Decentralized adaptive control and system identification, with applications to power systems

by Daniel James Trudnowski

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering
Montana State University

Abstract:
This thesis addresses the problem of damping electromechanical oscillations in power systems using advanced control theory. Two control strategies are developed. Controllers are then applied to a power system as power system stabilizer (PSS) units. The primary strategy is a decentralized indirect adaptive control scheme where multiple self-tuning adaptive controllers are coordinated. This adaptive scheme is developed in a general format and the stabilizing properties are shown using a vector Lyapunov analysis. The second strategy is a new method of designing conventional nonadaptive PSS units. An off-line system identification method based on Prony signal analysis is developed. This Prony identification method and a root-locus technique are used to design the conventional PSS units. Both the adaptive and the conventional strategies are applied to a 17-machine computer-simulated power system. PSS units are applied to four generators in the system. Detailed simulation results are presented that show the feasibility and properties of both control schemes.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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NOMENCLATURE

C	Complex number
I^n	n x n identity matrix
$\Re$	Real number
$\Re^n$	n x 1 vector with real entries
$\Re^{nxm}$	n x m matrix with real entries
$\otimes$	Matrix tensor product
$\|x\|$	Euclidean norm of x

ABSTRACT

This thesis addresses the problem of damping electromechanical oscillations in power systems using advanced control theory. Two control strategies are developed. Controllers are then applied to a power system as power system stabilizer (PSS) units. The primary strategy is a decentralized indirect adaptive control scheme where multiple self-tuning adaptive controllers are coordinated. This adaptive scheme is developed in a general format and the stabilizing properties are shown using a vector Lyapunov analysis. The second strategy is a new method of designing conventional nonadaptive PSS units. An off-line system identification method based on Prony signal analysis is developed. This Prony identification method and a root-locus technique are used to design the conventional PSS units. Both the adaptive and the conventional strategies are applied to a 17-machine computer-simulated power system. PSS units are applied to four generators in the system. Detailed simulation results are presented that show the feasibility and properties of both control schemes.

CHAPTER 1

INTRODUCTION

Often in large power systems lightly-damped oscillations, termed electromechanical oscillations, occur due to generators exchanging energy through transmission lines. Many types of unavoidable system disturbances can cause electromechanical oscillations, and severe oscillations can decrease the life of generators and limit the amount of transferable power over transmission lines. Because a power system is a large nonlinear time-varying system, it is often difficult to dampen these oscillations. Conventional methods of damping electromechanical oscillations have proven to be effective in many cases. But, as smaller localized systems are interconnected over large distances, conventional methods of controller design often fail to add adequate damping. In this thesis modern control techniques are applied to this power system problem. The control techniques include adaptive and decentralized control which are very attractive solution methods to this problem. Special attention is paid to the implementation of multiple controllers located throughout the system.

The size and complexity of a power system makes it a candidate for decentralized control methods, while the nonlinear and time-varying properties make the system a candidate for adaptive control. The main objective of this thesis is to present a decentralized adaptive control strategy that may be applied to power systems to dampen electromechanical oscillations. With the strategy, multiple adaptive controllers are coordinated using a decentralized technique. A second objective is to present a nonadaptive design technique for power-system damping controllers. This nonadaptive technique is based on a new system identification method presented in this thesis.

In developing the damping controllers in this thesis, emphasis is placed on the practicality of being able to apply them to an actual system. The control schemes are designed so that the control action at a given control station has minimal dependence on variables which cannot be measured locally. In this way the control scheme will not be highly dependent on communication between different locations in the network. Nondependence on communication is important as the same factors that cause electromechanical oscillations can also cause communication failures.

Because power systems are often difficult to accurately model, it is desired that the design of the controllers have minimal dependence on computer simulation of the system. Although the control schemes in this thesis are demonstrated on a computer-simulated system, the controllers are developed with the idea of being able to apply them to an actual system without dependence on computer models or simulations.

The remaining material of this chapter is organized into five sections. A description of the problem being addressed is given in the first section. Adaptive and decentralized control concepts are introduced in the second and third sections. A literature review of recent published work is contained in section four. In the last section the organization of the remaining thesis is outlined.

Power System Electromechanical Oscillations

In a power system, turbines are used to rotate the rotors of large synchronous generators. The generators then convert this rotational energy into electrical energy. In order to connect several generators together to form a power system, the machines must rotate on average at the same constant speed. In modern systems this synchronous speed relates to the electrical frequency of 50 or 60 Hz. Because the rotor of a synchronous generator is a large rotating mass, it must obey the laws of nature. When a sudden disturbance occurs in the system, the circuit laws of Kirchhoff force the electrical power from a synchronous generator to suddenly change, while the mechanical power into the generator has not changed. This imbalance of power causes the rotor to suddenly accelerate or decelerate away from synchronous speed initiating the electromechanical oscillations. If the generator cannot return to synchronous speed, it is said to have separated from the system. As generator rotors accelerate and decelerate energy is oscillated through the system. Because of the laws of conservation of energy, this energy is absorbed by loads and by other generators which causes various generators to "swing against one another." Generators that swing against one another oscillate 180° out of phase.

Most often electromechanical oscillations occur in the 0.2 to 3.0 Hz range with these frequencies being a function of many variables including rotor inertias. These oscillations can be initiated by a variety of "sudden" disturbances in the system, such as a transmission line fault. An electromechanical oscillation in a power system is often termed a system swing. Significant system swings can be detrimental to the power system. If the oscillations are negatively damped, then the system will separate during a swing which can cause significant damage to utility and customer equipment. If system swings are only lightly damped, then a combination of disturbances may cause the system to swing past its steady-state limits which can also cause system separation. In any case, it is important to add significant damping to power-system electromechanical oscillations in order to preserve system integrity.

Electromechanical oscillations are often considered to be of two types: local and interarea. A local mode of oscillation occurs when a single generator swings against the system. These modes tend to be localized near the given generator and are generally in the 0.8 to 3.0 Hz range. Interarea modes occur when a group of generators swing together against other groups of machines. Because interarea modes involve multiple machines (which implies more mass), they tend to be at lower frequencies than local modes. The range of frequencies for interarea modes are generally between 0.2 Hz and 0.8 Hz. Usually, interarea modes occur between groups that are weakly connected and are often the most troublesome modes in large systems.

Recent advancement of technology in the power industry has caused electromechanical oscillations to become more prevalent in many systems (especially interarea modes) [1]. With smaller faster-reacting generators being developed, it takes less energy to force a given generator to swing. Also, many systems are being operated near their steady-state limits with larger amounts of power being transferred greater distances which tends to increase the electromechanical oscillation problem. In many cases, conventional controllers are unable to adequately dampen these oscillations, especially interarea modes. Therefore, there is a need for more effective solutions for adding damping to power systems.

Various devices have been proposed to dampen electromechanical oscillations including power system stabilizer (PSS) units, static volt-amp-reactive compensators (SVC's), and modulation of high-voltage DC (HVDC) converter systems. Of these, PSS units have received the majority of attention and have proven to be successful in some cases. PSS units are feedback circuits applied to the excitation system of a synchronous generator. SVC's are variable reactive devices that are primarily used for voltage support; although, they have proven to be effective as a damping device as well. Modulation of HVDC systems involves varying the converter firing angle about a nominal point in order to modulate the power flow on the DC line.

The control schemes in this thesis are presented in a general format so that they may be applied to many different types of systems. When applied to the power system for simulation results, the schemes are implemented using PSS units. PSS units are used because this is the most widely used damping device in the power industry. It is believed that if a new control technique (such as those proposed in this thesis) is used by the industry, it will first be tried on a PSS unit.

The operating point of a power system changes both seasonally and hourly as loads change. With each different operating point the dynamics of the system change. This time-varying nature of the system makes it difficult and sometimes impossible to design a conventional controller that will satisfactorily dampen oscillations at each operating point. Obtaining system models for controller design using the laws of physics is often very difficult because of the size and complexity of power systems. Both the adaptive and the nonadaptive control methods presented in this thesis are based on system identification methods that result in system models by analyzing signals from the actual system.

Adaptive Control

Adaptive control is an area of feedback control theory that has recently received a great deal of attention. Although there is no clear-cut definition of adaptive control, an adaptive controller may be viewed as a regulator that can modify its behavior according to changes in the dynamics of the process it is controlling [2]. Conventional adaptive controllers have a self-learning ability in that the designer does not have to know a great deal about the plant that is to be controlled. The adaptive controller "learns" about the plant by analyzing its input/output relationship. The controller adjusts its feedback parameters as it learns about the plant or as the plant changes.

The learning ability of adaptive control makes it very attractive for application to the power system problem. It is often extremely difficult to obtain an accurate mathematical model of a power system. This is because a power system is a nonlinear time-varying system of very large order; the time-varying properties of the system are both stochastic and nonstochastic.

Adaptive controllers are generally broken into two different types: direct and indirect [2]. With the direct adaptive controller, regulator parameters are directly changed as the dynamics of the system change. This is demonstrated in Figure 1. The closed-loop plant is forced to act like a model system; the regulator parameters are adjusted until the error e in Figure 1 is driven to zero. Direct adaptive control is often termed model-reference adaptive control (MRAC).

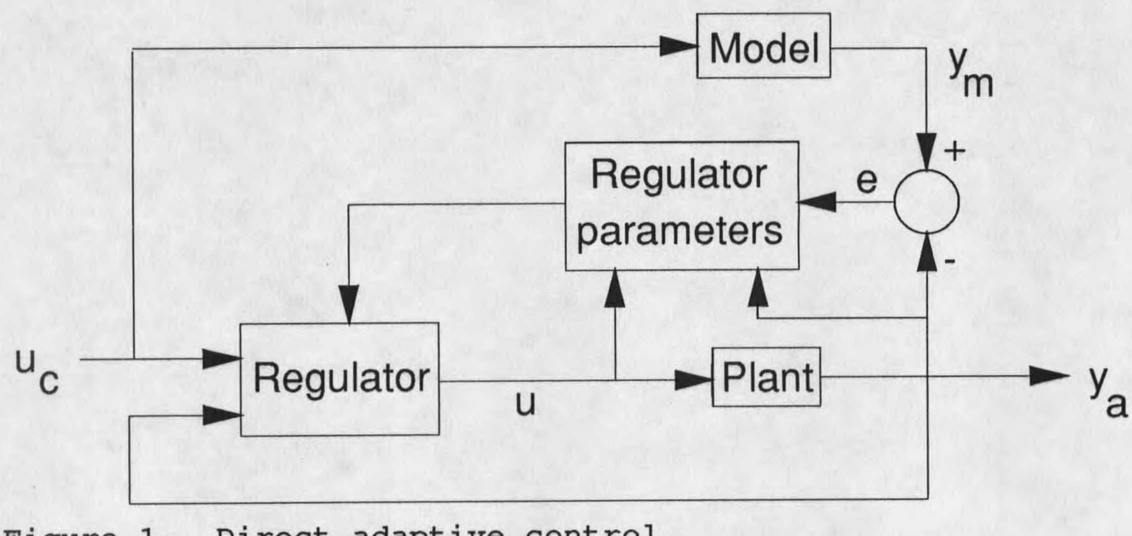

Figure 1. Direct adaptive control.

With an indirect adaptive controller the regulator parameters are indirectly updated; an indirect controller is shown in Figure 2. The controller's operation occurs in two distinct steps. First, the dynamics of the system are identified at a particular instant in time; then the regulator is adjusted according to the identified dynamics. The plant's input and output are passed to a recursive identifier which identifies a linear model of the plant. The linear model parameters are passed to a regulator design block. Here the regulator parameters are calculated and passed to the regulator. With a discrete-time adaptive controller, the whole process may be updated with each time sample. Indirect adaptive controllers are also termed self-tuning adaptive controllers.

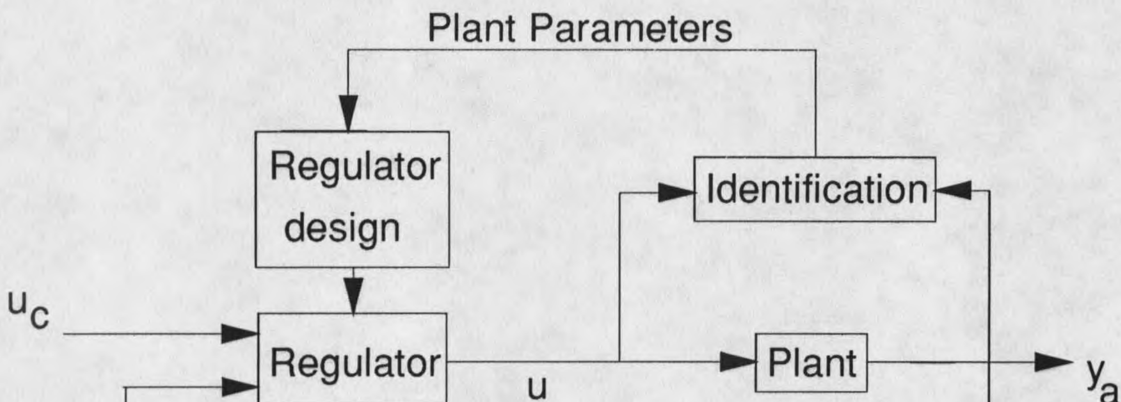

Figure 2. Indirect adaptive control.

A direct adaptive controller is not well suited for the power system problem because a reference model must be chosen for the closed-loop system. Since a power system is a time-varying plant, a reference model adequate at one point in time may not be adequate at other times. Also, it is difficult to obtain direct criteria for choosing a reference model. Therefore, the adaptive controller strategy presented in this thesis is an indirect type.

An important issue concerning an indirect adaptive controller is the choice of the regulator design algorithm. The objective of the controller is to dampen electromechanical oscillations as well as possible, given an allowable range of input. A pole-placement algorithm is ruled out as this requires a choice of closed-loop poles which can be difficult for a time-varying plant. A regulator based on a linear-quadratic (LQ) control law is a good candidate because it can be used to directly penalize swings in the system while at the same time limiting action in the controlled input. An LQ controller is easily placed in a recursive form using Riccati equations; this makes it easy to implement such a controller in an adaptive format. For these reasons the adaptive control strategy in this thesis is based on an LQ control law.

Decentralized Control

Many systems exist with multiple locations in the plant where input signals can be applied; these plants are often referred to as multiple control-station systems. Various options are available when considering the control of a multiple control-station system. For the power system problem it is desired that the control action at a given station have minimal dependence on variables which cannot be measured locally. In this way the control scheme will not be dependent on communication between different locations in the network. Nondependence on communication is important as the same factors that cause electromechanical oscillations can also cause communication failures. If communication is used, it is desired that the controllers still effectively operate when communication fails. This requirement points to a decentralized control solution.

With a decentralized scheme, controllers are applied at each control station with a central objective. The controller at a given station is designed to be primarily dependent on local measurable variables. Therefore, if communication of variables from outside sources fails, the controller can still properly operate. A second advantage of decentralized control strategies is that the failure of one controller has no detrimental effect on the performance of other controllers. There are two basic classes of decentralized control. The first class is often termed sequential control. For lack of a better term, the second class is referred to in this thesis as the nonsequential class.

With a sequential scheme the controller designs at the control stations are carried out sequentially one-by-one. Consider a plant consisting of m control stations. First a model of the system is obtained from the input to the output at station 1 while ignoring the inputs at other stations. A controller is designed for station 1 using this model, and the controller is applied to the plant. Then a model of the system is obtained from the input to the output at station 2, and the controller is designed and applied. The sequential process continues for all m control stations. If the objective of the controller at each station is the same, then this objective will be fulfilled in the end if certain observability and controllability conditions are satisfied. As an example, in [3] the objective for each controller design is to place the closed-loop poles in a certain specified region (Γ_s). Davison and Ozuguner [3] show that after the sequential design, all of the closed-loop poles are contained in Γ_s.

The sequential technique is not easily applicable to the case where the controller at each station is an adaptive one. This is because the sequential technique requires that when a given controller is designed, all previously designed controllers be fixed and applied to the system. An adaptive controller is constantly changing as the system changes; therefore, it would not be fixed when designing other controllers. Although the sequential method does not apply well to the adaptive case, it does apply well to the nonadaptive case where the controllers are fixed. A sequential method is used to implement multiple fixed damping controllers for a simulated power system later in this thesis.

Nonsequential decentralized controller design techniques assume the system is broken into a number of interconnected subsystems. With most designs, a local controller is designed for each subsystem while ignoring the subsystem interconnections. Then modifications are made to the designs to help negate any detrimental effect of the subsystem interconnections. Because the subsystem interconnections are ignored during the initial designs, the performance of the controllers are very robust to changes in subsystem interconnections. Also, since the designs of the controllers are independent, failure of one controller will have no detrimental effect on the performance of other controllers.

Characteristics of a nonsequential design are easily shown using the following example from [4]. Consider a system consisting of two subsystems. The state-space differential equations describing the system are

$$\dot{x}_1 = 5x_1 + (-3x_2) + u_1 \tag{1.1a}$$

$$\dot{x}_2 = 6x_2 + (-4x_1) + u_2 \tag{1.1b}$$

where u_1 is the input and x_1 is the output at subsystem 1; u_2 is the input and x_2 is the output at subsystem 2; and the terms in (•) are the subsystem interconnections.

First, let the control functions u_1 and u_2 be chosen in a centralized fashion by minimizing the standard LQ cost function

$$J = \int_0^\infty (x_1^2 + x_2^2 + u_1^2 + u_2^2)dt \tag{1.2}$$

In this case it is easy to show [5] that the optimal feedback functions are

$$u_1 = -10.49x_1 + 7.14x_2 \tag{1.3}$$
$$u_2 = 7.14x_1 - 11.18x_2$$

and the closed-loop eigenvalues are -8.9, -1.7. Now what happens if the subsystem interconnections are lost so that the plant becomes

$$\dot{x}_1 = 5x_1 + (-0x_2) + u_1 \tag{1.4a}$$

$$\dot{x}_2 = 6x_2 + (-0x_1) + u_2 \tag{1.4b}$$

The closed-loop system of the perturbed plant (1.4) and control law (1.3) is an unstable system with eigenvalues at -12.5 and 1.8. Therefore, the centralized control law of (1.3) is not robust to these changes in the subsystem interconnections.

Now, consider a nonsequential decentralized design for the system (1.1). The subsystem interconnections are ignored resulting in the two subsystems

$$\dot{x}_1 = 5x_1 + u_1 \qquad (1.5a)$$

$$\dot{x}_2 = 6x_2 + u_2 \qquad (1.5b)$$

and the cost function is broken into two functions:

$$J_1 = \int_0^\infty (x_1^2 + u_1^2)dt \qquad (1.6a)$$

$$J_2 = \int_0^\infty (x_2^2 + u_2^2)dt \qquad (1.6b)$$

A feedback function is found for subsystem 1 by obtaining the control law that minimizes (1.6a) for (1.5a); the same is done for subsystem 2. The resulting control laws are

$$u_1 = -10.10x_1, \quad u_2 = -12.05x_2 \qquad (1.7)$$

In order to negate the effects of the subsystem interconnections, the control laws of (1.7) are modified to

$$u_1 = -10.10x_1 + 3x_2 \qquad (1.8)$$
$$u_2 = -12.05x_2 + 4x_1$$

The closed-loop eigenvalues of the plant (1.1) and the control law (1.8) are -5.10 and -6.05. Again, consider the perturb plant (1.4), but now use the control law of (1.8). In this case the closed-loop eigenvalues are -2.1 and -9.1; therefore, the system is stable.

One does not have to modify the control law (1.7) to (1.8). The law (1.7) applied to the plants (1.1) and (1.4) also results in stable systems, and in this case the control functions at each subsystem are only a function of local variables. So why modify the feedback functions?

Modifying (1.7) to (1.8) negates any effect of the subsystem interconnections in the nominal plant case. The controllers were designed by ignoring the interconnections; therefore, modifying the control law to negate the interconnections results in the closed-loop system satisfying the design objective. For the above example, the design objective is to obtain the closed-loop system where the cost functions (1.6) are minimized for systems (1.5). Since the systems in (1.5) do not incorporate the interconnections, the control laws are modified to negate the effects of the interconnections.

The above example demonstrates that a nonsequential decentralized design can improve system robustness to perturbations in the interconnections. Decentralized controllers have other advantages. With a centralized controller, the control laws require communication between subsystems. For the above example u_i in (1.3) is a function of both x_1 and x_2. If communication fails between subsystems, then the control law is not valid and the results can be catastrophic. Any communication used with a decentralized control law is a modification to the original law. Therefore, if communication fails, the controllers still strives to fulfill the control objective. Another advantage of a decentralized design involves the failure of a given controller. If the control law at a subsystem fails for some reason, the remaining control actions at other subsystems still apply the proper input to the system. This is because the control law at each subsystem is designed separately from other controllers. In the centralized case all control laws are designed together; therefore, if one control law fails, all laws may fail.

It is possible to use a nonsequential design method when the controllers used at each subsystem are adaptive. With an indirect adaptive controller at a given subsystem the identifier has to obtain a model for that subsystem. The regulator design is based on that identified subsystem model. Modification could be done to account for the effects of the subsystem interconnections. This is the strategy used to develop the decentralized adaptive controller presented in Chapter 2. Adaptive controllers are applied at each station of a multistation system. The controllers are designed to control the subsystems connected to that station. Information that enhances the performance of the controllers is communicated between stations. The performance of the control scheme is improved using communication, but in many cases the controllers still properly operate if communication is lost because the design is based on a decentralized technique.

Literature Review

The purpose of this section is to review some of the literature relevant to issues addressed in this thesis.

Thousands of papers have been published in the areas of power system stability, adaptive control, and decentralized control. It would be very cumbersome to review all literature in these areas. Therefore, an attempt is made here to only review recent work that has direct relevance to the subjects contained in this thesis. The remainder of this section is organized into three parts with the following subjects reviewed: 1) conventional damping methods; 2) adaptive control in power systems; and 3) adaptive and decentralized control.

Conventional Damping Methods using PSS Units

The most widely used electromechanical damping device is the PSS unit. The heart of the conventional PSS unit consists of a low-pass wash-out filter and a series of lead-lag blocks. Filtering is used to remove any DC and high-frequency components from the feedback signal, and the lead-lag is used for the control compensation. Choosing the parameters for the PSS unit is termed "tuning." A classical set of papers on tuning PSS units by Larson and Swann is contained in [6]. Many of the concepts used in [6] were first introduced by de Mello and Concordia in [7]. The basic concept involves producing an electrical torque on the machine being controlled that is in phase with the speed error of the machine. Therefore, when the machine is speeding up, the electrical torque tends to slow the machine, and vice versa. Frequency response methods are used to obtain the PSS parameters that give the proper phase correction.

This classical design method has proven to work very well in many cases, and there have been many extensions of this method, e.g. see [8]-[12]. Detailed computer modeling and system eigenvalue analysis have been used in conjunction with frequency response methods (see [8]-[10] and [12]).

An alternative to obtaining an electrical torque component is to consider the machine as a general system with the input added to the exciter and the output being the chosen feedback signal. This is the approach taken by Bollinger and Chapin in [13]. In [13] a pseudo random signal is applied to the exciter in the open-loop case. A frequency response of the machine is obtained, and a linear transfer-function model is derived from the frequency response. It is not mentioned how the transfer function is derived. A root-locus design method is used to select the PSS parameters. This is done by making the eigenvalues associated with the electromechanical modes move farther into the left-hand plane.

Adaptive Control in Power Systems

Because adaptive control is an attractive solution for damping electromechanical oscillations, it has received a significant amount of attention in the literature. In [14]

Pierre gives a perspective on the status of adaptive control in power systems as of 1987. A number of papers published before 1987 are reviewed. Eight of the nine papers reviewed for the electromechanical problem use self-tuning adaptive control as opposed to model-reference adaptive control. In each of these nine papers the adaptive controller is implemented as a PSS unit on a single generator; none of them include multiple adaptive controllers. Five of the self-tuners are based on regulator algorithms that do not guarantee stability in the nonminimum-phase case. This can be a problem in a power system as the linearized plant is often nonminimum phase. All of these papers conclude that their adaptive controller is superior to a fixed controller. But, the test systems in many of these papers are overly simplified.

Since 1987 research has continued on applying adaptive control to power systems. Smith, et al., apply an LQ self-tuning adaptive controller to an SVC to control the susceptance of the compensator in [15]. The LQ cost function includes a penalty on the rate-of-change of the adaptive output signal (the susceptance). This allows the designer to temper the rate-of-change of the control action. Simulation results that demonstrate the damping ability of the controller are shown on a three-machine system. The authors of [15] expand their work in [16] to include a secondary proportional-integral (PI) loop in the controller. The conventional PI controller is used to force the steady-state voltage at the SVC bus to the set point. The LQ adaptive controller is used to modulate the SVC susceptance about the set point to dampen system oscillations. In both [15] and [16] electrical frequency error is used as the input to the adaptive controller, and in [16] the bus voltage is also used as an input to the controller. Also, recursive least-squares (RLS) identification is used to obtain a model of the system in the self tuner. Model orders are assumed to be third or fifth.

A self-tuning LQ controller is also used by Mao, et al., in [17]. The controller is used as a PSS unit. No penalty is included on the rate-of-change of the control action as in [15] and [16]. The feedback signal is a linear combination of terminal voltage and frequency error. Simulation results are shown for a one-machine and a three-machine system. In the three-machine case, all machines are equipped with adaptive controllers, but no coordination is used between controllers. The simulations demonstrate that the controllers add damping to the system. The authors of [17] apply their adaptive PSS unit to a laboratory machine in [18]. The machine is a 3 kVA, 210 V, three-phase micro-alternator. Simulations show that the adaptive PSS unit adds significant damping to the system.

In [19] Short, et al., use adaptive control to modulate a switched capacitor bank to obtain system damping. A form of self-tuning generalized predictive control (GPC) with discrete constraints placed on the control signal is used. An RLS identifier is used to obtain a model of the power system. GPC is a generalization of LQ control. With GPC system outputs are predicted over a specified horizon for each possible control action. The chosen control action is the one that minimizes a weighted-squares cost function of terms that include local system outputs and rate-of-change of control over the horizon. Simulation results are shown on the same three-machine system used in [15] and [16]. Good results are shown using frequency error, integrated frequency error, and bus voltage angle as feedback signals.

Pahalawaththa, et al., in [20], Gu and Bollinger in [21], and Wu and Hogg in [22] use a generalized minimum variance (GMV) control law as the regulator in a self-tuner. In these three papers the controller is implemented as a PSS unit on a one-machine infinite-bus system. Although minimum-variance algorithms are known to have trouble stabilizing nonminimum-phase plants, the authors in [20] claim that a GMV controller can stabilize such plants. RLS identification is used in these papers, and it is assumed that the plant is third order. The RLS algorithms in [20] and [21] use a variable forgetting factor. In [22] an extensive supervision scheme is outlined. The sampling period used in [20] is 100 ms, 50 ms in [21], and 20 ms in [22]. The results shown in these papers demonstrate that a

GMV self tuner can dampen system oscillations for various operating conditions. In [21] comparisons are made with a standard PSS unit. Bollinger and Gu extend their work in [23] by comparing the GMV self-tuner to a standard PSS design for a single machine in a nine-machine system. They conclude that the adaptive controller adds more damping to the system. Dash, et al., also use a minimum-variance regulator as a basis for a self-tuner used to control an SVC unit in [24].

In [25] Fan, et al., develop a multi-input self-tuning adaptive PSS unit. The controller is based on a GMV control law as in [20]-[23], and an RLS identifier with a variable forgetting factor is used as the identifier. A unique contribution of the technique in [25] is that a multi-input identification model is used. The extra inputs to the identifier are represented as system exogenous inputs. Terminal voltage magnitudes are used as these inputs. A multi-rate sampling scheme is used with the identifier model being updated every other sample. Simulation results are shown on a ten-machine system with various machines equipped with adaptive PSS units. These results indicate that the control scheme provides very good damping to the system.

The self-tuning PSS unit presented in [26] by Cheng, et al., uses a self-searching pole-shifting control technique as the regulator part of the adaptive controller. With the