Analysis and Control System Techniques for Electric Power Systems

Part 1 of 4

CONTROL AND DYNAMIC SYSTEMS

ADVANCES IN THEORY AND APPLICATIONS

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VOLUME 41: ANALYSIS AND CONTROL SYSTEM TECHNIQUES FOR ELECTRIC POWER SYSTEMS

Part 1 of 4

ACADEMIC PRESS, INC.
Harcourt Brace Jovanovich, Publishers
San Diego New York Boston
London Sydney Tokyo Toronto

Academic Press Rapid Manuscript Reproduction

This book is printed on acid-free paper. ∞

Academic Press, Inc.
San Diego, California 92101

United Kingdom Edition published by
ACADEMIC PRESS LIMITED
24-28 Oval Road, London NW1 7DX

Library of Congress Catalog Card Number: 64-8027

ISBN 0-12-012741-5 (alk. paper)

PRINTED IN THE UNITED STATES OF AMERICA
91 92 93 94 9 8 7 6 5 4 3 2 1

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Advances in Theory and Applications

Volume 41

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PREFACE

Research and development in electric power systems analysis and control techniques has been an area of significant activity for decades. However, because of increasingly powerful advances in techniques and technology, the activity in electric power systems analysis and control techniques has increased significantly over the past decade and continues to do so at an expanding rate because of the great economic significance of this field. Major centers of research and development in electrical power systems continue to grow and expand because of the great complexity, challenges, and significance of this field. These centers have become focal points for the brilliant research efforts of many academicians and industrial professionals and the exchange of ideas between these individuals. As a result, this is a particularly appropriate time to treat advances in the many issues and modern techniques involved in electric power systems in this international series. Thus, this is the first volume of a four volume sequence in this series devoted to the significant theme of "Analysis and Control Techniques for Electric Power Systems." The broad topics involved include transmission line and transformer modeling. Since the issues in these two fields are rather well in hand, although advances continue to be made, this four volume sequence will focus on advances in areas including power flow analysis, economic operation of power systems, generator modeling, power system stability, voltage and power control techniques, and system protection, among others.

The first contribution to this volume, "Modern Approaches to Modeling and Control of Electric Power Systems," by Marija Ilić, is a rather comprehensive assessment of the present state of the art of controlling large-scale electric power systems. Numerous significant avenues for research that will enable power systems of the future to meet new needs are presented. Professor Ilić, an outstanding figure on the international scene of activity in analysis and control techniques for electric power systems, has provided a remarkably comprehensive and incisive treatment of the many complex and significant issues for the broad theme of these four companion volumes, an outstanding contribution to set the stage for these four volumes.

The next contribution, "Dynamic State Estimation Techniques for Large-Scale Electric Power Systems," by P. Rousseaux and M. Pavella, deals with the issue of state estimation techniques that play a key role in the economic and secure operation of electric power systems. This requires advanced large-scale system techniques, furnishing the so-called energy management functions installed in the utility control centers. To run these functions in real time, it is necessary to dispose of a reliable, complete, and coherent database which is provided by a state estimator whose primary objective is to estimate the system state from (redundant) real-time measurements, together with information gathered on the network topology and status of protection devices. Presently, the state of the art in electric power systems is such that the estimation process is carried out by a static state estimator when, in fact, the complex electric power systems involved are dynamic systems. This contribution presents significant new techniques for dynamic state estimation for large-scale electric power systems, which can surely be expected to be the way that this issue will be addressed in the future. Simulation results are presented that confirm the power and significance of these new techniques.

The next contribution, "Optimal Power Flow Algorithms," by Hans Glavitsch and Rainer Bacher, presents important techniques for dealing with the highly complex nonlinear equations with system constraints that must be solved for the optimal power flow problem. Present requirements in large-scale electric power systems are aimed at solution methods suitable for computer implementations that are easy to handle, are capable of dealing with large systems, and that can rapidly converge to the solution. This important contribution to this series of volumes presents a thorough formulation of the optimal power flow problem and techniques that lend themselves to the efficient application of proven optimization methods, with the emphasis on the fact that we are dealing here with large-scale complex systems.

The next contribution, "Sparsity in Large-Scale Network Computation," by Fernando L. Alvarado, William F. Tinney, and Mark K. Enns, presents an in-depth and comprehensive review and analysis of techniques for sparse matrices, particularly as they relate to and are essential for dealing with large-scale electric power systems. Many problems in power systems result in formulations that require the use of large, sparse matrices. Well-known problems that fit this category include the so-called classic three: power flow, short circuit, and transient stability. To this list can be added numerous other important system problems: electromagnetic transients, economic dispatch, optimal power flows, state estimation, and contingency studies, just to name a few. As a result, this is a key contribution to this series of four volumes, as is, in fact, the case with all the other contributions.

Throughout the literature on analysis and control techniques for large-scale electric power systems, methods and techniques for decentralized control are presented as a means for efficiently and safely dealing with the problems of very substantive computational complexity that are so prevalently characteristic of such systems. The next contribution, "Techniques for Decentralized Control for Interconnected Systems," by Seog Chae and Zeungnam Bien, presents a comprehensive review and analysis of the techniques in this broad area. Some new techniques and methods that deal effectively with some of the limitations of results presented to date are also discussed.

The role of expert systems or knowledge based systems, when properly applied, can not only be a powerful means for dealing with complex systems problems but, indeed, as some classic examples make manifest, can be virtually essential. Specifically, the Chernobyl disaster occurred at about 1:45 a.m., when perhaps the system operators were tired and as a result somewhat less alert. An effectively designed knowledge based system, properly monitored by human operators and also properly alleviating some of the demands on "tired" system operators, could surely have been expected to avoid the Chernobyl disaster. The next contribution, "Knowledge Based Systems for Power System Security Assessment," by Richard D. Christie, presents techniques in this significant area and demonstrates their utility in on-line security assessment for electric power systems.

The rapid advances in technology are making many truly remarkable things possible, and, of course, these trends can be expected to continue. Neural networks are among the most interesting examples of this phenomenon. The next contribution, "Neural Networks and Their Application to Power Engineering," by Mohamed A. El-Sharkawi, Robert J. Marks II, and Siri Weerasooriya, provides an excellent, rather self-contained, tutorial on neural networks and demonstrates the potential power of their utility in electric power systems. Specifically, neural network applications have been broadly categorized in the literature under three main areas: regression, classification, and combinatorial optimization. In electric power systems, the applications involving regression include transient stability, load forecasting, synchronous machine modeling, contingency screening, and harmonic evolution. Applications involving classification include harmonic load identification, alarm processing, static security assessment, and dynamic security assessment. In the area of combinatorial optimization there are topological observability and capacitor control. Because of the richly significant potential of the role that neural networks can play in electic power systems, this is a particularly fitting chapter with which to conclude this first volume of this four volume sequence.

This volume is a particularly appropriate one as the first of a companion set of four volumes on analysis and control techniques in electric power systems. The authors are all to be commended for their superb contributions, which will provide a significant reference source for workers on the international scene for years to come.

CONTENTS

MODERN APPROACHES TO MODELING AND CONTROL OF ELECTRIC POWER SYSTEMS

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I. INTRODUCTION

The main purpose of this chapter is to assess the present state of the art of controlling large-scale electric power systems as well as to indicate avenues for research that would enable power systems of the future to meet new needs.

A primary objective of controls distributed throughout large electric power systems is to maintain frequency and voltages within allowable constraints as operating conditions on the system change. Under normal operating conditions, controls are expected to regulate system performance so that energy cost is minimized. When the system is subject to severe disturbances in its inputs and structure, controls are considered to be remedial tools that should act in unison to preserve system integrity and remedy the effects of a disturbance.

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Most utilities employ a two-level approach to power control: a secondary level, at which systemwide changes are monitored in Energy Management Systems (EMS), and a primary (local) level, where information from the EMS is used by a human operator to make decisions about setting reference points at particular control locations or about switching in more power support. Specific control tools are activated at the primary level to maintain desired local set points. These could be activated manually or automatically—for instance, governors, under load tap changing transformers (ULTCs), capacitor banks, and automatic voltage regulators (AVRs). If the tools are automated, they are often time-set to begin functioning at a time when load changes are expected, rather than being triggered by changes in the state of the system. At present, many power systems throughout the world are undergoing changes, for various reasons. This calls for exploring the potential of control tools that would respond more flexibly than they do now to changes in system state.

It is the premise of this chapter that many systems possess a certain amount of power reserves, which could be summoned in proper amounts and in response to system state changes to help achieve better system performance. It is believed that more adaptive control design could improve overall performance and slow down a rather expensive trend toward implementing excessive amounts of new power support on systems. (Even now, operational power resources could be equipped with more flexible microprocessor and electronics-based controls.) However, theoretical work to support such efforts is not simple and could be harmful if the theoretical assumptions do not adequately model the operating power system.

A detailed survey of the existing power control literature offers ideas ranging from those that view control problems as exclusively systemwide to those that would apply controls only at locations where a state violation is present. The latter thinking is based on the assumption that power changes do not have systemwide effects, primarily because of large power losses. This chapter seeks to put earlier work in perspective and to suggest open questions in this area. A system theoretic formulation is emphasized.

II. TRADITIONAL VIEW

Large-scale electric power systems are extremely complex, so up to now they have been designed very conservatively, to operate well within the region where dynamic problems would be unlikely to occur. The inputs to such systems have traditionally been viewed as quasi-stationary, that is, as long as first-generation inputs are adjusted for anticipated load demands, no dynamic problems are likely to occur.

The main emphasis in such normal system operation is on the most economical scheduling of events; cost is measured in terms of total generation cost of a single utility. In a multiutility environment, automatic generation control (AGC) is used to ensure economical operation. AGC, devised not by a control theorist but by an engineer, is one of the foremost examples of successful automatic control. Section III.7 discusses its contribution to the regulation of large-scale systems.

A typical way to ensure that the system does not experience serious problems when subject to sudden disturbances (contingencies) has been to perform off-line simulations of system responses to the most critical (frequent or serious) single outages and then, by trial and error combined with operator insight, to devise countermeasures to be taken in case such an outage occurs. Often, during the fault specification, system variable limits are relaxed. This approach known as preventive control approach, rather than on-line control, is very much ingrained in the current philosophy of operating interconnected systems.

Under such quasi-static conditions, not much challenge would appear to be left in operating a large-scale system. Computer-based software is viewed as useful for off-line studies, in preparation for actual events. The only time critical actions are called for in this kind of operation is when a sequence of unplanned changes takes place, as happened for instance, during the 1968 New York blackout. As such events unfold, operator actions or preventive type computer-assisted software do not suffice to establish control. Usually, such events are further complicated by human errors or equipment malfunctioning, and it is almost impossible to predict the proper constellation of automatic controls for such situations. In such extreme scenarios, modern control techniques often have not been very helpful because the underlying theoretical assumptions have not been valid. For instance, while many theoretical solutions do not take into account limits on controls and states, implemented on the actual system through a variety of protection devices, many out-of-control situations may have arisen because of the system's exceeding the limits of the controlling devices.

III. POWER SYSTEMS OF TODAY

The power systems of today require more dynamic operating conditions than in the past, and the trend has been in this direction, beginning with the Public Utilities Regulatory Policy Act (PURPA) [1], which allows privately owned generators to sell electricity into the electric power system and requires that utilities buy it. Two changes apparent in modern power system operation are the presence in the single utility setting of non-utility-owned generators (NUGs), and the increase in the multiutility environment of unusual modes of energy trades.

The NUGs are smaller and more dispersed without having firm obligations to supply minimum energy continuously, and their price-driven load management could move what used to be a nominal operating point closer to steady-state stability margins [2]. This means that if an unplanned change (including an outage) occurs, system response will not be identical to the response anticipated by off-line simulations that did not include effects of NUG's. There is a great deal of concern about the impact of NUGs on the dynamics of power systems, particularly if their numbers continue to increase. Clearly, under such conditions, controls must become more responsive to system state changes.

The situation is even more complex in a multiutility environment, where unusual modes of energy trades, such as a wheeling mode [3], are becoming a regular part of economics. In the past, interutility energy trades have been well understood and fully automated by AGC and load frequency control solutions [4, 5]. But the conventional AGC concept does not directly apply to energy wheeling from a seller utility to a buyer across utilities not directly engaged in its trade. The AGC concept is very ingenious in the sense that it is based on minimal information exchange among interconnected utilities. Power mismatch within each utility—in formation used for load frequency control—is reflected in the area control error associated with each subsystem. Since no theoretic proof is available, it is not clear whether recently reported problems with AGC is [6] could be related to the violation of conditions under which AGC guaranteed to be coordinated.

III.1. Real Power/Frequency Control Versus Reactive Power/Voltage Control

The purpose of power system control is to regulate both frequency and voltages. A review of basic concepts of real and reactive power in large-scale electric power systems could be found in [80], Chapter 2. While frequency is strongly affected by real power changes, voltages are affected primarily by changes in reactive power support and demand. The original design of power systems provided sufficient reactive power support to maintain voltage magnitudes very close to 1 p.u. In this sense, only frequency monitoring and control were of prime concern, because changes in frequency are very sensitive to changes in real power, and the use of real power is directly related