ADEQUACY ASSESSMENT OF COMPOSITE POWER SYSTEMS INCORPORATING FACTS

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PERMISSION TO USE

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ABSTRACT

The rapid development of flexible AC transmission technology and its immense potential for future use dictate the need to seriously consider the associated reliability benefits that can be obtained. The application of flexible AC transmission system (FACTS) in modern power systems, particularly in restructured power industries, has received considerable attention in recent years. This is due to the potential reliability, economic and environmental benefits from using this new technology to avoid building new transmission lines. It is, therefore, both necessary and important to develop reliability evaluation techniques to assess the actual benefit obtained from utilizing FACTS devices in a bulk power system.

This thesis describes the development of appropriate models and techniques to permit quantitative reliability evaluation of composite generation and transmission systems incorporating FACTS devices. The analyses are conducted using the contingency enumeration approach. The FACTS transmission unit is represented by a multi-state model. Two network evaluation techniques, the reinforced minimal tie set method and the modified DC load flow method are utilized to assess the impact of FACTS devices in composite power system adequacy.

The developed models and techniques can be used to conduct adequacy studies on a wide range of composite power systems. The utilization of these techniques is illustrated by application to two widely used reliability test systems. The results and discussions presented in this thesis should provide valuable information to electric power utilities engaged in planning and operating FACTS devices.

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LIST OF ABBREVIATIONS

AC	Alternating Current
BPII	Bulk Power Interruption Index
DC	Direct Current
HVDC	High Voltage Direct Current
EENS	Expected Energy Not Supplied
FACTS	Flexible AC Transmission System
HL-I	Hierarchical Level-I
HL-II	Hierarchical Level-II
HL-III	Hierarchical Level-III
IEEE	Institute of Electrical and Electronics Engineers
kV	KiloVolts
LDC	Load Duration Curve
MW	Megawatt
MWh	Megawatt-hour
p.u.	per unit
RBTS	Roy Billinton Test System
RTS	Reliability Test System
UPFC	Unified Power Flow Controller
yr	Year

1 Introduction

1.1 Introduction

The availability of electrical power supply is a dominant factor in the development of modern society. The rising dependence on electricity creates increasing pressure on the electrical power industry to provide the required energy. The basic function of an electric power system is to supply its customers with electrical energy as economically as possible and with a reasonable degree of continuity and quality [1-7]. Increasing the assurance level of power supply involves increasing financial investment. It is unrealistic to try to design a power system with a hundred percent reliability and therefore, power system planners and engineers have always attempted to achieve a reasonable level of reliability at an affordable cost.

The power industry is presently undergoing considerable change from traditional vertically integrated utility systems to unbundled structures [8]. Competition and marketing issues are becoming more and more important in the electric power industry. Uncertainties in many factors due to deregulation are having considerable impact on the planning and operation of power systems. Power system reliability assessment and prediction is becoming increasingly important in order to maintain the system reliability at reasonable levels in this competitive environment.

1.2 Power System Reliability

Reliability is, in a general sense, a measure of the ability of a component or a system to perform its intended function. In a mission orientated sense, reliability is defined as the ability of the system to perform a required function under certain conditions for a stated period of time [9]. In the case of an electric power system, the term "reliability" has a wide range of meaning and cannot be associated with a single specific definition [10]. In general terms, it is related to the existence of sufficient facilities within a system so that the system is capable of supplying electric power to its customers under both static and dynamic conditions, with a mutually acceptable assurance of continuity and quality [7]. A simple but reasonable subdivision of the concern designated as system reliability can be made by considering the two basic and functional aspects of system adequacy and security, as shown in Figure 1.1.

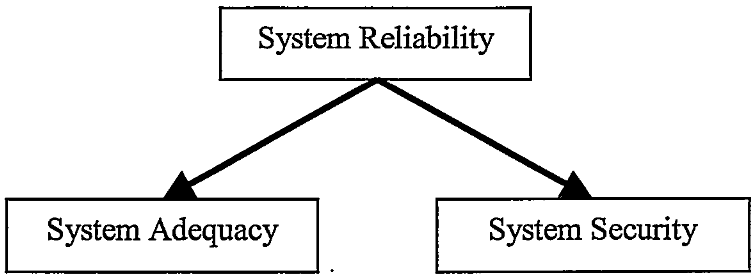

Figure 1.1 Subdivision of system reliability

System security relates to the ability of the system to respond to disturbances arising within the system. These generally include the conditions associated with both local and widespread disturbances and the loss of major generation and transmission facilities. System adequacy, on the other hand, relates to static system conditions and the existence of sufficient facilities within the system to satisfy the system load demand. These include both the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the customer load points. The research described in this thesis is restricted to adequacy assessment of electric power systems.

Power system adequacy assessment can be conducted in each of the three basic functional zones of generation, transmission, and distribution. These functional zones can be combined to form hierarchical levels (HL) [7] as shown in Figure 1.2.

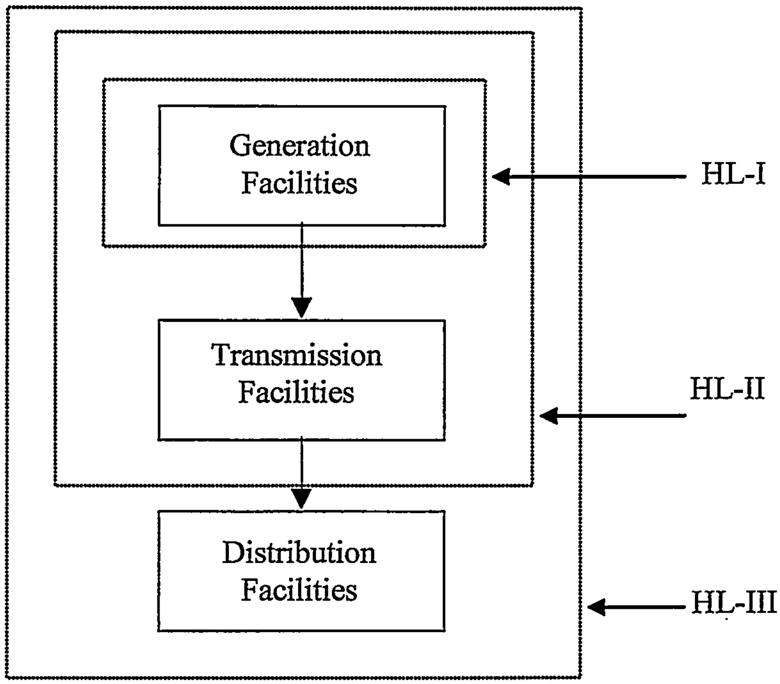

Figure 1.2 Hierarchical levels

Adequacy assessment at hierarchical level-I (HL-I) is concerned only with the generation facilities. In an HL-I study, the total system generation including interconnected assistance is examined to determine its adequacy to meet the total system load demand. Reliability assessment at HL-I is normally defined as generating capacity adequacy evaluation. The transmission network and the distribution facilities are not included in an assessment at the HL-I level. Adequacy evaluation at hierarchical level-II (HL-II) includes both the generation and transmission in an assessment of the integrated ability of the composite system to deliver energy to the bulk supply points. This analysis is usually termed as composite system reliability evaluation (or bulk power system reliability evaluation). Adequacy assessment at hierarchical level-III (HL-III) includes all of the three functional zones and is not easily conducted in a practical system due to the computational complexity and scale of the assessment. Analyses are, however, usually performed in the distribution functional zone. The focus of this thesis is on adequacy assessment at HL-II.

Quantitative assessment of the adequacy of a composite system can be performed using two basic approaches [7]:

1. Analytical method,
2. Monte Carlo simulation technique.

Analytical methods are based on the cause and effect relationship of the system components in a power system. The system state is examined for a specific outage event in a network using appropriate solution techniques. A set of adequacy indices is then calculated after employing suitable remedial actions. A simulation method estimates the reliability indices by simulating the actual process and random behaviour of a system. An analytical approach usually requires less computation time than a simulation approach and is able to provide accurate adequacy indices, when suitable models and techniques are developed. This thesis is focused on the utilization of an analytical approach to composite system adequacy evaluation.

1.3 Flexible AC Transmission Systems (FACTS)

Power system performance can be enhanced by the ability to control power flow without involving generation rescheduling or topological changes. Load flow patterns in a transmission system can be changed using controllable devices to optimize the system operation and increase the system stability margin without violating the economic generation dispatch. Flexible AC transmission system (FACTS) technology was developed to fulfill this requirement.

FACTS technology is the designation given to the concept of using solid-state power electronic converters for power flow control at the transmission level. The transmission components become active elements by self-adjusting their related parameters and play important roles in meeting power transfer requirements and increasing the security margins. This technology has attracted attention in recent years due to the ever-increasing electric power demand, the deregulation of bulk power systems and environmental concerns associated with building new transmission lines.

Implementing FACTS devices in transmission systems provides the following opportunities for increased efficiency and effectiveness [11]:

1. Improved steady-state system performance due to increased transmission capacity and controlled transmission flows;
2. Improved system transient and dynamic stability due to expanded dynamic voltage control and dampened system oscillations;
3. Reduced financial costs and environmental impacts associated with building new transmission lines.

FACTS devices are capable of controlling up to three system parameters: voltage magnitude, phase angle and transmission impedance. There are many different types of FACTS devices, each of which has its own unique working principles.

The Unified Power Flow Controller (UPFC) is the most versatile FACTS device that has emerged for the control and optimization of power flow in electric power transmission systems. It offers major potential advantages for static and dynamic operation of transmission lines since it combines the features of both a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC). In this thesis, UPFC devices are integrated in composite power system reliability evaluation to examine their impact in system adequacy.

1.4 Research Objectives and Scope of the Thesis

As discussed in the previous section, the utilization of FACTS technologies can have significant positive impacts on power system performance. There is obviously considerable need to develop suitable models and techniques to quantitatively assess the impacts of FACTS devices on power system reliability.

Considerable effort has been spent in developing techniques for composite power system reliability evaluation using analytical methods [12-16]. These methods are mainly focused on conventional generation and transmission facilities. References [17, 18] present methods to incorporate High Voltage Direct Current (HVDC) in a composite system reliability evaluation using analytical and Monte Carlo simulation methods, respectively. These studies combined the generation and the HVDC outage levels to create a single multi-state generation model, and were conducted using conventional composite system evaluation techniques. Reference [19] incorporated FACTS devices in the interconnecting links between major systems and conducted the analysis at the HL-I level.

There is relatively little literature that includes FACTS in reliability studies, particularly in composite system evaluation. The utilization of FACTS devices within bulk transmission systems to change the basic load flow patterns is, however, increasing in the new market environment, as existing systems became increasingly loaded and congested. The main objective of this research work is to develop appropriate models and techniques for composite power system reliability evaluation incorporating FACTS devices. It is expected that this research will help utilities and customers make decisions in regard to optimum planning and operation of FACTS devices. The objectives of this research include:

1. The development of appropriate adequacy assessment models and techniques;
2. The utilization of the models and techniques in a practical power system environment;
3. An examination of the effects of selected system parameters on the composite system assessment incorporating FACTS devices.

There are six chapters in this thesis. The main topics of each chapter are as follows.

Chapter 1 introduces the fundamental concepts related to power system reliability evaluation and the scope and objectives of the research.

Chapter 2 provides a description of the theoretical foundations, the basic concepts and the practical evaluation techniques for composite generation and transmission system adequacy evaluation using the analytical approach.

Chapter 3 presents the development of the evaluation models and algorithms required to perform composite power system adequacy evaluation incorporating FACTS devices using an analytical approach. A three-state reliability model is utilized to represent a FACTS transmission unit. Two network evaluation techniques, the reinforced minimal tie set method and the modified DC load flow method, are illustrated. A computer program for the general systems was developed in C++ to conduct the studies described in this thesis.

Chapter 4 illustrates the application of the developed evaluation models and techniques in adequacy studies conducted on the Roy Billinton Test System (RBTS) and IEEE Reliability Test System (IEEE-RTS). The studies results are compared and analyzed.

Chapter 5 examines the effects of various parameters on the system adequacy. The effects of system generating capacity and peak load, the FACTS device installation locations, the FACTS device capacity and forced unavailability are illustrated using the developed models and techniques.

Chapter 6 summarizes the research described in this thesis and presents some conclusions.

2 Basic Concepts and Evaluation Techniques in Composite System Assessment

2.1 Introduction

As noted in Chapter 1, composite system adequacy evaluation is concerned with the problem of assessing the ability of the combined generation and transmission system to satisfy the load demand at each major system load point. Quantitative assessment of the adequacy of a composite system can be performed using two basic techniques [7]: analytical methods and Monte Carlo simulation. An analytical approach usually requires less computation time than a simulation approach and is able to provide accurate adequacy indices, when suitable models and techniques are developed. This thesis is focused on the utilization of an analytical approach in composite system adequacy evaluation.

An analytical method represents the system by a mathematical model and evaluates the reliability indices from this model using suitable mathematical formulae. In a practical power system, the transmission configuration which links the generating units to the major load buses is usually relatively complicated and it is not possible to model the network using simple series and/or parallel reduction techniques [20]. The contingency enumeration approach [7,20,21] has proved to be a viable technique. The basic procedure in a contingency enumeration approach involves the systematic selection of contingencies, contingency evaluations according to predetermined failure criteria and the accumulation of related adequacy indices [21].

There is a wide range of adequacy indices that can be calculated for the overall system and for the load points distributed throughout the system. These indices are complementary, not alternatives. Individual load point adequacy indices are necessary to identify weak points in the system and to help establish optimum response to equipment investment. System indices provide valuable information on overall system adequacy and can be used in comparisons of different alternatives in composite system planning.

This chapter provides a description of the theoretical foundations, the basic concepts and the practical evaluation techniques for composite generation and transmission system adequacy evaluation using an analytical approach.

2.2 State Space Models

The availability and reliability of a power system depend on the performance of each element within the system. The probabilistic behavior of each major component therefore has to be mathematically modeled in order to conduct composite system reliability evaluation. Component behavior is usually modeled using a state space representation and is analyzed as a Markov process under the assumption that the component failure and repair processes follow the exponential distribution.

The state space diagram of a single repairable component (a generation or transmission unit) is shown in Figure 2.1, in which the system can reside in either state 1 (the up or operating state) or state 2 (the down or failed state). The transition rates between the two states are the component failure rate λ and repair rate μ, which are considered to be constant values.

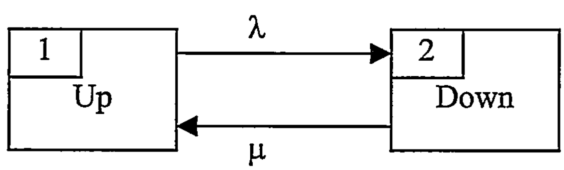

Figure 2.1 State space diagram of a single component system

The probabilities of residing in each state (P_1, P_2) and the frequency (f) of encountering each state can be calculated as follows,

$$P_1 = \frac{\mu}{\lambda + \mu}$$
$$P_2 = \frac{\lambda}{\lambda + \mu} \qquad (2.1)$$

$$f = P_1 * \lambda = P_2 * \mu = \frac{\lambda\mu}{\lambda + \mu} \qquad (2.2)$$

This model is used in this research to represent all the generation and transmission elements, except for those transmission units that incorporate FACTS devices. This is discussed in the next chapter.

2.3 Basic Procedure and Concepts

The basic procedure for composite system adequacy evaluation can be generally classified into the three steps of contingency ranking and selection, contingency evaluation according to predetermined failure criteria and the accumulation of adequacy indices, as illustrated in Figure 2.2.

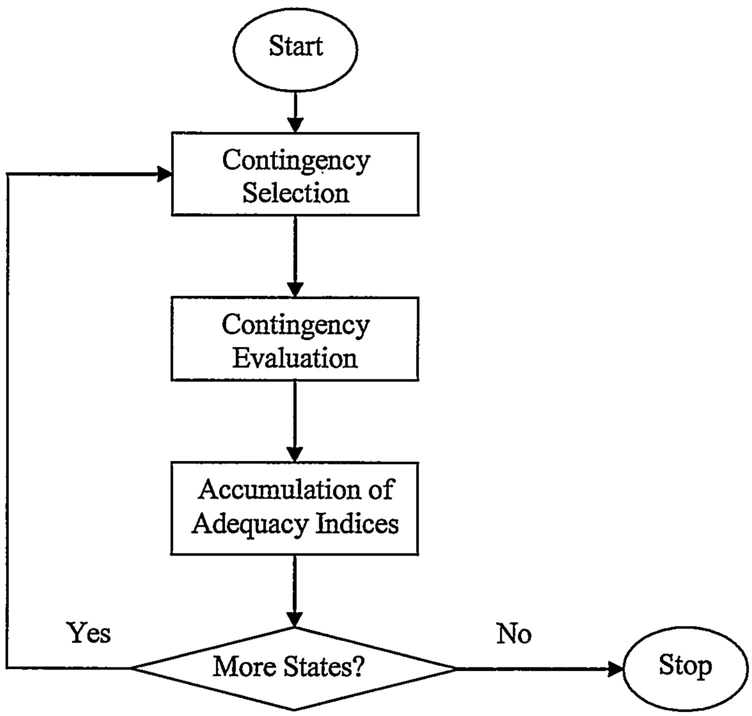

Figure 2.2 Basic analytical procedure

2.3.1 Contingency Selection

Composite generation and transmission system reliability assessment involves the simulation and computation of the system conditions for each possible outage situation in order to determine the voltage violations, line and/or generator overloads and reactive power violations etc [7]. Determination of the system state for each possible outage condition is the first step in the evaluation. The major difficulty is that the number of possible system states can be extremely large in a practical composite power system. It is therefore not feasible or even possible to analyze or investigate all the system states. In practice, only the significant or credible system states are investigated.

The most direct way to select the system states is to simply specify the system contingency levels up to certain values, such as considering system states with a contingency level less than or equal to four. The contingency probabilities generally decrease as the contingency level increases. It is therefore reasonable to curtail the credible system state list by not considering high level events, which have extremely low or negligible probabilities of existence.

The following equations can be used to calculate the system contingency probabilities and the system contingency repair and failure rates.

$$\begin{aligned} P_{si} &= \prod_{k\in U} p_k \prod_{m\in D} q_m \\ \mu_{si} &= \sum_{m\in D} \mu_m \quad \text{occ/yr} \\ \lambda_{si} &= \sum_{k\in U} \lambda_k \quad \text{occ/yr} \end{aligned} \tag{2.3}$$

where

U is the set of in-service components in state si,

D is the set of out-of-service components in state si,

p_k and λ_k are the availability and failure rate of component k respectively,

q_m and μ_m are the unavailability and repair rate of component m respectively.