COMPOSITE SYSTEM BASED MULTI-AREA RELIABILITY EVALUATION

A Thesis

by

RAMYA NAGARAJAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Electrical Engineering

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ABSTRACT

Composite System Based Multi-Area Reliability Evaluation.

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Currently, major power systems almost invariably operate under interconnected conditions to transfer power in a stable and reliable manner. Multi-area reliability evaluation has thus become an invaluable tool in the planning and operation of such systems. Multi – area reliability evaluation is typically done by considering equivalent tie lines between different areas in an integrated power system. It gives approximate results for the reliability indices of a power system as it models each of the areas as a single node to which are connected the entire area generation and loads. The intra-transmission lines are only indirectly modeled during the calculation of equivalent tie lines' capacities. This method is very widely used in the power industry, but the influence of the various approximations and assumptions, which are incorporated in this method, on reliability calculations has not been explored.

The objective of the research work presented in this thesis is the development of a new method called *Composite system based multi – area reliability model*, which does multi – area reliability evaluation considering the whole composite system. It models the transmission system in detail and also takes into account the loss sharing policy within an area and no – load loss sharing policy among the areas. The proposed method is applied to standard IEEE 24 bus Reliability Test System (RTS) and the traditional equivalent tie-line method is applied to the multi-area configuration of the same test system. The results obtained by both the methods are analyzed and compared. It is found that the traditional model, although having some advantages, may not give accurate results.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Currently power systems most invariably operate under interconnected conditions. Interconnections of power systems may offer significant technical, economical and environmental advantages. Some of these advantages are listed below.

1. Possibility to use larger and more economical power plants.
2. Reduction of the necessary reserve capacity in the system
3. Utilization of most favorable energy resources
4. Flexibility of building new power plants at favorable locations
5. Increase of reliability in the systems
6. Reduction of losses by an optimized system operation

The adequacy of the generating capacity in a power system is normally improved by interconnecting the system to another power system. Each interconnected system can then operate at a given risk level with a lower reserve than would be required without the interconnection. The actual interconnection benefits depend on the installed capacity in each system, the tie capacity, the forced outage rates of the tie lines, the load levels and their residual uncertainties in each system and the type of agreement in existence between the systems [1].

This thesis follows the style of *IEEE Transactions on Power Systems*.

Due to prevalence of integrated power systems, also called multi-area power systems, responsibility lies in the hands of utility companies, Independent System Operators (ISOs) and other related entities to evaluate and maintain the reliability of these systems.

1.2 Power System Reliability

Reliability is the probability of a device or system performing its function adequately, for the period of time intended, under the operating conditions intended. The reliability of a power system pertains to its ability to satisfy its load demand under the specified operating conditions and supporting policies.

Some of the most commonly used reliability measures are as follows [2].

1. *Loss of Load Probability* (LOLP) is the probability that a system will fail to satisfy its load demand under the specified operating conditions and policies. This index, being a probability measure, is dimensionless.
2. *Loss of Load Expectation* (LOLE) is the expected period of time during which the system will fail to meet its load demand, over a given period. Typical unit is *hours/year*, and the LOLE in *hours/year* can be obtained by multiplying the LOLP by 8760 (8760 is the total number of hours in a typical year).
3. *Expected Unserved Energy* (EUE) is the expected amount of energy which the system will be unable to supply to the consumers. This index is alternatively known as *Expected Energy Not Served* (EENS). Typical unit of measure is *MWh/year.*

The above mentioned reliability indices are expected values and as such indicate the long-term reliability that can be expected. Reliability evaluation of interconnected or multi-area systems involves calculation of these indices of the individual areas and hence the overall system.

1.3 Supporting Policies in Multi-Area Systems

A power system pool or interconnected system configuration is usually represented by a group of areas each of which is associated with a specific utility company or a jointly owned generation facility. It is therefore important to calculate area indices which indicate area reliability. In order to obtain realistic area indices which indicate area reliability, a supporting policy must be clearly specified. Different supporting policies lead to different area indices and therefore a different appreciation of area reliability.

The transmission lines which connect any two individual areas are called the tie lines and during normal operating conditions power flowing through them based on the contractual arrangements. When assistance is required these tie lines carry power from a source area to a sink area. There is a wide variety of supporting policies which guide this tie line flow. A firm interchange contract can be considered by adjusting the area load levels and the relative tie line capacity. The following two basic load sharing policies can be used in a loss-of-load situation [3].

1. *Load Loss Sharing Policy* – Under this policy the areas share the loss of load. The objective here is to minimize pool load loss. The areas, therefore,

help each other even at the expense of losing their own load to achieve this objective.

2. *No Load Loss Sharing Policy* – Based on this policy, an area will provide emergency assistance to other areas only to the extent of its surplus capacity. The first obligation is the area's own load. An area will, therefore, help other areas only after its own demand has been met.

These policies play an important role in distributing power among the various areas in an interconnected power system and hence different supporting policies will lead to different area reliability evaluation.

1.4 Multi-Area Systems

Most electric power companies operate as members of an interconnected power system owing to the mutual benefits associated with interconnected operation and planning. The reliability of a power system can usually be improved by interconnecting with other systems. Because of the diversification of load demands and generation unit failures, every interconnected system is able to share reserves through these interconnections.

When the total available capacity in an area is insufficient to meet its load, assistance can be received from neighboring areas. The amount of power assistance from one or more source areas to a sink area is dependent upon the following factors.

1. The load level of the supported area
2. The available generating capacities of the supporting areas
3. The tie line constraints

4. The import/export agreement between areas

Reliability evaluation of interconnected power systems is an important area of investigation. Several techniques and analytical methods for multi-area reliability evaluation have been proposed in literature [4-17].

The reliability of an interconnected system is affected not only by the capacities and reliability of the individual components, but also by issues such as operating policies, firm contracts and government legislation. Techniques for reliability evaluation of multi-area systems have attempted to address and incorporate some of these issues in addition to modeling and integrating the system components and topology [18].

Consider, for example, an interconnected system consisting of three areas, which are connected in a loop, and three tie lines. The multi-area system is thus formed and can be represented as a network comprising of 3 nodes and 3 arcs, as shown in Fig. 1 [18]. Each node represents an area or an individual power system interconnected with several other systems. The generation and load models, that are associated with an area, are described later on in this section. Each of these arcs represents an equivalent tie line between areas. The modeling issues involved in such a multi-area representation of the original interconnected system are discussed in the following sub-sections.

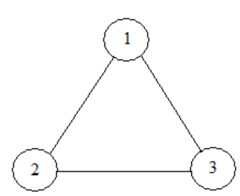

Fig. 1. Network representation of a 3-area system

1.4.1 Network

The network, as displayed in Fig. 1, consists of N_a nodes and N_t arcs connecting these nodes. Each node represents an area and the arcs between the nodes represent the tie lines. Each area is represented by a single node, to which are connected the entire area generation and loads. This does not mean that the intra-area transmission line constraints are totally ignored. The tie lines between areas represent equivalent ties and the intra-area bottlenecks are reflected, to a certain extent, on the tie line capacities. The term *area* is used in an arbitrary manner to represent either an electric power utility or part of a utility.

1.4.2 Component Capacity States

At any given time a component, such as a generator or a transmission line, can exist in one of several capacity states: it may be fully available or in derated state or totally unavailable. An *outage* refers to a state when an equipment is taken out of service. Two kinds of outages, that are usually considered, are planned and forced. An equipment is on planned outage when it is taken out for scheduled maintenance or pre-emptive repair. Forced outage occurs in the event of a random failure. An equipment may be in a derated state due to a part of it being on outage, or due to certain climatic conditions.

The probability of the totally unavailable state is specified in input data and in the so-called forced outage rate of the unit (FOR). The probability of the fully available state is then (1-FOR). When information about outages or deratings is available in advance, such information is used by dividing the study period into intervals over which the outages are assumed to result only from random failures.

1.4.3 Generation Model

Generator unit modeling is the most important factor and it provides an artificial history of the unit. Each of the generation nodes in the interconnected system have one or more generating units. A conventional two-state model is used in this research, by which the units are considered to be either fully available or totally unavailable.

The generating unit models described above define the probability distribution of available capacities for a unit. The state of a unit is then defined in the simulation process through the following procedure.

1. A uniformly distributed random number, R_N, is drawn from the range 0-1. It is to be noted that each of the generators has a dedicated random number generator to facilitate convergence.
2. The random number thus drawn as described, R_N, is used to determine the state of the unit according to the specified probability distribution through the following guidelines.
   a. Unit is fully available if,

      $R_N \geq FOR$

   b. Unit is totally unavailable if,

      $R_N < FOR$

The capacities of all the generation units that are fully available at a given bus are added. This cumulative value denotes the generation capacity at a given bus for a particular time period. Generator planned outages are not considered in this research for simplicity.

1.4.4 Load Model

Load modeling can be done by considering an annual load curve. The basic load data for each area of the interconnected system consists of an 8760 hour (considering 365 days in a year) or 8736 hour (considering 364 days in a year) chronological load cycle in Edison Electric Institute (EEI) format. This load cycle is used to create a per unit load cycle for each area.

The most basic approach to consider the annual load curve is to scan all hourly points of the chronological load curve. The loads are varied every hour based on a hierarchical structure. That is, the hourly peak load is expressed as a percentage of daily peaks, the daily peak load as a percentage of weekly peaks and the weekly peak load as a percentage of annual peaks. The annual peak load alone is expressed in MW. This way of modeling ensures that each hourly load in one year has an equal occurrence probability and it also facilitates faster convergence.

1.4.5 Transmission Line Model

In multi-area studies, equivalent tie-lines are used. Each of these tie lines is assigned an admittance value and capacities in the forward and backward flow directions. The methods for calculating these parameters are discussed in the Chapter II. It should be noted that it is often difficult to compute equivalent admittances for tie line representations [19-21].

In the research work presented in this thesis all these lines are assumed to be in fully available state at all times for simplicity. As the failure rate of transmission lines is very low when compared to generation outage rates, omission of transmission line outage factor is a valid assumption for analysis. But the line capacity constraints are considered throughout the analysis.

1.5 Composite Systems

In composite system model the generations, loads and transmission lines are modeled in a detailed manner for reliability evaluation. This model is more comprehensive when compared to the multi – area system model discussed earlier.

In composite system studies a similar network representation, as that of the multi-area system earlier discussed, is used with the nodes representing the buses and the arcs representing the transmission lines. Fig. 2 shows a simple composite system generation-load model [3].

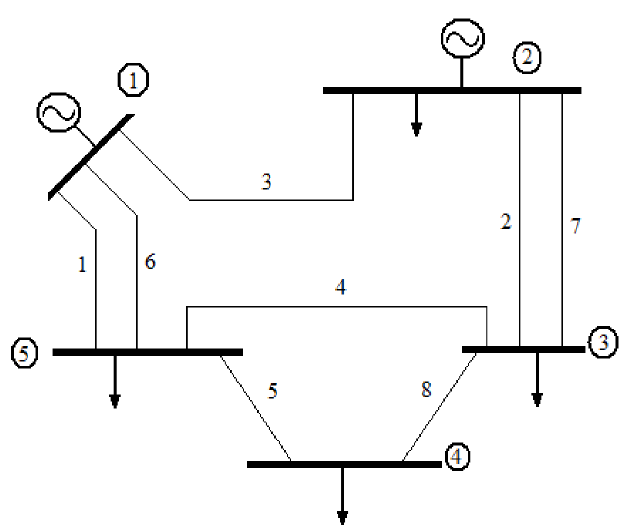

Fig. 2. A simple composite system model

The composite system modeling is similar to multi-area except that there are many more nodes as the transmission lines are modeled in more detail manner, preserving the structure of the bulk power transmission network. The analysis techniques are similar except for the network flow calculations. In multi-area calculations, transportation type modeling or DC power flow modeling are considered adequate. In composite system reliability analysis, transportation type model is not considered acceptable.

1.6 Research Objective

Power system reliability evaluation has been given great attention in system planning and load forecasting. Operation of power systems under interconnected conditions being highly prevalent has made reliability evaluation of complex interconnected systems a necessity. In order to cater to such needs and accurately evaluate the reliability several methods exist in literature [4-17]. It is important to keep checking the accuracy of such methods and development of more accurate methods. Also comparison of the methods on the basis of simplicity, accuracy, efficiency to handle the complexity of interconnected systems, computational effort and time is quite important.

The research work described in this thesis seeks to meet the needs stated above, to some extent.

Multi – Area Reliability Evaluation is typically done by considering equivalent tie lines and as a result the intra – area transmission lines are considered only indirectly in calculating the equivalent capacity of the tie lines. Once these equivalent capacities are determined, the generation and loads within each area are modeled as if they are connected to a single node. This equivalent method gives approximate results for the reliability indices as it cannot be expected to model the transmission system comprehensively. Load sharing policy can either be no load loss or load loss sharing between the areas for multi-area reliability evaluation and within the areas only load loss sharing is followed.

The traditional multi-area reliability model is quite simple in structure as the total number of nodes analyzed is equal to the number of areas within the interconnected system. Its implementation and reliability indices calculation using Monte Carlo Simulation is fast. Currently this method is widely used in power industry and several techniques and heuristics are also available [22] that make this model computationally more efficient.

Since the multi-area reliability model involves approximations that might not yield accurate reliability indices a composite system based model is suggested. If the more detailed composite system model is to be used as a basis for multi-area reliability evaluation then the new model to be developed should be able to handle simultaneous load loss sharing policy within the areas and no load loss sharing policy among the various areas.

The new methodology presented in this thesis is called the *Composite System based Multi – Area Reliability Model*. It does multi – area reliability evaluation considering the whole composite system. This method is more comprehensive as each of the transmission lines is taken into account for calculations and no approximations are made. Prioritizing the flow of power within the same area over the tie line flow ensures simultaneous handling of load loss sharing policy within the area and no load loss sharing policy between the areas.

The more comprehensive composite system based multi – area reliability model can be used as a standard to examine the accuracy level of the equivalent tie line model. Though the traditional method is used extensively for reliability evaluation of interconnected systems, its accuracy has never been addressed in the literature. Comparison of both these models on the basis of previously mentioned aspects, especially accuracy, will assist related entities to measure reliability indices of interconnected system with greater confidence.

1.7 Thesis Outline

Chapter I briefly discusses the general concepts of power system reliability and operation of interconnected power systems. The various reliability indices and load sharing policies are presented. The advantages of interconnection of power systems and the necessities for accurate evaluation of reliability of such systems are described. Multi-area and composite systems were explained along with their modeling. A brief overview of the tradition method and the newly proposed method for multi-area reliability evaluation are given.

In Chapter II the equivalent tie line method, which is typically used for multi-area reliability studies, is explained in detail. The Linear Programming (LP) formulation associated with this method has been presented. Also discussed briefly are aspects of Monte Carlo simulation and procedures for reliability indices estimation.

Chapter III presents the newly proposed composite system based multi-area reliability model. The LP formulation for implementing this model has been discussed in detail.

A case study has been discussed in Chapter IV. An IEEE 24-bus Reliability Test System (RTS) and a modified RTS (MRTS) are described briefly. Reliability indices evaluation for these systems by both methods was done and the results are presented. Comparison of both the models used for reliability calculations has been discussed.

Chapter V concludes the thesis by presenting the general conclusion of this research work.

CHAPTER II

MULTI-AREA RELIABILITY EVALUATION BY EQUIVALENT TIE LINE METHOD

2.1 Introduction

Most electric power utilities today operate as members of an interconnected power system. The reasoning behind interconnecting to other utilities is based on the improvements of system reliability brought about by these interconnections. Due to the diversification of loads and unit failures, members of an interconnected power system are able to share reserves, and therefore operate at higher levels of reliability for a given reserve or alternatively for the same level of reliability have lower reserve. For system planners, tools for performing reliability calculations of interconnected systems are of great need. These tools are of particular importance in deciding which interconnections need reinforcements, and which areas need installation of additional generating units [6].

Throughout the years a number of methods for reliability calculations of interconnected systems have been proposed. Almost all of these methods for reliability indices calculation are based on the equivalent tie line model. This model is favored owing to its simplicity and efficiency of calculation. The equivalent tie line model represents an interconnected system by incorporating several assumptions and approximations and has certain modeling issues. Though it has been prevalently used, the accuracy with which it calculates the reliability indices has never been addressed in the literature.

This chapter discusses the equivalent tie line model in detail and the modeling issues associated with it. It also briefly describes the LP formulation required to implement this model. Monte Carlo simulation and its uses while calculating reliability indices and basic reliability assessment concepts are presented.

2.2 Basic Concepts of Reliability Evaluation

The basic steps of reliability assessment are shown in Fig. 3 [23]. The first step is to define the system that is being analyzed. The system consists of components and therefore the models of the components and system need to be outlined. The combination of component states describes system states. Thus a possible approach would be complete enumeration, i.e., to select each state in turn and evaluate it for its status as success or failure defined for the system. In power systems, the failure of the system often means that the entire load cannot be satisfied and thus some part of it needs to be curtailed. Then based on the probability of the failed states and the magnitude and location of load loss, the relevant reliability indices can be computed.

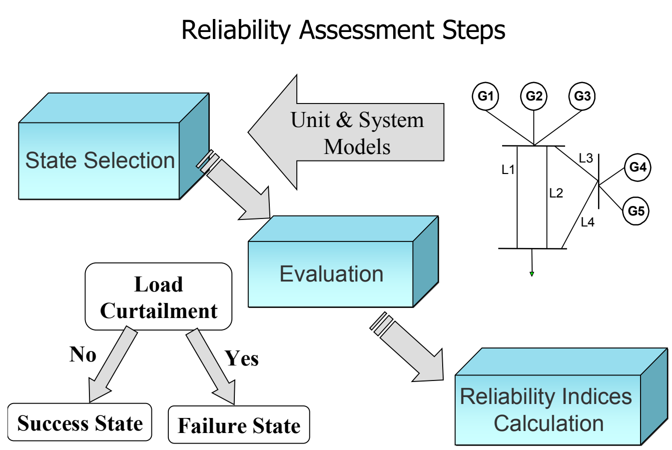

Fig. 3. Reliability evaluation steps

It can be seen from this process that the following are needed for the reliability evaluation.

1. Component and system models and data
2. A state evaluation procedure
3. Reliability indices to be computed

The procedure described above is generic and, here in this thesis, two methods are discussed for system modeling – equivalent tie line model and composite system based multi-area reliability model. State evaluation is done by using the LP formulations described for both the methods.

2.3 System Modeling – Equivalent Tie Line Method

Equivalent tie line model is based on the approximation of composite system model resulting in a very simple structure. Each of the areas in an integrated system is represented as a single node by this model. Hence it reduces the total number of nodes, in the actual interconnected system, to the number of individual members or areas. The loads and generations within an area are modeled to be connected to the node, which represents the corresponding area of the original interconnected system.

All the tie lines which can transfer power between any two areas are represented by an equivalent tie line. The capacity and admittance of an equivalent tie line can be computed by the methods explained later in this chapter. It is important to note that the intra-transmission lines' capacity constraints are not totally ignored in reliability calculations. Though they do not directly influence the reliability indices calculation, their capacity limits are reflected, to some extent, in equivalent tie line capacities.

Equivalent tie line model is quite simple in structure as the total number of nodes analyzed has been reduced greatly and also are the number of tie lines. The basic steps for calculating multi-area reliability using this method are as follows [3].

1) Construction of generating capacity and load models for each area.
2) Calculation of the available capacity margin for each area by combining the generation capacity model and the load model.
3) Incorporation of the tie line network and appropriate load sharing policies and calculation of the reliability indices for each area and the total integrated system using Linear Programming (LP) formulation and Monte Carlo simulation.

The implementation of this method and reliability calculation using Monte Carlo Simulation is quite fast. Several heuristics and techniques are presented in [22], which make this model highly time efficient.

Though the advantages of this method such as simplicity and fastness are quite appealing, they happen at the cost of certain approximations and assumptions. Direct influence of intra-area transmission line constraints on reliability indices has been neglected while modeling the network. Equivalent tie line admittance calculations are really difficult [19-21] and therefore relative admittance is taken into consideration. Such issues affect accurate reliability evaluation and the degree to which it is getting affected will be presented in this thesis.

The following sections have been designated to explain in detail on how to build the model and use it for reliability calculation.

2.3.1 Generation Model

Generator unit modeling is the most important factor and it provides an artificial history of the unit. Each of the generation nodes in the actual interconnected system have one or more number of generating units. A conventional two-state model comprising of fully available and totally unavailable states is used. The capacity and probability associated with these states are as follows.

1. Unit Fully Available State
   - (a) Capacity = Rated
   - (b) Probability = 1 – FOR
2. Unit Totally Unavailable State
   - (a) Capacity = 0
   - (b) Probability = FOR

The state of a unit at a specified time is determined by drawing a random number R_N from uniform distribution of range 0 – 1. As was discussed earlier in Chapter I,

c. Unit is fully available if,

$$R_N \geq FOR$$

d. Unit is totally unavailable if,

$$R_N < FOR$$

The capacities of all the generation units that are fully available at a given bus are added. This cumulative value denotes the generation capacity at that bus for a particular time period.

The above described generator unit model determines the generation available at a node in the equivalent tie line model. The capacities of all the available generation nodes, within an area of the original interconnected system, is thus added and assigned as the capacity available at the node which represents the corresponding area in the equivalent tie line model.

2.3.2 Load Model

All the loads in an area of the interconnected system are modeled to be connected to a single node representing the area in the equivalent network model. Once the load at each node in the original system is calculated using the load modeling approach described in Chapter I, the loads at each of the nodes in the equivalent tie line model is found. These vary once in every hour in a year and each load level is found to have an equal probability distribution of occurrence.

The annual load curve approach promotes faster convergence. Load forecast uncertainty has been neglected in this research work for simplicity as the primary focus is comparison of the basic methodologies of the equivalent tie line and composite system based multi-area reliability model.

2.3.3 Transmission Line Model

An equivalent tie line, as the model name suggests, represents all the tie lines that connect any two areas. These tie lines are assumed to be always in fully available state in this thesis, although multi-state equivalent models can also be similarly developed by considering failures of the transmission lines.

A. Equivalent Tie Line – Capacity Calculation

In this thesis, to find the equivalent tie line power carrying capacity between two areas, a procedure is discussed below.

1. *System*: Consider the original interconnected power system model.
2. *Load*: Take the peak demand as the load level at each of the buses.
3. *Generation*: Each area should be able to meets it own load demand, if there is sufficient capacity available. A generation node in each area is assigned a generation level such that it contributes to its area demand based on its rated capacity. Assuming that the capacity available in the area is higher than the load,

$$G_n = D_a \times \frac{G_{rn}}{G_{ra}} \tag{1}$$

where

G_n – Generation at node n in an area

D_a – Total load demand of an area

G_{rn} – Rated generation capacity at node n in an area

G_{ra} – Total rated generation capacity of an area.

4. *Power flow*: For the above specified load and generation level run a DC power flow. Sum up the flows in all the tie lines connecting the source and sink areas. Check if there are any transmission line violations.

   a. If there any transmission line limit violations are found then the equivalent tie line capacity is assigned this cumulative value, provided the cumulative value is positive, else the capacity is equated to zero. This ends the procedure.

b. If no transmission line violations occur, proceed to step 5.

5. Increase load level at each of the nodes in the sink area by a small multiplication factor. Also increase generation at source area proportional to the demand increase in sink area. That is,

$$G_n = (D_a + D_i) \times \frac{G_{rn}}{G_{ra}} \quad (2)$$

where

D_i – Total increase of load demand in sink area

6. Now once again run DC power flow.

a. If there are no transmission line limit violations, go to step 5.

b. Else go to step 7.

7. Sum up the flows in all the tie lines connecting the source and sink areas.

a. If the cumulative value is found to be a positive value then it is the capacity of the equivalent tie line between the considered source and sink areas.

b. If the cumulative value be negative then the net increase between the initial cumulative flow, calculated in step 4, and this final cumulative flow is taken as the equivalent tie line capacity.

Once the equivalent tie line capacity is found, it remains fixed irrespective of the varying load levels during reliability evaluation. DC Power flow is used in the above procedure owing to its simplicity and it sufficiently satisfies the need of the task involved.

B. Equivalent Tie Line – Relative Admittance Calculation

It is often difficult to compute equivalent admittances for tie line representations [19-21]. Here a procedure, which calculates relative admittance of an equivalent tie line, is discussed. The fact that admittance is directly proportional to power transfer is used in calculating the relative admittance. This value of admittance is relative to the source and sink area.

1. *System*: Consider the original interconnected power system model.
2. *Load*: Take the peak demand as the load level at each of the buses.
3. *Generation*: Each area should be able to meets it own load demand. A generation node in each area is assigned a generation level such that it contributes to its area demand based on its rated capacity. Thus the generation level at a node is given by,

$$G_n = D_a \times \frac{G_{rn}}{G_{ra}}$$

4. *Power flow*: For the above specified load and generation level run a DC power flow. Sum up the flows in all the tie lines connecting the source and sink areas.
5. Substantially increase power demand in sink area, say about 100 MW. Also increase an equal amount of generation in source area.
6. Once again run DC power flow. Sum up the flows in all the tie lines connecting the source and sink areas.

7. Find the percentage of power distributed, from the source area to the sink area through tie lines directly connecting both the areas, by subtracting the cumulative value of step 4 from that of step 6. (Note that for any value, other than 100 MW, the cumulative values ought to be divided by it before subtraction.)
8. Set admittance of equivalent tie line, which connects source and sink areas, to be equal to the percentage of power distribution calculated in step 7.
9. Using this value of admittance and by injection the same amount of power used in step 5, find the power distribution.
10. Alter admittance till the initial power distribution is met. (Even if no exact value of admittance that can reproduce the initial power distribution can be found, an approximate value of admittance can cause no major deviation in results.)

This method of admittance calculation is a relative one and hence the values are only approximate.

2.4 Monte Carlo Simulation

Reliability evaluation methods can be broadly classified into two categories, analytical methods and Monte Carlo simulation methods. In the analytical methods, the system is explicitly or implicitly modeled by a set of mathematical equations. Reliability indices are obtained by performing mathematical operations on these equations. On the other hand, in the Monte Carlo simulation, artificial histories of the system are created by using the probability distributions of component state residence times. Reliability indices are then estimated by statistical inference from these histories just in the same manner as would be done on the history of the real system. Both sets of methods have their own advantages and are used in reliability evaluation. The Monte Carlo enjoys a special advantage in its ability to accommodate higher levels of system complexity [22].

2.4.1 Features of Monte Carlo Methods in Reliability Evaluation

A fundamental parameter in reliability evaluation is the mathematical expectation of a given reliability index. Salient features of the Monte Carlo method for reliability evaluation therefore can be explained from an expectation point of view [3].

Let Q denote the unavailability (failure probability) of a system and x_i be a zero-one indicator variable which states that,

$x_i = 0$ if the system is in the up state

$x_i = 1$ if the system is in the down state

The estimate of the system unavailability is given by

$$\bar{Q} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3}$$

where N is the number of system state samples.

The unbiased sample variance is

$$V(x) = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{Q})^2 \tag{4}$$

When the sample size is large enough, (4) can be approximated by

$$V(x) = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{Q})^2 \tag{5}$$

Because x_i is zero-one variable, it follows that

$$\sum_{i=1}^{N} x_i^2 = \sum_{i=1}^{N} x_i \qquad (6)$$

Substituting (3) and (6) in (5) yields

$$V(x) = \frac{1}{N}\sum_{i=1}^{N} x_i^2 - \frac{1}{N}\sum_{i=1}^{N} 2x_i\bar{Q} + \frac{1}{N}\sum_{i=1}^{N} \bar{Q}^2$$

$$V(x) = \bar{Q} - 2\bar{Q}^2 + \bar{Q}^2$$

$$V(x) = \bar{Q} - \bar{Q}^2 \qquad (7)$$

It is important to note that (3) gives only an estimate of the system unavailability. The uncertainty around the estimate can be measured by the variance of the expectation estimate:

$$V(\bar{Q}) = \frac{1}{N} V(x)$$

$$V(\bar{Q}) = \frac{1}{N} V(\bar{Q} - \bar{Q}^2) \qquad (8)$$

The accuracy level of Monte Carlo simulation can be expressed by the coefficient of variation, which is defined as

$$\alpha = \frac{\sqrt{V(\bar{Q})}}{\bar{Q}} \qquad (9)$$

Substituting (8) in (9) gives

$$\alpha = \sqrt{\frac{1 - \bar{Q}}{N\bar{Q}}} \qquad (10)$$

Equation (10) can be rewritten as

$$N = \frac{1 - \bar{Q}}{\alpha^2\,\bar{Q}} \tag{11}$$

The above equation indicates two important points:

1. For a desired accuracy level α, the required number of samples N depends on the system unavailability but is independent of the size of the system. Monte Carlo methods are therefore suited to large-scale system reliability evaluation. This is an important advantage of Monte Carlo methods compared to analytical enumeration techniques for the reliability evaluation.

2. The unavailability (failure probability) in practical system reliability evaluation is usually much smaller than 1.0. Therefore,

$$N \approx \frac{1}{\alpha^2\,\bar{Q}} \tag{12}$$

This means that the number of samples N is approximately inversely proportionally to the unavailability of the system. In other words, in the case of a very reliable system, a large number of samples in required to satisfy the given accuracy level.

2.4.2 Random Number Generation

A random number can be generated by either a physical or a mathematical method. The mathematical method is most common as it can guarantee reproducibility and can be easily performed on a digital computer. A random number generated by a mathematical method is not really random and therefore is referred to as *pseudo-random* *number*. In principle, a pseudo-random number sequence should be tested statistically to assure its randomness.

The basic requirements for a random number generator to be used in Monte Carlo simulation are as follows.

1. *Uniformity*: The random number should be uniformly distributed between [0, 1].
2. *Independent*: There should be minimal correlation between random numbers.
3. *Long Cycle Time*: The repeat period should be sufficiently large.

2.4.3 Monte Carlo Simulation – Random Sampling

In conducting reliability evaluation of power system using Monte Carlo methods, the computing time and the variance are directly affected by the selected sampling techniques and system analysis requirements. Most Monte Carlo simulation methods that are used for system reliability analysis can be classified as sequential or non-sequential.

In this research work, Monte Carlo random sampling technique is used for calculating the reliability indices because of its simplicity. Random sampling, or non-sequential simulation, consists of performing random sampling over the aggregate of all possible states the system can assume during the period of interest. It ensures fast convergence and it is simpler when compared to frequency sampling technique of Monte Carlo simulation.

The state of all the generation units within the interconnected system is found using random sampling and hence their available capacities. A unit is said to be up state if the random number drawn is greater than or equal to the Forced Outage Rate (FOR) of that unit, else it is in down state. Most important factor in using random sampling is that the random number must have a uniform distribution.

2.4.4 Convergence Criteria of Random Sampling

The coefficient of variation shown in (9) is often used as the convergence criterion in Monte Carlo Simulation.

It is crucial to sample sufficient number of states to estimate reliability indices.

It can be seen from (9) that

1. Sample size is not affected by system size or complexity.
2. Accuracy required and the probability being estimated effect the sample size.
3. Computational effort depends on N and CPU time/sample.

A covariance of 2.5% at system level LOLE is used in this research work as the convergence criteria.

2.5 Linear Programming Formulation

The loads, generation and transmission lines define the system state at a load hour. Once the system state is defined, LP module is used to enumerate the unmet demand at the corresponding load hour. The state evaluation process described earlier is handled by the following LP technique. It evaluates if a system state is a success or failure state.

The system is said to suffer loss of load if any of the nodes, which actually are areas, goes without its demand being met. The loss of load of the system can be found using the following LP formulation [22, 24]. Some of the parameters and variables appearing in the LP module vary based on the loss sharing policy between the various nodes.

$$\text{Loss of Load} = \text{Min} \sum_{i=1}^{N_b} C_i \tag{13}$$

subject to:

$$\hat{B}\,\theta + G + C = D \tag{14}$$

$$G \leq G^{max} \tag{15}$$

$$C \leq D \tag{16}$$

$$b\,\hat{A}\,\theta \leq F^{max} \tag{17}$$

$$-\,b\,\hat{A}\,\theta \leq F^{max} \tag{18}$$

$$G, C \geq 0 \tag{19}$$

$$\theta \quad \text{unrestricted}$$

where

N_b - number of buses

N_t - number of transmission lines

b - $N_t \times N_t$ primitive (diagonal) matrix of transmission line susceptances

$\hat{A}$ - $N_t \times N_b$ element-node incidence matrix

$\hat{B}$ - $N_b \times N_b$ augmented node susceptance matrix

$\hat{B}$ = $\hat{A}^T\, b\, \hat{A}$

θ - N_b – vector of bus voltage angles

F^{max} - N_t – vector of flow capacities of transmission lines

F - N_t – vector of transmission line flows

For no load loss sharing policy between the nodes (or areas),

G - N_b – vector of net positive injections

D - N_b – vector of net negative injections

C - N_b – vector of negative injection curtailments

C_i - *i* - th element of C, i.e., negative injection curtailment at bus i

G^{max} - N_b – vector of maximum available net positive injection

For load loss sharing policy between the nodes (or areas),

G - N_b – vector of bus generation levels

D - N_b – vector of bus loads

C - N_b – vector of bus load curtailments

C_i - *i* - th element of C, i.e., unsatisfied demand at bus i

G^{max} - N_b – vector of maximum available bus generation levels

The reliability indices such as LOLE and EUE, for a sampled system state at a particular load hour, for the overall system or each area can be obtained by the above mentioned LP formulation.

2.6 Reliability Indices Evaluation

The basic steps involving the whole process leading to estimating the reliability indices are as follows.

1) Find the load levels at all the nodes for every hour in the annual load cycle.

2) Select a system state $S = (S_1, S_2, \ldots, S_n)$ by sampling techniques, where S_i is the state of the i^{th} component. The set of n components includes the generating units in each area, the loads in each area and all the tie lines.

3) Evaluate a reliability index $R(S)$ for the system state $S \epsilon G$ by an LP model, where G denotes the set of all sampled system states and $R(S)$ represents the selected reliability index for the overall system or each area.

4) Then calculate the expected value of $R(S)$ can be calculated by,

$$E(R) = \sum_{S \in G} R(S) \frac{n(S)}{N} \quad (20)$$

where N is the total number of samples and $n(S)$ is the number of occurrence of system state S.

This procedure is continued until the convergence criterion specified for the simulation is met. $E(R(S))$ denotes LOLE or EUE of the overall system or individual areas and for the mentioned tolerance the value obtained is quite accurate.

2.7 Conclusion

In this chapter the general steps involved in reliability assessment have been presented. The various techniques contributing to reliability indices calculation have been explained. From the discussions it is obvious that multi-area reliability evaluation using the equivalent tie line method proves to be simple. A case study is presented later in this thesis which shows the implementation of this method for estimating the reliability of a standard IEEE Reliability Test System. Comparison of this method with the newly proposed method has been presented in the coming chapters.

CHAPTER III

COMPOSITE SYSTEM BASED MULTI-AREA RELIABILITY MODEL

3.1 Introduction

Composite system reliability evaluation involves the joint analysis of the generation and bulk transmission facilities and is an important aspect in the planning and operation of power systems. When large or interconnected power systems are studied, reliability equivalent models were developed for parts of these networks. The primary objective of using equivalent models is to replace the large and complex structure of a power system by a simple model, which contains all the essential elements and possible states of the original system but eliminates much of the detailed information of this system. This equivalent model can then be utilized in further reliability evaluations.

By convention, the above mentioned equivalent model has been used for multi-area reliability evaluation. It is an approximate method and scales down the number of nodes in an interconnected system. This model though very simple to construct and eases computational effort and time, it suffers certain setbacks. Direct effect of intra-area transmission line capacity limitation on reliability indices cannot be observed. The effect of neglecting a detail structure of the system and the resulting reduction in accuracy level of calculations are to be explored.

This research work aims at building a detailed model of the original interconnected system based on composite system structure. Also, a comparative study of this model and the traditional model is to be presented. This chapter explains in detail the proposed model along with the state evaluation process required by this model for reliability assessment. A general algorithm for implementing this model and reliability indices calculation is presented.

3.2 Composite System Model

The composite system model incorporates the generation, loads and transmission lines in a detailed manner unlike the equivalent multi-area reliability model. The equivalent model is obtained by applying approximations to the composite system model.

In composite system studies a network representation, similar to that of the equivalent multi-area network discussed in Chapter II, is used with the nodes representing the buses and the arcs representing the transmission lines. Since this model is highly detailed it is often time consuming when used for reliability evaluation, especially when used for very large systems. Yet this detailed approach will result in accurate calculations.

Using this composite system model as a base to model interconnected systems for reliability estimation is suggested in this thesis. Detailed modeling of system components is definitely going to improve the accuracy, but the level to which the accuracy is pushed up will be discussed in the next chapter.

3.3 Composite System Based Multi-Area Reliability Model

A new model for reliability assessment based on composite network is proposed in this thesis, called the *Composite System based Multi-Area Reliability Model*. It is a well comprehensive model and no level of approximations is involved while modeling the system components.

Composite system based multi-area reliability model is a new approach and it gives attention to more details. This method, unlike the equivalent tie line method, evaluates reliability of interconnected system by consideration of the whole composite system model. By considering the original system without exclusions or approximations, a high degree of accuracy can be achieved and the reliability indices evaluated will directly reflect the influence of all the loads, generations and transmission lines. The capacity of intra-transmission lines on system and area reliability indices calculation will now be directly reflected in reliability assessment. These modifications ensure multi-area reliability calculations in the most detailed manner and will serve as a standard for measuring the accuracy of the equivalent tie line method.

This model can take into account the load loss sharing policy within the area and no load loss sharing policy between the areas simultaneously. Prioritizing the flow of power within the same area over the tie line flow ensures no – load sharing policy between areas. This aspect is very important to achieve reliability calculations of interconnected systems with varying supporting policies.

3.4 System Modeling

The network model, of this method, used in reliability evaluation is described here. Like the composite system reliability model every major node and transmission lines are considered while calculating the reliability indices. Generation limitations and transmission line power carrying capabilities are taken into account. The network consists of several nodes and arcs representing the buses and transmission lines in the actual interconnected system.

3.4.1 Generation Model

The generator unit modeling approach discussed in Chapter II is used. The generation at a bus coming from one or more generation units is modeled to be attached to the node which represents the bus in the network model.

Though only the two-state generator unit model is used in the research work, it is noteworthy that the new model developed is capable of handling multi-states too. Same is the case for loads and transmission line.

3.4.2 Load Model

Load modeling is similar to that of generation modeling described above. An annual load curve is used for faster convergence. Every hourly point of this chronological curve is scanned.

3.4.3 Transmission Line Model

The network model contains several arcs which represent each transmission line of the interconnected system. These lines are differentiated for calculation purposes based on the end nodes – lines with end nodes belonging to the same area and lines with end nodes belonging to different areas. Impedance and power carrying capability are assigned to all the transmission lines and are provided by the input data.

3.5 LP Formulation for System State Evaluation Process

The state evaluation process is used to check if the selected system state is successful or not. The LP formulation described below handles this task.

The LP formulation discussed in Chapter II can be used for the composite system based multi-area model, provided that all the nodes (or areas) in this model under complete loss sharing policy.

Using the composite system model for multi-area reliability evaluation necessitates simultaneous application of no load loss sharing policy between areas and load loss sharing policy within the areas. This is really important as interconnected systems may have varying supporting policies within an area and among the various areas.

One way of doing this is to set priority levels in the transmission line flows. Firstly, the flows are to be differentiated a follows.

1. Flow from a node to another which belongs to its area
2. Flow from a node to another which belongs to other areas in an interconnected system

Once differentiated, a LP technique can be used to prioritize the flows between the nodes belonging to the same area over that which belonging to different areas. The idea employed here is that, the optimization tool will make sure that for the selected system state the loss of load or load curtailments are minimal, but no area will aid another in need until all its load met. This prioritization ensures simultaneous application of both the load sharing policies described above for multi-area reliability evaluation. This module also helps in inclusion of limitations on generation capacity and transmission line power carrying capabilities.

The LP formulation incorporating all the above mentioned features is as follows. The explanation of a M-factor used in this formulation is provided later in this chapter.

Given Sets:

I - set of all nodes

N (i) - set of neighbors of *i* within its area

O (i) - set of neighbors of *i* outside its area

Given Parameters:

G_i^{max} - maximum power that can be generated by *i*

$D_i >= 0$, demand of power at *i*

Set the value of *M-factor*, which is to be used in the objective function, as shown below.

$$M = \sum_{i \in I} D_i \tag{21}$$

Declaration Variables:

$G_i >= 0$, generation of power by *i*

$C_i >= 0$, unmet demand at *i*

$f_{ij} >= 0$, power transferred from *i* to *j*

The objective function that satisfies the newly proposed method is given by,

$$\text{Min}\left\{ M^3 \sum_{i \in I} C_i + M^2 \sum_{i \in I,\ j \in O(i)} f_{ij} + M \sum_{i \in I,\ j \in N(i)} f_{ij} \right\} \tag{22}$$

subject to:

$$\sum_{j \in N(i)} f_{ji} + \sum_{j \in O(i)} f_{ji} + C_i + G_i = D_i, \qquad \forall \ i \in I \tag{23}$$

$$G_i \leq G_i^{max}$$

$$C_i \leq D_i$$

$$f_{i\in I, j\in N(i)} \leq F_{i\in I, j\in N(i)}^{max} \tag{24}$$

$$f_{i\in I, j\in O(i)} \leq F_{i\in I, j\in O(i)}^{max} \tag{25}$$

The LP formulation described above minimizes loss of load of the entire system but also obliges to the loss sharing policies as discussed previously.

3.5.1 M – Factor

Prioritization of flows is achieved by the use of M-factor in the objective function of the LP formulation. It will ensure simultaneous application of load loss sharing policy within an area and no load loss sharing policy between areas.

Mathematically speaking, it must be a very large positive number. It can be interpreted as the one that introduces penalty to be paid by any solution with a non-zero value (here, strictly positive).

It determines how the flows ought to be distributed among the nodes in the composite network. The priority is such that the load is first satisfied within an area and only the remaining generation in that area, that is found to be in excess of its load, is transported to other areas, if needed. That is, the generation at a node and the flows originating from the node will be calculated such that the priority of satisfying various loads is as follows.

1. Load at the node
2. Load at nodes, within the same area
3. Load at nodes, which belong to other areas

Therefore no area will attempt to transport power to other areas at the cost of not meeting its own load. Thus load loss sharing policy is followed within an area and among the various areas no load loss sharing policy is withheld.

While implementing this LP module choosing a right numerical value for the M-factor should be the most important thing to be noted. The value of M must be sufficiently large when compared to any other quantity. The peak load of the whole system is suggested as one such value to be used for the M factor as none of the flows or loss of load can be greater than it. Equation (20) can be used to calculate the value of M.

3.6 Reliability Indices Estimation

The procedure described in Chapter II can be used for reliability indices estimation. Using Monte Carlo simulation the generation at all nodes is selected for every hour in the annual load curve, which gives the load level at all nodes. Once the system state is defined, appropriate LP module can be activated to evaluate the state. Using the formulas discussed earlier the reliability indices can be calculated.

3.7 Conclusion

Reliability assessment of complex integrated system by the newly proposed composite system based reliability model has been presented in this chapter. The various differences between this model and the equivalent model have also been described. Implementation of both these models and applying them for the standard IEEE 24-bus Reliability Test System will be presented in the following chapter. The results will indicate the level of accuracy of the traditional model when compared with the much detailed proposed model.

CHAPTER IV

CASE STUDIES AND RESULTS

4.1 Introduction

Reliability evaluation of a test system by methods discussed in the previous chapters will be presented here in this chapter. The standard IEEE Reliability Test System (RTS) has been considered for analyzing both the models – the equivalent tie line model and composite system based reliability model. A Modified Reliability Test System (MRTS), which is obtained by applying certain variations to the RTS, is also presented and used analysis of both the models due to certain issues presented later in this chapter.

Reliability indices such as LOLE and EUE are obtained for the RTS and MRTS. System level reliability indices are alone considered for comparison of these models. A comparative study has been presented to elaborate the benefits of using these models for multi-area reliability studies.

4.2 Case Study – IEEE Reliability Test System (RTS)

The IEEE Reliability Test System (RTS) was developed by the Subcommittee on the Application of Probability Methods in the IEEE Power Engineering Society to provide a common test system which could be used for comparing the results obtained by different methods [3].

4.2.1 IEEE 24 – Bus Reliability Test System (RTS)

IEEE 24 bus Reliability Test System (RTS) is used in this paper and its reliability indices are calculated by the equivalent tie line model and composite system based multi-area reliability model. The network diagram of IEEE RTS (multi-area configuration) is shown in Fig. 4 [25]. The data of load model, generation and transmission system of the original IEEE 24-bus RTS have been reproduced in Appendix A.

In order to use this RTS for this multi-area study, it is divided into three areas, which are shown in Table I and Fig. 4. The tie lines between areas are listed in Table II.

TABLE I
THREE AREAS IN RTS

AREA	BUS	GEN. CAP (MW)	LOAD (MW)	MARGIN (MW)
1	14,15,16,17,18,19,21	1170	1125	45
2	5,6,8,9,10,11,12,13,20,22,23	1551	1141	410
3	1,2,3,4,7,24	684	584	100

TABLE II
TIE LINES BETWEEN AREAS

AREA	TIE LINES
Area 1 to Area 2	Line 21-22, 17-22, 19-20(2), 14-11
Area 1 to Area 3	Line 15-24
Area 2 to Area 3	Line 3-9, 4-9, 1-5, 2-6, 7-8

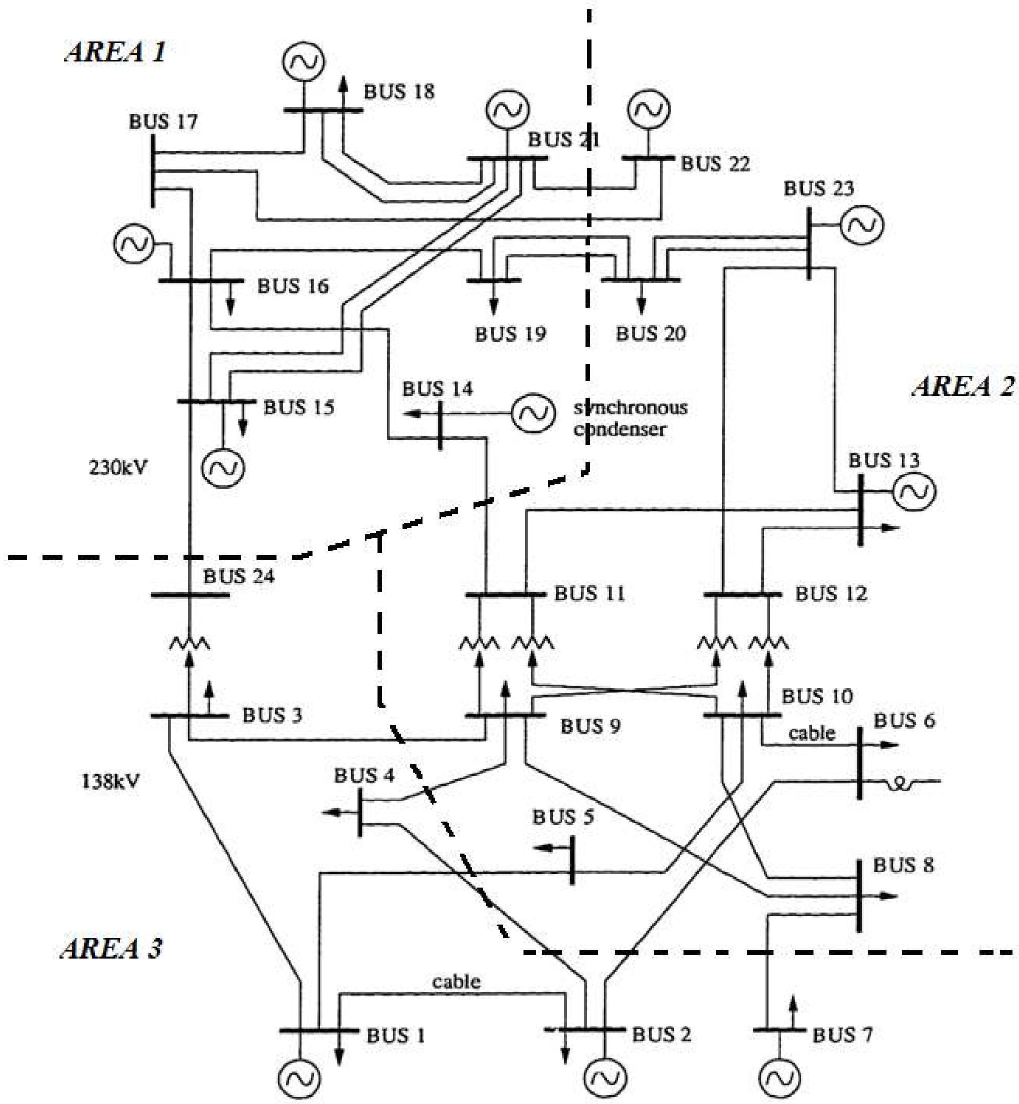

Fig. 4. IEEE 24-bus RTS divided into three areas

4.2.2 IEEE 24 – Bus Modified RTS (MRTS)

Modified Reliability Test System (MRTS) as described in [26, 27, 28] is also used for analysis of both the methods mentioned in this paper. MRTS is identical in topology and component outage rates to IEEE 24-bus RTS, except for the generation and load levels. MRTS has peak generation doubled and the loads are multiplied by a factor 1.8, when compared to original IEEE RTS, but the transmission line capacities are maintained the same. The transmission network of the original IEEE RTS is too strong and hence their power carrying capacities had little effect on the reliability indices [26].

The equivalent tie line capacities and admittances calculated for the multi-area configuration of the IEEE RTS is shown in Table III.

TABLE III
EQUIVALENT TIE LINE CAPACITIES AND ADMITTANCES OF MULTI-AREA CONFIGURATION OF IEEE RTS

TIE LINES BETWEEN	CAPACITY (MVA)	ADMITTANCE (P.U.)
Area 1 – 2	335.8802	0.7884
Area 2 – 3	582.7872	0.3783
Area 1 – 3	377.1394	0.1569
Area 2 – 1	1705.8	0.7884
Area 3 – 2	297.2906	0.3783
Area 3 – 1	30.0353	0.1569

Tables IV and V display the results obtained for IEEE-RTS and MRTS by both Equivalent Tie Line model and Composite System based Multi-Area Reliability Model under load loss sharing policy and no load loss sharing between the areas respectively.

TABLE IV
MULTI-AREA RELIABILITY INDICES OF RTS AND MRTS – LOAD LOSS SHARING POLICY

SYSTEM MODEL	RELIABILITY INDICES OBTAINED BY EQUIVALENT TIE LINE MODEL		RELIABILITY INDICES OBTAINED BY COMPOSITE SYSTEM BASED MULTI-AREA RELIABILITY MODEL	
	LOLE (h/year)	*EUE (MWh/year)*	*LOLE (h/year)*	*EUE (MWh/year)*
RTS (Constant Load)	792.7000	1.4422e+5	742.1000	1.2870e+5
RTS (Variable Load)	38.4565	4.3109e+3	10.7523	1.3629e+3
MRTS (Constant Load)	1982	2.1284e+5	548.9500	8.9475e+4

TABLE V
MULTI-AREA RELIABILITY INDICES OF RTS AND MRTS – NO LOAD LOSS SHARING POLICY

SYSTEM MODEL	RELIABILITY INDICES OBTAINED BY EQUIVALENT TIE LINE MODEL		RELIABILITY INDICES OBTAINED BY COMPOSITE SYSTEM BASED MULTI-AREA RELIABILITY MODEL	
	LOLE (h/year)	*EUE (MWh/year)*	*LOLE (h/year)*	*EUE (MWh/year)*
RTS (Constant Load)	804.2000	1.4450e+5	742.1000	1.2870e+5
RTS (Variable Load)	38.2917	4.2741e+3	10.7523	1.3629e+3
MRTS (Constant Load)	1.9954e+3	2.1349e+5	525.6500	1.3585e+5

The constant load mentioned in these tables is the peak loads of the system and hence the loads are assumed to be fixed throughout the calculations. Variable load scenario is produced by applying the annual load curve to the system, which makes the load vary every hour.

4.3 Discussion of Results and Error Estimation

The results obtained by using the newly proposed model under Load Loss Sharing policy can be validated using references [29] and [22]. It should be noted that under load loss sharing, the multi-area system indices should be the same as that of the normal composite system. The RTS LOLE obtained in [29] under variable load is 9.3942. This value is lower when compared to 10.7523 LOLE of obtained in this research work, as the former does single area reliability calculations, which is comparable to composite system reliability evaluation without consideration of transmission line violations. These figures are quite close as the transmission system of the RTS is very strong. The LOLE of MRTS is given as 600.001 in [22] is comparable to 548.9500 obtained in this paper. Both results are obtained for loss sharing policy, but [22] considers transmission line outage factors for analysis and hence it produced a higher LOLE.

The approximate results obtained by equivalent tie line model are compared with the accurate results provided by composite system based multi-area reliability model. The absolute value of the percentage errors can be obtained by using the following equation.

$$\text{PERCENTAGE ERROR} = \frac{|R_O(S) - R(S)|}{R(S)}\% \tag{26}$$

where R(S) is reliability index obtained by Composite System based Multi-Area Model and $R_o(S)$ is obtained by the traditional method. The percentage errors of these results are tabulated in Table VI.

TABLE VI
PERCENTAGE ERRORS OF RELIABILITY INDICES OBTAINED BY EQUIVALENT TIE LINE MODEL AND COMPOSITE SYSTEM BASED MULTI-AREA RELIABILITY MODEL

SYSTEM MODEL	PERCENTAGE ERROR OCCURRED UNDER LOAD LOSS SHARING POLICY IN		PERCENTAGE ERROR OCCURRED UNDER NO LOAD LOSS SHARING POLICY IN	
	LOLE	*EUE*	*LOLE*	*EUE*
RTS (Constant Load)	6.8185	12.0591	8.3681	12.2766
RTS (Variable Load)	257.6584	216.3035	256.1257	213.6033
MRTS (Constant Load)	261.0529	137.8765	279.6062	57.1513

The percentage errors obtained show that the equivalent method calculates LOLE and EUE with very less accuracy. The errors are quite high except for the case of IEEE RTS under constant load. Constant load used is the peak load of the system, which is also used in calculating the equivalent tie line capacities. For this case alone, since the capacities of the equivalent tie lines have been calculated most accurately, the results match most closely. The errors in other case are remarkably high making the equivalent method a poor choice for reliability studies for interconnected power systems.

It is worth mentioning that all the results were calculated by programming using *MATLAB*. For executing the LP modules, *MATLAB 'linprog'* function has been used as it is user friendly and highly accurate.

4.4 Comparative Study

Both the methods discussed in this paper have their own pros and cons. Here are main differentiations between the models based on certain important factors.

1) *Complexity* – The structure of the system model used by the equivalent tie line method has a really simple construction unlike the detailed composite system structure used by the composite system based multi-area reliability method. The former has total number of nodes equal to the number of interconnected areas, whereas the latter has retained all the nodes in the original integrated system. Though the equivalent method is really simple it ought to be noted that it is at the cost of approximations and assumptions. Even if equivalent tie line capacity calculations include the intra-area transmission line constraints to some extent, the direct influence on reliability indices has been prevented by this model. Calculation of equivalent tie line admittance is quite difficult and exact values cannot be obtained. This is another approximation that makes the equivalent model less appealing.

2) *Computational Effort* – The computational effort and time, involved in state evaluation process, is directly proportional to the number of nodes analyzed. This is due to the fact that the variables discussed in the LP modules grow as the system structure enlarges and the run time of a LP module increases as the number of variables increase. Hence the traditional method is quite fast and thus it is favored for multi-area reliability studies in power industries. The newly proposed method handles all the nodes while computing reliability indices and the variables used are much larger in number, making this model more time consuming.

3) *Ease of Implementation* – Both the models discussed are fairly simple to implement. But the equivalent model has certain parameters, such as the equivalent tie line capacity and admittance, which ought to be calculated while modeling the system and enter into the state evaluation process.

4) *Accuracy* – The most important of all the factors is accuracy of the results obtained. If the results produced by both the methods have less deviations then the traditional method have an edge over the other composite system based method, but as the percentage errors are quite high the need to use the latter method is recommended. Calculating multi-area reliability with real good accuracy is highly essential due to the vast prevalence of interconnected operation among power systems.

4.5 Conclusion

The newly proposed model and the traditional model have been successfully implemented and reliability indices of RTS and MRTS were calculated. IEEE RTS and MRTS are standard test systems which are used very widely for reliability studies.

The credibility of the new composite system based reliability model was checked using standard results obtain in the literature. This model due to its detailed modeling of the system produced accurate results and served as a standard to weigh the equivalent model's accuracy.

The results obtained were compared and the percentage errors were also calculated. The equivalent model produced very high error percentages which should definitely be considered by system planners while choosing reliability models for interconnected system.

Due to the highly accurate results produced by the new method, it is recommended to use it for interconnected system reliability calculations. Keeping the importance of the task involved and the impact of such results on system planning, accuracy should be given more priority than the computational time involved.

CHAPTER V

CONCLUSION

The primary function of an electric power system is to provide electrical energy to its customers as economically as possible and with an acceptable degree of continuity and quality. The adequacy of the generating capacity in a power system is normally improved by interconnecting the system to other power systems.

Operation of power systems under interconnected condition has been receiving growing attention. Interconnecting power systems becomes attractive from the view points of economics and reliability. When many systems are to be interconnected or when a new system is to join an existing interconnection they must oblige to certain conditions and provide a specified level of reliable operation. A proposed interconnection must not degrade the reliability or operating flexibility of the existing power system. System planning studies are carried on to assess such interconnections and evaluate their reliability.

Reliability evaluation of multi-area systems has always been an important topic for research owing to its importance. Power system reliability evaluation has been extensively developed utilizing probabilistic methods and wide range of appropriate indices can be determined. The main steps of reliability evaluation are state selection, state evaluation, and index estimation. The system has to be modeled to begin the state selection process. This thesis discusses two types of system modeling – equivalent tie line model and a newly proposed composite system based multi-area reliability model.

Traditionally, multi-area system reliability evaluation has been carried out by the equivalent tie line method. This model represents an area by a single node to which is connected the entire area's loads and generations. Hence the number of nodes analyzed is equal to the number of areas and this reduces complex integrated systems into a simple one. Tie lines connecting any two areas are replaced by an equivalent tie line, which is later assigned a power carrying capacity and admittance. Intra-area transmission line constraints are, to some extent, reflected by the equivalent tie line capacities. Such type of modeling facilitates fast computation of reliability indices and this is the main reason for using this model most prevalently.

A new model called the *Composite system based multi-area reliability model* is proposed in this thesis. It can serve as a standard to weigh the accuracy of the existing equivalent tie line model and would help system planning studies to carry out reliability evaluation more accurately. This model is comprehensive and is based on composite system structure as all the buses, loads and generations of the original interconnected system are modeled without any approximations or exclusions. This is an ideal way of system modeling to get accurate results. With the help of a simple LP prioritizing techniques operation of an interconnected system with varying load sharing policies can be easily modeled. This model was developed mainly for the purpose of gaining insight about the accuracy of the traditional method.

Monte Carlo simulation techniques have been favored in reliability enumerations as it has the ability to accommodate higher levels of system complexity. The reliability techniques using Monte Carlo simulation can be broadly classified into two methods which are random sampling and sequential sampling. In random sampling, or non-sequential sampling, a system state is sampled based on components distribution functions using proportional probability or probability distribution methods. Random sampling is preferred and used, in the work presented in this thesis, for system state selection as it is really simple to use and accomplishes the objectives of this research.

The IEEE 24-bus Reliability Test System and Modified Reliability Test System have been used in this research for comparing both the models described previously. Reliability indices such as LOLE and EUE were calculated for both the system by both the models and are presented in Chapter IV. The results are compared and the percentage errors produced were enumerated. The error percentages reflect the accuracy of the models. The newly proposed model being very comprehensive and detailed is said to produce accurate results for reliability indices. When comparing with these results the equivalent tie line method estimates reliability indices with huge errors.

Equivalent tie line model excels in calculation speed and simplified system structure but does not compare well with the new method in terms of accuracy, which is of greater importance. System planning studies use reliability indices for various purposes and any error in estimation of such indices may affect further dependant calculations.

The accuracy of reliability indices calculated by composite system based multi-area reliability model is used as since no simplifications have been made. It would make a better tool in system planning studies. The problem with the conventional method is that the values for the capacities are fixed and based on a certain scenario. The accuracy could be improved by using different values under different conditions but then it would become complicated to implement.

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APPENDIX A

THE IEEE 24 – BUS RELIABILITY TEST SYSTEM

The IEEE Reliability Test System (RTS) is a synthetic system which was developed with the objective of providing the research community with a benchmark test system and a common basis for comparing alternative techniques for reliability analysis [18]. Details of the RTS and its components are available in [26, 27]. Since the system was first developed in 1979, the system data has been extended and enhanced in two phases; the extensions are reported in [30] and [31]. However, the basic RTS has not been altered in terms of topology or component capacity and reliability, and all the data used in the research reported in this thesis is available in [27]. This data, i.e., the information used for this research is reproduced here.

The IEEE – RTS is a 24 – bus system, with 32 generators and 38 transmission lines. The configuration is shown in Fig. 5 and the generation, load and transmission line data are given in Tables VII through XIII.

Load Model: The basic annual peak load for the test system is 2850 MW. Table VII gives data on weekly peak loads in percentage of the annual peak load. If week 1 is taken as January, Table VII describes a winter peaking system. If week 1 is taken as a summer month, a summer peaking system can be described. Table VIII gives a daily peak load cycle, in percentage of the weekly peak. The same weekly peak load cycle is assumed to apply for all seasons. The data in Tables VII and VIII together with the annual peak load define a daily peak load model of 52 x 7 = 364 days with Monday as the first day of the year. Table IX gives weekday and weekend hourly load models for each of three seasons. Combination of Tables VII, VIII and IX with the annual peak load defines an hourly load model of 364 x 24 = 8736 hours.

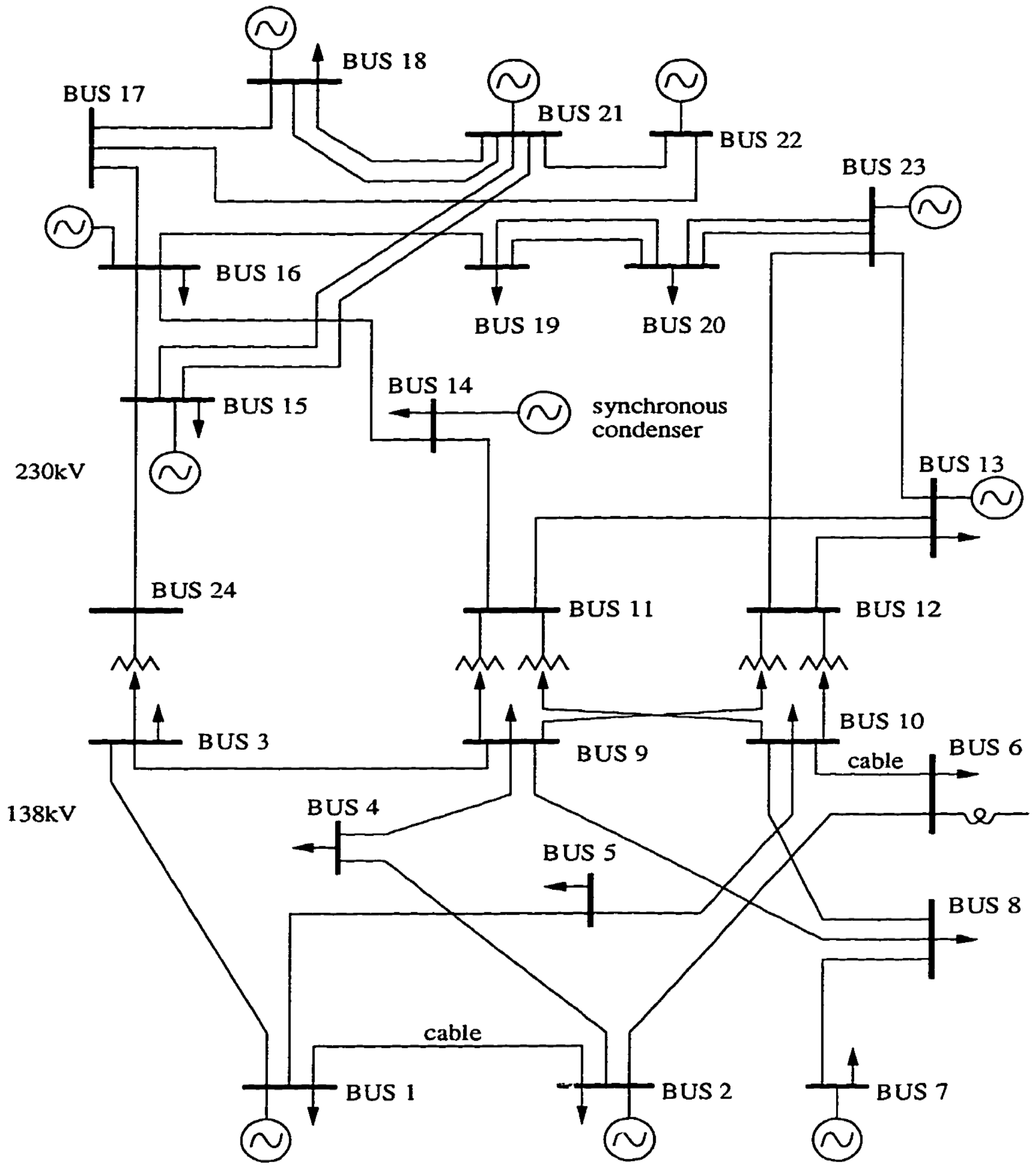

Fig. 5. Configuration of the IEEE Reliability Test System

TABLE VII
WEEKLY PEAK LOAD IN PERCENTAGE OF ANNUAL PEAK

WEEK	PEAK	WEEK	PEAK	WEEK	PEAK	WEEK	PEAK
1	86.2	14	75.0	27	75.5	40	72.4
2	90.0	15	72.1	28	81.6	41	74.3
3	87.7	16	80.0	29	80.1	42	74.4
4	83.4	17	75.4	30	88.0	43	80.0
5	88.0	18	83.7	31	72.2	44	88.1
6	84.1	19	87.0	32	77.6	45	88.5
7	83.2	20	88.0	33	80.0	46	90.9
8	80.6	21	85.6	34	72.9	47	94.0
9	74.0	22	81.1	35	72.6	48	89.0
10	73.7	23	90.0	36	70.5	49	94.2
11	71.5	24	88.7	37	78.0	50	97.0
12	72.7	25	89.6	38	69.5	51	100.0
13	70.4	26	86.1	39	72.4	52	95.2

TABLE VIII
DAILY PEAK LOAD IN PERCENT OF WEEKLY PEAK

DAY	PEAK LOAD
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

TABLE IX
HOURLY PEAK LOAD IN PERCENTAGE OF DAILY PEAK

HOUR	WINTER WEEK 1-8 & 44-52		SUMMER WEEKS 18-30		SPRING/FALL WEEKS 9-17 & 31-43	
	WKDY[A]	WKND[A]	WKDY	WKND	WKDY	WKND
12-1 am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-Noon	95	91	100	93	99	94
Noon-1 pm	95	90	99	93	93	91
1-2	95	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	91	88	86
4-5	99	91	96	92	90	85
5-6	100	100	96	94	92	88
6-7	100	99	93	95	96	92
7-8	96	97	92	95	98	100
8-9	91	94	92	100	96	97
9-10	83	92	93	93	90	95
10-11	73	87	87	88	80	90
11-12	63	81	72	80	70	85

[A]WKDY = weekday, WKND = weekend

Generation System: Table X shows the generating unit ratings and reliability data. Table X shows the locations of the generating units.

TABLE X
GENERATING UNIT RELIABILITY DATA

UNIT SIZE (MW)	NUMBER OF UNITS	FORCED OUTAGE RATE (FOR)
12	5	0.02
20	4	0.10
50	6	0.01
76	4	0.02
100	3	0.04
155	4	0.04
197	3	0.05
350	1	0.08
400	2	0.12

TABLE XI
GENERATING UNIT LOCATIONS

BUS	UNIT 1 (MW)	UNIT 2 (MW)	UNIT 2 (MW)	UNIT 2 (MW)	UNIT 2 (MW)	UNIT 2 (MW)
1	20	20	76	76		
2	20	20	76	76		
7	100	100	100			
13	197	197	197			
15	12	12	12	12	12	155
16	155					
18	400					
21	400					
22	50	50	50	50	50	50
23	155	155	350			

Transmission System: The transmission network consists of 24 bus locations connected by 38 lines and transformers, as shown in Fig. 5. The transmission lines are at two voltages, 138 kV and 230 kV. The 230-kV system is the top part of Fig. 5, with 230/138 kV tie stations at Buses 11, 12 and 24. The system has voltage corrective devices at Bus 14 (synchronous condenser) and Bus 6 (reactor). The synchronous condenser at bus 14 has a MVAr capacity of 50 (reactive) and 200 (capacitive) and the reactor at bus 6 has 100 (reactive). Bus load data at the time of system peak is shown below.

TABLE XII
BUS LOAD DATA

BUS	LOAD	
	MW	MVAR
1	108	22
2	97	20
3	180	37
4	74	15
5	71	14
6	136	28
7	125	25
8	171	35
9	175	36
10	195	40
13	265	54
14	194	39
15	317	64
16	100	20
18	333	68
19	181	37
20	128	26
TOTAL	2850	580

Impedance and rating data for lines and transformers are given below.

TABLE XIII
TRANSMISSION LINE AND TRANSFORMER DATA

FROM BUS	TO BUS	REACTANCE (P.U., 100 MVA BASE)	CAPACITY (MVA)
1	2	0.0139	175
1	3	0.2112	175
1	5	0.0845	175
2	4	0.1267	175
2	6	0.1920	175
3	9	0.1190	175
3	24	0.0839	400
4	9	0.1037	175
5	10	0.0883	175
6	10	0.0605	175
7	8	0.0614	175
8	9	0.1651	175
8	10	0.1651	175
9	11	0.0839	400
9	12	0.0839	400
10	11	0.0839	400
10	12	0.0839	400
11	13	0.0476	500
11	14	0.0418	500
12	13	0.0476	500
12	23	0.0966	500
13	23	0.0865	500
14	26	0.0389	500
15	16	0.0173	500
15	21	0.0490	500
15	21	0.0490	500

From Bus	To Bus	Reactance (p.u., 100 MVA Base)	Capacity (MVA)
15	24	0.0519	500
16	17	0.0259	500
16	19	0.0231	500
17	18	0.0144	500
17	22	0.1053	500
18	21	0.0259	500
18	21	0.0259	500
19	20	0.0396	500
19	20	0.0396	500
20	23	0.0216	500
20	23	0.0216	500
21	22	0.0678	500

VITA

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