Module-6

Subject: Flexible AC Transmission System (FACTS)

Content: Coordination of FACTS Controllers

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6.0 Introduction

Flexible ac transmission system (FACTS) controllers either extend the power transfer capability of existing transmission corridors or enhance the stability and security margins for given power-transmission limits. Fast controls associated with FACTS controllers do provide these system improvements, but they also can interact adversely with one another. In an interconnected power system, when the controller parameters of a dynamic device are tuned to obtain the best performance, the remaining power system is generally assumed to be passive or represented by slowly varying elements. This assumption is strictly not true; hence the adjusted parameters may not prove optimal when the dynamics of the various other controllers are, in effect, found in real systems.

This chapter presents different scenarios when various FACTS controllers interact unfavorably with one another. Linear-control techniques for coordinating the controls of different FACTS controllers are described, and nonlinear-control design methods that can be extended for the same purpose are described as well.

6.1 Controller Interactions

Controller interactions can occur in the following combinations:

1. Multiple FACTS controllers of a similar kind.
2. Multiple FACTS controllers of a dissimilar kind.
3. Multiple FACTS controllers and HVDC converter controllers.

Because of the many combinations that are possible, an urgent need arises for power systems to have the controls of their various dynamic devices coordinated. The term coordinated implies that the controllers have been tuned simultaneously to effect an overall positive improvement of the control scheme.

The frequency ranges of the different control interactions have been classified as follows

- 0 Hz for steady-state interactions
- 0–3□5 Hz for electromechanical oscillations
- 2–15 Hz for small-signal or control oscillations
- 10-□60 Hz for subsynchronous resonance (SSR) interactions
- <15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions

6.1.1 Steady-State Interactions

Steady-state interactions between different controllers (FACTS–FACTS or FACTS–HVDC) occur between their system-related controls. They are steady state in nature and do not involve any controller dynamics. These interactions are related to issues such as the stability limits of steady-state voltage and steady-state power; included are evaluations of the adequacy of reactive-power support at buses, system strength, and so on. An example of such control coordination may be that which occurs between the steady-state voltage control of FACTS equipment and the HVDC supplementary control for ac voltage regulation. Load-flow and stability programs with appropriate models of FACTS equipment and HVDC links are generally employed to investigate the foregoing control interactions. Steady-state indices, such as voltage-stability factors (VSF), are commonly used. Centralized controls and a combination of local and centralized controls of participating controllers are recommended for ensuring the desired coordinated performance.

6.1.2 Electromechanical-Oscillation Interactions

Electromechanical-oscillation interactions between FACTS controllers also involve synchronous generators, compensator machines, and associated power system stabilizer controls The oscillations include local mode oscillations, typically in the range of 0.8–2 Hz, and inter-area mode oscillations, typically in the range of 0.2–0.8 Hz. The local mode is contributed by synchronous generators in a plant or several generators located in close vicinity; the inter-area mode results from the power exchange between tightly coupled generators in two areas linked by weak transmission lines. Although FACTS controllers are used primarily for other objectives, such as voltage regulation, they can be used gainfully for the damping of electromechanical oscillations. In a coordinated operation of different FACTS controllers, the task of damping different electromechanical modes may be assumed by separate controllers. Alternatively, the FACTS controllers can act concertedly to damp the critical modes without any adverse interaction. Eigenvalue analysis programs are employed for determining the frequency and damping of sensitive modes.

6.1.3 Control or Small-Signal Oscillations

Control interactions between individual FACTS controllers and the network or between FACTS controllers and HVDC links may lead to the onset of oscillations in the range of 2–15 Hz (the range may even extend to 30 Hz). These oscillations are largely dependent on the network strength and the choice of FACTS controller parameters, and they are known to result from the interaction between voltage controllers of multiple SVCs, the resonance between series capacitors and shunt reactors in the frequency range of 4–15 Hz, and so forth. The emergence of these oscillations significantly influences the tuning of controller gains. Analysis of these relatively higher frequency oscillations is made possible by frequency-scanning programs, electromagnetic-transient programs (EMTPs), and physical simulators (analog or digital). Eigenvalue analysis programs with modeling capabilities extended to analyze higher-frequency modes as well may be used.

6.1.4 Subsynchronous Resonance (SSR) Interactions

Subsynchronous oscillations may be caused by the interaction between the generator torsional system and the series-compensated-transmission lines, the HVDC converter controls, the generator excitation controls, or even the SVCs. These oscillations, usually in the frequency range of 10–50/60 Hz, can potentially damage generator shafts. Subsynchronous damping controls have been designed for individual SVCs and HVDC links. In power systems with multiple FACTS controllers together with HVDC converters, a coordinated control can be more effective in curbing these torsional oscillations.

6.1.5 High-Frequency Interactions

High-frequency oscillations in excess of 15 Hz are caused by large nonlinear disturbances, such as the switching of capacitors, reactors, or transformers, for which reason they are classified as electromagnetic transients. Control coordination for obviating such interactions may be necessary if the FACTS and HVDC controllers are located within a distance of about three major buses. Instabilities of harmonics (those ranging from the 2nd to the 5th) are likely to occur in power systems because of the amplification of harmonics in FACTS controller loops. Harmonic instabilities may also occur from synchronization or voltage-measurement systems, transformer energization, or transformer saturation caused by geomagnetically induced currents (GICs). FACTS controllers need to be coordinated to minimize or negate such interactions.

6.2 The Frequency Response of FACTS Controllers

The composite-frequency response of a FACTS controller, together with its associated ac system, provides a good indication of the control-system stability, especially while an attempt is made to coordinate several FACTS or HVDC controllers.

A time domain–based frequency-scanning method (FSM) is used for obtaining the frequency responses of individual and coordinated FACTS controllers. A current source is used to inject a spectrum of frequencies at the FACTS controller bus. The local voltage developed at the bus is measured, and its harmonic content is evaluated through the use of Fourier analysis. The simulations are performed with an EMTP that has detailed models of FACTS controllers. To avoid the operation of any system component in its nonlinear region, the magnitudes of injected harmonic currents are chosen to be quite small, thereby ensuring linearized system behavior around the operating point. In HVDC converters, an injected-current magnitude is considered sufficiently small if it does not cause a firing-angle oscillation in excess of 0.58. Two frequencyresponse examples of FACTS controllers—one for the SVC, the other for the TCSC—are presented in the following text.

The Frequency Response of the SVC The study system considered is shown in Fig. 6.1. A 50 MVAR SVC is connected at the midpoint of the network that connects systems 1 and 2. The frequency response is obtained for two operating points. At the first operating point, the SVC maintains a bus voltage of 1.02 pu, with a firing angle α = 102° corresponding to a reactive-power absorption of 22.5 MVAR (inductive). Small-magnitude harmonic currents, Ih, are injected at discrete frequencies ranging from 5 to 45 Hz. The corresponding impedances are computed as the ratio of the developed voltage and the injected-harmonic disturbance current components. The impedance magnitude and angle-frequency responses are plotted in Figs. 6.2 and 6.3, respectively. The SVC presents a parallel resonance at 33 Hz and behaves inductively from 5 to 33 Hz, becoming capacitive at resonance and tending to resume inductive behavior as the frequency is increased beyond 33 Hz.

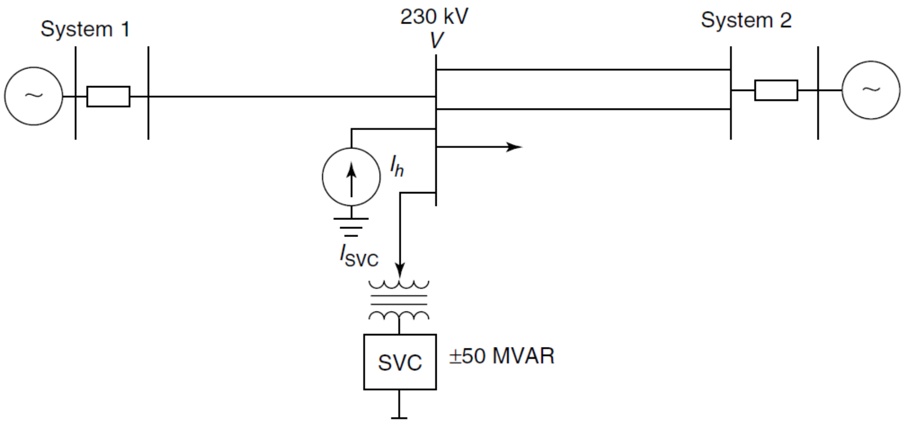

Figure 6.1 A study system for frequency scanning of the SVC.

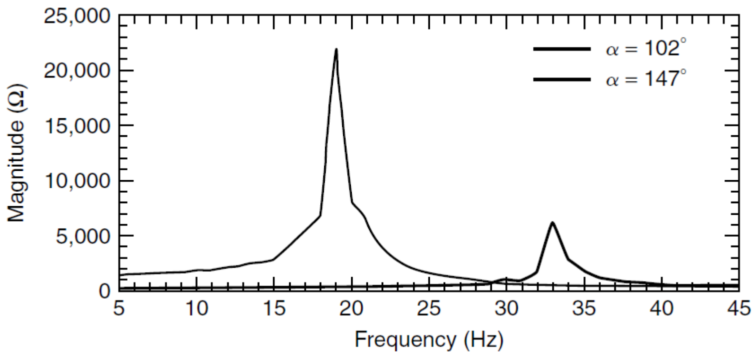

Figure 6.2 The impedance magnitude of the SVC frequency response.

The frequency response is obtained for the second steady state–operating point. The bus voltage is now regulated at 1.10 pu, with a thyristor firing angle α =147° corresponding to a reactive-power injection of 50 MVAR (capacitive). The corresponding magnitude and angle-frequency responses are, again, plotted in Figs. 6.2 and 6.3, respectively. It is seen that the resonant frequency modifies to 19 Hz and the impedance peak becomes three times that of the inductive SVC operation. The phase plot indicates that the higher the firing angle, the smaller the frequency range of inductive operation.

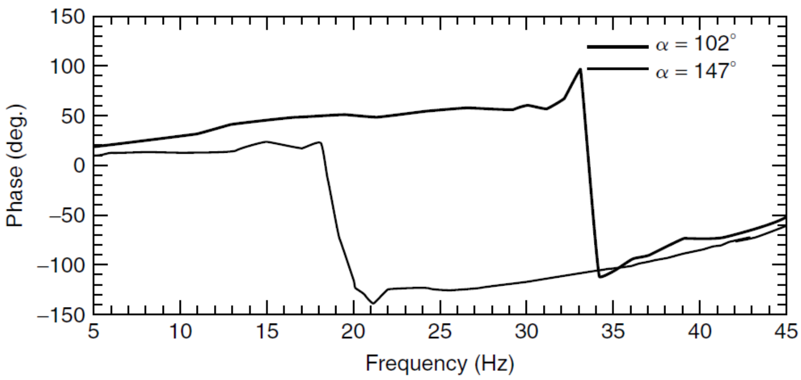

Figure 6.3 The impedance angle of the SVC frequency response.

6.3 SVC–SVC INTERACTION

A detailed case study of control interaction between multiple SVCs in a large power system is given. The interaction phenomena are investigated as functions of electrical distance (electrical coupling) between the SVCs and the short-circuit level at the SVC buses.

6.3.1 Uncoupled SVC Buses

A simplified test system shown in Fig. 6.4 is considered for the interaction analysis performed through eigenvalue analyses and root-loci plots. All the generating units are represented by infinite buses. If the transfer reactance between buses 1 and 2 is high, making the buses electrically uncoupled, then the SVCs connected to those buses do not interact adversely. Increasing the proportional gain of SVC 1 connected to bus 1, even to the extent of making the SVC unstable, does not affect the eigenvalues of SVC 2—implying that the controller designs of SVCs can be done independently for multiple SVCs in a power system if the transfer reactance between their connecting buses is high.

6.3.2 Coupled SVC Buses

If, however, the reactance between the two SVC buses is low, it constitutes a case of high electrical coupling between the SVCs. Here again, two possibilities exist with respect to short-circuit capacity of the region where the SVCs are installed: the SVC region with a high short circuit capacity and the SVC region with a low short-circuit capacity. For high short-circuit capacity conditions in the same system as Fig. 6.4, reveal that by increasing the proportional gain of one SVC, the eigen values of the other SVC are impacted very slightly. Almost no control interaction exists between the two SVCs irrespective of their electrical coupling, as long as they are in a high short-circuit-level region, that is, when the ac system is stiff. The reason for this condition is that the interlinking variable between the two SVCs is the bus voltage. Thus the controls of both SVCs can be independently designed and optimized, but if the short-circuit capacity of the SVC region is low, varying the proportional gain of SVC 1 will strongly influence the eigenvalues associated with SVC 2. It is therefore imperative that a coordinated control design be undertaken for both SVCs.

Despite simplifications in the study system and in the analysis approach, the aforementioned interaction results are general, for the phenomena investigated are independent of the number of buses, transmission lines, or generators.

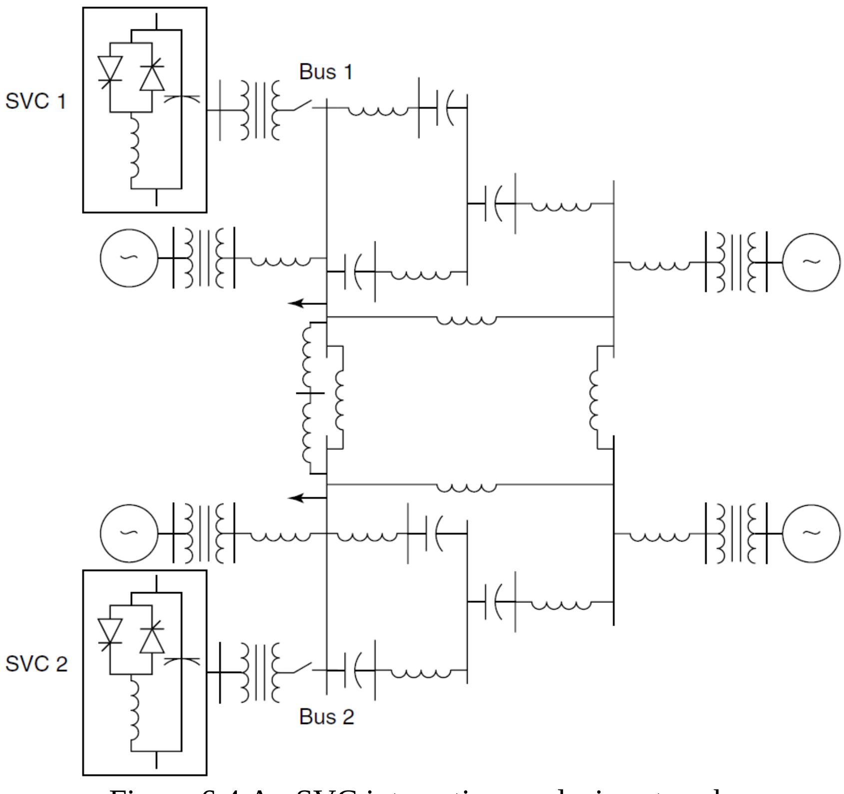

Figure 6.4 An SVC interaction-analysis network.

6.4 Coordination Of Multiple Controllers Using Linear-Control Techniques

The term coordination does not imply centralized control; rather, it implies the simultaneous tuning of the controllers to attain an effective, positive improvement of the overall control scheme. It is understood that each controller relies primarily on measurements of locally available quantities and acts independently on the local FACTS equipment.

The Basic Procedure for Controller Design

The controller-design procedure involves the following steps:

1. derivation of the system model;
2. enumeration of the system-performance specifications;
3. selection of the measurement and control signals;
4. coordination of the controller design; and
5. validation of the design and performance evaluation.

Derivation of the System Model First, a reduced-order nonlinearsystem model must be derived for the original power system. This model should retain the essential steady-state and dynamic characteristics of the power system. Then, the model is linearized around an operating point to make it amenable to the application of linear-control design techniques. If a controller must be designed for damping electromechanical oscillations, a further reducedlinear model is selected that exhibits the same modal characteristics over the relevant narrow range of frequencies as the original system. In situations where linearized-system models may not be easily obtainable, identification techniques are employed to derive simple linear models from time-response information.

6.4.1 Enumeration of the System-Performance Specifications

The damping controller is expected to satisfy the following criteria.

1. It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor is usually specified in terms of bus-voltage levels that should not be violated after a disturbance.
2. A minimum level of damping must be ensured in the steady state after a disturbance.
3. Potentially deleterious interactions with other installed controls should be avoided or minimized.
4. Desired objectives over a wide range of system-operating conditions should be met (i.e., it should be robust).

6.4.2 Selection of the Measurement and Control Signals

The choice of appropriate measurement and control signals is crucial to controller design.
The signals must have high observability and controllability of the relevant modes to be damped, and furthermore, the signals should only minimally affect the other system modes. The selection of these signals is usually based on system-modal magnitudes, shapes, and sensitivties—all of which can be obtained from small-signal-stability analysis.

Controller Design and Coordination the FACTS controller structures are usually chosen from industry practice. Typically, the controller transfer function, Hj(s), of controller j is assumed to be

$$H_j(s) = k_j G_j(s) = k_j \frac{sT_W}{1+sT_W}\left(\frac{1+s\tau_1}{1+s\tau_2}\right)^p \frac{1}{(1+sT_1)(1+sT_2)\cdots(1+sT_n)} \tag{6.1}$$

This transfer function consists of a gain, a washout stage, and a pth-order leadlag block, as well as low-pass filters. Alternatively, it can be expressed as

$$H_j(s) = k_j G_j(s) = k_j \left[k_0 \frac{(s+\cdots+b_m s^m)}{1+a_1 s+\cdots+a_n s^n}\right], \qquad m \le n \tag{6.2}$$

Although the basic structure of different controllers is assumed as from the preceding text, the coordination of controllers involves the simultaneous selection of gains and time constants through different techniques. Doing so permits the system-operating constraints and damping criteria to be satisfied over a wide range of operating conditions.

The coordination techniques may use linearized models of the power system and other embedded equipments, capitalizing on the existing sparsity in system representation. This model may be further reduced by eliminating certain algebraic variables yet still retaining the essential system behavior in the frequency range of interest.

Eigenvalue analysis–based controller-optimization and -coordination techniques are applicable to power systems typically with a thousand states— occurring when full modal analysis must be performed. However, sometimes a limited number of electromechanical modes must be damped; hence the eigenvalue analysis of a selected region can be performed even for relatively larger power systems.

In the case of large systems, procedures are employed that automate the tuning and coordination of controllers.

6.4.3 Validation of the Design and Performance Evaluation

Even though the controller design is performed on the simplified system model, the performance of the controller must still be established by using the most detailed system model. The controller should meet the specifications over a wide range of operating conditions and consider all credible contingencies. This validation is generally performed with nonlinear time-domain simulations of the system.

6.4.4 Controller Coordination for Damping Enhancement

This technique for the coordination of controllers to improve the damping of electromechanical modes is based on the damping-torque contribution of each FACTS controller, as well as that of any other controller present in the system—PSS, HVDC, and so on. The damping-torque contribution of a controller is related to the left shift that it introduces in the relevant electromechanical mode.

The relative effectiveness of each controller can thus be measured in terms of the attained left-shift magnitude in the relevant mode for a given change in the controller-transfer function gain after the interaction between the controllers has been accounted for. This study results in a controller-damping contribution diagram, illustrating the damping contribution of each controller. It is also possible to infer from this study which individual supplementary-feedback signal or combination of signals is most effective for a controller in augmenting the mode damping. Furthermore, the adverse effects of a controller on any mode other than the electromechanical one for which it was designed to damp are determined from this study as well.

Certain assumptions are made in the use of this technique:

1. All controllers in the system, including FACTS, have the transfer function of the type kjGj(s), as given in Eq. (6.1).
2. The component Gj(s) in the transfer function is responsible for causing the left shift in the electromechanical mode.
3. The gain kj in the transfer function decides the magnitude of left shift in the mode of interest.

The controller interactions can then be examined with respect to changes in the controller gains, and the exercise of coordinating the controllers is simplified to that of coordinating the gains kj of different controllers. Some constraints, however, are imposed in selecting the gains on individual controllers. The gains of the damping control loop in a FACTS controller must be reasonably low to not interfere with the main control loop of the controller. It may be recalled that the primary reason why FACTS controllers are installed may not be for damping enhancement in all cases.

The gains on the different PSSs, too, should be kept relatively small to minimize the following:

- the operating-limit influence in the stabilizer, the automatic voltage regulator (AVR), and the excitation systems.
- the reactive-power oscillations in generators for small contingencies.

The damping-enhancement controller-coordination technique provides useful insight and is simple to implement. It can be applied manually to power systems where the number of controllers to be coordinated (including FACTS) is small and/or the number of electromechanical modes to be damped is low. However, the manual process can be highly time-consuming and susceptible to errors when

1. the total controllers to be coordinated is substantial, and
2. the coordination of controllers must satisfy a wide range of performance specifications to ensure robustness.

A need then arises for using automated techniques for controller coordination. The control-coordination technique described here is automated by formulating it as a linear-programming problem. A weighted sum of gains k_j of all controllers is minimized and is subject to the following constraints:

1. The left shift of all electromechanical modes is greater than or equal to the specified desired values.
2. The change in various mode frequencies is less than certain limits. Because the controllers may be unable to impart pure damping—and also because of the controllers' interactions—the modal frequencies can become changed, possibly causing a deterioration of the synchronizing torque, which must be restricted. If large mode-frequency changes are unavoidable, the various parameters of controller $G_j(s)$ must be adjusted.
3. The magnitude of gains associated with the coordinated controllers should be less than specified values.

6.4.5 Linear Quadratic Regulator (LQR)–Based Technique

The LQR technique is one of optimal control that can be used to coordinate the controllers with the overall objective of damping low-frequency inter-area modes during highly stressed power-system operations. The system model is first linearized and later reduced to retain the modal features of the main system over the frequency range of interest. The control-system specifications are laid out as described previously. Appropriate measurement and control signals are selected, based on observability and controllability considerations, to have only a minimal interaction with other system modes. Using a projective-controls approach, the control-coordination method involves formulating an LQR problem to determine a full-state-feedback controller in which a quadratic performance index is minimized. An output-feedback controller is then obtained, based on the reduced eigen space of the full-state solution. The dominant modes of the full-state-feedback system are retained in the closed-loop system with output feedback. The order of the controller and the number of independent measurements influence the number of modes to be retained. The output-feedback solution results in the desired coordinated control.

The performance of coordinated controls is later tested and evaluated through time-domain simulation of the most detailed model of the nonlinear system.

6.4.6 Constrained Optimization

Constrained-optimization techniques for control coordination use control structures generally used in industry, but they may or may not use robustness criteria explicitly in the design process. In such a case controller robustness must be verified separate from the design process.

Techniques Without Explicit Robustness Criteria Pole placement is one technique in which the robustness requirement is not explicitly considered. In this method, the critical electromechanical modes are assigned a priori new locations that are placed deeper into the left half of the s plane. The controller parameters are then selected to result in these assigned pole locations. Let us consider that the jth controller is to be tuned. The characteristic equation for the closed-loop system can be expressed as

$$1 - F(s)G_j(s) = 0 \tag{6.3}$$

where F(s)=the transfer function between output yi and input ui as obtained from the state-space model of the linearized power system
Gj(s)=the transfer function of the FACTS damping controller

Let the critical mode, which is also a pole of the closed-loop system, be assigned a location l. If Gj(λ) is expressed as e + j f, then

$$e + jf = \frac{1}{F(\lambda)} \tag{6.4}$$

The parameters of the controller structure are then obtained by comparison ith Eq. (6.4). This procedure is applied sequentially to all the controllers to e tuned, thus completing one iteration. At each step, the tuning process of a ontroller considers the interactions with other controllers. The iterative process s continued until convergence is achieved, which is indicated when the argest absolute difference between the assigned eigenvalues in any two iterations becomes less than the specified tolerance. This method can be applied easily to large systems, as the inherent sparsity in system matrices can be used to the advantage of such systems.

Techniques with Explicit Robustness Criteria In techniques that explicitly consider the robustness requirements, any changes in the system operating points caused by line switching, load variations, or contingencies are incorporated as changes in the matrix elements of the linearized systems. These matrix-element variations are called admissible uncertainties. The robust-control design relates to the determination of a state-feedback matrix that can maintain stability of the closed-loop system for any admissible uncertainty. This method is somewhat difficult to apply to large systems, as it relies totally on a linearized-system model.

6.5 Control Coordination Using Genetic Algorithms

Genetic algorithms are optimization techniques based on the laws of natural selection and natural genetics that recently have been applied to the control design of power systems. These techniques provide robust, decentralized control design and are not restricted by problems of nondifferentiability, nonlinearity, and nonconvexity, all of which are often limiting in optimization exercises.

Genetic-algorithm techniques use the linearized state-space model of the power system. The objective function is defined as the sum of the damping ratios of all the modes of interest. This sum is evaluated over several likely operating conditions to introduce robustness. A minimum damping level is specified for all the modes; the other constraints include limits on the gain and time constants of the damping controllers assumed to be from a fixed structure, as given in Eq. (6.1). The optimization problem is therefore stated as follows:

Maximize

$$F = \sum_{i=1}^{m} \left[\sum_{j=1}^{n} (\xi_i) \right] \qquad (6.5)$$

subject to the following constraints:

$$k_{j\ \min} \le k_j \le k_{j\ \max}$$
$$\tau_{1\ \min} \le \tau_1 \le \tau_{1\ \max}$$
$$\tau_{2\ \min} \le \tau_2 \le \tau_{2\ \max}$$
$$\xi_{\min} \le (\xi_j)_i$$

This maximization yields the gain kj and the time constants t_1, t_2 for all the controllers for a prespecified order p of the lead-lag blocks. The time constant TW of the washout filter is assumed to be adequately large and known a priori. Likewise, the time constants T_1, T_2□□. . . □□T_n of the low-pass filters are selected beforehand.

The foregoing optimization problem involves a computation of eigenvalues of a large system matrix, which is usually difficult to solve with conventional techniques. An advantage of genetic-algorithm techniques is that the parameter limits can be varied during the optimization, making the techniques computationally efficient. Use of high-performance computation (parallel processing) is recommended for reducing the computational time associated with the application of these techniques.

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