Chapter 1

Introduction

This chapter presents to the problem to be considered in this thesis. The definition of power system stability according to IEEE standards is presented in Sec. 1.2. Electromechanical oscillations occurring in power systems are briefly discussed in Sec. 1.3 while the concept of reliability of power systems is discussed and the requirements of a reliable power system are summarized in Sec. 1.4. In Sec. 1.5, a brief survey of power system stabilization techniques is presented. Sec. 1.6 presents a brief historical background of linear matrix inequality applications in control systems. The motivations to carry out this research task are highlighted in Sec 1.7. Thesis objectives are summarized in Sec. 1.8 and thesis outline tags this chapter.

1.1 Problem Statement

Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes, set point changes and network topology changes occur continually; the system must be able to adjust to the changing conditions and thereafter operate satisfactorily. It must also be able to survive numerous disturbances of severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the isolation of the faulty elements. The problem of interest is one where a power system operating under a steady loading condition is perturbed, causing readjustment of the voltage angles of the synchronous machines. If an imbalance between the system generation and load occurs, it results in a new steady-state operating condition, with the subsequent adjustment of the voltage angles. The interval of adjustment to the new operating condition is called the transient period. The system behavior during this time is called the dynamic system performance, which is of concern in defining system stability. However, the main criterion for stability is that the synchronous machines maintain synchronism at the end of the transient period.

1.2 Definition of Power System Stability

This section provides the formal definition of power system stability as reported in [1]. The following definition is physically based and conforms to the definitions from system theory; however, it is easily understood and readily applied by power system practitioners.

Definition 1.1: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [1].

This definition applies to the interconnected power system as whole because a power system is a highly nonlinear system that operates in a constantly changing environment such as loads and generator outputs. When subjected to a disturbance, the stability of the system depends on the initial operating condition as well as the nature of the disturbance. Stability of an electric power system is thus a property of the system motion around an equilibrium set. At an equilibrium set, a power system may be stable for a large disturbance, and unstable for another. It is impractical to design power systems to be stable for every possible disturbance. The design contingencies are selected on the basis of a reasonably high probability of their occurrence. Hence, large-disturbance stability always refers to a specified disturbance scenario.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individualistic characteristics. Further, devices used to protect individual equipment may respond to variations in system variables and cause tripping of the equipment, thereby weakening the system and possibly leading to system instability.

In the case of a disturbance where the power system is stable, it will reach a new equilibrium state with the system integrity preserved i.e., with practically all generators and loads connected through a single contiguous transmission system. Consequently, some generators and loads may be disconnected by the isolation of faulted elements or intentional tripping to preserve the continuity of operation of bulk of the system. Interconnected systems, for certain severe disturbances, may also be intentionally split into two or more “islands” to preserve as much of the generation and load as possible. The actions of automatic controls and possibly human operators will eventually restore the system to normal state. On the other hand, if the system is unstable, it will result in a run-away or run-down situation; for example, a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages. An unstable system condition could lead to cascading outages and a shutdown of a major portion of the power system generation. Power systems are continually experiencing fluctuations of small magnitudes. However, for assessing stability when subjected to a specified disturbance, it is usually valid to assume that the system is initially in a true steady-state operating condition.

1.3 Power System Oscillations

Different types of oscillations are likely to occur following a power system perturbation. These oscillations could be classified into two categories, based on their frequency range, as follows:

1.3.1 Low frequency oscillations (LFOs)

These oscillations are of electromechanical nature and occur due to the swing of a rotor mass against an infinite system or swinging of the masses of different generator rotors against each other. These oscillations are most likely to appear in power systems and lead to small-signal stability problems which may be either local or global problems.

i. Local problems involve a small part of the system and they may be associated with rotor angle oscillations of a single generator or a single plant against the rest of the power system. The resulting oscillations are called local plant mode oscillations. Further, local problems may also be associated with oscillations between the rotors of a few generators close to each other. In such case, these oscillations are called inter-machine or inter-plant mode oscillations. Usually local plant mode and inter-plant mode oscillations have frequencies in the range of 0.7-2.0Hz [2]-[4].

ii. Global problems are caused due to the interactions among large groups of generators. They involve oscillations of a group of generators in one area swinging against a group of generators in another area. These oscillations are commonly termed inter-area mode oscillations. Large interconnected power systems have two distinct forms of inter-area oscillations [2]:

   a. A very low frequency mode involving all the generators in the system assuming that these generators are split into two parts, with the generators in one parts swinging against the generators in the other part. Typically, the frequency of this mode is on the order of 0.1 to 0.3Hz.

b. Higher frequency modes involving subgroups of generators swinging against each other. The frequency of these oscillations is typically in the range of 0.4 to 0.7Hz.

1.3.2 Subsynchronous Oscillations (SSOs)

In the analysis of power system dynamic performance, the rotor of a turbine generator was assumed to be made up of a lumped mass. This assumption accounts for the oscillation of the entire turbine-generator rotor to other generators. Practically, a steam turbine-generator rotor has a complex mechanical structure consisting of several predominant masses connected by shafts of finite stiffness and damping. Therefore, when a generator is perturbed torsional oscillations results between different sections of turbine-generator rotor. These torsional oscillations could interact with the electrical system in an adverse condition. Under this topic, the most commonly addressed problems are the self-excited oscillations (SEO) and the subsynchronous resonance (SSR). The oscillations that could occur even with a lumped mass rotor in the case of series capacitor compensated transmission line are termed self excited oscillations. The concept of self excited oscillation is related to the low X/R ratio of tie lines interconnecting a given power plant to a large system [5]. When the full structure of the turbine-generator rotor is considered, the phenomenon of SSR may occur for the case of series-capacitor compensated transmission lines. These oscillations are beyond the scope of this thesis.

1.4 Requirements of a Reliable Power System

Successful operation of a power system depends largely on the engineer's ability to provide reliable and un-interrupted service to the loads. The reliability of the power supply implies much more than merely being continuous. Ideally, the loads must be fed at constant voltage and frequency at all times. In practical terms this means that both voltage and frequency must be held within close tolerances so that the loads may operate satisfactorily.

The first requirement of reliable service is to keep the synchronous generators running in parallel and with adequate capacity to meet the load demand. If at any time a generator loses synchronism with the rest of the system, significant voltage and current fluctuations may occur and transmission lines may be automatically tripped by their relays at undesired locations. If a generator is withdrawn from the system, it must be resynchronized and then reloaded, assuming it has not been damaged and its prime mover has not been shut down due to the disturbance that caused the loss of synchronism.

The second requirement of reliable electrical service is to maintain the integrity of the power network. The high-voltage transmission system connects the generating stations and the load centers. Interruptions in this network may hinder the flow of power to the load. This usually requires a study of large geographical areas since almost all power systems are interconnected with neighboring systems. Therefore, successful operation of the system implies that interconnecting tie lines must remain in service if firm power is to be exchanged between the areas of the system. While it is frequently convenient to talk about the power system in the "steady state" such a state never exists in the true sense. Random changes in load are taking place at all times, with consequent adjustments in generation. Furthermore, major changes do take place at times, e.g., a fault on the network, failure in a piece of equipment, sudden application/rejection of a major load, loss of a line or generating unit. These disturbances will cause a change from one equilibrium state to another. It might be tempting to say that successful operation requires only that the new state be a "stable" state. For example, if a generator is lost, the remaining connected generators must be capable of meeting the load demand; or if a line is lost, the power it was carrying must be obtainable from another source.

1.5 A Brief Review of Power System Stabilization Techniques

From dynamic stability point of view, subsequent analyses has shown that rotor swings are due to poor damping characteristics caused by modern automatic voltage regulators (AVRs) with comparatively high gain and fast time response [6]-[7]. To compensate for the limitations of these voltage regulators, supplementary signals such as $\frac{dV}{dt}, I, \frac{dI}{dt}, \omega, Q, P_a, P$ and $\frac{dP}{dt}$ [8]-[9] are injected to improve the AVR performance. Essentially, they use the power amplification property of the generator to generate a damping torque component. This is achieved by injecting a stabilizing signal into the excitation voltage reference-summing junction. The equipment that provide such signals through a properly chosen transfer functions are termed "power system stabilizer (PSS)". The basic function of a PSS is to modulate the generator excitation voltage to provide sufficient damping for low frequency oscillations. Insufficient damping of these oscillations may limit the ability to transmit power. To provide damping, PSS must produce a component of electric torque which is in phase with the rotor speed deviation. The implantation details differ depending on the stabilizer input signal in use. However, the stabilizer must compensate for the phase lag of the combined generator, excitation system and power system. The functional block diagram of a typical supplementary signal controller is shown in Fig. 1.1 where the supplementary signal is measured and then passed through a low and a high pass filters. Phase compensators are then used to provide the adequate phase compensation for the signal. The output of the compensator is then amplified, passed through a limiter and added to the voltage error signal applied to the automatic voltage regulator.

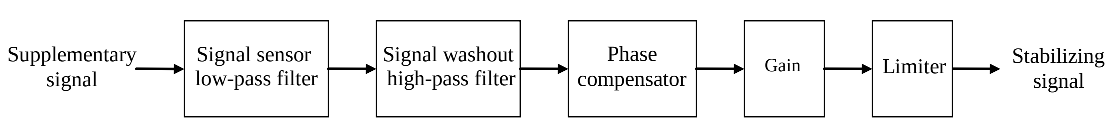

Fig. 1.1 Functional block diagram of a typical supplementary signal controller

1.5.1 Conventional Stabilizers

Conventional PSSs take the form of lead-lag or PID controllers which are the result of classic control theory such as phase and gain margin and root locus techniques. These controllers are used for the last three decades and still have the leading rule in the real world of PSSs. The main problem that encounters conventional PSS design is that power systems always experience changes in operating conditions due to continuous variations in loads and generators outputs, as well as changes in transmission networks. In such cases, a fixed-parameter conventional PSS may fail to maintain stability or lead to a degraded performance [6]-[7].

Different PSS designs using modern control methodologies such as adaptive control, robust control, fuzzy control and adaptive fuzzy control have been extremely addressed in literature. Further, different optimization techniques such as genetic algorithms, particle swarm, evolutionary algorithms and linear matrix inequalities have been used in tuning the PSS parameters.

1.5.2 Adaptive Stabilizers

Design of conventional PSSs is generally based on a linearized fixed parameter model. These stabilizers have performed well and improve system stability. However, they are unable to automatically track the variations in power system operating conditions and can not respond to the interactions between individual generating units. Adaptive PSSs overcome these difficulties because they have automatic system tracking features and thereby a positive interaction between stabilizers on individual units. Self-tuning control techniques offer these features. Results of a number of studies such as [10]-[12] showed that self tuning control is suitable for power system control. However, the implementation of an adaptive controller needs tough precautions to assure the persistent excitation conditions. Adaptive controllers generally have poor performance during the learning phase unless they are appropriately initialized [11].

1.5.3 Robust stabilizers

Robust control provides an effective approach to handle uncertainties introduced by continuous variation in generation and load patterns. Many papers addressed robust PSS design via different control approaches. The H_∞ approach is applied to the design of a robust PSS for a single-machine infinite-bus system in [13]. In this approach, the uncertainty in the plant parameters is captured in terms of bounds on the frequency response. Also, Kharitonov theorem is applied to the design of a robust PSS for a single machine infinite bus system in [14]-[15]. μ-synthesis is extensively used in the robust design of PSS [16]-[19]. Robust PSS design using genetic algorithms (GAs) is also reported in [20]-[22]. Robust design of multimachine power systems stabilizers using simulated annealing is reported in [23]. A low sensitive excitation control was presented in [24] to extend the stability region and excremental results of an optimal control were provided in [25]. Many papers addressed this problem via convex optimization techniques such as linear matrix inequality (LMIs) [26]-[31].

1.5.4 Fuzzy and adaptive fuzzy stabilizers

Recently, fuzzy logic has emerged as a potential technique for PSS design [32]. Besides its ability to accommodate the heuristic knowledge of a human expert, the advantage of a fuzzy PSS is that it represents a nonlinear mapping that can cope with the nonlinear nature of power systems. Several reported results confirm that a fuzzy PSS outperforms a conventional PSS once the deviation from the nominal design conditions becomes significant. Implementation of a fuzzy PSS for a multi-machine power system is reported in [33]. Tuning the scaling factors of a fuzzy PSS is discussed in [34]. Adaptive fuzzy PSS was presented in [35]-[36] and on-line tuning of fuzzy PSSs as a direct adaptive one is reported in [37]. Although the performance of a well-designed model-free fuzzy PSS is acceptable, it lacks to systematic stability analysis and controller synthesis. The reported work attempts to overcome this drawback by a providing a model-based fuzzy PSS that guarantees stability and performance of power systems. In the past ten years, search efforts on fuzzy logic control have been devoted to model-based fuzzy control systems [38].

1.5.5 Necessity for Applying Decentralized PSSs

As power systems have evolved through continuing growth in interconnections, a centralized design is neither practical nor reliable due to inherent constraints of large power systems such as geographic dispersion, topology variance and nonlinearity. Many efforts have been devoted to decentralized robust control strategy to overcome the difficulties imposed by centralized design [39]. The need for developing decentralized robust control strategies has been recognized by power system researchers for several decades and involved two fundamental requirements. Firstly, the control must be decentralized, since only local measurements are normally available to any given machine. Secondly, the control needs to be robust in the sense it must guarantee satisfactory performance over wide range of operating conditions and disturbances. The last decade has seen a number of new developments in the design of robust power system control. Although the proposed methods include both decentralized turbine/governor [40]-[43] and decentralized exciter control designs [44]-[48], it is fair to say that the latter approach has received more attention, given the relatively small time constants associated with the excitation system control loop. Much of the recent work related to robust exciter control has been based on the concept of direct feedback linearization, which transforms the original nonlinear model into a linear one. After such a transformation, the control design becomes quite straightforward, but the implementation is complicated by the fact that the resulting controller is nonlinear. Despite this difficulty, relatively few attempts have been made to develop reliable techniques for designing linear robust exciter control. Among these, it is of interest to mention the approach proposed in [46] where linear controller design is based on Lyapunov’s method. A problem that arises in this context is associated with the quadratic term in the model, which cannot be properly incorporated into the analysis.

1.6 Historical Background of Linear Matrix Inequalities (LMIs)

Recently, linear matrix inequalities (LMIs) have emerged as a powerful tool to approach control problems that appear hard if not impossible to solve in an analytic fashion. Although the history of LMIs goes back to the fourties with a major emphasis of their role in control in the sixties (Kalman, Yakubovich, Popov, Willems) [49], only recently powerful numerical interior point techniques have been developed to solve LMIs in a practically efficient manner [50]. Several Matlab software packages are available that allow a simple coding of general LMI problems and of those that arise in typical control problems (LMI Control Toolbox, LMI-Tool). Boosted by the availability of fast LMI solvers, research in robust control has experienced a paradigm shift. Instead of arriving at an analytical solution, the intention is to reformulate a given problem to verifying whether an LMI is solvable or to optimizing functional over LMI constraints.

The history begins in about 1890, when Lyapunov published his seminal work introducing what we now call Lyapunov theory. He showed that the dynamical system $\dot{x}(t) = Ax(t)$ is stable if and only if there exists a symmetric matrix P such that $P > 0$ and $A^T P + PA < 0$. These constraints form what we call Lyapunov inequality on P, which is a special form of an LMI. Briefly, the first LMI used to analyze stability of a dynamical system was the Lyapunov inequality which can be solved analytically.

The next major milestone occurs in the 1940's. Lur'e, Postnikov and others, in Soviet Union, were the first to apply Lyapunov's methods to practical control engineering problems. Although they did not explicitly form matrix inequalities, their stability criteria have the form of LMIs. These inequalities were reduced to polynomial inequalities which were then checked by hand for small systems only. In summary, Lur'e and others had the first trial of applying Lyapunov's method to small (second, third order) systems.

The next major breakthrough came in the early 1960's, when Yakubovich, Popov, Kalman, and other researchers succeeded in reducing the solution of the LMIs that arose in the problem of Lur'e to simple graphical criteria, using what we now call the positive-real (PR) lemma. This resulted in the celebrated Popov criterion, circle criterion and many variations. These criteria could be applied to higher order systems, but did not gracefully or usefully extend to systems containing more than single nonlinearity. From the view point of LMI in control theory, they showed how to solve a certain family of LMIs by graphical methods.

The important role of LMIs in control theory was already recognized in the early 1960's, especially by Yakubovich. This is clear simply from the titles of his papers from 1962. The PR lemma and extensions were intensively studied in the latter half of the 1960s, and were found to be related to the ideas of passivity, the small-gain criteria introduced by Zames and Sandberg, and quadratic optimal control. By 1970, it was known that the LMI appearing in the PR lemma could be solved not only by graphical means, but also by solving a certain algebraic Riccati equation (ARE) as shown by Willems in 1971. By 1971, researchers knew several methods for solving special types of LMIs: direct (for small systems), graphical methods, and by solving Lyapunov or Riccati equations. These methods are all “closed-form" or “analytic" solutions that can be used to solve special forms of LMIs.

The next major advance was the simple observation that: The LMIs that arise in system and control theory can be formulated as convex optimization problems that are amenable to computer solution. Although this is a simple observation, it has some important consequences, the most important of which is that we can reliably solve many LMIs for which no “analytic solution" has been found. This observation was made explicitly by several researchers. Pyatnitskii and Skorodinskii were perhaps the first researchers to make this point clearly and completely. They reduced the original problem of Lur'e to a convex optimization problem involving LMIs, which they then solved using the ellipsoid algorithm. Pyatnitskii and Skorodinskii were the first to formulate the search for a Lyapunov function as a convex optimization problem, and then apply an algorithm guaranteed to solve the optimization problem.

The final breakthrough in the LMI history is quite recent and of great practical importance: the development of powerful and efficient interior-point methods to solve the LMIs that arise in system and control theory. In 1984, Karmarkar [51] introduced a new linear programming algorithm that solves linear programs in polynomial-time, like the ellipsoid method, but in contrast to the ellipsoid method, is also very efficient in practice. Karmarkar's work spurred an enormous amount of work in the area of interior-point methods for linear programming (including the rediscovery of efficient methods that were developed in the 1960s but ignored). Essentially all of this research activity concentrated on algorithms for linear and quadratic programs. Then in 1988, Nesterov and Nemirovskii developed interior-point methods that apply directly to convex problems involving LMIs [50]. Although there remains much to be done in this area, several interior-point algorithms for LMI problems have been implemented and tested on specific families of LMIs that arise in control theory, and found to be extremely efficient.

Key events in the history of LMIs in control theory could be summarized as follows [49]:

- 1890: First LMI appears; analytic solution of the Lyapunov LMI via Lyapunov equation.
- 1940's: Application of Lyapunov's methods to real control engineering problems. Small LMIs solved by “hand”.
- Early 1960's: PR lemma gives graphical techniques for solving another family of LMIs.

- Late 1960's: Observation that the same family of LMIs can be solved by solving an ARE.
- Early 1980's: Recognition that many LMIs can be solved by computer via convex programming.
- Late 1980's: Development of interior-point algorithms for LMIs.

1.7 Motivation

The most of real world control problems refer to multi-objective control designs that guarantee several objectives simultaneously. It is clear that meeting all deign objective by a simple design is the ultimate objective of any control system designer. The first objective of a control system is to guarantee system robustness, i.e., to make the closed loop system stable under various external disturbances and model uncertainties. From the view point of power system control, robust stability becomes a minimum requirement for control systems. A good controller should also maintain better time response in terms of damping factor, damping ratio and maximum overshooting. Disturbance rejection is also an important objective of a control system, i.e., the exogenous signals that enter the system must have minimum effect on the tracking errors and the control effort. This objective refers to the H_∞ control problem. Good compromise, between tracking errors and control effort, is a fundamental control objective as well. This objective is referred to as the LQR problem or H_2 control problem. Further, in most situations, limits on system output and control signals must be imposed to ensure safe operation of the system and to prevent actuator saturation. Fortunately all these objectives could be formulated in the form of LMIs. Therefore all of these objectives could be mixed together in a single convex optimization problem that could be solved effectively using interior point algorithms.

The centralized design becomes neither practical nor reliable in the large scale power systems due to the constraints related to the system structure. A successful strategy for the control of large-scale power systems must satisfy two fundamental requirements. Firstly, the control must be decentralized, since only local measurements are normally available to any given machine. Secondly, the control needs to be robust in the sense it must guarantee satisfactory performance over wide range of operating conditions and disturbances.

Recently, fuzzy logic has emerged as a potential technique for PSS design [32]-[37]. Besides its ability to accommodate the heuristic knowledge of a human expert, the advantage of a fuzzy PSS is that it represents a nonlinear mapping that can cope with the nonlinear nature of power systems. However, fuzzy logic control applications in power system stabilization was originally introduced and developed as a model free control design approach. Although the performance of a well-designed model-free fuzzy PSS is acceptable, it unfortunately suffers form criticism of lacking of systematic stability analysis and controller synthesis.

1.8 Thesis Objectives

This thesis involves two fundamental objectives based on multi-objective control using an LMI approach. The first objective considers the robust design of a multiobjective PSS that guarantees a mix of H_∞ performance, H_2 performance, time-domain constraints, and constraints on the closed-loop pole location. This design considers the case of robust state and output feedback stabilizers. The robust syntheses of an output feedback PSS will consider full order dynamic output feedback PSSs, reduced order dynamic output feedback PSSs (phase-compensators) and PID-based PSS. In multimachine power systems, decentralized syntheses of full order output feedback PSSs, reduced order output feedback PSSs and PID-based PSSs are presented.

The second objective considers the design of model-based fuzzy stabilizers that accounts for robust stability and robust performance of power systems. This objective is initiated by the formulation of a single-machine power system as a Takagi-Sugeno (T-S) fuzzy model. Fuzzy syntheses will consider the model-based fuzzy state feedback and dynamic output feedback PSSs that guarantee a mix of the pervious objectives. Moreover, fuzzy synthesis of observer-based output feedback PSS that guarantees robust pole-placement in LMI regions and robust performance in terms of H_2 and H_∞ is considered. Finally, a model-based fuzzy static output feedback stabilizer, that guarantees robust pole placement in LMI regions and robust performance in terms of H_∞ is considered. A decentralized scheme is proposed for applying the proposed output feedback fuzzy stabilizers in a multimachine environment.

1.9 Thesis Outline

The rest of the thesis is organized as follows. Chapter 2 discusses the polytopic modeling of power systems and presents three different polytopic design models that account for uncertainties in the plant parameters due to continuous variation generator outputs and network topology. In Chapter 3, synthesis inequalities are provided for a robust multiobjective state feedback and full-order output feedback PSSs that guarantee a mix of H_∞ performance, H_2 performance, time-domain constraints, and constraints on the closed-loop pole location. Further, Robust syntheses of reduced order output feedback PSS are considered. Syntheses of reduced order output feedback PSSs include the synthesis of first and second order phase compensation based PSS and PID-based PSSs. The synthesis inequalities of reduced order output feedback controller are reduced to a generalized static output feedback problem and two iterative linear matrix inequalities (ILMI) algorithms are proposed to solve these inequalities. Moreover, syntheses of decentralized full order output feedback, reduced order output feedback and PID-based PSSs are considered for multimachine power systems. Simulation results based on single-machine infinite-bus system and multimachine power systems are presented to verify the effectiveness of the proposed algorithms.

Construction of Takagi-Sugeno fuzzy models that are adopted in the design of a multiobjective model-based fuzzy PSS is explained in Chapter 4 where two T-S fuzzy models are presented. A brief review of T-S fuzzy models and their stability conditions are included in this chapter as well. This chapter presents the synthesis inequalities of a model-based fuzzy static output feedback PSSs that guarantee robust stability in terms of decay rate and robust performance in terms of H_∞ criterion. Two ILMI algorithms are proposed to find the local controllers. Also, this chapter considers the design of multiobjective fuzzy observer-based output feedback PSS and presents sufficient inequalities for synthesizing such fuzzy PSS. An ILMI algorithm is proposed to solve the latter synthesis problem. Simulation results of the proposed PSS designs tag this chapter. Chapter 5 considers the construction of another T-S fuzzy model and then presents sufficient inequalities for synthesizing multiobjective fuzzy state and output feedback PSSs. The proposed designs guarantee a mix of the pervious control objectives. The design is carried out using different T-S fuzzy models. Moreover, this chapter presents a decentralized scheme to apply these designs in multimachine power systems. Simulations results of a benchmark model of two-area four-machine test power system are presented. Chapter 6 concludes this work and presents a proposal for future work and list of accomplishments and publications.