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ROBUST CONTROL IN POWER SYSTEMS

BIKASH PAL
Imperial College London

BALARKO CHAUDHURI
Imperial College London

Springer

Bikash Pal
Imperial College London

Balarko Chaudhuri
Imperial College London

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Dedicated to our Parents

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Preface

The aim of this monograph is to make a comprehensive presentation of recent research into the application of linear robust control theory to the damping of inter-area oscillations in power systems with FACTS devices. The subject is introduced with an overview of the application of power system stabilizers (PSS) and their coordination as described in the existing literature.

The monograph is directed at engineers engaged in the research, design and development of power systems with particular concern for power system stability and a background knowledge in this area is assumed. Reference books that are particularly relevant are:

Power System Stability and Control: Kundur 1994
Power System Dynamics and Stability: Sauer and Pai 1998
Multivariable Feedback Control: Skogestad and Postlethwaite 2001

Power System Oscillations by Rogers (2000) is also relevant as an introduction since it is focused on the application of PSS to damp local and inter-area oscillations.

A brief historical account of oscillatory behavior in power systems is given in chapter 2. The analytic tools that are commonly used in small-signal stability analysis are presented in chapter 3 and chapter 4 contains a description of the components participating in interarea oscillations including FACTS devices:

Static VAr capacitors (SVC)
Thyristor-controlled series capacitors (TCSC)
Thyristor-controlled phase shifters (TCPS)

The system model which is used to test damping controller designs is described in chapter 4.

Chapter 5 provides an overview of power system stabilizers (PSS) in a power system. The intention is to develop understanding and requirement of control design through damping torque concepts initially on a single machine infinite bus (SMIB) system. The extension of damping torque to the multi-machine system and different ways to achieve gain and phase compensation circuits used for PSS are discussed in the later part of this chapter.

A multiple-model based controller design is given in chapter 6 and chapter 7. A probability weighted approach is used to integrate the action of several controllers to give multiple-model adaptive control (MMAC). In chapter 7, a robust pole-placement approach giving eigenvalue distance minimization is used. Both methods address the robustness of the control schemes.

The $\mathcal{H}_\infty$ norm optimization is central to the controller design approaches in chapter 8 through 11. In chapter 8, a standard weighted mixed sensitivity optimization is made and a suitable set of linear matrix inequalities (LMI) being obtained numerically. Minimum closed-loop damping is ensured by pole-placement being taken as an additional LMI constraint.

In chapter 9, a left-coprime factorization approach gives a centralized control structure for a properly-shaped open loop plant using a loop-shaping technique. Again the numerical solution is obtained through LMI.

The effect of signal transmission delay on damping control is considered in chapter 10. A weighted-mixed sensitivity approach to the design of the central control structure is extended to include a delay in the output signal. Predictor techniques have been used in the controller design to obtain an $\mathcal{H}_\infty$ controller.

In all the above designs, robust damping for varying power level and changing network topology is confirmed by eigenvalue analysis and time-domain nonlinear simulations have been made to demonstrate the validity of the designs.

BIKASH PAL AND BALARKO CHAUDHURI

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Foreword

Low frequency electromechanical oscillations, with frequencies ranging from 0.1 to 2 Hz, are inherent to electric power systems. Problems due to inadequate damping of such oscillations have been encountered throughout the history of power systems. The earliest problems, which were experienced in the 1920s, were in the form of spontaneous oscillations or hunting. These were solved by the use of damper windings in the generators and turbine-type prime movers with favorable torque speed characteristics.

As power systems evolved, they were operated ever closer to transient and small-signal rotor angle stability limits. System stability characteristics were largely influenced by the strength of the transmission network, and the lack of sufficient synchronizing torque was the principal cause of system instability. The application of continuously acting voltage regulators contributed to the improvement in small-signal (or steady-state) stability. In the 1950s and 1960s, utilities were primarily concerned with transient stability. However, this situation has gradually changed since the late 1960s. Significant improvements in transient stability performance have been achieved through the use of high response exciters and special stability aids.

The above trends have been accompanied by an increased tendency of power systems to exhibit oscillatory instability. High response exciters, while improving transient stability, adversely affect the damping of local plant modes of oscillation, which have frequencies ranging from 0.8 to 2 Hz. The effects of fast exciters are compounded by the decreasing strength of transmission network relative to the size of generating stations. Adequate damping of local plant mode oscillations can be readily achieved by using power system stabilizers to modulate generator excitation controls.

Another source of oscillatory instability has been the formation of large groups of loosely coupled machines connected by weak links. This situation has developed as a consequence of growth in interconnections among power systems. With heavy power transfers, such systems exhibit inter-area modes of oscillation of low frequency. The stability of these modes has become a source of concern in today's power systems. There have been many reported occurrences of poorly damped or unstable inter-area oscillations. In some cases, this form of oscillatory instability has been the cause of major system blackouts. Large interconnected power systems usually exhibit several dominant modes of inter-area oscillations with frequencies ranging from 0.1 Hz to 0.8 Hz.

The use of supplementary controls is generally the only practical method of mitigating inter-area oscillation problems, without resorting to costly operating restrictions or transmission reinforcements. A number of power system devices have the potential for contributing to the damping of the oscillations by supplemental control. The use of power system stabilizers to control excitation of generators is often the most cost-effective method. The controllability of the inter-area modes of oscillation through excitation control is a function of many factors: location of the generator in relation to the oscillation mode shape, size and characteristics of nearby loads, and types of exciters on other nearby generators.

Supplemental stabilizing signals may also be used to control HVDC transmission links and SVCs to enhance damping of inter-area oscillations, depending on their location. While these devices are installed based primarily on other system considerations, their potential for controlling poorly damped system oscillations are often taken advantage of; many HVDC transmission and SVC installations are equipped with special modulation controls to stabilize inter-area oscillations.

In recent years, there has been considerable interest in the application of power electronic devices for enhancing the controllability, and hence the power transfer capability, of ac transmission; this concept is referred to as "FACTS" (Flexible AC Transmission System). The FACTS devices can provide fast continuous control of power flow in the transmission system by controlling voltages at critical buses, by changing the impedance of transmission lines, or by controlling the phase angles between the ends of transmission lines. This is an extension of the concept used by SVCs for enhancing transmission system capacity by rapid control of bus voltages. Apart from the SVC, two FACTS devices that can be effectively used for damping of system oscillations are the thyristor controlled series capacitor (TCSC) and the thyristor controlled phase angle regulator (TCPAR). FACTS devices, depending on the power system configuration and nature of the inter-area oscillations, may offer the most economic means of mitigating the problems.

A number of approaches and techniques are available for the design of controls for damping of inter-area oscillations. One important issue in the design and performance of the controllers is robustness. The controller should perform the desired function over the wide range of conditions encountered in the