Power System Transient Stability Study Fundamentals

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Introduction

For years, system stability was a problem almost exclusively to electric utility engineers. Small independent power producers (IPPs) and co-generation (co-gen) companies were treated as part of the load and modelled casually. Today, the structure of the utility industry is going through a revolutionary change under the process of deregulation. A full-scale competition in the generation market is on the horizon. Increasing numbers of industrial and commercial facilities have installed local generation, large synchronous motors, or both. The role of IPP/co-gen companies and other plants with on-site generation in maintaining system stability is a new area of interest in power system studies. When a co-generation plant (which, in the context of this course, is used in reference to any facility containing large synchronous machinery) is connected to the transmission grid, it changes the system configuration as well as the power flow pattern. This may result in stability problems both in the plant and the supplying utility. Figure 1 and Figure 2 are the time-domain simulation results of a system before and after the connection of a co-generation plant. The increased magnitude and decreased damping of machine rotor oscillations shown in these figures indicate that the system dynamic stability performance has deteriorated after the connection. This requires joint studies between utility and co-gen systems to identify the source of the problem and develop possible mitigation measures.

Stability Fundamentals

Definition of Stability

Fundamentally, stability is a property of a power system containing two or more synchronous machines. A system is stable, under a specified set of conditions, if, when subjected to one or more bounded disturbances (less than infinite magnitude), the resulting system response(s) are bounded. After a disturbance, a stable system could be described by variables that show continuous oscillations of finite magnitude (ac voltages and currents, for example) or by constants, or both. In practice, engineers familiar with stability studies expect that oscillations of machine rotors should be damped to an acceptable level within 6 s following a major disturbance. It is important to realize that a system that is stable by definition can still have stability problems from an operational point of view (oscillations may take too long to decay to zero, for example).

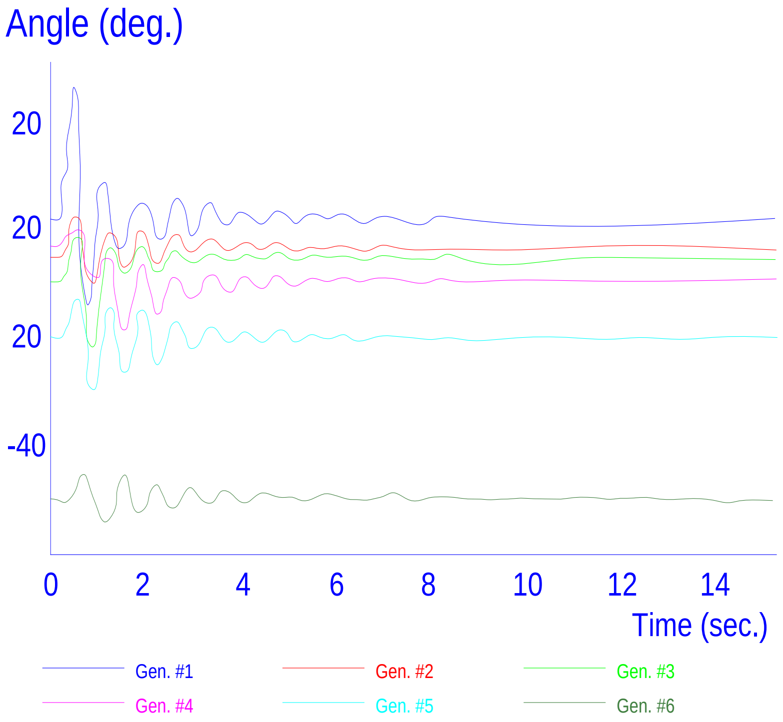

Figure 1—System response – No co-gen plant

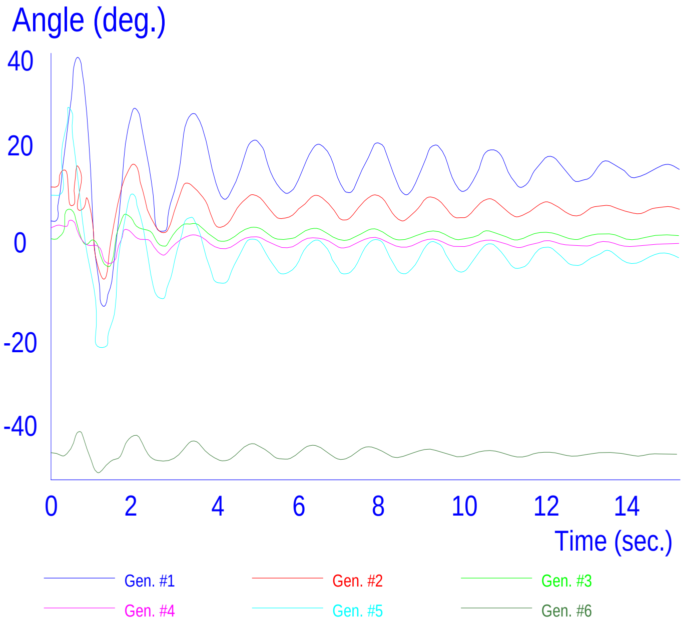

Figure 2—Low-frequency oscillation after the connection of the co-gen plant

Steady-state Stability

Although the discussion in the rest of this course revolves around stability under transient and/or dynamic conditions, such as faults, switching operations, etc., there should also be awareness that a power system can become unstable under steady-state conditions. The simplest power system, to which stability considerations apply, consists of a pair of synchronous machines; one acting as a generator and the other acting as a motor, connected together through a reactance (see Figure 3). (In this model, the reactance is the sum of the transient reactance of the two machines and the reactance of the connecting circuit. Losses in the machines and the resistance of the line are neglected for simplicity.)

If the internal voltages of the two machines are E_G and E_M and the phase angle between them is θ, it can easily be demonstrated that the real power transmitted from the generator to the motor is:

$$P = \frac{E_G E_M}{X} \sin \theta$$

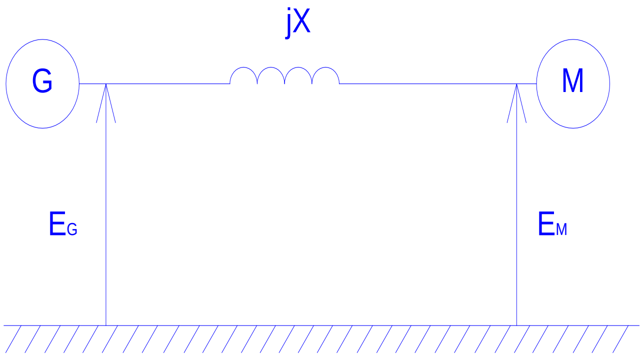

Figure 3—Simplified two-machine power system

The maximum value of P obviously occurs when θ = 90°. Thus

$$P_{max} = \frac{E_G E_M}{X}$$

This is the steady-state stability limit for the simplified two-machine system. Any attempt to transmit more power than $P_{\max}$ will cause the two machines to pull out of step (loose synchronism with each other) for particular values of internal voltages.
This simple example shows that at least three electrical characteristics of a power system affect stability. They are as follows:

- Internal voltage of the generator(s)
- Reactance(s) of the machines and transmission system
- Internal voltage of the motor(s), if any

The higher the internal voltages and the lower the system and machine reactances, the greater the power that can be transmitted under steady-state conditions.

Transient and Dynamic Stability

The preceding look at steady-state stability serves as a background for an examination of the more complicated problem of transient stability. This is true because the same three electrical characteristics that determine steady-state stability limits affect transient stability. However, a system that is stable under steady-state conditions is not necessarily stable when subjected to a transient disturbance.

Transient stability means the ability of a power system to experience a sudden change in generation, load, or system characteristics without a prolonged loss of synchronism. To see how a disturbance affects a synchronous machine, consider the steady-state characteristics described by the steady-state torque equation first.

$$T = \frac{\pi P^2}{8} \varphi_{SR} F_R \sin \delta_R$$

where
T is the mechanical shaft torque
P is the number of poles of machine
φ_{SR} is the air-gap flux
F_R is the rotor field MMF
δ_R is the mechanical angle between rotor and stator field lobes

The air-gap flux φ_{SR} stays constant as long as the internal voltage (which is directly related to field excitation) at the machine does not change and if the effects of saturation of the iron are neglected. Therefore, if the field excitation remains unchanged, a change in shaft torque T will cause a corresponding change in rotor angle δ_R. (This is the angle by which, for a motor, the peaks of the rotating stator field lead the corresponding peaks of the rotor field. For a generator, the relation is reversed.) Figure 4 graphically illustrates the variation of rotor angle with shaft torque. With the machine operating as a motor (when rotor angle and torque are positive), torque increases with rotor angle until δ_R reaches 90 electrical degrees. Beyond 90°, torque decreases with increasing rotor angle. As a result, if the required torque output of a synchronous motor is increased beyond the level corresponding to 90° rotor angle, it will *slip a pole*. Unless the load torque is reduced below the 90° level (the pullout torque), the motor will continue slipping poles indefinitely and is said to have lost synchronism with the supply system (and become unstable).

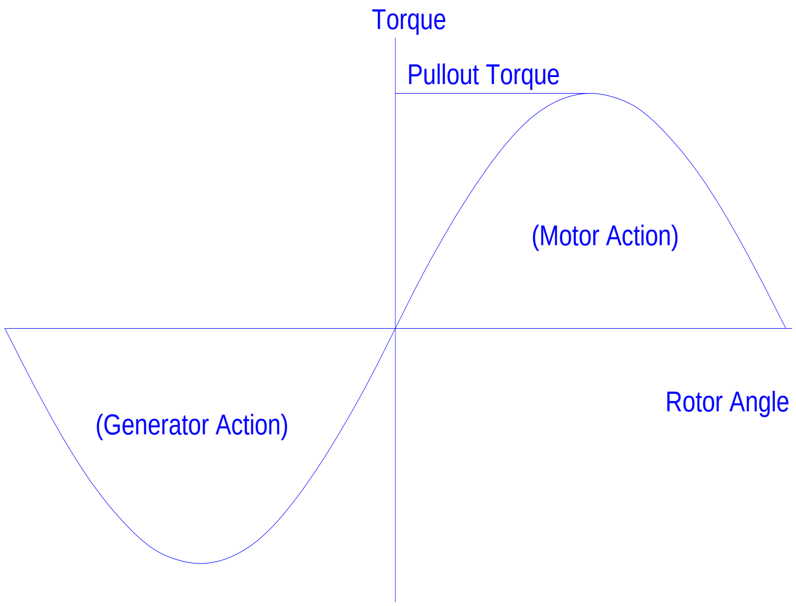

Figure 3—Torque vs. rotor angle relationship for synchronous machines in steady state

A generator operates similarly. Increasing torque input until the rotor angle exceeds 90° results in pole slipping and loss of synchronism with the power system, assuming constant electrical load.

Similar relations apply to the other parameters of the torque equation. For example, air-gap flux φ_{SR} is a function of voltage at the machine. Thus, if the other factors remain constant, a change in system voltage will cause a change in rotor angle. Likewise, changing the field excitation will cause a change in rotor angle if constant torque and voltage are maintained.

The preceding discussion refers to rather gradual changes in the conditions affecting the torque angle, so that approximate steady-state conditions always exist. The coupling between the stator and rotor fields of a synchronous machine, however, is somewhat elastic. This means that if an abrupt rather than a gradual change occurs in one or more of the parameters of the torque equation, the rotor angle will tend to overshoot the final value determined by the changed conditions. This disturbance can be severe enough to carry the ultimate steady-state rotor angle past 90° or the transient swing rotor angle past 180°. Either event results in the slipping of a pole. If the conditions that caused the original disturbance are not corrected, the machine will then continue to slip poles; in short, pulling out of step or loosing synchronism with the power system to which it is connected.

Of course, if the transient overshoot of the rotor angle does not exceed 180°, or if the disturbance causing the rotor swing is promptly removed, the machine may remain in synchronism with the system. The rotor angle then oscillates in decreasing swings until it settles to its final value (less than 90°). The oscillations are damped by electrical load and mechanical and electrical losses in the machine and system, especially in the damper windings of the machine.

A change in rotor angle of a machine requires a change in speed of the rotor. For example, if we assume that the stator field frequency is constant, it is necessary to at least momentarily slow down the rotor of a synchronous motor to permit the rotor field to fall farther behind the stator field and thus increases δ_R. The rate at which rotor speed can change is determined by the moment of inertia of the rotor plus whatever is mechanically coupled to it (prime mover, load, reduction gears, etc.).With all other variables equal, this means a machine with high inertia is less likely to become unstable given a disturbance of brief duration than a low-inertia machine. Traditionally, transient stability is determined by considering only the inherent mechanical and electromagnetic characteristics of the synchronous machines and the impedance of the circuits connecting them. The responses of the excitation or governor systems to the changes in generator speed or electrical output induced by a system disturbance are neglected. On the other hand, *dynamic* stability takes automatic voltage regulator and governor system responses into account. The traditional definition of transient stability is closely tied to the ability of a system to remain in synchronism for a disturbance. Transient stability studies are usually conducted under the assumptions that excitation and governor-prime mover time constants are much longer than the duration of the instability-inducing disturbance.

However, technological advances have rendered the assumption underlying these conventional concepts of transient stability obsolete in most cases. These include the advent of fast electronic excitation systems and governors, the recognition of the value of stability analysis for investigating conditions of widely varying severity and duration, and the virtual elimination of computational power as a constraint on system modelling complexity. Most transient stability studies performed today consider at least the generator excitation system, and are therefore actually dynamic studies under the conventional conceptual definition.

Two-machine Systems

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