6. Synchronous Machines

6.1 INTRODUCTION TO POLYPHASE SYNCHRONOUS MACHINES

A synchronous machine is one in which alternating current flows in the armature winding and dc rotor flux is produced by dc excitation to a field winding or by permanent magnets. The armature winding is almost invariably on the stator and is frequently a three-phase winding, as discussed in Chaper4. The cylindrical rotor construction is used for two- and four-pole turbine generators. The salient pole construction is best adapted to multi-polar, slow-speed hydroelectric generators and to many synchronous motors.

The dc power required for excitation of a synchronous machine field winding approximately one to a few percent of the rating of the synchronous machine- is supplied by the *excitation system*. In the case of a permanent magnet synchronous machine, no power is required to excite the dc rotor flux and hence there is the potential for higher machine efficiency. There is a tradeoff however because with permanent-magnet excitation it is no possible to adjust the magnitude of the dc rotor flux in response to machine operating conditions.

In older machines, the field excitation current was typically supplied through slip rings from a dc machine, referred to as the *exciter*, which was often mounted on the same shaft as the synchronous machine. In more modern systems, the excitation is supplied from ac exciters and solid-state rectifiers (either simple diode bridges or phase-controlled rectifiers). In some cases, the rectification occurs in the stationary frame, and the rectified excitation current is fed to the rotor via slip rings. In other systems, referred to as *brushless excitation systems*, the alternator of the ac exciter is on the rotor, as is the rectification system, and the current is supplied directly to the field-winding without the need for slip rings.

A single synchronous generator acts as a voltage source whose frequency is determined by the speed of its mechanical drive (or *prime mover*). The amplitude of the generated voltage is proportional to the rotor speed and the field current. As we will see, the generator terminal current and power factor are determined by the generator field excitation and the impedance of the generator and load.

Synchronous generators can be readily operated in parallel, and, in fact, the electricity supply systems of industrialized countries typically have scores or even hundreds of them operating in parallel, interconnected by thousands of miles of transmission lines, and supplying electric energy to loads scattered over areas of many thousands of square miles. These huge systems have grown in spite of the necessity for designing the system so that synchronism between generators is maintained following disturbances and the problems, both technical and administrative, which must be solved to coordinate the operation of such a complex system.

When a synchronous generator is connected to a large interconnected system containing many other synchronous generators, the voltage and frequency at its armature terminals are substantially fixed by the system. The magnetic flux corresponding to this applied voltage thus rotates at the synchronous speed ($n_s=60f/p$) as determined by the system electrical frequency f. For the production of a steady, unidirectional electromechanical torque, the fields of the stator and rotor must rotate at the same speed, and therefore the rotor must turn at precisely the system-imposed synchronous speed. Because any individual generator is a small fraction of the total system generation, it cannot significantly affect the system voltage or frequency. It is thus often useful, when studying the behavior of an individual generator or group of generators, to represent the remainder of the system as a constant-frequency, constant-voltage source, commonly referred to as an *infinite bus*.

Many important features of synchronous machine behavior can be understood from the analysis of a single machine connected to an infinite bus. In normal steady-state operation, the electromechanical torque balances the mechanical torque applied to the shaft. In a generator, the prime-mover torque acts in the direction of rotation of the rotor, pushing the rotor mmf wave ahead of the resultant air-gap flux. The electromechanical torque then oppose rotation. The opposite situation exists in a synchronous motor, where the electromechanical torque is in the direction of rotation, in opposition to the retarding torque of mechanical load on the shaft.

Variations in the electromechanical torque result in corresponding the *torque angle* (or power angle), δ. δ is electrical phase angle between magnetic axes of resultant air-gap flux per pole Φ and mmf of the dc field winding F_f. Positive values of torque represent generator action, corresponding to positive values of δ for which the rotor mmf leads the resultant air-gap flux.

As the prime-mover torque is increased, the magnitude of δ must increase until the electromechanical torque balances the shaft torque. The readjustment process is actually a dynamic one, requiring a change in the mechanical speed of the rotor, typically accompanied by a damped mechanical oscillation of the rotor about its new steady-state torque angle. This oscillation is referred to as a *hunting transient*. In a practical machine undergoing such a transient, some changes in the amplitudes of the resultant flux-density and field-winding mmf wave may also occur because of various factors such as saturation effects, the effect of the machine leakage impedances, the response of the machine's excitation system, and so on. To emphasize the fundamental principles of synchronous machine operation, such effects will be neglected in the present discussion.

An increase in prime-mover torque will result in a corresponding increase in the torque angle. When δ becomes 90^o, the electromechanical torque reaches its maximum value, known as the *pull-out torque*. Any further increase in prime-mover torque cannot be balanced by a corresponding increase in synchronous electromechanical torque, with the result that synchronism will no longer be maintained and the rotor will speed up. This phenomenon is known as *loss of synchronism* or *pulling out of step*. Under these conditions, the generator is usually disconnected from the external electrical system by the automatic operation of circuit breakers, and the prime mover is quickly shut down to prevent dangerous overspeed. The value of the pull-out torque can be increased by increasing either the field current or the resultant air gap flux. However, this cannot be done without limit; the field current is limited by the ability to cool the field winding and the air-gap flux is limited by saturation of the machine iron.

Since a synchronous motor develops torque only at synchronous speed, it cannot be started simply by the application of armature voltages of rated frequency. In some cases, a squirrel-cage structure is included in the rotor in which case the motor can be started as an induction motor and it will synchronize when it is close to synchronous speed. Alternatively, synchronous motors are often operated from variable-frequency/variable voltage electronic drives which are controlled in such a fashion as to insure synchronous operation as the motor is brought up to its operating speed.

6.2 STEADY-STATE POWER-ANGLE CHARACTERISTICS

The maximum power a synchronous machine can deliver is determined by the maximum torque which can be applied without loss of synchronism with the external system to which it is connected. In the context of this discussion, the term “maximum power” refers to the maximum power which can theoretically be delivered without loss of synchronism. In practice, this value may be significantly higher than the machine’s rated power which is the practical operating power limit of the machine and which is determined by thermal limitations. The purpose of this section is to derive expressions for the steady-state power limits of synchronous machines in simple situations for which the external system can be represented as an impedance in series with a voltage source.

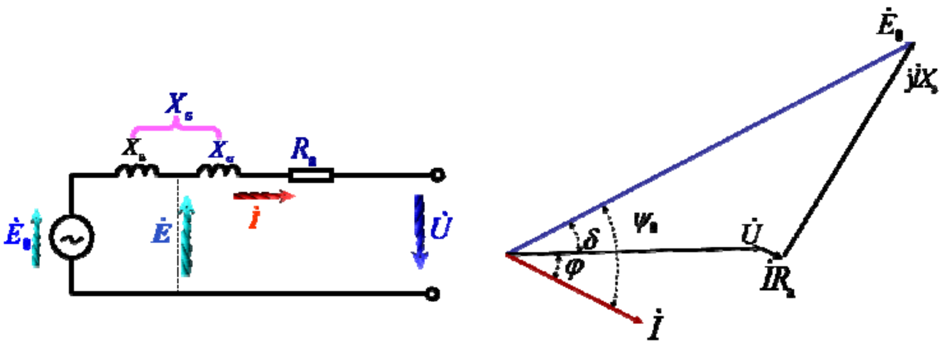

Figure 1 (a) Impedance interconnecting two voltages; (b) phasor diagram

Since both the external system and the machine itself can be represented as an impedance in series with a voltage source, the study of power limits becomes merely a special case of the more general problem of the limitations on power flow through a series impedance. The impedance will include the synchronous impedance of the synchronous machine as well as an equivalent impedance of the external system (which may consist of transmission lines and transformer banks as well as additional synchronous machines).

Consider the simple circuit of Fig. 1a, consisting of two ac voltages, $\dot{E}_0$ and $\dot{U}$, connected by an impedance $Z = R_a + jX_s$ through which the current is $\dot{I}$. The phasor diagram is shown in Fig.1b. Note that in this phasor diagram, the voltage $\dot{U}$ is chosen as the reference phasor and the reference direction for positive angles is counter-clockwise. Thus, in Fig. 1b, the phase angle δ of $\dot{E}_0$ is positive while the phase angle φ of the current can be seen to be positive.

If, as is frequently the case in the analysis of large power systems, the resistance R_a is negligible, then there is no power dissipated in the series impedance and the power P_e supplied by the source $\dot{E}_0$ is equal to P_2. Under this assumption,

$$P_e \approx P_2 = mUI\cos\varphi = mU(IX_s\cos\varphi)/X_s = mUE_0\sin\delta/X_s \tag{1}$$

Equation 1 is a very important equation in the study of synchronous machines and indeed in the study of ac power systems in general. Eq. 1 is commonly referred to as the *power angle characteristic*, and the angle δ is known the *power angle*. Note that if δ is positive, $\dot{E}_0$ leads $\dot{U}$ and power flows from source $\dot{E}_0$ to $\dot{U}$. Similarly, when δ is negative, $\dot{E}_0$ lags $\dot{U}$ and power flows from source $\dot{U}$ to $\dot{E}_0$. From Eq.1 the maximum power which can be transferred between sources and load is

$$P_{e\,max} = P_{2max} = mUE_0/X_s \tag{2}$$

which occurs when δ=90°.

6.3 Steady State Operating Characteristics

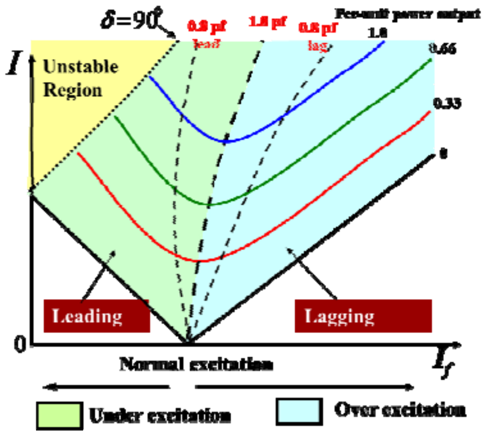

Figure 2 Typical form of synchronous-generator V curves

For a given real-power loading and terminal voltage, the power factor at which a synchronous machine operates, and hence its armature current, can be controlled by adjusting its field excitation. A plot of armature current as a function of field current at constant real power and terminal voltage is known as a *V curve* because of its characteristic shape. A family of V curves for asynchronous generator corresponding to various real power loadings takes the form of those shown in Fig 2.

The dashed lines are loci of constant power factor; they are referred to as *compounding curves*, showing how the field current must be varied as the load is changed to maintain constant power factor. Points to the right of the unity power factor compounding curve correspond to over-excitation and lagging power factor; points to the left correspond to under-excitation and leading power factor. Synchronous motor V curves and compounding curves are very similar to those of synchronous generators. In fact, if it were not for the small effects of armature resistance, motor and generator compounding curves would be identical except that the lagging- and leading power-factor curves would be interchanged.

The nature of a V curve is best understood with the aid of a phasor diagram. Consider the phasor diagram of Fig. 3, representing for a synchronous generator operating at constant terminal voltage U, constant real power P and three different values of field current. To simplify this discussion, the real power is given by

$$P_2 = mUI\cos\varphi \tag{3}$$

where φ is the angle of armature current $\dot{I}$ with respect to terminal voltage $\dot{U}$. Because U and P_2 are constant, we see from Eq.3 that

$$I\cos\varphi = \text{constant} \tag{4}$$

and thus, the projection of $\dot{I}$ onto $\dot{U}$ is constant. As a result, the tips of all the phasors $\dot{I}$ must lie along the vertical dotted line labeled "Locus of $\dot{I}$" in Fig.3.

In the other, the electromagnetic power is given by

$$P_e = mUE_0\sin\delta / X_s \tag{5}$$

Because U and P_e are constant, we see from Eq.5 that

$$E_0\sin\delta = \text{constant} \tag{6}$$

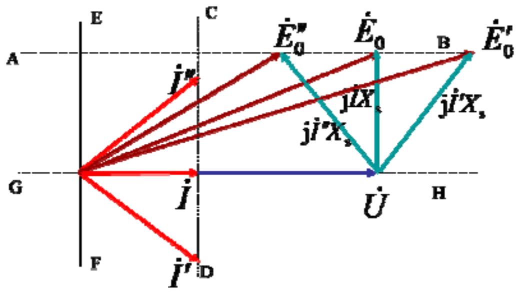

Figure 3 Phasor diagram for constant-power operation at constant terminal voltage

Similarly, because $\dot{E}_0$ is obtained by adding the phasor $j\dot{I}X_s$, which is perpendicular to the phasor $\dot{I}$ to $\dot{U}$, it can be shown that the tips of all the phasors $\dot{E}_0$ must lie along the horizontal dashed line labeled "Locus of $\dot{E}_0$" in Fig.3.

Consider operation at current $\dot{I}''$ in Fig. 3, in which case the generator is operating at a leading power factor (φ is negative) and hence its reactive power output, given by

$$Q_2 = mUI\sin\varphi \tag{7}$$

is negative, i.e. the generator is absorbing reactive power from the external system. Notice that under this operating condition, the corresponding generated voltage $\dot{E}_0''$ has the smallest magnitude of the three operating points, corresponding to the smallest value of field current. When a synchronous generator is absorbing reactive power, it is said to be *under-excited*.

Next consider unity-power-factor operation, corresponding to the terminal current $\dot{I}$ in the phasor diagram. We see that the magnitude of the corresponding generated voltage $\dot{E}_0$ is larger than that of the first operating condition. Thus, we see that if the generator is operating under-excited, an increase in field current will reduce the armature current and improve the power factor, reducing the reactive power absorbed by the generator. A minimum of armature current will occur when the generator is operating at unity power factor (zero reactive power).

As can be seen from the phasor diagram, a further increase in field current (and a corresponding increase in E_0) will result in an increase in armature current from its minimum value; for example, consider the operating point corresponding to terminal current $\dot{I}'$ and generated voltage $\dot{E}_0'$. Under these conditions the generator is operating at lagging power factor (φ is positive) and hence the terminal reactive power is positive and the generator is supplying reactive power to the external system. When a synchronous generator is supplying reactive power, it is said to be *over-excited*.