

SYNCHRONOUS MACHINES

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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.

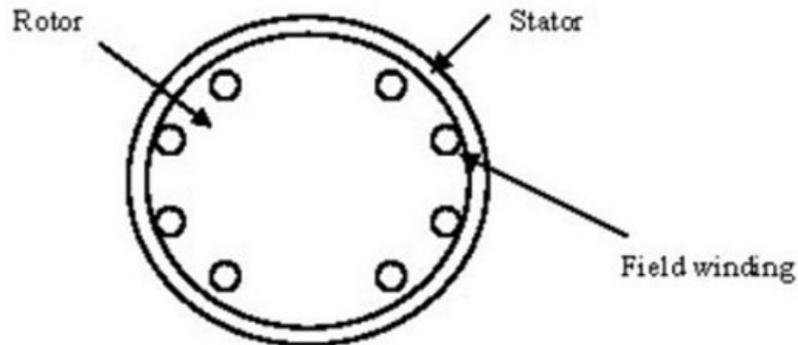


Figure 1. Construction of cylindrical-rotor synchronous machine

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.

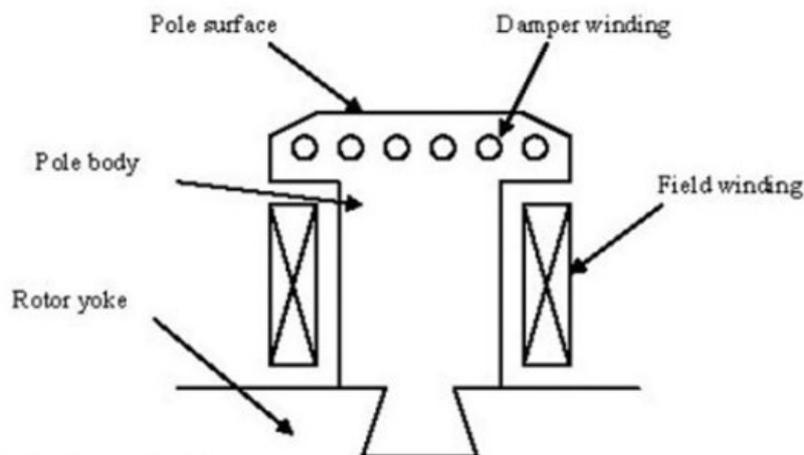


Figure 2. Salient-pole rotor construction

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.

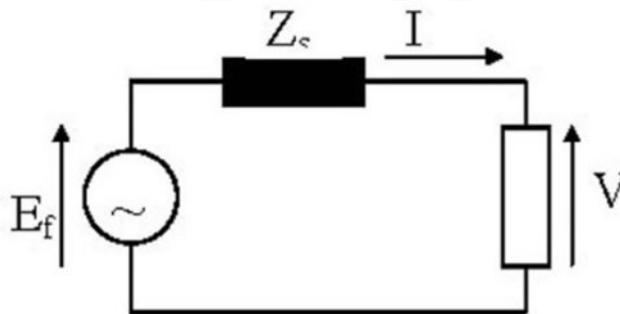


Figure 3. Per-phase equivalent circuit of synchronous generator

The circuit equation of the synchronous generator is:

$$E_f = V + I \cdot Z_s \quad (1)$$

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*.

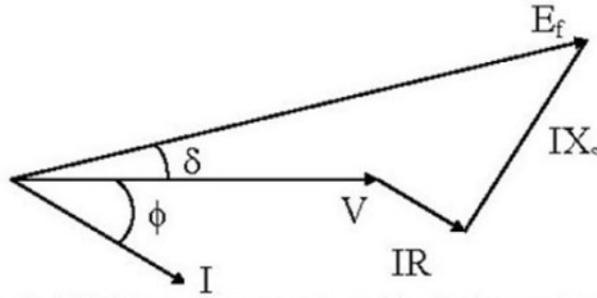


Figure 4. Phasor diagram of cylindrical-rotor synchronous generator supplying a lagging power factor load
 δ – load angle; ϕ – power factor angle.

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

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

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.

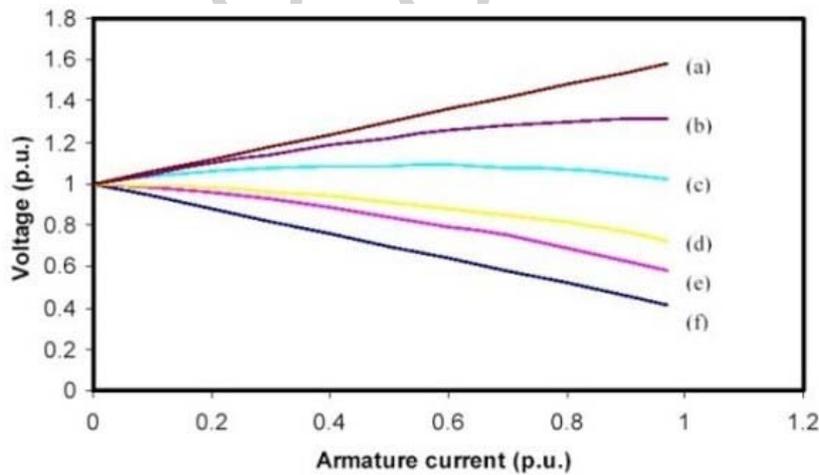


Figure 5. Voltage characteristics of cylindrical-rotor synchronous generator at constant field excitation

- (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*.

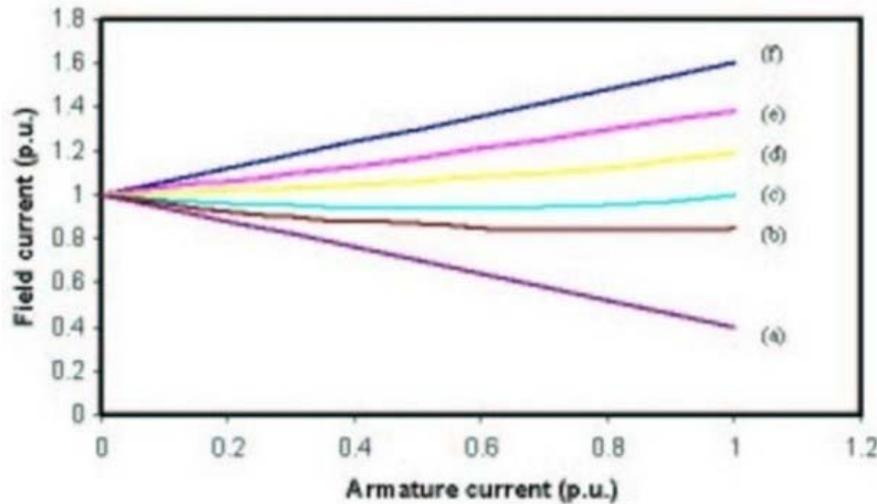


Figure 6. Excitation characteristics of cylindrical-rotor synchronous generator at constant voltage

(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.

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Biographical Sketch

Tze-Fun Chan received B.Sc. (Eng.) and M.Phil. degrees in electrical engineering from the University of Hong Kong in 1974 and 1980. Since 1978, he has been with the Department of Electrical Engineering, the Hong Kong Polytechnic University, where he is now an Associate Professor. His current research interests are self-excited AC generators and permanent-magnet machines. He is a Chartered Engineer, and a member of the Institution of Electrical Engineers (UK), the Institute of Electrical and Electronic Engineers (USA), and the Hong Kong Institution of Engineers.

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