Chapter 1

Introduction and Overview

1.1 INTRODUCTION

Power system instabilities are unacceptable to society. Indeed, recent major blackouts in North America and in Europe have vividly demonstrated that power interruptions, grid congestions, or blackouts significantly impact the economy and society. In August 1996, disturbances cascaded through the West Coast transmission system, causing widespread blackouts that cost an estimated $2 billion and left 12 million customers without electricity for up to 8 h. In June 1998, transmission system constraints disrupted the wholesale power market in the Midwest, causing price rises from an average of $30 per megawatt hour to peaks as high as $10,000 per megawatt hour. Similar price spikes also occurred in the summers of 1999 and 2000. In 2003, the Northeast blackout left 50 million customers without electricity and the financial loss was estimated at $6 billion. According to a research firm, the annual cost of power outages and fluctuations worldwide was estimated to be between $119 and $188 billion yearly. Power outages and interruptions clearly have significant economic consequences for society.

The ever-increasing loading of transmission networks coupled with a steady increase in load demands has pushed the operating conditions of many worldwide power systems ever closer to their stability limits. The combination of limited investment in new transmission and generation facilities, new regulatory requirements for transmission open access, and environmental concerns are forcing transmission networks to carry more power than they were designed to withstand. This problem of reduced operating security margins is further compounded by factors such as (1) the increasing number of bulk power interchange transactions and non-utility generators, (2) the trend towards installing higher-output generators with lower inertia constants and higher short circuit ratios, and (3) the increasing amount of renewable energies. Under these conditions, it is now well recognized that any violation of power system dynamic security limits leads to far-reaching consequences for the entire power system.

Direct Methods for Stability Analysis of Electric Power Systems, by Hsiao-Dong Chiang

By nature, a power system continually experiences two types of disturbances: *event disturbances* and *load variations*. Event disturbances (contingencies) include loss of generating units or transmission components (lines, transformers, and substations) due to short circuits caused by lightning, high winds, and failures such as incorrect relay operations, insulation breakdowns, sudden large load changes, or a combination of such events. Event disturbances usually lead to a change in the network configuration of the power system due to actions from protective relays and circuit breakers. They can occur as a single equipment (or component) outage or as multiple simultaneous outages when taking relay actions into account. Load variations are variations in load demands at buses and/or power transfers among buses. The network configuration may remain unchanged after load variations. Power systems are planned and operated to withstand certain disturbances. The North American Electric Reliability Council defines security as the ability to prevent cascading outages when the bulk power supply is subjected to severe disturbances. Individual reliability councils establish the types of disturbances that their systems must withstand without cascading outages.

A major activity in power system planning and operation is the examination of the impact a set of credible disturbances has on a power system's dynamic behavior such as stability. Power system stability analysis is concerned with a power system's ability to reach an acceptable steady state (operating condition) following a disturbance. For operational purposes, power system stability analysis plays an important role in determining the system operating limits and operating guidelines. During the planning stage, power system stability analysis is performed to assess the need for additional facilities and the locations at which additional control devices to enhance the system's static and dynamic security should be placed. Stability analysis is also performed to check relay settings and to set the parameters of control devices. Important conclusions and decisions about power system operations and planning are made based on the results of stability studies.

Transient stability problems, a class of power system stability problems, have been a major operating constraint in regions that rely on long-distance transfers of bulk power (e.g., in most parts of the Western Interconnection in the United States, Hydro-Québec, the interfaces between the Ontario/New York area and the Manitoba/Minnesota area, and in certain parts of China and Brazil). The trend now is that many parts of the various interconnected systems are becoming constrained by transient stability limitations. The wave of recent changes has caused an increase in the adverse effects of both event disturbances and load variations in power system stability. Hence, it is imperative to develop powerful tools to examine power system stability in a timely and accurate manner and to derive necessary control actions for both preventive and enhancement control.

1.2 TRENDS OF OPERATING ENVIRONMENT

The aging power grid is vulnerable to power system disturbances. Many transformers in the grid approach or surpass their design life. The transmission system is often under-invested and overstrained. These result in vulnerable power grids constantly operating near their operating limits. In addition, this operating environment encounters more challenges brought about by dispersed generations whose prime movers can be any renewable energy source such as wind power. As is well recognized, these small-size dispersed generation systems raise even greater concerns of power system stability. Hence, with current power system operating environments, it is increasingly difficult for power system operators to generate all the operating limits for all possible operating conditions under a list of credible contingencies.

At present, most energy management systems periodically perform online power system static security assessment (SSA) and control to ensure that the power system can withstand a set of credible contingencies. The assessment involves selecting a set of credible contingencies and evaluating the system's response to those contingencies. Various software packages for security assessment and control have been implemented in modern energy control centers. These packages provide comprehensive online security analysis and control based almost exclusively on steady-state analysis, making them applicable to SSA and control but not to online transient stability assessment (TSA). Instead, off-line transient stability analysis has been performed for postulated operating conditions. The turn-around time for a typical study can range from hours to days depending on the number of postulated operating conditions and the dynamic study period of each contingency. This off-line practice is inadequate to deal with current operating environments and calls for online evaluations of the constantly changing overall system conditions.

The lack of performing online TSAs in an energy management system can have serious consequences. Indeed, any violation of dynamic security limits has far-reaching impacts on the entire power system and thus on the society. From a financial viewpoint, the costs associated with a power outage can be tremendous. Online dynamic security assessment is an important tool for avoiding dynamic security limit violations. It is fair to say that the more stressed a power system, the stronger the need for online dynamic security assessments.

Several significant benefits and potential applications are expected from the movement of transient stability analysis from the off-line mode to the online operating environment. The first benefit is that a power system can be operated with operating margins reduced by a factor of 10 or more if the dynamic security assessment is based on the actual system configuration and actual operating conditions instead of assumed worst-case conditions, as is done in off-line studies. This ability is especially significant since current environments have pushed power systems to operate with low reserve margins closer to their stability limits. A second benefit to online analysis is that the large number of credible contingencies that needs to be assessed can be reduced to those contingencies relevant to actual operating conditions. Important consequences obtained from this benefit are that more accurate operating margins can be determined and more power transfers among different areas, or different zones of power networks, can be realized. Compared to off-line studies, online studies require much less engineering resources, thereby freeing these resources for other critical activities.

1.3 ONLINE TSA

Online TSA is designed to provide system operators with critical system stability information including (1) TSA of the current operating condition subject to a list of contingencies and (2) available (power) transfer limits at key interfaces subject to transient stability constraints. A complete online TSA assessment cycle is typically in the order of minutes, say, 5 min. This cycle starts when all necessary data are available to the system and ends when the system is ready for the next cycle. Depending on the size of the underlying power systems, it is estimated that, for a large-size power system such as a 15,000-bus power system, the number of contingencies in a contingency list is between 2000 and 3000. The contingency types will include both a three-phase fault with primary clearance and a single line-to-ground fault with backup clearance.

When a cycle of online TSA is initiated, a list of credible contingencies, along with information from the state estimator and topological analysis, is applied to the online TSA program whose basic function is to identify unstable contingencies from the contingency list. An operating condition is said to be transiently stable if the contingency list contains no unstable contingencies; otherwise, it is transiently unstable. The task of online TSA, however, is very challenging.

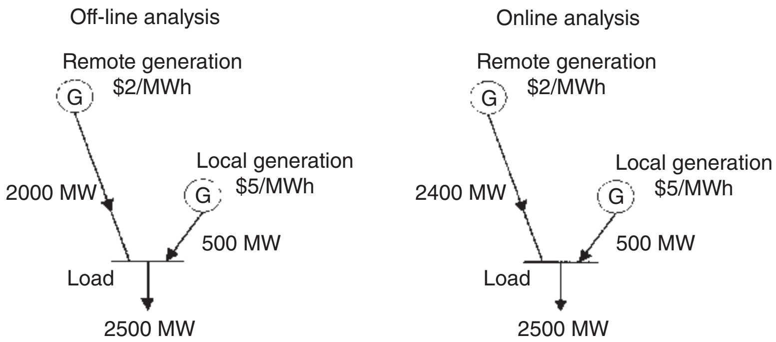
The strategy of using an effective scheme to screen out a large number of stable contingencies, capture critical contingencies, and apply detailed simulation programs only to potentially unstable contingencies is well recognized. This strategy has been successfully implemented in online SSA. The ability to screen several hundred contingencies to capture tens of the critical contingencies has made the online SSA feasible. This strategy can be applied to online TSA. Given a set of credible contingencies, the strategy would break the task of online TSA into two stages of assessments (Chadalavada et al., 1997; Chiang et al., 1997):

Step 1. Perform the task of dynamic contingency screening to quickly screen out contingencies that are definitely stable from a set of credible contingencies.

Step 2. Perform detailed assessment of dynamic performance for each contingency remaining in Stage 1.

Dynamic contingency screening is a fundamental function of an online TSA system. The overall computational speed of an online TSA system depends greatly on the effectiveness of the dynamic contingency screening, the objective of which is to identify contingencies that are definitely stable and thereby to avoid further stability analysis for these contingencies. It is due to the definite classification of stable contingencies that considerable speedup can be achieved for TSA. Contingencies that are either undecided or identified as critical or unstable are then sent to the time–domain transient stability simulation program for further stability analysis.

Online TSA can provide an accurate determination of online transfer capability constrained by transient stability limits. This accurate calculation of transfer capability allows remote generators with low production cost to be economically dispatched



Savings
= (1 h) 400 MW × ($5/MWh – $2/MWh) = $1200
= (24 h) $28,800
= (30 days) $864,000
= (1 year) $10.4 million

Figure 1.1 A hypothetical power system and analysis of financial savings.

to serve load centers. We consider a hypothetical power system containing a remote generator with low production cost, say, a hydro generator of $2 per megawatt hour and a local generator with a high production cost of $5 per megawatt hour that all supply electricity to a load center of 2500 MW (see Figure 1.1). According to the off-line analysis, the transfer capability between the remote generator and the load center was 2105 MW. With a 5% security margin, the output of the remote generator was set to 2000 MW. The local generator then needs to supply 500 MW to the load center to meet the load demand. On the other hand, the actual transfer capability between the remote generator and the load center, according to online TSA, was 2526 MW instead of 2105 MW. With a 5% security margin, the output of the remote generator was set to 2400 MW, while the output of the local generator was set to 100 MW to meet the load demand. By comparing these two different schemes of real power dispatch based on two different transfer capability calculations, the difference in production cost is about $1200 per hour or $28,800 per day. It can be observed that even for such a relatively small load demand of 2500 MW, online TSA allows for significant financial savings amounting to about $10.5 million per year. We recognize that practical power systems may not resemble this hypothetical power system; however, it does illustrate the significant financial benefits of online TSA.

1.4 NEED FOR NEW TOOLS

At present, stability analysis programs routinely used in utilities around the world are based mostly on step-by-step numerical integrations of power system stability models used to simulate system dynamic behaviors. This practice of power system stability analysis based on the time–domain approach has a long history. The stability of the postfault system is assessed based on simulated postfault trajectories. The typical simulation period for the postfault system is 10 s and can go beyond 15 s if multiswing instability is of concern, making this conventional approach rather time-consuming.

The traditional time–domain simulation approach has several disadvantages. First, it requires intensive, time-consuming computation efforts; therefore, it has not been suitable for online application. Second, it does not provide information as to how to derive preventive control when the system is deemed unstable nor how to derive enhancement control when the system is deemed critically stable, and finally, it does not provide information regarding the degree of stability (when the system is stable) and the degree of instability (when the system is unstable) of a power system. This information is valuable for both power system planning and operation.

From a computational viewpoint, online TSA involves solving a large set of mathematical models, which is described by a large set of nonlinear differential equations in addition to the nonlinear algebraic equations involved in the SSA. For a 14,000-bus power system transient stability model, one dynamic contingency analysis can involve solving a set of 15,000 differential equations and 40,000 nonlinear algebraic equations for a time duration of 10–20 s in order to assess the power system stability under the study contingency. Online TSA requires the ability to analyze hundreds or even thousands of contingencies every 5–10 min using online data and system state estimation results. Thus, the traditional time–domain simulation approach cannot meet this requirement.

The computational effort required by online TSA is roughly three magnitudes higher than that of the SSA. This explains why TSA has long remained an off-line activity instead of an online activity in the energy management system. Extending the functions of energy management systems to take into account online TSA and control is a challenging task and requires several breakthroughs in measurement systems, analytical tools, computation methods, and control schemes.

1.5 DIRECT METHODS: LIMITATIONS AND CHALLENGES

An alternate approach to transient stability analysis employing energy functions, called *direct methods*, or termed energy function-based direct methods, was originally proposed by Magnusson (1947) in the late 1940s and was pursued in the 1950s by Aylett (1958). Direct methods have a long developmental history spanning six decades. Significant progress, however, has been made only recently in the practical application of direct methods to transient stability analysis. Direct methods can determine transient stability without the time-consuming numerical integration of a (postfault) power system. In addition to their speed, direct methods also provide a quantitative measure of the degree of system stability. This additional information makes direct methods very attractive when the relative stability of different network configuration plans must be compared or when system operating limits constrained by transient stability must be calculated quickly. Another advantage to direct methods is that they provide useful information regarding the derivation of preventive control actions when the underlying power system is deemed unstable and the derivation of enhancement control actions when the underlying power system is deemed critically stable.

Despite the fact that significant progress has been made in energy function-based direct methods over the last several decades, they have been considered impractical by many researchers and users for power system applications. Indeed, direct methods must overcome several challenges and limitations before they can become a practical tool.

From an analytical viewpoint, direct methods were originally developed for power systems with autonomous postfault systems. As such, there are several challenges and limitations involved in the practical applications of direct methods for power system transient stability analysis, some of which are inherent to these methods while others are related to their applicability to power system models. These challenges and limitations can be classified as follows:

Challenges

- The modeling challenge
- The function challenge
- The reliability challenge

Limitations

- The scenario limitation
- The condition limitation
- The accuracy limitation

The modeling challenge stems from the requirement that there exists an energy function for the (postfault) transient stability model of study. However, the problem is that not every (postfault) transient stability model admits an energy function; consequently, simplified transient stability models have been used in direct methods. A major shortcoming of direct methods in the past has been the simplicity of the models they can handle. Recent work in this area has made significant advances. The current progress in this direction is that a general procedure of constructing numerical energy functions for complex transient stability models is available. This book will devote Chapters 6 and 7 to this topic.

The function limitation stipulates that direct methods are only applicable to first swing stability analysis of power system transient stability models described by pure differential equations. Recent work in the development of the controlling UEP method has extended the first-swing stability analysis into a multiswing stability analysis. In addition, the controlling UEP method is applicable to power system transient stability models described by differential and algebraic equations. This book will devote Chapters 11 through 13 to this topic.

The scenario limitation for direct methods comes from the requirement that the initial condition of a study postfault system must be available and the requirement that the postfault system must be autonomous. It is owing to the requirement of the availability of the initial condition that makes numerical integration of the study fault-on system a must for direct methods. Hence, the initial condition of a study postfault system can only be obtained via the time–domain approach and cannot be available beforehand. On the other hand, the requirement that the postfault system be autonomous imposes the condition that the fault sequence on the system must be well-defined in advance. Currently, the limitation that the postfault system must be an autonomous dynamical system is partially removed. In particular, the postfault system does not need to be a "pure" autonomous system and it can be constituted by a series of autonomous dynamical systems.

The condition limitation is an analytical concern related to the required conditions for postfault power systems: a postfault stable equilibrium point must exist and the prefault stable equilibrium point must lie inside the stability region of the postfault stable equilibrium point. This limitation is inherent to the foundation of direct methods. Generally speaking, these required conditions are satisfied on stable contingencies, while they may not be satisfied on unstable contingencies. From an application viewpoint, this condition limitation is a minor concern and direct methods can be developed to overcome this limitation.

The accuracy limitation stems from the fact that analytical energy functions for general power system transient stability models do not exist. Regarding the accuracy limitation, it has been observed in numerous studies that the controlling UEP method, in conjunction with appropriate numerical energy functions, yields accurate stability assessments. Numerical energy functions are practically useful in direct methods. In this book, methods and procedures to construct accurate numerical energy functions will be presented.

The reliability challenge is related to the reliability of a computational method in computing the controlling UEP for every study contingency. From a theoretical viewpoint, this text will demonstrate the existence and uniqueness of the controlling UEP with respect to a fault-on trajectory. Furthermore, the controlling UEP is independent of the energy function used in the direct stability assessment. Hence, the task of constructing an energy function and the task of computing the controlling UEP are not interrelational. From a computational viewpoint, the task of computing the controlling UEP is very challenging. We will present in Chapter 12 the computational challenges in computing the controlling UEP. A total of seven challenges in computing the controlling UEP will be highlighted. These challenges call into doubt the correctness of any attempt to directly compute the controlling UEP of the original power system stability model. This analysis serves to explain why previous methods proposed in the literature fail to compute the controlling UEP.

The above analysis reveals three important implications for the development of a reliable numerical method for computing controlling UEPs:

1. These computational challenges should be taken into account in the development of numerical methods for computing the controlling UEP.
2. It is impossible to directly compute the controlling UEP of a power system stability model without using the iterative time–domain method.

3. It is possible to directly compute the controlling UEP of an artificial, reduced-state power system stability model without using the iterative time–domain method.

In this book, it will be shown that it is fruitful to develop a tailored solution algorithm for finding the controlling UEPs by exploiting special properties as well as some physical and mathematical insights into the underlying power system stability model. We will discuss in great detail such a systematic method, called the BCU method, for finding controlling UEPs for power system models in Chapters 14 through 17. The BCU method does not attempt to directly compute the controlling UEP of a power system stability model (original model); instead, it computes the controlling UEP of a reduced-state model and relates the computed controlling UEP to the controlling UEP of the original model. This book will devote Chapters 14 through 24 to present the following family of BCU methods:

- The BCU method
- The BCU–exit point method
- The group-based BCU–exit point method
- The group-based BCU–CUEP method
- The group-based BCU method

This book will also explain how to develop tailored solution methodologies by exploring special properties as well as some physical and mathematical insights into the underlying power system stability model. For instance, it will be explained how the group properties of contingencies in power systems are discovered. These group properties will be explored and incorporated into the development of a group-based BCU method. This exploration of group properties leads to a significant reduction in computational efforts for reliably computing controlling UEPs for a group of coherent contingencies and to the development of effective preventive control actions against a set of insecure contingencies and enhancement control actions for a set of critical contingencies.

1.6 PURPOSES OF THIS BOOK

The main purpose of this book is to present a comprehensive theoretical foundation for direct methods and to develop comprehensive BCU solution methodologies along with their theoretical foundations. BCU methodologies have been developed to reliably compute controlling UEPs and to reliably compute accurate critical values, which are essential pieces of information needed in the controlling UEP method. In addition, a comprehensive energy function theory, which is an extension of the Lyapunov function theory, is presented along with a general procedure for constructing numerical energy functions for general power system transient stability models.

This author believes that solving challenging practical problems efficiently can be accomplished through a thorough understanding of the underlying theory, in

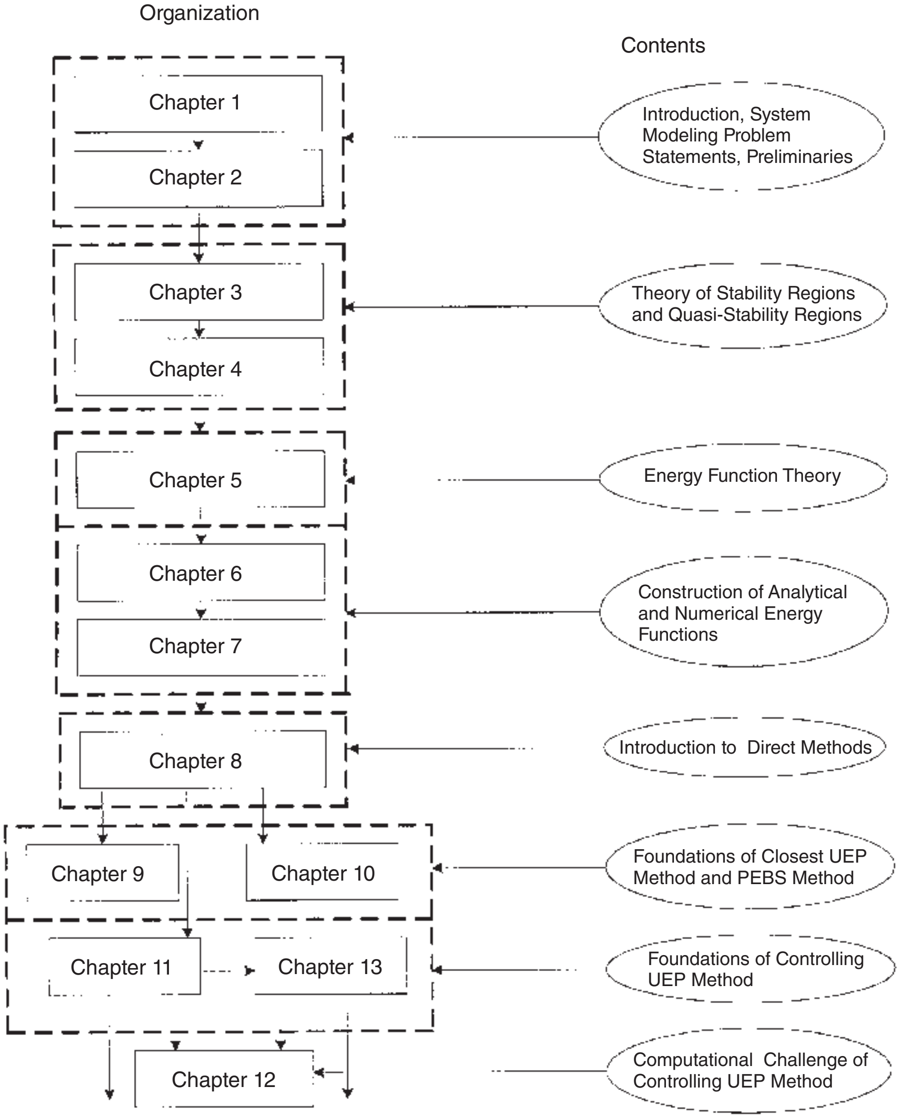


Figure 1.2 An overview of the organization and content of this book.

conjunction with exploring the special features of the practical problem under study, to develop effective solution methodologies. This book covers both a comprehensive theoretical foundation for direct methods and comprehensive BCU solution methodologies.

There are 25 chapters contained in this book. These chapters can be classified into the following (see Figure 1.2):

Chapter 2: System Modeling and Stability Problems

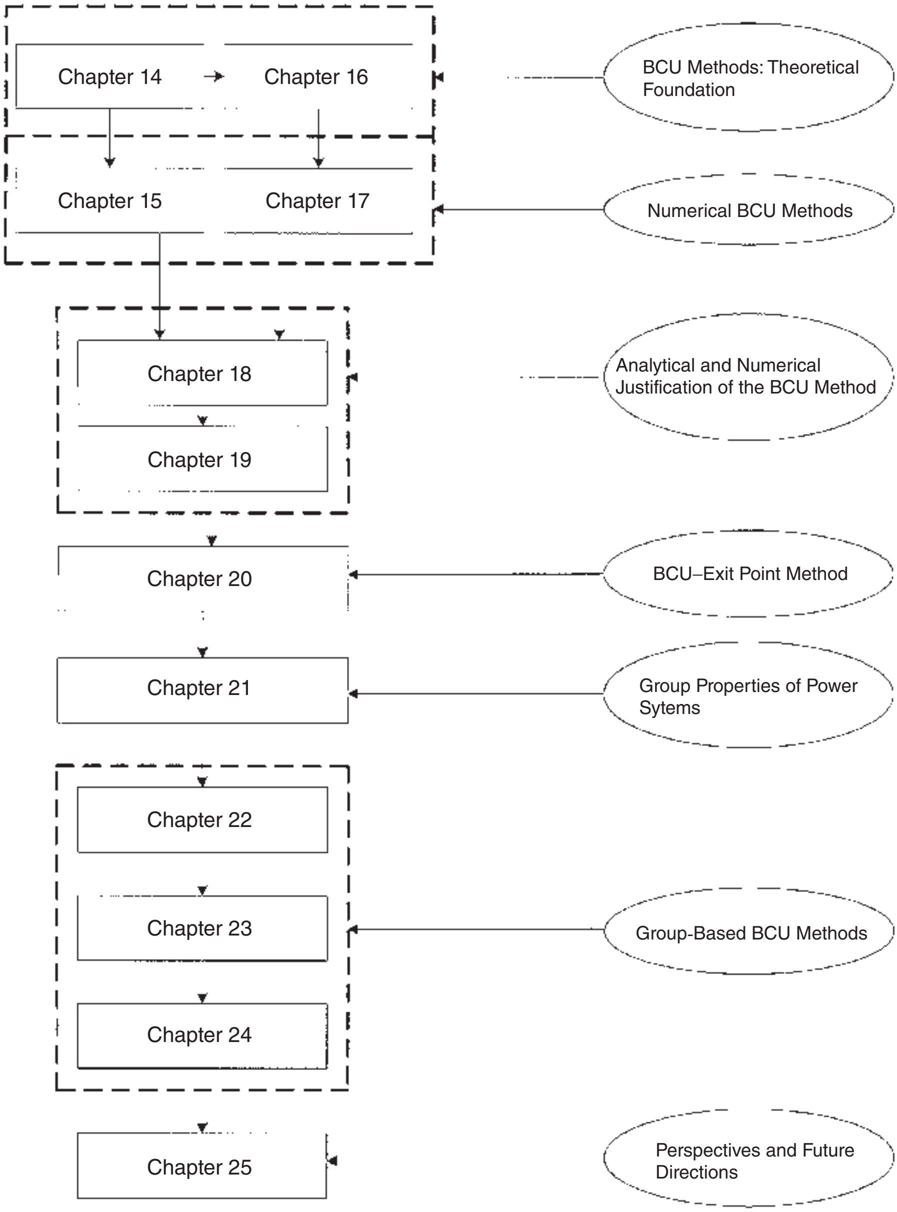


Figure 1.2 Continued

Theory of Stability Regions

Chapter 3: Lyapunov Stability and Stability Regions of Nonlinear Dynamical Systems

Chapter 4: Quasi-Stability Regions: Analysis and Characterization

Energy Functions: Theory and Constructions

Chapter 5: Energy Function Theory and Direct Methods

Chapter 6: Constructing Analytical Energy Functions for Transient Stability Models

Chapter 7: Construction of Numerical Energy Functions for Lossy Transient Stability Models

Direct Methods: Introduction and Foundations

Chapter 8: Direct Methods for Stability Analysis: An Introduction

Chapter 9: Foundation of the Closest UEP Method

Chapter 10: Foundations of the Potential Energy Boundary Surface Method

Controlling UEP Method: Theoretical Foundation and Computation

Chapter 11: Controlling UEP Method: Theory

Chapter 12: Controlling UEP Method: Computations

Chapter 13: Foundations of Controlling UEP Methods for Network-Preserving Transient Stability Models

BCU Methods: Methodologies and Theoretical Foundations

Chapter 14: Network-Reduction BCU Method and Its Theoretical Foundation

Chapter 15: Numerical Network-Reduction BCU Method

Chapter 16: Network-Preserving BCU Method and Its Theoretical Foundation

Chapter 17: Numerical Network-Preserving BCU Method

Chapter 18: Numerical Studies of BCU Methods from Stability Boundary Perspectives

Chapter 19: Study of Transversality Conditions of the BCU Method

Chapter 20: The BCU–Exit Point Method

Group-Based BCU Methods: Group Properties and Methodologies

Chapter 21: Group Properties of Contingencies in Power Systems

Chapter 22: Group-Based BCU–Exit Method

Chapter 23: Group-Based BCU–CUEP Methods

Chapter 24: Group-Based BCU Method

Chapter 25: Perspectives and Future Directions

In summary, this book presents the following theoretical developments as well as solution methodologies with a focus on practical applications for the direct analysis of large-scale power system transient stability; in particular, this book

- provides a general framework for general direct methods, particularly the controlling UEP method;
- develops a comprehensive theoretical foundation for the controlling UEP method, the potential energy boundary surface (PEBS) method, and the closest UEP method;

- presents the BCU methodologies, including the network-reduction BCU method and the network-preserving BCU method;
- presents the theoretical foundation for both the network-reduction BCU method and the network-preserving BCU method;
- develops numerical implementations of both the network-reduction BCU method and the network-preserving BCU method;
- demonstrates the computational procedure of numerical BCU methods using the stability boundary of the original system model and that of the reduced-state model;
- conducts analytical studies of the transversality condition of the BCU method and relates the transversality condition with the boundary condition;
- presents the BCU–exit point method;
- develops group properties of power system contingencies;
- explores the static and dynamic group properties of power system coherent contingencies;
- develops the group-based BCU–exit point method and the group-based BCU–CUEP method; and
- develops group-based BCU methodologies, including the group-based BCU–exit point method, the group-based BCU–CUEP method, and the group-based BCU method.