

Chapter Five

Synchronous Generators

5.1 Introduction

Three phase synchronous generators are the primary source of all the electrical energy we consume. These machines are the largest energy converters in the world. They convert mechanical energy into electrical energy, in powers ranging up to 1500 MW. In this chapter we will study the construction and characteristics of these large, modern generators. They are based upon the elementary principles.

5.2 Commercial Synchronous Generators

Commercial synchronous generators are built with either a stationary or a rotating DC magnetic field.

A stationary field synchronous generator has the same outward appearance as a DC generator. The salient poles create the DC field, which is cut by a revolving armature. The armature possesses a 3-phase winding whose terminals are connected to three slip-rings mounted on the shaft. A set of brushes, sliding on the slip-rings, enables the armature to be connected to an external 3-phase load. The armature is driven by a gasoline engine, or some other source of motive power. As it rotates, a 3-phase voltage is

induced, whose value depends upon the speed of rotation and upon the DC exciting current in the stationary poles. The frequency of the voltage depends upon the speed and the number of poles on the field. Stationary-field generators are used when the power output is less than 5 kVA. However, for greater outputs, it is cheaper, safer, and more practical to employ a revolving DC field.

A revolving field synchronous generator has a stationary armature called a stator. The 3-phase stator winding is directly connected to the load, without going through large, unreliable slip-rings and brushes. A stationary stator also makes it easier to insulate the windings because they are not subjected to centrifugal forces. Fig.5.1 is a schematic diagram of such a generator, sometimes called an *alternator*. The field is excited by a DC generator, usually mounted on the same shaft. Note that the brushes on the commutator have to be connected to another set of brushes riding on slip-rings to feed the DC current I_X into the revolving field.

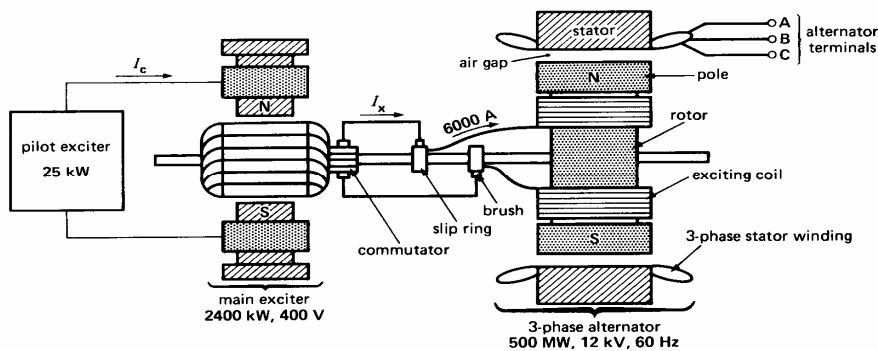


Fig.5.1 Schematic diagram and cross-section view of a typical 500 MW synchronous generator.

5.3 Number of Poles

The number of poles on a synchronous generator depends upon the speed of rotation and the frequency we wish to produce. Consider, for example, a stator conductor that is successively swept by the N and S poles of the rotor. If a positive voltage is induced when an N pole sweeps across the conductor, a similar negative voltage is induced when the S pole speeds by. Thus, every time a complete pair of poles crosses the conductor, the induced voltage goes through a complete cycle. The same is true for every other conductor on the stator; we can therefore deduce that the alternator frequency is given by

$$f = \frac{Pn}{120} \quad (5.1)$$

f = frequency of the induced voltage [Hz].

P = number of poles on the rotor.

n = speed of the rotor [r/min].

Example 5.1 A hydraulic turbine turning at 200 r/min is connected to a synchronous generator. If the induced voltage has a frequency of 60 Hz, how many poles does the rotor have?

Solution:

From Eqn.(5.1), we have :

$$P = 120 * 60 / 200$$

= 36 poles, or 18 pairs of N and S poles.

5.4 Main Features Of The Stator

From an electrical standpoint, the stator of a synchronous generator is identical to that of a 3-phase induction motor. It is composed of a cylindrical laminated core containing a set of slots that carry a 3-phase lap winding. The winding is always connected in wye and the neutral is connected to ground. A wye connection is preferred to a delta connection because:

1. The voltage per phase is only $1/\sqrt{3}$ or 58% of the voltage between the lines. This means that the highest voltage between a stator conductor and the grounded stator core is only 58% of the line voltage. We can therefore reduce the amount of insulation in the slots that in turn, enables us to increase the cross section of the conductors. A larger conductor permits us to increase the current and, hence, the power output of the machine.

2. When a synchronous generator is under load, the voltage induced in each phase becomes distorted, and the waveform is no longer sinusoidal. The distortion is mainly due to an undesired third harmonic voltage whose frequency is three times that of the fundamental frequency. With a wye connection, the distorting line-to-neutral harmonics do not appear between the lines because they effectively cancel each other. Consequently, the line voltages remain sinusoidal under all load conditions. Unfortunately, when a delta connection is used, the harmonic voltages do not cancel, but

add up. Because the delta is closed on itself, they produce a third-harmonic circulating current, which increases the $I^2 R$ losses.

The nominal line voltage of a synchronous generator depends upon its kVA rating. In general, the greater the power rating, the higher the voltage. However, the nominal line-to-line voltage seldom exceeds 25 kV because the increased slot insulation takes up valuable space at the expense of the copper conductors.

5.5 Main Features Of The Rotor

Synchronous generators are built with two types of rotors: salient pole rotors and smooth, cylindrical rotors. Salient pole rotors are usually driven by low-speed hydraulic turbines, and cylindrical rotors are driven by high-speed steam turbines.

1. **Salient pole rotors.** Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min) in order to extract the maximum power from a waterfall. Because the rotor is directly coupled to the waterwheel, and because a frequency of 50 Hz or 60 Hz is required, a large number of poles are required on the rotor. Low-speed rotors always possess a large diameter to provide the necessary space for the poles. The salient poles are mounted on a large circular steel frame which is fixed to a revolving vertical shaft. To ensure good cooling, the field coils are made of bare copper bars, with the turns insulated from each other by strips of

mica. The coils are connected in series, with adjacent poles having opposite polarities.

In addition to the DC field winding, we often add a squirrel-cage winding, embedded in the pole faces. Under normal conditions, this winding does not carry any current because the rotor turns at synchronous speed. However, when the load on the generator changes suddenly, the rotor speed begins to fluctuate, producing momentary speed variations above and below synchronous speed. This induces a voltage in the squirrel-cage winding, causing a large current to flow therein. The current reacts with the magnetic field of the stator, producing forces which dampen the oscillation of the rotor. For this reason, the squirrel-cage winding is sometimes called a *damper winding*.

The *damper winding* also tends to maintain balanced 3-phase voltages between the lines, even when the line currents are unequal due to unbalanced load conditions.

2. ***Cylindrical rotors***. It is well known that high-speed steam turbines are smaller and more efficient than low-speed turbines. The same is true of high-speed synchronous generators. However, to generate the required frequency we cannot use less than 2 poles, and this fixes the highest possible speed. On a 60 Hz system it is 3600 r/min. The next lower speed is 1800 r/min, corresponding to a 4-pole machine. Consequently, these steam-turbine generators possess either 2 or 4 poles.

The rotor of a turbine-generator is a long, solid steel cylinder which contains a series of longitudinal slots milled out of the cylindrical mass. Concentric field coils, firmly wedged into the slots and retained by high-strength end-rings serve to create the N and S poles.

The high speed of rotation produces strong centrifugal forces, which impose an upper limit on the diameter of the rotor. In the case of a rotor turning at 3600 r/min, the elastic limit of the steel requires the manufacturer to limit the diameter to a maximum of 1.2 m. On the other hand, to build the powerful 1000 MVA to 1500 MVA generators the volume of the rotors has to be large. It follows that high-power, high-speed rotors have to be very long.

5.6 Field Excitation And Exciters

The DC field excitation of a large synchronous generator is an important part of its overall design. The reason is that the field must ensure not only a stable ac terminal voltage, but must also respond to sudden load changes in order to maintain system stability. Quickness of response is one of the important features of the field excitation. In order to attain it, two DC generators are used: a main exciter and a pilot exciter. Static exciters that involve no rotating parts at all are also employed.

The main exciter feeds the exciting current to the field of the synchronous generator by way of brushes and slip-rings. Under

normal conditions the exciter voltage lies between 125 V and 600 V. It is regulated manually or automatically by control signals that vary the current I_c , produced by the pilot exciter (Fig.5.1).

The power rating of the main exciter depends upon the capacity of the synchronous generator. Typically, a 25 kW exciter is needed to excite a 1000 kVA alternator (2.5% of its rating) whereas a 2500 kW exciter suffices for an alternator of 500 MW (only 0.5% of its rating).

Under normal conditions the excitation is varied automatically. It responds to the load changes so as to maintain a constant ac line voltage or to control the reactive power delivered to the electric utility system. A serious disturbance on the system may produce a sudden voltage drop across the terminals of the alternator. The exciter must then react very quickly to keep the ac voltage constant. For example, the exciter voltage may have to rise to twice its normal value in as little as 300 to 400 milliseconds. This represents a very quick response, considering that the power of the exciter may be several thousand kilowatts.

5.7 Brushless Excitation

Due to brush wear and carbon dust, we constantly have to clean, repair, and replace brushes, slip-rings, and commutators on conventional DC excitation systems. To eliminate the problem, brushless excitation systems have been developed. Such a system

consists of a 3-phase stationary field generator whose ac output is rectified by a group of rectifiers. The DC output from the rectifiers is fed directly into the field of the synchronous generator (Fig.5.2).

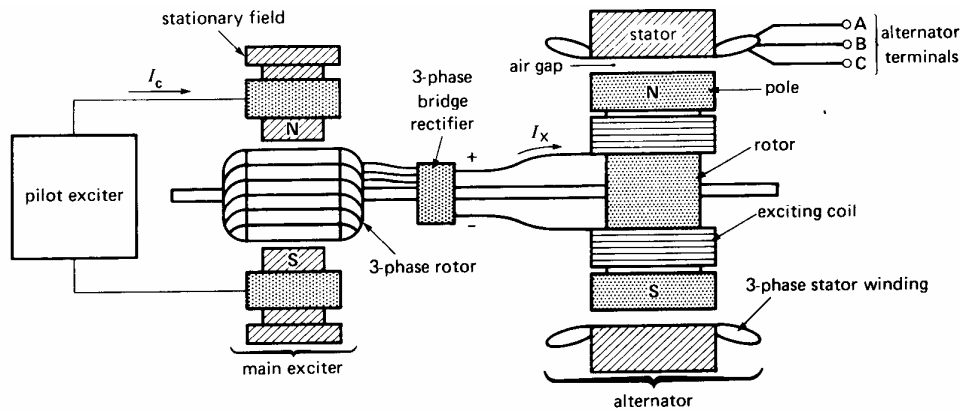


Fig.5.2 Brushless exciter system.

The armature of the ac exciter and the rectifiers are mounted on the main shaft and turn together with the synchronous generator. In comparing the excitation system of Fig.5.2 with that of Fig.5.1, we can see they are identical, except that the 3-phase rectifier replaces the commutator, slip rings, and brushes. In other words, the commutator (which is really a mechanical rectifier) is replaced by an electronic rectifier. The result is that the brushes and slip-rings are no longer needed.

The DC control current I_c from the pilot exciter regulates the main exciter output I_x , as in the case of a conventional DC exciter. The frequency of the main exciter is generally two to three times

the synchronous generator frequency (50 Hz). The increase in frequency is obtained by using more poles on the exciter than on the synchronous generator. Static exciters that involve no rotating parts at all are also employed.

5.8 Factors Affecting The Size Of Synchronous Generators

The prodigious amount of energy generated by electrical utility companies has made them very conscious about the efficiency of their generators. For example, if the efficiency of a 1000 MW generating station improves by only 1 %, it represents extra revenues of several thousand dollars per day. In this regard, the size of the generator is particularly important because its efficiency automatically improves as the power increases. For example, if a small 1 kilowatt synchronous generator has an efficiency of 50%, a larger, but similar model having a capacity of 10 MW inevitably has an efficiency of about 90%. This improvement in efficiency with size is the reason why synchronous generators of 1000 MW and up possess efficiencies of the order of 99%.

Another advantage of large machines is that the power output per kilogram increases as the power increases. For example, if a 1 kW generator weighs 20 kg (yielding $1000 \text{ W}/20 \text{ kg} = 50 \text{ W/kg}$), a 10 MW generator of similar construction will weigh only 20 000

kg, thus yielding 500 W/kg. From a power standpoint, large machines weigh relatively less than small machines; consequently, they are cheaper. Section 16.24 at the end of this chapter explains why the efficiency and output per kilogram increase with size.

Everything, therefore, favors the large machines. However, as they increase in size, we run into serious cooling problems. In effect, large machines inherently produce high power losses per unit surface area (W/m^2); consequently, they tend to overheat. To prevent an unacceptable temperature rise, we must design efficient cooling systems that become ever more elaborate as the power increases. For example, a circulating cold air system is adequate to cool synchronous generators whose rating is below 50 MW but between 50 MW and 300 MW we have to resort to hydrogen cooling. Very big generators in the 1000 MW range have to be equipped with hollow, water-cooled conductors. Ultimately, a point is reached where the increased cost of cooling exceeds the savings made elsewhere, and this fixes the upper limit to size.

To sum up, the evolution of big alternators has mainly been determined by the evolution of sophisticated cooling techniques. Other technological breakthroughs, such as better materials, and novel windings have also played a major part in modifying the design of early machines.

As regards speed, low-speed generators are always bigger than high-speed machines of equal power. Slow-speed bigness

simplifies the cooling problem; a good air-cooling system, completed with a heat exchanger, usually suffices. For example, the large, slow-speed 500 MVA, 200 r/min synchronous generators installed in a typical hydropower plant are air-cooled whereas the much smaller high-speed 500 MVA, 1800 r/min units installed in a steam plant have to be hydrogen-cooled.

5.9 No-Load Saturation Curve

Fig.5.3 shows a 2-pole synchronous generator operating at no-load. It is driven at constant speed by a turbine. The leads from the 3-phase, wye-connected stator are brought out to terminals A, B, C, N, and a variable exciting current I_x produces the flux in the air gap.

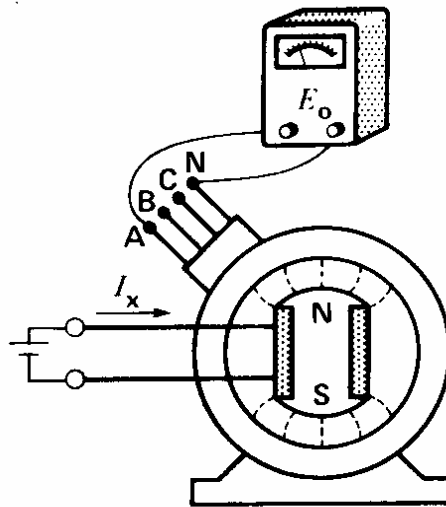


Fig.5.3 Generator operation at no-load.

Let us gradually increase the exciting current while observing the ac voltage E_o between terminal A, say, and the neutral N. For small values of I_x , the voltage increases in direct proportion to the exciting current. However, as the iron begins to saturate, the voltage rises much less for the same increase in I_x . If we plot the curve of E_o versus I_x , we obtain the no-load saturation curve of the synchronous generator.

Fig.5.4 shows the actual no-load saturation curve of a 36 MW, 3-phase generator having a nominal voltage of 12 kV (line to neutral). Up to about 9 kV, the voltage increases in proportion to the current, but then the iron begins to saturate. Thus, an exciting current of 100 A produces an output of 12 kV, but if the current is doubled, the voltage rises only to 15 kV.

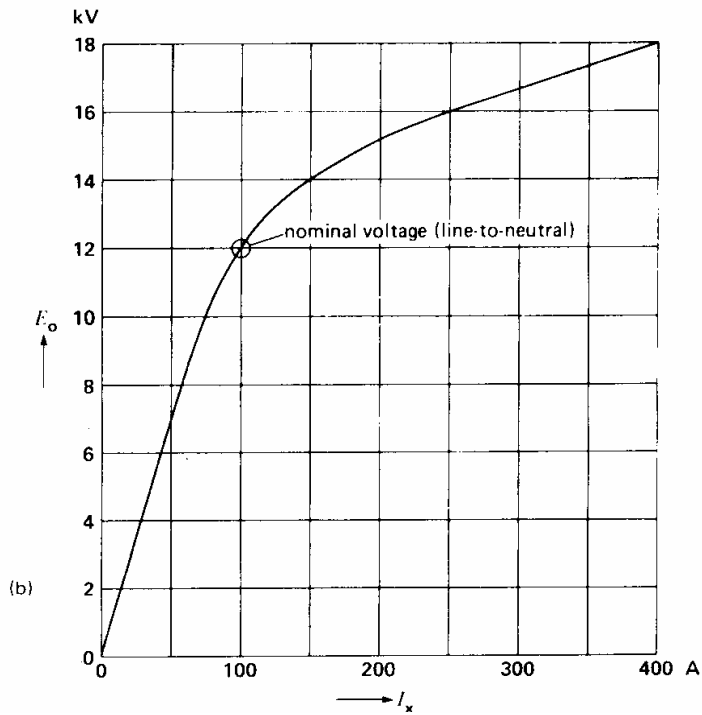


Fig.5.5 is a schematic diagram of the generator showing the revolving rotor and the three phases on the stator.

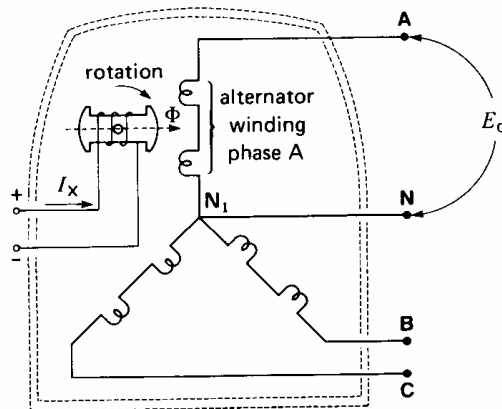


Fig.5.5 Electric circuit representing the generator of Fig.5.3

5.10 Synchronous Reactance Equivalent Circuit Of An Ac Generator

Consider a 3-phase synchronous generator having terminals A, B, C feeding a balanced 3-phase load. The generator is driven by a turbine, and is excited by a DC current I_x . The machine and its load are both connected in wye, yielding the circuit of Fig.5.6. Although neutrals N_1 and N_2 are not connected, they are at the same potential because the load is balanced. Consequently, we could connect them together (as indicated by the short dash line) without affecting the behavior of the voltages or currents in the circuit.

The field carries an exciting current which produces a flux ϕ . As the field revolves, the flux induces in the stator three equal voltages E_o that are 120 degrees out of phase (Fig.5.7). Each phase of the stator winding possesses a resistance R and a certain inductance L. Because this

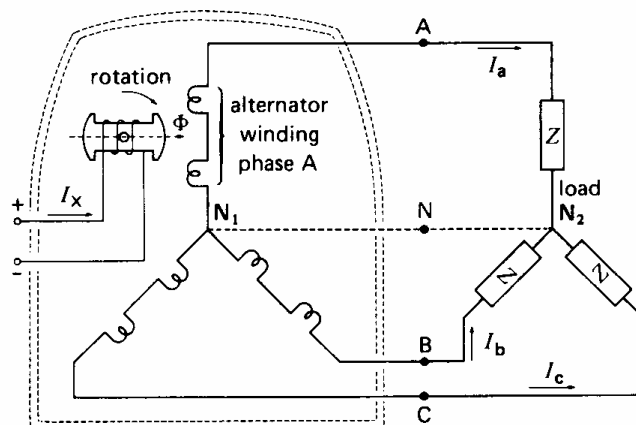


Fig.5.6 Electric circuit representing the alternator connected with 3-phase load.

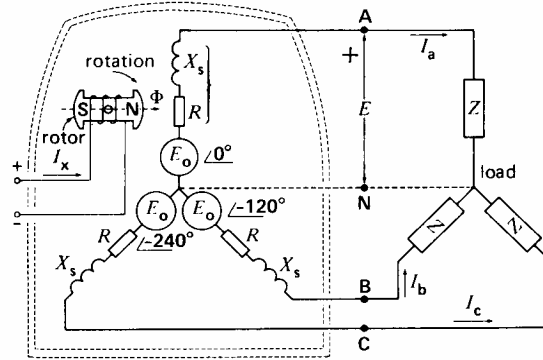


Fig.5.7 Voltage and impedances in a 3-phase generator and its connected load

The synchronous reactance of a generator is an internal impedance, just like its internal resistance R . The impedance is there, but it can neither be seen nor touched. The value of X_S is typically 10 to 100 times greater than R ; consequently, we can always neglect the resistance, unless we are interested in efficiency or heating effects.

We can simplify the schematic diagram of Fig.5.7 by showing only one phase of the stator. In effect, the two other phases are identical, except that their respective voltages (and currents) are out of phase by 120 degrees. Furthermore, if we neglect the resistance of the windings, we obtain the very simple circuit of Fig.5.8. A synchronous generator can therefore be represented by an equivalent circuit composed of an induced voltage E_o in series with a reactance X_S .

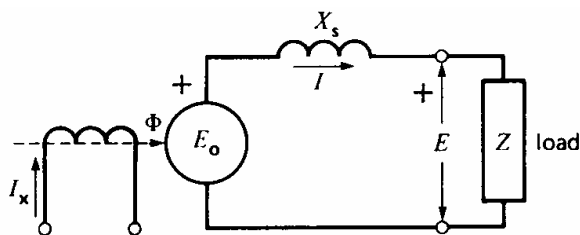


Fig.5.8 Equivalent circuit of a 3-phase generator, showing only one phase.

In this circuit the exciting current I_x produces the flux ϕ which induces the internal voltage E_o . For a given synchronous reactance, the voltage E at the terminals of the generator depends upon E_o and the load Z . Note that E_o and E are line-to-neutral voltages and I is the line current.

Example 5.2 A 3-phase synchronous generator produces an open-circuit line voltage of 6928 V when the do exciting current is 50 A. The ac terminals are then short-circuited, and the three line currents are found to be 800 A.

- Calculate the synchronous reactance per phase.
- Calculate the terminal voltage if three 12Ω resistors are connected in wye across the terminals.

Solution:

a. The line-to-neutral induced voltage is

$$E_o = E_L / \sqrt{3} = 6928 / \sqrt{3} = 4000V$$

When the terminals are short-circuited, the only impedance limiting the current flow is that due to the synchronous reactance.

Consequently,

$$X_s = E_o / I = 4000 / 80 = 5\Omega$$

The synchronous reactance per phase is therefore 5 fl.

b. The equivalent circuit per phase is shown in Fig.5.9a.

The impedance of the circuit is:

$$Z = \sqrt{R^2 + X_s^2} = \sqrt{12^2 + 5^2} = 13\Omega$$

The current is :

$$I = E_o / Z = 4000 / 13 = 308A$$

The voltage across the load resistor is

$$E = IR = 308 * 12 = 3696 V$$

The line voltage under load is:

$$E_L = \sqrt{3}E = \sqrt{3} * 3696 = 6402 V$$

The schematic diagram of Fig.5.9b helps us visualize what is happening in the actual circuit.

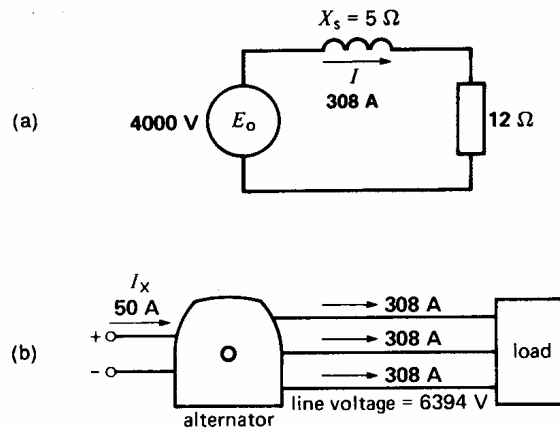


Fig.5.9. See Example 5.2. b. Actual line voltages and currents.

5.11 Synchronous Generator Under Load

The behavior of a synchronous generator depends upon the type of load it has to supply. There are many types of loads, but they can all be reduced to two basic categories:

- 1.-Isolated loads, supplied by a single generator
- 2.-Consider a 3-phase generator that supplies power to a load having a lagging power factor. Fig.5.10 represents the equivalent circuit for one phase. In order to construct the phasor diagram for this circuit, we list the following facts:

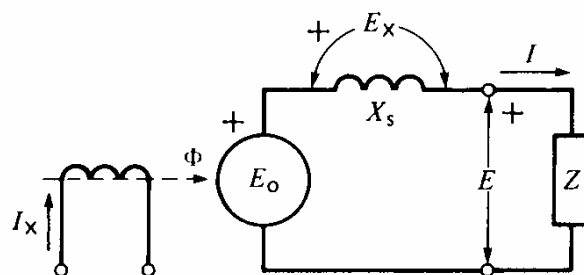


Fig.5.10 Equivalent circuit of a generator under load.

1. Current I lags behind terminal voltage E by an angle θ .
2. Cosine $\theta =$ power factor of the load.
3. Voltage E_X across the synchronous reactance leads current I by 90 degrees. It is given by the expression $E_x = jIX_S$.
4. Voltage E_o generated by the flux ϕ is equal to the phasor sum of E plus E_X .
5. Both E_o and E_X are voltages that exist inside the synchronous generator windings and cannot be measured.
6. Flux ϕ is that produced by the DC exciting current I_x .

The resulting phasor diagram is given in Fig.5.11. Note that E_o leads E by δ degrees. Furthermore, the internally-generated voltage E_o is greater than the terminal voltage, as we would expect.

In some cases the load is somewhat capacitive, so that current I leads the terminal voltage by an angle θ . What effect does this have on the phasor diagram? The answer is found in Fig.5.11. The voltage E_X across the synchronous reactance is still 90 degrees ahead of the current. Furthermore, E_o is again equal to the phasor sum of E and E_X . However, the terminal voltage is now greater than the induced voltage E_o , which is a very surprising result. In

effect, the inductive reactance X_S enters into partial resonance with the capacitive reactance of the load. Although it may appear we are getting something for nothing, the higher terminal voltage does not yield any more power.

If the load is entirely capacitive, a very high terminal voltage can be produced with a small exciting current. However, in later chapters, we will see that such under-excitation is undesirable.

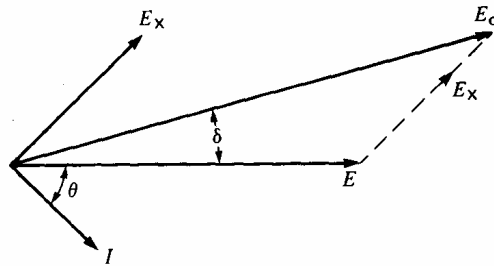


Fig.5.11 Phasor diagram for a lagging power factor load.

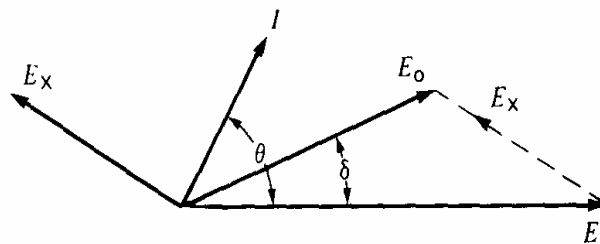


Fig5.12 Phasor diagram for a leading power factor load.

Example 5.3 A 36 MVA, 20.8 kV, 3-phase alternator has a synchronous reactance of 9Ω and a nominal current of 1 kA. The no-load saturation curve giving the relationship between E_o and I , is given in Fig.5.5. If the excitation is adjusted so that the terminal

voltage remains fixed at 21 kV, calculate the exciting current required and draw the phasor diagram for the following conditions:

- a. No-load
- b. Resistive load of 36 MW
- c. Capacitive load of 12 Mvar

Solution:

We shall immediately simplify the circuit to show only one phase.

The line-to-neutral terminal voltage for all cases is fixed at

$$E = 20.8 / \sqrt{3} = 12 \text{ kV}$$

- a. At no-load there is no voltage drop in the synchronous reactance; consequently,

$$E_o = E = 12 \text{ kV}$$

The exciting current is :

$$I_x = 100 \text{ A} \quad (\text{See Fig.5.5})$$

In no load E and E_o will be in phase

With a resistive load of 36 MW:

- b. The power per phase is

$$P = 36 / 3 = 12 \text{ MW}$$

The full load line current is

$$I = P / E = 12 * 10^6 / 12\ 000 = 1000 \text{ A}$$

The current is in phase with the terminal voltage.

The voltage across X_S is:

$$E_x = jX_S = j1000 * 9 = 9 \text{ kV} \angle 90^\circ$$

The voltage E_o generated by I_x is equal to the phasor sum of E and E_x . Referring to the phasor diagram, its value is given by:

$$E_o = \sqrt{E^2 + E_x^2} = \sqrt{12^2 + 9^2} = 15 \text{ kV}$$

The required exciting current is

$$I_x = 200 \text{ A} \quad (\text{See Fig.5.5})$$

The phasor diagram is given in Fig.5.13.

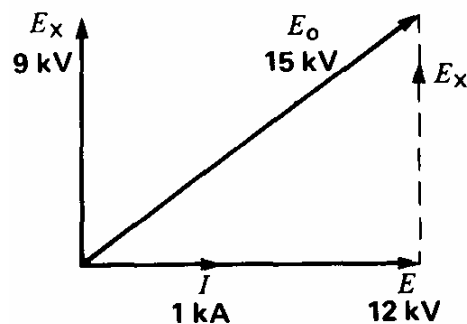


Fig.5.13 Phasor diagram with a unity power factor load.

With a capacitive load of 12 Mvar:

c. The reactive power per phase is

$$Q = 12/3 = 4 \text{ Mvar.}$$

The line current is

$$I = Q / E = 4 * 10^6 / 12000 = 333 \text{ A}$$

The voltage across X_S is

$$E_x = jX_S = j333 * 9 = 3 \angle 90^\circ \text{ kV}$$

As before E_x leads I by 90 degrees. (Fig.5.14)

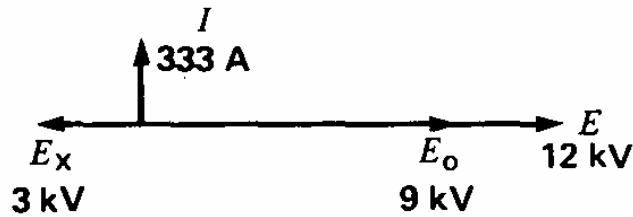


Fig.5.14 Phasor diagram with a capacitive load.

The voltage E_o generated by I_x is equal to the phasor sum of E_x and E .

$$E_o = E + E_x = 12 + (-3) = 9 \text{ kV}$$

The corresponding exciting current is

$$I_x = 70 \text{ A} \quad (\text{See Fig.5.5})$$

Note that E_o is again less than the terminal voltage E .

The phasor diagram for this capacitive load is given in Fig.5.14.