Robust var unit control strategies for damping of power system oscillations
by James Robert Smith

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 is concerned with the development of var unit control strategies to improve the damping of electromechanical oscillations (0.1 to 2.0 hertz) which commonly occur in power systems. The objective is to use network information, locally available at the var unit bus, to produce a signal which determines the appropriate time-varying susceptance of the var unit.

Two strategies, one nonadaptive and one adaptive, are developed. The nonadaptive control strategy is based on a computer generated linearization of the nonlinear power system model. A fixed controller design is then obtained using eigenvalue analysis. The adaptive control strategy is based on real-time identification of reduced-order models of the system. An adaptive, linear quadratic, optimal controller is then formulated which determines the var unit susceptance values needed to quickly reduce system oscillations. The effectiveness of each of these control strategies is tested by computer simulation of a nine-bus power system. A detailed explanation of the methods used to simulate power system dynamics are also presented.

The simulation results illustrate the potential usefulness of applying these types of controllers to dampen oscillations of large inter-connected power networks. The robust character of these controllers is also illustrated.

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

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Electrical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 1988

APPROVAL

of a thesis submitted by

James Robert Smith

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.

7/22/88 — Date

D. A. Pierre — Chairperson, Graduate Committee

Approved for the Major Department

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[signature] — Head, Major Department

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ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Donald A. Pierre for his guidance and constructive criticism during the research and writing of this thesis. Dr. Donald Rudberg and Dr. Mohammed Nehrir have also kindly provided corrections and helpful suggestions. Dr. Roy Johnson's contribution of the numerical integration package, INTEG, and his guidance and encouragement are also greatly appreciated.

Several other graduate students have been involved in this research project and some parts of their programming work have been used in this thesis. Mr. Jon Kuppinger was involved in the coding of the computer generated linearization algorithm and especially the interfacing of the ORACLS routines to that algorithm. Mr. Anthony Johnson coded the original form of the adaptive controller algorithm. Mr. Iraj Sadighi developed and coded the identification algorithm which is used here and which is briefly presented in Chapter 4. A more detailed presentation of this algorithm will likely be given in his doctoral thesis.

The financial support of the Electrical Engineering Department of Montana State University and of the Bonneville Power Administration is gratefully appreciated. Numerous helpful discussions with Dr. John Hauer of Bonneville Power are also greatfully acknowledged.

Finally, the author would like to express his appreciation to his wife, Jennifer, and children, Kallie and Drew, for their patience and understanding.

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ABSTRACT

This thesis is concerned with the development of var unit control strategies to improve the damping of electromechanical oscillations (0.1 to 2.0 hertz) which commonly occur in power systems. The objective is to use network information, locally available at the var unit bus, to produce a signal which determines the appropriate time-varying susceptance of the var unit.

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The simulation results illustrate the potential usefulness of applying these types of controllers to dampen oscillations of large inter-connected power networks. The robust character of these controllers is also illustrated.

CHAPTER 1

INTRODUCTION

Problem Description and Background

This thesis is concerned with the development of control strategies which can be applied to a static var compensator (SVC) in order to enhance the damping of electromechanical oscillations which occur among generators in power networks. These oscillations generally occur in the frequency range from around 0.1 to around 1.5 hertz. Consideration of different strategies has been limited to those control strategies which will require only local information readily available at the bus where the var unit is located. This requirement means that effective control action will not depend on the measurement and communication of information from widely dispersed parts of the network. The benefit here is that the controller reliability will not be subject to the reliability of the communication system. This is a concern in power systems since the same environmental factors which cause disturbances to power systems may also cause disturbances to communication systems.

A static var compensator is one of several devices that can be utilized to enhance damping in a power system. Other devices to accomplish the same goal include power system stabilizer (PSS) control on exciters, control of series compensators, and control of high voltage DC (HVDC) converter systems. Static var compensators have an advantage over power system stabilizers in that they can be centrally located in the power network in order to obtain maximum effectiveness. Also they may be more feasible to use for a utility company that is primarily a power transmission company and not a power generation company. Static var compensators are often installed primarily for voltage support in a network, and controlling the device to improve system damping as a secondary function adds additional benefit. High voltage DC systems have many of the same advantages as static var compensators for improving system dynamics. A disadvantage of using high voltage DC converter control is that a primary need of enhanced system damping may be when the DC intertie is lost. In this case the disturbance itself eliminates the HVDC system from being part of the solution to the problem. The control of series compensation devices has not been considered here since the continuous control of such devices is very new and their reliability and economic feasibility in the power system environment has not been tested. It should be noted however, that the control strategies developed here and applied to static var compensators can just as well be applied to these other devices.

The need to improve damping in power systems networks has been growing over the years [1]. Poorly damped oscillations have been noticed in power systems in many parts of the world. The major factor contributing to these oscillations is often the use of long transmission lines carrying large power flows from one area of a system to another. In some cases this situation is due to the development of generating facilities that are located in remote areas from the major load centers. Undamped or poorly damped oscillations are often the limiting factor encountered in determining how much power can be transported from one area of a system to another. This situation may arise when a utility faces the problem of meeting growing load demands on an existing system where expanding transmission capacity is limited by increasing restrictions and costs of new transmission lines. Maximizing power transfers over existing lines is a major goal of many utilities, and system damping is often the obstacle to overcome. Damping problems are also sometimes attributed to peculiar load dynamics or to the widespread use of fast acting generator excitation systems. These excitation systems are important to maintain system integrity in the event of sudden disturbances. Some utility companies report that their transient stability studies of projected system operating conditions indicate that the poor damping problem will get worse in the years ahead [2].

There are several problems associated with sustained or poorly damped oscillations in power system networks. The presence of the oscillations themselves indicates a lack of stability in the system operating point which may potentially worsen causing the system to be unstable. There is also the possibility that a second disturbance occurring during the oscillatory period may cause the system to go unstable and separate, whereas the same disturbance occurring in a more settled situation would not. Large oscillations in voltage and power flows threaten the system integrity by causing damage to equipment belonging to both the utility and the customer. There is also the danger of undamped oscillations initiating or aggravating a cascading outage.

Power systems in general present a challenging problem for designers of control systems who want to try to modify the power system dynamics. There are four characteristics of power systems which need special attention. First, a power system is a nonlinear system. Since there are very few generally applicable control techniques for nonlinear systems, controller design for a power system usually involves a linearized representation of the nonlinear system. Second, the power system is a time-varying system. Generally there is a slow continuous change in the operating point of the system with daily as well as yearly cyclical patterns being present. This means that the dynamics of the system are constantly changing also. These changes are usually slow and occur over periods of hours but occasionally the system dynamics can undergo large changes in a period of seconds or less. This time-varying nature of the system is often neglected in designing controllers for power systems with the result that the controllers are usually only effective for certain operating conditions and may actually be detrimental to system dynamics under other operating conditions. Third, a power system is usually a very high-order system. Even a small utility is often interconnected with other utilities so that a thorough representation of the system will involve hundreds or even thousands of buses. This characteristic of power systems causes problems for many standard approaches to controller design. Fourth, power systems are multivariable systems with numerous inputs and outputs scattered over long distances so that coordination of controllers in different parts of the system can be difficult.

In this thesis two approaches to controller design are presented. Both of these approaches attempt to deal with all four characteristics mentioned above with special emphasis on the time-varying aspect of the system. The first approach utilizes a linearized system representation and eigenvalue analysis to design a controller which meets the needs of the system over a wide range of operating points. The second approach utilizes an adaptive controller with on-line identification of a reduced-order transfer function of the power system.

Power System Damping

A simplified power system model having n generators will have n-1 modes or frequencies of oscillation [3]. These are often referred to as natural frequencies of oscillation. Normally in a power system all these modes will be positively damped. Occasionally some of these modes may have only slight positive damping in which case oscillations will persist for a long time after a disturbance before they die out. If a mode becomes negatively damped then oscillations will arise spontaneously. An oscillation or mode that is poorly damped may involve only one or two machines or it may involve large groups of machines. In general oscillations involving only a few machines occur in the frequency range from 1 to 2 hertz. Oscillations involving large groups of machines generally occur at frequencies below 1 hertz [3]. Oscillations involving large numbers of machines are usually difficult to analyze because of the amount of detail required in the computer representation to reproduce the oscillations in simulations. There are a few papers which have appeared in the literature which report on efforts to analyze the causes and factors affecting the occurrence of certain modes which have been recorded in power systems [4], [5] and [6].

There are two basic approaches to understanding power system damping which often are mentioned in the literature. One approach is based on the concepts of synchronizing and damping torques which were developed by deMello and Concordia [7] in order to gain insight into the design of power system stabilizers. The second involves the concepts of eigenvalue analysis which have been utilized by many authors for both the analysis of factors causing poor damping and the design of controllers to improve system damping. While the synchronizing and damping torques concept is based on a one-machine infinite-bus system it has proven very insightful and useful even in multimachine systems and has been used with very good success in the design of power system stabilizers. Many authors have been attempting to extend the use of these concepts for designing other types of damping control also. Recently eigenvalue analysis programs have been developed which are capable of finding eigenvalues of very large power systems [8] and [9]. Eigenvalue analysis has been used to design stabilizing controllers for many different types of control approaches including, HVDC converters, SVC systems and power system stabilizers.

The concept of damping torques and synchronizing torques was developed based on the one-machine infinite-bus power system. These concepts illustrate how machine stability is affected by the excitation system as well as by network parameters and operating conditions. Equations (1.1) and (1.2) below are the swing equations written in state equation form where M is machine inertia constant, ω is the rotor slip speed in per unit, δ is the rotor angle in radians, T_m and T_e are the mechanical input torque and electrical output torque respectively, and D is the damping coefficient.

$$\dot{\omega} = \frac{1}{M} (T_m - T_e - \omega D) \tag{1.1}$$

$$\dot{\delta} = 377\omega \tag{1.2}$$

If we define the synchronizing torque coefficient K_1, as $K_1 = \Delta T_e / \Delta\delta$, then a linearized small perturbation representation of these equations can be put into a block diagram as in Figure 1.

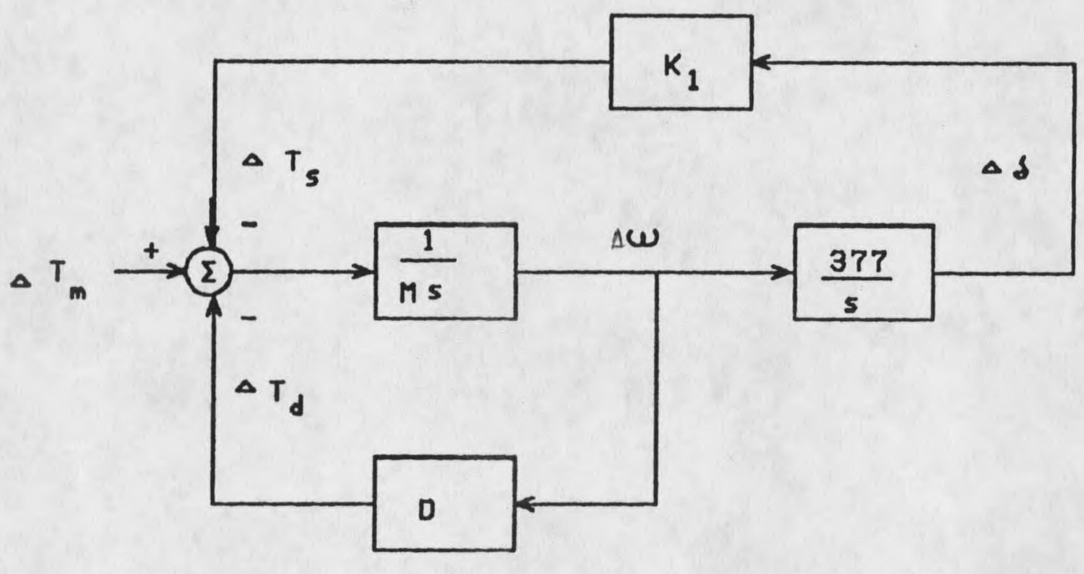

Figure 1. A diagram of linearized machine torque relations.

In this diagram a change in the mechanical torque input of the machine ΔT_m is counteracted by two opposing torques. ΔT_s is referred to as the synchronizing torque, and ΔT_d is referred to as the damping torque. These two torque components have a 90 degree phase shift between them. Any torque in phase with rotor velocity is referred to as a damping torque and those in phase with rotor angle are synchronizing torques. An arbitrary mechanical torque input will require a combination of both counteracting torques in order to reach a steady-state operating point again. The synchronizing torque acts to prevent the machine from losing synchronism with the rest of the network and is strongly dependent on network parameters as well as the machine excitation system. The damping torque is affected by factors such as rotor amortisseur windings and the excitation system. The torque-angle characteristic equation of this block diagram is

$$s^2 + (D/M)s + (K_1 377/M) = 0 \tag{1.3}$$

which has an undamped natural frequency of $\omega_n = \sqrt{377K_1/M}$ and a damping ratio of $\zeta = 0.5D/\sqrt{377K_1M}$. With these ideas established it can be shown, [7], that under certain commonly encountered conditions the voltage regulator can have a beneficial effect on synchronizing torques while simultaneously reducing the damping torque of the machine.

Eigenvalue techniques have been used in some cases to analyze the factors contributing to well documented oscillations that have occurred in power systems. The Ludington Pumped Storage Plant located in Michigan experienced undamped oscillations early in the morning of December 28,1973. System conditions and operating parameters at the time were well documented [4]. The plant contains six reversible generator/pump units. Water is pumped up to a reservior and later released to generate electricity with an electrical efficiency of 70%. The oscillations occurred at a frequency of about 0.77 hertz when the sixth unit was put on line to start pumping. The authors report that eigenvalue analysis indicated that a lack of damping of normal mechanical oscillations is what was causing the sustained oscillations.

The factors affecting the damping were found to include the external system equivalent reactance. Higher values of external equivalent reactance due to transmission lines being out of service caused negative damping of the system. Increasing the pumping power being consumed at the plant also contributed to negative damping. Damping was found to be improved slightly by increasing voltage levels in the system. The most significant factors related to changes in damping were found to be changes in excitation system parameters. The authors also report that neglecting amortisseur windings on the machines had only a slight effect on eigenvalues while neglecting stator resistance in the machine models had no significant effect on eigenvalues.

It is interesting to note that these oscillations occurred in a tightly connected and lightly loaded transmissions system. Damping in this study was found to be most strongly affected by machine loading and excitation system parameter settings.

A detailed analysis of an instability that occurred in Illinois at the Powerton Generating Station is described in [5]. This situation, in which a large generator is being operated at the end of a long transmission line, is well known to have stability and damping problems. An oscillation frequency of about 1.0 hertz was observed to occur whenever the generation from the facility exceeded a certain limit. It was noticed that the oscillations could always be eliminated by reducing the power output or by disconnecting the automatic voltage regulator. After further investigation it was established that adjustment of excitation system parameters could also restore stability. All of these observations were reproduced by simulation and verified by eigenvalue analysis. It was found that the largest effect on critical eigenvalues came from forward loop gain and the feedback gain on the excitation system. Stability could also be affected in this case by raising the terminal voltage.

Review of Literature on SVC Control for System Damping

This section will review some controller designs for SVC's which have appeared in the literature for the purpose of improving system damping and stability. Ohyama, et al., [10] have proposed a method of SVC control to enhance system damping using a so-called "reset filter". The purpose of the reset filter is to allow SVC utilization for steady-state voltage control along with damping control. The controller is designed for a one-machine infinite-bus system. Using this system the authors derive expressions relating the SVC reactance to the machine synchronizing torque coefficient. A relationship is also derived relating SVC setting to machine oscillation frequency. By increasing the oscillating frequency it is argued that the machine damping torque is increased slightly. An eigenvalue study on a large system shows that controlling the SVC increases system damping of the main mode but no details of the particular control system are provided. The reset filter basically prevents the damping portion of the SVC control from reacting to voltage level adjustments of the SVC.

Hammad [11],[12], has given a review of some SVC control techniques as well as proposing an optimal control strategy. The system proposed here has damping control as a separate loop from voltage regulation control. The damping control proposed is of the "bang-bang" type. Arguments are presented, based on a one-machine infinite-bus system, that pure voltage control alone will provide machine synchronizing torque but not damping torque. It is then shown that SVC control based on rotor speed or change in power will provide damping. For velocity feedback, the increased synchronizing torque is proportional to the gain of the controller which then leads to a justification for the use of bang-bang control. The author uses Pontryagin's maximum principle to derive an optimal bang-bang control strategy for the one-machine case.

Olwegard, et al., [13] also have looked at the application of SVC's to enhance system damping. The authors are interested in the Nordel power system which covers Sweden, Finland, Norway, and Denmark. Damping has been a factor of critical concern for this system since the 1960's. The authors use a one-machine system to develop a simple scheme of switching in SVC reactance based on power transfer fluctuations. The control scheme comes into effect only when power oscillations exceed a certain threshold value but also are less than a certain maximum value. Computer simulations of the Nordel system indicate undamped oscillations will occur when a certain tie-line is lost which can be stabilized by the SVC control. The application of SVC control enables higher power transfers in the system which translates into an SVC effectiveness measure of so many MW of power transfer increase per MVAR of SVC capability. The authors briefly discuss the control of thyristor controlled series capacitors but report that a suitable control scheme has not been found. They feel that series capacitors are more readily suited for enhancement of first swing transient stability than is a shunt device.

Hamouda, Iravani, and Hackam [14] have considered coordinating SVC control with PSS control in order to damp machine inertial oscillations as well as torsional shaft oscillations. The main application of the SVC is voltage control with an auxiliary input voltage signal to damp oscillations obtained from generator speed deviation. Their work describes an SVC application for a one-machine system. Their emphasis is mainly on subsynchronous resonance with a reported improvement in system damping of around 3% for some modes.

Larsen and Chow [15] have given some insights for SVC control applied to both voltage level control and system damping. They report that the transient response of their voltage control loop used in voltage level control has a limit to its speed of response which is determined by the tendency of the loop to undergo oscillations at around 20 hertz. The approach they use toward enhancing system damping is to look at each system mode independently and apply the concepts of synchronizing and damping torques to the machines. For each modal frequency, a diagram is developed representing the effects of the SVC control on synchronizing and damping torques for a machine. Transfer functions are developed relating SVC voltage level to modal speed and angle. The torque components due to the SVC, in phase with modal speed and angle, are identified. Since the torque component in phase with modal speed is usually very small, a supplementary control function is developed to utilize another controller input signal to modulate SVC voltage to increase this torque component. Three basic system signals are considered as inputs to the damping controller: ac voltage frequency, current or power flow on a tieline, and voltage magnitude. The issues of swing mode controllability and observability for each of these controller inputs is discussed. Because the authors are controlling the voltage level of the SVC as the controller output and using another system signal as the controller input, they have an "inner loop" in their control system where the controller output is affecting the controller input signal without affecting system damping. The gain of this inner loop is an important factor in the selection of a suitable controller input signal. The problem of designing a controller involves minimizing the gain of this inner loop while providing purely positive damping from the controller output. The amount of damping obtained will vary with power system operating condition as will the inner loop sensitivity. The authors note that using active current as the controller input signal has the advantage of low inner loop sensitivity whereas voltage magnitude is dropped from consideration because of high inner loop sensitivity. Both active current and power change sign as a function of operating condition and so the authors report that an adaptive control scheme would be necessary to utilize these signals effectively. Current magnitude is reported as having the best attributes overall as an input signal to the controller. Controller design also has to incorporate washout and high frequency filtering stages to isolate the swing mode of interest. Improved system damping using this control scheme is simulated on two-area and three-area systems. In these simulations each area is represented by an equivalent machine.

Martin [16] proposes an SVC control strategy for combining both voltage control and system damping. In this case the damping signal is an auxiliary input into the SVC regulator. He proposes using only bang-bang type control for system damping with the SVC at either its maximum or minimum reactive power output. Some inputs that are considered are: rate of change of angle between two system areas, rate of change of power on the tieline, and system frequency or machine rotor speed in one of the areas. A three-area system (with each area represented by one equivalent machine) was simulated to test the controller design. The author reports that using rate of change of angle between two areas is not a practical signal and rate of change of power, though easy to measure, was not an effective signal. Frequency of one of the areas proved to be the most effective choice. The final design used frequency of area one with proper filtering to limit the SVC response to the frequencies of interest. The author also develops the performance measure of MW/MVAR which indicates the amount of increased allowable tieline power flow per MVAR of SVC capacity that is required to obtain acceptable system damping.

Adaptive Controllers in Power Systems

The time-varying nature of power system dynamics makes the industry an inviting area for the application of adaptive controllers. Power system dynamics are constantly changing with load levels and generation pattern adjustments both on a daily and seasonal cycle. This characteristic means that a fixed type of controller designed by conventional means can be expected to perform with high effectiveness during only a small part of its operating time. In some circumstances or operating conditions the fixed controller may actually have adverse effects on system dynamics. An adaptive controller which continually updates or "tunes" itself to the current operating conditions is one way to solve this problem.

Many adaptive controllers for power system applications have been proposed in the literature, but the actual implementation of adaptive controllers in power systems is nonexistent or at least very rare [17]. Most of these proposed applications have been applied to generator excitation systems and load-frequency controllers, with a few proposed for HVDC systems and, until recently, only one for SVC control. This review of adaptive controllers in power systems will be limited to a series of papers on a pole-shifting type of adaptive controller applied to PSS systems and to a brief mention of the one SVC adaptive control strategy. A more thorough review of adaptive control strategies proposed for power systems can be found in [17] or [18]. Background relevant to an enhanced LQ adaptive controller is given in the introductory section of Chapter IV.

Cheng, Malik, and Hope with several other coauthors have written several papers [19], [20], [21], describing a self-tuning adaptive controller based on a pole-shifting strategy and applied to PSS control in order to enhance system damping. The authors have designed their controller using a dual-rate sampling scheme in order to keep the sampling interval small and yet still have enough time to perform the necessary computations between samples. The computations are done using multiple microprocessors. Their controller uses a self-adjusting pole shifting strategy, which attempts to shift the poles of the controlled system toward the origin of the z plane by a factor α. This factor, α, varies between zero and one to produce a control effort that results in maximum damping of the system oscillations, yet does not exceed controller limits. The controller is basically a feedback compensator which is tuned to shift the poles of the closed-loop system. The desired control law for the machine is obtained as a function of: the system parameter vector obtained from an identifier, a vector containing the present and past system outputs, and a vector of past inputs.

The basic assumption made in this controller and in many self-tuning controllers is that a very high-order system can be modeled as a much lower order system and an effective control law can be calculated based on this low-order model. It is also implied that the essential time-varying parameters of the system can be identified and tracked over periods of time and the control law adjusted to maintain maximum effectiveness. The identifier used by the authors is of the recursive least squares (RLS) type with a varying forgetting factor to enhance its tracking ability.

The authors report that using the pole-shifting adaptive control strategy has the advantages of being applicable to nonminimum phase systems as well as the desirable characteristic of always producing a smooth control action. The parameters of the feedback compensator are found by solving a system of linear equations of size 2n-1 where n is the order of the identified model. It is reported that a third-order model gives good results in their studies and a fifth-order model is impractical for real-time implementation using 8086 microprocessors.

The authors have obtained very promising simulation results using this control scheme. In reference [19] they have tested the method on a one-machine system. In [20] they have demonstrated its effectiveness in a three-machine system which has two lightly damped modes of oscillation. Their latest paper [21] illustrates the effectiveness of having this controller on one, two or all three machines in the system.

It is interesting to note that Wu and Hsu [22] have used the pole shifting method also to adaptively adjust the parameters of a PID controller for a PSS system. They have reported successful simulation results using a second-order identified model. Their controller was tested by simulation on a nine-bus system which is a variation of the same nine bus system to be used later in this thesis.

Other than the adaptive strategies proposed by this author and associates [23], [24], [25], the only adaptive strategy proposed so far for application to an SVC is given in reference [26]. In [26] the SVC is designed to increase damping on a one-machine system. The SVC controller uses machine rotor velocity as the feedback variable, and the gain settings of the PI feedback compensator are adjusted according to a table lookup method by reference to the machine real and reactive power loading. Off-line eigenvalue analysis is used to determine the gain settings for each operating condition and to form the lookup table. The SVC in this system is located at the machine terminal bus and can be used in lieu of a PSS.

Robust Fixed Controllers in Power Systems

It is well accepted that when system conditions are accurately known then successful power system controllers can be designed for those conditions. When damping enhancement is desired for several different operating conditions then controller design techniques are less established and the problem is often categorized as a robustness problem. Robustness is generally regarded as a quality of the controller that enables it to be effective despite some modeling errors in the initial design and despite some amount of parameter drift in the system. The power system environment in some cases may require an extreme degree of robustness in controller design. There have been a few recent papers concerning the design of robust controllers for power system applications.

Chow and Sanchez-Gasca [27] have used frequency response analysis to evaluate PSS controllers at different operating points and to combine them into a single robust controller. In their paper a PSS controller is designed for a one-machine infinite-bus system. The controller is designed to provide machine damping under two operating conditions. One condition has a large line impedance which is referred to as the weak coupling case. The other condition is the same except for with a small line impedance or a strong coupling case. A second-order controller is designed for both of these cases and then they are multiplied by a weighting factor and combined to get a fourth-order controller. Since both controllers have similar frequency responses it is possible to reduce the combined controller to second-order using a technique called the Hankel Norm algorithm. The frequency response of the resulting controller is approximately the average of the frequency responses of the original two controllers. The authors report that the method does not guarantee stability but is simple to use and provides adequate results when used with good judgement.

A paper by Petrovski and Athans [28] considers the robustness properties of controllers used in a multiterminal DC/AC power system. The authors are interested in using a multiterminal DC system imbedded in an AC power system to enhance overall system damping. A five terminal DC system is used to analyze different control strategies in terms of robustness. The authors are looking at suitable robustness to tolerate actuator and sensor failures, unmodeled dynamics, and changes in system parameters. The authors evaluate robustness by use of two approaches. One way is to introduce errors into the system input transducers and then evaluate the system stability by Lyapunov methods. The size of the error that can be tolerated before instability results is one measure of robustness. In another test the linearized representation of the system is perturbed by a scalar multiplicative factor and also by an additive perturbation matrix, and again stability is assessed by Lyapunov methods. The matrix norm of the perturbation that can be tolerated before instability results is a measure of the robustness of the system. Three decentralized controller designs all involving linear quadratic optimal control strategies are evaluated using these methods, and their relative strengths and weaknesses are tabulated.

Scope and Organization of Remaining Chapters

The following pages are organized into four main parts or chapters. The first part (Chapter 2) contains a detailed description of the program used to carry out the computer simulation of power system dynamics. The second part (Chapter 3) describes the process of controller design using eigenvalue analysis of the linearized system and presents simulation results. The third part (Chapter 4) describes the adaptive controller design and simulation results. The fourth part (Chapter 5) is the conclusion and discussion of aspects warranting further study. The contribution of this work to engineering literature lies primarily in the areas of adaptive control, robust control, and damping control of electrical power systems.

CHAPTER 2

SIMULATION OF POWER SYSTEM DYNAMICS

Introduction

The purpose of this chapter is to describe the methods used for computer simulation of electromechanical oscillations or swing transients of power systems. The major goal of the computer program is to provide a flexible means for simulation of power system dynamics with the same level of detail of modeling that is generally used in the power industry. Computational efficiency, while desirable, is a secondary consideration to program clarity and flexibility in the implementation of control strategies. Modifying an existing code to implement these ideas would seem to be the most efficient course of action. Most commercially available programs however are prohibitively expensive in addition to being cumbersome because of the extensive options that are included. Bonneville Power has a very good swing program that is readily available to the public but its size and lack of documentation make it very difficult to modify. Under these circumstances it was decided to write a program around an available Runge-Kutta integration package called INTEG [29], even though it is generally recognized that trapezoidal integration is more computationally efficient for this type of problem [30],[31].

In general nearly all variables of a power system require some time to respond to a change in the system so that a detailed model of even a small power system would contain an enormous number of differential equations. The main problem of simulating such a detailed model is the very large range of time constants present or the so-called "stiffness" of the system. To make the simulation practical to implement it is usually necessary to select a time frame of the network behavior which is of interest to study and then make simplifying assumptions for variables which change very rapidly or very slowly compared to this time period. Very small time constants can be changed to zero which transforms the associated differential equation into an algebraic equation. Longer time constants can be made to approach infinity which then turns the variable being simulated into a constant. Time constants associated with the network are very small compared to the electromechanical periods of oscillations, and so it is the usual practice [30],[31] and [32], to assume that network variable changes occur instantaneously. Thus the network variables are treated as algebraic constraints coupled to the differential equations without any significant loss of accuracy. The result of these assumptions is the "quasi-steady-state" network solution utilized in swing programs. Since the system frequency deviation from 60 hertz is very small the network reactances can all be expressed at this frequency with insignificant loss of accuracy. This enables the network variables to be represented as phasor quantities with an implied frequency of 60 hertz. This phasor or steady-state solution of the network variables is updated after changes in the machine state variables are calculated from the integration procedure.

The problem is now formulated as a differential-algebraic initial value problem. The differential equations are solved by Runge-Kutta integration, and the algebraic constraints on the system are resolved by an iterative procedure at each step of the Runge-Kutta integration. The machine rotor angles relative to the network phasor reference frame are allowed to vary according to differential equations which describe machine rotor speed deviations from the 60 hertz synchronous speed. The resulting network phasor voltages are assumed to always be in steady-state equilibrium with the voltages produced by the machines. Once machine rotor angles and internal voltage magnitudes are determined from the differential equations, the machine and network algebraic relations are solved to determine the voltages and power flows in the network. These network variables then become the forcing functions for the next step in the solution of the differential equations.

Differential Equations

In describing the differential equations used in this swing program the notations and reference frame conventions of [31] are adopted. A more thorough description of machine modeling is given in [33], but the reference frame convention adopted there is different from that in [31]. As mentioned previously this program is written around a Runge-Kutta integration package called INTEG. The INTEG program calls two subroutines, one called SIDE and the other called STATE. The STATE subroutine contains the first-order differential equations or state equations which are integrated by the Runge-Kutta algorithm. The SIDE subroutine contains algebraic constraints on the differential equations or in our case the machine and network algebraic equations. Both the STATE and SIDE subroutines are contained in a file called 2MIED.FOR which is listed in Appendix A at the end of the thesis.

The majority of the differential equations used in a swing program are of three types: machine mechanical equations; machine electrical equations; and exciter equations. Machine mechanical differential equations describe the motion of the machine rotor angle, relative to its 60 hertz synchronous speed, due to imbalances between mechanical power input to the machine and electrical power output. The rotor angle of each machine in the network is assigned a value based on reference frame conventions which are described in more detail in section 2.3. If δ represents the rotor angle of a machine, then the expression for machine rotor acceleration is

$$d^2\delta/dt^2 = (1/M_g)(P_m - P_e - D(d\delta/dt)) \qquad (2.1)$$

where P_m is mechanical input power, P_e is electrical output power, and M_g is the angular momentum. The constant D is a damping term which is often used to account for damping contributions in the system which are not accurately modeled by other means such as amortisseur windings and nonlinear loads. Rewriting this equation as two first-order differential equations or state equations and neglecting the damping term gives

$$d\omega/dt = (1/M_g)(P_m - P_e) \qquad (2.2)$$

$$d\delta/dt = \omega - 2\pi f_o \qquad (2.3)$$

where f_o is the system base frequency (60 hertz in our case) and ω is the rotor frequency in radians per second. Another form [32] of this equation utilizes ω as a per-unit quantity in which case the right-hand side of equation (2.3) is replaced by the product of ω and $2\pi f_o$. In this case the steady-state value of ω is zero. Both forms of this equation are widely used and they give the same result in simulations except for a difference in the units being used to represent machine rotor speed. The form shown in (2.3) is used in this work. The electrical power being produced by the machine is a function of voltages and admittances throughout the network to which the machine is connected.

The machine electrical differential equations describe how changes in the machine stator or field currents cause the internal machine voltages to vary. The voltage variations are also influenced by how the machine rotor angle is affecting the path of magnetic fields between the rotor and stator. These differential equations are based on Park's transformation [32], [33]. This mathematical treatment of machine modeling transforms machine impedance values from time-varying, three-phase quantities which depend on machine rotor angle, to constant value parameters in equivalent circuits which lie directly in line with the rotor main axis (the d-axis) or in quadrature with it (the q-axis). This d-q reference frame is fixed to the rotor and moves with the rotor relative to network variables. Different numbers of d and q-axis circuits represent different levels of detailed modeling from slower to very fast time constants. Reference [34] gives a detailed diagram illustrating the interaction between different modeling levels and the machine torques that are developed. The level of modeling used in this program will incorporate slow transient voltages inside the machine as is usually deemed adequate for this type of study [31]. The differential equations are

$$dE_q'/dt = (E_f - E_q)/T'_{do} = (E_f + (X_d - X_d')I_d - E_q')/T_{do}' \quad (2.4)$$

$$dE_d'/dt = E_d/T_{qo}' = (- (X_q - X_q')I_q - E_d')/T_{qo}' \quad (2.5)$$

and the associated algebraic equations are

$$E_q' - V_q = R_a I_q - X_d' I_d \quad (2.6)$$

and

$$E_d' - V_d = R_a I_d + X_q' I_q \quad (2.7)$$

In these equations the subscripts d and q represent direct and quadrature axis quantities respectively. The constant R_a is the armature resistance, E_f is the field voltage, and the time constants T_{do}' and T_{qo}' are transient open-circuit time constants. An explanation of these equations based on heuristic arguments of machine behavior will be given [33].

The machine reactances are the most important parameters for modeling machine behavior, and resistances are often neglected. To determine reactances consider the rotor circuits as closed loop circuits which are not excited. Also the rotor is being turned at synchronous speed, and current of the proper sequence is applied to the armature windings. The voltages measured at the armature terminals can then be used to determine the reactance which is just the measured voltage divided by the applied current. The different reactance values in the equations above are obtained using different rotor positions and either a steady-state current or a suddenly applied current.

Positive sequence, steady-state currents flowing in the armature windings produce a rotating magnetic field inside the machine. If the main axis or direct axis of the rotor is in line with this rotating flux wave then the flux wave will have its maximum value for a given amount of armature current, and the armature inductive reactance will be at its maximum. This reactance is the direct-axis synchronous reactance. The flux linkage of each armature winding varies sinusoidally with time, and the armature phase voltage induced by the change in this flux wave as it sweeps by the winding is in quadrature with the applied current. The ratio of this voltage to the current is the direct-axis synchronous reactance, X_d.

Now if the rotor is made to rotate at synchronous speed with its interpolar axis or q-axis in line with the rotating flux wave, then the rotating flux wave will have a minimum value. In this case the ratio of the armature voltage component in quadrature with the current, divided by the armature current is the quadrature-axis synchronous reactance X_q.

The conditions under which the transient reactances are defined are the same except that a transient armature current is used rather than a steady-state current. In this case the armature currents are suddenly applied and the voltages are measured immediately after the application of the currents. In the case of the direct-axis transient reactance, X_d', the rotor is rotated with its d-axis in line with the crest of the flux wave. The voltage measured immediately after the application of the armature current is $E_q' = X_d'I_d$ and this eventually decays down to the steady-state value $E_q = X_dI_d$. The time constant associated with this decay is the direct-axis open-circuit time constant T_{do}'. In an analogous way the quadrature-axis open-circuit time constant and transient reactance are defined. In this case however, the q-axis of the rotor is in line with the armature flux wave. The measured voltage is $E'_q = X'_q I_q$ which in the steady state becomes $E_q = X_q I_q$.

When the field winding is excited, the voltage $E'_d + jE'_q$ is the voltage behind the transient reactance of the machine. The difference between E'_q and E_q is

$$E'_q - E_q = (X'_d - X_d)I_d \tag{2.8}$$

and similarly the difference between E'_d and E_d is

$$E'_d - E_d = (X'_q - X_q)I_q \tag{2.9}$$

In the steady state E_d is zero because the rotor d-axis will be in line with the armature flux wave and no voltage component in phase with the armature current is induced. E'_d however, is not zero but is equal to $(X'_q - X_q)I_q$ provided that X'_q is not equal to X_q (they are usually equal in salient pole machines).

If a sudden change in armature currents occurs then E'_d and E'_q undergo slow changes according to the differential equations (2.4) and (2.5). The values of E_q and E_d however, undergo immediate changes according to the relations

$$\Delta E_q = (X_d - X'_d)\Delta I_d \tag{2.10}$$

$$\Delta E_d = (X_q - X'_q)\Delta I_q \tag{2.11}$$

which can be seen in the right-hand sides of equations (2.4) and (2.5) respectively. Thus the transient voltages will change according to their time constants until they reach steady state where E_q is equal to the field voltage E_f and E_d is zero.