CHAPTER 1

CHAPTER – 1: INTRODUCTION

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CHAPTER 1

1.1 Introduction

The excitation system exerts a large influence on the stability of the rotor angle of synchronous generators because the generator excitation has faster control capability than the governor control. There have been considerable research efforts put into the design of the generator excitation system both from the academicians and the industry. Regulation of the terminal voltage in the normal and conditions of post-fault operation is the prime purpose of a generator excitation controller. During the end of 1950’s and the initial years of 1960’s with the introduction of the continuously acting voltage regulators (AVR), negative effect of small signals on the stability of power systems’ small signals [2] had been realized due to voltage regulator action. The presence of small magnitude and lower frequency (in the range of 0.1Hz to 2.5Hz) adversely affects power transfer capability on the transmission lines [3]. The system damping performance is improved by modulating the generator excitation voltage employing auxiliary controllers called power system stabilizers (PSS). All the same, it still remains a complex task to effectively synthesise PSS for all sorts of operating conditions due to the varying parameters of the plant caused by the configuration alterations in the network, intricacies involved in figuring out such mathematical models which can offer adequate description of the generator under different conditions of operation, the vastly varying operation conditions
themselves and the possibility of the occurrence of diverse disturbances during normal operation.

Proper tuning can enhance the performance of the fixed-gain PSS using lead-lag compensators [4]. Extensive expertise is required to tune these stabilizers having simple robust structures through simulations of digital systems and providing due validations by actual field tests, in addition to the understanding of the parameters of the system external to the generating station [4], [5], [6]. These parameters could be unavailable immediately or may vastly vary in the process of the power system’s normal operations. Even in the instances of single machine infinite bus model, approximations of equivalent impedance of the line and the voltage existing at the external bus and the computed rotor angle $\delta$ regarding an external bus, at times are not measured directly and require estimation on the basis of reduced order model. The PSS with conventional design causes poor performance of the system due to inaccurate information available for the rest of the system. Almost all the power grids around the world are being operated near the limits of their stability due to enormous increase of demand for electricity. Traditionally the AVR and PSS controllers have been distinctly designed based on linearized models of the power system and as a consequence the desired degree of voltage regulation and enhancement of system stability are often difficult to attain simultaneously [7], [8].

The linearized models which form the basis of the controllers rely on the operating conditions of the system. The controllers perform considerably less in case of any major divergence from the nominal
condition of operation. The need for maintaining a reliable power grid both for the industrial and domestic customers has prompted the researchers to explore various alternative control techniques capable of enhancing the operating range of power systems. Over the years the following broad categories of control techniques have been emerging in the power system control:

- Linear Control Techniques (Linear quadratic Regulator (LQR), pole placement etc.)
- Nonlinear Control Techniques (Adaptive Control, Feedback Linearization, Port Hamiltonian Modelling, etc.)
- Robust Control Techniques ($H_\infty$ Control, Linear Matrix Inequalities etc.)
- Intelligent Control Techniques (Genetic Algorithms, Fuzzy Logic, Neural Networks, Approximate Dynamic programming, Adaptive-Critic, reinforcement learning etc.)

The basic concepts related to the power system rotor angle stability, literature survey related to the power system stabilization using linear control techniques and the motivation for the present thesis work have been discussed in the following sections. The considered definitions are taken from the IEEE / CIGRE Joint Task Force on Stability Terms and Definitions 2004 [9].

1.2 Power System Stability

Power system stability is the capability 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 [9].

**Figure 0-1: Classification of Power System Stability [3]**

The initial conditions of operation and the type of disturbance can be the basis for establishing the system’s stability following a disturbance. Though the stability of the power system is a single problem, it has been classified into three categories for easy comprehension and analysis as displayed in Figure 0-1 and listed below:

1. Rotor Angle Stability
2. Frequency Stability
3. Voltage Stability

Rotor angle stability and voltage stability can be further classified into small-disturbance and large-disturbance stability. Frequency stability and the voltage stability phenomena can be either short term
or long term. However, the rotor angle stability is a short-term phenomenon. The rotor angle stability technique has been employed for power system stability and is presented in detail.

1.2.1 Rotor Angle Stability

Rotor angle stability could be perceived as the capability of synchronous machines to remain in a state of synchronism in an interconnected power system, even after being exposed to conditions of disturbance. It is based on the capability to maintain the condition of equilibrium between the mechanical torque and electromagnetic torque of each specific synchronous machine integrated to the system. The possible resultant instability could manifest in the form of enhanced angular swings of various generators causing loss of synchronism with reference to other generators.

The alterations in electromagnetic torque affected in a synchronous machine after being subjected to a disturbance can be perceived through two components:

- Synchronizing torque component, in association with the deviation of the rotor angle.
- Damping torque component, in association with the deviation of the speed.

The stability of the system relies on the presence of both the elements of torque for every synchronous machine. Absence of required
synchronizing torque causes an intermittent or non-oscillatory instability, while the absence of damping torque leads to oscillatory instability. Rotor angle stability is further sub-categorized into two for the purpose of expediency in analysis and to acquire comprehensive understanding of the nature of problems related to stability.

1.1.1.1. Small-disturbance (or small-signal) rotor angle stability

Stability of this category concerns with the synchronism of the power system under conditions of disturbances insignificant enough that the linearization of system equations can be permitted for analytical purposes[10], [11]. Small-disturbance stability is based on the system’s initial state of operation. The possible resultant instability could exist in two forms:

i) Enhancement in rotor angle through a periodic or non-oscillatory mode - a non-oscillatory or aperiodic mode because of the absence of synchronizing torque, or

ii) Increase in the amplitude of the rotor oscillations because of insufficient damping torque.

In recent power systems the problem of rotor angle stability pertaining to small disturbance concerns largely with the inadequate damping of oscillations. The incessantly functioning regulators of generator voltage can assist in the elimination of the problem of periodic instability. But recurrence of the problem is still possible
during the operation of the generators under constant excitation when conditioned by the behaviour of excitation limiters (field current limiters). In practical power systems, three types of modes (of oscillation) can be found:

- **Intra-plant modes** where a power plant generators alone participate. Here the frequencies of the oscillation are usually high, normally in the ranges of 1.5 to 3.0Hz.

- **Local modes** in which several generators in a denoted area participate. The normal range of frequencies of oscillations here are between 0.8 and 2.8Hz. The stability levels of these oscillations are based on the system’s transmission strength as perceived by the power plant, control systems pertaining to generator excitation and output of the plant.

- **Inter-area modes** where several generators spread over an extensive area participate. The frequencies of oscillation are considerably low and usually are in the range between 0.1 and 0.8Hz. They have very complex characteristics differing significantly from the features of the oscillations of local plant mode. The load related aspects in particular have a great effect on the stability of inter-area modes.

Figure 1-2 shows the scenarios in which the above types of modes manifest in the system. In an ‘m’ machine system there will be ‘m-1’ modes. In the studies of small-disturbance stability the time frame of interest is usually on the scale of 10 to 20 seconds succeeding a disturbance.
1.1.1.2. Large-disturbance rotor angle stability or transient stability

Stability of this category concerns with power system's capability to maintain synchronism in the instances of exposure to severe disturbance such as a short circuit occurring on the lines of transmission. The resultant response of the system entails huge excursions of rotor angles of the generator and is influenced by the relationship of nonlinear power-angle.

Transient stability is based on system's initial state of operation as well as the extent of the disturbance. The manifestation of instability is generally through angular separations from time to time due to inadequate synchronizing torque, apparent as first swing instability [3]. However, transient instability in bigger power systems may not manifest all the times as first swing instability allied with a single mode. The reasons for this could be the superposition of the swing mode of a slow inter-area and the swing mode of a local plant resulting in a large excursion of rotor angle farther than the first swing. It could be consequential to the nonlinear effects influencing a single mode resulting in instability farther than the first swing.
In studies of transient stability the time frame of interest usually is between 3 and 5 seconds subsequent to a disturbance. At times it could be extended to a range of 10 to 20 seconds for very vast systems having strong inter-area swings. The stability of rotor angle of small disturbance as well as the transient stability belong to the same category of short term phenomenon.

1.2.1.1 **Power System Stabilizer**

The behaviour of a power system can be influenced by injecting external signals at suitable points in the system by using feedback controllers. Such controllers [3],[12] can be introduced at ideal facilitating locations in a power system such as the Automatic Voltage Regulator (AVR) loop, the governor loop and the control loops of Flexible AC Transmission System (FACTS) devices.
Avery cost-efficient method of countering the instability problem of the small signal in a power system is the introduction of a feedback signal in conjunction with the deviations of speed, with a phase advance, at the summing junction of the AVR voltage reference input in order to produce further damping torque on the rotor. This auxiliary controller in the AVR loop is called Power System Stabilizer (PSS) [1], [3], [10]. The industry customarily utilizes these power system stabilizers.

1.3 Literature Review

Extensive literature on power system stability phenomenon and the design of stabilizing controllers is available. There are several important books, [3], [2], [10], [13], [14], [15], covering the power system stability phenomenon, analysis, design and tuning of various stabilizing controllers. In [16], [17] The Voltage stability phenomenon has been extensively treated.

In [1], F.P.Demello and C.Concordia, have comprehensively brought out the fundamentals of the traditional and economic solution to the problem of small-signal instability, i.e., the injection of a signal in conjunction with the deviation of speed through a lead compensator, into the summing junction of the excitation system voltage reference input. The design of auxiliary controllers in the AVR loop has received much attention in the research community after this paper. The Heffron-Phillip’s model (also known as K-constant model) developed in [18] is the basis for the analysis presented in [1]. Tuning these compensators poses stiff challenges in a multi-machine system
due to the presence of multiple oscillatory modes. An exhaustive coverage of the broad procedures of tuning for this category of stabilizers is discussed by E.V.Larsen and D.Swan, in their celebrated three part paper [12]. Part I of their paper deals with the general concepts related to the PSS application using different control signals such as rotor speed, ac bus frequency and electrical power. Part II deals with the performance objectives of the PSSs, the operating conditions for which the PSSs are designed. In part III some of the practical considerations and the procedures for applying PSSs are elaborated. Application of these guidelines to a multi-machine system requires the estimation of an equivalent external reactance and the Generator Exciter Plant GEP(s) transfer function.

The industry standard procedures for the PSS design and tuning procedures are discussed by R.G.Farmer and B.L.Agrawal in [6]. The multi-machine Heffron-Phillip’s model has been developed by Bhatti and Hill in [19]. In[20], [21], the design of Delta-P-Omega PSS has been proposed which employs accelerating power signal synthesized from speed and electrical power signals to eliminate the torsional interactions. Development of PSS based on the accelerating power signal for Ontario Hydro generating station has been presented by Lee et al in [22]. Selection of PSS parameters and coordinated tuning procedures for multi-machine systems are discussed in [23], [24], [25], [26], [27]. A detailed design methodology and implementation of PSS in a generating station at Ontario is explained by Kundur et al [28]. The frequency responses of the electrical torques of the generator are
analysed in [29] in the context of multi-machine systems. In [30] the factors influencing the PSS performance and inter-area oscillations have been discussed. The approach of damping torque has been adopted for a coordinated design of the PSS in widely varying conditions of operation in [31], [32]. This method utilizes a transfer function acquired through disabling the dynamics of shaft of each machine between the terminal voltage and the power output (i.e. torque developed) of the generator, called PVR(s) characteristic. Eigenvalue sensitivities, participation factors and transfer function residues have been utilized while designing and placing the power system stabilizers in [33],[34], [35],[36]. The PSS design method based on PVR(s) or residues require the comprehensive system data. There is a corresponding increase in the computational requirements of these methods depending on the increase of the system’s size.

Several researchers investigated the state feedback controllers as a possible alternative to conventional stabilizers [2]. Optimal control theory is implemented in [37], [38] for design purpose of PSS. B. Habibullah and Yao Nan Yu in [39] have developed a linear optimal control that can be realized physically in terms of easily quantifiable state variables for power system’s stabilization. In [40] suboptimal controls are proposed for damping enhancement. Hamdy A. M. Moussa in [53] developed a novel method to resolve Q in phase with a left shift of the dominant eigenvalues as far as the practical controllers permit. A. J. A. Simoes Costa et.al in [41] proposed a decentralized control design exploiting sparsity for large power systems.
S. S. Choi and C.M. Lim in [42] described power system stabilizer’s design using pole placement technique such that a prescribed degree of stability is ensured over a wide range of operation. M.A. Mohan et al. in [43] have proposed eigenvalue placement technique for PSS design. In [54] E.J. Davison and N.S. Rou have proposed output feedback controllers. In [44] K R Padiyar et al. have proposed a pole assignment technique with output feedback for PSS design. D. Arnautovic and J. Medanic in [45] have developed an approach utilizing projective controls in designing multivariable decentralized excitation controllers in power systems having multiple machines. In [46] J.H. Chow and J.J. Sanchez-Gasca have examined the techniques of four pole-placement in designing the power system stabilizers, concentrating on the characteristics of frequency response of these controllers. Though the state feedback controllers in the reviewed references above have demonstrated improved performance over the conventional PSS, they have not experienced adequate realization in practice because in a majority of cases the power system state variables are not quantifiable.

In the design of multi-machine systems, full state feedback controllers need to enforce the constraints of block diagonal structure for the optimal control solution and techniques of model reduction [41], [46], [45] which is computationally intensive for large scale power systems. In [47] Gurunath Gurrala and Indraneel Sen have proposed an apt design for practical applications for the stabilization of power systems, with a possibility to include the multi-machine applications which do not have accurate system information available immediately.
In [48] Gurunath Gurrala and Indraneel Sen have proposed a method for the design of fixed parameter decentralized PSS for inter-connected power systems of multiple machines utilizing such available signals at the generating station on the basis of the modified Heffron Phillip’s model.

1.4 Motivation and Objectives

The focus of this thesis is on the design of decentralized power system stabilizers in the environment of multiple machines making use of the designs of the state feedback control. From the literature review above, it can be comprehended that the state feedback controllers show significant performance improvements in comparison with the conventional lead-lag power system stabilizers. However, the following drawbacks are experienced:

1. The need for external system information.
2. The requirement of the feedback of various other machine states.
3. The need for a model reduction for obtaining a low order controller.
4. The need to enforce the constraints of the block diagonal structure while finding solutions for the control problems.

These drawbacks necessitate the development of new state feedback PSS designs which are simple to design, implement and rely on local information within the power plant. This study attempts to focus on the design possibilities of the state feedback controllers employing the modified Heffron Phillip’s model as proposed in [47], [48]. The modified Heffron Phillip’s model is evolved by considering the step-up transformer’s secondary voltage as reference in place of the voltage of
the infinite bus. The parameters of this model are not based on the equivalent external reactance and the voltage of the infinite bus. Any controller design based on this model can be realized in the field by using the local measurements within the power plant. The objectives of this thesis constitute:

1. Design of decentralized Linear Quadratic Regulators (LQR) for the single machine infinite bus (SMIB) using local measurements.
2. Extension of LQR stabilizers for multi-machine power systems.
3. Design of state feedback power system stabilizers based on the pole placement for SMIB utilizing local measurements.
4. Extension of stabilizers based on pole placement for power systems of multiple machines.

1.5 Thesis Organization

The thesis organization is laid out into seven chapters followed by a chapter-wise summary as detailed below:

**Chapter 1**: General introduction and basic concepts concerning the rotor angle stability are discussed in this chapter. A comprehensive review of the literature related to the present thesis work is reported. Motivations for the present work and objectives of the thesis are summarized.

**Chapter 2**: This chapter highlights the modelling of power systems for state feedback stabilizers the design of which is based on modified Heffron Phillip’s model [47], [48]. The chapter also presents the
development of the mathematical model based on modified Heffron
Phillip’s model.

**Chapter 3**: An investigation of the design of Linear Quadratic Power
System Stabilizers adopting the modified Heffron Phillip’s model is
encapsulated in this chapter. It permits a simple design of linear
quadratic control because the state variables of this model can be
secured through local measurements. The LQR stabilizers are derived
for an SMIB system and the performance is validated over diverse
conditions of operation.

**Chapter 4**: In this chapter the proposed LQR stabilizer design is
further extended to power systems with multiple machines. The
performance of the proposed controller has been evaluated on two
extensively employed multi-machine power systems, 4 generators 10
bus system and 10 generator 39 bus system.

**Chapter 5**: The designs of power system stabilizers based on pole
placement are noted for their enhanced capabilities of control in
comparison with the conventional lead-lag power system stabilizers.
This chapter offers a novel approach for PSS based on pole placement
relying on the modified Heffron Phillip’s model. The proposed controller
is evaluated for its performance on a single machine infinite bus system
in varying conditions of operation.

**Chapter 6**: In this chapter, the proposed pole placement design is
extended to multi-machine power systems. The performance of the
proposed controller is evaluated on 10 generator 39 bus multi-machine
system over a wide range of operating conditions.
Chapter 7: This chapter draws the conclusions of the thesis providing a summary of the contributions besides projecting the scope for the possible extension of the work in future.