ELECTRIC POWER RESEARCH INSTITUTE
Power System Engineering series

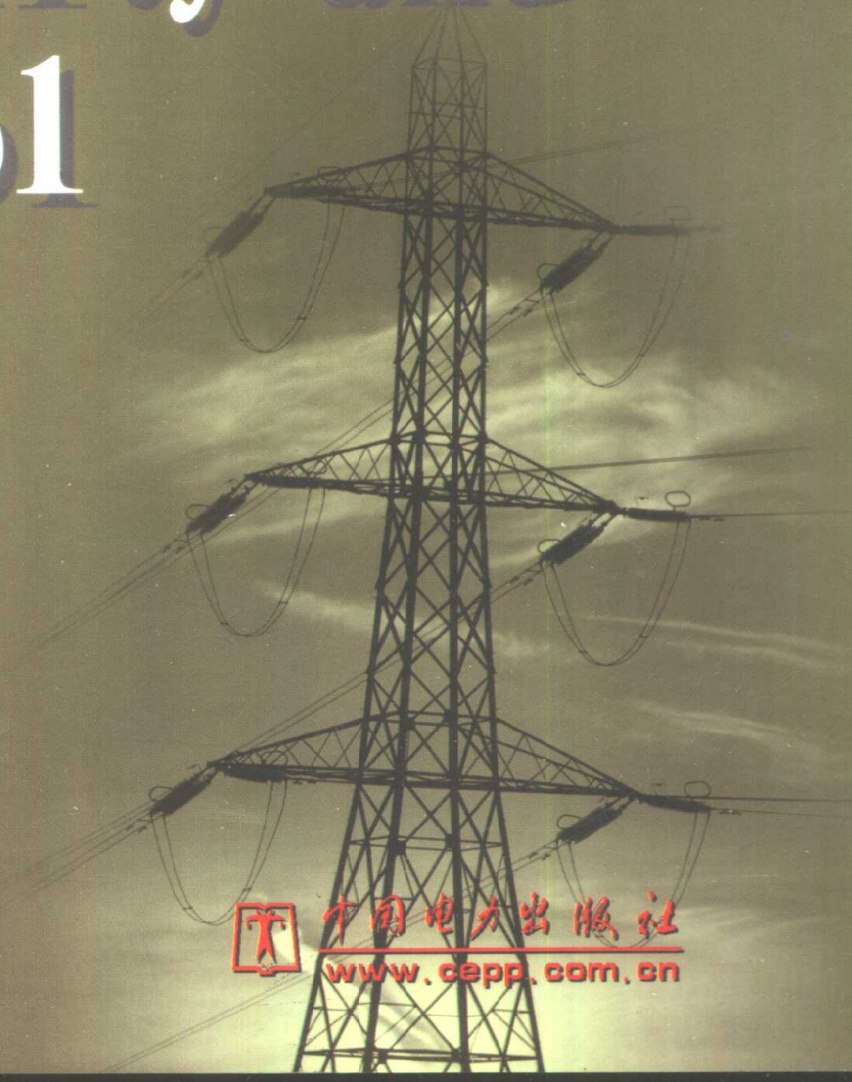
EPRI 电力系统工程丛书

电力系统稳定与控制

（影印版）

Power System Stability and Control

PRABHA KUNDUR



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Power System Stability and Control

影印版序一

电力系统稳定性的破坏，往往会导致电力系统的解列和崩溃，发生大面积的停电，造成巨大的社会影响和经济损失。所以，电力系统稳定性在电力系统的规划设计和实际运行中都是需要十分仔细考虑的问题，是保证电力系统安全稳定运行的必要条件。

半个多世纪以来，人们从电力系统运行的实际出发，对电力系统的静态和暂态稳定性进行了大量的理论和实验研究，取得了很大成绩，为电力系统的安全稳定运行奠定了坚实基础。

电力系统稳定性是一个非常复杂的非线性问题，现代数学、控制理论、计算机等先进科学和技术的发展，为电力系统稳定性的研究提供了理论依据和实践手段。

本书的作者 P.Kundur 教授长期从事电力系统稳定性的研究。根据他多年来对电力系统稳定性的研究和实践，在系统总结各国电力系统稳定性的最新研究成果的基础上，撰写了 Power System Stability and Control（1994 年 McGraw-Hill Inc. 出版）一书。该书条理清晰，内容丰富，为读者提供了对电力系统稳定性问题的物理描述，理论的表达和评价；讨论了实际工作中有兴趣的问题，如同步电机和负荷的模型，提高稳定性的方法等；还从基本理论出发，系统和深入地阐明了电力系统稳定性的计算原理，提供了广泛的分析计算方法。

全书分为三部分，共 17 章。第一部分概述了现代电力系统的一般特性，介绍电力系统稳定性的基本概念和定义，提出电力系统稳定性的分类，并对电力系统各种稳定性问题做了简要说明。第二部分介绍了电力系统各种主要元件的特性和模拟方法，包括同步电机、输电线、负荷、励磁系统、原动机和一次能源系统、高压直流输电以及有功和无功功率的控制。第三部分是全书的核心，深入地论述了电力系统的功角稳定性（包括小干扰稳定性和暂态稳定性）、电压稳定性、次同步振荡、中长期稳定性，以及各种提高稳定性的措施。在全书的重要章节后均附有相应的算例或仿真计算的结果。

影印本书将为我国电力系统及其自动化专业的本科和研究生提供一本很好的教学参考书，同时也是电力系统工程领域的工程技术人员的一本很好的自学用书，书中的主要内容对电力系统的规划和运行也有一定的指导意义。

韩祯祥
浙江大学电机系
2001 年 8 月

Power System Stability and Control

影印版序二

由 Prabha Shankar Kundur 编著的 Power System Stability and Control 是美国电力研究院（EPRI）电力系统工程丛书之一，是二十年以来全面、系统而综合地阐述电力系统稳定和控制问题的一本巨著。

近年来，系统互联和新技术的采用使电力系统日益复杂。经济上的考虑使系统运行更接近稳定边界。这两方面因素使电力系统必须依靠特殊控制以保证安全性，对设计的经济性以及运行的灵活性也提出了更高要求。另一方面随着计算机技术、数值分析、控制理论和设备建模等学科上的发展使分析工具和系统设计过程都有很大改善。本书内容反映了上述这些科学和技术的进步。

本书论述了电力系统稳定和控制问题的原理、建模、分析和调节。其特点是不仅具有一定的理论深度，更紧密结合电力系统工程实际。无论作为电力系统有关专业研究生的教材，还是作为工程技术人员和研究人员的主要参考资料，本书都得到了高度评价。

本书的第一部分为引言和概论，包括两章。第一章介绍现代电力系统的特点。第二章为电力系统稳定问题概论。

第二部分包括第三到十一章，阐述电力系统主要设备及其建模：其中包括同步发电机理论、模型和参数以及在稳定研究中的表示方法；交流输电线路；电力系统负荷；励磁系统；原动机和能源系统；高压直流输电；第十一章专门论述了有功功率与频率的控制以及无功功率与电压的控制。

第三部分包括第十二到十七章，讨论不同类型的电力系统稳定问题：小信号稳定，暂态稳定，电压稳定，次同步振荡和中长期稳定，最后还介绍了现有各种改善稳定性的方法。电力系统稳定性的概念和电力系统控制的概念是密切相关的。对电力系统总体的控制实际上是高度分散在分层递阶结构的各个层次上，系统的稳定性很大程度上受到这些控制的影响。

感谢中国电力出版社肖兰、刘宇峰、邓春等编辑热情工作，使本书的影印版得以早日问世。这对我们研究生教学和我国电力系统的技术工作都将是一个很大的支持和帮助。

陈　陈

上海交通大学

2001 年 8 月

Power System Stability and Control

影印版序三

由 Prabha Kunder 编著的 Power System Stability and Control 一书是美国电力科学研究院（EPRI）组织出版的“电力系统工程丛书”之一，是这一领域的重要代表性著作，在国际学术界和工程界享有盛誉，影响深远。

电力系统稳定和控制一直是基础理论和工程实践的热门问题。随着世界电力系统的不断发展，电网大范围互联，电力电子等新工艺的应用和电力市场的改革要求，对电力系统的规划、设计和运行提出很多新的问题和要求。电力系统的稳定和控制如何适应这种新形势，就是特别突出的问题。我国有大量科技工作者在从事这一领域的实际规划运行和科学研究工作。他们迫切需要充实和更新其理论和应用知识，以适应现代电力系统发展的要求。

国际上关于电力系统稳定方面的专著，大都出版时间较早，对电力系统的近期进展和科技进步成果未能充分纳入。我国近期曾出版一些有关著作，但大多是侧重某一领域的研究成果或实践经验，还缺乏全面的、系统的、能充分反映现代电力系统技术发展的、理论联系实际的著作。

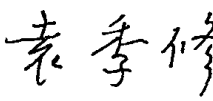
P.Kundur 的这本著作全面介绍了电力系统稳定的基本理论、建模技术、分析方法和提高系统稳定的控制措施。作者是这一领域的国际著名专家，曾在北美的大电力企业、研究机构和高等学校长期从事电力系统稳定分析和提高稳定措施的研究和生产实践工作，积累了丰富的经验，曾发表大量有关论文。本书是作者总结国际上发表的大量有关文献、EPRI 的研究报告和作者本人的研究及工作成果而完成的著作，它充分反映了现代电力系统的发展成果，既系统深入介绍了电力系统稳定的有关理论基础，又给出了实际可用的数学模型和分析方法。这是一本我国学术界和工程界迫切需要，预期可起重要作用的著作。

本书分为三部分：第一部分（1、2 两章）为总的背景介绍。叙述现代电力系统的结构及要求的控制管理水平，介绍系统稳定的基本概念，给出定义和分类。第二部分（3～11 章）为设备特性描述和建模。电力系统中各主要元件的物理特性和工作能力对于了解和分析电力系统稳定是至关重要的。书中对发电机、励磁系统、原动机、交流输电线路及变压器、负荷和高压直流系统等的性能进行了详细、经典的数学描述，分析了各种因素的影响，进而给出了严谨、适用的数学模型及相关参数。同时还介绍了潮流计算、有功和无功功率控制等基本概念和方法。第三部分（12～17 章）是介绍电力系统中各种稳定的性质和分析方法。书中对电力系统的小信号稳定、暂态稳定、电压稳定、中期及长期稳定、次同步谐振等的物理现象、理论基础、分析方法都给出了详细介绍和示例。同时还对提高系统稳定的各类控制措施的机理

和效果进行了概要介绍，如改善暂态稳定的快速清除故障、单相重合闸、串联及并联补偿、切机及快速控制汽门、快速及离散励磁控制、解列及切负荷等，改善小干扰稳定的 PSS 及 HVDC 调制等。

本书的特点是既包括电力系统稳定的传统技术，又包括系统发展提出的许多新的稳定问题，如小信号稳定、电压稳定和次同步谐振等以及相应的新分析方法和处理对策。这正是我国当前电力系统发展中一些迫切需要解决，但广大科技工作者还不是很熟悉的问题。本书的叙述从较基本的概念和简单数学分析开始，逐渐深入到较复杂的动态过程和现代控制理论，有较严谨的数学分析，但又避免使用过于艰深的数学理论。这既能适应初学者的要求，又能满足有一定基础的科技人员的提高要求。特别是书中的数学模型和分析方法一般是适合实际工程使用的，因而对电力系统中从事实际工作的广大的工程技术人员非常具有吸引力。

影印本书可以作为电力系统科技人员提高理论水平和实践能力的高等培训教材和参考书，也可作为高校电力系统专业高年级和研究生的教学参考书。



2001 年 8 月

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
Power System Planning and Operations
Electrical Systems Division
Electric Power Research Institute

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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PART II EQUIPMENT CHARACTERISTICS AND MODELLING