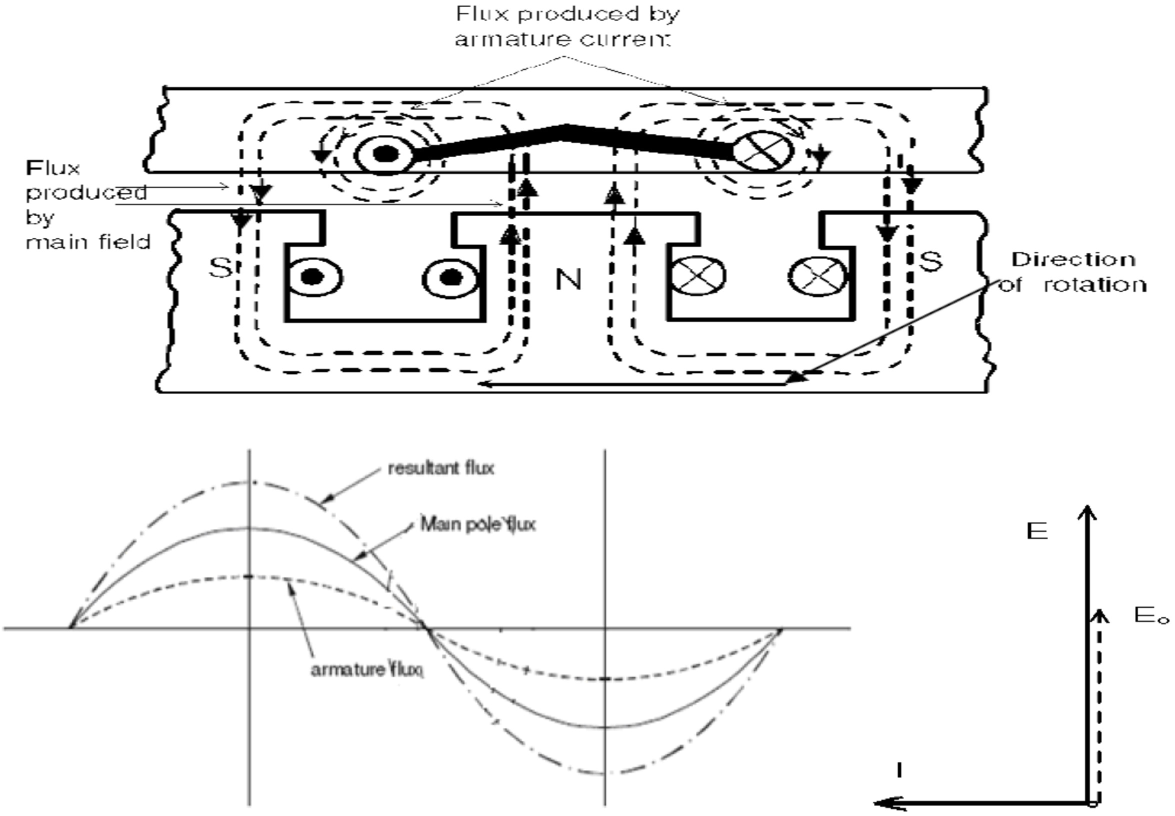


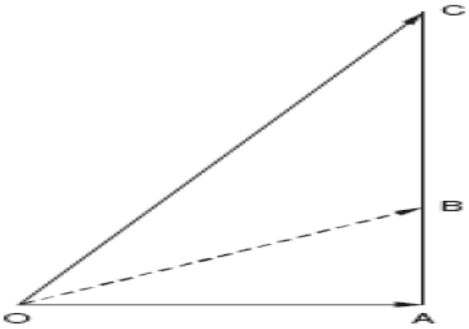
Figure3.8. Magnetizing effect of armature reaction

When the rotor is run, a voltage E is induced in the stator windings. If a load is connected to the terminals of the generator, a current flows. The 3-phase stator current flow will produce a magnetic field of its own. This stator magnetic field will distort the original rotor magnetic field, changing the resulting phase voltage. This effect is called armature reaction because the armature (stator) current affects the magnetic field.

From the phasor diagrams of the armature reaction it can be seen that E_0 is the emf induced under no load condition and E can be considered as the emf under loaded condition. It can also be understood that the E_0 is the emf induced due to the field winding acting alone and E is the emf induced when both field winding and stator winding are acting in combination. Hence emf E can be considered as sum of E_0 and another fictitious emf E_a proportional to the stator current. From the figures it can be seen that the emf E_a is always in quadrature with current. This resembles the emf induced in an inductive reactance. Hence the effect of armature reaction is exactly same as if the stator has an additional reactance $x_a = E_a/I$. This is called the armature reaction reactance. The leakage reactance is the true reactance and the armature reaction reactance is a fictitious reactance.

Synchronous Reactance and Synchronous Impedance

The synchronous reactance is an equivalent reactance the effects of which are supposed to reproduce the combined effects of both the armature leakage reactance and the armature reaction. The alternator is supposed to have no armature reaction at all, but is supposed to possess an armature reactance in excess of its true leakage reactance. When the synchronous reactance is combined vectorially with the armature resistance, a quantity called the synchronous impedance is obtained as shown in figure.



OA = Armature Resistance
AB = Leakage Reactance
BC = Equivalent Reactance of Armature Reaction
AC = Synchronous Reactance
OC = Synchronous Impedance

The armature winding has one more reactance called armature reaction reactance in addition to leakage reactance and resistance. Considering all the three parameters the equivalent circuit of a synchronous generator can be written as shown below. The sum of leakage reactance and armature reaction reactance is called synchronous reactance X_s. Under this condition impedance of the armature winding is called the synchronous impedance Z_s.

Hence synchronous reactance $\mathbf{X_s = X_{\mathit{l}} + X_a}$ per phase and
synchronous impedance $\mathbf{Z_s = R_a + j\,X_s}$ per phase

As the armature reaction reactance is dependent on armature current so is synchronous reactance and hence synchronous impedance is dependent on armature current or load current.

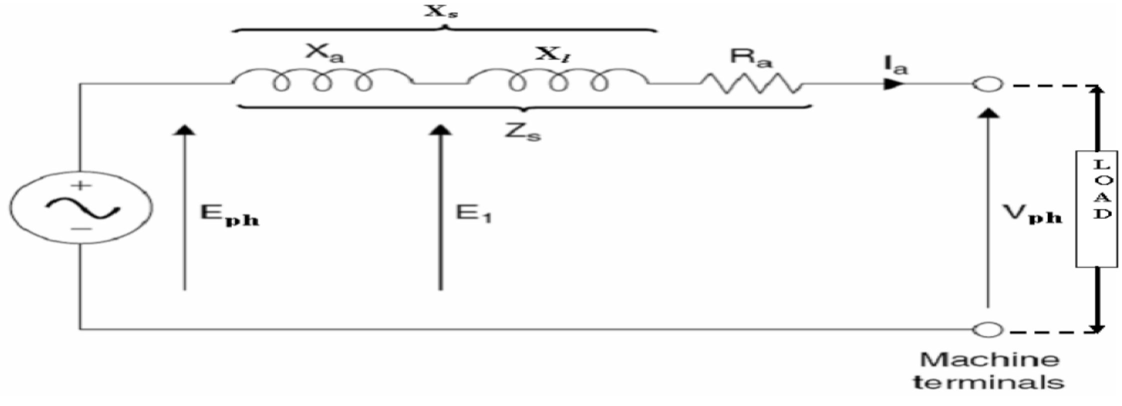


Figure: 3.9. Equivalent circuit of alternator

Phasor diagram

In the phasor diagrams E is the induced emf /phase = E_{ph} and V is the terminal voltage /phase = V_{ph}. From each of the phasor diagrams the expression for the induced emf E_{ph} can be expressed in terms of V_{ph}, armature current, resistance, reactances and impedance of the machine as follows.

(i) Unity power factor load

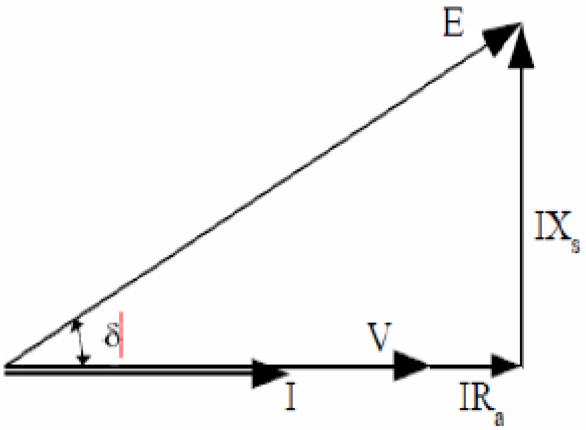


Figure: 3.10. Phasor diagram at Unity power factor load

Under unity power factor load: $E_{ph} = (V + IR_a) + j\,(IX_S)$

$$E_{ph} = \sqrt{[\,(V + IR_a)^2 + (IX_S)^2]}$$

(ii) Zero power factor lagging

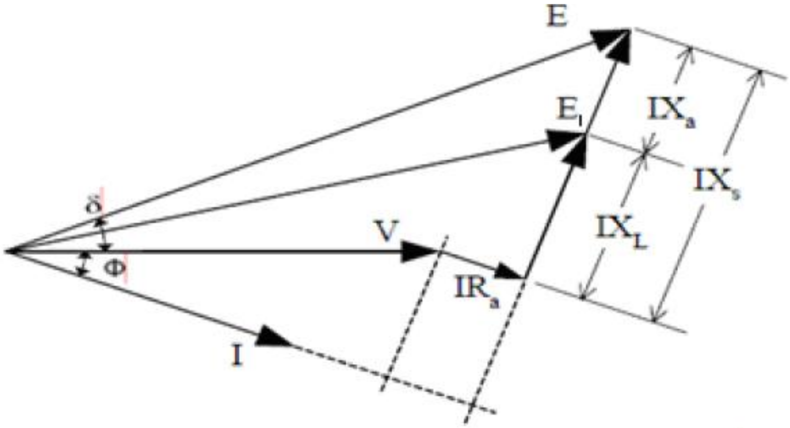


Figure: 1.11. Phasor diagram at zero power factor lagging

Under zero power factor lagging: $E_{ph} = V + (IR_a + j\,IX_S) = V + I(R_a + j\,X_S)$

The above expression can also be written as $E_{ph} = \sqrt{[\,(V\cos\;\; + IR_a)^2 + (V\sin\;\; + IX_S)^2]}$

a) Zero power factor leading

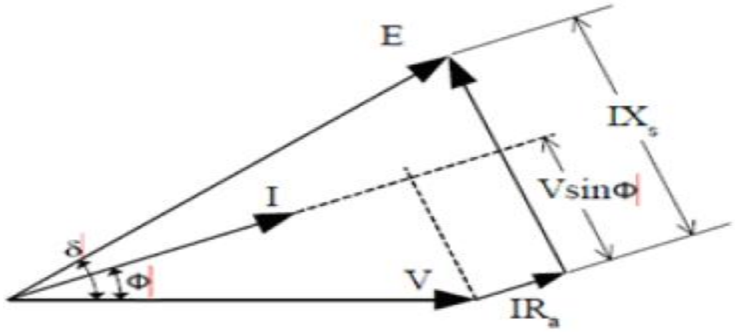


Figure: 3.12. Phasor diagram at zero power factor leading.

Numerical problems:

1. A 3Φ, 50 Hz, star connected salient pole alternator has 216 slots with 5 conductors per slot. All the conductors of each phase are connected in series; the winding is distributed and full pitched. The flux per pole is 30 mwb and the alternator runs at 250 rpm. Determine the phase and line voltages of emf induced.

Slon: N_S = 250 rpm, f = 50 Hz,

P = 120 x f/N_S = 120 x 50/250 = 24 poles

m = number of slots/pole/phase = 216/(24 x 3) = 3

$\beta = 180^0$ / number of slots/pole = 180^0 / (216/24) = 20^0 Hence distribution factor K_d = (sin mβ/2) / (m sin β/2)

= (sin 3 x 20 / 2) / (3 sin 20/2)

= 0.9597

Pitch factor K_p = 1 for full pitched winding. We have emf induced per conductor

T_{ph}= Z_{ph}/2 ; Z_{ph}= Z/3

Z = conductor/ slot x number of slots T_{ph}= Z/6 = 216 x 5 /6 = 180

Therefore E_{ph} = 4.44 K_pK_d f 8 T_{ph} vlolts

= 4.44 x 1 x 0.9597 x 50 x 30 x 10^{-3} x 180 = 1150.488 volts

Hence the line Voltage E_L = √3 x phase voltage = √3 E_{ph} = √3 x1150.488 = 1992.65 volts

2. A 3Φ, 16 pole, star connected salient pole alternator has 144 slots with 10 conductors per slot. The alternator is run at 375 rpm. The terminal voltage of the generator found to be 2.657 kV. Dteremine the frequency of the induced emf and the flux per pole.

Soln: N_S = 375 rpm, p =16, slots = 144, Total no. of conductors = 144 x 10 = 1440 E_L = 2.657 kV,

f = P N_S/120 = 16 x 375/120 = 50 Hz

Assuming full pitched winding k_p = 1

Number of slots per pole per phase = 144/(16 x 3) = 3

Slot angle β = 180^0 / number of slots/pole = 180^0 /9 = 20^0

Hence distribution factor K_d = (sin mβ/2) / (m sin β/2)

= (sin 3 x 20 / 2) / (3 sin 20/2)

= 0.9597

Turns per phase T_{ph} = 144 x 10/ 6 = 240 E_{ph} = $E_L/\sqrt{3}$ = $2.657/\sqrt{3}$ = 1.534 kV

E_{ph} = 4.44 K_pK_d f 8 T_{ph} vlolts

1534.0 = 4.44 x 1 x 0.9597 x 50 x 8 x 240

8 = 0.03 wb = 30 mwb

3. A 4 pole, 3 phase, 50 Hz, star connected alternator has 60 slots with 4 conductors per slot. The coils are short pitched by 3 slots. If the phase spread is 60^0, find the line voltage induced for a flux per pole of 0.943 wb.

Slon: p = 4, f = 50 Hz, Slots = 60, cond/slot = 4 , short pitched by 3 slots, phase spread = 60^0, Φ = 0.943 wb

Number of slots/pole/phase m = 60/(4 x 3) = 5

Slot angle β = phase spread/ number of slots per pole/phase = 60/5 = 12

Distribution factor k_d = (sin mβ/2) / (m sinβ/2)

= sin (5 x 12/2) / 5 sin(12/2)

= 0.957

Pitch factor = cos α/2

Coils are short chorded by 3 slots Slot angle = 180/number of slots/pole = 180/15 = 12

Therefore coil is short pitched by α = 3 x slot angle = 3 x 12 = 36^0

Hence pitch factor k_p = cos α/2 = cos 36/2 = 0.95

Number of turns per phase T_{ph} = $Z_{ph}/2$ = (Z/3)/2 = Z /6 = 60 x 4 /6 = 40 EMF induced per phase E_{ph} = 4.44 k_p k_d f Φ T_{ph} volts

= 4.44 x 0.95 x 0.957 x 50 x 0.943 x 40

= 7613 volts

Line voltage E_L = √3 x E_{ph}

= √3 x 7613 = 13185 volts

4. In a 3 phase star connected alternator, there are 2 coil sides per slot and 16 turns per coil. The stator has 288 slots. When run at 250 rpm the line voltage is 6600 volts at 50 Hz. The coils are shot pitched by 2 slots. Calculate the flux per pole.

Slon: N_S = 250 rpm, f = 50 Hz, slots = 288, E_L= 6600 volts, 2 coilsides/slot, 16 turns /coil Short pitched by 2 slots

Number of poles = 120f/ N_S = 120 x 50/250 = 24

Number of slots /pole/phase m = 288 / (24 x 3) = 4

Number of slots /pole = 288 / 24 = 12

Slot angle β = 180/ number of slots per pole = 180 / 12 = 15^0

Distribution factor k_d = (sin mβ/2) / (m sinβ/2)

= sin (4 x 15/2) / 4 sin(15/2)

= 0.9576

Coils are short chorded by 2 slots Slot angle = 15

Therefore coil is short pitched by α = 2 x slot angle = 2 x 15 = 30^0 Hence pitch factor k_p = cos α/2 = cos 30/2 = 0.9659

Two coil sides per slot and 16 turns per coil
Total number of conductors per slot = 2 x 16 = 32 turns Total conductors = 32 x 288
Turns per phase = 32 x 288 / 6 = 1536

E_{ph} = 6600 / √3 = 3810.51 volts,

We have EMF induced per phase E_{ph} = 4.44 k_p k_d f Φ T_{ph} volts

3810.51 = 4.44 x 0.9659 x 0.9576 x 50 x Φ x 1536

Φ = 0.02 wb

5. A 10 pole, 600 rpm, 50Hz, alternator has the following sinusoidal flux density distribution. B = sin θ + 0.4 sin 3θ + 0.2 sin 5θ wb/m^2. The alternator has 180 slots with 2 layer 3 turn coils with a coil span of 15 slots. The coils are connected in 60^0 groups. If the armature diameter is 1.2 m and core length is 0.4 m, calculate (a) the expression for instantaneous emf/conductor (b) the expression for instantaneous emf/coil (c) the phase and line voltages if the machine is star connected.

Slon: Area under one pole pitch = π DL/p = π x 1.2 x 0.4/10 = 0.1508 m^2 Fundamental flux/pole, Φ_1 = average flux density x area

= 2/ π x 1 x 0.1508

= 0.096 wb

(a) rms value of emf induced/conductor = 2.22f Φ_1 = 2.22 x 50 x 0.096 = 10.656 volts

maximum value of emf/conductor = √2 x 10.656 = 15.07 volts 3^{rd} harmonic voltage = 0.4 x 15.07 = 6.02 volts

5^{th} harmonic voltage = 0.2 x 15.07 = 3.01 volts

the expression for instantaneous emf/conductor e = 15.07 sin θ + 6.02 sin 3θ + 3.01 sin 5θ volts

(b) conductors/slot = 6 = conductors/coil, slots = 180, coil span = 15 slots slots/pole = 18

slot angle β = 180/number of slots/ pole = 180/ 18 = 10^0 coil is short chorded by 3 slots hence $\alpha = 30^0$

Pitch factor $k_{pn} = \cos n\alpha /2$

$k_{p1} = \cos \alpha /2 = \cos 30/2 = 0.9659$ $k_{p3} =$
$\cos 3 \times 30/2 = 0.707$
$k_{p5} = \cos 5 \times 30/2 = 0.2588$

Fundamental rms value of emf induced/coil = $2.22\ k_p\ f\ \Phi_1\ Z$
$= 2.22 \times 0.9659 \times 50 \times 0.096 \times 6$
$= 61.76$ volts

Maximum value of emf induced/coil = $\sqrt{2} \times 61.76 = 87.34$ volts

Similarly 3rd harmonic voltage = 25.53 volts

5th harmonic voltage = 4.677 volts

expression for instantaneous emf/coil $e = 87.34 \sin \theta + 25.53 \sin 3\theta + 4.677 \sin 5\theta$ volts

slot angle $\beta = 180/\text{number of slots/ pole} = 180/ 18 = 10^0$

number of slots/pole/phase = 180/(10 x 3) = 6 Distribution factor $k_{dn} =$
$(\sin m\, n\beta/2) / (m \sin n\beta/2)$

$k_{d1} = \sin (6 \times 10/2) / 6 \sin(10/2) =$
0.956

$k_{d3} = \sin (6 \times 3 \times 10/2) / 6 \sin (3 \times 10/2) = 0.644$

$k_{d5} = \sin (6 \times 5 \times 10/2) / 6 \sin (5 \times 10/2) =$
0.197

Turns/phase $T_{ph} = 180 \times 6/6 = 180$

rms value of emf induced = $4.44\ k_{pn}\ k_{dn}\ (nf)\ \Phi_n\ T_{ph}$ for any nth harmonic

fundamental voltage $E_{ph1} = 4.44\ k_{p1}\ k_{d1}\ f\ \Phi_1\ T_{ph}$

$= 4.44 \times 0.9659 \times 0.956 \times 50 \times 0.096 \times 180$
$= 3542.68$ volts

Similarly 3rd harmonic voltage $E_{ph3} = 697.65$ volts
5th harmonic voltage $E_{ph5} = 39.09$ volts

Phase voltage = $\sqrt{(E^2_{ph1} + E^2_{ph3} + E^2_{ph5})}$

$= \sqrt{(3542.68^2 + 697.65^2 + 39.09^2)}$

$= 3610.93$ volts

Line voltage = $\sqrt{3} \times \sqrt{(E^2_{ph1} + E^2_{ph5})}$
$= \sqrt{3} \times \sqrt{(3542.68^2 + 39.09^2)}$
$= 6136.48$ volts

6. A three phase 600 kVA, 400 volts, delta connected alternator is reconnected in star. Calculate its new ratings in terms of voltage, current and volt-ampere.

Slon: (i) when the machine is delta connected $V_L = V_{ph}$ = 400 volts

Volt-ampere = $\sqrt{3} \times V_L \times I_L$ = 600 kVA Hence I_L = 600 kVA/ $\sqrt{3} \times 400$ = 866 amps

and $I_{ph} = I_L / \sqrt{3} = 866 / \sqrt{3}$ = 500 amps

When it is reconnected in star phase voltage and phase current will remain same, as
$E_{ph} = 4.44\, k_p\, k_d\, f\, \Phi\, T_{ph}$ and $I_{ph} = V_{ph} / Z_{ph}$

(ii) When star connected

V_{ph} = 400 volts and $V_L = \sqrt{3} \times V_{ph} = \sqrt{3} \times 400$ = 692.8 volts

$I_L = I_{ph}$ = 500 amps

Hence VA rating = $\sqrt{3} \times V_L \times I_L = \sqrt{3} \times 692.8 \times 500$ = 600 kVA

Irrespective of the type of connection the power output of the alternator remains same. Only line voltage and line currents will change.

REGULATION OF SYNCHRONOUS GENERATOR

Voltage Regulation

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed with out change in speed and excitation. Or The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.
Hence regulation can be expressed as

% Regulation = $(E_{ph} - V_{ph} / V_{ph}) \times 100$

where E_{ph} = induced emf /phase, V_{ph} = rated terminal voltage/phase

Methods of finding Voltage Regulation: The voltage regulation of an alternator can be determined by different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it cannot determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

1) Direct loading method
2) EMF method or Synchronous impedance method
3) MMF method or Ampere turns method
4) ASA modified MMF method

5) ZPF method or Potier triangle method

All the above methods other than direct loading are valid for non salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

EMF method: This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following informations are to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

OC & SC test on alternator

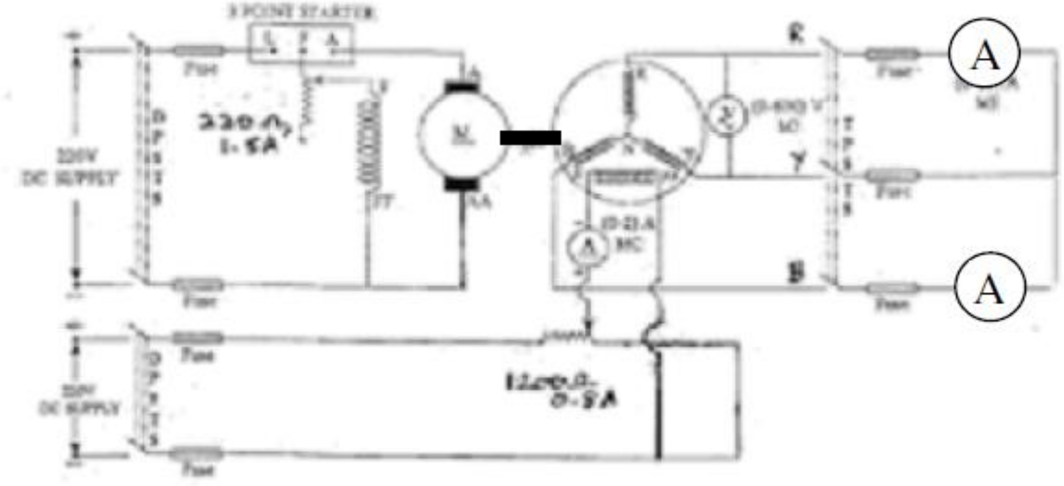


Figure: 3.13. OC & SC test on alternator

Open Circuit Characteristic (O.C.C.)

The open-circuit characteristic or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator. Indeed, in large turbo-alternators, where the air gap is relatively long, the curve shows a gradual bend. It is determined by inserting resistance in the field circuit and measuring corresponding value of terminal voltage and field current. Two voltmeters are connected across the armature terminals. The machine is run at rated speed and field current is increased gradually to I_{f1} till armature voltage reaches rated value or even 25% more than the rated voltage. Figure 32 illustrates a typical circuit for OC and SC test and figure 33 illustrates OC and SC curve. The major portion of the exciting ampere-turns is required to force the flux across the air gap, the reluctance of which is assumed to be constant. A straight line called the air gap line can therefore be drawn as shown, dividing the excitation for any voltage into two portions, (a) that required to force the flux across the air gap, and (b) that required to force it through the remainder of the magnetic circuit. The shorter the air gap, the steeper is the air gap line.

Procedure to conduct OC test:

i) Start the prime mover and adjust the speed to the synchronous speed of the alternator.
ii) Keep the field circuit rheostat in cut in position and switch on DC supply.

iii) Keep the TPST switch of the stator circuit in open position.

iv) Vary the field current from minimum in steps and take the readings of field current and stator terminal voltage, till the voltage read by the voltmeter reaches up to 110% of rated voltage. Reduce the field current and stop the machine.

i) Plot of terminal voltage/ phase vs field current gives the OC curve.

Short Circuit Characteristic (S.C.C.)

The short-circuit characteristic, as its name implies, refers to the behaviour of the alternator when its armature is short-circuited. In a single-phase machine the armature terminals are short-circuited through an ammeter, but in a three-phase machine all three phases must be short-circuited. An ammeter is connected in series with each armature terminal, the three remaining ammeter terminals being short-circuited. The machine is run at rated speed and field current is increased gradually to I_{f2} till armature current reaches rated value. The armature short-circuit current and the field current are found to be proportional to each other over a wide range, as shown in Figure 33, so that the short-circuit characteristic is a straight line. Under short-circuit conditions the armature current is almost 90° out of phase with the voltage, and the armature mmf has a direct demagnetizing action on the field. The resultant ampere − turns inducing the armature emf are, therefore, very small and is equal to the difference between the field and the armature ampere − turns. This results in low mmf in the magnetic circuit, which remains in unsaturated condition and hence the small value of induced emf increases linearly with field current. This small induced armature emf is equal to the voltage drop in the winding itself, since the terminal voltage is zero by assumption. It is the voltage required to circulate the short-circuit current through the armature windings. The armature resistance is usually small compared with the reactance.

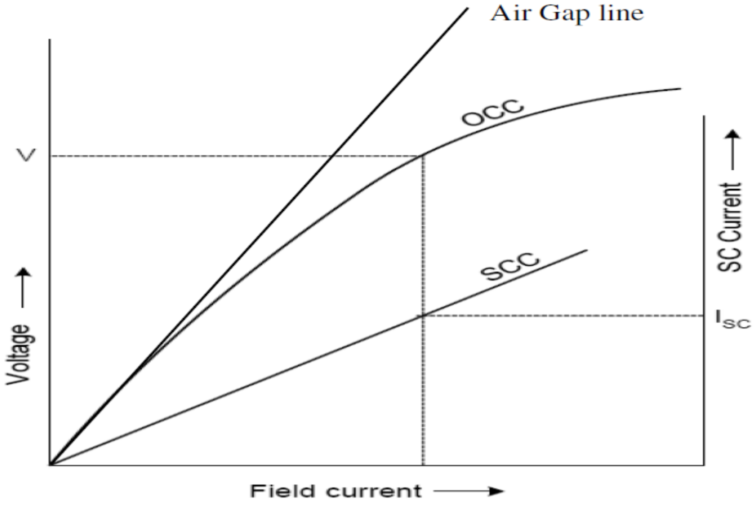


Figure: 3.14 OCC & SCC of an alternator

Short-Circuit Ratio:

The short-circuit ratio is defined as the ratio of the field current required to produce rated volts on open circuit to field current required to circulate full-load current with the armature short-circuited.

Short-circuit ratio = I_{f1}/I_{f2}

Determination of synchronous impedance Z_s:

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated form the oc and sc characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

synchronous impedance Z_s = (open circuit voltage per phase)/(short circuit current per phase) $_{\text{for same}}\ I_f$

Hence $Z_s = (V_{oc}) / (I_{sc})\ _{\text{for same}}\ I_f$
From figure 33 synchronous impedance $Z_s = V/I_{sc}$

Armature resistance R_a of the stator can be measured using Voltmeter – Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.
$Z_s = \sqrt{(R_a)^2 + (X_S)^2}$ and Synchronous reactance $X_s = \sqrt{(Z_s)^2 - (R_a)^2}$

Hence induced emf per phase can be found as $E_{ph} = \sqrt{[(V\cos + IR_a)^2 + (V\sin \pm IX_S)^2]}$ where
V = phase voltage per phase = V_{ph} , I = load current per phase

in the above expression in second term + sign is for lagging pwer factor ans – sign is for leading power factor.

% Regulation = $[(E_{ph} - V_{ph} / V_{ph})] \times 100$
where E_{ph} = induced emf /phase, V_{ph} = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence this method is called pessimistic method. The complete phasor diagram for the emf method is shown in figure

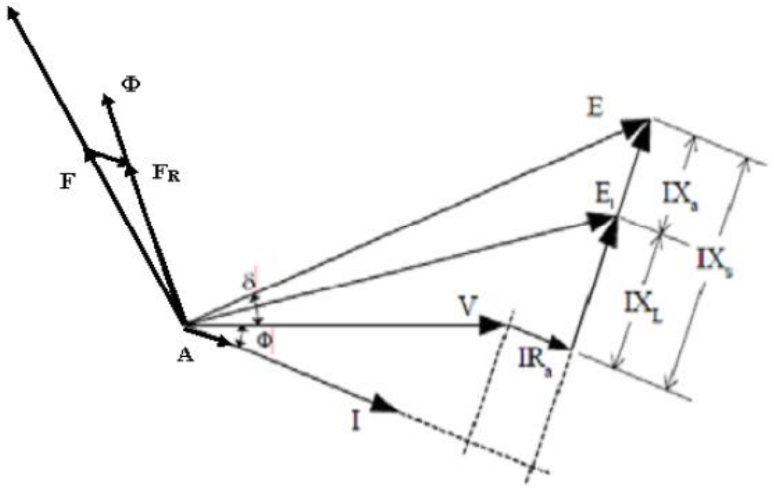


Figure: 3.15. Phasor diagram of alternator.

MMF method

This method is also known as amp - turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence called mmf method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Figure 35 shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. The details are shown in figure 36. Using the details it is possible determine the regulation at different power factors.

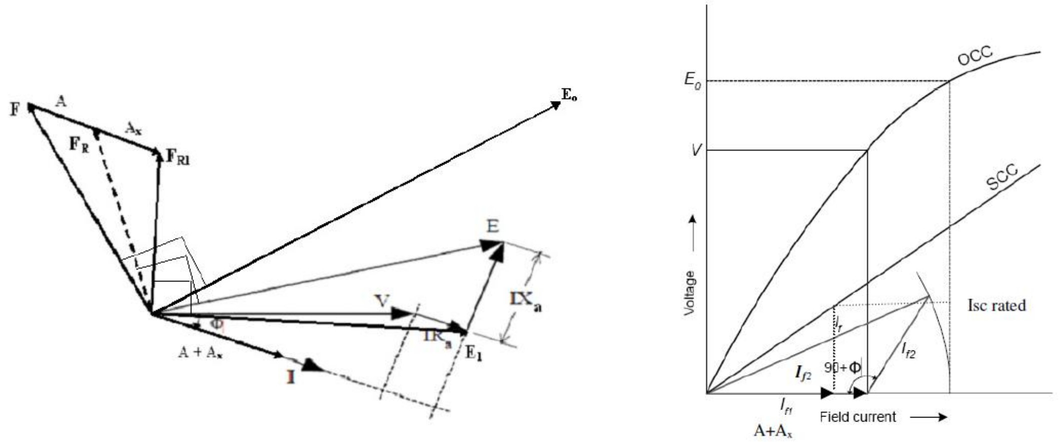


Figure: 3.16 Phasor diagram for MMF method and characteristics.

From the phasor diagram it can be seen that the mmf required to produce the emf E_1= (V + IR_a) is F_{R1}.In large machines resistance drop may neglected.

The mmf required to overcome the reactance drops is (A+A_x) as shown in phasor diagram. The mmf (A+A_x) can be found from SC characteristic as under SC condition both reactance drops will be present.

Following procedure can be used for determination of regulation by mmf method.

(i) By conducting OC and SC test plot OCC and SCC as shown in figure 36.
(ii) From the OCC find the field current *If1* required to produce the voltage, E_1= (V + IR_a).
(iii) From SCC find the magnitude of field current *If2* (≈ A+A_x) to produce the required armature current. A+A_x can also found from ZPF characteristics.
(iv) Draw *If2* at angle (90+Φ) from *If1*, where Φ is the phase angle of current w. r. t voltage. If current is leading, take the angle of *If2* as (90-Φ) as shown in figure 36.
(v) Determine the resultant field current, *If* and mark its magnitude on the field current axis.
(vi) From OCC. find the voltage corresponding to *If*, which will be *E0* and hence find the Regulation.

Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

ASA Modified MMF Method

Because of the unrealistic assumption of unsaturated magnetic circuit neither the emf method nor the mmf method are giving the realistic value of regulation. In spite of these short comings these methods are being used because of their simplicity. Hence ASA has modified mmf method for calculation of regulation. With reference to the phasor diagram of mmf method it can be seen that F = F_{R1} - (A+A_x). In the mmf method the total mmf F computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount FF_2 which can be computed from occ, scc and air gap lines as explained below referring to figure

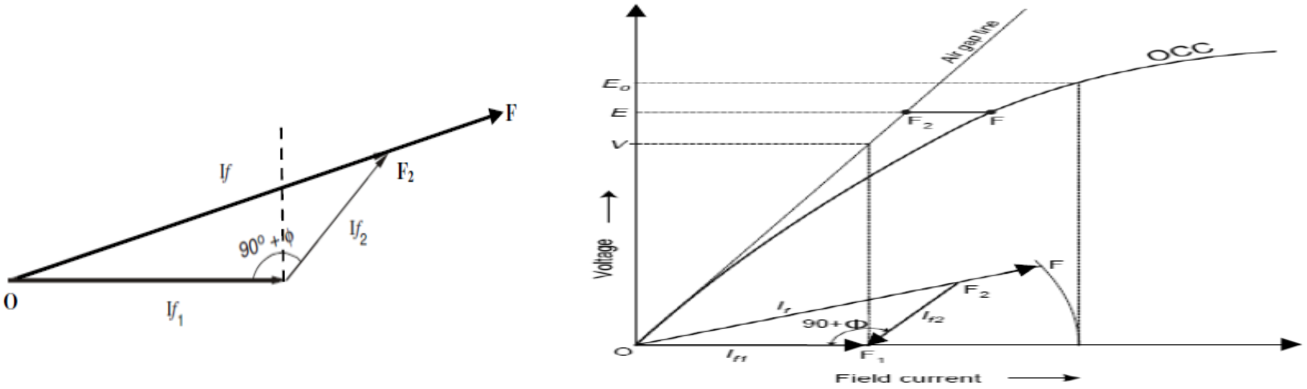


Figure: 3.17. Phasor diagram for ASA method and characteristics

If1 is the field current required to induce the rated voltage on open circuit. Draw *If2* with length equal to field current required to circulate rated current during short circuit condition at an angle (90+Φ) from *If1*. The resultant of *If1* and *If2* gives *If* (OF2 in figure). Extend OF2 upto F so that F2F accounts for the additional field current required for accounting the effect of partial saturation of magnetic circuit. F2F is found for voltage E (refer to phasor diagram of mmf method) as shown in figure 41. Project total field current OF to the field current axis and find corresponding voltage E0 using OCC. Hence regulation can found by ASA method which is more realistic.

Zero Power Factor (ZPF) method Potier Triangle Method

During the operation of the alternator, resistance voltage drop I_aR_a and armature leakage reactance drop I_aX_L are actually emf quantities and the armature reaction reactance is a mmf quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. AS explained earlier oc and sc tests are conducted and OCC and SCC are drawn. ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like *OCC* but shifted by a factor *IXL* vertically and horizontally by armature reaction mmf as shown below in figure. Following are the steps to draw ZPF characteristics.

By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop *IXL* and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from *V*, *IRa*, *IXL* and Φ. Use the expression $E = \sqrt{}(V\cos\Phi + IRa)^2 + (V\sin\Phi) + IXL)^2$ to compute E. Find field current corresponding to *E*. Draw FG with magnitude equal to BE at angle (90+Ψ) from field current axis, where Ψ is the phase angle of current from voltage vector *E* (internal phase angle).

The resultant field current is given by OG. Mark this length on field current axis. From OCC find the corresponding *E0*. Find the regulation.

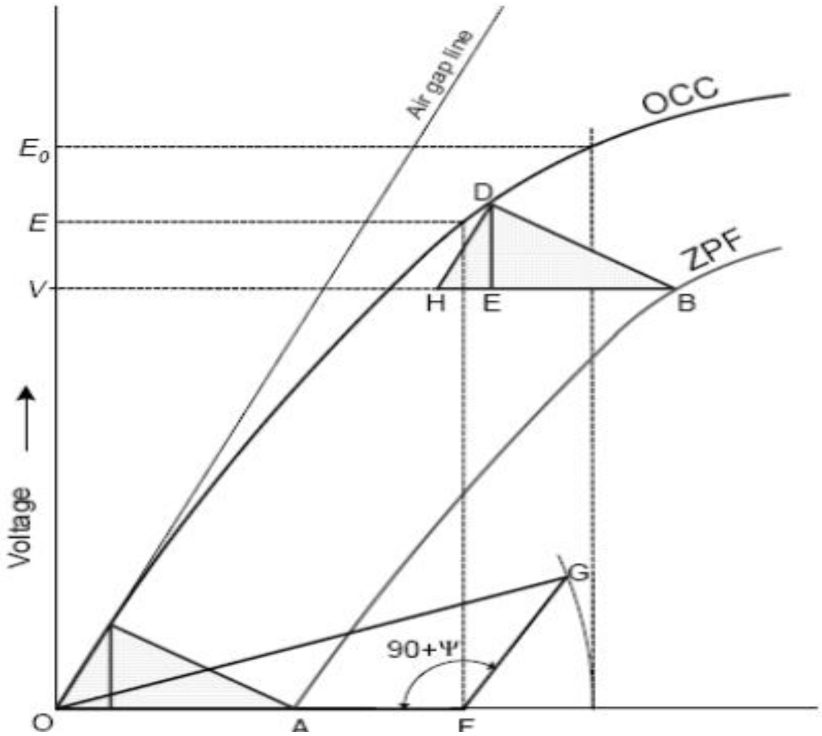


Figure: 3.18 ZPF method characteristics

Salient pole alternators and Blondel's Two reaction Theory

The details of synchronous generators developed so far is applicable to only round rotor or non salient pole alternators. In such machines the air gap is uniform throughout and hence the effect of mmf will be same whether it acts along the pole axis or the inter polar axis. Hence reactance of the stator is same throughout and hence it is called synchronous reactance. But in case salient pole machines the air gap is non uniform and it is smaller along pole axis and is larger along the inter polar axis. These axes are called direct axis or d-axis and quadrature axis or q-axis. Hence the effect of mmf when acting along direct axis will be different than that when it is acting along quadrature axis. Hence the reactance of the stator cannot be same when the mmf is acting along d – axis and q- axis. As the length of the air gap is small along direct axis reluctance of the magnetic circuit is less and the air gap along the q – axis is larger and hence the along the quadrature axis will be comparatively higher. Hence along d-axis more flux is produced than q-axis. Therefore the reactance due to armature reaction will be different along d-axis and q-axis. These reactances are

X_{ad} = direct axis reactance; X_{aq} = quadrature axis reactance

Hence the effect of armature reaction in the case of a salient pole synchronous machine can be taken as two components - one acting along the direct axis (coinciding with the main field pole axis) and the other acting along the quadrature axis (inter-polar region or magnetic neutral axis) - and as such the mmf components of armature-reaction in a salient-pole machine cannot be considered as acting on the same magnetic circuit. Hence the effect of the armature reaction cannot be taken into account by considering only the synchronous reactance, in the case of a salient pole synchronous machine.

In fact, the direct-axis component Fad acts over a magnetic circuit identical with that of the main field system and produces a comparable effect while the quadrature-axis component Faq acts along the inter polar axis, resulting in an altogether smaller effect and, in addition, a flux distribution totally different from that of Fad or the main field m.m.f. This explains why the application of cylindrical-rotor theory to salient-pole machines for predicting the performance gives results not conforming to the performance obtained from an actual test.

Blondel’s two-reaction theory considers the effects of the quadrature and direct-axis components of the armature reaction separately. Neglecting saturation, their different effects are considered by assigning to each an appropriate value of armature-reaction “reactance,” respectively xad and xaq . The effects of armature resistance and true leakage reactance (X_L) may be treated separately, or may be added to the armature reaction coefficients on the assumption that they are the same, for either the direct-axis or quadrature-axis components of the armature current (which is almost true). Thus the combined reactance values can be expressed as : $Xsd = xad + x_l$ *and* $Xsq = xaq + x_l$ for the direct- and cross-reaction axes respectively.

In a salient-pole machine, xaq, the quadrature-axis reactance is smaller than xad, the direct-axis reactance, since the flux produced by a given current component in that axis is smaller as the reluctance of the magnetic path consists mostly of the interpolar spaces. It is essential to clearly note the difference between the quadrature and direct-axis components Iaq, and Iad of the armature current Ia, and the reactive and active components Iaa and Iar. Although both pairs are represented by phasors in phase quadrature, the former are related to the induced emf Et while the latter are referred to the terminal voltage V. These phasors are clearly indicated with reference to the phasor diagram of a (salient pole) synchronous generator supplying a lagging power factor (pf) load, shown in Fig

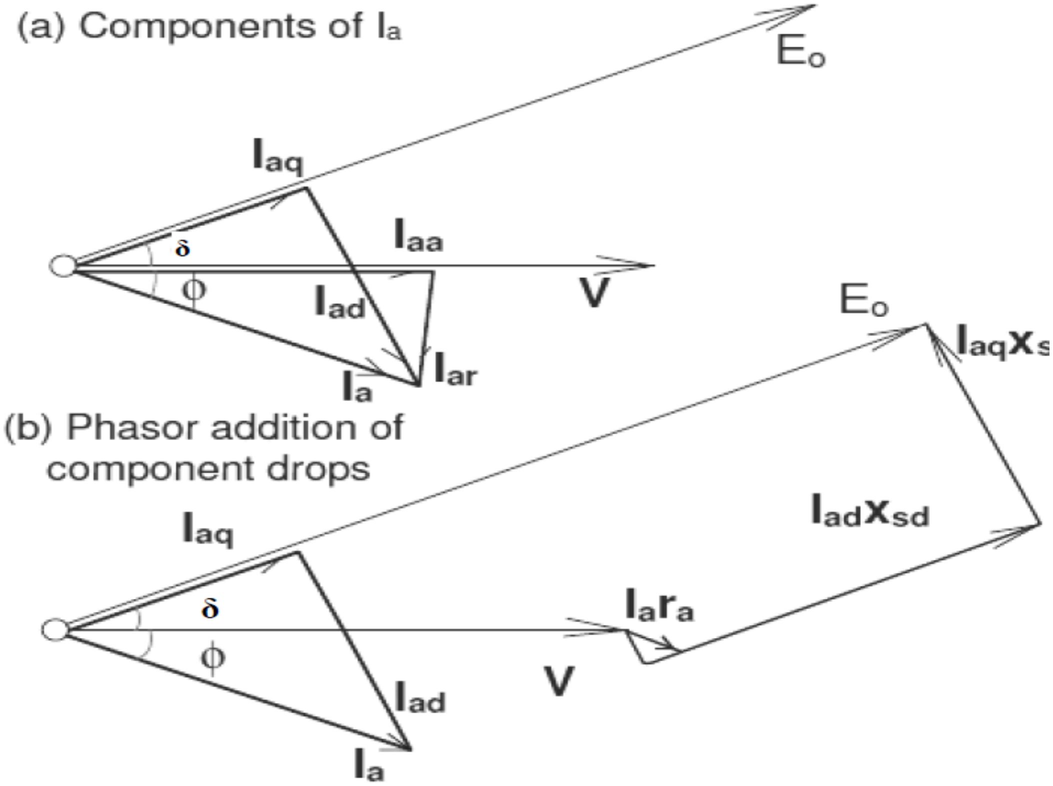


Figure: 3.19. Phasor diagram of salient pole alternator

Iaq = Ia cos(δ+φ); Iad = Ia sin(δ+φ); and Ia = $\sqrt{[(Iaq)^2 + (Iad)^2]}$
Iaa = Ia cos φ; Iar = Ia sin φ; and Ia = $\sqrt{[(Iaa)^2 + (Iar)^2]}$

where δ = torque or power angle and φ = the p.f. angle of the load.

The phasor diagram shows the two reactance voltage components Iaq *Xsq and Iad * Xsd which are in quadrature with their respective components of the armature current. The resistance drop Ia x Ra is added in phase with Ia although we could take it as Iaq x Ra and Iad x Ra separately, which is unnecessary as Ia = Iad + jIaq.

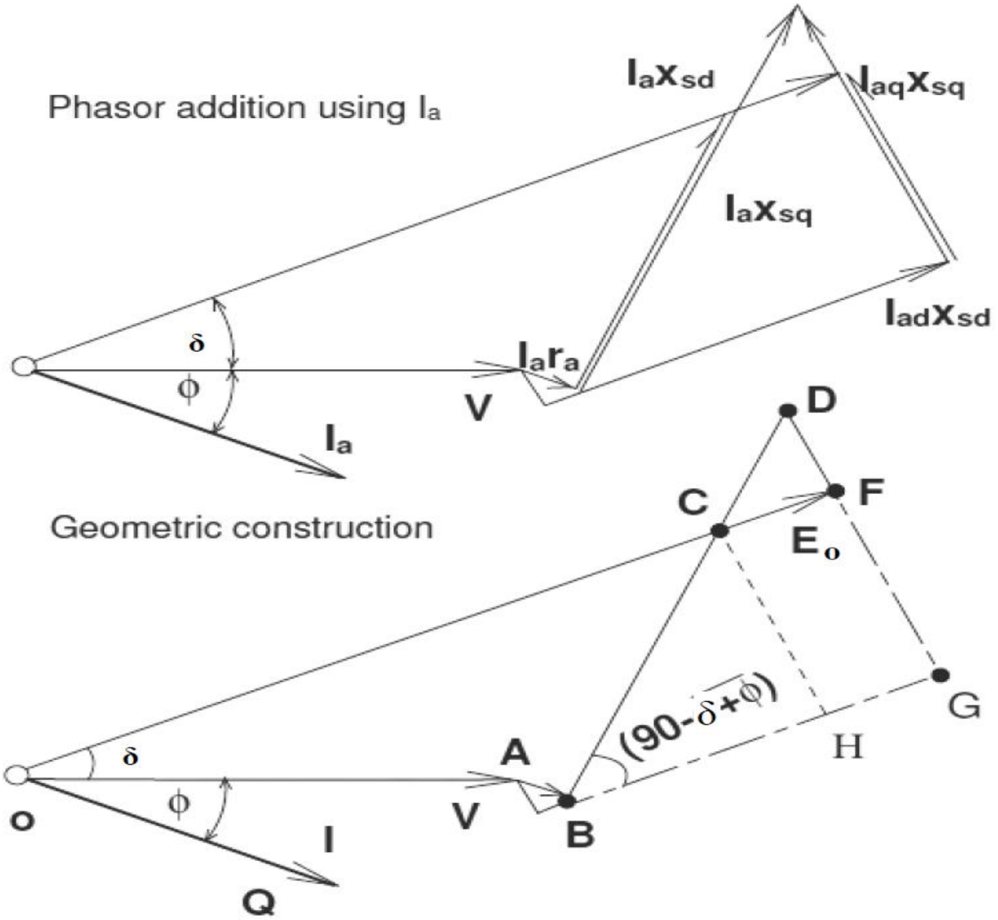


Figure: 3.20. Phasor diagram of salient pole alternator.

Power output of a Salient Pole Synchronous Machine

Neglecting the armature winding resistance, the power output of the generator is given by:

$$P = V \text{ x } I_a \text{ x } \cos \varphi$$

This can be expressed in terms of δ, by noting that

$Ia \cos \varphi = Iaq \cos \delta + Iad \sin \delta$

$V \cos \delta = Eo - Iad * Xsd$ and $V \sin \delta = Iaq * Xsq$

Substituting the above expressions for power we get

$P = V [(V \sin \delta / Xsd) * \cos \delta + (Eo - V \cos \delta)/Xsd * \sin \delta]$

On simplification we get

$P = (V * Eo/Xsd) \sin \delta + V^2 * (Xsd - Xsq)/(2 * Xsq * Xsq) * \sin 2 \delta$

The above expression for power can also be written as

$$P = (Eo * V * \sin \delta / Xd) + V^2 * (Xd - Xq) * \sin 2 \delta /(2 * Xq * Xq)$$

The above expression for power consists of two terms first is called electromagnetic power and the second is called reluctance power.

It is clear from the above expression that the power is a little more than that for a cylindrical rotor synchronous machine, as the first term alone represents the power for a cylindrical rotor synchronous machine. A term in (sin 2δ) is added into the power – angle characteristic of a non-salient pole synchronous machine. This also shows that it is possible to generate an emf even if the excitation E0 is zero. However this magnitude is quite less compared with that obtained with a finite E0. Likewise it can be shown that the machine develops a torque - called the reluctance torque - as this torque is developed due to the variation of the reluctance in the magnetic circuit even if the excitation E0 is zero.

Determination of X_d and X_q by slip test:

The direct and quadrature axis reactances X_d and X_q can be of a synchronous machine can be experimentally determined by a simple test known as slip test. Basic circuit diagram for conducting this test is shown in figure. Here the armature terminals are supplied with a subnormal voltage of rated frequency with field circuit left open. The generator is driven by a prime mover at a slip speed which is slightly more or less than the synchronous speed. This is equivalent to the condition in which the armature mmf remains stationary and rotor rotates at a slip speed with respect to the armature mmf. As the rotor poles slip through the armature mmf the armature mmf will be in line with direct axis and quadrature axis alternately. When it is in line with the direct axis the armature mmf directly acts on the magnetic circuit and at this instant the voltage applied divided by armature current gives the direct axis synchronous reactance. When the armature mmf coincides with the quadrature axis then the voltage impressed divided by armature current gives the quadrature axis synchronous reactance. Since $X_d > X_q$ the pointers of the ammeter reading the armature current will oscillate from a minimum to a maximum. Similarly the terminal voltage will also oscillate between the minimum and maximum.

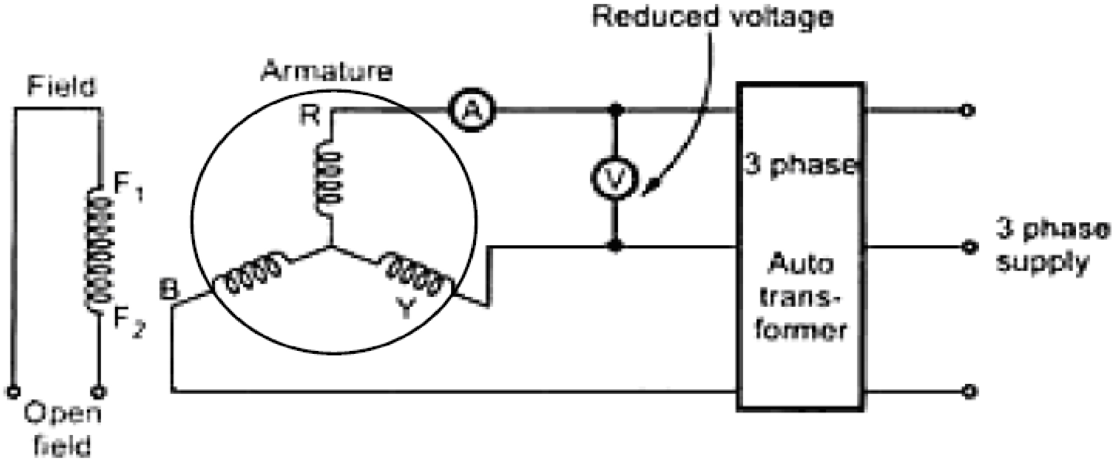


Figure: 3.21. Slip test

∴ X_d = Maximum voltage / minimum current

X_q = Minimum voltage / maximum current.

Ex.1. A 1200 kVA, 3300 volts, 50 Hz, three phase star connected alternator has an armature resistance of 0.25 Ω per phase. A field current of 40 Amps produces a short circuit current of 200 Amps and an open circuit emf of 1100 volts line to line. Find the % regulation at full load 0.8 pf lagging and leading by using emf method.

Soln: Full load current = 1200 x 10^3/ (√3 x 3300) = 210 amps;

Voltage per phase V_{ph} = 3300/√3 = 1905 volts

Synchronous impedance Z_S = oc voltage per phase/ sc current per phase …….. for same excitation

$= (1100/\sqrt{3}) / 200 = 3.17\ \Omega$

Synchronous reactance = $X_S = \sqrt{[(Z_S)^2 - (R_a)^2]} = \sqrt{(3.17)^2 + (0.25)^2} = 3.16\ \Omega$

0.8 pf lagging: referring to the phasor diagram

$E_{ph} = \sqrt{[(V \cos 8 + IR_a)^2 + (V \sin 8 + IX_S)^2]}$

$= \sqrt{[(1905 \times 0.8 + 210 \times 0.25)^2 + (1905 \times 0.6 + 210 \times 3.16)^2}$

= 2398 volts

Voltage regulation = $[(E_{ph} – V_{ph})/ V_{ph}] \times 100$

$= [(2398 – 1905) / 1905] \times 100$

= 25.9 %

0.8 pf leading: $E_{ph} = \sqrt{[(V \cos 8 + IR_a)^2 + (V \sin 8 - IX_S)^2]}$

$= \sqrt{[(1905 \times 0.8 + 210 \times 0.25)^2 + (1905 \times 0.6 - 210 \times 3.16)^2}$

= 1647 volts

Voltage regulation = $[(E_{ph} – V_{ph} / V_{ph})] \times 100$

$= [(1647 – 1905) / 1905] \times 100$

= - 13.54 %

Ex 2: A 10 MVA 6.6 kV, 3phase star connected alternator gave open circuit and short circuit data as follows.

Field current in amps:	25	50	75	100	125	150
OC voltage in kV (L-L):	2.4	4.8	6.1	7.1	7.6	7.9
SC Current in Amps:	288	528	875			

Find the voltage regulation at full load 0.8 pf lagging by emf method. Armature resistance per phase = 0.13 Ω.

Soln: Full load current = $10 \times 10^6 / (\sqrt{3} \times 6600) = 875$ amps;

Voltage per phase $V_{ph} = 6600/\sqrt{3} = 3810$volts

Corresponding to the full load current of 875 amps oc voltage from the oc and sc characteristics is 6100 volts

Hence synchronous impedance Z_S = oc voltage per phase/ sc current per phase

$= (6100/\sqrt{3})/ 875$

$= 4.02\ \Omega$

pf lagging: $E_{ph} = \sqrt{[(V \cos 8 + IR_a)^2 + (V \sin 8 + IX_S)^2]}$

$= \sqrt{[(3810 \times 0.8 + 875 \times 0.13)^2 + (3810 \times 0.6 – 875 \times 4.01789)^2}$

= 6607.26 volts

Voltage regulation = $[(E_{ph} – V_{ph} / V_{ph})] \times 100$

$= [(6607.26 – 3810) / 3810] \times 100$

= 73.42%

PARALLEL OPERATION OF SYNCHRONOUS GENERATORS

Synchronizing of alternators:

The operation of connecting two alternators in parallel is known as synchronizing. Certain conditions must be fulfilled before this can be effected. The incoming machine must have its voltage and frequency equal to that of the bus bars and, should be in same phase with bus bar voltage. The instruments or apparatus for determining when these conditions are fulfilled are called synchroscopes. Synchronizing can be done with the help of (i) dark lamp method or (ii) by using synchroscope.

Reasons for operating in parallel:

a) Handling larger loads.
b) Maintenance can be done without power disruption.
c) Increasing system reliability.
d) Increased efficiency.

Conditions required for Paralleling:

The figure below shows a synchronous generator G1 supplying power to a load, with another generator G2 about to be paralleled with G1 by closing switch S1. What conditions must be met before the switch can be closed and the 2 generators connected in parallel?

Paralleling 2 or more generators must be done carefully as to avoid generator or other system component damage. Conditions to be satisfied are as follows:

a) RMS line voltages must be equal.
b) The generators to be paralleled must have the same phase sequence.
c) The oncoming generator (the new generator) must have the same operating frequency as compared to the system frequency.

General Procedure for Paralleling Generators:

Consider the figure shown below. Suppose that generator G2 is to be connected to the running system as shown below:

1. Using Voltmeters, the field current of the oncoming generator should be adjusted until its terminal voltage is equal to the line voltage of the running system.
2. Check and verify phase sequence to be identical to the system phase sequence. There are 2 methods to do this:

   i. One way is using the 3 lamp method, where the lamps are stretched across the open terminals of the switch connecting the generator to the system (as shown in the figure below). As the phase changes between the 2 systems, the lamps first get bright (large phase difference) and then get dim (small phase difference). If all 3 lamps get bright and dark together, then the systems have the same phase sequence. If the lamps brighten in succession, then the systems have the opposite phase sequence, and one of the sequences must be reversed.

   ii. Using a Synchroscope – a meter that measures the difference in phase angles (it does not check phase sequences only phase angles).
3. Check and verify generator frequency is same as that of the system frequency. This is done by watching a frequency of brightening and dimming of the lamps until the frequencies are close by making them to change very slowly.

4. Once the frequencies are nearly equal, the voltages in the 2 systems will change phase with respect to each other very slowly. The phase changes are observed, and when the phase angles are equal, the switch connecting the 2 systems is closed.

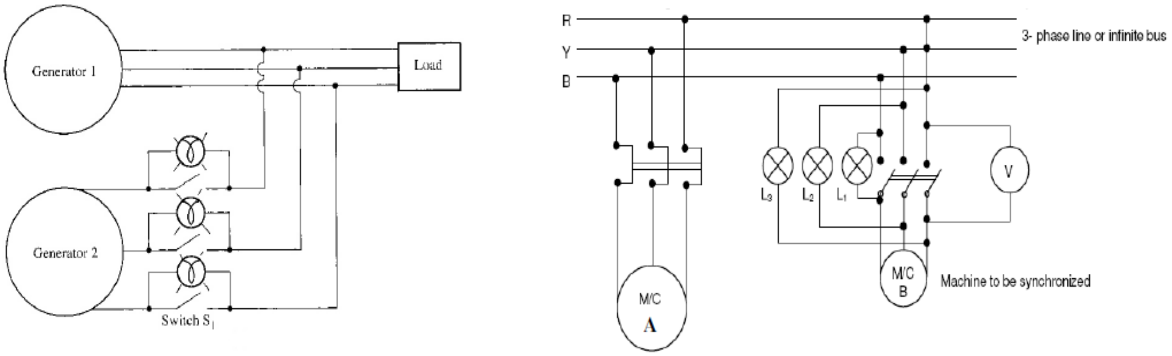


Figure: 3.22. Synchronization of alternators

Synchronizing Current

If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1, i.e. *E*1 is equal to and in phase opposition to emf of alternator 2, i.e. *E*2 as shown in the Figure .There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by an angle θ.

The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current *Is* is very nearly in quadrature with the resultant emf *Er* acting on the circuit. Figure represents a single phase case, where *E*1 and *E*2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, *Er*, is almost in quadrature with both the emfs, and gives rise to a current, *Is*, lagging behind *Er* by an angle approximating to a right angle. It is, thus, seen that *E*1 and *Is* are almost in phase. The first alternator is generating a power *E*1 *Is* cos Φ1, which is positive, while the second one is generating a power *E*2 *Is* cos Φ2, which is negative, since cos Φ2 is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current *Is* flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it till such a time that *E*1 and *E*2 are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current, *Is*, is called the synchronizing current.

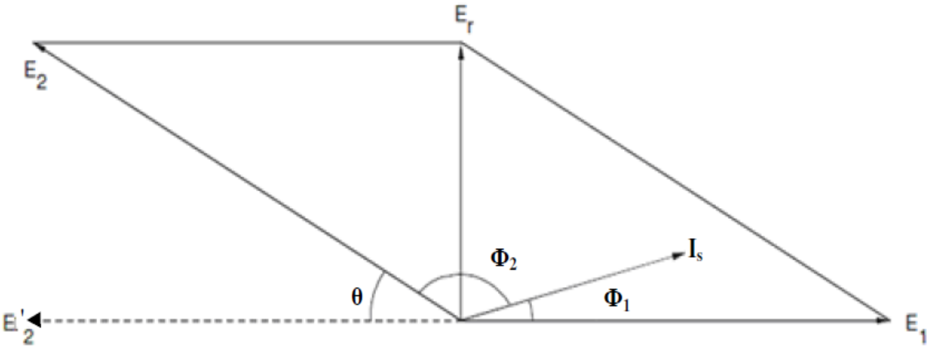


Figure: 3.23. Phasor diagram for synchronizing current.

Synchronizing Power

Suppose that one alternator has fallen behind its ideal position by an electrical angle θ, measured in radians. Since $E1$ and $E2$ are assumed equal and θ is very small Er is very nearly equal to $\theta E1$. Moreover, since Er is practically in quadrature with $E1$ and Is may be assumed to be in phase with $E1$ as a first approximation. The synchronizing power may, therefore, be taken as,

$$P_s = E1\, Is \text{ and } Is \approx E_r / 2Z_s \text{ and } E_r = \theta E1$$

$$P_s \approx \theta E1^2 / 2Z_s \text{ or } P_s \approx \theta E1^2 / 2X_s$$

Where Z_s is the synchronous impedance, $Z_s = X_s$ when the resistance is neglected.

When one alternator is considered as running on a set of bus bars the power capacity of which is very large compared with its own, the combined reactance of the others sets connected to the bus bars is negligible, so that , in this case $Z_s = X_s$ is the synchronous reactance of the one alternator under consideration.

Total synchronizing power P_{sy} $\approx \theta E1^2 / 2Z_s$ or

$$P_{sy} \approx \theta E1^2 / 2X_s$$

When the machine is connected to an infinite bus bar the synchronizing power is given by

$$P_{sy} \approx \theta E1^2 / Z_s \text{ or}$$

$$P_{sy} \approx \theta E1^2 / X_s$$

And synchronizing torque $T_{sy} = P_{sy} \times 60 / 2 \pi N_s$

Alternators with a large ratio of reactance to resistance are superior from a synchronizing point of view to those which have a smaller ratio, as then the synchronizing current Is cannot be considered as being in phase with $E1$. Thus, while reactance is bad from a regulation point of view, it is good for synchronizing purposes. It is also good from the point of view of self-protection in the event of a fault.

Effect of Change of Excitation

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output. Let two similar alternators of the same rating be operating in parallel, receiving equal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same. When delivering a total load of I amperes at a power-factor of cos φ, each alternator delivers half the total current and $I1 = I2 = I/2$.

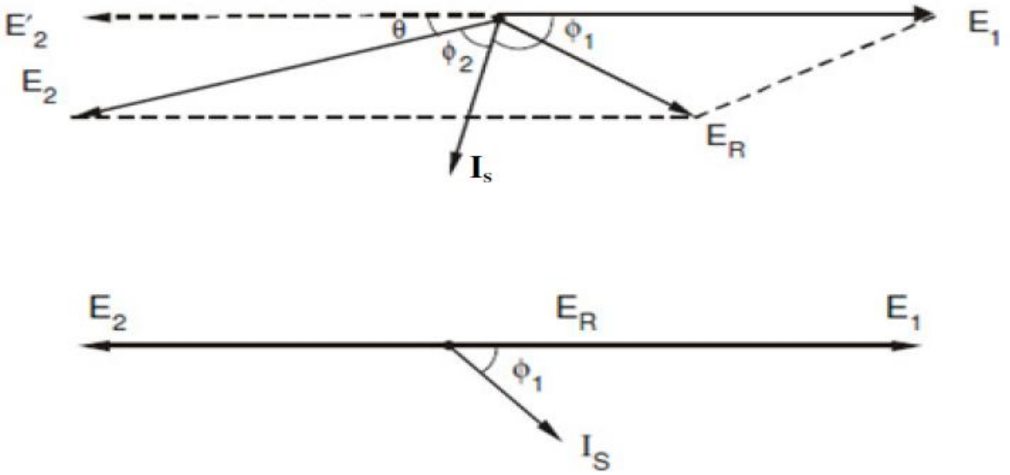


Figure: 3.24. Effect of change of excitation

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, Is, is zero. Since the armature resistance is neglected, the vector difference between $E1 = E2$ and V is equal to, I_1X_{s1} □ I_2X_{s2} , this vector leading the current I by 90□, where X_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively.

Now consider the effect of reducing the excitation of the second alternator. E_2 is therefore reduced as shown in Figure. This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased so as to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current I_2 is changed due to the change in E_2, but the active components of both I_1 and I_2 remain unaltered. It can be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator. It can also be observed that $I_1 + I_2 = I$, the total load current.

Effect of Change of Input Torque

The amount of power output delivered by an alternator running in parallel with others is governed solely by the power input received from its prime mover. If two alternators only are operating in parallel the increase in power input may be accompanied by a minute increase in their speeds, causing a proportional rise in frequency. This can be corrected by reducing the power input to the other alternator, until the frequency is brought back to its original value. In practice, when load is transferred from one alternator to another, the power input to the alternator required to take additional load is increased, the power input to the other alternator being simultaneously decreased. In this way, the change in power output can be effected without measurable change in the frequency. The effect of increasing the input to one prime mover is, thus, seen to make its alternator take an increased share of the load, the other being relieved to a corresponding extent. The final power-factors are also altered, since the ratio of the reactive components of the load has also been changed. The power-factors of the two alternators can be brought back to their original values, if desired, by adjusting the excitations of alternators.

Load Sharing

When several alternators are required to run in parallel, it probably happens that their rated outputs differ. In such cases it is usual to divide the total load between them in such a way that each alternator takes the load in the same proportion of its rated load in total rated outputs. The total load is not divided equally. Alternatively, it may be desired to run one large alternator permanently on full load, the fluctuations in load being borne by one or more of the others.

If the alternators are sharing the load equally the power triangles are as shown in figure below.

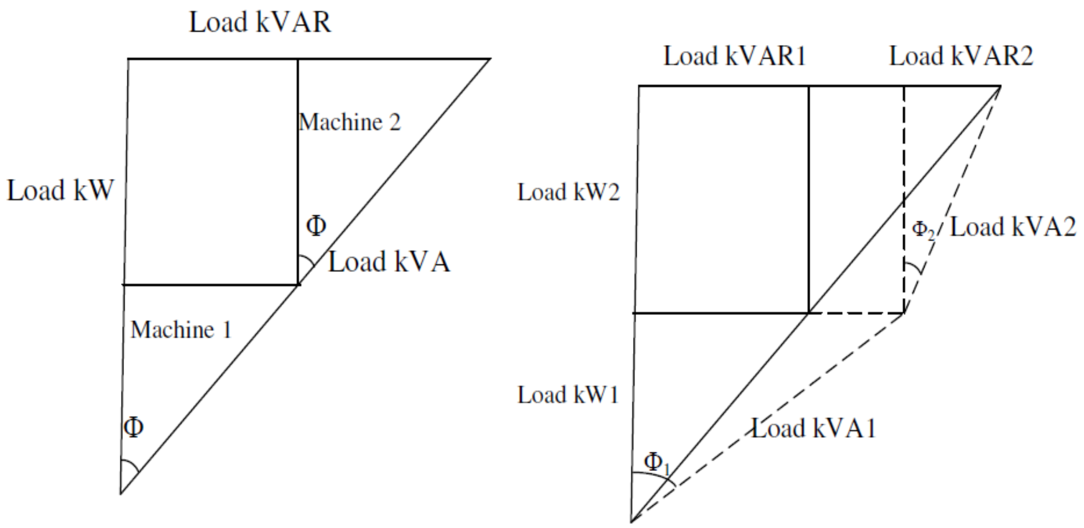
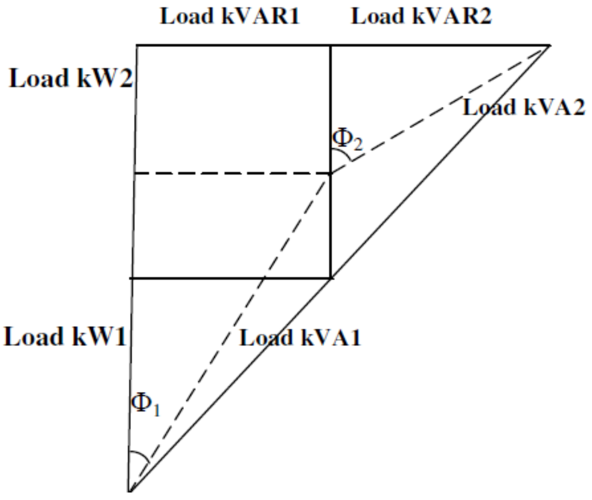


Figure: 3.25. Load sharing of alternators.



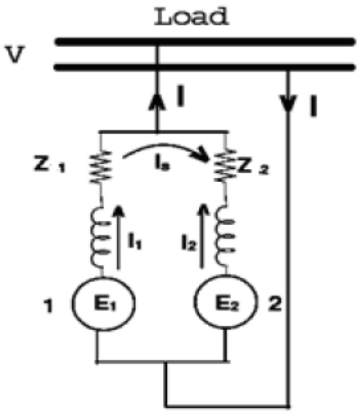


Figure: 4.13. Load sharing of alternators.

Sharing of load when two alternators are in parallel

Consider two alternators with identical speed load characteristics connected in parallel as shown in figure above.

Let E_1, E_2 be the induced emf per phase,
Z_1, Z_2 be the impedances per phase ,

I_1, I_2 be the current supplied by each machine per phase
Z be the load impedance per phase,

V be the terminal voltage per phase

From the circuit we have $V = E_1 - I_1Z_1 = E_2 – I_2Z_2$ and hence

$I_1 = E_1 - V/Z1$ and $I_2 = E_2 – V/Z_2$

and also $V = (I_1 + I_2) Z = IZ$ solving above equations

$$I_1 = [(E_1- E_2) Z + E_1 Z_2]/ [Z(Z_1 + Z_2) + Z_1Z_2]$$

$$I_2 = [(E_2- E_1) Z + E_2 Z_1]/ [Z(Z_1 + Z_2) + Z_1Z_2]$$

The total current $I = I_1 + I_2 = [E_1Z_2 + E_2Z_1] / [Z(Z_1 + Z_2) + Z_1Z_2]$

And the circulating current or synchronizing current $I_s = (E_1 - E_2) / (Z_1 + Z_2)$

UNIT-IV

SYNCHRONOUS MOTORS

Principle of operation

In order to understand the principle of operation of a synchronous motor, assume that the armature winding (laid out in the stator) of a 3-phase synchronous machine is connected to a suitable balanced 3-phase source and the field winding to a D.C source of rated voltage. The current flowing through the field coils will set up stationary magnetic poles of alternate North and South. On the other hand, the 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. In other words there will be moving North and South poles established in the stator due to the 3-phase currents i.e. at any location in the stator there will be a North Pole at some instant of time and it will become a South Pole after a time period corresponding to half a cycle. (After a time = 1/2f , where f = frequency of the supply). Assume that the stationary South pole in the rotor is aligned with the North pole in the stator moving in clockwise direction at a particular instant of time, as shown in Figure below. These two poles get attracted and try to maintain this alignment (as per Lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions are suitable for the production of torque in the clockwise direction. However, the rotor cannot move instantaneously due to its mechanical inertia, and so it needs some time to move.

In the mean time, the stator pole would quickly (a time duration corresponding to half a cycle) change its polarity and becomes a South Pole. So the force of attraction will no longer be present and instead the like poles experience a force of Repulsion as shown in Figure below. In other words, the conditions are now suitable for the production of torque in the anticlockwise direction. Even this condition will not last longer as the stator pole.

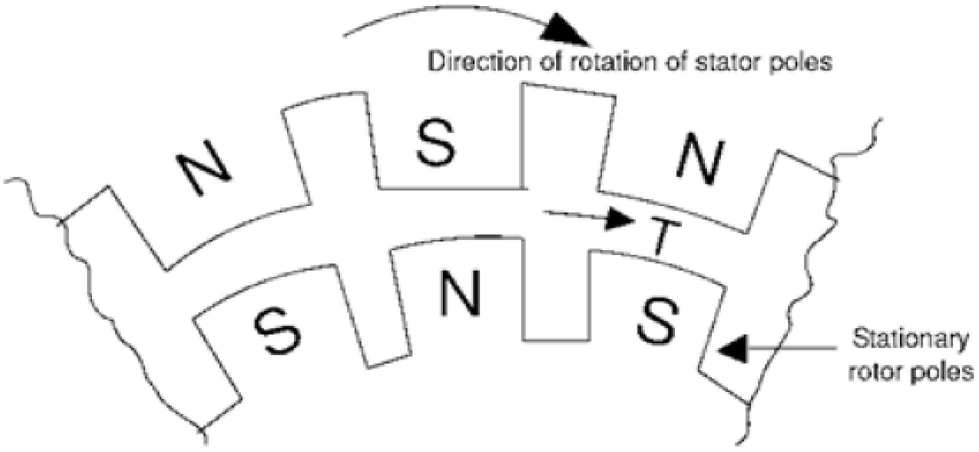


Figure: 4.1. Force of attraction between stator poles and rotor poles - resulting in production of torque in clockwise direction.

Would again change to North pole after a time of 1/2f. Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to 1/2f seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

On the contrary if the rotor is brought to near synchronous speed by some external device say a small motor mounted on the same shaft as that of the rotor, the rotor poles get locked to the unlike poles in the stator and the rotor continues to run at the synchronous speed even if the supply to the motor is disconnected. Thus the synchronous rotor cannot start rotating on its own when the rotor and stator are supplied with rated voltage and frequency and hence the synchronous motor has no starting torque. So, some special provision has to be made either inside the machine or outside of the machine so that the rotor is brought to near about its synchronous speed. At that time, if the armature is supplied with electrical power, the rotor can pull into step and continue to run at its synchronous speed. Some of the commonly used methods for starting synchronous rotor are described in the following paragraph.

Would again change to North Pole after a time of 1/2f. Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to 1/2f seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

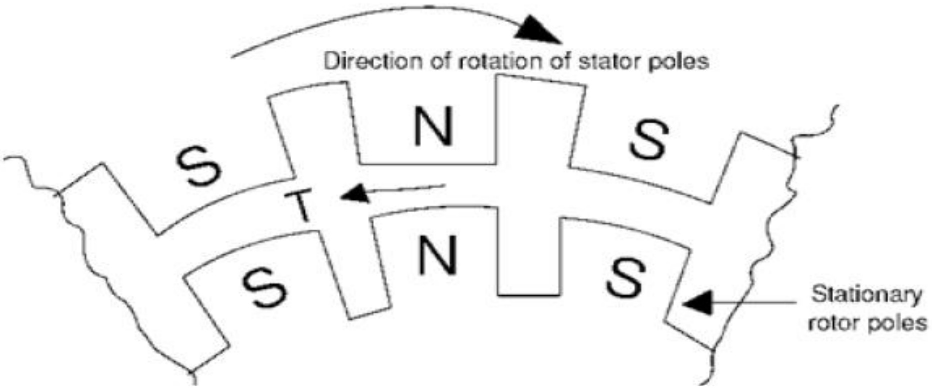


Figure: 4.2. Force of repulsion between stator poles and rotor poles - resulting in production of torque in anticlockwise direction

Methods of starting synchronous motor

Basically there are three methods that are used to start a synchronous motor:

- To reduce the speed of the rotating magnetic field of the stator to a low enough value that the rotor can easily accelerate and lock in with it during one half-cycle of the rotating magnetic field’s rotation. This is done by reducing the frequency of the applied electric power. This method is usually followed in the case of inverter-fed synchronous motor operating under variable speed drive applications.
- To use an external prime mover to accelerate the rotor of synchronous motor near to its synchronous speed and then supply the rotor as well as stator. Of course care should be taken to ensure that the directions of rotation of the rotor as well as that of the rotating magnetic field of the stator are the same. This method is usually followed in the laboratory- the synchronous machine is started as a generator and is then connected to the supply mains by following the synchronization or paralleling procedure. Then the power supply to the prime mover is disconnected so that the synchronous machine will continue to operate as a motor.
- To use damper windings if these are provided in the machine. The damper windings are provided in most of the large synchronous motors in order to nullify the oscillations of the rotor whenever the synchronous machine is subjected to a periodically varying load.

Behaviour of a synchronous motor

The behaviour of a synchronous motor can be predicted by considering its equivalent circuit on similar lines to that of a synchronous generator as described below.

Equivalent circuit model and phasor diagram of a synchronous motor

The equivalent-circuit model for one armature phase of a cylindrical rotor three phase synchronous motor is shown in Figure below exactly similar to that of a synchronous generator except that the current flows in to the armature from the supply. Applying Kirchhoff's voltage law to Figure below

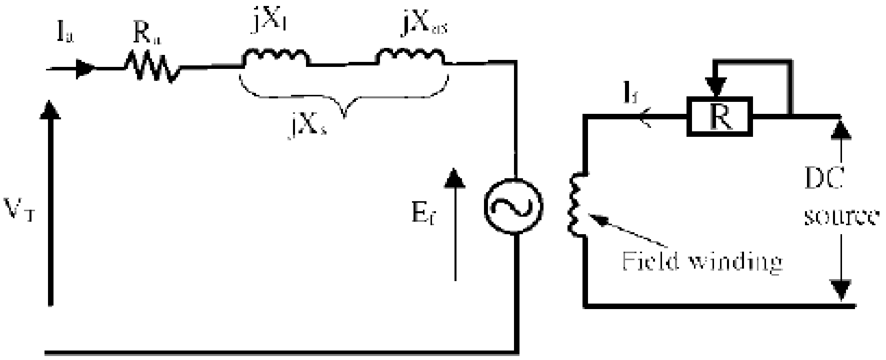


Figure: 4.3. Equivalent circuit model for one phase of a synchronous motor armature

VT = IaRa + jIaXl + jIaXas + Ef

Combining reactances, Xs = Xl + Xas

VT = Ef + Ia(Ra + jXs)

or VT = Ef + IaZs

where:

Ra = armature resistance (/phase)

Xl = armature leakage reactance (/phase)
Xs = synchronous reactance (/phase)

Zs = synchronous impedance (/phase)
VT = applied voltage/phase (V)

Ia = armature current/phase (A)

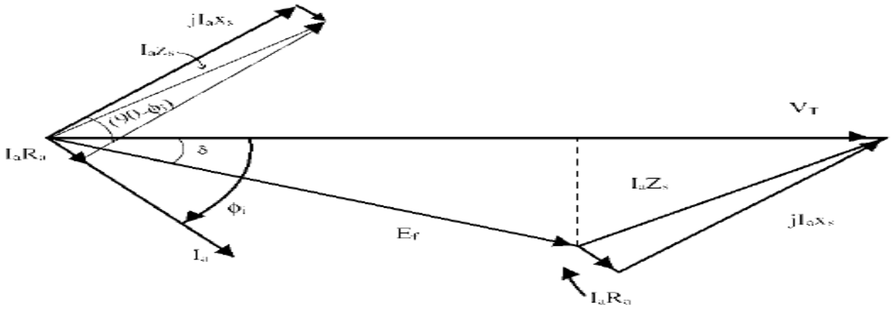


Figure: 4.4. Phasor diagram corresponding to the equivalent-circuit model

A phasor diagram shown in Figure above, illustrates the method of determining the counter EMF which is obtained from the phasor equation;

Ef = VT − IaZs

The phase angle δ between the terminal voltage VT and the excitation voltage Ef in Figure above is usually termed the torque angle. The torque angle is also called the load angle or power angle.

Effect of changes in load on, $I_{a,}$ δ, and p. f. of synchronous motor

The effects of changes in mechanical or shaft load on armature current, power angle, and power factor can be seen from the phasor diagram shown in Figure below; As already stated, the applied stator voltage, frequency, and field excitation are assumed, constant. The initial load conditions are represented by the thick lines. The effect of increasing the shaft load to twice its initial value is represented by the light lines indicating the new steady state conditions. While drawing the phasor diagrams to show new steady-state conditions, the line of action of the new jIaXs phasor must be perpendicular to the new Ia phasor. Furthermore, as shown in figure if the excitation is not changed, increasing the shaft load causes the locus of the Ef phasor to follow a circular arc, thereby increasing its phase angle with increasing shaft load. Note also that an increase in shaft load is also accompanied by a decrease in Φi; resulting in an increase in power factor.

As additional load is placed on the machine, the rotor continues to increase its angle of lag relative to the rotating magnetic field, thereby increasing both the angle of lag of the counter EMF phasor and the magnitude of the stator current. It is interesting to note that during all this load variation; however, except for the duration of transient conditions whereby the rotor assumes a new position in relation to the rotating magnetic field, the average speed of the machine does not change. As the load is being increased, a final point is reached at which a further increase in δ fails to cause a corresponding increase in motor torque, and the rotor pulls out of synchronism. In fact as stated earlier, the rotor poles at this point, will fall behind the stator poles such that they now come under the influence of like poles and the force of attraction no longer exists. Thus, the point of maximum torque occurs at a power angle of approximately 90◦ for a cylindrical-rotor machine. This maximum value of torque that causes a synchronous motor to pull out of synchronism is called the pull-out torque. In actual practice, the motor will never be operated at power angles close to 90^0 as armature current will be many times its rated value at this load.

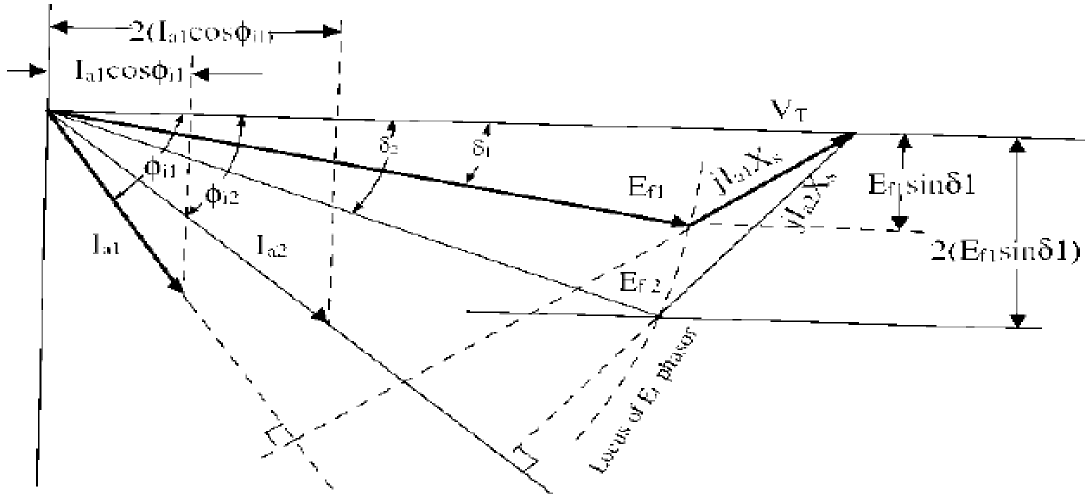


Figure: 4.5. Effect of changes in load on, $I_{a,}$ δ, and p. f.

Effect of changes in excitation on the performance synchronous motor

Increasing the strength of the magnets will increase the magnetic attraction, and thereby cause the rotor magnets to have a closer alignment with the corresponding opposite poles of the rotating magnetic poles of the stator. This will obviously result in a smaller power angle. This fact can also be seen from power angle equation. When the shaft load is assumed to be constant, the steady-state value of Ef sinδ must also be constant. An increase in Ef will cause a transient increase in Ef sinδ, and the rotor will accelerate. As the rotor changes its angular position, δ decreases until Ef sinδ has the same steady-state value as before, at which time the rotor is again operating at synchronous speed, as it should run only at the synchronous speed. This change in angular position of the rotor magnets relative to the poles of rotating magnetic field of the stator occurs in a fraction of a second. The effect of changes in field excitation on armature current, power angle, and power factor of a synchronous motor operating with a constant shaft load, from a constant voltage, constant frequency supply, is illustrated in figure below.

$Ef1 \sin \delta 1 = Ef2 \sin \delta\ 2 = Ef3 \sin \delta\ 3 = Ef \sin \delta$

This is shown in Figure below, where the locus of the tip of the Ef phasor is a straight line parallel to the VT phasor. Similarly,

$Ia1 \cos \Phi i1 = Ia2 \cos \Phi i2 = Ia3 \cos \Phi i3 = Ia \cos \Phi i$

This is also shown in Figure below, where the locus of the tip of the Ia phasor is a line perpendicular to the phasor VT.

Note that increasing the excitation from Ef1 to Ef3 caused the phase angle of the current phasor with respect to the terminal voltage VT (and hence the power factor) to go from lagging to leading. The value of field excitation that results in unity power factor is called normal excitation. Excitation greater than normal is called over excitation, and excitation less than normal is called under excitation.

Further, as indicated in Figure, when operating in the overexcited mode, |Ef | > |VT |. A synchronous motor operating under over excited condition is called a synchronous condenser.

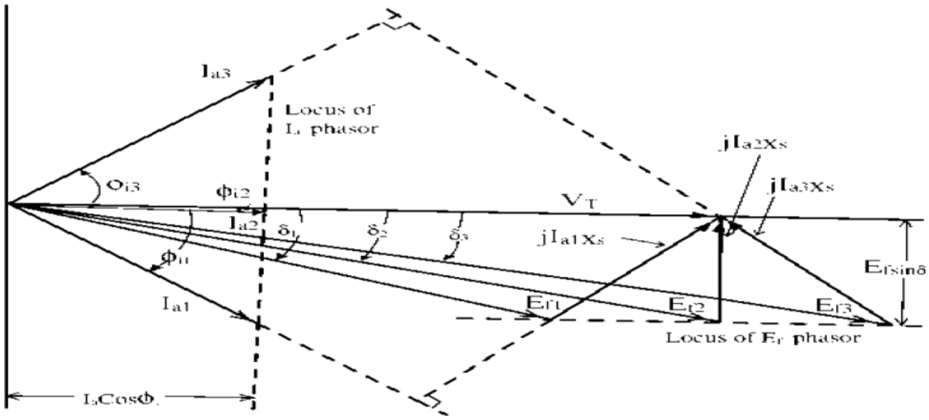


Figure: 4.6. Phasor diagram showing effect of changes in field excitation on armature current, power angle and power factor of a synchronous motor

V and inverted V curve of synchronous motor

Graphs of armature current vs. field current of synchronous motors are called V curves and are shown in Figure below for typical values of synchronous motor loads. The curves are related to the phasor diagram shown in figure below, and illustrate the effect of the variation of field excitation on armature current and power factor. It can be easily noted from these curves that an increase in shaft loads require an increase in field excitation in order to maintain the power factor at unity.

The points marked *a*, *b*, and *c* on the upper curve corresponds to the operating conditions of the phasor diagrams shown. Note that for $P = 0$, the lagging power factor operation is electrically equivalent to an inductor and the leading power factor operation is electrically equivalent to a capacitor. Leading power factor operation with $P = 0$ is sometimes referred to as synchronous condenser or synchronous capacitor operation. Typically, the synchronous machine V-curves are provided by the manufacturer so that the user can determine the resulting operation under a given set of conditions.

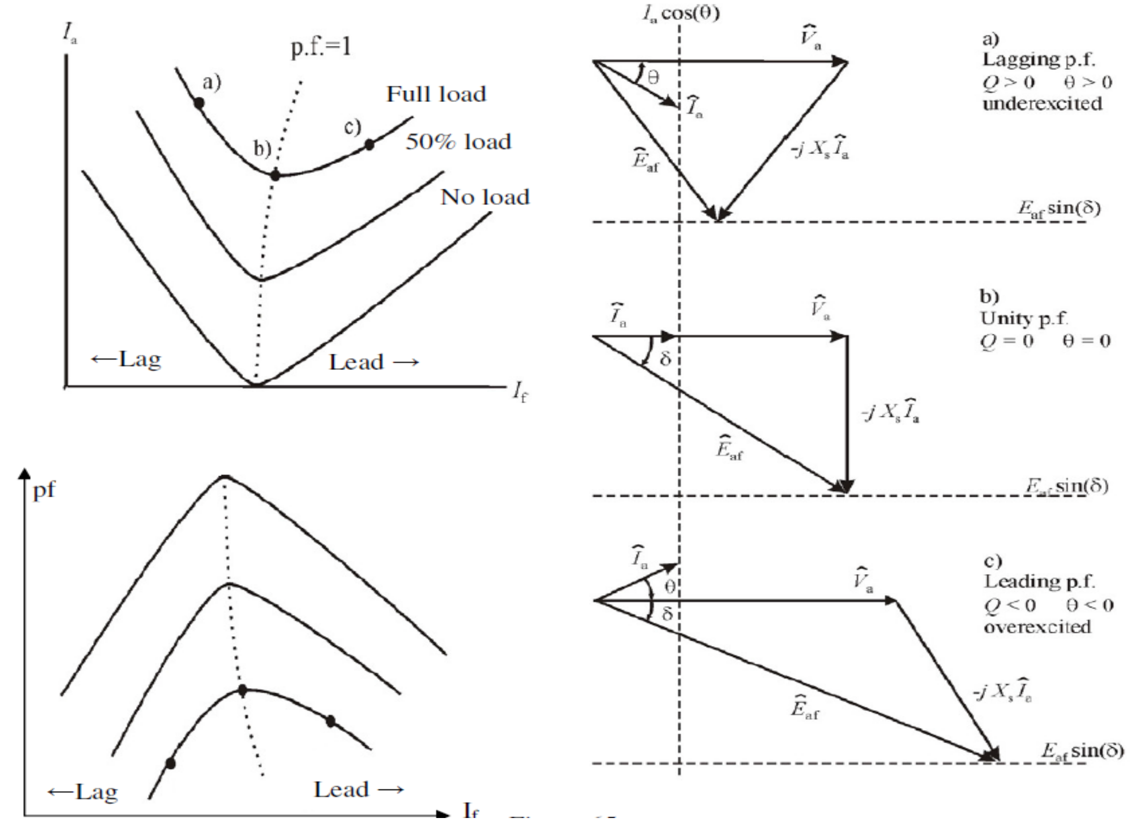


Figure: 4.7. Plots of power factor vs. field current of synchronous motors are called inverted V curves and are shown in Figure above for different values of synchronous motor loads.

Power Flow in Synchronous Motor

The figure below gives the details regarding the power flow in synchronous motor.

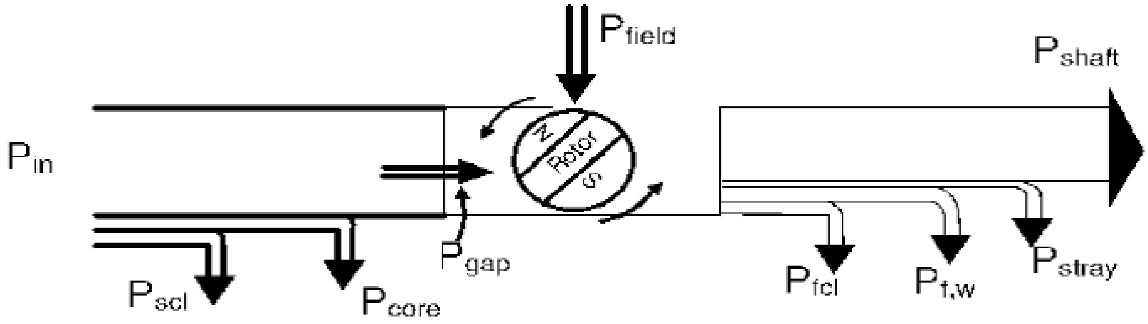


Figure: 4.8. Power stages in synchronous motor.

Where
P_{in} = Power input to the motor

P_{scl} = Power loss as stator copper
loss P_{core}= Power loss as core loss
P_{gap}= Power in the air gap
P_{fcl} = Power loss as field copper loss
P_{fw}= Power loss as friction and windage loss
P_{stray} = Power loss as stray loss
P_{shaft} = Shaft output of the machine

Power input to a synchronous motor is given by $P = 3V_{ph}I_{ph}\cos\Phi = \sqrt{3}V_LI_L\cos\Phi$. In stator as per the diagram there will be core loss and copper losses taking place. The remaining power will be converted to gross mechanical power.

Hence P_m= Power input to the motor – Total losses in stator.

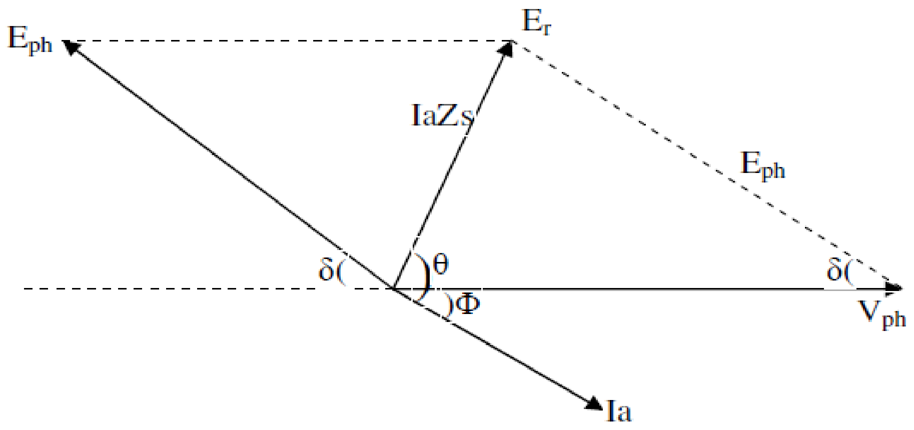


Figure: 4.9. Phasor diagram

From the phasor diagram we can write Power input /phase $P_i = V_{ph}I_{ph}\cos\Phi$

Mechanical power developed by the motor $P_m = E_bI_a \cos$ ∟ E_b & $I_a = E_bI_a \cos(\delta - \Phi)$

Assuming iron losses as negligible stator cu losses = $P_i - P_m$

Power output /phase = P_m – (field cu loss + friction & windage loss +stray loss)

Torque developed in Motor

Mechanical power is given by $P_m = 2\pi N_sT_g/60$ where Ns is the synchronous speed and the Tg is the gross torque developed.

$$P_m = 2\pi N_s T_g /60$$

Hence $T_g = 60\, P_m/2\pi N_s$

$$T_g = 9.55\, P_m/N_s \text{ N-m}$$

Shaft output torque $T_{sh} = 60 \times P_{out}/2\pi N_s$

$$T_{sh} = 9.55\, P_{out}/N_s \text{ N-m}$$

Hunting and Damper Winding

Hunting

Sudden changes of load on synchronous motors may sometimes set up oscillations that are superimposed upon the normal rotation, resulting in 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 approximately equal to the hunting period. When the synchronous motor phase-swings into the unstable region, the motor may fall out of synchronism.

Damper winding

The tendency of hunting can be minimized by the use of a damper winding. Damper windings are placed in the pole faces. 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 oscillations in the speed, 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 and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars.

Synchronous Condenser

An over excited synchronous motor operates at unity or leading power factor. Generally, in large industrial plants the load power factor will be lagging. The specially designed synchronous motor running at zero load, taking leading current, approximately equal to 90°. 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.

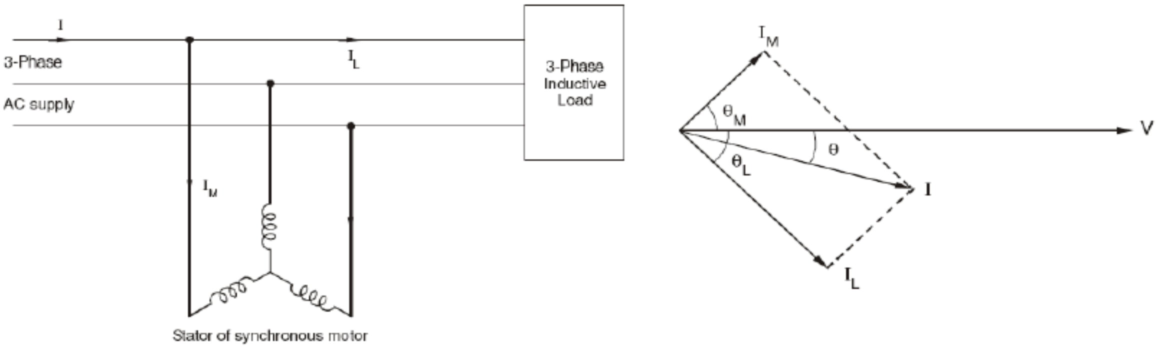


Figure: 4.10. Synchronous condenser and phasor diagram

UNIT-V

SINGLE PHASE MOTORS & SPECIAL MACHINES

Introduction

The characteristics of single phase induction motors are identical to 3-phase induction motors except that single phase induction motor has no inherent starting torque and some special arrangements have to be made for making itself starting. It follows that during starting period the single phase induction motor must be converted to a type which is not a single phase induction motor in the sense in which the term is ordinarily used and it becomes a true single phase induction motor when it is running and after the speed and torque have been raised to a point beyond which the additional device may be dispensed with. For these reasons, it is necessary to distinguish clearly between the starting period when the motor is not a single phase induction motor and the normal running condition when it is a single phase induction motor. The starting device adds to the cost of the motor and also requires more space. For the same output a 1-phase motor is about 30% larger than a corresponding 3-phase motor.

The single phase induction motor in its simplest form is structurally the same as a poly- phase induction motor having a squirrel cage rotor, the only difference is that the single phase induction motor has single winding on the stator which produces mmf stationary in space but alternating in time, a poly phase stator winding carrying balanced currents produces mmf rotating in space around the air gap and constant in time with respect to an observer moving with the mmf. The stator winding of the single phase motor is disposed in slots around the inner periphery of a laminated ring similar to the 3-phase motor.

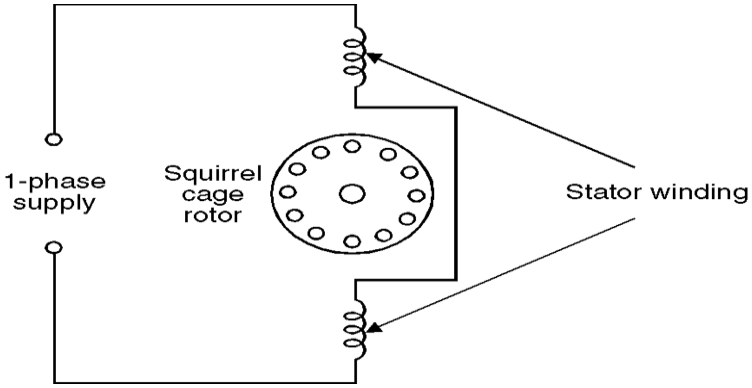


Figure: 5.1. Elementary single phase induction motor

An induction motor with a cage rotor and single phase stator winding is shown schematically in Fig. 5.1. The actual stator winding as mentioned earlier is distributed in slots so as to produce an approximately sinusoidal space distribution of mmf.

Principle of Operation

Suppose the rotor is at rest and 1-phase supply is given to stator winding. The current flowing in the stator winding gives rise to an mmf whose axis is along the winding and it is a pulsating mmf, stationary in space and varying in magnitude, as a function of time, varying from positive maxi- mum to zero to negative maximum and this pulsating mmf induces currents in the short-circuited rotor of the motor which gives rise to an mmf. The currents in the rotor are induced due to transformer action and the direction of the currents is such that the mmf so developed opposes the stator mmf. The axis of the rotor mmf is same as that of the stator mmf. Since the torque developed is proportional to sine of the angle between the two mmf and since the angle is zero, the net torque acting on the rotor is zero and hence the rotor remains stationary.

For analytical purposes a pulsating field can be resolved into two revolving fields of constant magnitude and rotating in opposite directions as shown in Fig. 5.2 and each field has a magnitude equal to half the maximum length of the original pulsating phasor.

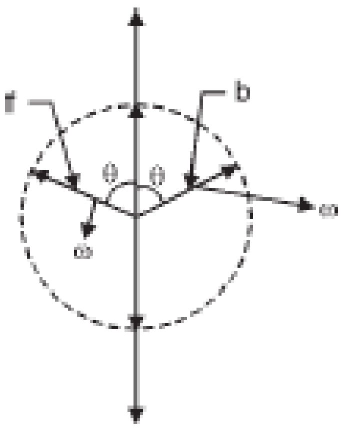


Figure: 5.2. Representation of the pulsating field by space phasors.

These component waves rotate in opposite direction at synchronous speed. The forward (anticlockwise) and backward-rotating (clockwise) mmf waves f and b are shown in Fig. 5.2. In case of 3-phase induction motor there is only one forward rotating magnetic field and hence torque is developed and the motor is self-starting. However, in single phase induction motor each of this component mmf waves produces induction motor action but the corresponding torques are in opposite direction. With the rotor at rest the forward and backward field produce equal torques but opposite in direction and hence no net torque is developed on the motor and the motor remains stationary. If the forward and backward air gap fields remained equal when the rotor is revolving, each of the component fields would produce a torque-speed characteristic similar to that of a Poly phase induction motor with negligible leakage impedance as shown by the dashed curves f And b in Fig. 5.3.

The resultant torque-speed characteristic which is the algebraic sum of the two component curves shows that if the motor were started by auxiliary means it would produce torque in what- ever direction it was started.

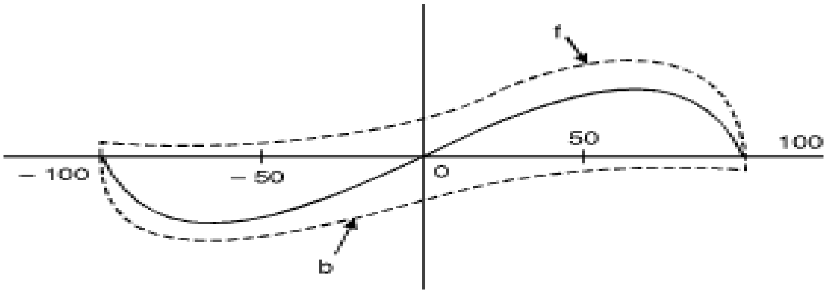


Figure: 5.3. Torque-speed characteristic of a 1-phase induction motor based on constant forward and backward flux waves.

In reality the two fields, forward and backward do not remain constant in the air gap and also the effect of stator leakage impedance can't be ignored. In the above qualitative analysis the effects of induced rotor currents have not been properly accounted for.

When single phase supply is connected to the stator and the rotor is given a push along the forward rotating field, the relative speed between the rotor and the forward rotating magnetic field goes on decreasing and hence the magnitude of induced currents also decreases and hence the mmf due to the induced current in the rotor decreases and its opposing effect to the forward rotating field decreases which means the forward rotating field becomes stronger as the rotor speeds up. However for the backward rotating field the relative speed between the rotor and the backward field increases as the rotor rotates and hence the rotor emf increases and hence the mmf due to this component of current increases and its opposing effect to the backward rotating field increases and the net backward rotating field weakens as the rotor rotates along the forward rotating field. However, the sum of the two fields remains constant since it must induce the stator counter emf which is approximately constant if the stator leakage impedance drop is negligible. Hence, with the rotor in motion the torque of the forward field is greater and that of the backward field is less than what is shown in Fig. 5.3. The true situation being as is shown in Fig. 5.4.

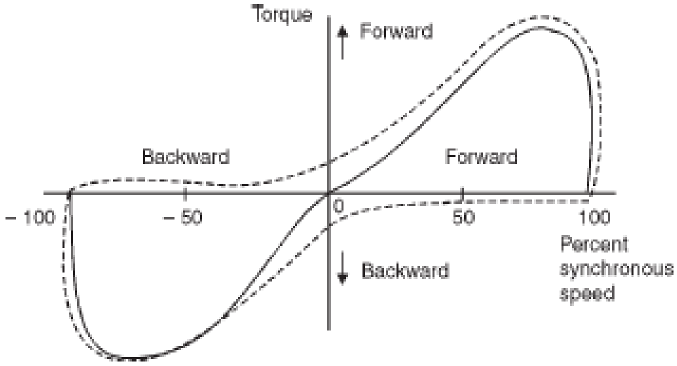


Figure: 5.4. Torque-speed characteristic of a 1-phase induction motor taking into account changes in the flux waves.

In the normal running region at a few per cent slip the forward field is several times stronger than the backward field and the flux wave does not differ materially from the constant

Amplitude revolving field in the air gap of a balanced poly phase motor. Therefore, in the normal running range of the motor, the torque-speed characteristic of a single phase motor is not very much different from that of a poly phase motor having the same rotor and operating with the same maximum air gap flux density.

In addition to the torque shown in Fig. 5.4, double-stator frequency torque pulsation are produced by the interaction of the oppositely rotating flux and mmf waves which move past each other at twice synchronous speed. These double frequency torques produce no average torque as these pulsations are sinusoidal and over the complete cycle the average torque is zero. However, sometimes these are additive to the main torque and for another half a cycle these are subtractive and therefore a variable torque acts on the shaft of the motor which makes the motor noisier as compared to a poly phase induction motor where the total torque is constant. Such torque pulsations are unavoidable in single phase circuits. Mathematically

$$T \alpha I^2$$

$$I = I_m \sin wt$$

$$T=K\,I_m^2\sin^2 wt$$
$$=K\,I_m^2(1-\cos 2wt)/2$$

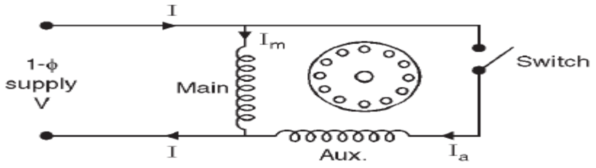
Starting Of Single Phase Induction Motors

The single phase induction motors are classified based on the method of starting method and in fact are known by the same name descriptive of the method. Appropriate selection of these motors depends upon the starting and running torque requirements of the load, the duty cycle and limitations on starting and running current drawn from the supply by these motors. The cost of single phase induction motor increases with the size of the motor and with the performance such as starting torque to current ratio (higher ratio is desirable), hence, the user will like to go in for a smaller size (hp) motor with minimum cost, of course, meeting all the operational requirements. However, if a very large no. of fractional horsepower motors are required, a specific design can always be worked out which might give minimum cost for a given performance requirements. Following are the starting methods.

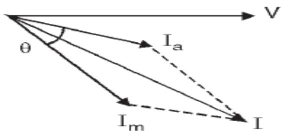
(a) Split-phase induction motor. The stator of a split phase induction motor has two windings, the main winding and the auxiliary winding. These windings are displaced in space by 90 electrical degrees as shown in Fig. 9.5 (a). The auxiliary winding is made of thin wire (super enamel copper wire) so that it has a high R/X ratio as compared to the main winding which has thick super enamel copper wire. Since the two windings are connected across the supply the

Torque is developed and the motor becomes a self-starting motor. After the motor starts, the auxiliary winding is disconnected usually by means of centrifugal switch that operates at about t5 per cent of synchronous speed. Finally the motor runs because of the main winding. Since this being single phase some level of humming noise is always associated with the motor during
Running. A typical torque speed characteristic is shown. It is to be noted that the direction of rotation of the motor can be reversed by reversing the connection to either the main winding or the auxiliary windings.

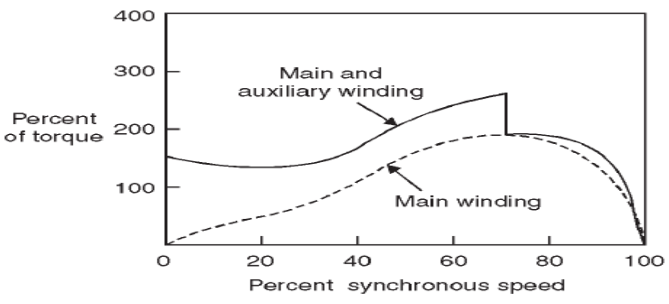
Current I_m and I_a in the main winding and auxiliary winding lag behind the supply voltage V, I_a leading the current I_m This means the current through auxiliary winding reaches maximum value first and the mmf or flux due to I_a lies along the axis of the auxiliary winding and after some time the current I_m reaches maximum value and the mmf or flux due to I_m lies along the main winding axis. Thus the motor becomes a 2-phase unbalanced motor. It is unbalanced
Since the two currents are not exactly 90 degrees apart. Because of these two fields a starting



(a)



(b)



(c)

Figure: 5.5. Split phase induction motor (a) Connection

(b) Phasor diagram at starting (c) typical torque-speed characteristic.

(b) **Capacitor starts induction motor**: Capacitors are used to improve the starting and running performance of the single phase inductions motors.

The capacitor start induction motor is also a split phase motor. The capacitor of suitable value is connected in series with the auxiliary coil through a switch such that I_a the current in the auxiliary coil leads the current I_m in the main coil by 90 electrical degrees in time phase so that the starting torque is maximum for certain values of I_a and I_m. This becomes a balanced 2- phase motor if the magnitude of I_a and I_m are equal and are displaced in time phase by 90° electrical degrees. Since the two windings are displaced in space by 90 electrical degrees as shown in Fig. 9.6 maximum torque is developed at start. However, the auxiliary winding and capacitor are disconnected after the motor has picked up t5 per cent of the synchronous speed. The motor will start without any humming noise. However, after the auxiliary winding is disconnected, there will be some humming noise.

Since the auxiliary winding and capacitor are to be used intermittently, these can be designed for minimum cost. However, it is found that the best compromise among the factors of starting torque, starting current and costs results with a phase angle somewhat less than 90° between I_m and I_a. A typical torque-speed characteristic is shown in Fig. 5.6 (c) high starting torque being an outstanding feature.

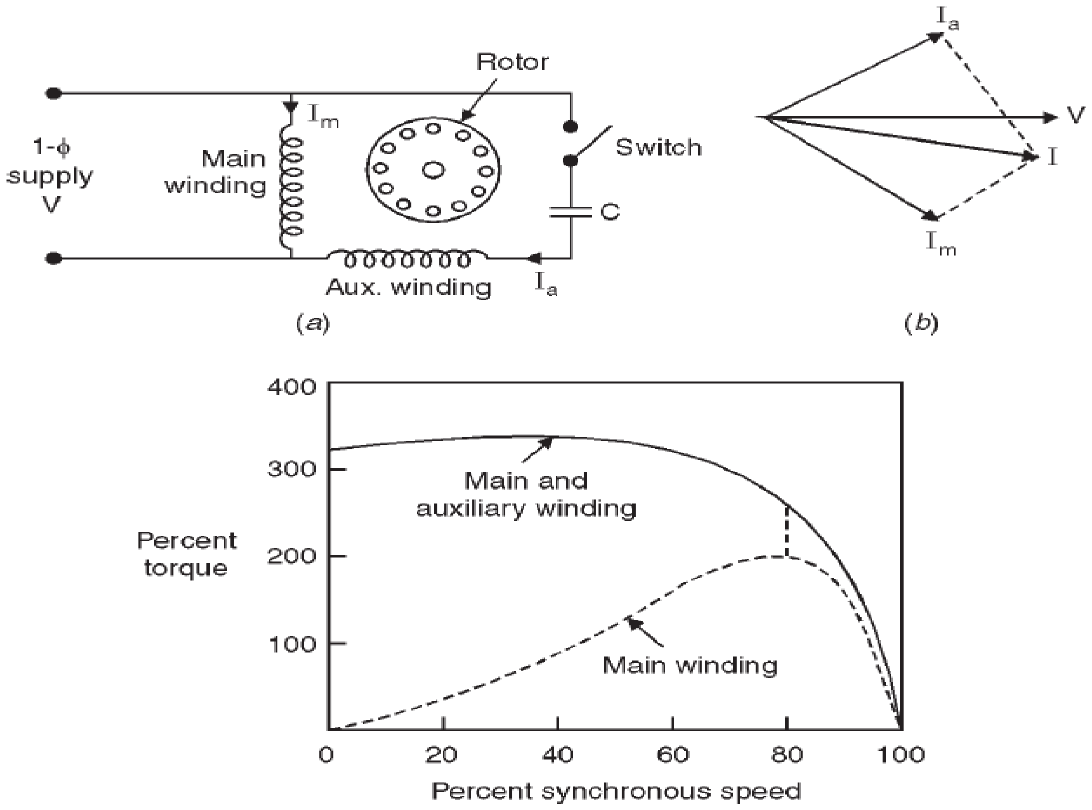


Figure: 5.6. Capacitor start motor (a) Connection

(b) Phasor diagram at start (c) Speed torque curve.

(c) Permanent-split capacitor motor. In this motor the auxiliary winding and capacitor are not disconnected from the motor after starting, thus the construction is simplified by the omission of the switch as shown in Fig. 5.7(a).

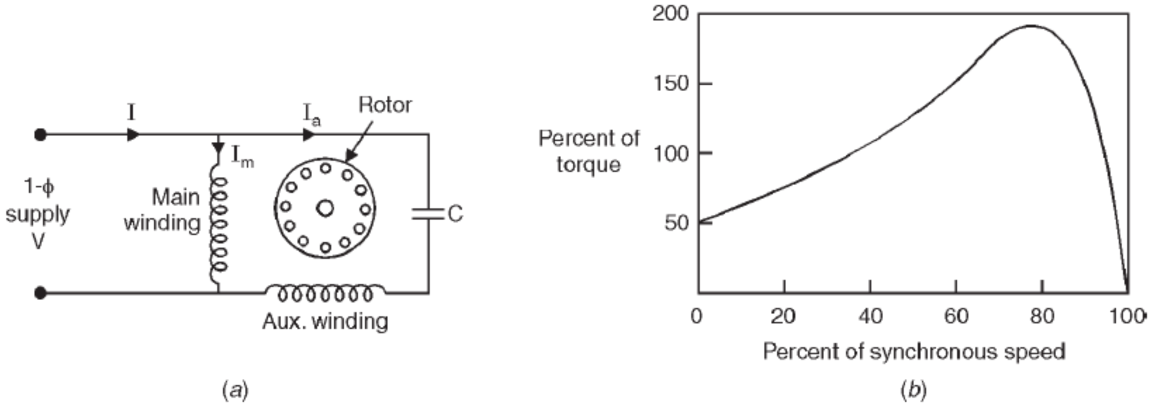


Figure: 5.7. Permanent split capacitor motor (a) Connection (b) Torque-speed characteristic.

Here the auxiliary winding and capacitor could be so designed that the motor works as a perfect 2-phase motor at anyone desired load. With this the backward rotating magnetic field would be completely eliminated. The double stator frequency torque pulsations would also be eliminated, thereby the motor starts and runs as a noise free motor. With this there is improve- ment in p.f. and efficiency of the motor. However, the starting torque must be sacrificed as the capacitance is necessarily a compromise between the best starting and running characteristics.

The torque-speed characteristic of the motor is shown in Fig. 9.7 (b).

(c) Capacitor start capacitor rum motor. If two capacitors are used with the auxiliary winding as shown in Fig. 5.8 (a), one for starting and other during the start and run, theoretically optimum starting and running performance can both be achieved.

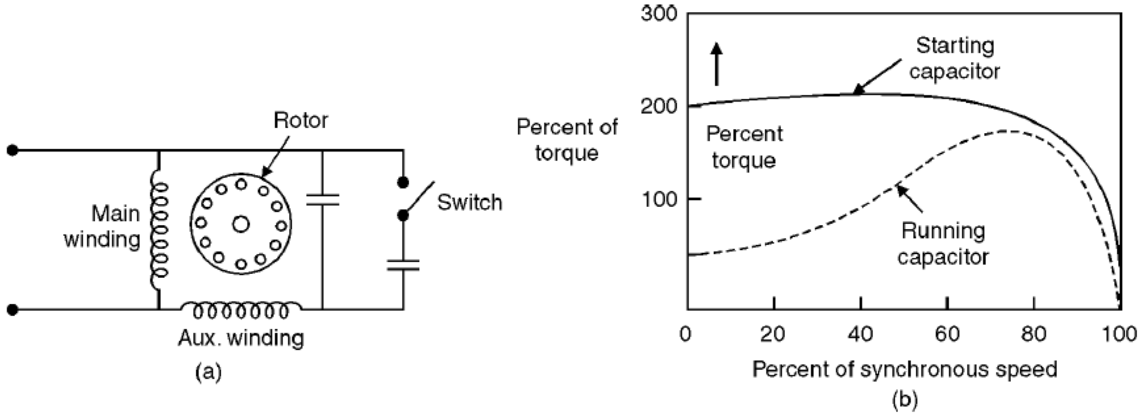


Fig. 5.8. (a) Capacitor start capacitor run motor (b) Torque-speed characteristic.

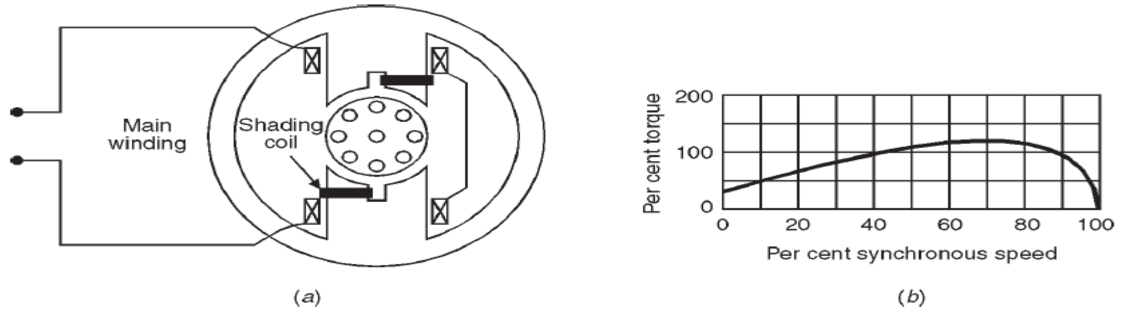
The small value capacitor required for optimum running conditions is permanently connected in series with the auxiliary winding and the much larger value required for starting is obtained by a capacitor connected in parallel with the running capacitor. The starting capacitor is disconnected after the motor starts.

The value of the capacitor for a capacitor start motor is about 300 μF for 1/2_hp motor Since

This capacitor must carry current for a short starting period; the capacitor is a special compact ac

Electrolytic type made for motor starting duty. However, the capacitor permanently connected has a typical rating of 40 µF; since it is connected permanently, the capacitor is an ac paper, foil and oil type. The cost of the motor is related to the performance;the permanent capacitor motor is the lowest cost, the capacitor start motor next and the capacitor start capacitor run has the highest cost.

(c) Shaded pole induction motor. Fig. 5.9 (a) shows schematic diagram of shaded pole induction motor. The stator has salient poles with one portion of each pole surrounded by a short- circuited turn of copper called a shading coil. Induced currents in the shading coil (acts as an inductor) cause the flux in the shaded portion of the pole to lag the flux in the other portion. Hence the flux under the un shaded pole leads the flux under the shaded pole which results in a rotating field moving in the direction from un shaded to the shaded portion of the pole and a low starting torque is produced which rotates the rotor in the direction from un shaded to the shaded pole. A typical torque speed characteristic is shown in Fig. 5.9 (b). The efficiency is low. These motors are the least expensive type of fractional horse power motor and are built up to about 1/20 hp. Since the rotation of the motor is in the direction from un shaded towards the shaded part of the pole, a shaded pole motor can be reversed only by providing two sets of shading coils which may be opened and closed or it may be reversed permanently by inverting the core.



(*a*) (*b*)

Figure: 5.9. Shaded-pole motor and typical torque-speed characteristic.

Universal Motor

We know that single phase motors are not self starting. We have to provide additional features to make itself starting.

The other solution to the single phase problem is to design a d.c. motor so that it will run on a.c. as well. The direction of rotation of a d.c. machine depends upon the polarities of the armature circuit and the field circuit. If a d.c. machine is designed so that (i) when line current reverses direction the field and armature currents reverse simultaneously and (ii) the core loss with alternating flux is relatively low, then a successful single phase machine results.

The first criterion is met by connecting armature and field windings in series. The second is achieved by using a laminated core. A d.c. shunt motor on the other hand cannot be used on a.c. because of high inductance of the field winding as compared to armature winding which causes the field pole reversals to be out of phase with the current reversals in the armature and the result is that the torque is backward during part of each half cycle lowering average torque and reducing the efficiency.

A d.c. series motor designed to operate also on a.c. is called a universal motor as it will run efficiently on any frequency from d.c. upto its design frequency. Fig. 5.10 shows the principle of operation of the motor.

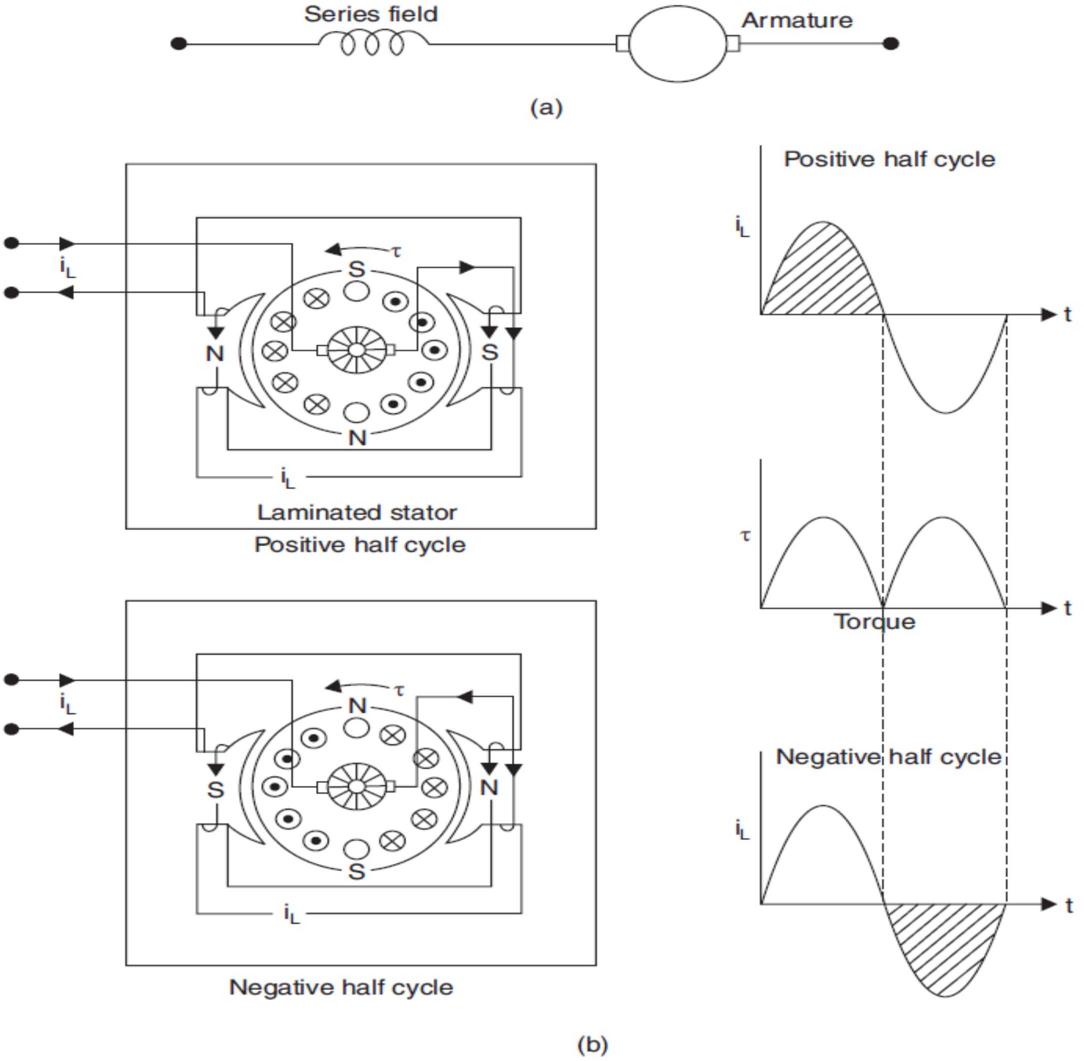


Figure 5.10 The universal motor. (a) Circuit diagram. (b) Principle of operation.

Universal motors are designed for voltages ranging from 32 to 250 volts, frequencies zero to 60Hx and ratings upto 3/4 hp. The average speed is high in the range of t000 rpm at normal load. The torque/speed characteristic of the motor is shown in Fig. 5.11 No load speed is quite high often in the range of 20,000 rpm. It is limited by windage and friction. Having high speed capability, universal motor of a given horse power rating is significantly smaller than other kinds of a.c. motors operating at the same frequency. Their starting torque is relatively high. These characteristics make universal motors ideal for devices such as hand drills, hand grinders, food mixers, vacuum cleaners and the like which require compact motors operating at speeds greater than 3000/3600 rpm. Universal motors must be designed with weak magnetic fields to minimize commutation difficulties. High resistance carbon brushes are used to limit the circulating current due to the transformer voltage in the short circuited coils.

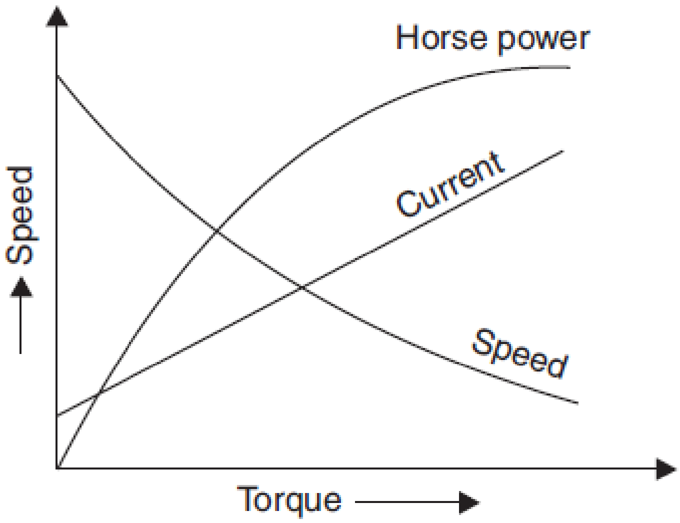


Figure: 5.11 Characteristics of universal motors

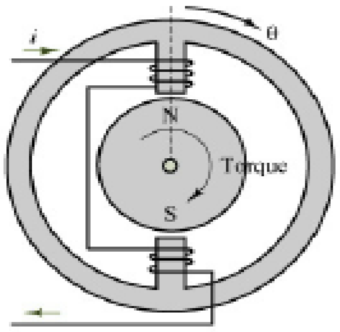
Stepper motors

A special type of synchronous motor which is designed to rotate a specific number of degrees for every electric pulse received by its control unit. Typical steps are 7.5 or 15^{o} per pulse. It is a motor that can rotate in both directions, move in precise angular increments, sustain a holding torque at zero speed, and be controlled with digital circuits. It moves in accurate angular increments known as steps, in response to the application of digital pulses to the electric drivecircuit.

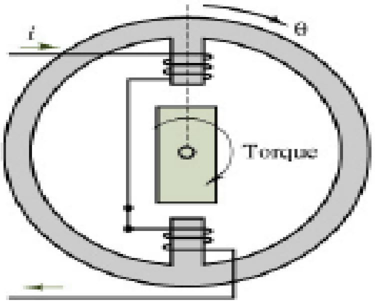
Generally, such motors are manufactured with steps per revolution. Step motors are either bipolar, requiring two power sources or uni polar requiring only one power source.

$$\Theta_m = 2/p * \theta_e$$

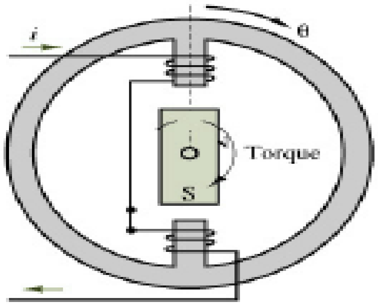
$$w_m = 2/p * w_e$$



(a) Permanent-magnet stepping motor



(b) Variable-reluctance
stepping motor



(c) Hybrid stepping motor

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