Synchronous Machines

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Contents

1 Synchronous machines

A synchronous machine has in essence a 3 phase distributed winding generally on the stator and a field winding on the rotor as shown in the figure 1. The field winding is excited from d.c supply to produce rotor poles while energisation of the stator three phase winding produces a rotating magnetic field the speed (called the synchronous speed)of which is decided by the supply frequency and the number of poles of the machine. Obviously steady electromagnetic torque will be developed only when rotor too will move at synchronous speed. In other words, a synchronous machine will either run at synchronous speed or not run at all in steady state. This means rotor speed is always synchronous, hence the name synchronous machine. This is precisely the reason why a synchronous motor has no inherent starting torque.

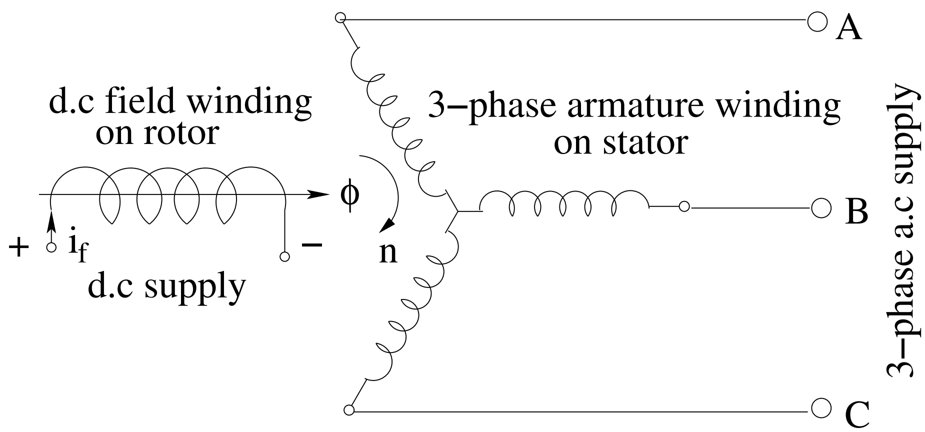
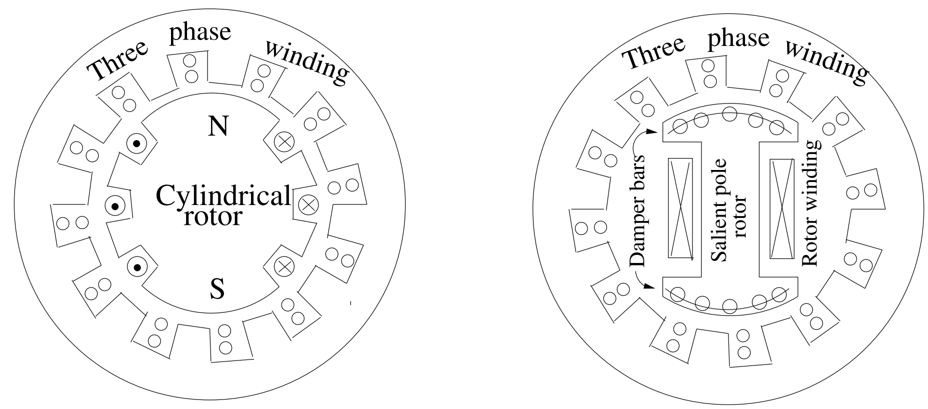


Figure 1: Representation of a 3-phase synchronous machine

There are two types of synchronous machines: namely (1) round rotor or uniform air gap or non-salient pole synchronous machine and (2) salient pole synchronous machine. The difference in these two types is mainly in the rotor which houses the d.c field winding as shown in figure 2

We shall first study non-salient pole type synchronous machine whose air gap is uniform. Analysis of salient synchronous machine is slightly involved and we shall discuss about it later.

Let us suppose that we want to run a synchronous machine as a motor by giving supply to the rotor from a d.c source and to the 3 phase winding from 3 phase source. The poles created by the rotor excitation will remain stationary with respect to stationary observer while the field created by the stator winding rotates at synchronous speed wrt stationery observer. This means the angle between the stator and rotor field is time varying and as told earlier, average torque under this condition is zero hence machine will fail to start as a motor. however once the rotor is brought to speed by some auxiliary means (as we shall see later in the section *starting of synchronous motor*) then machine may produce steady motoring torque. The crux of the matter is, I repeat once again, the speed of a synchronous machine connected to the supply bus is essentially constant at synchronous speed. When a synchronous machine acts as a generator then the machine is said to be operating as a *synchronous generator* or as an *alternator*. It should be noted d.c field winding can be placed in the stator while the 3 phase winding can be placed on the rotor without any loss of generality. However, practical considerations depending on the size of the machine, dictates the choice.



(a) Non−salient pole synchronous machine (b) Salient pole synchronous machine

Figure 2: Types of synchronous machines

2 Synchronous generator

A synchronous generator generates a.c power which is then transmitted and distributed using transmission line and network. When we talk of a.c generator primarily two things namely the frequency f and the magnitude of the generated emf E_f are of greatest importance. In the following sections we shall see on factors does the frequency and the magnitude of the generated emf depend.

2.1 Frequency

Like any other generator the rotor of a synchronous generator is to be driven by a *prime mover*.Now a days, electric power is generated using 3-phase generators. In a thermal generating station, prime mover is a steam turbine while in a hydel power station it is a water turbine which drives the generator. The frequency of the generated emf across the armature terminals depends upon the speed of the generator and its number of poles in fact it is given by $f = \frac{pn}{2}$ Hz, where n is the speed of the machine in rps. In our country the standard and stipulated a.c supply frequency is 50 Hz. The number of poles for a steam turbine driven alternator is 2. Hence the rotor speed must be 50 rps or 3000 rpm to generate 50 Hz a.c voltage. Alternators having number of poles 4, 6 and 8 should be driven 1500 rpm, 1000rpm and 750 rpm respectively in order to generate 50 Hz. the speed of water turbine being low, large number of poles are used. In such cases 16,24 poles are quite common.

2.2 Magnitude of the induced emf

The expression for the rms value of the generated emf per phase is given by

$$E_f = \sqrt{2}\pi \frac{pn}{2} \phi_f N_{\text{effective}} = 4.44 f \phi_f N_{\text{effective}}$$

Where,

$$\begin{aligned} n &= \text{speed of the generator in rps.} \\ \phi &= \text{flux per pole, produced by } i_f \\ N_{\text{effective}} &= \text{actual number of turns multiplied by the winding factors.} \end{aligned} \quad (1)$$

In a given generator, number of poles and the number of turns are fixed. Therefore, magnitude of the induced emf can be changed either by changing speed n or by changing flux per pole ϕ, i.e., the field current. But as we know the speed of the alternator gets fixed by the frequency of the induced voltage. Hence induced voltage can be varied only by varying the d.c field current.

2.3 Phasor diagram of synchronous generator

With reference to figure 1, we see that as the rotor rotates, flux linkages with A, B and C phase coils changes with time. A phase voltage leading B phase voltage by 120^o and B phase voltage leading C phase voltage by 120^o. The alternator is operating under no-load condition means that A, B and C terminals are left opened. In a particular phase, say A phase, induced voltage will be maximum when flux linkage is minimum i.e., when the position of ϕ is at quadrature with the axis of the A phase and will be zero when the the position of ϕ will be along the axis of the A phase. The space vector ϕ will lead the time phasor of the induced emf by 90^o. In figure 3 the no load and load phasor diagrams has been shown. Suppose the alternator is now loaded at some lagging power factor. So armature carries now a current $\overline{I}_a$ as shown. The balanced three phase currents produces as we know, a constant magnitude *rotating magnetic field* $\overline{M}_a$. When a particular phase caries maximum current, $\overline{M}_a$ will be directed in space along that phase axis. Therefore it is correct to show the the armature mmf $\overline{M}_a$ along the direction of the current. Unlike no load condition, the net air gap field is no longer $\overline{M}_f$ but the resultant of $\overline{M}_f$ and $\overline{M}_a$ i.e., $\overline{M}_r$. The induced voltage in the winding should now be decided by $\overline{M}_r$ and obviously not by $\overline{M}_f$. The induced voltage per phase becomes,

$$E_r = \sqrt{2}\pi\frac{pn}{2}\phi_r N_{\text{effective}} = 4.44 f\phi_r N_{\text{effective}}$$

Also we note that E_r will be lagging $\overline{M}_r$ by 90^o and If saturation is neglected then $\frac{E_f}{M_f} = \frac{E_r}{M_r}$.

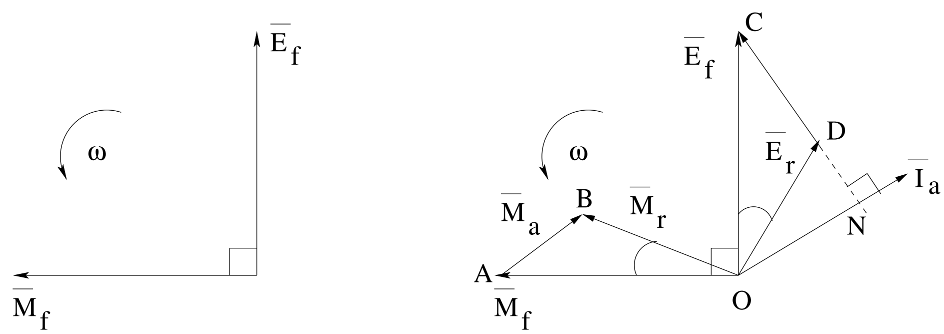


Figure 3: Phasor diagram of a 3-phase synchronous generator under no load and load conditions.

The $\triangle OAB$ and the $\triangle OCD$ are similar because $\frac{OA}{OC} = \frac{OB}{OD}$ and $\angle AOB = \angle COD$. Therefor CD will be at quadrature with the AB. In other words it is at right angle with the current phasor $\overline{I}_a$. the change in the induced voltage from $\overline{E}_f$ to $\overline{E}_r$ when the machine is loaded can therefore be attributed to *fictitious reactance voltage drop* $= j\overline{I}_a x_{ar}$. Which means that to analyze the machine under loaded condition, we can assume the induced voltage remains at E_f but the armature has got a series armature reaction reactance connected. However, armature winding has got its per phase resistance r_a and leakage reactance x_{al}. For a well designed machine the leakage impedance drop is much less than the armature reaction reactance drop. Per phase internal impedance of the alternator therefore comes out to be $r_a + jx_{al} + jx_{ar} = r_a + j(x_{al} + x_{ar}) = r_a + jx_s$. The sum of leakage reactance and the armature reaction reactance is called x_s, the *synchronous reactance* of the machine. Terminal voltage therefore can be obtained by subtracting the leakage impedance drop from $\overline{E}_r$. We are now in a position to draw the *complete* phasor diagram when the generator supplies a lagging or leading power factor loads as shown in the following phasor diagrams 4 and 5. It may be noted that in case of generator, $\overline{E}_f$ phasor will be always above $\overline{E}_t$. Since the leakage impedance drop is quite small compared to the armature reaction reactance drop, $\delta \approx \delta_{fr}$. The amount of torque produced we already know has a direct bearing with the angle δ_{fr} or approximately with δ. It is because of this reason the knowledge of δ, called the load angle, is so important.

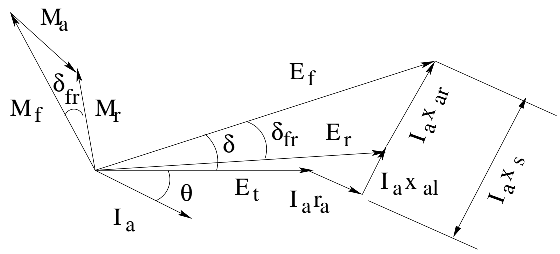


Figure 4: Phasor diagram : lagging load

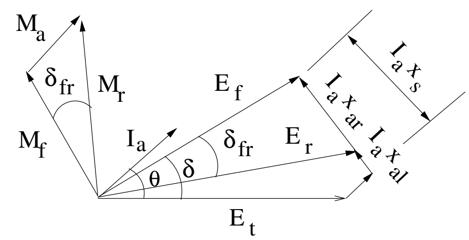


Figure 5: Phasor diagram : leading load

2.4 Phasor diagrams neglecting r_a

reactance x_s is generally many times higher than the armature resistance r_a. The ratio between these two may have values between 5 to 10. Therefore, a great deal of simplicity can be achieved in drawing phasor diagrams and more importantly, in understanding performance characteristics of the generator quickly and efficiently when r_a is neglected. Following figures 6 and 7 show the simplified phasor diagram assuming armature resistance drop to be vanishingly small.

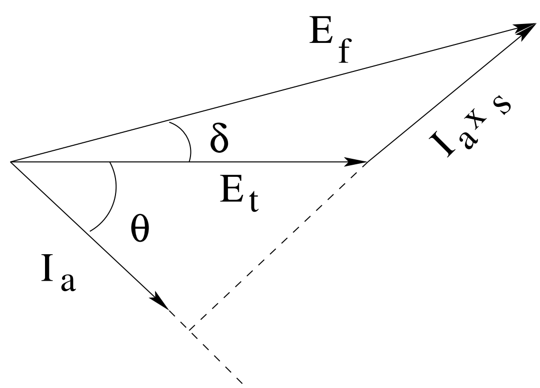


Figure 6: Phasor diagram : lagging load

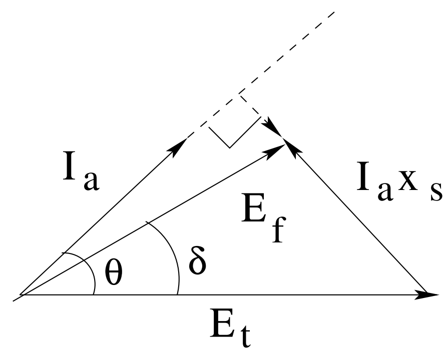


Figure 7: Phasor diagram : leading load

3 Normal, over and under excitation

When a synchronous generator is connected to the infinite bus, the terminal voltage E_t gets fixed and remains constant no matter to what level of excitation the machine has been subjected to. This means, $E_r \approx E_t$ = a constant. The resultant air gap mmf M_r thus practically remains constant. By , we mean M_f produced by the field current i_f. When the order M_f is same as the order of M_r, we say the motor is normally excited. on the other hand , depending upon whether $M_f > M_r$ or $M_f < M_r$ the machine is said to be *over excited* or *under excited* respectively. Looking at the phasor diagrams 4 and 5 we can easily see that for a synchronous generator to supply a lagging power factor load must be over excited while it must be under excited to supply a leading power factor load.

4 Power expression for synchronous generator.

To obtain expression for power output from the generator, let us refer to the equivalent circuit per phase of the generator as shown in the figure 8. Let us define the variables as follows:

$$\begin{aligned}
\overline{E}_t &= E_t\angle 0 \text{ Terminal voltage per phase.} \\
\overline{E}_f &= E_t\angle\delta \text{ excitation or internal emf of the generator per phase.} \\
\overline{I}_a &= I_a\angle\theta \text{ per phase armature current.} \\
\overline{Z}_s &= Z_s\angle\beta \text{ synchronous impedance per phase} \\
P &= \text{total real power output per phase.}
\end{aligned} \tag{2}$$

Power output of the generator can be calculated now in the following way:

$$\begin{aligned}
P_{output} + jQ_{output} &= 3\left[\overline{E}_t\overline{I}_a^{\star}\right] \\
&= 3\overline{E}_t\left[\frac{\overline{E}_f - \overline{E}_t}{\overline{Z}_s}\right]^{\star} \\
&= E_t\angle 0\left[\frac{E_f\angle-\delta - E_t\angle 0}{Z_s\angle-\beta}\right] \\
&= \frac{3E_tE_f}{Z_s}\angle(\beta-\delta) - \frac{3E_t^2}{Z_s}\angle\beta \\
&= 3\left[\frac{E_tE_f}{Z_s}\cos(\beta-\delta) - \frac{E_t^2}{Z_s}\cos\beta\right] + j3\left[\frac{E_tE_f}{Z_s}\sin(\beta-\delta) - \frac{E_t^2}{Z_s}\sin\beta\right]
\end{aligned} \tag{3}$$

The input power can be obtained by adding the armature copper loss to the output power i.e., $P_{input} = P_{output} + 3I_a^2 r_a$. As a special case when the armature resistance r_a is neglected then a simplified but useful expression shown below, for power can be obtained by putting $\beta = 90^o$ in the above expression for power.

$$P_{output} = 3\frac{E_f\, E_t}{x_s}\sin\delta = P_{max}\sin\delta \tag{4}$$

The *power-angle* or $P - \delta$ characteristic of a synchronous generator is shown in figure 9.

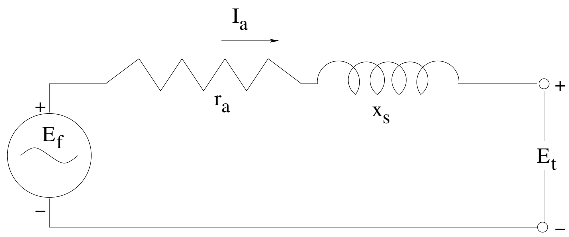


Figure 8: Per phase equivalent circuit.

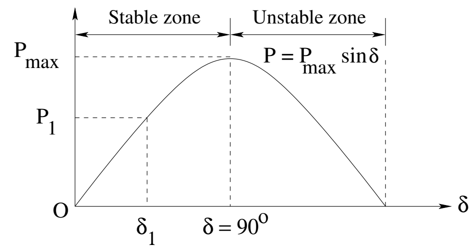


Figure 9: Power-angle characteristic of synchronous generator.

The $P - \delta$ characteristic in figure 9 shows how δ changes with the level of power change. The no load operating point is given by the point O. If power demand is changed to P1 level the corresponding steady state δ will become $\delta 1$. No operating point is available if the power demand is made greater than P_{max}. Hence steady state stability limit is P_{max} with $\delta = 90^o$. The aspect of stability limit will be taken up in detail in later section.

5 Synchronous machine : Generator and Motor operation

A synchronous machine connected to the infinite bus, can run either as a generator or as a motor. No matter in which mode it works, it has to run at a constant speed n_s called synchronous speed in order that it can develop a steady electromagnetic torque.

5.1 Generator mode

With the help of a *prime mover*, the generator is driven close to the synchronous speed and by adjusting the excitation current the terminal voltage is made equal to the existing bus voltage. The machine is now *synchronized* with the bus by a suitable method and said to be *floating* with the bus. if prime mover input is increased, the machine will start acting as a synchronous generator injecting power into the bus. More input to the prime mover means more injected power into the bus and increased value of δ. the generator will loose synchronism however when the value δ is close to 90^o

5.2 Motor mode

Immediately after synchronization with the bus, as told earlier the machine will be floating with the bus i.e., it will neither act as a generator nor act as a motor. Now if the prime mover is removed, the machine will continue to run and definitely it runs as a motor. If mechanical load is placed on the shaft of the machine, the rotor will fall back creating an appropriate δ. in this way machine can be loaded to the extent that δ is not more than about 90^o. Synchronism with the bus will be lost if the δ goes beyond this limit.

The floating, generating and motoring actions can be best understood by referring to figures 10,11 and 12. When the machine is just synchronized and floating with the bus, load angle $\delta \approx 0$. The stator and the resultant field act along the same line producing no torque. The situation is depicted in the figure10. However, if the prime mover input is increased rotor moves ahead of the stator field creating a positive load angle δ. the direction of the *electromagnetic torque*, T_e acts in the opposite direction of rotation as shown in the figure 11. On the other hand, if after synchronization, prime mover is removed and mechanical load torque is demanded, then the rotor will fall back creating a negative δ and producing T_e in the direction of rotation as shown in the figure 12.

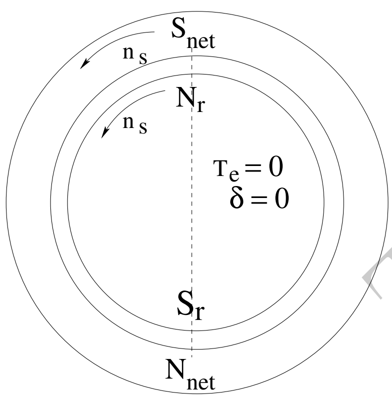


Figure 10: Floating condition

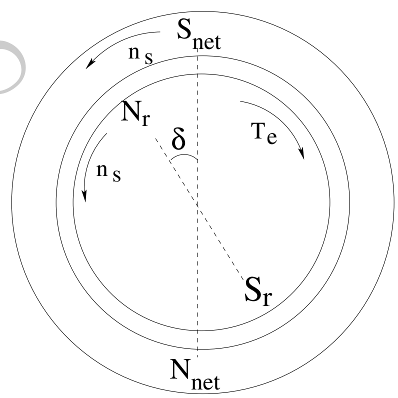


Figure 11: Generating mode

Physical pictures about what is happening inside a synchronous machine have been shown in the figures 10,11 and 12. One should not be under the impression, after going through this section, that only way of starting a synchronous motor, is to run it first as a generator, then synchronize and finally put on the mechanical load on the shaft. On the contrary, the above method is seldom used to make a synchronous machine run as a motor. In fact there are quite a number of different but easier methods of starting synchronous motor which will be discussed in later section.

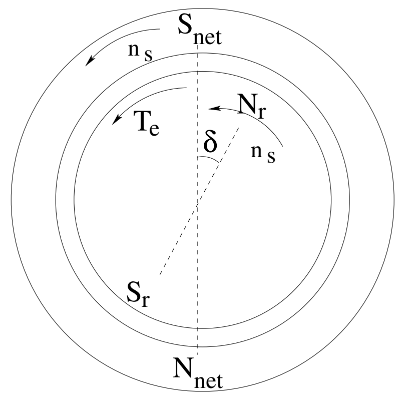


Figure 12: Motoring mode.

5.3 Phasor diagram of synchronous motor

The phasor diagram of synchronous motor can be developed by referring to its equivalent circuit shown in figure 13 and KVL equation. The KVL equation in the armature circuit is given by

$$\overline{E}_t - \overline{I}_a \overline{Z}_s = \overline{E}_f$$

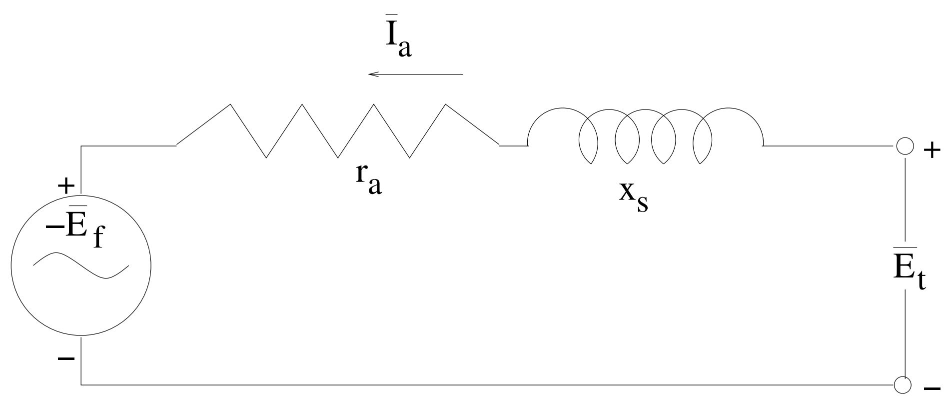


Figure 13: Equivalent circuit of a synchronous motor

The phasor diagram of a synchronous machine operating as a motor and drawing lagging and leading power factor currents are shown in figures 14 and 15. It can be easily concluded from the phasor diagram that over excitation causes leading power factor operation while under excitation makes the motor to operate at lagging power factor.

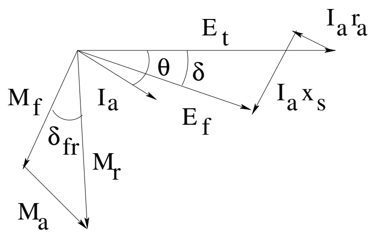


Figure 14: Motor mode : lagging power factor

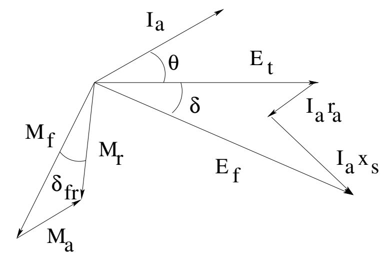


Figure 15: Motor mode : leading power factor.

6 Power expression for motor mode

The expression for the input power for a synchronous motor can be obtained in the same line as adopted for a generator in the previous section.

The complex output power power t of the generator S_g can be calculated now in the following way:

$$\begin{aligned}
S_g &= 3\left[\overline{E}_t \overline{I}_a^{\star}\right] \\
&= 3\overline{E}_t \left[\frac{\overline{E}_t - \overline{E}_f}{\overline{Z}_s}\right]^{\star} \\
&= E_t \angle 0^o \left[\frac{E_t \angle 0^o - E_f \angle \delta}{Z_s \angle -\beta}\right] \\
&= \frac{3E_t^2}{Z_s}\angle \beta - \frac{3E_t E_f}{Z_s}\angle(\beta+\delta) \\
&= 3\left[\frac{E_t^2}{Z_s}\cos\beta - \frac{E_t E_f}{Z_s}\cos(\beta+\delta)\right] + j3\left[\frac{E_t^2}{Z_s}\sin\beta - \frac{E_t E_f}{Z_s}\sin(\beta+\delta)\right] \qquad (5)
\end{aligned}$$

7 Effect of variation of excitation

We shall discuss here the effect of variation of excitation on the performance of a synchronous machines operating in parallel with the infinite bus and under the condition that the shaft load remains constant. In case of alternator this means *prime mover* input remains constant while in case of motor it means that the *mechanical load* is constant. it will be seen that excitation variation causes operating power factor of the machine to change. Alternator power factor changes from leading to lagging as excitation is increased. Where as motor power factor changes from lagging to leading with more and more excitation. To summaries, effect of excitation variation are:

- An under excited alternator operates at leading power factor.
- An overexcited alternator operates at lagging power factor.
- An under excited motor operates at lagging power factor.
- An overexcited motor operates at leading power factor.

7.1 Effect of excitation control:Explanation

Now we shall explain why synchronous machine behaves in a manner listed above when excitation is varied under constant power condition. First we explain this considering armature resistance r_a to be vanishingly small and the machine is acting as a generator connected to the bus. The power equation is then simply $P = \frac{E_f E_t}{x_s} \sin\delta$. For a constant P, $E_f \sin\delta$ has to remain constant as E_t, the bus voltage, is constant. Also constant power demands that $I_a \cos\theta$ remains constant no matter what is excitation. The phasor diagram is shown in figure 16.

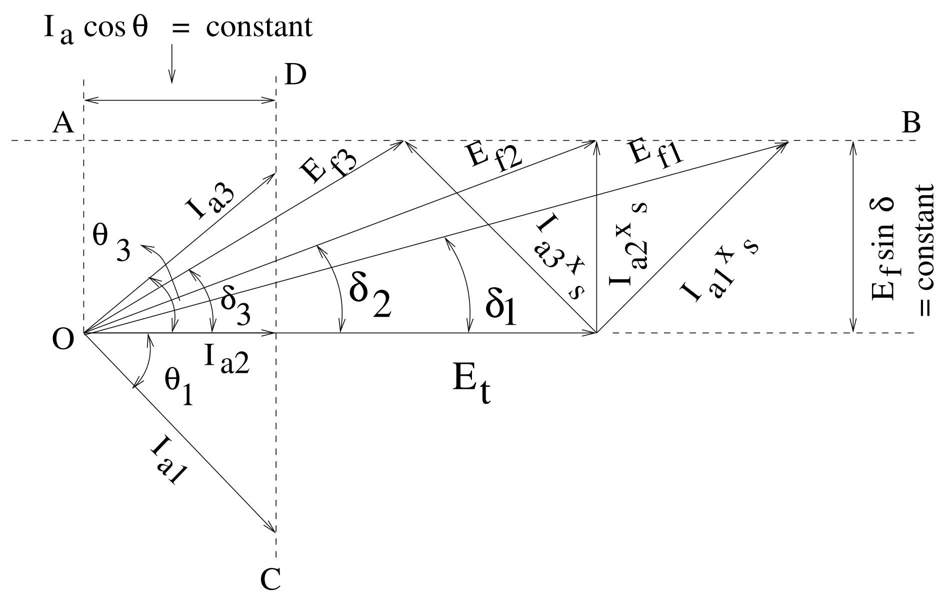


Figure 16: Phasor diagram showing the effect of excitation in an alternator.

Suppose the initial operating point of the alternator is such that it delivers a lagging current I_{a1} at a power factor angle of θ_1. The corresponding excitation emf is E_{f1}. Under constant power condition if excitation i.e., the magnitude of E_f is varied, then both $I_a \cos\theta$ and $E_f \sin\delta$ have to remain constant. Therefore through the tip of $\overline{I}_{a1}$ phasor a line CD is drawn at right angle to the $\overline{E}_t$ phasor. Whatever be the level of excitation the tip of the $\overline{I}_a$ phasor has to lie on CD. Similarly the tip of the $\overline{E}_f$ has to lie on the line AB as excitation is varied where AB is drawn through the tip of the $\overline{E}_{f1}$ phasor and parallel to the $\overline{E}_t$ phasor as shown in the figure 16. If excitation is decreased from E_{f1} to E_{f2}, then $\overline{E}_{f2}$ phasor gets fixed and the difference between the $\overline{E}_{f2}$ and $\overline{E}_t$ fixes the drop in the synchronous reactance ($= \overline{I}_{a2}\overline{x}_s$). Hence the current phasor $\overline{I}_{a2}$ can be fixed and new operating power factor can be ascertained. In this case excitation E_{f2} is such that, $\overline{I}_{a2}$ is in phase with the $\overline{E}_t$ indicating unity power factor operation. With respect to the initial armature current I_{a1}, the magnitude of the new armature current I_{a2} has reduced as excitation is decreased. In the same way if excitation is further decreased, new current will become I_{a3} and operating power factor will be lagging in nature. The magnitude of the armature current I_{a3} is obviously more than the armature current at unity power factor operation.

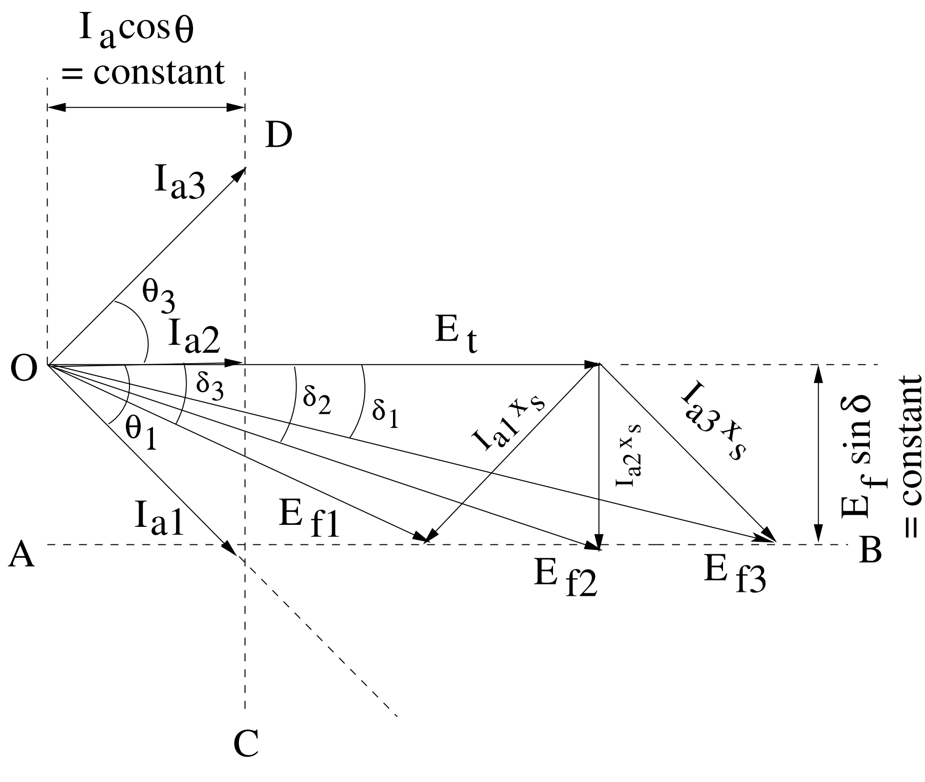


Figure 17: Phasor diagram showing the effect of excitation in synchronous motor.

Similarly referring to the phasor diagram shown in figure 17, one can understand the effects of excitation variation for a synchronous motor. In this case it will be observed that lower excitation causes the machine to operate at lagging power factor while higher excitation means leading power factor operation at a constant level of power. A synchronous motor can therefore be utilized for correction of power factor and when it is used for such purpose it is called a *synchronous condenser*. If a synchronous motor is to be used solely for the purpose of power factor improvement, its shaft can be thinner. For improving power factor of a factory, an over excited synchronous motor is connected at the incoming supply lines of the factory. Sometimes a synchronous motor is used for both improving the power factor as well as for supplying mechanical load. Synchronous condenser has advantage over capacitor for power factor improvement in the sense that capacitance values are to be changed in *steps* as the load of the factory undergo changes both in magnitude and quality; installing a synchronous condenser in place of capacitor will be handy as step less control of the leading current can be done by varying the field current smoothly.

The variation of the magnitude of the armature current as a function field current for no load and different power levels are shown in figures 18 and 19. As because the shape of the curves look like V, these are called V-curves. These curves clearly depict that for an alternator lower excitation corresponds to leading current and higher excitation corresponds to lagging current. For the motor operation, it is just opposite namely, lower excitation means lagging current and higher excitation means leading current. In both the cases however, *minimum* armature current corresponds to *unity power factor* operation.

It should be remembered that the derivation of V-curves and the other general conclusions drawn about the effect of excitation variation in synchronous machines were based on rather simplified phasor diagrams where the effect of armature resistance was totally neglected. In the next section we shall include the effect of armature resistance in shaping the V-curves.

8 Starting of synchronous motor

As pointed out earlier, a 3-phase synchronous motor has no running torque, however it has a steady running torque at synchronous speed.

8.1 Starting by damper bars

A scheme for starting a synchronous motor using damper bars is shown in figure 20. Damper bars are located on the *pole face* of the rotor and shorted at both ends in the same way as the Cage bars of induction motor are closed by *end rings*. Obviously here the cage will not be present continuously along the air gap. The following steps are followed for starting.

1. Field winding of the motor is connected across a suitable resistance.

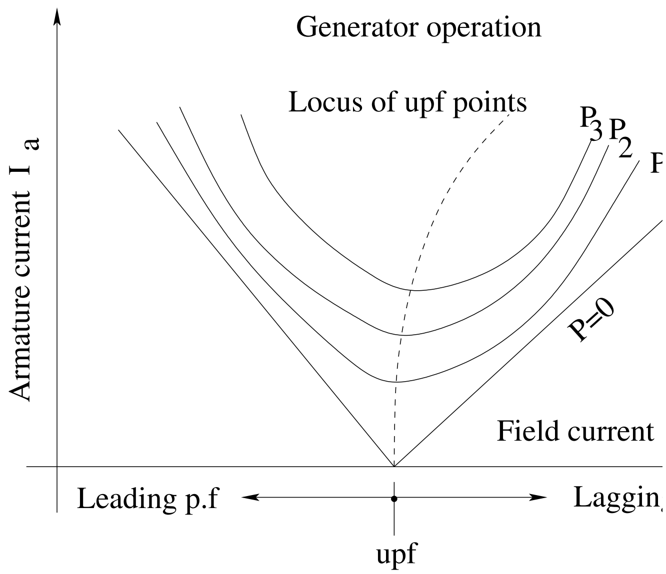


Figure 18: V curves of generators.

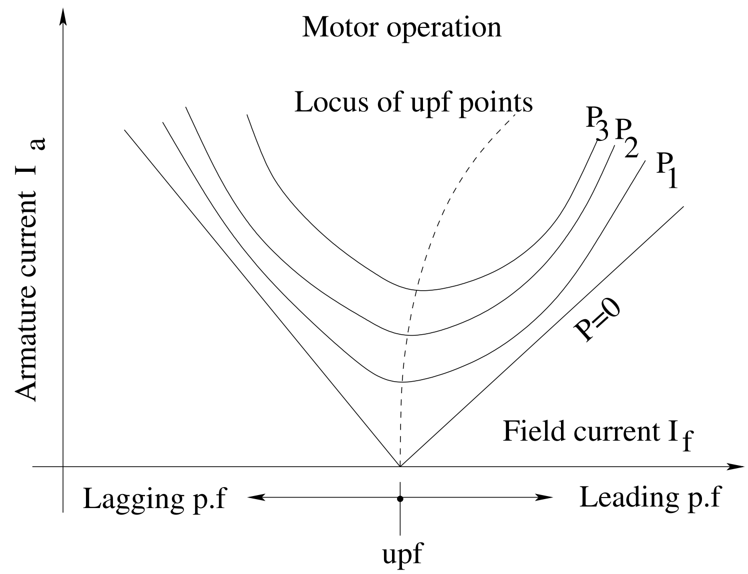


Figure 19: V curves of motors.

2. Balanced 3-phase supply is gradually increased from zero using an autotransformer and applied to the 3-phase armature of the synchronous motor. The motor picks up speed like a induction motor.

3. When speed becomes close to synchronous speed, the field winding is disconnected from the resistance and excited from d.c source.

4. the motor will be *pulled into synchronism* and run as synchronous motor. *Damper bars* will now become inactive.

8.2 Starting using pony motor

Synchronous motor can be started with the help of an *auxiliary* motor called *pony motor*. Pony motor is nothing but a small induction motor (preferably having 2-poles less than the synchronous motor) coupled to the synchronous motor. Pony motor is first started and is allowed to speed up beyond the synchronous speed of the synchronous motor. Now pony motor is disconnected from the supply and when the speed of the set comes close to synchronous speed, armature and the field windings of the synchronous motors are excited and the the motor is pulled into synchronism. This method is adopted for situation where the synchronous motor has to be started under no load.

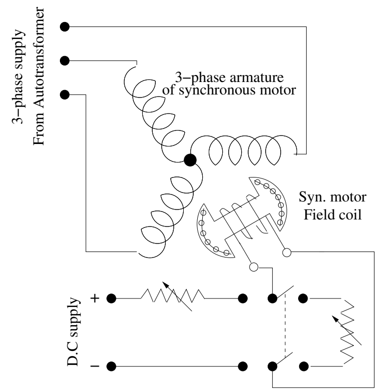


Figure 20: Starting of synchronous motor using damper bars.

8.3 Starting by using variable frequency source

In this scheme supply to the armature is obtained from the output of a variable frequency *inverter*. Initially field is excited and armature is supplied from variable voltage, variable frequency source keeping $\frac{v}{f}$ ratio constant for keeping flux at rated value. In this case the rotor will be able to follow the slowly moving stator field as the initial supply frequency is quite small. Motor speed can be smoothly increased by increasing the supply frequency gradually Upton the rated value.

9 Phasor diagrams of synchronous machines under typical conditions

To draw phasor diagram correctly of synchronous machines operating as generator or motor; at lagging or leading power factor following steps may be adopted.

1. Is the phasor diagram to be drawn for generator or motor mode?
2. If it is generator mode, then $\bar{E}_f$ will be ahead of $\bar{V}$.
3. Draw $\bar{V}$ and $\bar{I}_a$ first. Position of $\bar{I}_a$ wrt to $\bar{V}$ is decided by power factor angle θ.
4. For generator start from $\bar{V}$ and use the relation $\bar{E}_f = barV + \bar{I}_a r_a + j\bar{I}_a x_s$ to obtain $\bar{E}_f$.
5. If it is motor mode, then $\bar{E}_f$ will be behind of $\bar{V}$.
6. Draw $\bar{E}_f$ and $\bar{I}_a$ first. Position of $\bar{I}_a$ wrt to $\bar{E}_f$ is decided by internal power factor angle ψ.

7. For motor mode, start from $\bar{E}_f$ and use the relation $\bar{V} = \bar{E}_f + \bar{I}_a r_a + j\bar{I}_a x_s$ to obtain $\bar{V}$.

8. Remember Over excited synchronous generator means lagging power factor and under excited synchronous generator means leading power factor.

9. Remember Over excited synchronous motor means leading power factor and under excited synchronous motor means lagging power factor.

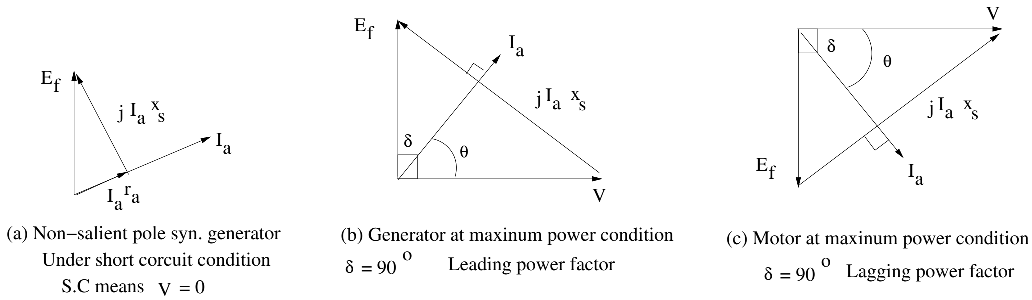


Figure 21: Phasor diagram under some typical conditions.