Analysis and Control System Techniques for Electric Power Systems

Part 3 of 4

CONTROL AND DYNAMIC SYSTEMS

ADVANCES IN THEORY AND APPLICATIONS

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VOLUME 43: ANALYSIS AND CONTROL SYSTEM TECHNIQUES FOR ELECTRIC POWER SYSTEMS
Part 3 of 4

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

Academic Press Rapid Manuscript Reproduction

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 0-12-012743-1 (alk. paper)

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

CONTROL AND DYNAMIC SYSTEMS

Advances in Theory and Applications

Volume 43

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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 for 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 third volume of a four volume sequence in this series devoted to the significant theme of "Analysis and Control System 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 in this volume is "Modeling and Simulation of Multimachine Power System Dynamics," by P.W. Sauer and M.A. Pai. Modeling and simulation of multimachine power system dynamics has had a long history beginning with network analyzers and analog computers. Many of the models in use today were developed for these earlier computational techniques. The numerical methods for digital simulation have evolved separately within a basic mathematical framework. This contribution introduces fundamental component modeling and presents it in a conceptually coherent framework. As it turns out, in most cases the final models conform to what the power industry has been using for some time. Reduced-order models are presented from an integral manifold approach where the simplest approximation usually coincides with traditional practice. The computation of initial conditions for the set of differential-algebraic equations is presented in a step-by-step manner for typical simulations. The actual numerical solution methods are discussed in terms of standard integration methods and equivalent industry practice. The formulation is done in such a way that the interface between standard load-flow analysis and dynamic simulation is clear.

The next contribution is "Computer Simulation Techniques in Electric Distribution Systems," by Mo-Shing Chen and Tsai-Hsiang Chen. It has become increasingly clear that utilities and consumers need demand-side management. The least-cost planning as well as demand-side strategies are being widely adopted and mandated. The demand-side management, least-cost planning, network transformer placement study, and many other distribution analyses need rigorous operational-type analysis rather than planning-oriented analysis. The difference between these two types of analyses should be properly emphasized, otherwise the misuse of the planning-type method to analyze the operational behavior of the system will distort the explanation of the calculated results and lead to incorrect conclusions. The concept and methodologies for detailed electric distribution system simulation are discussed here. The features of general distribution systems are also addressed.

The next contribution is "Power System Transient Stability Assessment Using the Transient Energy Function Method," by A.A. Fouad and V. Vittal. Power system transient stability deals with the power system's response to disturbances. The period of interest is the transient period before the new steady-state conditions are reached. If the power system is subjected to a large disturbance and it is able to reach an acceptable steady-state condition, it is (transiently) stable. A large disturbance is a sudden change in a power system parameter or operating condition such that linearization of the system equations, for the purpose of analysis, cannot be justified. Transient stability studies are made by electric utilities in North America (and in other parts of the world) to ensure the reliability of the bulk power supply. The conventional, and still the standard, method to determine the transient stability of a power system is to solve for the system variables and parameters for a given sequence of events. Power system transient stability assessment using energy functions has been around for many years. In the late 1970s interest in the energy functions was revived by the development of a new energy function. The transient energy function described in this contribution is based on that function.

The next contribution is "Dynamic Stability Analysis and Control of Power Systems," by Young-Hwan Moon, Wei-Jen Lee, and Mo-Shing Chen. In order to maintain integrity, power systems should be designed to withstand the specified contingencies with finite probability of occurring. The stability study of electric power systems can be separated into two distinct problems, the transient (short-term) problem and the dynamic (long-term) problem. In the transient stability analysis, the performance of the power system when subjected to sudden severe impacts is studied. The concern is whether the system is able to maintain synchronism during and following these disturbances. The period of interest is relatively short (a few seconds), with the first swing being of primary importance. The stability depends strongly upon the magnitude and location of the disturbance and to a lesser extent upon the initial state or operating condition of the system. In contrast to transient stability, dynamic stability tends to be a property of the state of the system. Dynamic stability indicates the ability of all machines in a system to adjust to small load changes or impacts. The concern is whether the system has growing oscillation phenomena and their damping. As modern power systems become equipped with more fast control systems and become more complicated, dynamic stability becomes more important. The stability strongly depends on the initial state or operating condition of the system. Without question, both transient stability and dynamic stability must be secured for successful planning and operation of the system. This contribution is an in-depth presentation of issues and techniques in this area of great significance.

The next contribution, "Analytical Results on Direct Methods for Power System Transient Stability Analysis," by Hsiao-Dong Chiang, reviews recent advances in the development of analytical results for direct methods in power system transient stability analysis and provides important insight into the underlying concepts and properties of the various direct methods. Aside from a coherent view of the field, new material is presented. The exposition emphasizes fundamentals of direct methods rather than the heuristics which most direct methods are based on. In order to demonstrate one of the advantages of employing the analytical approach instead of the heuristic approach to developing direct methods for transient stability analysis, these fundamentals are then applied to a recently developed direct method, called the boundary of stability region controlling unstable equilibrium point method (BCU method) for direct analysis of power system transient stability. The BCU method has been compared favorably with other methods on large-scale power systems, according to a recent EPRI report. One implication from the development of the BCU method is that analytical results can sometimes lead to the development of reliable, yet fast, solution algorithms for solving transient stability problems in electric power systems.

A power system is one of the largest dynamic systems in existence. Generators of electric power are interconnected with loads by means of an extensive transmission and distribution network. The size of the power network is usually on the scale of continents. The secure and economic operation of the electric power network is a complex problem, involving a distributed, hierarchical, and multicentered structure. Very sophisticated monitoring, protection, and control systems have been devised to achieve a system which provides electric power of high quality and reliability. Recent developments in the field of computer-based substation functions and satellite based dissemination of high-accuracy time reference signals have provided power system engineers with a new tool for achieving even better overall system performance more economically. The next contribution, "Improved Control and Protection of Power Systems through Synchronized Phasor Measurements," by Arun G. Phadke and James S. Thorpe, describes the techniques and uses of synchronizing phasor measurements for improved monitoring, protection, and control of an electric system power network. Recent field trials for synchronized phasor measurements, based on new technology, and directions for future significant research are presented in this contribution.

The next contribution is "Real Time Power System Control: Issues Related to Variable Nonlinear Tie-line Frequency Bias for Load Frequency Control," by Raymond R. Shoults and Jesus A. Jativa. The interconnection of power systems has allowed various economic and technical advantages that were otherwise unavailable. Incremental increases in system reliability; ability to sell, buy, or exchange energy; feasibility of installing larger power plants; incremental increases in system stability; sharing of spinning reserve capacities; and taking advantage of load diversity for economy of operation are the main achievements. However, the interconnection carries with it some difficulties and obligations such as incremental increases in operational complexity, reduced ability to control steady-state power flows, propagation of the effect of faults through the entire system, propagation of steady-state oscillations, responsibility of matching generation to load within each control area, and shared responsibility to maintain frequency and time error within certain established limits. The area secondary control, referred to as automatic generation control (AGC), is responsible for regulating the system frequency within acceptable error bounds, maintaining correct interchange schedules, and distributing generation within each area according to minimum operating cost criteria. Even though tie-line frequency-bias control has been in practice for many years, it still represents the state of the art in AGC. It is based on an area control error (ACE) defined as the generation change required to restore frequency and net interchange to desired values. The derivation of ACE is based upon the assumption of steady-state conditions. A nonzero ACE represents the load-generation-net interchange unbalance within an area. It has been observed that frequency bias should follow the variable and nonlinear frequency response of a given control area. This contribution is an in-depth presentation of the role of the frequency bias parameter in the ACE calculation. The area control principle of an interconnected power system requires only the measurements of area frequency and area net interchange to calculate the ACE. This principle leads to a straightforward and efficient method of decentralized control. The input to ACE, which is assumed steady-state calculation, represents a continua of dynamic behavior. During dynamic conditions, ACE comprises the key input to load-frequency control (LFC). The final controller design for LFC may be carried out by either on-line tuning or some sort of control theory approach.

The control necessary to maintain stability in electric power systems can be achieved through either field voltage control or mechanical power control. The next contribution, "High Dynamic Performance Microcomputer Control of Electrical

Drives," by Werner Leonhard, is an in-depth presentation of the modern technology for achieving effective electric drive control necessary to achieve mechanical power control through servo control techniques.

This volume is a particularly appropriate one as the third 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

Modeling and Simulation of Multimachine Power System Dynamics†

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1 Introduction

Modeling and simulation of multimachine power system dynamics has had a long history beginning with network analyzers and analog computers. Many of the models in use today were developed for these earlier computational techniques. The numerical methods for digital simulation have evolved separately within a basic mathematical framework.

In this chapter we introduce fundamental component modeling and present it in a conceptually coherent framework. As it turns out, in most cases the final models conform to what the power industry has been using for some time. Reduced-order models are presented from an integral manifold approach where the simplest approximation usually coincides with traditional practice. The computation of initial conditions for the set of differential-algebraic equations is presented in a step-by-step manner for typical simulations.

The actual numerical solution methods are discussed both in terms of standard integration methods and equivalent industry practice. The formulation is done in such a way that the interface between standard load-flow analysis and dynamic simulation is clear.

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†Major portions of the material contained in this chapter have been excerpted from the book entitled *Power System Dynamics and Stability* by P. W. Sauer and M. A. Pai, to be published by Prentice-Hall in 1992.

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2 Synchronous Machine Modeling

There is probably more literature on synchronous machines than on any other device in electrical engineering. Unfortunately, it is this vast amount of material which often makes the subject complex and confusing. In addition, the largest portion of work on reduced-order modeling is based primarily on physical intuition, practical experience and years of experimentation. The evolution of dynamic analysis has caused some problem in notation as it relates to common symbols which eventually require data from manufacturers. This chapter uses the conventions and notations of [1], which essentially follows that of many publications on synchronous machines [2]-[11]. The original Park's transformation is used together with the "X_{ad}" per-unit system [12, 13].

2.1 Three Damper Winding Model

This subsection presents the basic dynamic equations for a balanced symmetrical three-phase, synchronous machine with a field winding and three damper windings on the rotor. The simplified schematic of Figure 1 shows the coil orientation, assumed polarities, and rotor position reference. The stator windings have axes 120 electrical degrees apart and are assumed to have an equivalent sinusoidal distribution [1]. While a 2-pole machine is shown, all equations are written for a P-pole machine with $\omega = \frac{P}{2}\omega_{shaft}$ expressed in electrical radians per second. The circles with dots and x's indicate the windings. Current flow is assumed to be in the "x" and out of the "dot". The voltage polarity of the coils is assumed to be plus to minus from the "x" to the "dot".

This notation uses "motor" current notation for all the windings at this time. The transformed stator currents will be changed to "generator" current notation at the time when per-unit scaling is introduced. The fundamental Kirchhoff, Faraday and Newton's laws give:

$$v_a = i_a r_s + \frac{d\lambda_a}{dt} \tag{1}$$

$$v_b = i_b r_s + \frac{d\lambda_b}{dt} \tag{2}$$

$$v_c = i_c r_s + \frac{d\lambda_c}{dt} \tag{3}$$

$$v_{fd} = i_{fd} r_{fd} + \frac{d\lambda_{fd}}{dt} \tag{4}$$

$$v_{1d} = i_{1d} r_{1d} + \frac{d\lambda_{1d}}{dt} \tag{5}$$

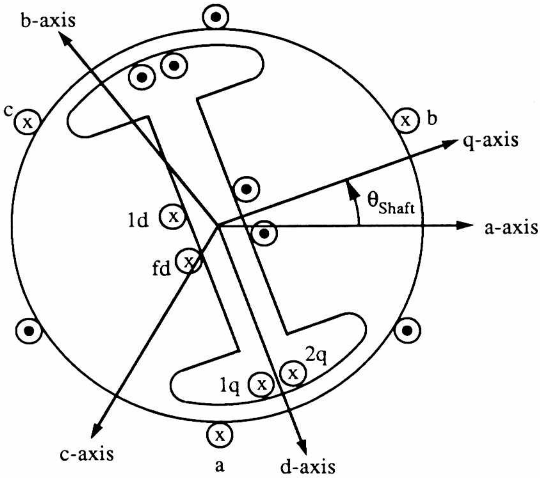

Figure 1: Synchronous machine schematic

$$v_{1q} = i_{1q}r_{1q} + \frac{d\lambda_{1q}}{dt} \tag{6}$$

$$v_{2q} = i_{2q}r_{2q} + \frac{d\lambda_{2q}}{dt} \tag{7}$$

$$\frac{d\theta_{shaft}}{dt} = \frac{2}{P}\omega \tag{8}$$

$$J\frac{2}{P}\frac{d\omega}{dt} = T_m - T_{elec} - T_{fw} \tag{9}$$

where λ is the flux linkage, r is the winding resistance, J is the inertia constant, P is the number of magnetic poles per phase, T_m is the mechanical torque to the shaft, $-T_{elec}$ is the torque of electrical origin, and $-T_{fw}$ is a friction windage torque. A major modeling challenge is to obtain the relationships between flux linkage and current. These relationships will be presented in a later subsection.

2.2 Transformations and Scaling

The first major step in synchronous machine modeling is to transform the stator variables into a reference frame fixed in the machine rotor. The general form of the transformation which accomplishes this is [1],