ELECTRIC POWER RESEARCH INSTITUTE

Power System
Engineering Series

Power System Stability and Control

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POWER SYSTEM STABILITY AND CONTROL

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The EPRI Power System Engineering Series

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Power System Stability and Control

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Dedicated to My Parents

Foreword

To paraphrase the renowned electrical engineer, Charles Steinmetz, the North American interconnected power system is the largest and most complex machine ever devised by man. It is truly amazing that such a system has operated with a high degree of reliability for over a century.

The robustness of a power system is measured by the ability of the system to operate in a state of equilibrium under normal and perturbed conditions. Power system stability deals with the study of the behavior of power systems under conditions such as sudden changes in load or generation or short circuits on transmission lines. A power system is said to be stable if the interconnected generating units remain in synchronism.

The ability of a power system to maintain stability depends to a large extent on the controls available on the system to damp the electromechanical oscillations. Hence, the study and design of controls are very important.

Of all the complex phenomena on power systems, power system stability is the most intricate to understand and challenging to analyze. Electric power systems of the 21st century will present an even more formidable challenge as they are forced to operate closer to their stability limits.

I cannot think of a more qualified person than Dr. Prabha Kundur to write a book on power system stability and control. Dr. Kundur is an internationally recognized authority on power system stability. His expertise and practical experience in developing solutions to stability problems is second to none. Dr. Kundur not only has a thorough grasp of the fundamental concepts but also has worked on solving electric utility system stability problems worldwide. He has taught many courses, made excellent presentations at professional society and industry committee meetings,

and has written numerous technical papers on power system stability and control.

It gives me great pleasure to write the Foreword for this timely book, which I am confident will be of great value to practicing engineers and students in the field of power engineering.

Dr. Neal J. Balu
Program Manager
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Preface

This book is concerned with understanding, modelling, analyzing, and mitigating power system stability and control problems. Such problems constitute very important considerations in the planning, design, and operation of modern power systems. The complexity of power systems is continually increasing because of the growth in interconnections and use of new technologies. At the same time, financial and regulatory constraints have forced utilities to operate the systems nearly at stability limits. These two factors have created new types of stability problems. Greater reliance is, therefore, being placed on the use of special control aids to enhance system security, facilitate economic design, and provide greater flexibility of system operation. In addition, advances in computer technology, numerical analysis, control theory, and equipment modelling have contributed to the development of improved analytical tools and better system-design procedures. The primary motivation for writing this book has been to describe these new developments and to provide a comprehensive treatment of the subject.

The text presented in this book draws together material on power system stability and control from many sources: graduate courses I have taught at the University of Toronto since 1979, several EPRI research projects (RP1208, RP2447, RP3040, RP3141, RP4000, RP849, and RP997) with which I have been closely associated, and a vast number of technical papers published by the IEEE, IEE, and CIGRE.

This book is intended to meet the needs of practicing engineers associated with the electric utility industry as well as those of graduate students and researchers. Books on this subject are at least 15 years old; some well-known books are 30 to 40 years old. In the absence of a comprehensive text, courses on power system stability

often tend to address narrow aspects of the subject with emphasis on special analytical techniques. Moreover, both the teaching staff and students do not have ready access to information on the practical aspects. Since the subject requires an understanding of a wide range of areas, practicing engineers just entering this field are faced with the formidable task of gathering the necessary information from widely scattered sources.

This book attempts to fill the gap by providing the necessary fundamentals, explaining the practical aspects, and giving an integrated treatment of the latest developments in modelling techniques and analytical tools. It is divided into three parts. Part I provides general background information in two chapters. Chapter 1 describes the structure of modern power systems and identifies different levels of control. Chapter 2 introduces the stability problem and provides basic concepts, definitions, and classification.

Part II of the book, comprising Chapters 3 to 11, is devoted to equipment characteristics and modelling. System stability is affected by the characteristics of every major element of the power system. A knowledge of the physical characteristics of the individual elements and their capabilities is essential for the understanding of system stability. The representation of these elements by means of appropriate mathematical models is critical to the analysis of stability. Chapters 3 to 10 are devoted to generators, excitation systems, prime movers, ac and dc transmission, and system loads. Chapter 11 describes the principles of active power and reactive power control and develops models for the control equipment.

Part III, comprising Chapters 12 to 17, considers different categories of power system stability. Emphasis is placed on physical understanding of many facets of the stability phenomena. Methods of analysis along with control measures for mitigation of stability problems are described in detail.

The notions of power system stability and power system control are closely related. The overall controls in a power system are highly distributed in a hierarchical structure. System stability is strongly influenced by these controls.

In each chapter, the theory is developed from simple beginnings and is gradually evolved so that it can be applied to complex practical situations. This is supplemented by a large number of illustrative examples. Wherever appropriate, historical perspectives and past experiences are highlighted.

Because this is the first edition, it is likely that some aspects of the subject may not be adequately covered. It is also likely that there may be some errors, typographical or otherwise. I welcome feedback on such errors as well as suggestions for improvements in the event that a second edition should be published.

I am indebted to many people who assisted me in the preparation of this book. Baofu Gao and Sainath Moorty helped me with many of the calculations and computer simulations included in the book. Kip Morison, Solomon Yirga, Meir Klein, Chi Tang, and Deepa Kundur also helped me with some of the results presented.

Atef Morched, Kip Morison, Ernie Neudorf, Graham Rogers, David Wong, Hamid Hamadanizadeh, Behnam Danai, Saeed Arabi, and Lew Rubino reviewed various chapters of the book and provided valuable comments.

David Lee reviewed Chapters 8 and 9 and provided valuable comments and suggestions. I have worked very closely with Mr. Lee for the last 22 years on a number of complex power system stability-related problems; the results of our joint effort are reflected in various parts of the book.

Carson Taylor reviewed the manuscript and provided many helpful suggestions for improving the text. In addition, many stimulating discussions I have had with Mr. Taylor, Dr. Charles Concordia, and with Mr. Yakout Mansour helped me develop a better perspective of current and future needs of power system stability analysis.

Patti Scott and Christine Hebscher edited the first draft of the manuscript. Janet Kibblewhite edited the final draft and suggested many improvements.

I am deeply indebted to Lei Wang and his wife, Xiaolu Meng, for their outstanding work in the preparation of the manuscript, including the illustrations.

I wish to take this opportunity to express my gratitude to Mr. Paul L. Dandeno for the encouragement he gave me and the confidence he showed in me during the early part of my career at Ontario Hydro. It is because of him that I joined the electric utility industry and then ventured into the many areas of power system dynamic performance covered in this book.

I am grateful to the Electric Power Research Institute for sponsoring this book. In particular, I am thankful to Dr. Neal Balu and Mr. Mark Lauby for their inspiration and support. Mark Lauby also reviewed the manuscript and provided many helpful suggestions.

I wish to express my appreciation to Liz Doherty and Patty Jones for helping me with the correspondence and other business matters related to this book.

Finally, I wish to thank my wife, Geetha Kundur, for her unfailing support and patience during the many months I worked on this book.

Prabha Shankar Kundur

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