Appendix J

A New Look at Damping Control

This appendix relates to Chapter 7, §7.5, and more generally to fundamental concepts of damping by mechanical-side torques versus electrical-side torques.

Considerable effort has been spent over the years addressing the problem of power system oscillations. The initial attempt to control oscillations was the use of damper windings in the machine rotors. This was followed by the use of supplementary control in the excitation system, which became known as the power system stabilizer (PSS). The application of the PSS was developed and refined over a period of more than thirty years. The stabilizer parameter values were initially obtained through system linearization and applying the concepts of damping torque and/or eigenvalue shift and using lead-lag compensation methods. This was followed by proposal for use of optimal control theory and parameter optimization techniques in which the control law was derived to minimize a performance index or objective function.

To overcome the shortcomings of applying linear systems theory to the highly nonlinear power systems, adaptive control algorithms such as self-tuning regulators and adaptive optimal control were developed in the 1980s. More recently, stabilizer design using artificial neural networks and fuzzy logic controls have been reported in the literature. The above list is not all-inclusive.

In the past few years the use of equipment such as SVC and other FACTS devices that exploit the recent advancement in power electronics have been considered as an alternative or supplement to the PSS. A variety of controllers have been developed for this purpose, using both linear and non-linear control theory.

While each of these novel applications of PSS or FACTS devices shows impressive performance improvement in a single machine-infinite bus system and occasionally in somewhat more complex three or four machine systems, there is hardly any performance improvement in studies of large practical-sized power systems compared to that obtainable from a properly tuned conventional PSS. In many situations there is even performance degradation through adverse interactions between controls.

Following a major disturbance the immediate problem is to prevent loss of synchronism (maintain the first swing stability). If the system does not have the inherent capability to maintain synchronism, stability aids such as high performance excitation system, autoreclosing, fast valving, braking resistor, etc. are available. To this list can be added series capacitor switching and phase shifter operation. The effectiveness of these devices in maintaining first swing stability is well documented and is not in dispute.

Theoretical possibilities of damping control using FACTS devices. It may be worthwhile, however, to make a fundamental assessment of the theoretical possibilities of damping control using some of the newer devices. To clarify concepts the simplest possible system is used. The simple illustrations will also point to the potential problems in multi-machine applications.

Consider a single machine-infinite bus system. Following a disturbance and its subsequent clearing, if the machine does not lose synchronism in the first swing, it will go into oscillation against the infinite bus. This is depicted in Figure J-1, assuming the simplest machine representation and constant input power. The rotor will oscillate between points A and B on the power-angle curve, and, in the absence of damping the oscillation will continue. Damping will gradually reduce the oscillation amplitude, eventually bringing the rotor to the equilibrium point O. During the oscillation the rotor speed comes to zero at points A and B, but oscillation continues because of the accelerating and decelerating forces. By suitably modifying the network at the right instants, point A or B can be made to coincide with O, without the benefit of the system's inherent damping. Theoretically, this can be achieved almost instantly as illustrated in Figures J-2–J-4.

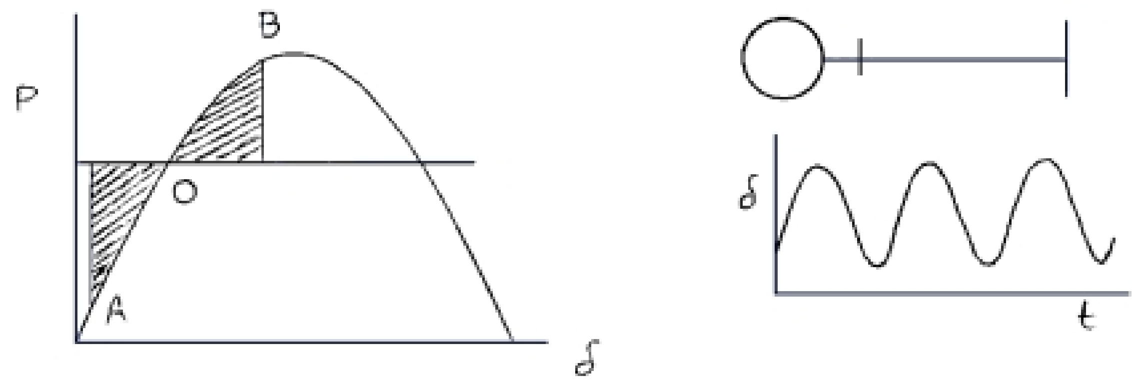

Fig. J-1. Power-angle curve of one machine system illustrating sustained oscillation.

In Figure J-2 series capacitor switching is employed. In this idealized analysis we assume that sufficient capacitive reactance is available for switching in or out to satisfy the equal-area criterion as depicted in the figure. The series capacitor is switched out when the rotor is at B. The operating point moves to C and follows the lower power-angle curve. At point D, the capacitor is switched back in. The operating point moves to the equilibrium point O. The resulting swing curve will look somewhat like that shown in the figure. Note that the same effect can be obtained by switching in series capacitor when the rotor is at point A (Figure J-1) and then switching back out at the appropriate moment.

If the value of the capacitive reactance is not selectable but fixed, the switching instants can be adjusted to obtain similar performance. If the available capacitive reactance is too small, significant performance improvement is still possible through multiple switching, although the response will not be as spectacular as shown on the figure. In this simple system, following a disturbance and its subsequent clearing, it's possible, by appropriate series capacitor switching (as well as by phase shifter operation as discussed below), to steer the system from pre-disturbance equilibrium to the post-disturbance equilibrium without any oscillation whatsoever.

Since a SVC (or a switched shunt capacitor) can effectively modify the power-angle curve similarly to the way shown in Figure J-2, it could duplicate the action of the series capacitor as illustrated.

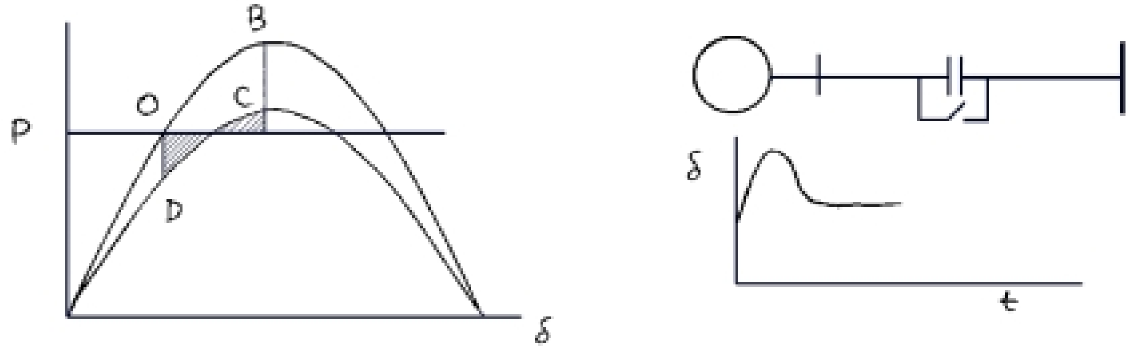

Fig. J-2. Illustration of damping by series capacitor switching.

Figure J-3 shows similar performance improvement through the action of a phase shifter. At point B an appropriate amount of negative phase shift is applied to bring the operating point to C. At point D the original phase shift is restored. The response curve would be as shown.

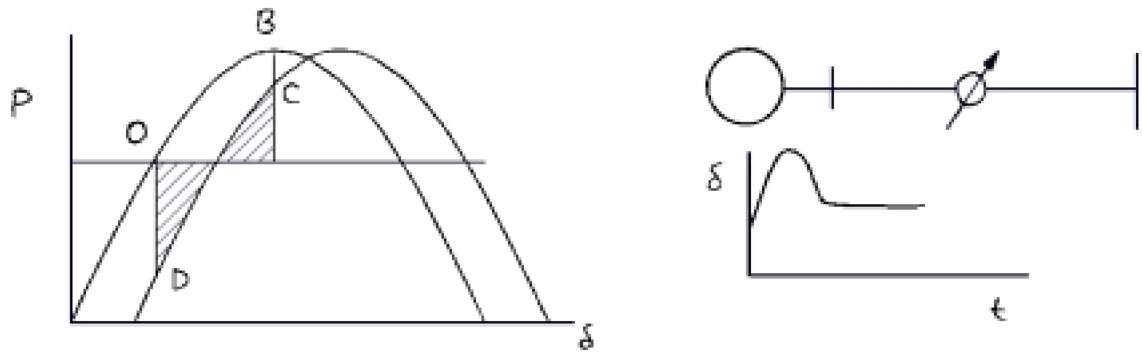

Fig. J-3. Illustration of damping by phase shifter action.

Figure J-4 shows the performance improvement obtainable by load switching. Note that switching out and switching in of load at the location shown in Figure J-4 are equivalent to increasing and decreasing the mechanical input power, respectively, represented by shifting the input line. In the illustration load is switched out when the operating point is at B and switched back in when the operating point moves to O. The response curve would be as shown in the figure.

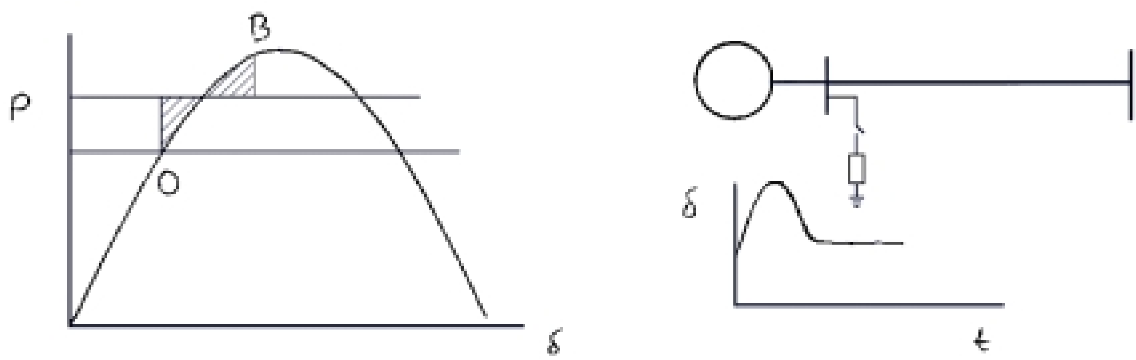

Fig. J-4. Illustration of damping by load switching.

In the above illustrations the controls were applied in a bang-bang mode. The control can also be in a continuous mode. In the continuous mode of control the power-angle curve can be envisioned to change continuously instead of in steps and the same mechanism will work in providing damping. For this simple system the control law can be easily obtained by applying results from control theory. Also, the technology for implementation of the control either in bang-bang or in continuous mode is available. The simple illustration was chosen to demonstrate that no mathematical analysis is needed for a basic understanding of the damping control possibilities of the various FACTS devices when applied to a simple system. This is, however, academic because, as argued in what follows, this level of damping is not generally obtainable in a real life power system.

Limitations of conventional damping control. Going back to the illustrations of Figures J-2–J-4, the best times for switching are when the angle is at one of the extreme points on the power-angle curve and is about to change direction. For example, using switched capacitor the best time to switch in is when the angle is at the lowest point during the swing and is about to start to increase (the accelerating power is at a maximum). The switching in will remain very effective for a short time beyond this point. The effectiveness, however, falls off thereafter. The switching back to the original state also needs careful timing. Similarly, the best time to switch out is when the angle is at the highest point and for a short time thereafter. The control effectiveness falls off rapidly as the switching policies deviate from those described, becoming detrimental (i.e., turning a stable system unstable) as the deviation increases beyond some point. (This is analogous to the damping torque concepts in the continuous mode of control—a torque component in phase with speed provides positive damping, the damping effect decreasing as the torque falls out of phase with speed, becoming zero at 90°, and negative thereafter.) The extreme case is when the switching sequence is reversed. This has important implication in large system applications.

In a large power system, following a disturbance the machines do not oscillate in phase or with the same time period. Even when they divide into coherent groups, considerable phase difference exists among machines within a group. In the damping control using the devices and techniques described above it's clear that while the application of the device is beneficial to a group of machines, it's bound to be neutral or even detrimental to others. In some cases great benefit can be derived, such as when a single generator is transferring power over a transmission line to a large system and experiencing a stability problem independently of the system it's connected to, or when a tie-line oscillation is severely restricting power transfer. In general applications, however, the overall benefit may be quite modest.

If we define damping as the natural force that tends to restore the generator shaft from deviation from synchronous speed, there are really three sources from the standpoint of angle stability: the small inherent damping due to the turbine torque-speed characteristics and load-frequency characteristics, and the damping due to the induced currents in the amortisseur windings. The resulting damping acts like the familiar viscous damping, being proportional to the rotor speed deviation, and cumulative throughout the system.

A properly tuned PSS acts by canceling the negative damping, if any, produced by the excitation system and providing damping through the same mechanism as the network modification devices as describe above. Instead of modifying the network it modulates the excitation in response to rotor speed change or some other signal to produce a change in the electrical output in phase with speed. It does so partly through direct modulation of real power output and partly through modulation of reactive power output that indirectly modulates real power output by modulating voltage-sensitive loads. Therefore, in damping interarea modes the effectiveness is heavily dependent on the location and type of load. Thus, while providing (positive) damping to a group of machines it is likely to contribute some negative damping to other machines because the machines in the system are not swinging in unison and because the location and type of load are constantly changing.

FACTS devices (as opposed to the specific controls used in the application of these devices) can improve the general health of a system by increasing synchronizing torques all around. However, this will only improve “transient stability” (the first or second swing stability). This may not solve the oscillation problem that is due to lack of sufficient positive damping or is due to negative damping that might be contributed by various controllers. For example, a generator connected to an infinite bus through a transmission line and operating at no load has no transient stability problem, since the overall accelerating power is always zero (fault or no fault in the system). This generator can, however, still be unstable due to negative damping that might be caused by the excitation control.

FACTS devices, such as SVCs, are very good at maintaining voltages (among other things). Maintaining voltages, however, will only increase system synchronizing torque, not the damping that the system might need. Damping is provided by introducing a torque in phase with speed. This torque can be either through mechanical input power modulation or through electrical output power modulation. Conventional PSS and FACTS controllers provide damping by modulating the output power. Note that a change in output power in one machine immediately affects the output power of other machines, especially if the load voltages are maintained by fast acting devices such as SVCs (electrical power output is always equal to load plus losses). Since during oscillations the machine speeds are not in phase, depending on the phase relationships, improving damping on one machine might mean degrading damping on another, even after careful control coordination.

There can be situations when this would be perfectly acceptable and desirable. For example, when it is impossible to operate a tie line connecting two major systems because of undamped or negatively damped oscillation, an effective solution may be found using a thyristor controlled series capacitor or a phase shifter. The control signal might be derived from the rate of change of angle or some other quantity. The resulting degradation of damping in the rest of the system might be negligible compared to the overall performance improvement.

Better damping control through modulation of generator mechanical input. From the above discussion it should be evident that a non-interacting damping controller would have to be based on the control (direct or indirect) of generator input power. Indirect control of generator mechanical input can be obtained through input/output control of energy storage devices such as superconducting magnetic energy storage or battery energy storage devices, placed close to generating plants. When an energy storage device is placed close to a generator, modulation of its output will be effectively equivalent to modulating the generator mechanical input. Therefore, with proper phasing it should provide interaction-free damping. The damping mechanism would be as illustrated in Fig.4 where damping is through effective shifting of the input line. When placed at other locations, however, these will be no more effective than the conventional stabilizers. In order for a damping controller to be effective and not have adverse interactions with other controllers, it would have to rely on modulating the machine input (which is also the mechanism of damping due to amortisseur windings), as opposed to modulating the power output (which is the mechanism of damping due to PSS and FACTS devices).

The above contention is also supported by energy consideration. In a two-machine system when a disturbance occurs, one machine gains kinetic energy while the other loses an equal amount. As there is no net gain or loss of energy it is possible to quickly restore equilibrium by redistributing the energy by simple changes in the network. In a single machine-infinite bus system the infinite bus can be made to absorb the excess energy to restore equilibrium quickly. In a multi-machine system much of the load is not inertial load, and as such the energy intake that was momentarily interrupted or curtailed during the disturbance is not demanded back. There is, therefore, a net gain in energy in the system. As there is no infinite bus, the only way to quickly restore equilibrium is to absorb this extra energy by some other means.

Note that simple load switching will not be a very effective damping device because of its inability to absorb excess energy. Although load consumes energy when switched on, for the purpose of damping control the first switching action will always be “switching off,” following which “on” and “off” will alternate according to the control logic. The load that is already “off” cannot be turned on for control purposes; the initial turning on of load is under the control of the consumer. It is not reasonable to have load on stand-by, that will be turned on only when needed for damping control (a few minutes a day!). Braking resistors can serve this purpose, but these are not normally considered “load.” Thus, normal load cannot be relied upon to absorb excess energy on demand.

Load switching can be effectively used to simulate generation of excess energy followed by reabsorption, in that order. In simple systems, where the interaction problem is minimal, this can achieve very effective damping as illustrated in Figure J-4. However, in complex systems it’s doubtful whether this would fare any better than a well-designed PSS or any of the FACTS controllers, both in terms of damping and interaction.

Field tests conducted on a turbo-generator with a state-of-the-art governor have shown that steam-turbine governors can respond fast enough to act as a damping controller. The concept can be extended to other steam-turbine governors. With a large power source it would be possible to damp the oscillations with even a small (5%) change of the generator mechanical input. Modulation of gas turbine generation may also be effective. These damping controllers would not only be simple to tune and very effective, but also eliminate all interaction problems.

It may be argued that conventional damping control (such as PSS and FACTS) can be designed for the entire system by simultaneously optimizing all the parameters in the system taking into consideration the interaction among the controllers using techniques such as genetic algorithms. This is nothing more than wishful thinking even in a moderately sized power system, however, because of the sheer number of control elements and the complex interaction with one another. At best, it's not likely to be much better than the current state-of-the-art.