SYNCHRONOUS MACHINES

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Contents

Summary

Synchronous machines are principally used as alternating current (AC) generators. They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural, and domestic. Synchronous machines are sometimes used as constant-speed motors, or as compensators for reactive power control in large power systems. This article explains the constructional features and operating principles of the synchronous machine. Generator performance for stand-alone and grid applications is discussed. The effects of load and field excitation on the synchronous motor are investigated. The hunting behavior of a synchronous machine is studied, and a review of various excitation systems provided.

1. Introduction

The *synchronous machine* is an important electromechanical energy converter. Synchronous generators usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers. For these applications synchronous machines are built in large units, their rating ranging from tens to hundreds of megawatts. For high-speed machines, the prime movers are usually steam turbines employing fossil or nuclear energy resources. Low-speed machines are often driven by hydro-turbines that employ water power for generation. Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers.

Synchronous machines can also be used as motors, but they are usually built in very large sizes. The synchronous motor operates at a precise synchronous speed, and hence is a constant-speed motor. Unlike the induction motor, whose operation always involves a lagging power factor, the synchronous motor possesses a variable-power-factor characteristic, and hence is suitable for power-factor correction applications.

A synchronous motor operating without mechanical load is called a *compensator*. It behaves as a variable capacitor when the field is overexcited, and as a variable inductor when the field is underexcited. It is often used in critical positions in a power system for reactive power control.

2. Types of Synchronous Machine

According to the arrangement of the field and armature windings, synchronous machines may be classified as *rotating-armature type* or *rotating-field type*.

2.1. Rotating-Armature Type

The armature winding is on the rotor and the field system is on the stator. The generated current is brought out to the load via three (or four) slip-rings. Insulation problems, and the difficulty involved in transmitting large currents via the brushes, limit the maximum power output and the generated electromagnetic field (emf). This type is only used in small units, and its main application is as the main exciter in large alternators with brushless excitation systems.

2.2. Rotating-Field Type

The armature winding is on the stator and the field system is on the rotor. Field current is supplied from the exciter via two slip-rings, while the armature current is directly supplied to the load. This type is employed universally since very high power can be delivered. Unless otherwise stated, the subsequent discussion refers specifically to rotating-field type synchronous machines.

According to the shape of the field, synchronous machines may be classified as *cylindrical-rotor* (*non-salient pole*) *machines* (Figure 1) and *salient-pole machines* (Figure 2).

The cylindrical-rotor construction is used in generators that operate at high speeds, such as steam-turbine generators (usually two-pole machines). This type of machine usually has a small diameter-to-length ratio, in order to avoid excessive mechanical stress on the rotor due to the large centrifugal forces.

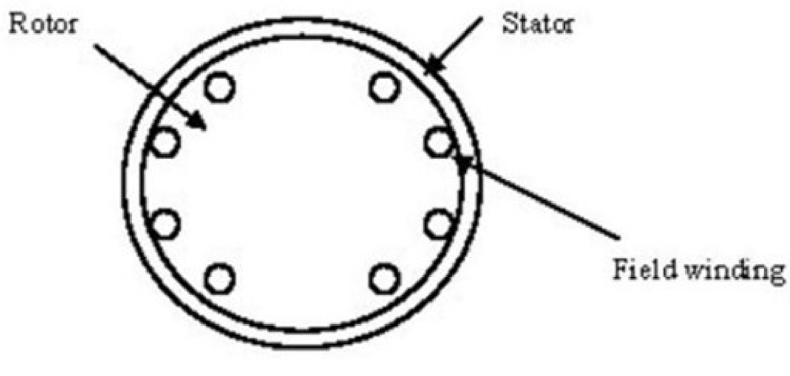

Figure 1. Construction of cylindrical-rotor synchronous machine

The salient-pole construction is used in low-speed alternating current (AC) generators (such as hydro-turbine generators), and also in synchronous motors. This type of machine usually has a large number of poles for low-speed operation, and a large diameter-to-length ratio. The field coils are wound on the bodies of projecting poles. A damper winding (which is a partial squirrel-cage winding) is usually fitted in slots at the pole surface for synchronous motor starting and for improving the stability of the machine.

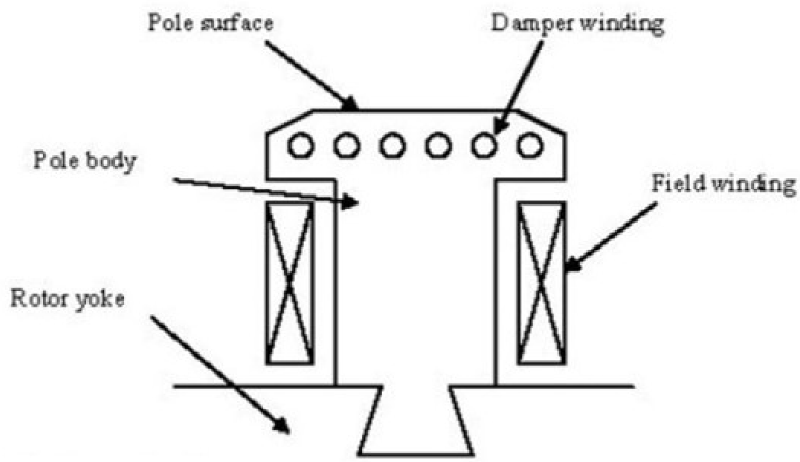

Figure 2. Salient-pole rotor construction

3. Cylindrical-Rotor Synchronous Generators

3.1. Synchronous Generator Supplying an Isolated Load

3.1.1. Principle

When a synchronous generator is excited with field current and is driven at a constant speed, a balanced voltage is generated in the armature winding. If a balanced load is now connected to the armature winding, a balanced armature current at the same frequency as the emf will flow. Since the frequency of generated emf is related to the rotor speed, while the speed of the armature rotating mmf is related to the frequency of the current, it follows that the armature mmf rotates synchronously with the rotor field. An increase in rotor speed results in a rise in the frequency of emf and current, while the power factor is determined by the nature of the load.

The effect of the armature mmf on the resultant field distribution is called *armature reaction*. Since the armature mmf rotates at the same speed as the main field, it produces a corresponding emf in the armature winding. For steady-state performance analysis, the per-phase equivalent circuit shown in Figure 3 is used. The effects of armature reaction and armature winding leakage are considered to produce an equivalent internal voltage drop across the synchronous reactance X_s, while the field excitation is accounted for by the open-circuit armature voltage E_f. The impedance $Z_s = (R + jX_s)$ is known as the synchronous impedance of the synchronous generator, where R is the armature resistance.

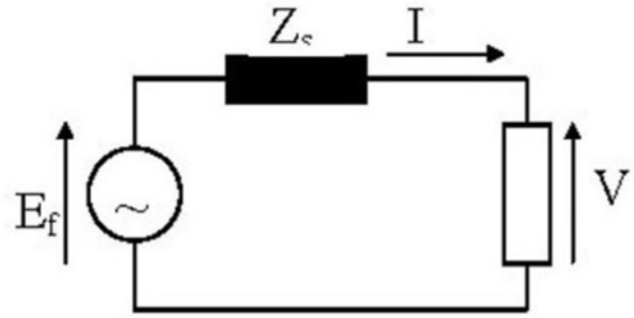

Figure 3. Per-phase equivalent circuit of synchronous generator

The circuit equation of the synchronous generator is:

$$E_f = V + I.Z_s \qquad (1)$$

Figure 4 shows a voltage phasor diagram of a cylindrical-rotor synchronous generator supplying a lagging-power-factor load. Due to the synchronous impedance drop, the terminal voltage is less than the open-circuit voltage E_f. For generator operation, the E_f phasor leads the terminal voltage phasor V by the angle δ, often referred to as the *load angle*.

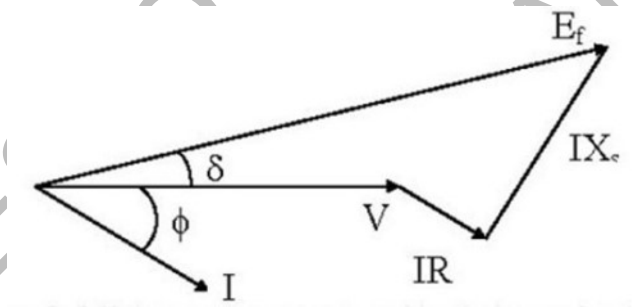

Figure 4. Phasor diagram of cylindrical-rotor synchronous generator supplying a lagging power factor load
δ – load angle; ϕ – power factor angle.

3.1.2. Voltage Regulation

The variation in the terminal voltage with load is called *voltage regulation*. Mathematically, per-unit voltage regulation is defined as the fractional rise in the terminal voltage when a given load is removed: in other word

Per-unit voltage regulation = $(|V_{NL}| - |V_{FL}|)/|V_{FL}| = (|E_f| - |V|)/|V|$

Figure 5 shows the variation in terminal voltage with load current when the field excitation is constant. When the load is resistive or inductive, the terminal voltage drops when the load current increases; when the load is capacitive, however, the terminal voltage may exceed the open-circuit voltage.

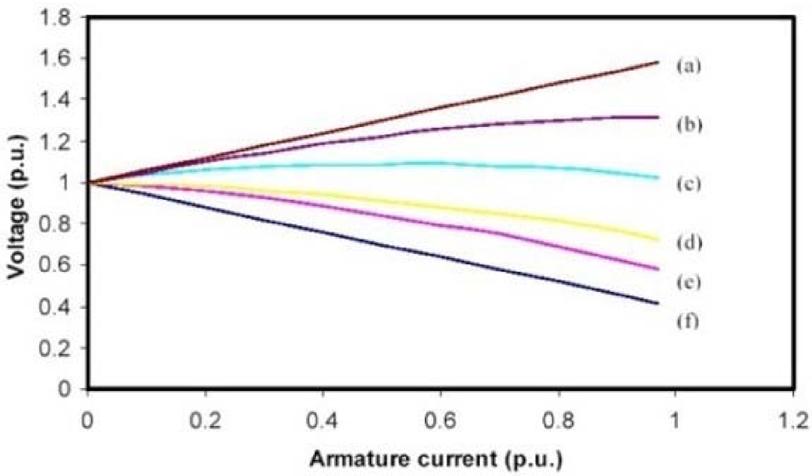

Figure 5. Voltage characteristics of cylindrical-rotor synchronous generator at constant field excitation
(a) zero power factor leading; (b) 0.8 power factor leading; (c) 0.9 power factor leading; (d) unity power factor; (e) 0.9 power factor lagging; (f) zero power factor lagging.

For practical applications, the field excitation is varied to maintain a constant terminal voltage across the load, using a device called an *automatic voltage regulator* (AVR). Figure 6 shows the variation of the field current with load current when the terminal voltage is maintained constant, often known as the *excitation characteristics*.

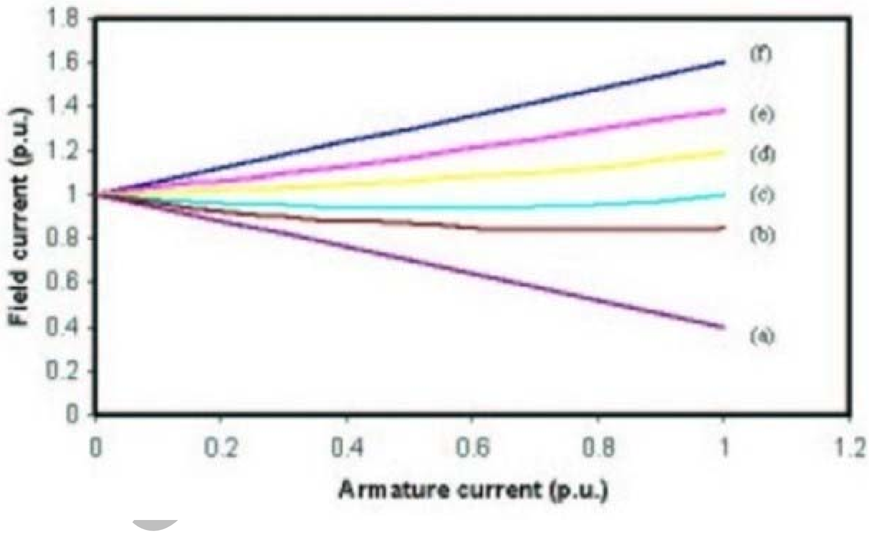

Figure 6. Excitation characteristics of cylindrical-rotor synchronous generator at constant voltage
(a) zero power factor leading; (b) 0.8 power factor leading; (c) 0.9 power factor leading; (d) unity power factor; (e) 0.9 power factor lagging; (f) zero power factor lagging.

3.2. Synchronous Generator Connected to the Grid

In practice, synchronous generators seldom operate in the isolated mode. A large number of synchronous machines are usually connected in parallel to supply the loads, forming a large power system known as a *grid*. The voltage and the frequency of the grid remain substantially constant. When a synchronous generator is connected to the grid, its rotor speed and terminal voltage are fixed by the grid and it is said to be operating on infinite busbars. In general, a change in field excitation will result in a change in the operating power factor, while a change in mechanical power input will cause a corresponding change in the electrical power output.

3.2.1. Synchronizing Procedure

The process of paralleling a synchronous machine onto infinite busbars is known as *synchronizing*.

Before a synchronous generator can be synchronized onto live busbars, the following conditions must be satisfied:

- the voltage of the generator must be equal to that of the busbars;
- the frequency of the generator must be equal to that of the busbars;
- the phase sequence of the generator must be the same as that of the busbars; and
- at the instant of synchronizing, the voltage phasors of the generator and the busbars must coincide.

Synchronizing may be achieved with the help of synchronizing lamps, the rotary lamp method being the most popular. Alternatively, a device known as the synchroscope may conveniently be used to facilitate synchronizing.

3.2.2. Operating Conditions of Synchronous Generator

Depending upon the field excitation and the mechanical power input, a synchronous generator may operate in one of the operating conditions shown in Figure 7. The phasor diagrams show that when a synchronous generator operates on infinite busbars, overexcitation will cause the machine to deliver power at a lagging power factor, while underexcitation will cause the generator to deliver power at a leading power factor. The synchronous generator is thus a source or sink of reactive power.

3.2.3. Power/Load Angle Relationship

Taking the terminal voltage *V* as the reference phasor, and expressing Eq. (1) in polar form,

$$E_f\angle\delta = V\angle 0 + I.Z_s\angle\theta_s \qquad (2)$$

where θ_s = synchronous impedance angle.

The armature current *I* is

$$I = \frac{E_f\angle\delta - V\angle 0}{Z_s\angle\theta_s} \qquad (3)$$

in other words

$$I = \frac{E_f}{Z_s}\angle(\delta - \theta_s) - \frac{V}{Z_s}\angle - \theta_s \tag{4}$$

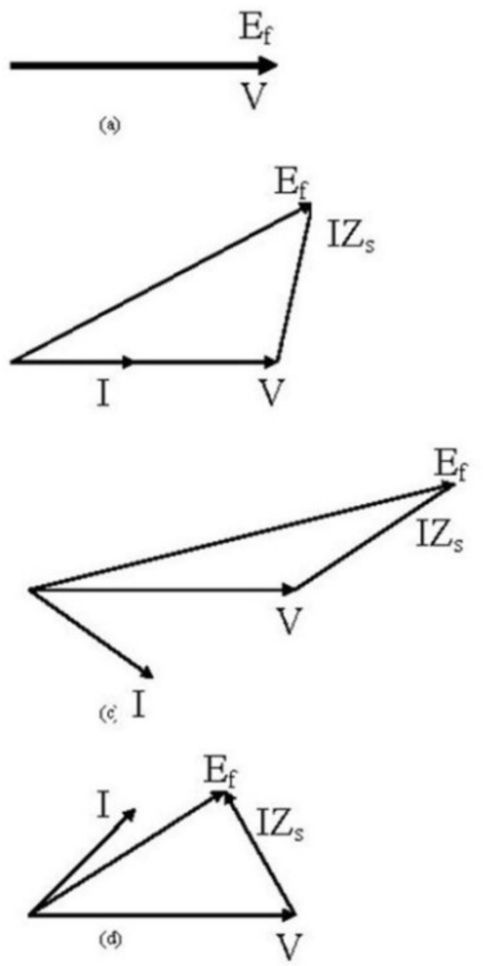

Figure 7. Phasor diagrams of cylindrical-rotor synchronous generator connected to the grid
(a) floating condition; (b) unity power factor operation; (c) lagging power factor operation; (d) leading power factor operation.

The in-phase (active) component of armature current is

$$I.\cos\Phi = \frac{E_f}{Z_s}\cos(\delta - \theta_s) - \frac{V}{Z_s}\cos\theta_s \tag{5}$$

The output power per phase is

$$P = VI.\cos\Phi = \frac{E_f V}{Z_s}\cos(\delta - \theta_s) - \frac{V^2}{Z_s}\cos\theta_s \tag{6}$$

In general, $R << X_s$, $\therefore\ \theta_s \cong 90°$ and $Z_s \cong X_s$. Hence the total output power is

$$P = \frac{3E_f V}{X_s}\sin\delta = P_m \sin\delta \tag{7}$$

where $P_m = 3(E_f\,.V/X_s)$ is known as the *steady-state stability limit*. This is the maximum power the generator can deliver when the load is applied gradually. Figure 8 shows the power/load angle curve of a cylindrical-rotor synchronous generator. Stable operation is theoretically possible provided the load angle is less than 90°. In practice, however, the load angle at full load is limited to around 30°–40°, in order to provide a sufficient safety margin for the synchronous generator to remain in synchronism with the grid after transients and momentary overloads.

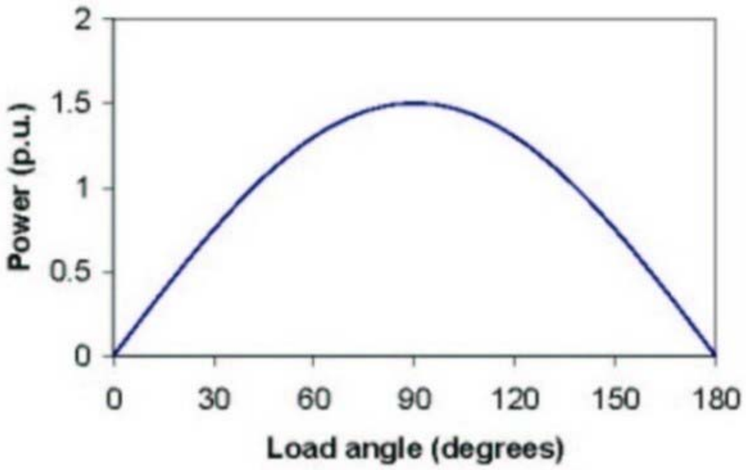

Figure 8. Power-load angle curve of a cylindrical-rotor synchronous machine

3.2.4. Synchronizing Power and Torque

A synchronous machine has an inherent tendency to remain in synchronism with the power system on which it operates, due to the presence of synchronizing power. As an example, consider a synchronous generator connected to the grid and driven by a prime mover that provides a constant mechanical input power. If the rotor accelerates due to some disturbance the load angle increases, resulting in an increase in electrical power output (Eq. (7)). The extra output power is derived from the stored kinetic energy of the rotor; consequently the rotor slows down as the rotor mechanical energy is being extracted, and the generator will return to synchronous operation.

Synchronizing power P_s is defined as the power per electrical radian of rotor displacement; in other words

$$P_s = \frac{\partial P}{\partial \delta} = \frac{3E_f V}{X_s}\cos\delta \tag{8}$$

The synchronizing torque T_s is given by

$$T_s = \frac{P_s}{\omega_s} \tag{9}$$

where ω_s is the synchronous angular speed of the machine.

From Eq. (8), it is clear that the synchronizing power is a maximum for no load ($\delta = 0$) and decreases as the load on the machine increases. For a load angle of 90 electrical degrees, the synchronizing power is zero, meaning that the machine is on the verge of instability. The larger the load angle, the less stable the synchronous machine becomes.

3.2.5. Hunting

Hunting is the sustained oscillation of the rotor following a disturbance in a synchronous machine operating on infinite busbars.

The synchronizing torque T_s and the rotor moment of inertia J of the synchronous machine are analogous to the stiffness and mass of a spring-mass mechanical system. When subjected to an external disturbance, the load angle follows a simple harmonic motion and the natural frequency of oscillation is given by

$$\omega_n = \sqrt{\frac{T_s}{J}} \tag{10}$$

If the driving torque provided by the prime mover is cyclic with a frequency close to ω_n, hunting may develop into vigorous rotor swings, with a consequent danger of instability.

In practice, some of the rotor energy is dissipated in the stator and field resistances; hence the oscillations will die down and the synchronous machine will settle to steady state again after a disturbance. A damper winding may be fitted to the pole surfaces of the salient-pole synchronous machine to prevent hunting and to improve stability.

4. Synchronous Motors

4.1. Operating Principle

A synchronous motor develops a constant torque only when the field system and the armature mmf rotate in synchronism. When the motor is fed from the grid, the supply frequency is constant and the motor must run at synchronous speed. The synchronous motor is thus a constant-speed motor.

The steady-state performance characteristics of the synchronous motor may be studied using the equivalent circuit shown in Figure 9. Comparing this with Figure 3, it should be noted that the direction of armature current has been reversed. The circuit equation for a synchronous motor is thus

$$V = E_f + I.Z_s \tag{11}$$

In order to satisfy the above circuit equation, the phasor E_f (often regarded as the back emf of the motor) must lag the terminal voltage V by the load angle δ.

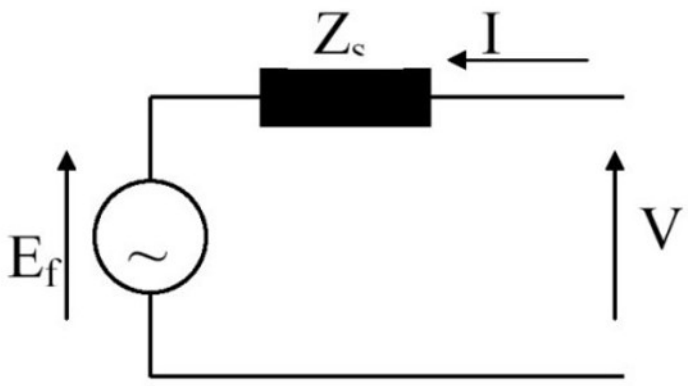

Figure 9. Equivalent circuit of cylindrical-rotor synchronous motor

4.2. Effect of Field Excitation: V-curves

When studying the effect of field excitation on motor performance, it is often assumed that the motor is loaded such that it draws a constant power from the supply. Since both the power and the voltage are constant, it follows that

$$I.\cos\Phi = I_a = constant \tag{12}$$

where I_a is the active component of armature current, and

$$I_a.Z_s = constant \tag{13}$$

Figure 10 shows the effect of change in field excitation on the operation of the synchronous motor. As the field current is changed, the tip of armature current phasor I will follow the locus XX (a line perpendicular to V), while the tip of the back emf phasor E_f will follow the locus YY (a line perpendicular to $I_2.Z_s$, where I_2 is the in-phase component of armature current).

Suppose the synchronous motor is initially overexcited (in other words, excited with a large field current) and is operating at point 1, as shown in Figure 10. The corresponding armature current I_1 is leading V, and hence the input power factor is leading. Reduction of field current causes the tip of E_f phasor to move towards point 2: the armature current decreases to a minimum (I_2) and the motor input power factor increases to unity. Further reduction of field current causes E_f to move to point 3: the armature current increases to I_3, and the input power factor becomes lagging.

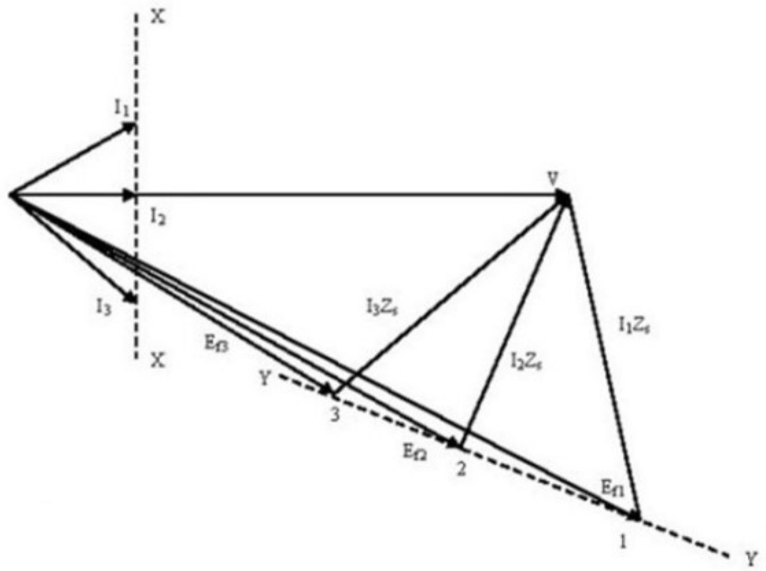

Figure 10. Effect of field excitation on performance of a synchronous motor
XX – locus of armature current at constant power; YY – locus of open-circuit voltage at constant power.

When the synchronous motor operates with constant power input, the variation of armature current with field current is thus a V-shaped curve, as illustrated in Figure 11. In general, overexcitation will cause the synchronous motor to operate at a leading power factor, while underexcitation will cause the motor to operate at a lagging power factor. The synchronous motor thus possesses a variable-power-factor characteristic.

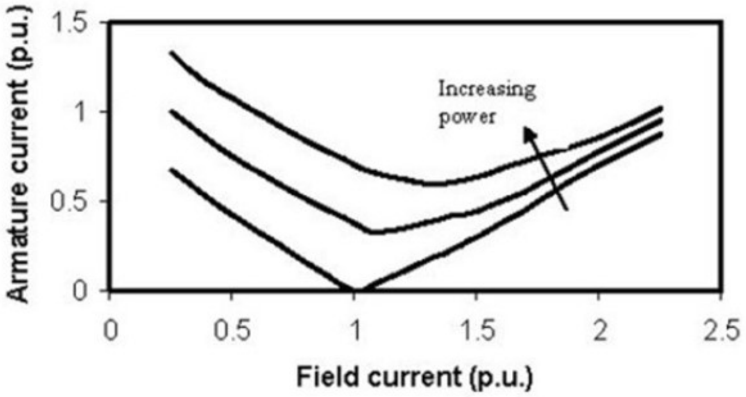

Figure 11. Synchronous motor V-curves

4.3. Effect of Mechanical Load

When the shaft load on the motor is varied, there is an internal adjustment in phase relations between the supply voltage and the motor back emf, resulting in a change in the load angle and a momentary acceleration or deceleration. After a transient period of rotor oscillation, the rotor settles down again to synchronous speed, but with the load angle and armature current changed in order to develop the required torque. In general, the load angle increases when mechanical load is applied, with a corresponding increase in armature current. If the applied load exceeds the stability limit, the motor may pull out of synchronism.

4.4. Starting Synchronous Motors

With the rotor at standstill and a three-phase voltage applied to the armature winding, the resultant rotating armature mmf moves past the rotor at synchronous velocity, producing an alternating torque with an average value of zero. The plain synchronous motor thus has no inherent starting torque. To start the motor, the following methods may be employed:

- *Pony motor starting*. Earlier machines were started using this method. A small directly coupled induction motor is used to drive the synchronous machine close to synchronous speed, and synchronizing is carried out by means of a synchroscope. The induction motor usually has two poles fewer than the synchronous motor, and so is capable of raising the speed of the main motor to synchronous speed. This method is not convenient for industrial applications.
- *Starting as an induction motor*. Modern machines are usually of the self-synchronizing type and are arranged to start as induction motors. The pole faces of the synchronous motor are fitted with a damper winding (similar to a partial squirrel-cage winding). With the field winding open-circuited, the armature winding is connected to a reduced voltage provided by an autotransformer. The rotor accelerates by induction motor action and runs up to a speed slightly less than the synchronous speed. Excitation is then applied and synchronizing torque produced. Provided that the slip is not too large, the rotor will pull into synchronism. The autotransformer tapping is then quickly changed to normal for the machine to run on full voltage.

4.5. Applications of Synchronous Motors

The synchronous motor may be used as a constant-speed drive, particularly for ratings exceeding 15 kW: for example, motor-generator sets for a DC power system, compressors, fans, and blowers. Large synchronous motors have higher efficiencies and can operate at unity power factor; hence they are smaller in size and weight than induction motors of the same rating.

Synchronous motors can also be used for power-factor correction in an industrial plant consisting of a large number of induction motors. An overexcited synchronous motor without mechanical load behaves as a variable capacitor that can be used for reactive power control in a large power system. For the latter application, the machine is often referred to as a *synchronous capacitor* or a *compensator*.

5. Excitation System

The direct current required for field excitation is furnished by the excitation system. The source of power can be a shaft-mounted exciter, a motor-generator set, or a static rectifier.

- *DC exciter*. This is the traditional method. A DC generator mounted on the main shaft may be of either the shunt-wound or the separately-excited type. The output current is fed to the rotor of the synchronous machine through slip-rings.
- *Static excitation*. Here, DC excitation can be obtained by means of a rectifier and a suitable AC supply. This method eliminates the commutation limits inherent in DC exciters. The rectifier unit has no moving parts, requires very little maintenance, and is immune to hazardous or dusty atmospheres.
- *AC exciter*. The AC exciter is mounted on the main shaft. Its field is fed from a pilot exciter, whose field in turn is obtained from a permanent-magnet generator. The AC exciter output voltage is rectified and fed to the field of the synchronous machine via slip-rings.
- *Brushless excitation system*. An exciter of rotating-armature type is mounted on the main shaft. The AC output is converted to DC by means of a rotating rectifier. The direct current is fed directly to the field winding of the synchronous machine, no slip-rings or brushgear being needed.

Glossary

AC:	Alternating current.
Armature:	The part of an electrical machine in which emf is generated and the load current flows.
Armature reaction:	Effect of armature current on the resultant magnetic field distribution in an electrical machine.
Automatic voltage regulator (AVR):	A device that senses the terminal voltage and adjusts the field excitation so that the terminal voltage is maintained at the specified value. For a grid-connected synchronous machine, the AVR is used for reactive power control and to improve stability.
Busbars:	Busbars are the locations to which synchronous generators and loads are connected in a power system.
DC:	Direct current.
Field:	The part of an electrical machine producing the magnetic flux.
Load angle:	This is the electrical angle between the no-load voltage E_f and the terminal voltage V of a synchronous machine.
Phasor diagram:	Diagram showing the relationship between electrical quantities, the concise phasor representation being used for each quantity.
Synchronous speed:	This is the speed of the armature rotating mmf If the frequency of the armature current is f Hz and the number of pole pairs is p, then the synchronous speed is equal to f/p revolutions per second.
Synchronous reactance:	This is a hypothetical internal reactance used in the per-phase equivalent circuit model of a synchronous machine. The synchronous reactance is the sum of the armature reaction reactance and leakage reactance of the armature winding. The typical value of synchronous reactance is 1.5–2.0 p.u.
Voltage regulation:	For a synchronous generator, the voltage regulation is the voltage rise at the terminals when a given load is removed, both the speed and field excitation remaining unchanged.

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Biographical Sketch

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