LOAD FORECAST UNCERTAINTY CONSIDERATIONS IN BULK ELECTRICAL SYSTEM ADEQUACY ASSESSMENT

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ABSTRACT

The basic objective in bulk electrical system planning is to determine the necessary generating facilities required to ensure an adequate and economic supply of electrical energy and the development of an adequate transmission network to transport the generated energy to the customers. Quantitative adequacy assessment is a basic task in achieving this objective. An important requirement in this task is the ability to forecast the system load requirements at specific times in the future. These forecasts must also recognize the inherent uncertainty in predicting the future load demands.

The primary focus of the research described in this thesis is to examine the effects and implications of load forecast uncertainty on the load point and system adequacy indices of a composite generation and transmission system. This thesis considers two techniques to incorporate the inherent uncertainty associated with future load forecasts in the adequacy assessment of bulk electrical systems. Base case and factor analyses are performed on a number of power system configurations to identify and address the relative contributions to the load point and system indices due to load forecast uncertainty. A transmission reinforcement option and a number of generation system expansion options are presented to examine the system reliability response due to load forecast uncertainty.

The actual magnitudes of the changes due to load forecast uncertainty in the load bus and system risk indices and in the percentage change values are different for each generation expansion scenario. The topology and parameters of the system are different in each of the studied power system configurations. The effect of load forecast uncertainty on the system and load point adequacy can be quantified and utilized in the decision-making process associated with system generation and transmission planning. Load forecast uncertainty has important impacts on the system and load point indices that can only be appreciated by conducting comprehensive bulk system adequacy assessment. The actual effects are a complicated function of the system topology and parameters, and the system load curtailment philosophy.

In life I have fallen in as much as I have had success…

At the end I always wonder…

I would have never seen it, if I would have never believed it…

"There is a principle at the heart of Life:

Life is not what you find, it is what you create"

(Charles Templeton)

En la Vida he caído en la medida en que he tenido éxito…

Al final siempre pienso…

Nunca lo hubiera visto, si nunca lo hubiera creído…

"Hay un principio en el corazón de la Vida:

La Vida no es lo que tu encuentras en ella, es lo que tu creas en ella"

(Charles Templeton: Spanish Translation)

Lovingly Dedicated to

Nozomi Morohoshi

&

In the lovely memory of my Mother & Brother
Esther Hernandez Suarez
(1940-1990)
Salvador Cabrera Hernandez
(1982-2005)

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LIST OF ACRONYMS AND ABBREVIATIONS

$	Dollar
ADLC	Average Duration of Load Curtailment
BC Hydro	A Power Utility in British Columbia
BES	Bulk Electrical System
BPACI	Bulk Power–Supply Average MW Curtailment Index
BPECI	Bulk Power–Energy Curtailment Index
BPII	Bulk Power Interruption Index
BPO	Bus Priority Order
BPO1	Initial BPO
BPO2	Change in the BPO
CEA	Canadian Electricity Association
C_i	Load Curtailment of system state i
DC	Direct Current
D_i	Duration of system state i
DISCOS	Distribution Companies
E-1	Generation Expansion 1
E-2	Generation Expansion 2
E-3	Generation Expansion 3
EDC	Expected Damage Cost
EDLC	Expected Duration of Load Curtailment
EDNS	Expected Demand Not Supplied
EENS	Expected Energy Not Supplied
EFLC	Expected Frequency of Load Curtailment
ELC	Expected Load Curtailment
ENLC	Expected Number of Load Curtailment
EPSRA	Electric Power System Reliability Assessment
$F(X_j)$	Reliability index function over the year j
f/year	Failures per year
Failure Prob.	Failure Probability
F_i	Frequency of departing system state i
f_i	A portion of *Fi*
FL	Forecast Load
FL_i	Forecast Load of the *ith*-class interval

FOR	Forced Outage Rate
FPL	Forecast Peak Load
GENCOS	Generation Companies
HL I	Hierarchical Level I
HL II	Hierarchical Level II
HL III	Hierarchical Level III
hrs	Hours
i	System State or Class Interval
i.e.	that is to say
IEAR	Interrupted Energy Assessment Rate
IEEE	Institute of Electrical and Electronic Engineers
IEEE-RTS	IEEE Reliability Test System
ISO	Independent System Operator
j	*jth*-step load level
k	Load bus number
k$	kilo-Dollars
kWh	kilo-Watt-hour
L	Annual System Peak Load
LDC	Load Duration Curve
LFMLC	Load Forecast Modified Load Curve Approach
LFPD	Load Forecast Probability Distribution Approach
LFU	Load Forecast Uncertainty
MATLAB	Matrix Laboratory Software
MBPCI	Modified Bulk Power Curtailment Index
MCS	Monte Carlo Simulation
MECORE	Monte Carlo Evaluation of Composite System Reliability Program
$\text{MRBTS}_{\text{BPO1}}$	MRBTS-Bus Priority Order 1
$\text{MRBTS}_{\text{BPO2}}$	MRBTS-Bus Priority Order 2
MW	Mega-Watts
N	Set of all possible departure rates
n	Number of class intervals
NB	Total number of load buses in the system
Noon	Afternoon
NUG's	Non-Utility Generators
occ/year	Occurrences per year
OPF	Optimal Power Flow
p.u.	per-unit
PDR	Probability of a Single Derated State
P_i	Probability of system state i
p_i	Probability that the load exists at the i-class interval

PLC	Probability of Load Curtailment
PX	Power Exchange
q_k	A fraction of the system load
RBTS	Roy Billinton Test System
$\text{RBTS}_{\text{BPO1}}$	RBTS-Bus Priority Order 1
$\text{RBTS}_{\text{BPO2}}$	RBTS-Bus Priority Order 2
$REIN_i$	Reliability Index for the *ith*-class interval
$REIN_{LFU}$	Reliability Index including uncertainty
RESCOS	Retail Energy Services Companies
RTS	Reliability Test System
S	Set of all system states
SD_{FV}	A percentage or fixed value, or standard deviation from the *FPL*
S_i	System state of the *ith*-component
SI	Severity Index
S_m	Vector *S* of *m* components
t_{dsj}	Time-duration values for the *jth*-step load level
TRANSCOS	Transmission Companies
U_i	Pseudo-Random Number for the *ith*-component
W	Unit Damage Cost
Wkd	Weekday
Wkend	Weekend
X_j	Sequence of system state *S* in year *j*
X_j	Load level of the *jth*-step load level
λ_i	Failure Rate or Repair Rate of the *ith*-component
λ_k	Departure rate of component corresponding to system state *i*

1. INTRODUCTION

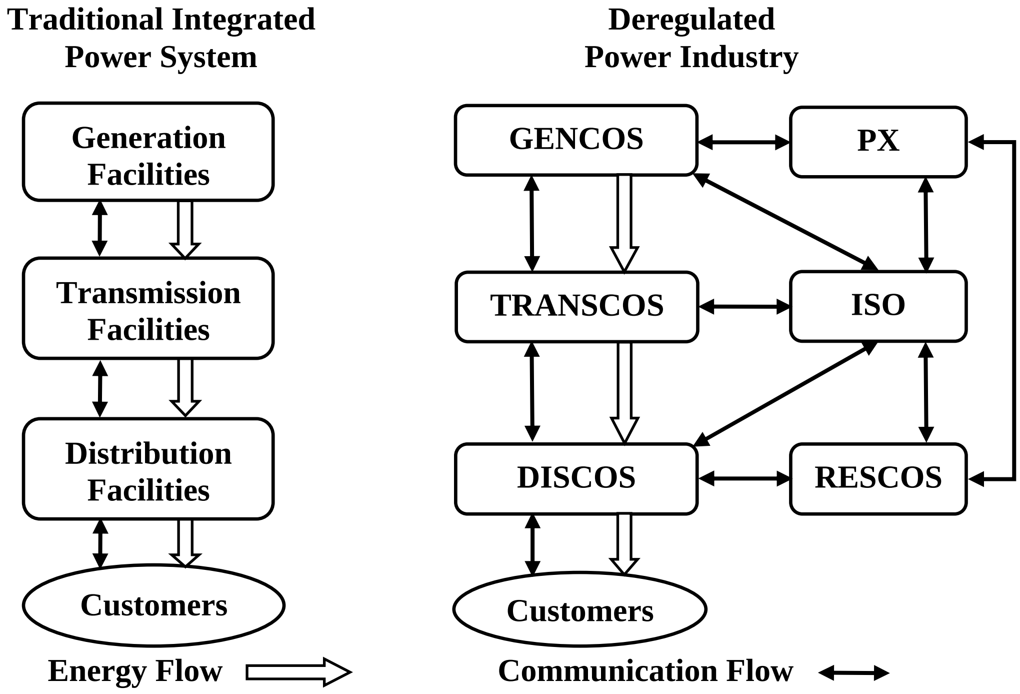
1.1 Background

Considerable effort has been applied to the reliability assessment of electric power systems in recent years. Electrical companies have focused on investments in generation capacity due to the inherent growth in the load demands and the relatively low returns from investing in transmission. As a result transmission deficiencies tend to exist in many jurisdictions. In the new deregulated market, it is not only important to strengthen the transmission facilities to satisfy the customer demands but also to ensure a healthy competitive power market. The most comprehensive approach to identifying generation and transmission deficiencies in an electric power system involves composite generation and transmission system reliability analysis.

A major objective of system planning is to determine the generating and transmission capacity requirements needed to assure continuity of electricity supply to the system customers. Such requirements should be delivered as economical as possible and with an adequate level of reliability [1]. The generation and transmission systems should be capable of achieving their objectives under conditions of generating and transmission facility forced outages and unforeseen growth in the system load. Planning involves the analysis of future system performance, which is inherently uncertain. Decision making in the light of uncertainty is therefore a basic requirement in system planning in an electric power utility.

1.2 The Power Industry in a Deregulated Market Environment

Over the years, the electric power industries in countries with highly developed power systems have been subjected to considerable modifications in their configurations and operation. The principal structure of traditional vertically integrated utilities [2] based on generation, transmission and distribution functional zones have been separated into different entities. In this “disjoint” electric power system, each utility has its own specific function in the overall task of delivering electricity to customers. In the competitive market of electricity pricing, deregulation has provided opportunities for customers to choose their energy suppliers based on their reliability performance and the cost of electricity. This transition in the electrical power utility environment has created a competitive market through non-utility generators (NUG's) and third party access (e.g. transmission providers) [2], particularly in those countries where both public and private electric utilities have open access to the electrical power system. The establishment of "unbundled" power utilities has created the necessity for new planning criteria to address explicit considerations of competition in generation (e.g. generation capacity additions), transmission growth (transmission providers), and competition in the distribution and supply sectors. Figure 1.1 [3] shows a general diagram of the deregulation structure in power industries.



GENCOS — Generation Companies
TRANSCOS — Transmission Companies
DISCOS — Distribution Companies
PX — Power Exchange
ISO — Independent System Operator
RESCOS — Retail Energy Services Companies

Figure 1.1 Deregulated Structure Power Utilities

A suggested major advantage of deregulated power industries over traditionally structured systems is the creation of competition in electric supply. Competition is expected to benefit customers, the utilities concerned and consequently society. The financial risks in generation and/or transmission investment due to uncertainty in the deregulated market have been and still are a significant problem. The reliability techniques described in this research work can be used to evaluate the adequacy of power utilities in both traditional and deregulated power industries.

1.3 Basic Concepts in the Reliability Evaluation of Electric Power Systems

Reliability assessment of electric power systems is achieved using a wide range of deterministic and probabilistic techniques. The application of deterministic techniques does not consider the stochastic behaviour of the system. Probabilistic techniques, on the other hand, can take into account the system random behaviour in the form of customer demands and component failures [1] and include these considerations in the determination of reliability indices. Both deterministic and probabilistic techniques are widely applied in modern electric power systems. Quantitative reliability indices can be evaluated in the form of absolute and relative measures.

Absolute reliability indices are expected future values that can be estimated in terms of the past performance of a system. The determination of these expected future indices is not an easy task because future performance contains considerable uncertainties in the numerical data related to the system and the predicted system requirements. Relative reliability indices are much easier to determine as the system performance is evaluated before and after considering specified system design or operating modifications. Relative indices tend to include similar uncertainties expected in the data and system requirements before and after a proposed system modification. The benefits due to system modification are estimated by evaluating the relative reliability improvement [1]. An appreciation of the definitions and limits of both absolute and relative indices is important in the application of these reliability indices.

The word reliability in a power system context is used in many ways. In general, reliability is a measure of the ability of a component or system to perform its intended function. System reliability can be divided into the two general areas of system adequacy and security as shown in Figure 1.2.

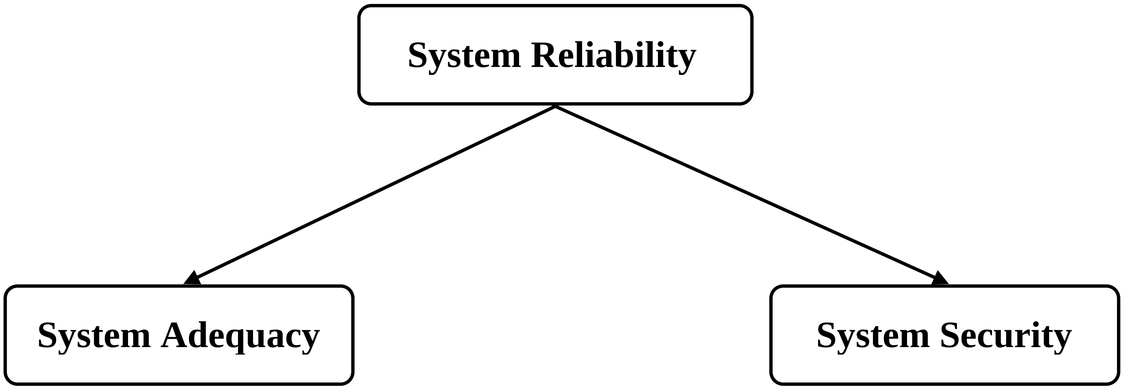


Figure 1.2 System Reliability, Adequacy and Security

System adequacy refers to the existence of sufficient facilities within the system to satisfy the customer load requirements. This involves the necessity to not only generate sufficient energy but also to have sufficient transmission and distribution facilities to transport the generated energy to the customer load points. Adequacy is normally associated with static conditions which do not incorporate system disturbances [1].

System security is related to the ability of the system to withstand disturbances arising on the system. These include those circumstances that cause local and widely distributed effects and the loss of major generation and transmission facilities [1]. An understanding of the definitions and evaluation of adequacy and security is an important element in the analysis of power system reliability as these aspects are mutually dependent and interrelated [1]. The focus in this thesis is on the application of adequacy evaluation to composite generation and transmission systems.

1.4 Reliability Assessment in Bulk Electrical Systems

A basic objective in overall power system planning is to determine the generating capacity required to satisfy the system load at an acceptable reliability level. The main concern is to ensure that sufficient energy is generated to fulfill the system load requirements. In the overall planning process, it is also important to develop an appropriate transmission network to transport the generated energy to the consumers. The application of reliability concepts in overall system planning is quite complex and there are many considerations involved in the analysis, *i.e.* exhaustive evaluation of the overall system and the integrated impacts of interconnected facilities. In order to minimize this problem, a power system can be divided into the three functional zones of generation, transmission, and distribution [1]. The basic functional zones shown in Figure 1.1 can be combined to create the hierarchical levels [1] shown in Figure 1.3

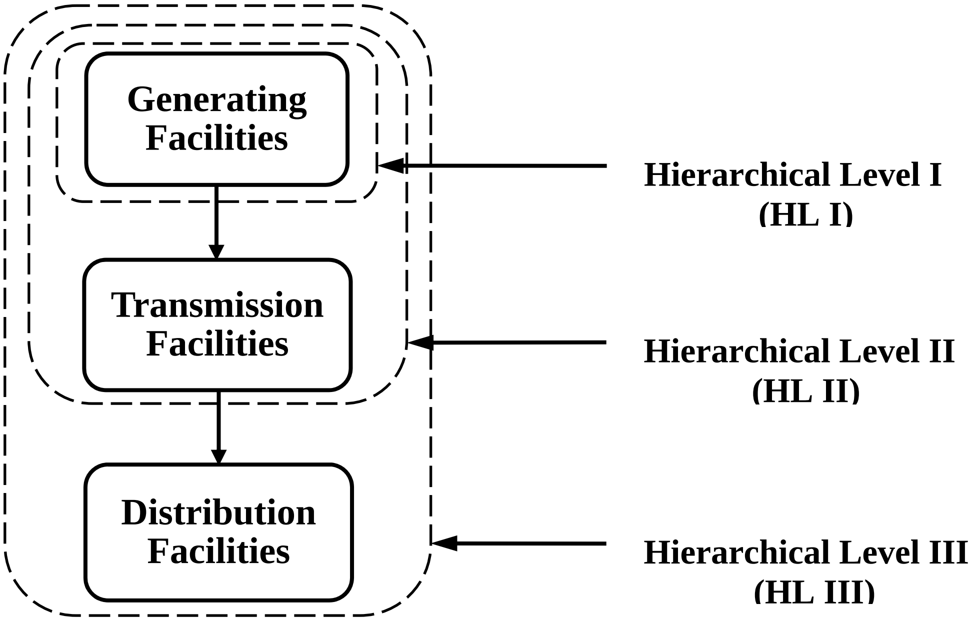


Figure 1.3 Power System Functional Zones and Hierarchical Levels

Reliability analysis at HL I is usually referred to as generating capacity adequacy assessment and involves the generating capacity required to meet the expected future system demand and the additional reserve necessary to perform corrective and preventive maintenance [4]. Transmission is generally not included in the analysis at this level.

Reliability analysis at HL II is frequently referred to as composite system or bulk electrical system evaluation and involves the integrated generation and transmission system. Reliability assessment at this level focuses on evaluating the ability of the system to transport the energy produced by the generating system to the major load points [5]. Adequacy evaluation at HL II includes load flow analysis, contingency analysis, generation rescheduling, transmission overload alleviation, and load curtailment philosophies [6]. Composite generation and transmission system reliability evaluation can include a wide range of tasks and requirements as shown in [4-13].

Reliability analysis at HL III involves the overall system including the distribution facilities required to provide adequate levels of power and energy at the customer load points. The main function of a distribution system is to deliver the energy conveyed at bulk supply points to individual customers within certain quality constraints of voltage, frequency, harmonics, flicker, etc. [7]. Due to its complexity, reliability analysis at this hierarchical level is usually performed in the distribution functional zone instead of including all three functional zones [6].

Considerable research work has been devoted on reliability assessment in the generation and distribution functional zones. As noted earlier, assessment of composite systems is very complex since it includes both the generation and transmission facilities. The concepts, models and evaluation techniques at HL II can be considered to be still under development. The research work presented in this thesis is focused on adequacy assessment at HL II.

1.5 Basic Elements in Composite System Analysis

As noted above, the appraisal of composite system reliability is quite complex due to the many considerations involved in the integrated analysis of generation and transmission facilities. Composite system reliability evaluation can be used to evaluate the relative impacts on the adequacy of the overall system due to the facilities in the generation and transmission functional zones [8]. Quantitative adequacy assessment can be performed by applying analytical approaches, simulation methods or hybrid approaches using both analytical and simulation techniques. Analytical methods evaluate the system reliability from mathematical models using mathematical solutions. A specific solution is produced for a given model and a given set of input data. Simulation techniques often known as Monte Carlo simulation methods, evaluate the system reliability by simulating the actual process and stochastic behaviour of the system.

Two main sets of indices can be calculated in an adequacy assessment of a composite system. They are the load point and system indices. The two sets of reliability indices have different functions but complement each other in an overall appraisal of the system adequacy. System indices indicate the adequacy of the overall system and can provide valuable information when comparing different alternatives in composite system planning. Load point indices indicate the reliability at individual load points in the system and can be used to identify the effects of individual reinforcement schemes and to assess the local effects of capital investment. Load bus indices provide valuable input data to HL III assessment.

Composite system reliability assessment normally assumes that the system and bus loads are known and are therefore specific values. This is not the case when dealing with future loads and these values are typically predicted based on past performance. In an actual power system, the demand for electricity generally increases each year and it has been widely recognized that load forecast uncertainty can have a significant impact in power system reliability evaluation [6]. Recognition of load forecast uncertainty is an important element in composite system adequacy assessment.

1.6 Scope and Objectives of the Thesis

The primary focus of the research described in this thesis is to examine the effects and implications of load forecast uncertainty on the load point and system adequacy indices of composite generation and transmission systems. The research uses a small educational test system to examine the implications of load forecast uncertainty using system and load point reliability indices. The test system is expanded using a transmission reinforcement option and a number of generation system expansion options to create a total of twenty different configurations upon which to examine the system reliability response due to load forecast uncertainty.

1.7 Summary of the Thesis

This thesis is organized into five chapters and five Appendices.

Chapter 1 contains some background information on bulk electrical system adequacy assessment and the scope and objectives of the thesis.

The basic concepts and techniques for adequacy assessment of bulk electrical systems are briefly describe in Chapter 2. The chapter also introduces the basic test system used in this research and the computer software applied in the analysis. Base case studies for comparison purposes in the subsequent studies and the corresponding assumptions for the test system are presented. A procedure to identify generation and transmission deficiencies is illustrated and a load curtailment philosophy in the form of load bus priority order is considered. The composite system reliability techniques described in this chapter are further applied to assess the adequacy of a number of composite systems.

Chapter 3 describes two methods that can be used to include the effects of load forecast uncertainty in the reliability assessment of a composite system. Some basic advantages in their application are briefly described. The two techniques are illustrated by an example using the basic test system introduced in Chapter 2 (Section 2.5) with a simple step-load duration model. The system results are used as base values in the load forecast uncertainty and system expansion scenarios presented later in the thesis.

The effects of load forecast uncertainty in a generation expansion framework are illustrated in Chapter 4. Base case and factor analyses are performed on the two basic composite test systems in Chapter 2 to identify and address the relative contributions to the load point and system indices due to load forecast uncertainty. The effects of changing the load curtailment philosophy introduced in Chapter 2 are also examined. Twenty different power system configurations are considered in this chapter. These include the base case systems and three generation expansion scenarios, each with three case additions.

The summary and general conclusions of the research work described in this thesis are presented in Chapter 5.

2. COMPOSITE SYSTEM ADEQUACY ASSESSMENT

2.1 Introduction

A basic objective in power system planning is to evaluate the necessary generating facilities required to ensure an adequate and economic energy supply and the development of an adequate transmission network to transport the generated energy to the major load points. The generating capacity should be capable of meeting the system requirements under conditions of generating unit forced outages, incorporating preventive and corrective maintenance and unforeseen variations in the system load [14]. The reliability at a particular load point depends upon the total system installed capacity, the location of the load point within the system, and the available interconnecting transmission facilities [15]. Bulk electrical system (BES) expansion planning involves an overall assessment of both the generation and the transmission facilities. A proposed power system expansion analysis should include both system reliability evaluation and economic considerations in the decision making-process [16, 17].

The task of appraising the overall adequacy of the BES with respect to delivering reliable and acceptable levels of energy at the terminal stations has been defined as composite system reliability evaluation [18]. Adequacy assessment of both generation and transmission facilities is extremely complex not only because the electric power network (bulk transmission system) must be carefully matched with the generation system to allow energy movement to the often radial configurations encountered at the distribution or sub-transmission load points but it must also be capable of maintaining adequate voltage levels, loadings within the thermal limits of individual circuits, and system stability limits including both static and dynamic considerations [1]. Appraisal of composite systems must consider load flow analysis, contingency and ranking considerations, generation rescheduling analysis, bulk transmission overload alleviation, load priority curtailment philosophies, etc [6]. Composite system analysis can be used to assess the adequacy of both existing and proposed facilities. This includes the consideration of generation and transmission additions in a reinforcement or expansion framework. As noted in Chapter 1, adequacy assessment of composite systems can be evaluated using analytical methods or simulation techniques. Brief descriptions of these two methods for quantitative reliability assessment are presented in the following section.

2.2 Quantitative Reliability Assessment and Reliability Indices

Analytical methods are based on mathematical representations of the system and calculate the reliability of the developed model using direct numerical solutions. One of the most widely used analytical methods in composite systems is the state or contingency enumeration approach. In this method, disturbances in the system are systematically analyzed and aggregated to produce an assessment of the system reliability. The contingencies are classified in accordance with predetermined failure criteria. The contingency enumeration procedure and its application are illustrated in [19].

Simulation techniques evaluate the system adequacy by simulating the stochastic behaviour of the system. In recent years, the application of Monte Carlo simulation (MCS) techniques in the determination of system reliability has increased considerably. These techniques can theoretically include virtually all the aspects and contingencies inherent in the planning, design and operation of a composite system, and high speed and high capacity computing systems are now readily available. One advantage of this method is that system outage events can be simulated in great detail. Most of the reliability indices obtained using either analytical or MCS techniques are expected values. The variability of these indices around the expected values can be obtained using MCS [6]. The research studies described this thesis are based on Monte Carlo simulation. A detailed description of the approach used is presented later in this chapter.

The two basic indices in power system adequacy evaluation are the probability and frequency of an outage event. These indices can be evaluated for a component, and at the load point and system levels. The two fundamental indices can be extended to create a range of additional indices that describe load point and system adequacy. There is a wide range of indices that can be used to asses the adequacy at each load bus and the overall system. Both individual load bus and system indices are used to evaluate composite system adequacy and can be used to provide a comparison between different alternatives from different points of view [12].

As noted in Chapter 1, the load point and system indices have different functions but complement each other. System indices provide a general appraisal of the total system reliability and are valuable information when comparing different alternatives in bulk electrical system planning. Load bus indices indicate the reliability at individual load points and can be used to identify weak points in the system and to assess the local effects of capital investment. Load point indices also provide valuable input data to distribution functional zone assessment.

Historical and future performance assessment techniques have been developed [20-22] to respectively analyze the past performance and to predict the future performance of bulk power systems. Past performance indices are associated with actual operating conditions and provide a quantitative analysis of the system reliability. These records establish the chronological behaviour in regard to reliability and can be used to reveal and identify system deficiencies. System reinforcement plans can be predicated on the past system performance. Predictive indices provide an indication of future system and load point reliability performance. They can be used to analyze the benefits of system design, expansion and reinforcement options in a reliability improvement assessment, worth and cost framework. Most future reliability performance indices are associated with adequacy assessment. Past reliability performance indices normally include both system adequacy and system security considerations. Both sets of indices are important reliability parameters in the decision making-process of overall development and energy system management as they provide valuable input data on the reliability performance of bulk generation and transmission systems. Most of the power utilities in Canada collect past performance indices through the Canadian Electricity

Association (CEA) Electric Power System Reliability Assessment (EPSRA) protocols [23]. The definition of some basic reliability indices and IEEE proposed indices are presented in the following section [6, 24].

2.2.1 Basic Reliability Indices [6, 24]

1. **Probability of Load Curtailment: PLC**

$$PLC = \sum_{i \in S} P_i \tag{2.1}$$

where P_i is the the probability of system state i and S is the set of all system states associated with load curtailments.

2. **Expected Frequency of Load Curtailment: EFLC (occurrence/year)**

$$EFLC = \sum_{i \in S} (F_i - f_i) \tag{2.2}$$

where F_i is the frequency of departing system state i and f_i is the portion of F_i which corresponds to not going through the boundary wall between the loss-of-load state set and the no-loss-of-load state set. In bulk electrical systems, it is difficult to calculate the frequency index applying the state sampling technique. This is basically because for each load curtailment state i, it is necessary to identify all the no-load-curtailment states which can be reached from state i in one transition. The Expected Number of Load Curtailment (ENLC) index (occurrence/year) is often used to approximate the EFLC index. Equation (2.2) then reduces to:

$$ENLC = \sum_{i \in S} F_i \qquad (occurrence/year) \tag{2.3}$$

The ENLC index is the sum of the occurrences of the load curtailment states and is therefore an upper boundary on the actual frequency index. The system state frequency F_i can be calculated by the following relationship between the frequency and the system state probability P_i if transition processes of component states follow an exponential distribution:

$$F_i = P_i \sum_{k \in N} \lambda_k \qquad (occurrence/year) \tag{2.4}$$

where λ_k is the departure rate of component k corresponding to system state i and N is the set of all possible departure rates corresponding to state i.

3. **Expected Duration of Load Curtailment: EDLC (hrs/year)**

$$EDLC = PLC \times 8760 \tag{2.5}$$

4. **Average Duration of Load Curtailment: ADLC (hrs/disturbance)**

$$ADLC = \frac{EDLC}{EFLC} \tag{2.6}$$

5. **Expected Load Curtailment: ELC (MW/year)**

$$ELC = \sum_{i \in S} C_i \, F_i \tag{2.7}$$

where C_i is the load curtailment of system state i.

6. **Expected Demand Not Supplied: EDNS (MW)**

$$EDNS = \sum_{i \in S} C_i \, P_i \tag{2.8}$$

7. **Expected Energy Not Supplied: EENS (MWh/year)**

$$EENS = \sum_{i \in S} C_i \, F_i \, D_i = \sum_{i \in S} 8760 \, C_i \, P_i \tag{2.9}$$

where D_i is the duration of system state i.

8. **Expected Damage Cost: EDC (k\$/year)**

$$EDC = \sum_{i \in S} C_i \, F_i \, D_i \, W \tag{2.10}$$

where C_i is the load curtailment of system state i, F_i and D_i are the frequency and the duration of system state i, W is the unit damage cost in *\$/kWh*.

2.2.2 IEEE-Proposed Reliability Indices

9. **Bulk Power Interruption Index: BPII (MW/MW-year)**

$$BPII = \frac{\sum_{i \in S} C_i \, F_i}{L} \tag{2.11}$$

where L is the annual system peak load in *MW*. This index can be interpreted as the equivalent per unit interruption of the annual peak load where one complete system outage during peak load conditions contributes *1.0* to this index [24].

10. **Bulk Power–Energy Curtailment Index: BPECI (MWh/MW-year)**

$$BPECI = \frac{EENS}{L} \tag{2.12}$$

11. **Bulk Power–Supply Average MW Curtailment Index: BPACI (MW/disturbance)**

$$BPACI = \frac{ELC}{EFLC} \tag{2.13}$$

12. **Modified Bulk Power Curtailment Index: MBPCI (MW/MW)**

$$MBPCI = \frac{EDNS}{L} \tag{2.14}$$

13. **Severity Index: SI (system minutes/year)**

$$SI = BPECI \times 60 \tag{2.15}$$

The Bulk Power Energy Curtailment Index is directly related to the Severity Index. The total expected energy not supplied expressed in *MW-minutes* is divided by the system peak load in *MW*. Severity is therefore expressed in *System-Minutes*. One system minute is equivalent to an interruption of the total system load for one minute at the time of system peak [1]. The IEEE proposed indices are generally based on the basic reliability indices normalized using the system peak load. This set of indices can be used to compare the system adequacy of different sized systems. While the basic indices can be calculated for either a single load bus or for the overall system, the IEEE proposed indices can only be evaluated for the overall system. Both sets of indices can be evaluated at the system peak load and expressed on a one-year basis (annualized indices) or calculated considering a chronological load pattern or the system load duration curve (annual indices).

2.3 Monte Carlo Simulation Methods

Monte Carlo simulation involves the analysis of repeated samples or trials created using random numbers. Monte Carlo methods have been used widely in analyzing complex mathematical problems, stochastic processes, medical applications, engineering systems, and reliability evaluation [6]. In a reliability application, the simulation process basically attempts to model the actual system components and create the system behavior patterns including the random nature of the processes involved. The number of failures, the time between failures, the restoration times, etc, can be evaluated as the process evolves. The mathematically expected or long run average values can be obtained, and if required, the probability and frequency distributions of each reliability variable [1]. The stochastic process is facilitated by generating random numbers which are then converted into density functions to describe the behavior of the system components and variables under consideration. The generated random numbers and density functions form a significant and essential part of Monte Carlo simulation. Some of the major advantages of Monte Carlo techniques over analytical methods are as follows [6]:

1. The analysis may include system sequences or processes which may have to be approximated in an analytical method.

2. The level of accuracy for the required number of samples is independent of the size of the system under analysis. Consequently, Monte Carlo simulation is suited to the evaluation of large-scale systems.

3. MCS can be used to simulate the probability distributions associated with component failure and restoration activities, which in general cannot be achieved using analytical methods.

4. MCS can be used to estimate the system reliability parameters in the form of expected values of the random variables and their associated distributions, which analytical techniques generally cannot.

5. MCS can include system factors such as reservoir operating conditions in hydro systems, weather effects, etc. in the stochastic simulation process.

There are two main approaches to assessing the adequacy of composite systems using Monte Carlo methods. These techniques are generally designated as sequential and non-sequential procedures. Non-sequential techniques sample the states of all components and assess the obtained system states in a non-chronological pattern. Non-sequential techniques can be divided into the two groups of state sampling and state transition sampling [6]. Sequential techniques simulate the up and down states of all the components to obtain the system operating states. The resulting system condition is evaluated by combining all the component states in a chronological pattern from which the required reliability indices are obtained. The three basic methods for composite system reliability assessment are described in the following sections [6].

2.3.1 State Sampling Technique

The main task in the state sampling (non-sequential) approach is to sample the states of all components and to determine the state of the system. The sampling method is conducted by describing the behavior of each component by a uniform probability distribution between $[0, 1]$. Each component can be sampled as either a two-state or multi-state representation depending on the actual conditions. The system state can be represented by the vector of components $S = (S_1, S_2, S_3, \ldots\ldots, S_i, \ldots\ldots, S_m)$. The vector S of m components includes the state of each element in the system (generators, lines, transformers, etc.) [25]. If it can be assumed that a component has the two states of success and failure and that the component failures are independent events, then the system state of the *ith*-component and its forced outage rate (*FOR*) can be denoted by S_i and FOR_i, respectively.

The following simulation steps illustrate the process used to assess a bulk electrical system.

1. Specify the initial state of each component. Generally, it is assumed that all components are initially in the available or up state.

2. For the *ith*-component, a pseudo-random number U_i distributed uniformly between *[0, 1]* is calculated.

3. Depending on the obtained random number, the *ith*-component can be judged to be in a success or outage condition according to:

$$S_i = \begin{cases} 0 \quad (Success\ State) & if \quad U_i \geq FOR_i \\ \\ 1 \quad (Failure\ State) & if \quad U_i < FOR_i \end{cases} \tag{2.16}$$

Multi-state components can be included in the simulation analysis in terms of their derated state probabilities without a considerable increase in the required computing time [26]. The probability of a single derated state for the *ith*-component (PDR_i) can be incorporated in Equation 2.16.

$$S_i = \begin{cases} 0 \quad (Up\ State) & if \quad U_i \geq PDR_i + FOR_i \\ 1 \quad (Down\ State) & if \quad PDR_i \leq U_i < PDR_i + FOR_i \\ 2 \quad (Derated\ State) & if \quad 0 \leq U_i < PDR_i \end{cases} \tag{2.17}$$

4. The system state is calculated by repeating Step 2 for all the components in the system.

5. If the calculated system state is in the normal condition ($S_m = 0$), then the system can satisfy all load requirements and no load curtailment will occur. However, if the system state is in the outage condition ($S_m = 1$), then the system cannot satisfy all the loads and load curtailment is required.

6. A linear programming minimization model [27] is normally used to reschedule generation, alleviate line overloads and to avoid load curtailment, if avoidable, or to minimize the total load curtailment, when possible.

7. The adequacy indices at each load bus and for the overall system are accumulated and Steps 1 to 5 are repeated until the coefficient of variation of a designated reliability index such as the Expected Energy Not Supplied becomes less than a specified value.

2.3.2 State Transition Sampling Technique

The state sampling technique takes into consideration the system state transitions of the entire system rather than just the component states. All the state residence times in the simulation process are assumed to be exponentially distributed. The simulation process used to evaluate the adequacy of composite systems is briefly summarized as follows [25].

1. Specify the initial state of each component. Generally, it is assumed that all components are initially in the available or up state.

2. The simulation process starts from the normal system state in which all the generating units and transmission lines are in the up or available state.

3. If the present system state is a contingency state in which at least one component is in the outage state, the minimization model of load curtailment is used to evaluate the adequacy of this system state. Otherwise, the simulation proceeds to the next step without utilizing the minimization model.

4. A uniform distributed random number is generated to determine the next system state using the state transition sampling procedure. Since a system state transition sequence is directly created in this method, the actual frequency indices of the load points and for the overall system can be calculated. This cannot be achieved using the state sampling technique [28].

5. The simulation process is repeated until the selected convergence criterion is satisfied.

2.3.3 Sequential Technique

The sequential or state duration sampling technique is based on sampling the probability distributions of the component state durations. This method can be used to model the chronological component state transition processes including all contingencies and operating characteristics inherent in the system. The component state duration distribution functions are used in this approach. In a two state component representation, these are the operating and repair duration distribution functions. The state residence times are usually assumed to be exponentially distributed. The actual frequency index can be easily calculated and other state duration distribution functions can be applied if necessary. The following general procedure is used in bulk electrical system adequacy assessment [6, 25].

1. Specify the initial state of each component. Generally, it is assumed that all components are initially in the available or up state.

2. Sample the duration of each component state. For a given exponential distribution such as $f(t) = \lambda e^{-\lambda t}$, the random sampling variable of the state duration is:

$$T_i = -\frac{1}{\lambda_i} \ln\ U_i \tag{2.18}$$

where U_i is a uniformly distributed random number in the interval *[0, 1]* for the *ith*-component. If the present state is the up state, λ_i is the failure rate of the *ith*-component. If the present state is the down state, λ_i is the repair rate of the *ith*-component [29].

3. Repeat Step 2 and record the sampling values of each state-duration for all components. The chronological component state transition processes for each component can be then obtained.

4. The chronological system state is determined by combining the chronological component states of all the components.

5. System analysis is then conducted for each different system state to accumulate the reliability indices given by $F(X_j)$; where X_j is the sequence of system state S in year j, and $F(X_j)$ is the reliability index function over the year j.

6. Steps 1 to 5 are repeated until the coefficient of variation of the chosen index is less than the specified value.

The three briefly described Monte Carlo methods each have their own advantages and disadvantages. The state sampling approach is relatively simple to perform due to the fact that it is only required to generate uniformly distributed random numbers in the range of $[0, 1]$. Sampling from distribution functions is not necessary. The component state probabilities are the only basic reliability data required to perform this method. The state sampling method evaluates the expected frequency of load curtailments as the sum of the occurrences of load curtailment states, which is an upper bound of the actual frequency index. In the state transition sampling approach, it is possible to evaluate the actual frequency index without sampling the state duration distribution functions of all the components and storing chronological information, as required in the sequential technique. There is, however, an important restriction in this method that it only applies to exponentially distributed component state durations. The sequential or state duration sampling method can be used to accurately obtain the actual frequency indices and can consider any state residence time distribution [6, 28]. Compared to the simple state sampling technique, this method requires considerable computer solution time and storage as it has to generate a random variable for each component and to store the chronological component state transition information for a suitably long time span [6]. The computer software used in the studies described in this thesis is based on the state sampling technique and is described in the following section.

2.4 Introduction to the MECORE Software

The Monte Carlo Evaluation of COmposite system REliability (MECORE) software was initially developed at the University of Saskatchewan and subsequently enhanced by BC Hydro [24]. MECORE is a Monte Carlo based composite generation and transmission system reliability evaluation tool designed to perform reliability and reliability worth assessment of bulk electrical systems. It can be used to evaluate composite generation and transmission reliability, generation system reliability in a composite system, or transmission system reliability in a composite system. It can provide a set of reliability indices at individual load points and for the overall composite generation and transmission system. Bus indices indicate adequacy at individual load points and are dependent on the system load curtailment philosophy. They can be aggregated to produce a set of system indices that provide an overall evaluation of the total system reliability.

The program can also provide unreliability cost indices that reflect reliability worth. These indices can be utilized from a reliability perspective to compare different planning alternatives including those needed to provide overall economic comparisons. MECORE is based on a combination of Monte Carlo simulation (state sampling) and enumeration techniques. The state sampling approach is used to simulate system component states and to estimate annualized system indices (expressed on a one-year basis) at the system peak load level. A hybrid method implementing an enumeration approach for aggregated load states is used to calculate annual indices using an annual load duration curve.

2.4.1 The MECORE Capabilities [24]

The following summarizes the MECORE capabilities.

A. System Size

- The program is designed to manage up to *1000* Buses and *2000* Branches

B. System Analysis, The Program can Evaluate

- Generation Outages Only: The failure data of transmission lines/transformers is ignored
- Transmission Outages Only: The failure data of generating units is ignored
- Both Generation and Transmission Outages: The failure data of both generating and transmission facilities is considered

C. Failure Modes

- Independent Failures of Generators, Lines and Transformers
- Common Cause Outages of Transmission Lines
- Generating Unit Derating States

D. Failure Criteria

- Capacity Deficiency
- Line Overload
- System Separation – Load Loss
- Bus Isolation – Load Loss

E. Load Model

- Annual, Seasonal, and Monthly Load Curve
- Multi–Step Models up to 100 Step-Load Levels
- Bus Load Proportional Scaling and Flat Level Model

F. Probability Indices

- System and Bus Reliability Indices
- Annualized and Monthly/Seasonal/Annual Reliability Indices
- Basic and IEEE–Proposed Reliability Indices:
  - Basic Indices: ENLC, ADLC, EDLC, PLC, EDNS, EENS, EDC, and ELC
  - IEEE–Proposed Indices: BPII, BPECI, BPACI, MBPCI, and SI

The PLC, ENLC, ELC, EDNS, and EENS indices are calculated for each individual load bus. The ENLC, ADLC, EDLC, PLC, EDNS, EENS, EDC, BPII, BPECI, BPACI, MBPCI, and SI indices are calculated at the system level.

G. Linear Programming Optimization Model

The MECORE program uses a linearized DC-based power load flow to conduct contingency analysis, and a linear programming Optimal Power Flow (OPF) model to reschedule generation (change generation patterns), alleviate line overloads and avoid load curtailments, if possible, or minimize total load curtailments, if unavoidable [6].

H. Load Bus Priority Order

Individual load bus indices are highly dependent on the system load curtailment philosophy which reflects the different importance of each load bus. A load curtailment philosophy in the form of a load bus priority order can be included in the minimization model. If a load priority order is not specified, MECORE automatically assumes that all loads have equal likelihood of being curtailed when load curtailments are unavailable in the linear programming optimization model.

I. Annualized and Annual Indices

The program can provide both individual load point and system indices. If these indices are calculated at the annual system peak load level, they are designated as annualized indices and expressed on a one-year basis. When these indices are calculated using an annual load duration curve, they are denoted as annual indices since they represent the entire annual period.

J. Rate of Convergence

The program is based on Monte Carlo simulation methods to select system component states in a fluctuating convergent process. In general, a larger number of samples leads to a higher accuracy but requires more computing time. The coefficient of variation of a selected index can be used as the convergence criterion. The coefficient of variation for the EDNS (Expected Demand Not Supplied) index which is directly related to the EENS index has been widely used and is included with the calculated results.

2.5 The Composite Test System

An educational test system designated as the *Roy Billinton Test System* (RBTS) was used to conduct the research work in this thesis. The single line diagram of the RBTS is shown in Figure 2.1.

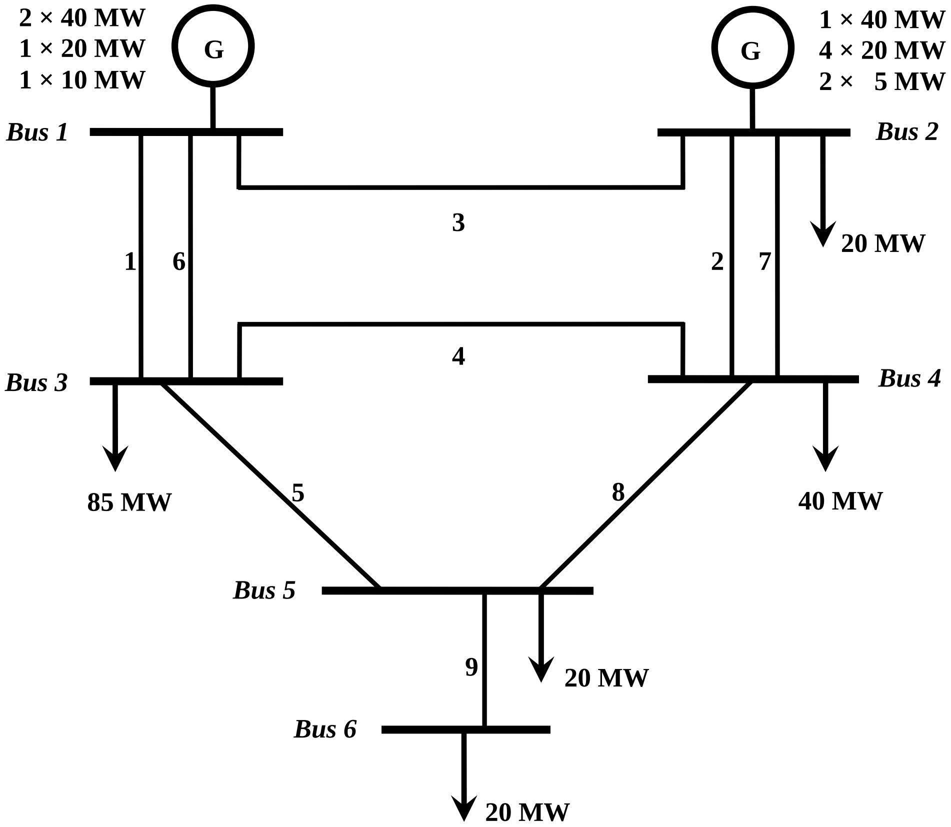


Figure 2.1 Single Line Diagram of the RBTS

The RBTS is a relatively small composite system developed by the Power System Research Group at the University of Saskatchewan for educational and research purposes [30]. It is a six-bus system with eleven generators rated from *5 MW* to *40 MW* located at two generator buses. The total installed generating capacity is *240 MW* and the total system load demand is *185 MW* supplied at five load buses. The transmission system consists of nine interconnected transmission lines. The system voltage level is *230 kV*. The RBTS utilizes the per-unit load model provided in the *IEEE Reliability Test System* (RTS) [1]. This load model can be used to generate *8760* hourly chronological loads on a per-unit basis to simulate daily, weekly, and seasonal patterns depending on the study under consideration. The complete system data including generators, transmission lines, buses and load model are given in Appendix A, Tables A.1 to A.7.

2.6 Initial Considerations in the RBTS Base Case Analysis

Initial base case studies provide a reference framework to analyze the effects of system modification and data sensitivity. Composite system reliability assessment can take into consideration the effects of generating unit derated states, common cause outages of transmission lines, station originated failures, and so forth [8]. In order to appreciate the base case conditions, it is important to identify any pertinent factors that have not been incorporated in the evaluation. The following factors were not included in the base case analysis of the RBTS in the research performed in this thesis.

1. The step-down transformers at transformer stations are assumed to be customer-owned and the reliability indices are calculated at the high voltage bus bars.
2. Station configurations are not incorporated in the evaluation process.
3. Transmission line common mode failures are not considered.
4. The economic priority order for load curtailment is utilized.

2.6.1 Individual Load Bus and System Indices

As noted earlier, both individual load and system indices can be utilized to evaluated bulk electrical systems. Individual load bus values are a valuable source of information in system design and in comparing different alternative configurations in system expansion. They are useful as input data in the reliability evaluation of distribution systems supplied at the bulk electrical delivery points. The load bus indices are accumulated to produce a set of system indices. System indices provide an overall assessment of the total system reliability and reliability worth. They are useful to system management and system planners in overall system adequacy assessment as they indicate the ability of the system to satisfy the load demand and energy requirements [1]. Both sets of indices are used in the BES analysis described in this thesis.

2.6.2 Economic Load Bus Priority Order

Individual load bus indices are highly dependent on the system load curtailment philosophy. In an actual system, different load points have different priorities that are dependent on the importance of each bus. Some loads are considered to be more important than others. The load bus priority order should be selected according to an agreed load shedding philosophy. It may be desirable to only shed loads at some buses once loads have been curtailed at other buses. The MECORE software can perform load shedding following a predetermined priority order. A common approach to establish a load bus priority order is based on economic considerations that recognize the customer cost associated with the failure of supply. The most convenient parameter for this objective is the Interrupted Energy Assessment Rate (IEAR), as it measures the customer monetary loss as a function of the energy not supplied [1]. The IEAR is an important index as it links system reliability with the customer interruption cost and is expressed in *\$/kWh* of unsupplied energy. The priority order of each individual load point can be determined using the designated IEAR index. The higher the IEAR, the more disruptive is the loss of supply and a higher priority code is applied [8]. Table 2.1 shows the load bus priority order and the corresponding IEAR index for the RBTS.

Table 2.1 Load Bus Priority Order and IEAR Values for the RBTS

Load Priority Order	Bus	IEAR ($/kWh)
1	2	7.41
2	4	6.78
3	5	4.82
4	6	3.63
5	3	2.69

The load bus priority order dictates the load curtailment at the possible load buses to be curtailed when a given contingency state requires load curtailment. The priority order has a significant effect in the individual load bus indices but has relatively little effect on the overall system indices, as the total amount of load curtailment for a given contingency system state is minimized [8]. The effects of changing the RBTS load bus priority order are discussed later in this thesis. The Expected Damage Cost (EDC) is an important index that can be used to perform economic analysis in composite system adequacy assessment. The MECORE program calculates this index by multiplying the EENS of the overall system by the average system IEAR calculated using the following equation [1].

$$Average\ System\ IEAR = \sum_{k=1}^{NB} IEAR_k\, q_k \tag{2.19}$$

where NB is the total number of load buses in the system, $IEAR_k$ is the Interrupted Energy Assessment Rate (IEAR) at load bus k, and q_k is the fraction of the system load utilized by the customers at load bus k. The average System IEAR for the RBTS calculated using the data given Table 2.1 and Table A.1 is *4.42 $/kWh*. In Table 2.1, Bus 2 is highest in the priority order as it has the largest interruption cost and therefore, from an economic viewpoint, is the most important bus in the RBTS. Bus 3 is the lowest in the priority order with the lowest IEAR.

2.6.3 Annualized and Annual Indices

As previously noted, the annualized load bus and system indices are evaluated at the annual system peak load level and expressed on a one-year basis. In an actual system, the load varies within the year in accordance with the time-of-day, the day and the season in the year. In a conventional state enumeration assessment, the effect of a variable load curve can be accommodated by creating a multi-step load model in which loads are accumulated into step-levels and their probability of occurrence determined from the non-chronological data in the load duration curve (LDC). Annualized indices are consequently calculated for each load step and weighted by the corresponding probability of existence. These values are then aggregated to reproduce a representative set of indices designated as annual indices [31]. Both annual load bus and system indices are calculated using a representative load duration curve. Annual indices are the most useful indices since they incorporate the variation in load level throughout an entire year. Annualized indices are usually much higher than the actual annual indices as under normal circumstances, the load resides at the peak value for only a relatively short period of time. The reliability studies performed in this thesis were conducted using a multi-step annual system load model [32] and only annual indices are presented. A *20* step-load duration curve was created based on the IEEE-RTS load model and was used in the studies presented in this research work. Table A.8 and Figure A.1, respectively, show the per-unit *20* step-load data and model used for the RBTS analysis.

2.6.4 Number of Simulation Samples

The number of simulation samples should be carefully selected in order to obtain meaningful reliability results. Studies conducted earlier [3, 8] show that an acceptable level of accuracy at HL II can be achieved when the number of samples for the RBTS is *2,000,000*. This sample size is used in the RBTS HL II adequacy analyses described in this thesis.

2.6.5 The $\mathrm{RBTS}_{\mathrm{BPO1}}$ Analysis

As previously noted, the load bus priority order (BPO) assumed for the original RBTS is given in Table 2.1. This bus priority order was designated as BPO1. Under this condition, the RBTS is designated as the $\mathrm{RBTS}_{\mathrm{BPO1}}$. The annual load bus indices for the $\mathrm{RBTS}_{\mathrm{BPO1}}$ base case are shown in Table 2.2. The annual system indices are given in Table 2.3. The base case system peak load is *185 MW*.

Table 2.2 $\mathrm{RBTS}_{\mathrm{BPO1}}$ Annual Load Bus Reliability Indices

Bus	PLC	EDLC (hrs/year)	ENLC (1/year)	ELC (MW/year)	EDNS (MW)	EENS (MWh/year)
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0001	1.2264	0.0787	0.8910	0.0014	12.5610
4	0.0000	0.0000	0.0011	0.0060	0.0000	0.0290
5	0.0000	0.0000	0.0055	0.0600	0.0000	0.2910
6	0.0012	10.5120	1.1822	15.4890	0.0158	137.9420

Table 2.3 RBTS$_{BPO1}$ Annual System Indices

Reliability Indices	Annual Values
ENLC (1/year)	1.2568
ADLC (hrs/disturbance)	9.3198
EDLC (hrs/year)	11.7130
PLC	0.0013
EDNS (MW)	0.0172
EENS (MWh/year)	150.8225
EDC (k$/year)	666.6355
BPII (MW/MW-year)	0.0889
BECI (MWh/MW-year)	0.8153
BPACI (MW/disturbance)	13.0859
MBECI (MW/MW)	0.0001
SI (system minutes/year)	48.9154

The results in Tables 2.2 and 2.3 and in subsequent tables are shown to 4 decimal places for the purpose of comparison, not to suggest this accuracy in the Monte Carlo simulation.

2.7 The RBTS$_{BPO1}$ Base Case Analysis

The variation in the load point indices are shown pictorially in Figures 2.2, 2.3 and 2.4 for the EDLC, ENLC and EENS, respectively. The system peak load level for the RBTS$_{BPO1}$ was increased from *170 MW* to *200 MW* in steps of *10 MW*. The maximum load of *200 MW* recognizes that the largest generating unit in the RBTS is *40 MW*. The original RBTS$_{BPO1}$ peak load level of *185 MW* is included in the figures. Figures 2.5 and 2.6, respectively, show the system EENS and SI over the peak load range. The effect of increasing the system peak load level provides important information regarding the reliability indices at the different load buses and for the overall system. Figures 2.2 to 2.4 clearly show that the individual load buses have quite different levels of reliability due to the system topology and the load curtailment philosophy. The figures show the EDLC, ENLC and EENS at the individual load buses, and the system EENS and SI indices. If desired, additional load bus and system indices can be used. The numerical results are shown in Appendix B, Tables B.1 and B.2.

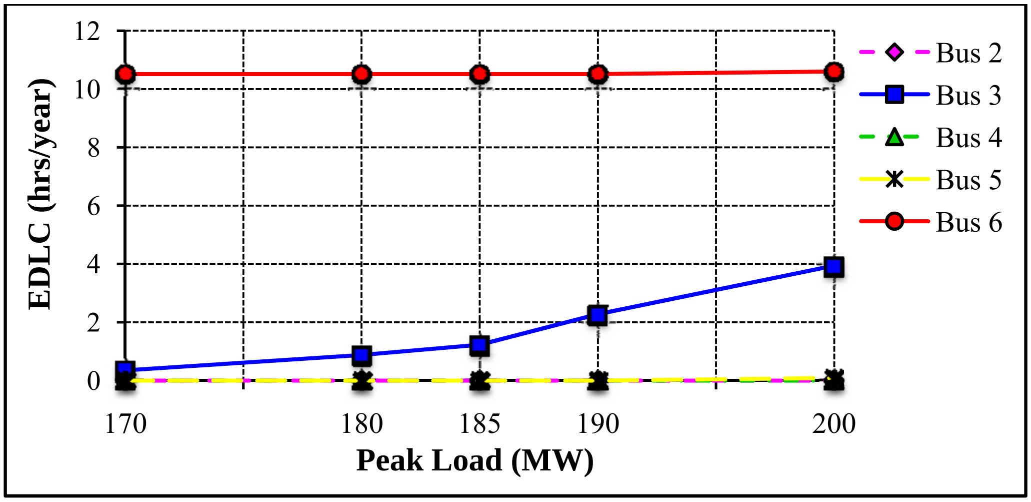


Figure 2.2 EDLC at each Load Bus in the RBTS$_{BPO1}$ as a Function of the Peak Load

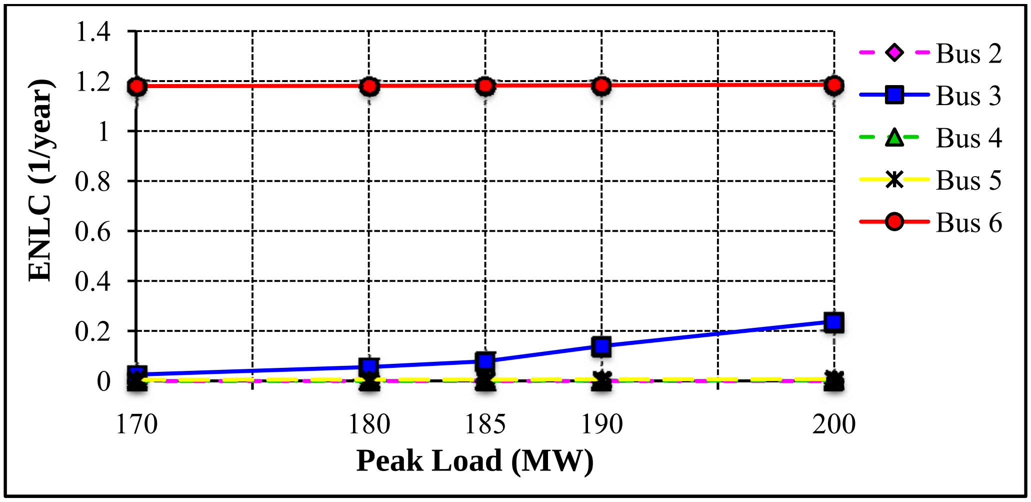


Figure 2.3 ENLC at each Load Bus in the RBTS$_{BPO1}$ as a Function of the Peak Load

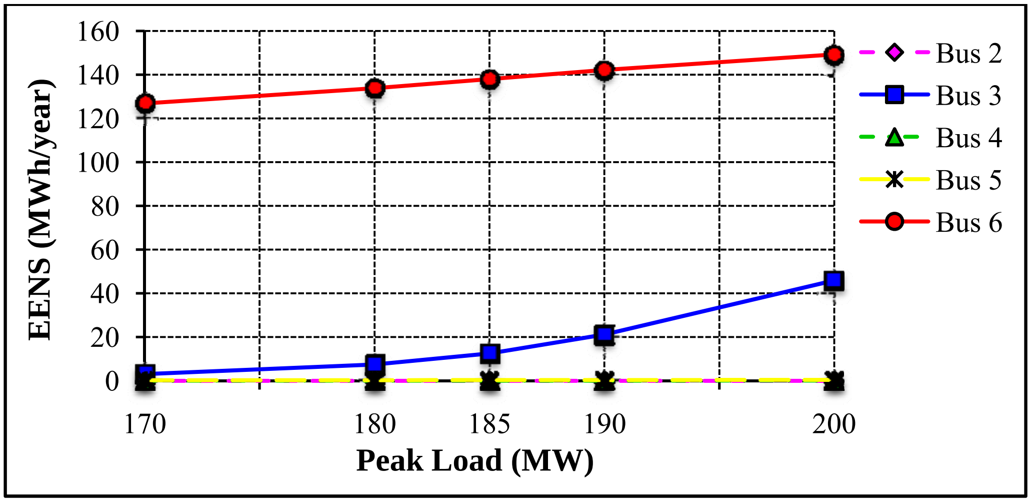


Figure 2.4 EENS at each Load Bus in the RBTS$_{BPO1}$ as a Function of the Peak Load

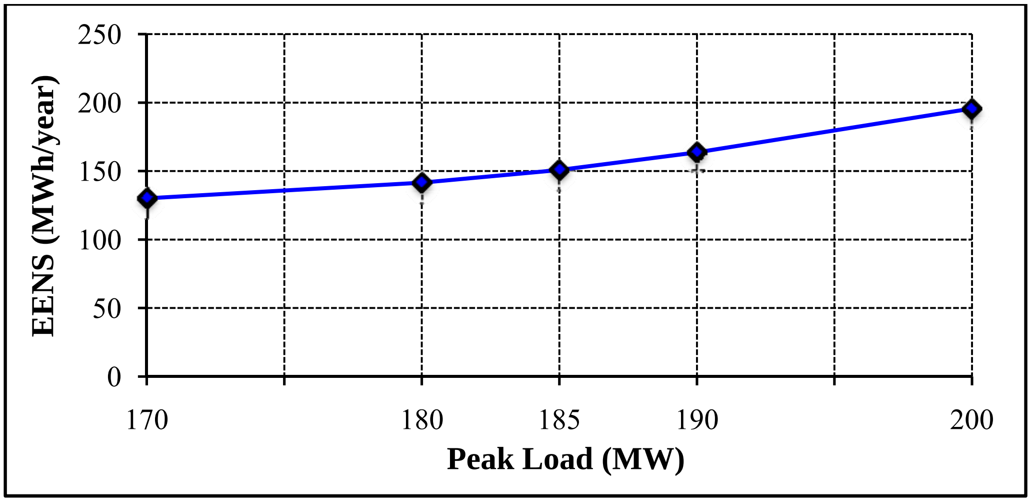


Figure 2.5 System EENS for the $RBTS_{BPO1}$ as a Function of the Peak Load

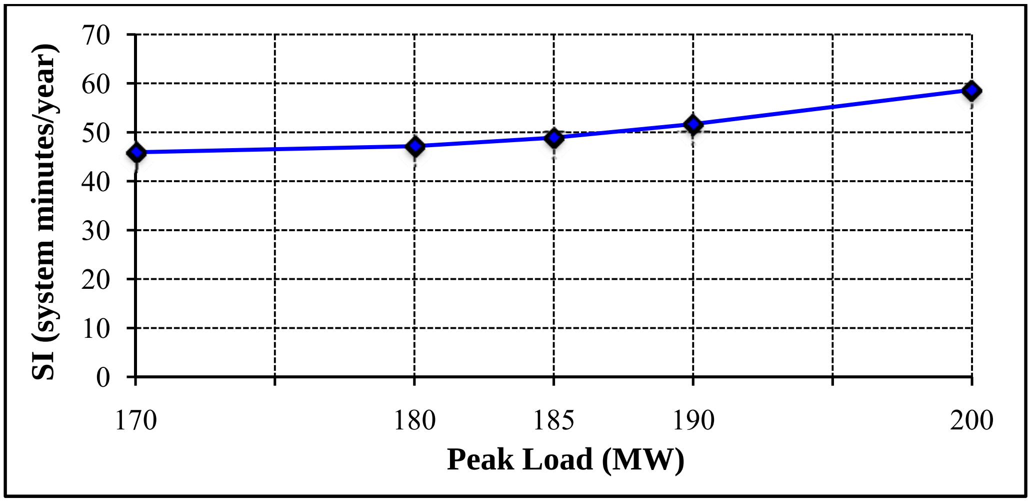


Figure 2.6 System SI for the $RBTS_{BPO1}$ as a Function of the Peak Load

Figures 2.2 to 2.4 show the different effects on the load point indices due to system peak load growth. The indices at Bus 3 tend to increase rapidly as the peak load exceeds the original system peak load. Bus 6 has the highest indices at all load levels due to the radial supply at this load point. It can be seen that the least reliable load buses in the system are Bus 3 and Bus 6. Figures 2.5 and 2.6 show how the system EENS and SI indices increase as the peak load increases. The SI is a normalized index that can be used as a base value as the system changes with time.

2.7.1 Factor Analysis of the $\mathrm{RBTS}_{\mathrm{BPO1}}$ Base Case

The adequacy of a composite power system with weak areas can be strengthened by first identifying what causes the problems. Generation and/or transmission facilities can be added to alleviate the problems and to reinforce the system. The procedure used to examine the relative reliability contributions of generation and transmission facilities is known as factor analysis [3, 8] and is illustrated by application to the $\mathrm{RBTS}_{\mathrm{BPO1}}$. Generation Failure analysis includes only those outages due to the generation system and does not include failures of transmission lines, *i.e.* the transmission system is assumed to be *100%* reliable. Transmission Failure analysis includes only those outages due to the transmission system and does not include failures of generating units, *i.e.* the generation system is assumed to be *100%* reliable. Both the load bus and system indices are calculated in each case.

Figures 2.7 to 2.14 show the annual load bus and system indices for the $\mathrm{RBTS}_{\mathrm{BPO1}}$ assuming generation outages only, transmission outages only and both generation and transmission outages. Figures 2.7 to 2.9 and Figures 2.10 to 2.12 show the annual load point indices at Bus 3 and Bus 6 as a function of the peak load, respectively. Figures 2.13 and 2.14 show the system indices as a function of the peak load. The numerical results are shown in Appendix B, Tables B.3 to B.8.

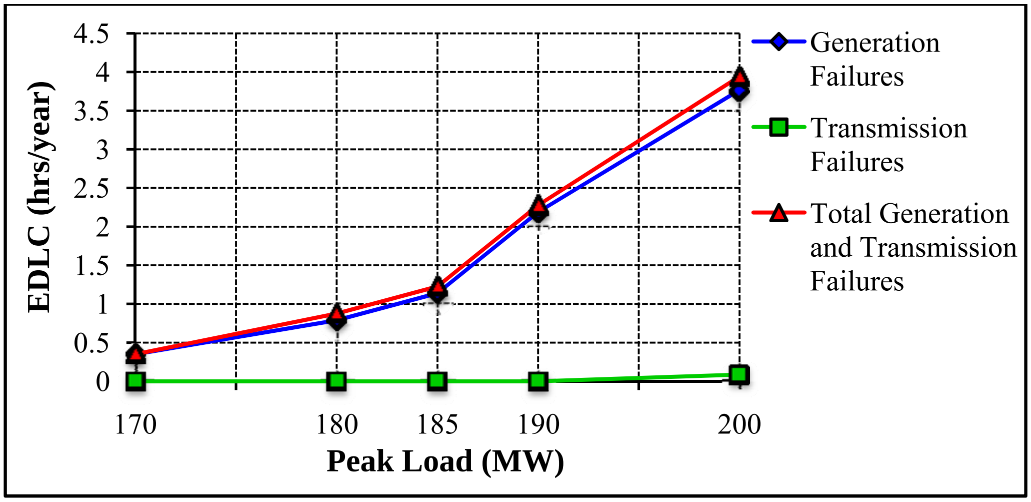


Figure 2.7 Contribution to the EDLC at Bus 3 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

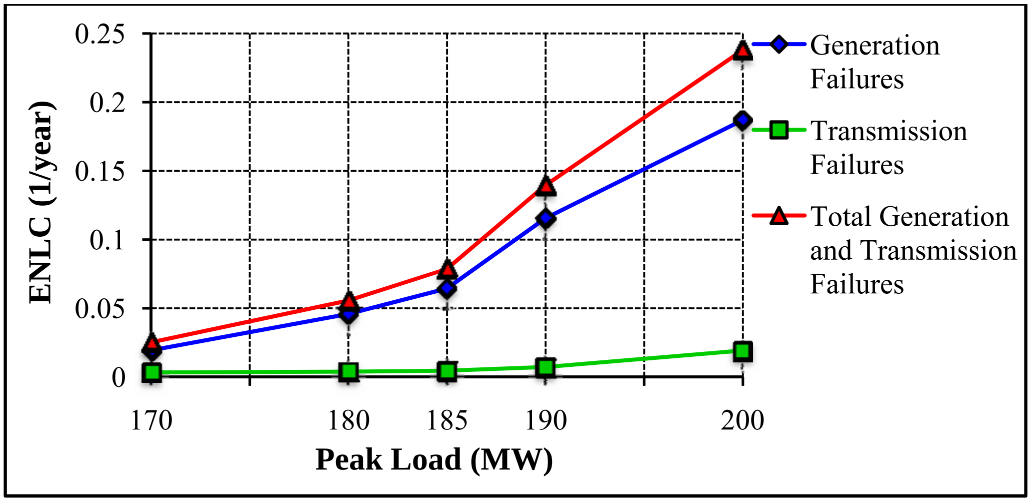


Figure 2.8 Contribution to the ENLC at Bus 3 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

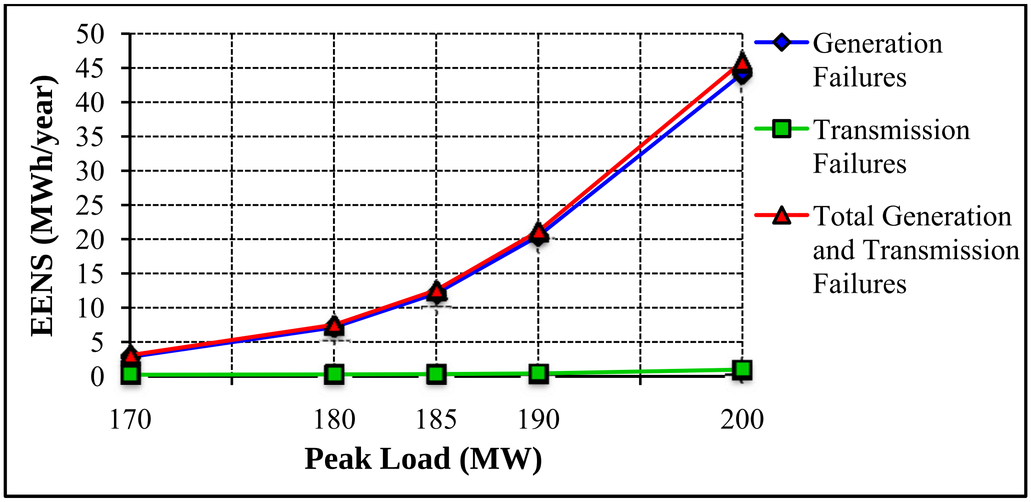


Figure 2.9 Contribution to the EENS at Bus 3 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

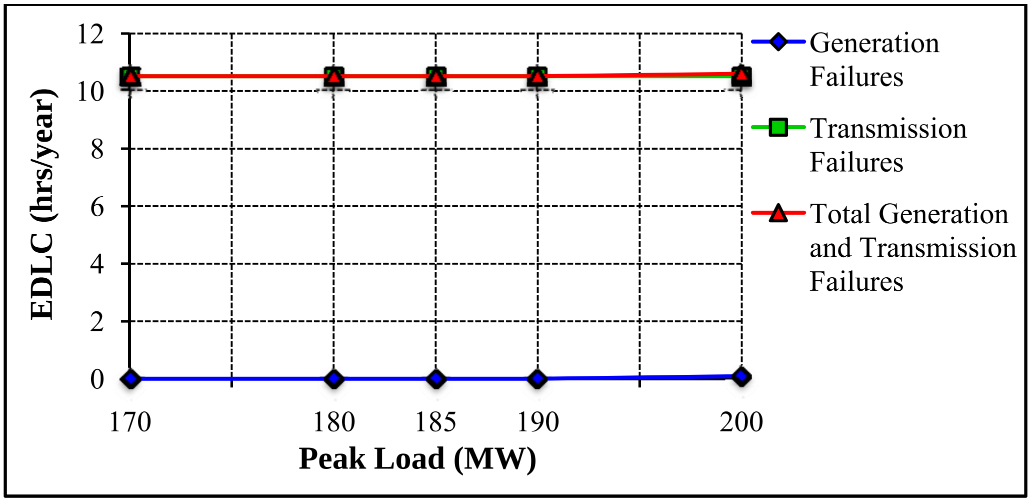


Figure 2.10 Contribution to the EDLC at Bus 6 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

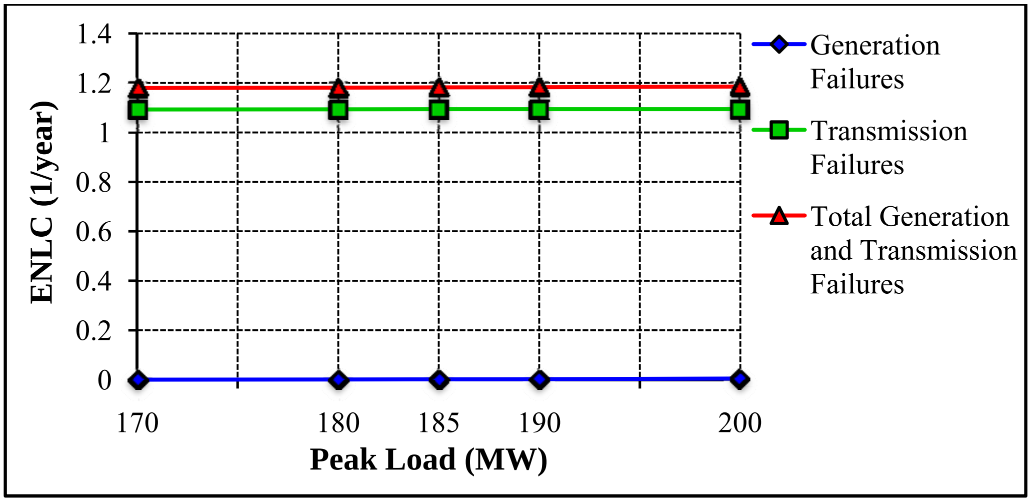


Figure 2.11 Contribution to the ENLC at Bus 6 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

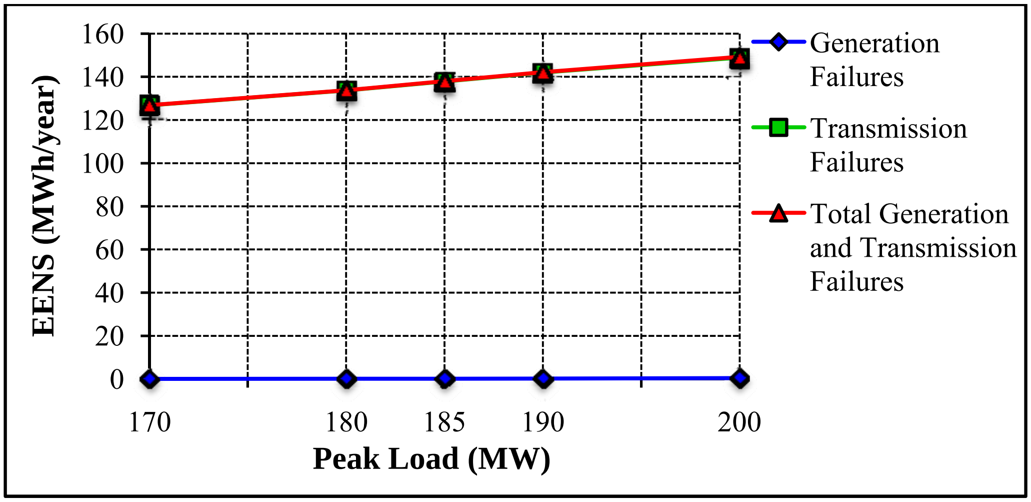


Figure 2.12 Contribution to the EENS at Bus 6 in the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

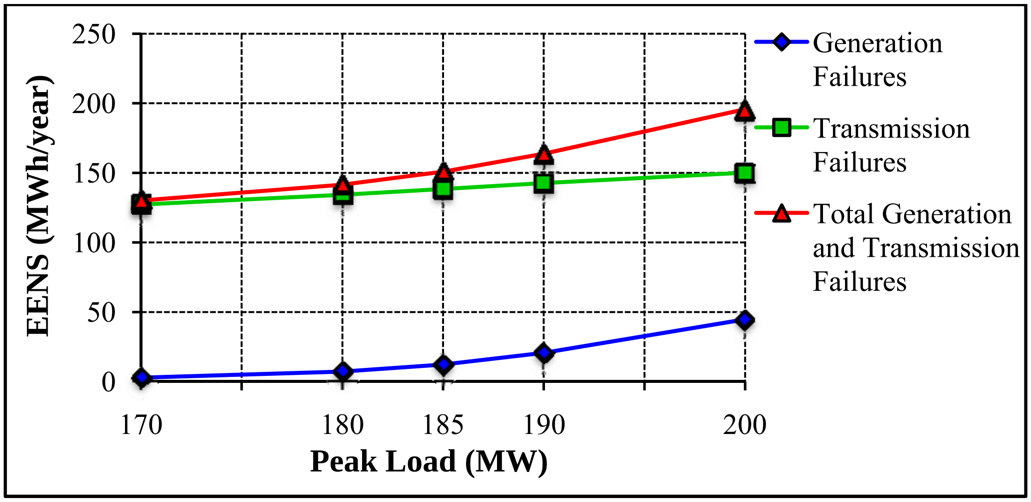


Figure 2.13 Contribution to the System EENS for the $\mathrm{RBTS}_{\mathrm{BPO1}}$ versus Peak Load

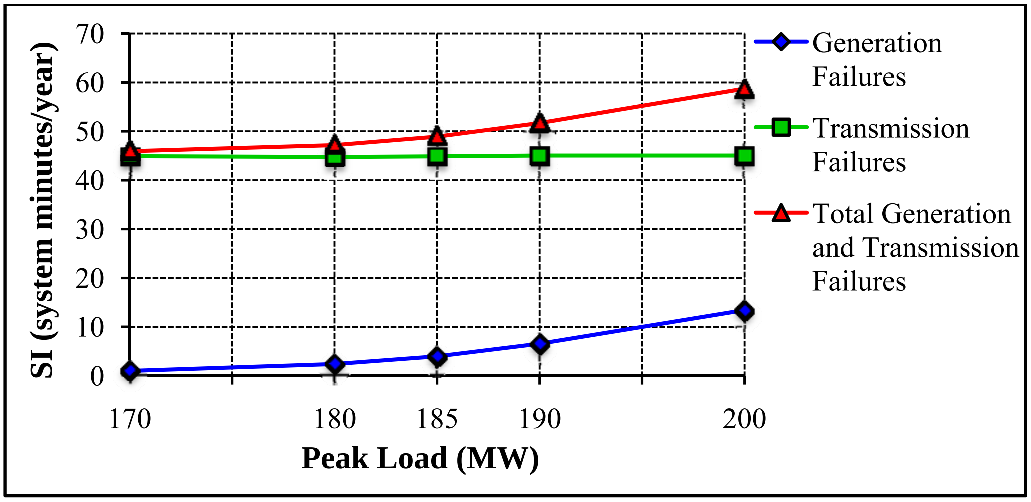


Figure 2.14 Contribution to the System SI for the $\text{RBTS}_{\text{BPO1}}$ versus Peak Load

Figure 2.1 shows that Bus 3 is supplied by four transmission lines and is directly connected to the generating station at Bus 1. Figures 2.7 to 2.9 show that generation system outages highly influence the reliability indices at Bus 3 and that transmission line outages have a much lower influence. The increasing EENS seen in Figure 2.9 shows that the adequacy at this load bus decreases as the generation reserve decreases and the system peak load grows. Bus 6 is located at the bottom of the system in Figure 2.1, and is relatively remote from the generation facilities and is supplied by a single radial transmission line.

It can be seen from Figures 2.10 to 2.12 that the reliability performance at Bus 6 is dominated by transmission system outages rather than generation failures. This suggests that generation is adequate at this load point as the peak load increases. Figures 2.13 and 2.14 show that the overall system reliability indices increase as the system peak load grows including both generation and transmission outages. While the contribution to transmission failures slowly increase, the contribution due to generation outages tends to increase rapidly as the peak load exceeds the *185 MW* peak level. Transmission failures have higher reliability contribution to the system indices than generation failures as a result of the single transmission line that connects Bus 5 and Bus 6.

The original RBTS is a relatively small system designed with some transmission deficiencies. The adequacy contributions due to generation and transmission facilities at different load levels provide useful information that can be used to identify the necessary system reinforcements to improve the overall system reliability. The effects of generation failures are basically dependent on the system peak load and the effects of transmission failures are essentially dependent on the installed generation facilities within the system and the system topology. Bus 3 and Bus 6 were identified as the least reliable load points in the analysis conducted on the $\text{RBTS}_{\text{BPO1}}$. The analysis shows that the overall system can be considered to have relatively adequate generation and transmission facilities. Based on these results, generation reinforcement can be considered to improve the reliability at Bus 3 and transmission reinforcement can be used to improve the adequacy at Bus 6.

In a general sense, generation and transmission additions can be assumed to be provided by market participants, directed by the ISO, who has the direct responsibility for the entire system. The following section focuses on transmission reinforcement to improve the load bus and system adequacy.

2.8 A Transmission Reinforcement Analysis

The reliability indices at Bus 6 in the original RBTS are relatively high and therefore the addition of another transmission line between Bus 5 and Bus 6 is an obvious modification. It is assumed that this new transmission line (line 10) has the same characteristics as line 9 in Figure 2.1. Its failure rate is therefore *1.0 (f/year)* and the repair rate is *10 (hrs)*. The modified $\text{RBTS}_{\text{BPO1}}$ is designated as the $\text{MRBTS}_{\text{BPO1}}$.

2.8.1 The $\text{MRBTS}_{\text{BPO1}}$ Base Case Analysis

Figures 2.15 to 2.19 show the variation in the load bus and system reliability as the peak load increases. The numerical values are given in Tables B.9 and B.10.

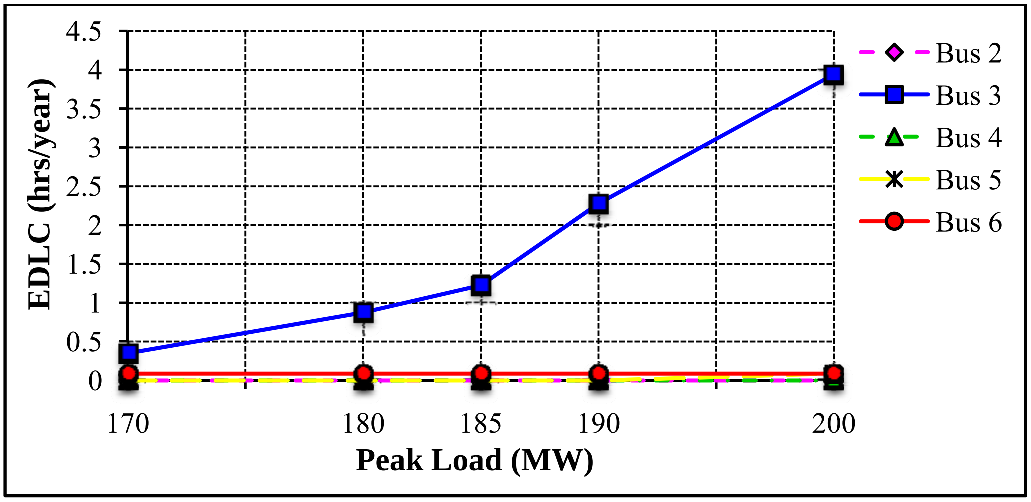


Figure 2.15 EDLC at each Load Bus in the MRBTS$_{BPO1}$ as a Function of the Peak Load

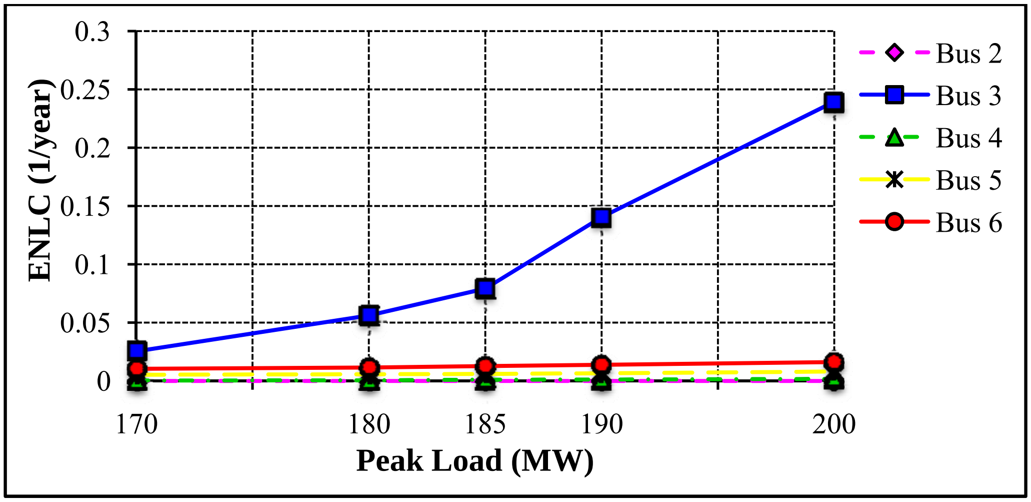


Figure 2.16 ENLC at each Load Bus in the MRBTS$_{BPO1}$ as a Function of the Peak Load

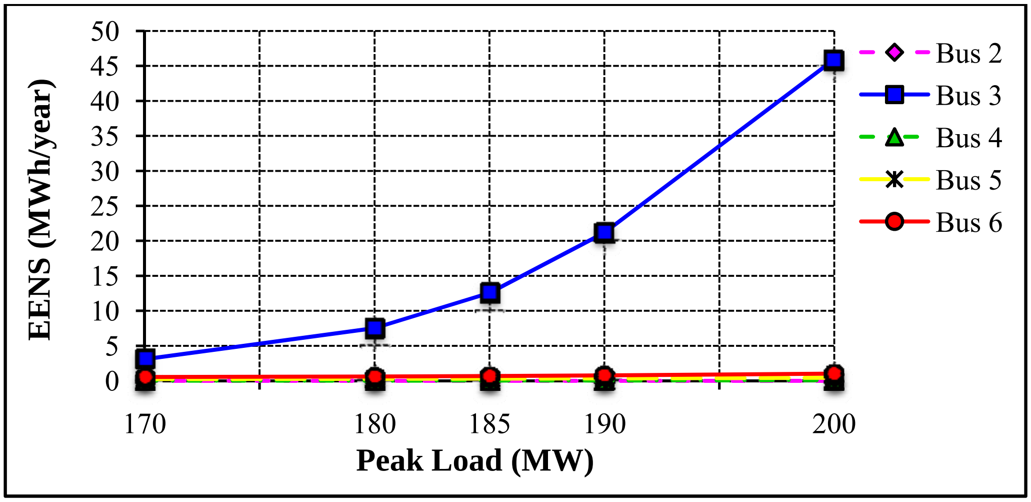


Figure 2.17 EENS at each Load Bus in the MRBTS$_{BPO1}$ as a Function of the Peak Load

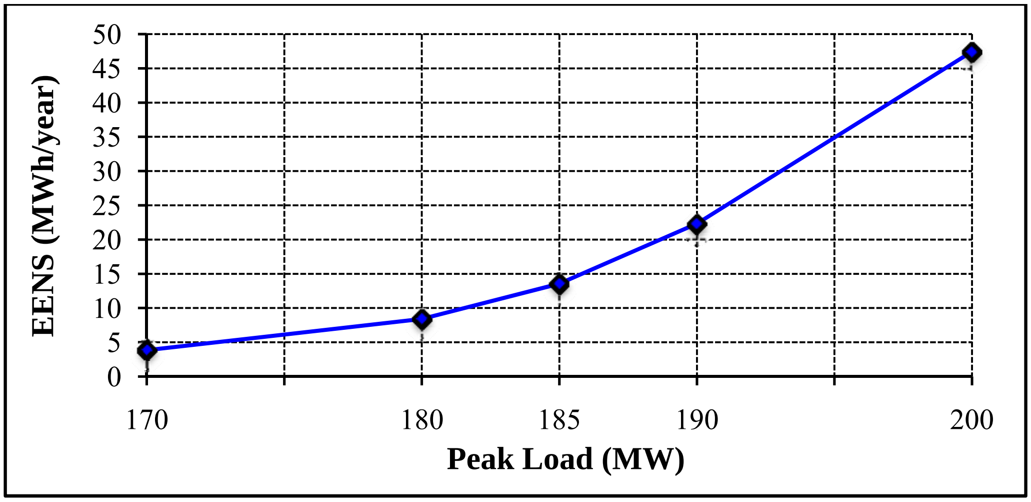


Figure 2.18 System EENS for the $\text{MRBTS}_{\text{BPO1}}$ as a Function of the Peak Load

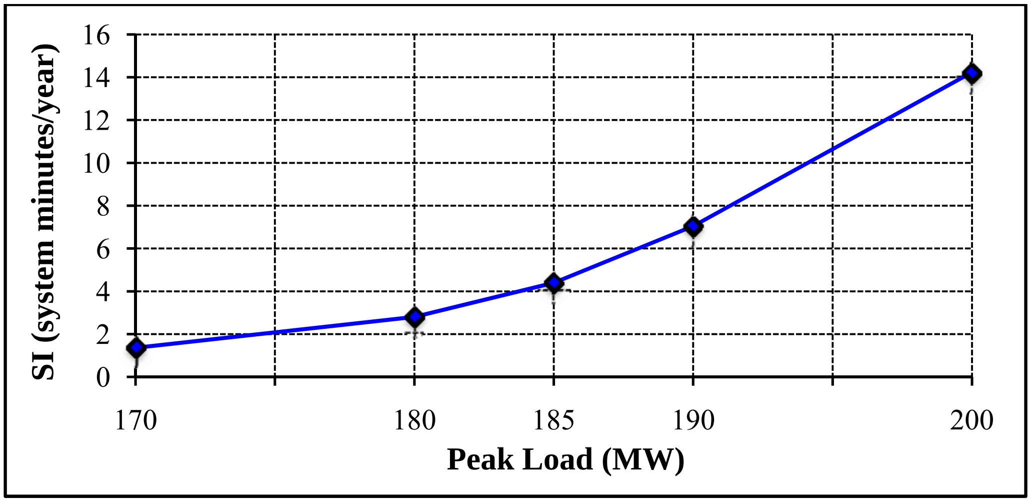


Figure 2.19 Systems SI for the $\text{MRBTS}_{\text{BPO1}}$ as a Function of the Peak Load

Figures 2.15 to 2.17 show that the reliability indices at Bus 3 significantly increase as the peak load grows and that the reliability indices at Bus 6 are greatly alleviated by the transmission line added between Bus 5 and Bus 6 in the original RBTS. These indices increase rapidly when the peak load surpasses the *185 MW*. The least reliable bus in the $\text{MRBTS}_{\text{BPO1}}$ is Bus 3. Figures 2.18 and 2.19 present the variation in the system EENS and SI with the system peak load level.

2.8.2 Factor Analysis of the MRBTS$_{BPO1}$ Base Case

Figures 2.20 to 2.27 show the annual load bus and system indices for the MRBTS$_{BPO1}$ assuming generation outages only, transmission outages only and both generation and transmission outages. Figures 2.20 to 2.22 and Figures 2.23 to 2.25 show the annual load point indices at Bus 3 and Bus 6 as a function of the peak load, respectively. Figures 2.26 and 2.27 show the system indices as a function of the peak load. The numerical results are given in Appendix B, Tables B.11 to B.16.

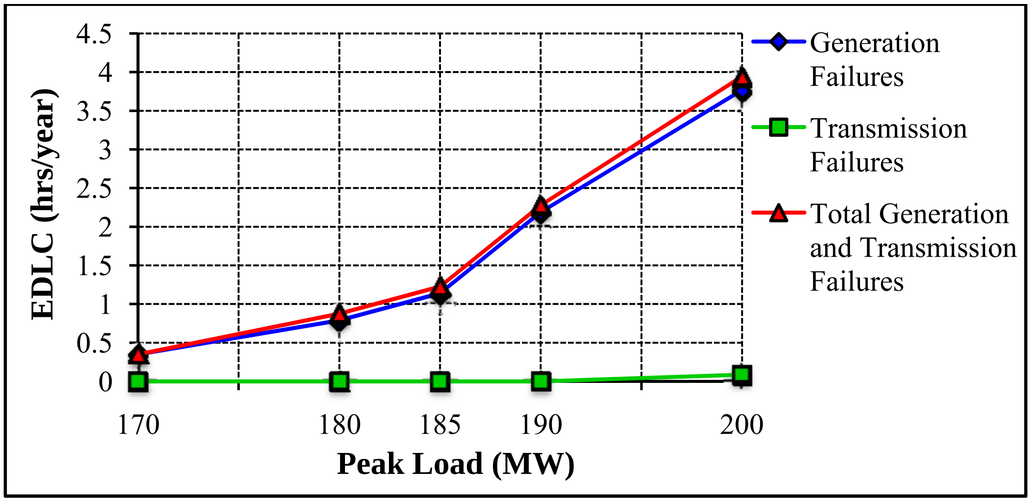


Figure 2.20 Contribution to EDLC at Bus 3 in the MRBTS$_{BPO1}$ versus Peak Load

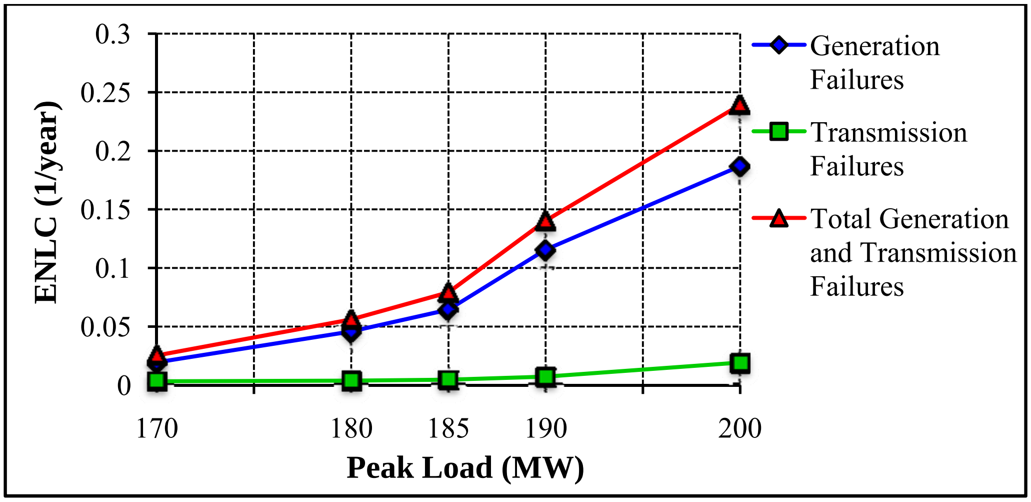


Figure 2.21 Contribution to ENLC at Bus 3 in the MRBTS$_{BPO1}$ versus Peak Load

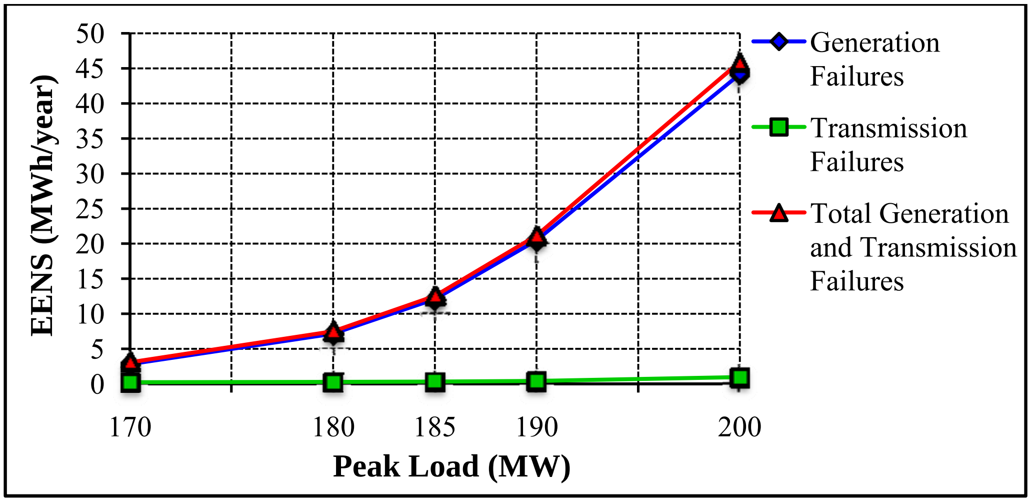


Figure 2.22 Contribution to EENS at Bus 3 in the MRBTS$_{\text{BPO1}}$ versus Peak Load

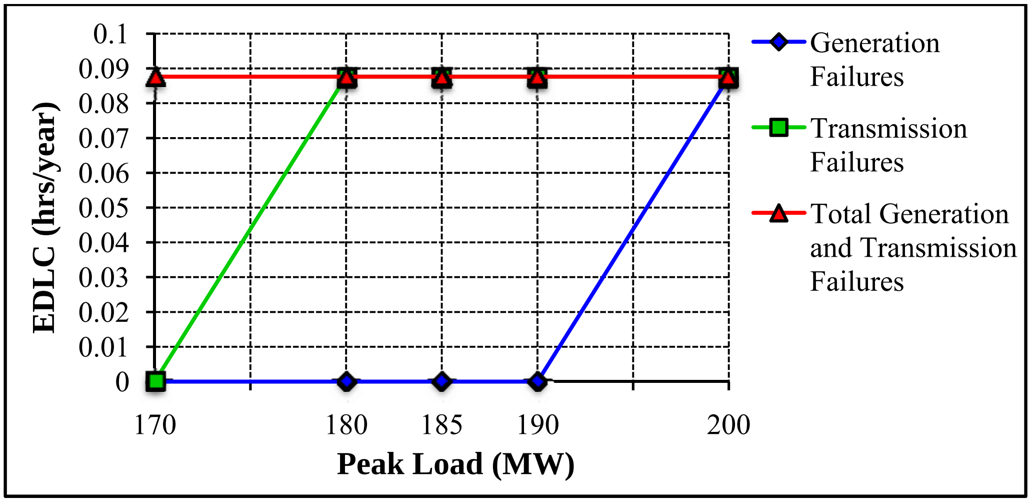


Figure 2.23 Contribution to EDLC at Bus 6 in the MRBTS$_{\text{BPO1}}$ versus Peak Load

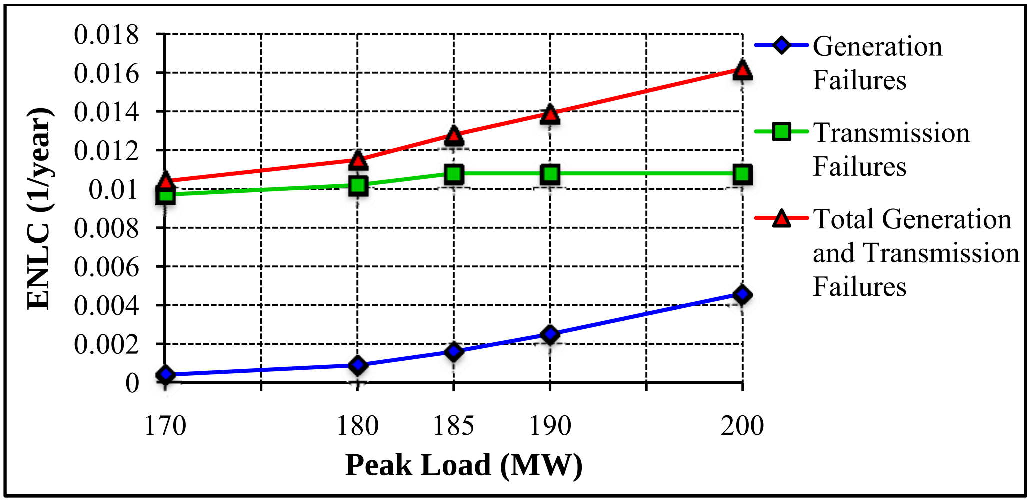


Figure 2.24 Contribution to ENLC at Bus 6 in the MRBTS$_{\text{BPO1}}$ versus Peak Load

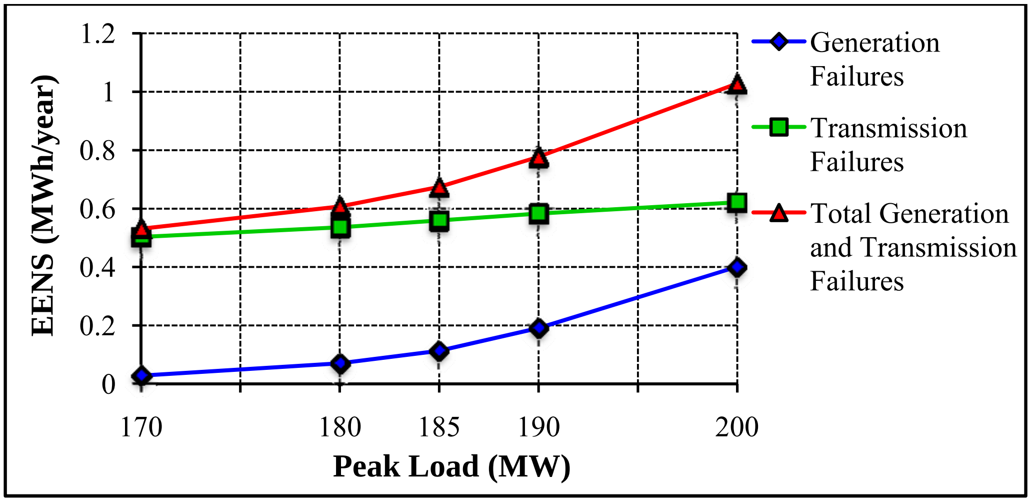


Figure 2.25 Contribution to EENS at Bus 6 in the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ versus Peak Load

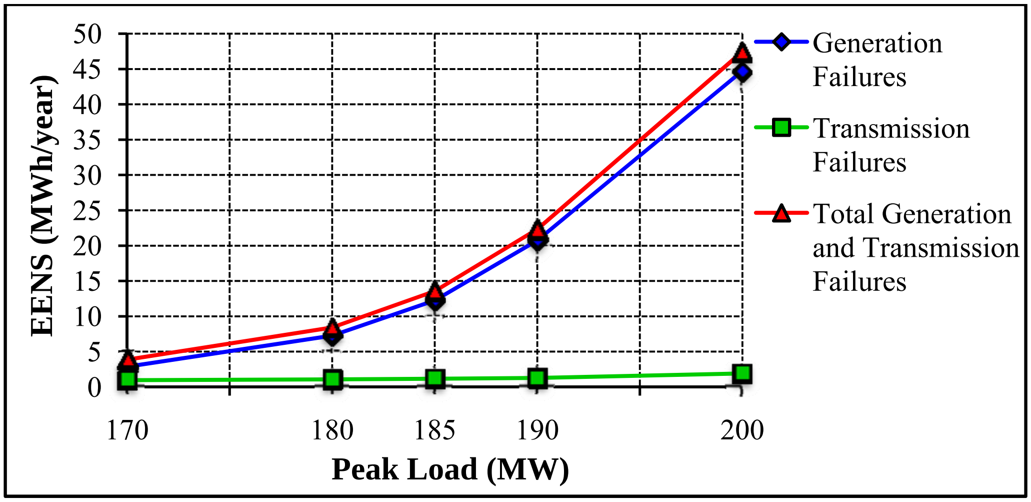


Figure 2.26 Contribution to System EENS for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ versus Peak Load

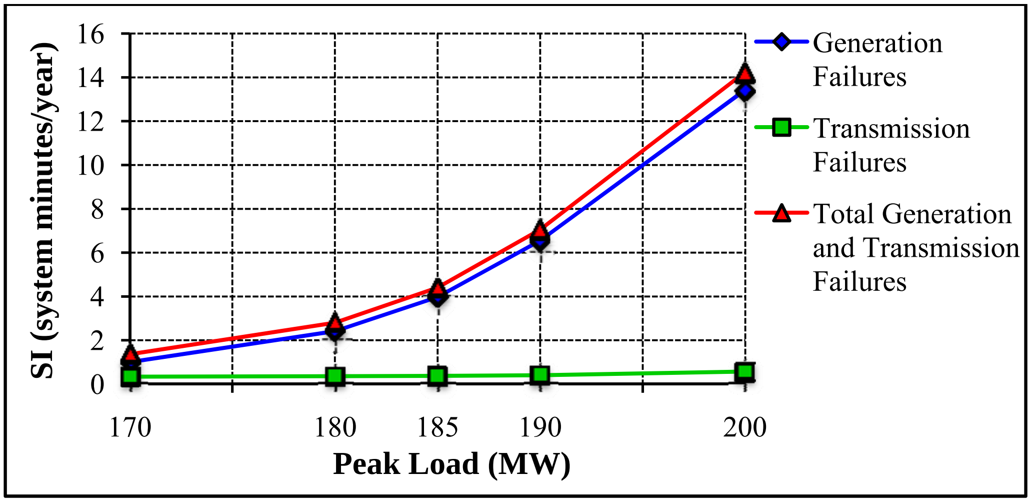


Figure 2.27 Contribution to the SI for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ versus Peak Load

Figures 2.20 to 2.22 clearly show that both generation and transmission outages contribute to the reliability indices at Bus 6 rather than just transmission failures. It can be seen in Figures 2.23 to 2.25 that the former transmission difficulties at Bus 6 are greatly reduced by adding the transmission line. Figure 2.25 shows that the generation effects increase as the peak load exceeds *185 MW* and transmission outages still continue to dominate the reliability at Bus 6. Figures 2.26 and 2.27 show that the system EENS and SI indices increase as the peak load grows and that generation system outages continue to dominate the overall reliability indices. The analysis conducted in this section shows that Bus 3 is now the least reliable bus in the MRBTS$_{BPO1}$.

2.9 Comparison Analysis for the RBTS$_{BPO1}$ and MRBTS$_{BPO1}$

Figures 2.28 to 2.35 present and compare the individual load point and system indices for the RBTS$_{BPO1}$ and the MRBTS$_{BPO1}$ as a function of the system peak load. Figure 2.28 to 2.30 and Figures 2.31 to 2.33 compare the annual load bus indices at Bus 3 and Bus 6, respectively. Figures 2.34 and 2.35 compare the overall system indices. The numerical results for the RBTS$_{BPO1}$ and MRBTS$_{BPO1}$ are presented in Appendix B, Tables B.1 and B.2, and Tables B.9 and B.10, respectively.

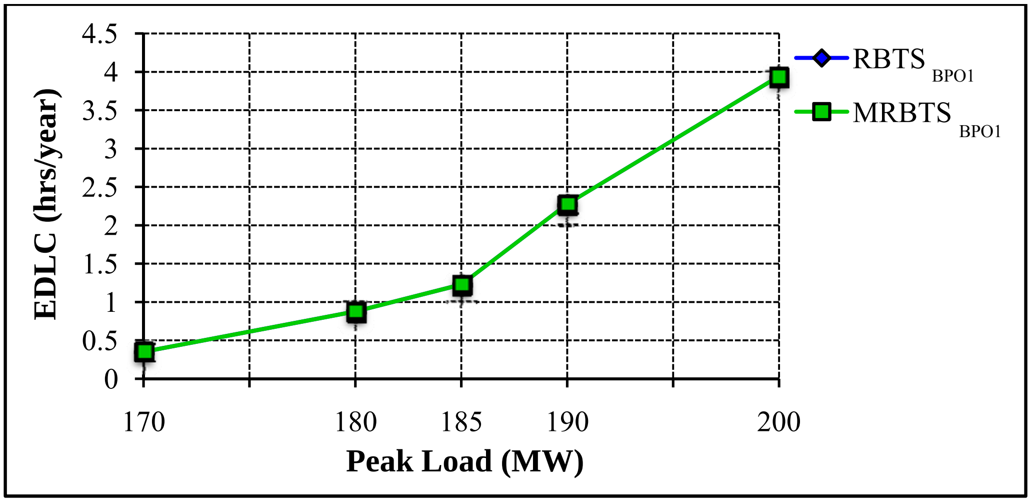


Figure 2.28 Comparison of the EDLC at Bus 3 for the RBTS$_{BPO1}$ and MRBTS$_{BPO1}$

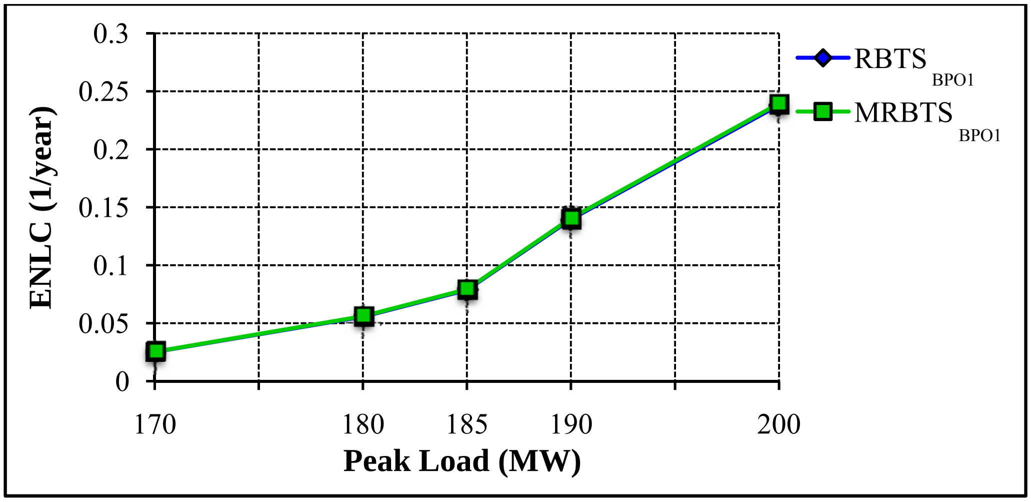


Figure 2.29 Comparison of the ENLC at Bus 3 for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

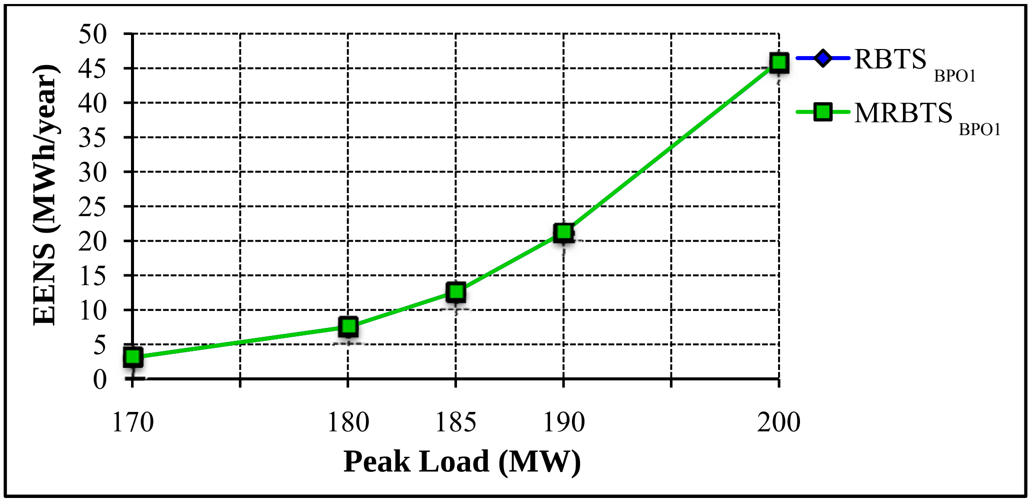


Figure 2.30 Comparison of the EENS at Bus 3 for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

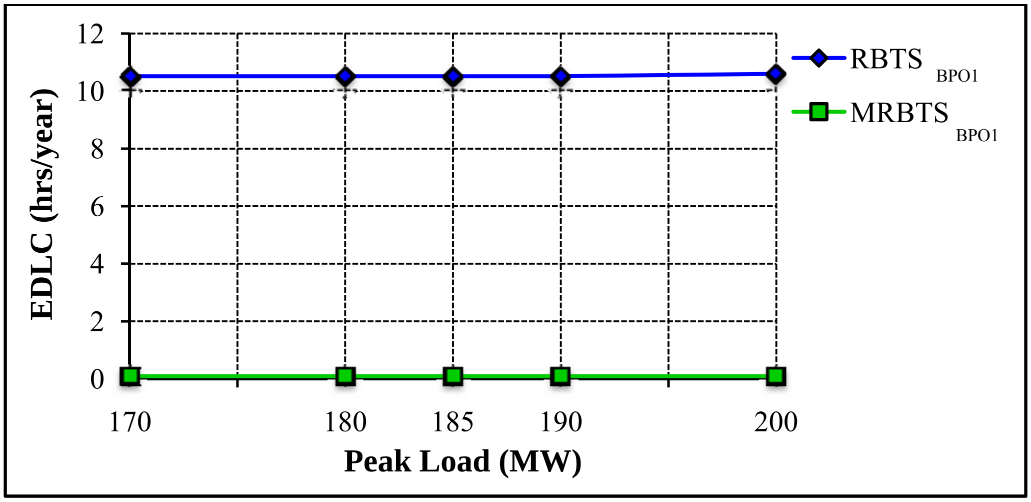


Figure 2.31 Comparison of the EDLC at Bus 6 for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

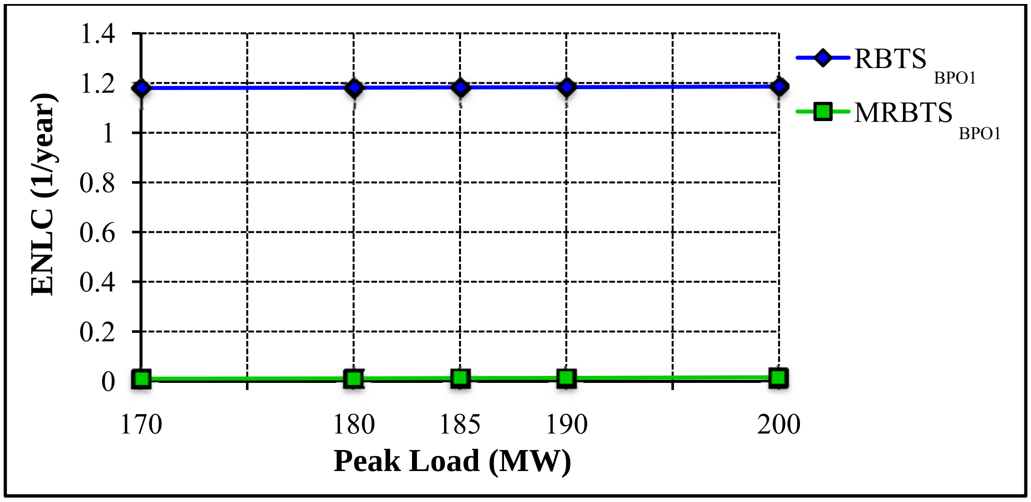


Figure 2.32 Comparison of the ENLC at Bus 6 for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

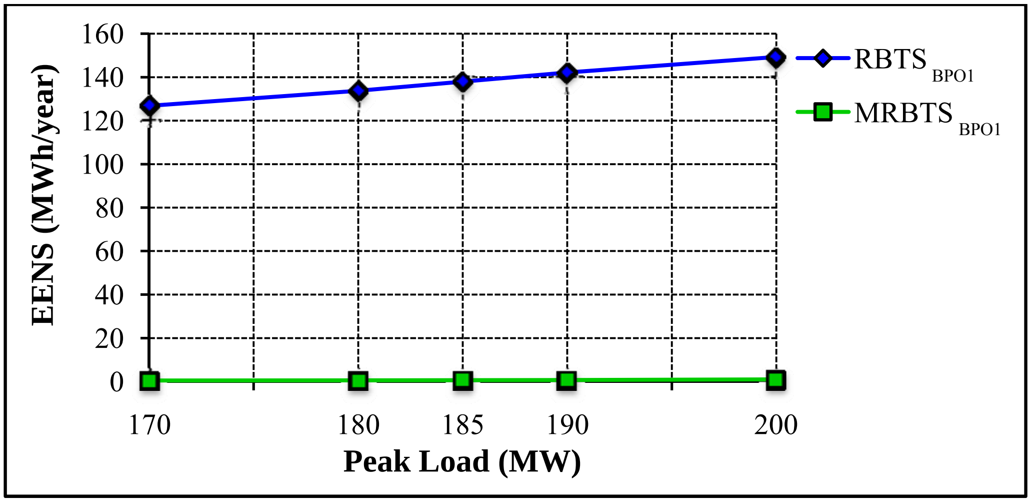


Figure 2.33 Comparison of the EENS at Bus 6 for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

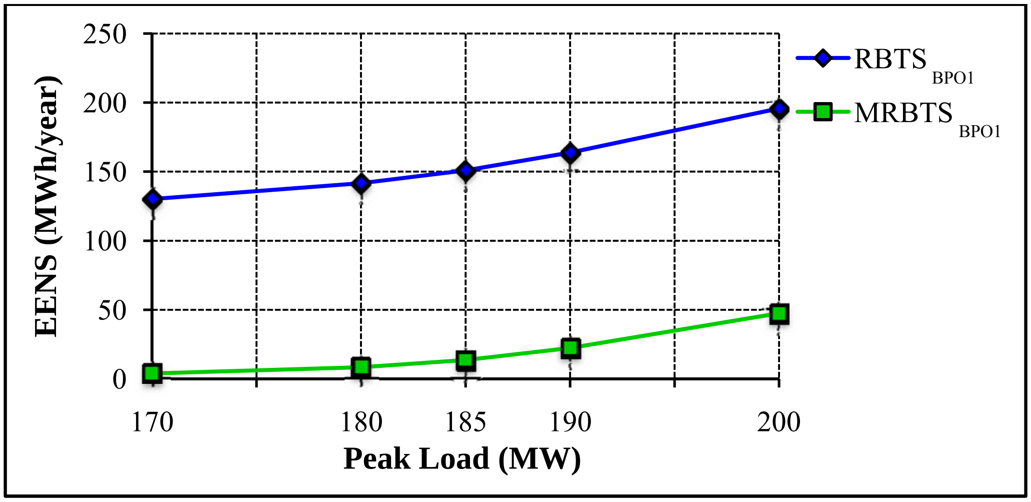


Figure 2.34 Comparison of the System EENS for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$

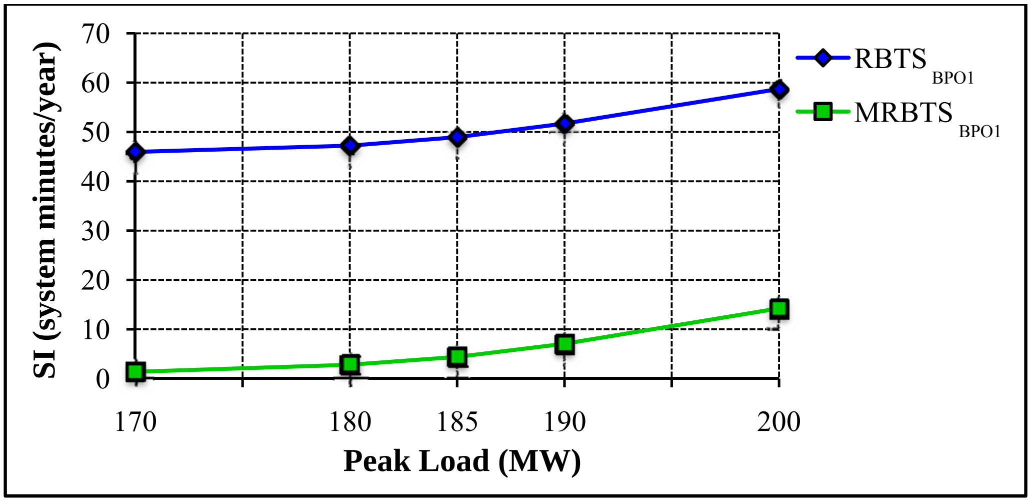


Figure 2.35 Comparison of the System SI for the $RBTS_{BPO1}$ and $MRBTS_{BPO1}$

The factor analysis performed in Section 2.7.1 shows that the low reliability at Bus 3 and Bus 6 is caused by generation and transmission, respectively. It can be seen from Figures 2.28 to 2.30 and Tables B.1 and B.9 that the reliability indices at Bus 3 are basically unchanged with the transmission addition. The added transmission line between Bus 5 and Bus 6 has relatively no effect at this load point. As previously determined, Bus 3 has generation deficiencies rather than transmission deficiencies. The benefits of transmission additions can be seen in Figures 2.31 to 2.33 which clearly show that the added line greatly alleviates the transmission deficiencies previously observed at Bus 6.

Figures 2.34 to 2.35 and Tables B.2 and B.10 show that the overall system reliability of the $RBTS_{BPO1}$ is significantly improved by the reinforcement at Bus 6. Adding transmission facilities at different locations can result in different load bus and system reliability benefits. It can be expected, therefore, that generation additions can also have the same effects. Transmission reinforcement only improves the reliability at those load buses supplied by inadequate transmission and does not change the reliability at those load buses influenced by inadequate generation [3]. The overall decision-making process of system reinforcement also includes economic parameters such as reliability cost and reliability worth analysis [1].

2.10 The Effects of Changing the Load Bus Curtailment Philosophy

The objective of the linearized DC-based power load flow and the linear programming optimal power flow model included in the MECORE program is to minimize the total load curtailment while the power balance, the linearized load flow relationships, and the limits of line power flows and generation outputs are satisfied. Load bus indices can be calculated by incorporating an acceptable load curtailment philosophy in the minimization load model [6]. The MECORE program automatically selects both the load curtailment order and the optimal load curtailment methodology, if there is no specified load priority order. The load bus curtailment strategy is modified when the load bus priority order is changed.

The individual load point indices in a composite system adequacy assessment are highly dependent on the load curtailment philosophy. Loads can be classified in accordance with their importance based on economic factors that recognize the customer cost associated the failure of energy not supplied. In the $\mathrm{RBTS}_{\mathrm{BPO1}}$ and $\mathrm{MRBTS}_{\mathrm{BPO1}}$, Bus 3 has the lowest bus priority and Bus 5 has the third lowest priority.

The analysis presented in this section addresses the effects of changing the system load curtailment philosophy. The load bus priority order (BPO) was changed by switching the load bus priorities at Buses 3 and 5. Bus 5 now has the lowest priority and Bus 3 has the third lowest priority. This new load curtailment philosophy is designated as BPO2. The two systems are now designated as the $\mathrm{RBTS}_{\mathrm{BPO2}}$ and $\mathrm{MRBTS}_{\mathrm{BPO2}}$. Table 2.4 shows the new load bus priority order for both systems.

Table 2.4 Change in the Load Bus Priority Order and IEAR for the $\mathrm{RBTS}_{\mathrm{BPO2}}$ and $\mathrm{MRBTS}_{\mathrm{BPO2}}$

Load Priority Order	Bus	IEAR ($/kWh)
1	2	7.41
2	4	6.78
3	3	2.69
4	6	3.63
5	5	4.82

2.10.1 The RBTS$_{BPO2}$ Case Analysis

This section illustrates the effects of changing the load bus priority order in the RBTS$_{BPO1}$. Figures 2.36 to 2.38 show the load bus EDLC, ENLC and EENS indices, and Figures 2.39 and 2.40 show the system EENS and SI indices as a function of the peak load. The numerical results are shown in Appendix C, Tables C.1 and C.2.

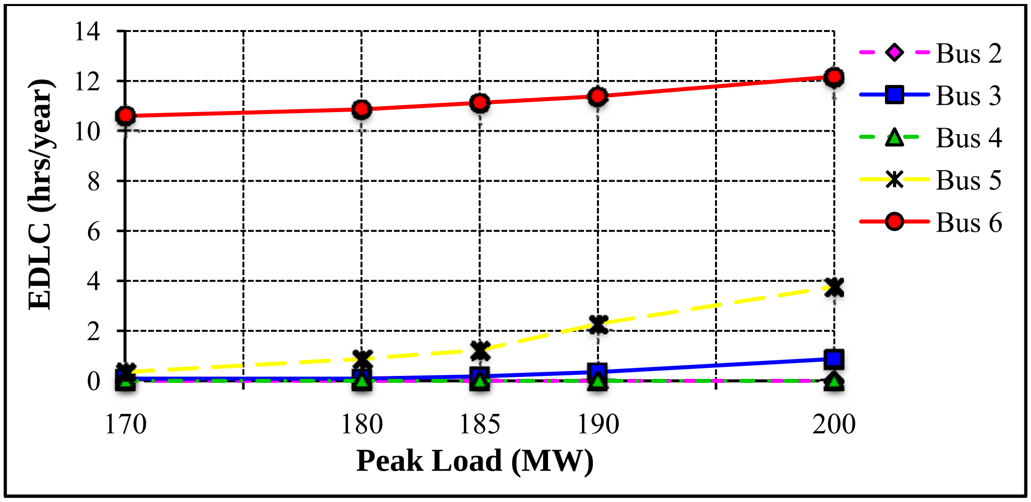


Figure 2.36 EDLC at each Load Bus in the RBTS$_{BPO2}$ as a Function of the Peak Load

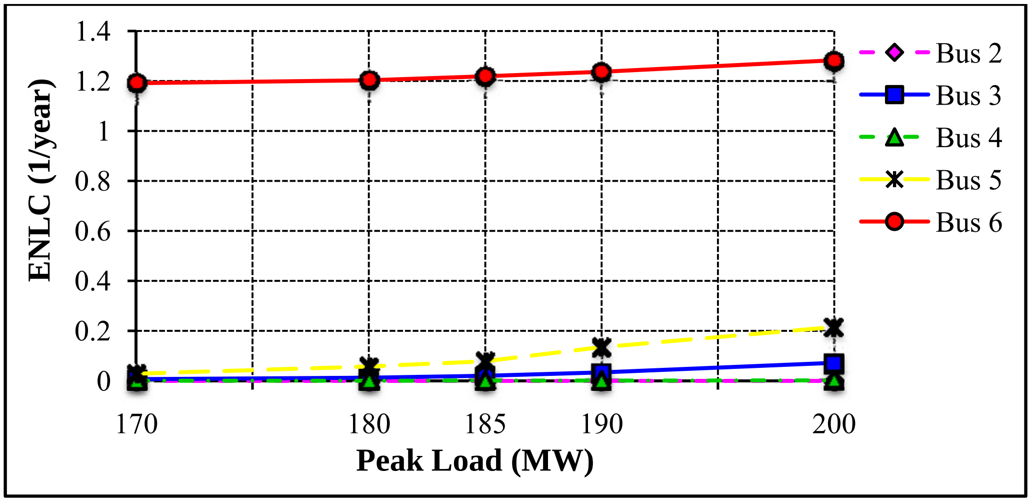


Figure 2.37 ENLC at each Load Bus in the RBTS$_{BPO2}$ as a Function of the Peak Load

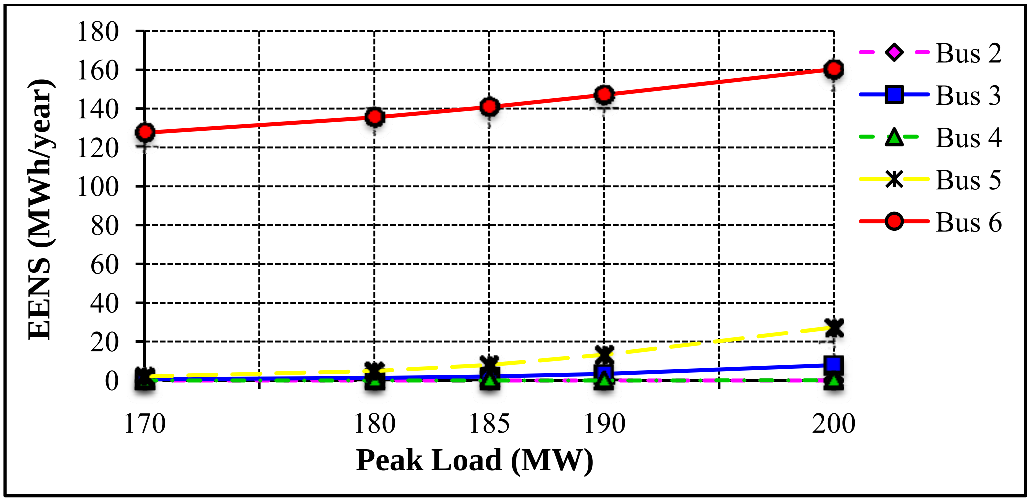


Figure 2.38 EENS at each Load Bus in the $RBTS_{BPO2}$ as a Function of the Peak Load

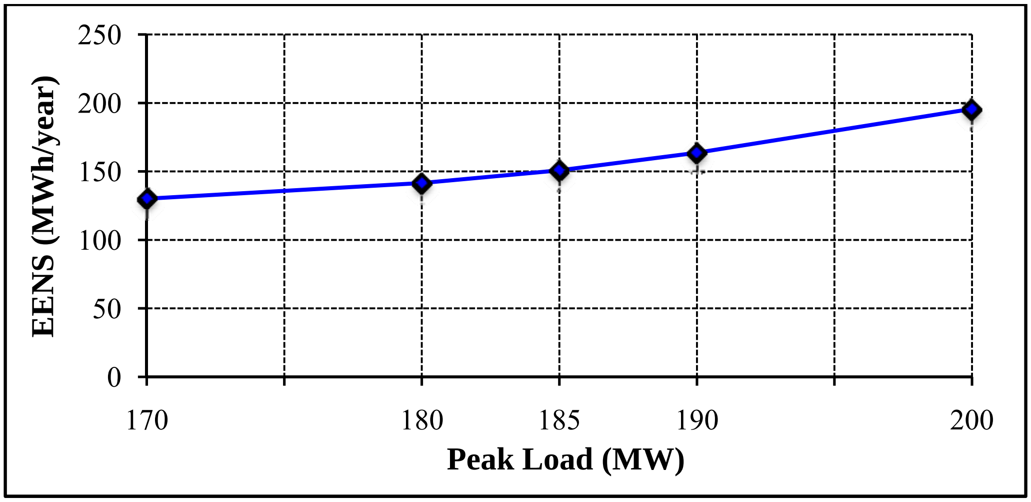


Figure 2.39 System EENS for the $RBTS_{BPO2}$ as a Function of the Peak Load

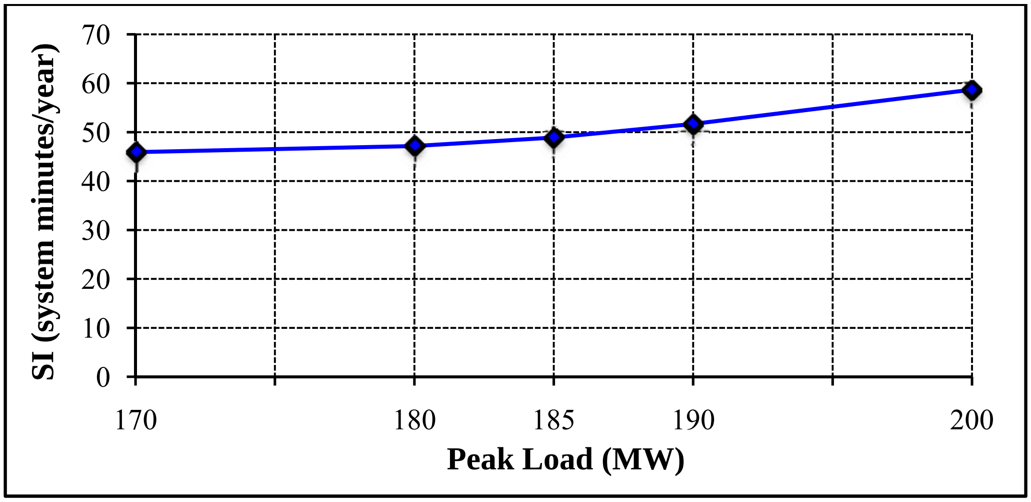


Figure 2.40 System SI for the $RBTS_{BPO2}$ as a Function of the Peak Load

Bus 3 and Bus 6 are the least reliable buses in the $RBTS_{BPO1}$. Bus 3 has the lowest priority, Bus 5 the third lowest priority and Bus 6 is connected by a single transmission line in the RBTS. The effects of the load bus curtailment philosophy can be observed by comparing the load bus indices shown in Section 2.7 with those in Figures 2.36 to 2.38. It can be seen that changing the load priority order has considerable effect on the individual load points. Bus 5 has the lowest priority and Bus 3 has the third lowest order in the $RBTS_{BPO2}$. As Figures 2.36 to 2.38 and Table C.1 show, the reliability indices at Bus 3 are considerable lower than those obtained for the $RBTS_{BPO1}$. The load bus indices at Bus 5 are much higher in the $RBTS_{BPO2}$ and increase rapidly as the system peak load level exceeds the *185 MW*. The reliability indices calculated at Bus 6 in the $RBTS_{BPO2}$ are slightly higher and tend to increase rapidly as the peak load grows. The increase is basically due to the radial line between Bus 5 and Bus 6. The load bus indices shown in this section indicate that the least reliable buses in the $RBTS_{BPO2}$ are Bus 6 and 5 followed by Bus 3. A factor analysis could be conducted to determine the contributory factors.

It can be seen by comparing the overall system results obtained in Section 2.7 and Figures 2.39 and 2.40 that the change in the load bus priority order has relatively negligible effects. The system indices shown in Tables B.2 and C.2 for the $RBTS_{BPO1}$ and $RBTS_{BPO2}$, respectively, are basically the same. The load bus curtailment philosophy has considerable effect on the system load bus indices and negligible effects on the overall system values.

2.10.2 The $MRBTS_{BPO2}$ Case Analysis

The effects of changing the load bus priority order in the $MRBTS_{BPO1}$ are illustrated in this section. Figures 2.41 to 2.43 show the load bus EDLC, ENLC and EENS indices, and Figures 2.44 and 2.45 show the system EENS and SI indices for the $MRBTS_{BPO2}$ as a function of the peak load level. The numerical results are shown in Appendix C, Tables C.3 and C.4.

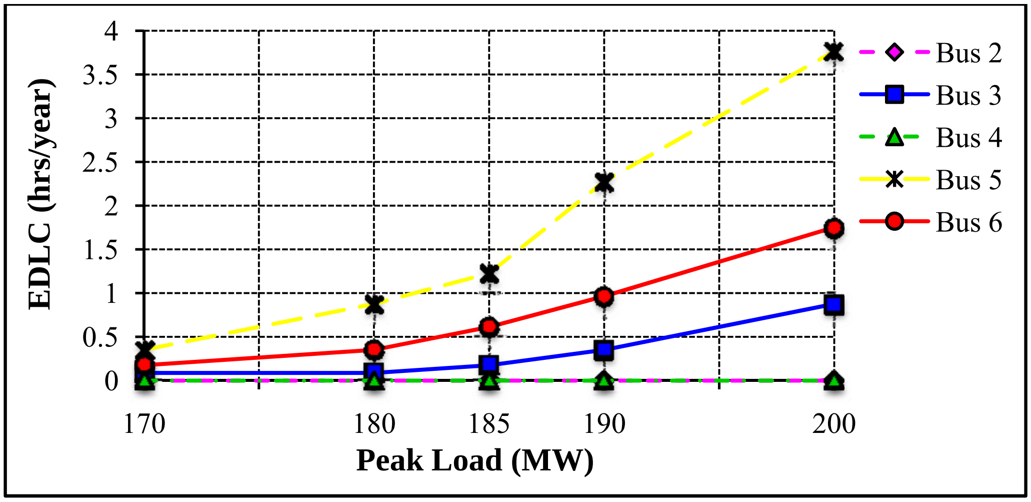


Figure 2.41 EDLC at each Load Bus in the $MRBTS_{BPO2}$ as a Function of the Peak Load

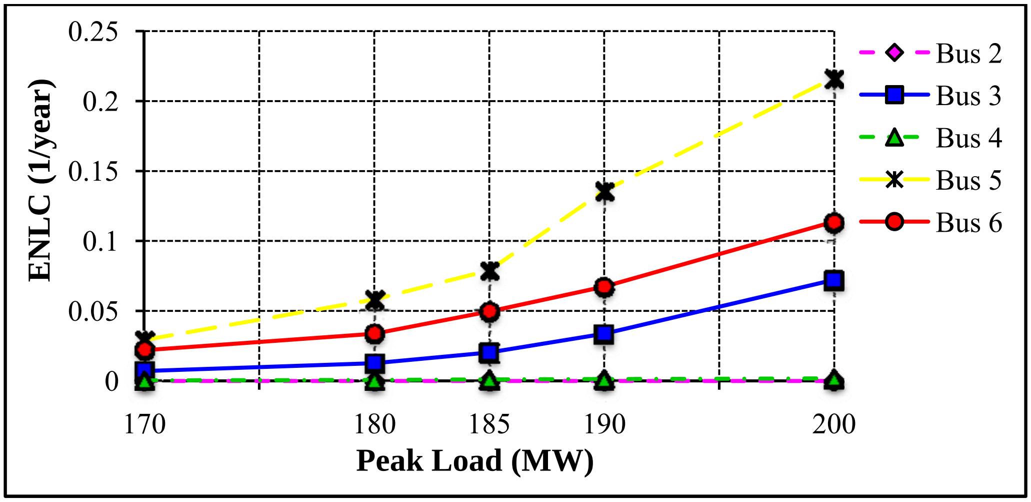


Figure 2.42 ENLC at each Load Bus in the $MRBTS_{BPO2}$ as a Function of the Peak Load

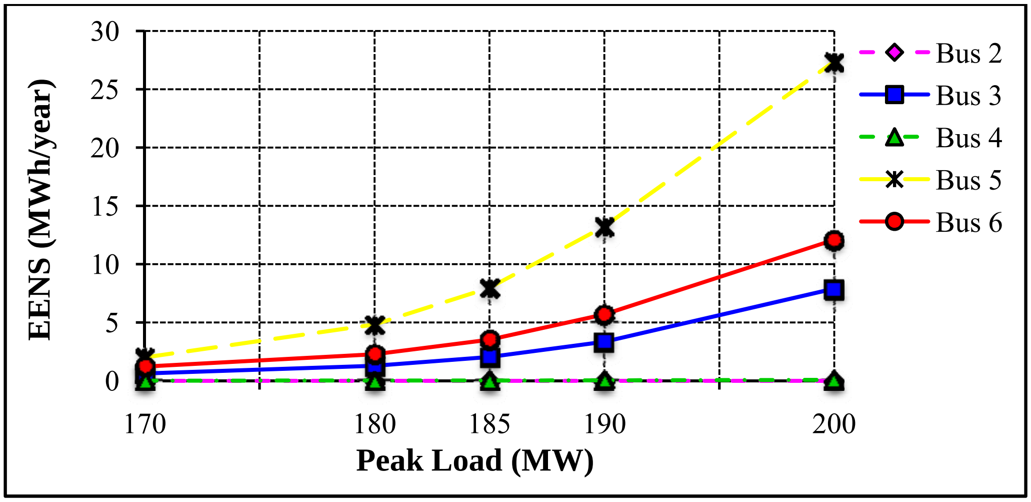


Figure 2.43 EENS at each Load Bus in the $MRBTS_{BPO2}$ as a Function of the Peak Load

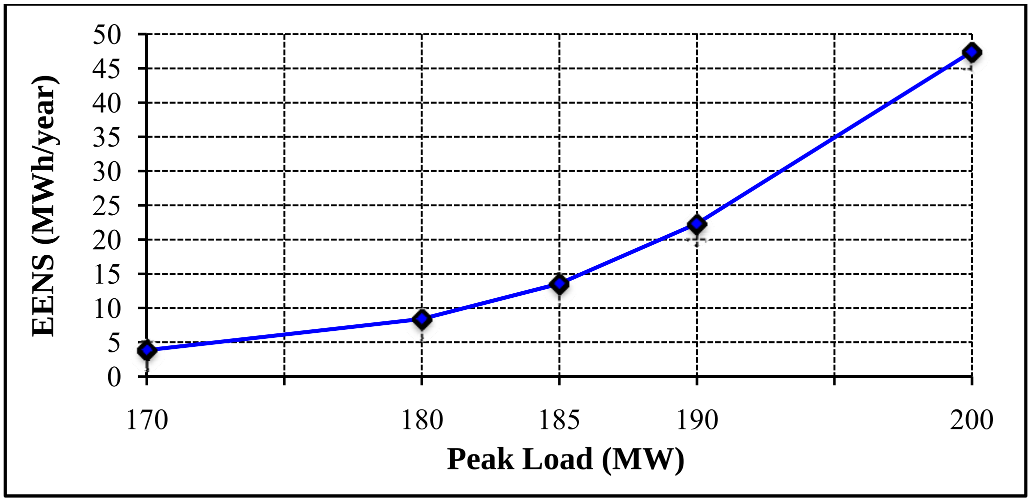


Figure 2.44 System EENS for the $\mathrm{MRBTS}_{\mathrm{BPO2}}$ as a Function of the Peak Load

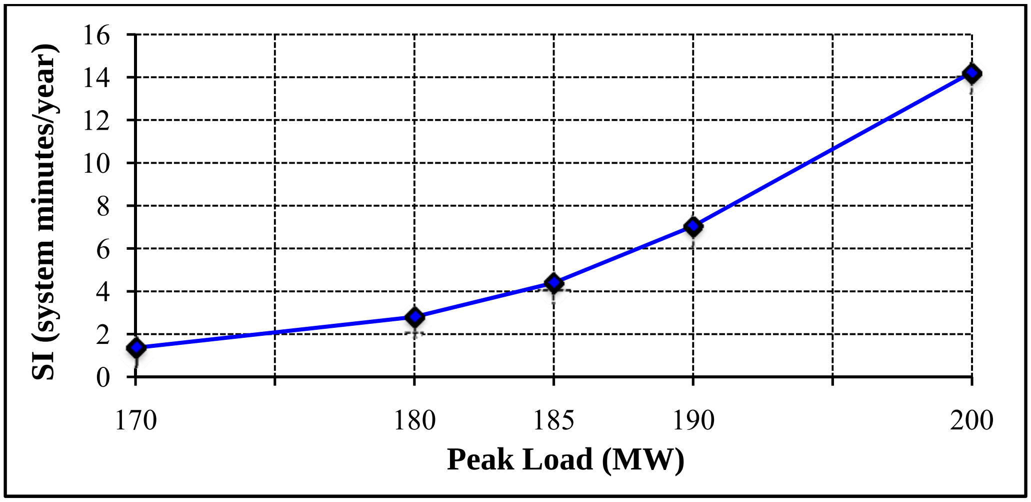


Figure 2.45 System SI for the $\mathrm{MRBTS}_{\mathrm{BPO2}}$ as a Function of the Peak Load

Bus 5 has the lowest priority order, Bus 6 has the second lowest priority order and Bus 3 has the third lowest priority order in the $\mathrm{MRBTS}_{\mathrm{BPO2}}$. Figures 2.41 to 2.43 and Table C.3 show that the reliability indices at Bus 3 are lower than those obtained for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$. The load bus indices at Bus 5 however are much higher in the $\mathrm{MRBTS}_{\mathrm{BPO2}}$. The reliability indices at Bus 6 are affected by the change in the load bus priority order and are higher in the $\mathrm{MRBTS}_{\mathrm{BPO2}}$. The indices at this load point increases as the system peak load grows even though transmission deficiencies were previously addressed.

It can be seen by comparing the overall system results obtained in Section 2.8.1 and Figures 2.44 and 2.45 that the change in the load bus priority has relatively negligible effects. The system indices shown in Tables B.2 and C.2 for $\text{MRBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO2}}$ are basically the same.

2.11 Summary

Composite system adequacy assessment is an important aspect of system planning. The adequacy assessment of composite systems can be achieved by applying analytical methods or simulation techniques. Analytical methods involve direct numerical solutions using the contingency enumeration approach. Simulation techniques use Monte Carlo methods to evaluate the stochastic behaviour of the system using random numbers. Monte Carlo simulation can be divided into three different approaches known as State Sampling, State Transition Sampling and Sequential techniques. Their advantages and disadvantages are briefly discussed in this chapter.

The computer program known as MECORE described in this chapter is a Monte Carlo based composite generation and transmission system reliability evaluation tool designed to perform reliability and reliability worth assessment of bulk electrical systems. It is based on the state sampling technique. The MECORE program can provide both annualized and annual load bus and system indices to assess the adequacy of a composite system. It produces eight basic indices and five IEEE-proposed indices.

Annualized indices are calculated at the system peak load level and expressed on a one-year basis. Annual indices are obtained by incorporating the variations in the load level throughout a given period. The calculated annual values shown in this chapter are a base case reference for comparison purposes in the studies described later in this thesis. The number of samples used in the simulation process was based on past reliability studies [8].

A discrete *20* step-load duration curve model is used in the calculation of the annual reliability indices in all the studies in this thesis. Load point indices provide useful information in system design and in comparing different alternative configurations in system expansion. They are used as input data to determine delivery point indices at the distribution level or HL III. System indices provide an overall adequacy assessment of the ability of the system to satisfy the load demand and energy requirements. They are useful to system management and system planners in an overall adequacy assessment. The concepts and techniques described in the thesis are applied to a composite test system known as the *Roy Billinton Test system* (RBTS). The RBTS is a relatively small composite system designed for educational and research purposes.

A load curtailment philosophy in the form of load bus priority order (BPO) is used in the reliability evaluations performed in this chapter and is later extended in Chapter 4. If a load bus priority order is not specified, MECORE automatically assume that all loads have equal likelihood to be curtailed and the priority order is selected according to the bus numbers. The Interrupted Energy Assessment Rate (IEAR) which recognize the customer cost in *\$/kWh* associated with unsupplied energy is utilized to establish an initial load bus priority order (BPO1). A load bus priority order has significant effects on the individual load bus indices and almost negligible effects on the overall system indices as the total amount of load curtailment for a given contingency system state is minimized [8]. The least important loads are curtailed first followed by the more important loads. Two different load bus priority orders designated as the BPO1 and BPO2 are applied to the RBTS.

A quantitative reliability approach for composite system development and reinforcement planning is also presented in this chapter and applied to the $\mathrm{RBTS}_{\mathrm{BPO1}}$. This includes a procedure to identify generation and transmission deficiencies in a system expansion framework due to growth in energy demand. The composite system reliability techniques described in this chapter were used to assess the reliability adequacy of four systems designated as the $\mathrm{RBTS}_{\mathrm{BPO1}}$, $\mathrm{MRBTS}_{\mathrm{BPO1}}$, $\mathrm{RBTS}_{\mathrm{BPO2}}$, and $\mathrm{MRBTS}_{\mathrm{BPO2}}$.

The adequacy of larger systems can be assessed by applying the techniques and procedures presented in this chapter. The system results shown in this chapter are used as base case values in the load forecast uncertainty and system expansion studies described later in this thesis.

3. LOAD FORECAST UNCERTAINTY CONSIDERATIONS IN COMPOSITE SYSTEM ADEQUACY ASSESSMENT

3.1 Introduction

The continuing growth in size and complexity of electric power systems requires the development of applicable load forecasting models to estimate the future energy demands. The application of these models can assist power engineers and managers to make important decisions on the required addition of new generation, transmission and distribution facilities [33]. Predictions of the system load at a future time are difficult because of the uncertainties associated with the load requirements. Generating capacity assessment is normally based on a forecast system peak load value. The actual system peak load at some time in the future can be considerably different from the forecast value [1]. Load forecast uncertainty is an important parameter in the reliability assessment of bulk electrical systems [6].

As noted in Chapters 1 and 2, a power system must have sufficient facilities to meet the system load and additional facilities to respond to equipment outages and maintenance requirements. The additional facilities required in the operation of bulk electrical systems require careful study of the uncertainty in the growing demand. The operation and long range planning process involves specific time periods in the future. The uncertainty in the load forecast is directly related to the facility lead times. Load forecasting as used in operational or expansion planning is classified as short-term, medium-term and long-term [33]. The method of assessment in each load forecasting period depends on the specified objectives. Load forecasting studies can be conducted to assess short-term, medium-term and long-term planning of fuel purchases, maintenance requirements, distribution networks, electricity production, electricity pricing, tariffs, etc [34, 35] in both traditional and deregulated power systems.

Short-term load forecasting can be considered to cover one hour to one week and is used in short-term facility scheduling. Medium-term load forecasting can be considered to cover a week to a year and is used to determine electricity pricing, mid-term production planning and fuel purchasing. Long-term load forecasting is directed at periods longer than a year [33] and is used to perform long-term planning in the decision-making process of facility additions and to estimate power plan investment [34]. One of the main objectives in incorporating load forecast uncertainty is to take into account the inherent probability that the system load differs from the expected forecast value. Uncertainty studies on load demand are important input in the task of estimating when facilities should be added to the system in order to meet the specified reliability criteria. This chapter describes two methods that can be used to include the effects of load forecast uncertainty in the reliability assessment of composite systems. These two techniques are designated as follows:

1.- The Load Forecast Probability Distribution (LFPD) Approach
2.- The Load Forecast Modified Load Curve (LFMLC) Approach

A procedure is presented for each method followed by an application of that method using a small hypothetical load duration curve model. The two methods are further applied to the $RBTS_{BPO1}$ and $MRBTS_{BPO1}$.

3.2 The Load Forecast Probability Distribution (LFPD) Approach

This section describes a procedure to determine composite system reliability indices which include uncertainty. The forecast peak load in the adequacy assessment of a power system is normally predicted on past experience. Load forecast uncertainty (LFU) can be represented by a probability distribution whose parameters can be determined from past experience, future load modeling and possible subjective evaluation [1]. The must common representation for load forecast uncertainty is the normal distribution [1]. Uncertainty in load forecasting can be included in the reliability risk calculation by segmenting the system load forecast probability distribution into discrete class intervals. The number of discrete class intervals depends on the level of accuracy desired. Figure 3.1 shows a normal distribution segmented into a seven-step approximation.

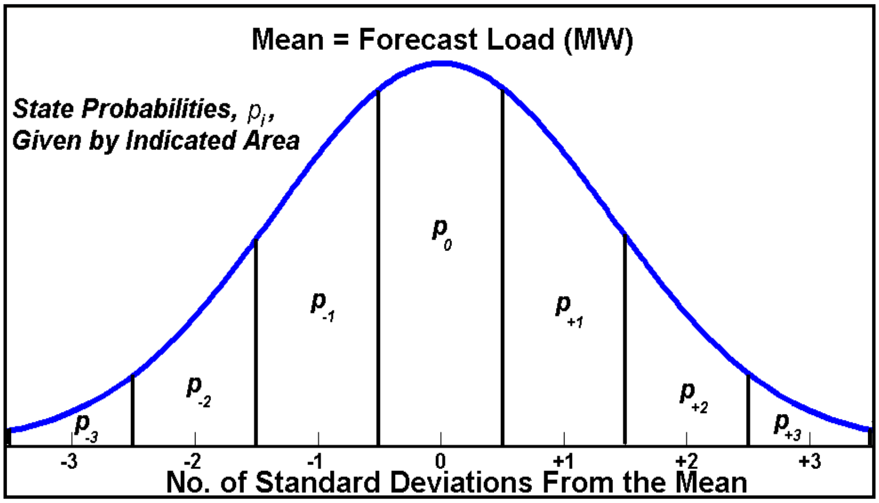


Figure 3.1 Seven-Step Approximation of the Normal Distribution

Each load mid-value in Figure 3.1 can be obtained as follows:

- The forecast peak load (*FPL*) mid-value is represented by the *0*-class interval.
- A percentage or fixed value, or standard deviation (SD_{FV}) from the *FPL* is taken.
- The load mid-values, Forecast Loads (*FL*), are obtained using Equation 3.1.

$$FL_i = FPL + (i \times SD_{FV}) \tag{3.1}$$

where *i* is the *ith*-class interval with values of *-3*, *-2*, *-1*, *0*, *+1*, *+2*, *+3* as shown in Figure 3.1.

The area of each class interval represents the probability that the load is the class interval middle value. In Figure 3.1, these areas are given by the p_{-1}, p_{-2}, p_{-3}, p_0, p_{+1}, p_{+2}, and p_{+3} values. The reliability index for each load represented by the class interval is evaluated and multiplied by the probability of existence of that load. The sum of these products is the expected reliability index for the forecast load, as shown in Equation 3.2.

$$REIN_{LFU} = \sum_{i=1}^{n} REIN_i \, p_i \tag{3.2}$$

where $REIN_{LFU}$ is the reliability index including uncertainty

n and i denote the number of class intervals and the class interval, respectively

$REIN_i$ is the reliability index for the *ith*-class interval

p_i is the probability that the load exists at the *i*-class interval

Representing the load forecast uncertainty distribution by a small number of discrete class intervals can provide an approximate evaluation of the system risk indices. A relatively larger number of discrete class intervals, *e.g. 7 to 49*, can be used to obtain a more accurate answer. It has been found [1] that a seven-step approximation of the normal curve is generally quite acceptable. It is difficult to obtain sufficient historical data to determine actual distributions of load forecast uncertainty and the normal distribution is commonly used.

3.2.1 The LFPD Approach Case Analysis

This section describes the procedure to obtain reliability indices which include uncertainty using the approach described in Section 3.2. The $RBTS_{BPO1}$ composite system is used to illustrate the method. The forecast peak load is *185 MW* with uncertainty assumed to be distributed as shown by the three discrete class interval model in Figure 3.2.

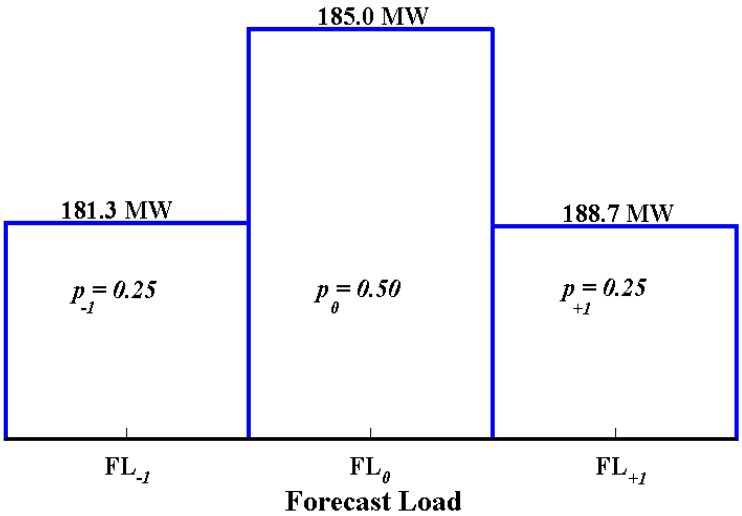


Figure 3.2 Load Uncertainty Represented by Three Discrete Class Intervals

System indices are calculated considering two fixed values of *2%* and *5%* from the forecast peak load. The forecast loads for the fixed value of 2% are given by the values $FL_{-1} = 181.3\ MW$, $FL_0 = 185\ MW$, and $FL_{+1} = 188.7\ MW$ in Figure 3.2 and are obtained using Equation 3.1. The probabilities that the forecast load is the class interval middle value are given by $p_{-1} = 0.25$, $p_0 = 0.50$ and $p_{+1} = 0.25$. The forecast loads for the fixed value of 5% can be obtained following the same procedure. The assumed annual load profile is the three step-load model shown in Figure 3.3.

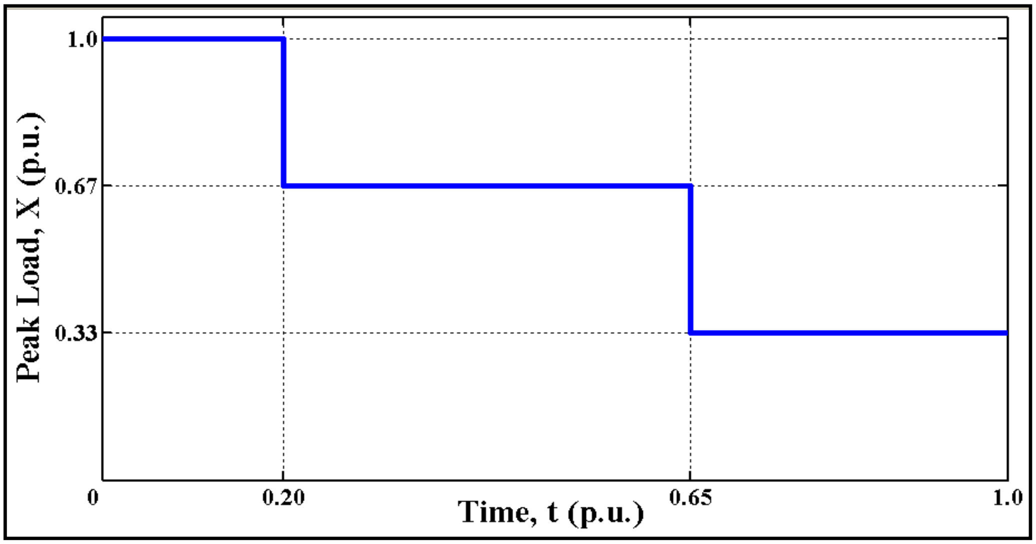


Figure 3.3 A Three-Step Annual Load Duration Curve Model

This multi-step load curve consists of three-step load levels at $X_1 = 1.0$, $X_2 = 0.67$ and $X_3 = 0.33\ p.u$ with time-durations of $t_1 = 0.20$, $t_2 = 0.45$ and $t_3 = 0.35\ p.u.$, respectively. This load model was used as input data to the MECORE program to evaluate the system indices. The *1.0 p.u.* peak load value in Figure 3.3 corresponds to the *185 MW* forecast load in Figure 3.2. The system EDLC, ENLC and EENS indices including uncertainty were evaluated for each forecast load. The MECORE software was run three times to produce three sets of reliability indices. Each reliability index was weighted by the probability of existence at that forecast load. The final system indices are expected values of a group of expected system indices. This calculation was conducted using Equation 3.2. Table 3.1 shows the system EDLC, ENLC and EENS indices not including uncertainty and including *2%* and *5%* uncertainty.

Table 3.1 Effects of Load Uncertainty Applying the LFPD Method Annual System EDLC, ENLC and EENS Indices

LFU (%)	Peak Load Level: 185 MW		
	EDLC (hrs/year)	ENLC (1/year)	EENS (MWh/year)
0	25.8251	2.0032	302.4484
2	25.8742	2.0089	302.5608
5	25.1805	2.0549	321.5593

It can be seen from Table 3.1 that the reliability indices generally increase as the uncertainty increases. The EDLC and the ENLC indices are not related to the magnitude of the outage events only to the fact that system load is not satisfied. The EENS index is the expected energy not supplied and incorporates the frequency and duration of outage events and the magnitude of the unsupplied load. The EENS index is very responsive to load forecast uncertainty.

3.3 The Load Forecast Modified Load Curve (LFMLC) Approach

The calculation of reliability indices including uncertainty can be conducted using a different approach. The system load duration curve in this case is modified to produce a load duration curve that includes uncertainty. If uncertainty is fixed at some specified value and the load shape remains unchanged, considerable saving in computer time can be achieved by using the modified load duration curve as input data in a range of studies [1]. The modified load duration curve is obtained using a group of conditional load shape segments. The procedure is illustrated below and a numerical example is presented in the following section.

- The forecast peak loads are represented by the discrete class intervals of a probability distribution as shown in Figure 3.1 and 3.2. Each forecast load is represented by the class interval mid-value.
- The number of conditional load shapes is the number of discrete class intervals in the load forecast distribution, each with a probability of existence as shown in Figure 3.1.

- Each conditional load shape is obtained by multiplying the original load model by each load class interval mid-value in Figure 3.1.

- The conditional load shapes represent the set of conditional load duration curves.

- Calculate the expected time segment corresponding to each load level, X_j, to determine the time-duration values, t_{dsj}, where j is the *jth*-step load level in the conditional load shapes.

- Create the modified load duration curve using the time-duration values and the step load levels in the condition load duration curves. The modified load duration curve is now composed of a group of conditional segments.

The procedure is illustrated in detail in the following section. The modified load duration curve can be represented in *MW* of peak load or expressed in percentage or per-unit of the forecast peak load. It can also be utilized with any load forecast peak assuming the basic characteristic and on the condition that the uncertainty remains constant. The definition of conditional load curves to obtain a modified curve can be quite useful in conducting a wide range of studies on composite system reliability indices with considerable savings in computer time [1].

3.3.1 The LFMLC Approach Case Analysis

The procedure to obtain a single load characteristic that includes uncertainty is applied in this section. The analysis utilizes the $\text{RBTS}_{\text{BPO1}}$ in order to compare the system risk indices with those in Table 3.1. The procedure to obtain a modified load duration curve which includes uncertainty is as follows:

- The three-step load model of an annual load profile shown in Figure 3.3 is used. The multi-step load curve consists of three-step peak load levels at $X_1 = 1.0$, $X_2 = 0.67$ and $X_3 = 0.33\ p.u$ with time-durations $t_1 = 0.20$, $t_2 = 0.45$ and $t_3 = 0.35\ p.u.$, respectively.

- The forecast peak load is *185 MW* with uncertainty distributed in the three-discrete class intervals shown in Figure 3.2. Load uncertainty is considered with designated percentages of *2%* and *5%* of the *185 MW* forecast load.

- The three conditional load shapes, each with a probability of existence of $p_{-1} = 0.25$, $p_0 = 0.50$ and $p_{+1} = 0.25$, respectively are shown in Figure 3.4.

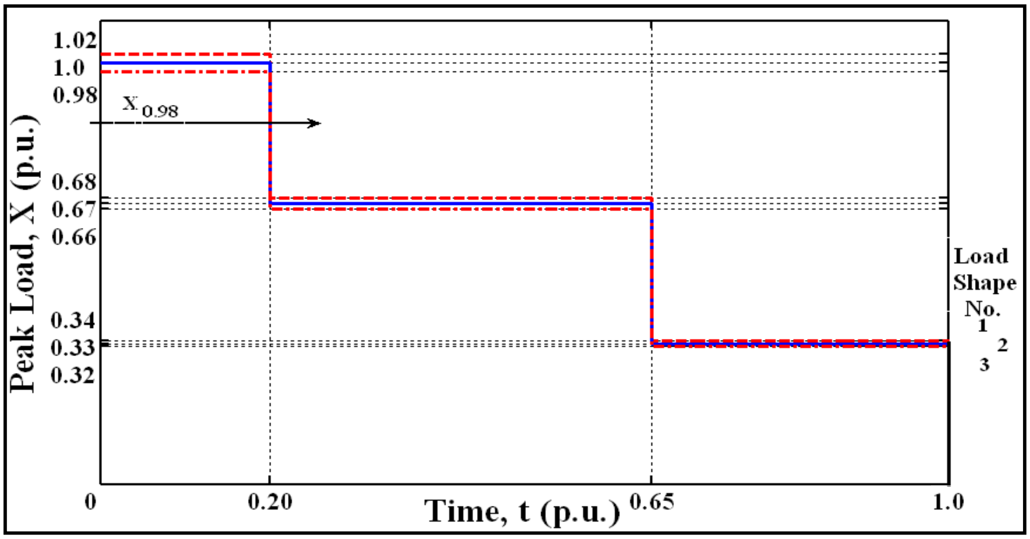


Figure 3.4 A Three-Step 2% Uncertainty Model

- The evaluation of each time segment in Figure 3.4 to determine time-duration values, t_{dsj}, is as follows:

For Segment 1 at the Peak Level of X_1 = 1.02 p.u.

$t_{ds1} = p_{-1} \times t_1 = 0.05 \qquad \mathit{for}\ 1.0 < X \le 1.02$

For Segment 2 at the Peak Level of X_2 = 1.0 p.u.

$t_{ds2} = p_{-1} \times t_1 + p_0 \times t_1 = 0.15 \qquad \mathit{for}\ 0.98 < X \le 1.0$

For Segment 3 at the Peak Level of X_3 = 0.98 p.u.

$t_{ds3} = p_{-1} \times t_1 + p_0 \times t_1 + p_{+1} \times t_1 = 0.20 \qquad \mathit{for}\ 0.683 < X \le 0.98$

For Segment 4 at the Peak Level of X_4 = 0.683 p.u.

$t_{ds4} = p_0 \times t_1 + p_{+1} \times t_1 + p_{-1} \times t_2 = 0.3125 \qquad \mathit{for}\ 0.67 < X \le 0.683$

For Segment 5 at the Peak Level of X_5 = 0.67 p.u.

$t_{ds5} = p_{+1} \times t_1 + p_{-1} \times t_2 + p_0 \times t_2 = 0.5375 \qquad for\ 0.657 < X \leq 0.67$

For Segment 6 at the Peak Level of X_6 = 0.657 p.u.

$t_{ds6} = p_{-1} \times t_2 + p_0 \times t_2 + p_{+1} \times t_2 = 0.65 \qquad for\ 0.337 < X \leq 0.657$

For Segment 7 at the Peak Level of X_7 = 0.337 p.u.

$t_{ds7} = p_0 \times t_2 + p_{+1} \times t_2 + p_{-1} \times t_3 = 0.7375 \qquad for\ 0.33 < X \leq 0.337$

For Segment 8 at the Peak Level of X_8 = 0.33 p.u.

$t_{ds8} = p_{+1} \times t_2 + p_0 \times t_3 + p_{-1} \times t_3 = 0.9125 \qquad for\ 0.323 < X \leq 0.33$

For Segment 9 at the Peak Level of X_9 = 0.323 p.u.

$t_{ds9} = p_{+1} \times t_3 + p_0 \times t_3 + p_{-1} \times t_3 = 1.0 \qquad for\ 0.0 < X \leq 0.323$

- The modified load duration curve assuming *2%* uncertainty in the forecast peak load is now composed of a group of conditional segments as shown in Figure 3.5.

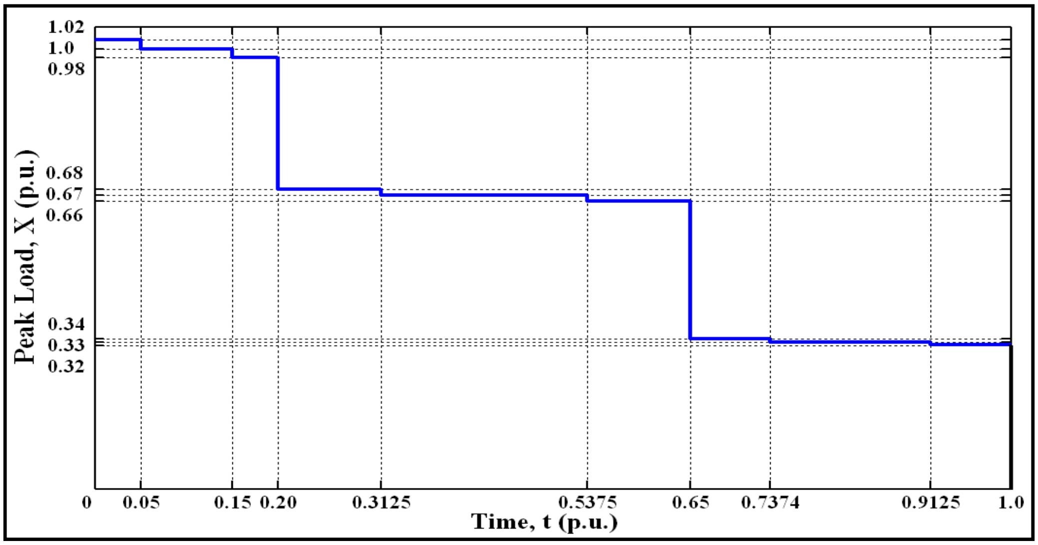


Figure 3.5 Modified Load Duration Curve with 2% Uncertainty

The modified load duration curve with *5%* uncertainty was obtained using the above steps. The two modified load duration curves obtained assuming uncertainties of *2%* and *5%* of the RBTS$_{\mathrm{BPO1}}$ forecast peak load were used as input data to MECORE to evaluate the system indices. Table 3.2 shows the system EDLC, ENLC and EENS indices not including uncertainty and including *2%* and *5%* uncertainty.

Table 3.2 Effects of Load Uncertainty Applying the LFMLC Method Annual System EDLC, ENLC and EENS Indices

LFU (%)	Peak Load Level: 185 MW		
	EDLC (hrs/yea)	ENLC (1/year)	EENS (MWh/year)
0	25.8251	2.0032	302.4484
2	25.8742	2.0089	302.5846
5	25.1805	2.0549	321.5991

The system reliability indices presented in Table 3.1 and 3.2 show that both methods can be used in the reliability assessment of composite systems and provide similar results. Both load bus and system reliability indices can be evaluated using the two approaches.

In the LFPD method, the load uncertainty is included in the reliability analysis by assuming that the forecast peak load is represented by a number of discrete class intervals. The reliability indices using the MECORE program are then calculated at the corresponding forecast loads and weighted by their probability of existence in the forecast load. The expected reliability indices including uncertainty are determined by summing the weighted values.

In the LFMLC approach, the load uncertainty is included in the reliability indices by creating a set of conditional load duration shapes. This group of conditional load duration curves is aggregated to produce a single modified load duration curve which includes uncertainty. The modified load duration curve is then used as input data to the MECORE program to produce a set of reliability indices. The main advantage of this method is the considerable saving in the computer time required to produce a set of reliability indices including uncertainty.

3.4 The LFMLC Approach Applied in Composite Systems

The comparison analysis between the two techniques described previously shows that the LFMLC approach is advantageous in saving computer time. This section illustrates the application of the LFMLC approach using the $\text{RBTS}_{\text{BPO1}}$ twenty-step load duration curve model. The procedure to obtain this modified load duration curve is summarized as follows:

Figure 3.6 shows the per-unit RBTS *20*-step load model. Each step-load value and the corresponding time-durations are shown in Appendix A, Table A.8. The forecast peak load is *185 MW*.

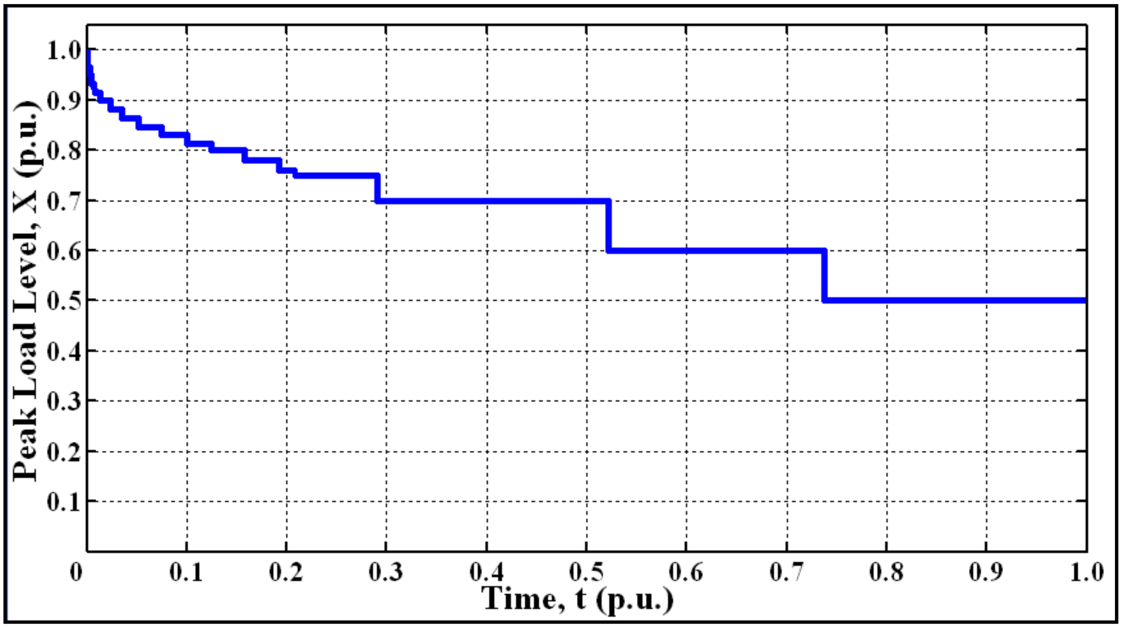


Figure 3.6 The Original RBTS *20* Step-Load Duration Curve Model

Uncertainty in the forecast peak load is assumed be represented by the seven-step distribution shown in Figure 3.1, where the class intervals in the distribution have probabilities of existence of $p_{-3} = 0.006$, $p_{-2} = 0.061$, $p_{-1} = 0.242$, $p_0 = 0.382$, $p_{+1} = 0.242$, $p_{+2} = 0.061$, and $p_{+3} = 0.006$. The standard deviation of this distribution is assumed to be *2%* of the forecast peak load. There are seven conditional load shapes as shown in Figure 3.7, each with a probability of existence.

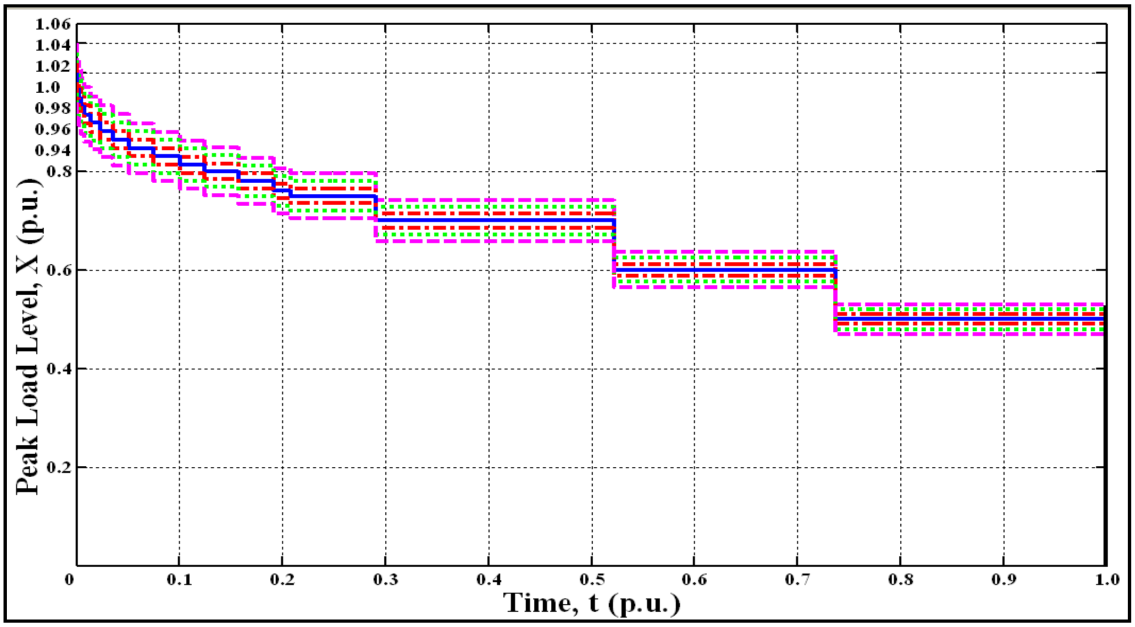


Figure 3.7 A 7-Step 2% Uncertainty Model

The modified load duration curve is shown in Figure 3.8. The evaluation of each time segment, t_{dsj}, in this figure was obtained using a computer program coded in MATLAB. The number of step load levels in Figure 3.8 is *140*. In order to demonstrate the process, the determination of seven of the *140* segments is illustrated in the following:

For Segment 1 at the Peak Level of X_1 = 1.06 p.u.

$$t_{ds1} = 1.36986314 \times 10^{-6} \qquad for\ 1.0494 < X \leq 1.06$$

For Segment 30 at the Peak Level of X_{30} = 0.9504 p.u.

$$t_{ds30} = 0.00407945 \qquad for\ 0.9490 < X \leq 0.9504$$

For Segment 60 at the Peak Level of X_{60} = 0.880 p.u.

$$t_{ds60} = 0.03695685 \qquad for\ 0.8798 < X \leq 0.8800$$

For Segment 90 at the Peak Level of X_{90} = 0.8112 p.u.

$$t_{ds90} = 0.127414041 \qquad for\ 0.8056 < X \leq 0.8112$$

For Segment 120 at the Peak Level of X_{120} = 0.7144 p.u.

$$t_{ds120} = 0.30532226 \qquad for\ 0.7140 < X \leq 0.7144$$

For Segment 130 at the Peak Level of X_{130} = 0.60 p.u.

$$t_{ds130} = 0.67084566 \qquad for\ 0.588 < X \leq 0.60$$

For Segment 140 at the Peak Level of X_{140} = 0.47 p.u.

$$t_{ds140} = 1.0 \qquad for\ 0.0 < X \leq 0.47$$

The modified load duration curve including *2%* uncertainty in the forecast peak load is now composed of a group of conditional segments as shown in Figure 3.8.

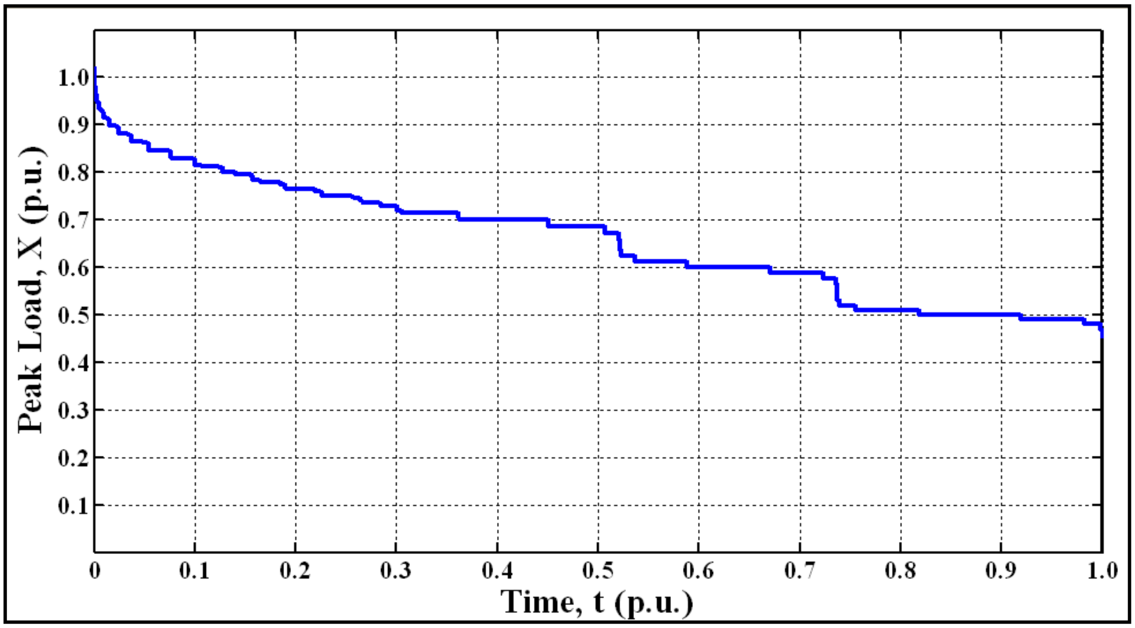


Figure 3.8 Modified Load Duration Curve with Uncertainty of 2%

The modified load duration curve shown above can be used as input data in a range of repetitive studies, with considerable savings in computer time. As noted in Chapter 2, the MECORE software can handle up to *100* step-load levels in a multi-step load duration curve model. This capability limits the application of the LFMLC approach in the reliability evaluation of composite systems. In order to use the modified load duration model as input data to MECORE, it is necessary to reduce the final model to one containing *100* or less step-load levels. This involves creating an approximate model which will reduce the accuracy associated with the analysis. This could be an area of further study. It was therefore decided to use the Load Forecast Probability

Distribution (LFPD) method in the subsequent load forecast uncertainty studies conducted on the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$.

3.5 The LFPD Approach Applied in Composite Systems

This section illustrates the application of the LFPD approach to examining the effects of load forecast uncertainty in the reliability assessment of a composite system. The adequacy of the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$ with load forecast uncertainty is evaluated assuming that the system forecast peak load is increased from *170 MW to 200 MW* in steps of *10 MW*. This range recognizes the reserve criterion of the largest unit. The *185 MW* original system peak load is also considered in this analysis. The annual *20*-step load duration curve used to compute both load bus and system indices is shown in Figure 3.6.

The uncertainty in each forecast peak load is assumed to be represented by the seven-step probability distribution shown in Figure 3.1. Two standard deviations of *2%* and *5%* of the forecast peak load are considered. In each study, the MECORE software was therefore run seven times to produce seven sets of reliability indices. Each individual set of indices were weighted by their probabilities of existence. The final system indices are expected values of a group of expected indices and were calculated using Equation 3.2.

The effects of load forecast uncertainty (LFU) for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$ are shown in Tables 3.3 to 3.5 and Tables 3.6 to 3.8, respectively. These tables show the annual load bus and system EDLC, ENLC and EENS indices as a function of the system peak load. The annual load bus and system PLC, ELC, EDNS and SI indices as a function of the system peak load for these two systems are shown in Appendix D, Tables D.1 to D4 and Tables D5 to D8, respectively.

Table 3.3 Effects of LFU on the RBTS$_{BPO1}$
Annual Load Bus and System EDLC (hrs/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.3504	0.8760	1.2264	2.2776	3.9420
	2	0.3839	0.9075	1.3130	2.3854	4.4080
	5	0.4765	1.1471	1.8054	2.7683	6.4992
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0005
5	0	0.0000	0.0000	0.0000	0.0000	0.0876
	2	0.0000	0.0000	0.0000	0.0005	0.0605
	5	0.0000	0.0005	0.0059	0.0271	0.0611
6	0	10.5120	10.5120	10.5120	10.5120	10.5996
	2	10.5120	10.5120	10.5125	10.5179	10.5943
	5	10.5125	10.5179	10.5184	10.5401	10.6129
System	0	10.8624	11.3004	11.7384	12.7896	14.4540
	2	10.8688	11.3860	11.8138	12.8703	14.9147
	5	10.9461	11.6203	12.2962	13.2798	17.0005

Table 3.4 Effects of LFU on the RBTS$_{BPO1}$
Annual Load Bus and System ENLC (1/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0253	0.0557	0.0787	0.1396	0.2380
	2	0.0274	0.0596	0.0847	0.1446	0.2613
	5	0.0322	0.0724	0.1114	0.1660	0.3522
4	0	0.0004	0.0006	0.0011	0.0013	0.0018
	2	0.0004	0.0007	0.0010	0.0013	0.0018
	5	0.0004	0.0008	0.0011	0.0013	0.0021
5	0	0.0048	0.0053	0.0055	0.0062	0.0076
	2	0.0048	0.0053	0.0056	0.0062	0.0078
	5	0.0048	0.0054	0.0058	0.0065	0.0082
6	0	1.1797	1.1808	1.1822	1.1832	1.1855
	2	1.1799	1.1809	1.1822	1.1832	1.1859
	5	1.1800	1.1813	1.1823	1.1836	1.1875
System	0	1.2034	1.2338	1.2568	1.3176	1.4160
	2	1.2054	1.2377	1.2628	1.3226	1.4393
	5	1.2103	1.2504	1.2894	1.3440	1.5302

Table 3.5 Effects of LFU on the $\text{RBTS}_{\text{BPO1}}$
Annual Load Bus and System EENS (MWh/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	3.0800	7.5090	12.5610	21.1640	45.9150
	2	3.2955	8.0009	13.3754	22.2361	48.7490
	5	4.1795	10.9396	17.9595	28.9517	69.3835
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	0.2320	0.2650	0.2910	0.3260	0.4150
	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2744	0.3057	0.3478	0.4753
6	0	126.8180	133.7570	137.9420	142.1640	149.2780
	2	126.8118	133.7616	137.9505	142.1719	149.2986
	5	126.4944	133.8809	137.9882	142.1283	149.7631
System	0	130.1384	141.5507	150.8225	163.6990	195.6910
	2	130.3486	142.0483	151.6495	164.7829	198.5585
	5	130.9188	145.1196	156.2897	171.4818	219.7299

Table 3.6 Effects of LFU on the $\text{MRBTS}_{\text{BPO1}}$
Annual Load Bus and System EDLC (hrs/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.3504	0.8760	1.2264	2.2776	3.9420
	2	0.3839	0.9074	1.3130	2.3853	4.4292
	5	0.4765	1.1471	1.8107	2.7683	6.4992
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0005
5	0	0.0000	0.0000	0.0000	0.0000	0.0876
	2	0.0000	0.0000	0.0000	0.0005	0.0605
	5	0.0000	0.0005	0.0059	0.0271	0.0611
6	0	0.0876	0.0876	0.0876	0.0876	0.0876
	2	0.0876	0.0876	0.0876	0.0876	0.1147
	5	0.0817	0.0876	0.0935	0.0940	0.1285
System	0	0.3504	0.8760	1.2264	2.3652	4.0296
	2	0.3844	0.9504	1.3554	2.4242	4.4691
	5	0.4770	1.1688	1.8329	2.8447	6.5756

Table 3.7 Effects of LFU on the MRBTS$_{BPO1}$
Annual Load Bus and System ENLC (1/year)

Bus	LFU (%)	System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0254	0.0561	0.0792	0.1405	0.2395
	2	0.0275	0.0599	0.0852	0.1455	0.2630
	5	0.0324	0.0728	0.1120	0.1671	0.3547
4	0	0.0004	0.0006	0.0011	0.0013	0.0018
	2	0.0004	0.0007	0.0010	0.0013	0.0018
	5	0.0004	0.0007	0.0011	0.0013	0.0020
5	0	0.0053	0.0057	0.0060	0.0066	0.0081
	2	0.0052	0.0057	0.0061	0.0066	0.0082
	5	0.0052	0.0058	0.0062	0.0069	0.0086
6	0	0.0104	0.0115	0.0128	0.0138	0.0162
	2	0.0105	0.0115	0.0128	0.0138	0.0165
	5	0.0106	0.0120	0.0130	0.0142	0.0182
System	0	0.0341	0.0647	0.0879	0.1492	0.2482
	2	0.0362	0.0686	0.0939	0.1542	0.2717
	5	0.0411	0.0815	0.1207	0.1757	0.3633

Table 3.8 Effects of LFU on the MRBTS$_{BPO1}$
Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	3.0810	7.5120	12.5660	21.1740	45.9400
	2	3.2962	8.0037	13.3809	22.2471	48.7764
	5	4.1806	10.9446	17.9683	28.9672	69.4287
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	0.2320	0.2650	0.2910	0.3260	0.4150
	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2743	0.3057	0.3478	0.4753
6	0	0.5310	0.6070	0.6740	0.7770	1.0280
	2	0.5333	0.6113	0.6827	0.7855	1.0406
	5	0.5396	0.6389	0.7202	0.8338	1.1809
System	0	3.8520	8.4029	13.5593	22.3228	47.4669
	2	4.0707	8.9008	14.3869	23.4074	50.3281
	5	4.9653	11.8820	19.0301	30.2032	71.1934

As seen in Tables 3.3 to 3.5 and Tables 3.6 to 3.8, the reliability indices shown for the $\text{RBTS}_{\text{BPO1}}$ and $\text{MRBTS}_{\text{BPO1}}$ increase as the uncertainty in the forecast load increases. As noted earlier, there are some small anomalies in the EDLC and ENLC indices, where the indices are constant or decrease slightly as the load forecast uncertainty increases. These are due to the discrete load steps used in the model, the nature of the index and the use of Monte Carlo simulation.

3.6 Summary

Predicting the energy required to satisfy customer demands is a continuous operational and planning task in an electric power utility. Methods to forecast future load are fundamental requirements in modern power systems. This chapter illustrates two techniques that can be used to include the effects of load forecast uncertainty in the reliability assessment of a composite system. These methods are designated as the Load Forecast Probability Distribution (LFPD) Method and the Load Forecast Modified Load Curve (LFMLC) Approach.

The LFPD method is a direct extension of the basic technique used to calculate the system reliability indices at a single load level. The load levels associated with the uncertainty distribution are used to calculate a group of reliability indices. These indices are then weighted and aggregated using the associated probabilities to produce a set of expected indices that include the uncertainty parameter.

The LFMLC method develops a modified load duration curve model that incorporates the load forecast uncertainty probability distribution. The application of the modified load model results in a set of reliability indices that directly includes the uncertainty in the load forecast.

The concept of using the load forecast uncertainty distribution to create a modified load duration curve is a useful approach which can be used to conduct a wide range of repetitive studies with considerable savings in computer time. This technique is particular useful in generating capacity adequacy assessment [1], but creates some difficulties when applied to the step-load model used in the MECORE program [6]. The two techniques are illustrated by an example using the $\text{RBTS}_{\text{BPO1}}$ with a simple load duration curve model. The EDLC, ENLC and EENS system indices were calculated by applying both techniques using the MECORE program. The comparison of the results obtained, shows that the two methods provide virtually identical system reliability indices. The basic advantage of the LFMLC approach is that it requires less computer time to produce practically the same reliability indices than that required using the LFPD method. This could be of great importance in large system analysis. The studies conducted in this research are based on a relatively small test system and the object is to examine the effects of load forecast uncertainty (LFU).

The modified load duration curve in Figure 3.8 is composed of *140* step-load levels. The MECORE software can handle up to *100* step-load levels in a multi-step load duration curve model. This capability limits the application of the LFMLC approach in the reliability evaluation of composite systems. In order to use the modified load duration model as input data to MECORE, it is necessary to reduce the final model to one containing *100* or less step-load levels. This involves creating an approximate model which will reduce the accuracy associated with the analysis. This could be an area of further study. It was therefore decided to use the Load Forecast Probability Distribution (LFPD) method in the subsequent load forecast uncertainty studies described in this thesis.

4. GENERATION EXPANSION ANALYSIS CONSIDERATING LOAD FORECAST UNCERTAINTY

4.1 Introduction

The demand for electrical energy varies on a continuous basis throughout the year. Electrical power systems continue to grow in size and complexity requiring a balance between the generation and consumption of electricity [36]. The nature of electricity is such that it cannot be easily and economically stored, particularly in a large grid, and must be produced and supplied at the same instant it is required [37]. Generation and transmission facilities are needed to supply the expected load profile and balance the demand/load cycle [36]. The lead time required to plan, design, construct and commission a new generation facility can be quite lengthy and varies with the type of facility, *i.e.* hydroelectric, thermoelectric, nuclear, wind turbine, and includes a wide range of environmental and regulatory considerations [1]. Generation expansion planning is a major task in the overall design of an adequate bulk electrical system. As new power generation is installed to meet the load demand, transmission system reinforcement or expansion must be considered to ensure that the available generation is transmitted to the customers. A transmission system reinforcement or expansion plan should include the effects of load forecast uncertainty (LFU) and the possible generation scenarios that could be considered in response to the uncertain demand for electricity [37-39]. Generation expansion analysis with load forecast uncertainty considerations involves long-term planning that includes the consideration of energy resources available in the future for electrical generation. It is therefore necessary to consider generation addition scenarios with a long time horizon. Such scenarios should recognize the uncertainty in the forecast load.

Different generation expansion scenarios must be considered and compared to determine an optimum expansion pattern for the system. This chapter describes the effects of load forecast uncertainty in generation expansion analysis. Generation expansion analysis is conducted on the test systems described earlier using three different scenarios. The first case considers the addition of one *20 MW* generating unit. The test systems in this case are designated as the $\text{RBTS}_{\text{BPO1-E1}}$ and the $\text{MRBTS}_{\text{BPO1-E1}}$. The second case examines the addition of two *20 MW* generating units and the two test systems are designated as the $\text{RBTS}_{\text{BPO1-E2}}$ and the $\text{MRBTS}_{\text{BPO1-E2}}$. The third case considers the addition of one *40 MW* generating unit and the test systems are designated as the $\text{RBTS}_{\text{BPO1-E3}}$ and the $\text{MRBTS}_{\text{BPO1-E3}}$. Each case considers the effects of adding the generation at either Bus 1, Bus 5 or Bus 6. Appendix E contains the results for similar studies when the load bus priority order is changed. The focus in this chapter is on the effects of LFU on the adequacy of the two systems with the various generation additions.

4.2 The $\text{RBTS}_{\text{BPO1}}$ Base Case Analysis Considering LFU

As stated earlier, a base case analysis can be performed to identify the least reliable load buses in a system and a factor analysis can be conducted to determine those load buses affected by generation and/or transmission deficiencies. The reliability at those load points with deficiencies can be improved by adding generation or transmission facilities. The studies and results in Chapter 3 (Section 3.5) are used in this section as the $\text{RBTS}_{\text{BPO1}}$ base case values including load forecast uncertainty. The studies assume that the forecast peak load has an inherent uncertainty that can be described by a normal probability distribution. The standard deviation of this distribution is assumed to be *2%* and *5%* of the forecast peak load. The variation in the individual load bus and system reliabilities as a function of the peak load is analyzed. The system peak load level is considered to increase from *170 MW* to *200 MW* in steps of *10 MW*. The original system peak load of *185 MW* is also incorporated in the analysis.

As noted earlier in Chapter 2, there is a wide range of indices that could be used to study the effects of load forecast uncertainty. From an application point of view, the most common reliability index in an assessment of a composite system is the EENS index which indicates the expected energy not supplied due to generation and/or transmission failures. The EENS index has therefore been selected in this research to study the impacts of load forecast uncertainty. The LFPD approach presented in Chapter 3 is used to evaluate the EENS index in all the subsequent studies in this thesis. The impact on the load point and system EENS due to load forecast uncertainty are shown in the form of percentage changes as the LFU standard deviation increases.

Table 4.1 shows the annual EENS load bus and system indices and Table 4.2 displays the EENS percentage change. Figures 2.4 and 2.5, respectively, show the EENS load bus and system indices not including uncertainty as a function of the system peak load. Figure 4.1 shows the system EENS as a function of the peak load including LFU.

Table 4.1 Effects of LFU on the RBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	3.0800	7.5090	12.5610	21.1640	45.9150
	2	3.2955	8.0009	13.3754	22.2361	48.7490
	5	4.1795	10.9396	17.9595	28.9517	69.3835
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	0.2320	0.2650	0.2910	0.3260	0.4150
	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2744	0.3057	0.3478	0.4753
6	0	126.8180	133.7570	137.9420	142.1640	149.2780
	2	126.8118	133.7616	137.9505	142.1719	149.2986
	5	126.4944	133.8809	137.9882	142.1283	149.7631
System	0	130.1384	141.5507	150.8225	163.6990	195.6910
	2	130.3486	142.0483	151.6495	164.7829	198.5585
	5	130.9188	145.1196	156.2897	171.4818	219.7299

It should be noted that the percentage change values are the ratios of the EENS with the specified LFU and the EENS with no LFU and can change significantly when the EENS with no LFU is a very small value.

Table 4.2 EENS Percentage Change (%) due to LFU for the RBTS$_{BPO1}$ Base Case Analysis

	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.0	6.6	6.5	5.1	6.2
	0	5	35.7	45.7	43.0	36.8	51.1
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	0.3	0.5	0.8	0.8	2.2
	0	5	1.2	3.5	5.1	6.7	14.5
6	0	2	0.0	0.0	0.0	0.0	0.0
	0	5	-0.3	0.1	0.0	0.0	0.3
System	0	2	0.2	0.4	0.5	0.7	1.5
	0	5	0.6	2.5	3.6	4.8	12.3

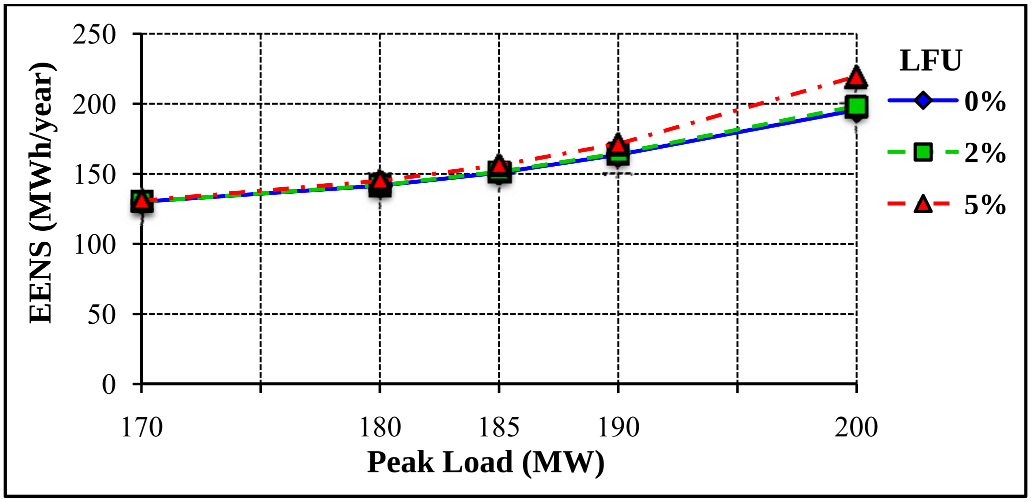


Figure 4.1 System EENS for the RBTS$_{BPO1}$ as a Function of the Peak Load Including LFU

Table 4.2 shows the percentage changes as uncertainty is included in the analysis. The percentage change values are evaluated in two steps, where the LFU changes from *0%* to *2%* and from *0%* to *5%*. The percentage change is a measure of the risk impact of LFU at a specific peak load. It can be seen that these values increase as the LFU increases. The largest values are at Bus 3. It can be seen from Table 4.2 that the risk impacts on the percentage changes in the EENS are different for different buses and for the system. These changes are a complex function of the system topology and parameters, and the system load curtailment philosophy.

The base case analysis performed on the RBTS$_{BPO1}$ shows that the least reliable load buses are Bus 3 and Bus 6. As noted earlier, a factor analysis can be used to identify the cause of the problems. In the following section, factor analysis as introduced in Chapter 2 is conducted to examine the EENS at Bus 3 and Bus 6 with LFU. The reliability indices calculated for the RBTS$_{BPO1}$ system show that the EENS increases as the uncertainty in the system peak load increases. Table 4.1 shows that the highest unreliability indices are at Bus 6 and that these increase only slightly with uncertainty. This is due to the radial transmission line that connects Bus 6 to the rest of the system.

The effects of LFU are most observable at Bus 3, where the EENS index increases not only as the system peak load increases but also as the LFU increases. Factor analysis can be used to identify if Bus 3 has generation and/or transmission deficiencies. Bus 3 has the lowest load curtailment priority order and Bus 6 has the second lowest priority order in the RBTS$_{BPO1}$. The system EENS shows small changes due to LFU at system peak load levels lower than *185 MW* and increases rapidly as the system peak load and the LFU increase.

4.2.1 Factor Analysis of the RBTS$_{BPO1}$ Base Case Considering LFU

The following factor analysis is focused on the reliability performance of the RBTS$_{BPO1}$ including uncertainty. Tables 4.3 to 4.5 show the EENS load bus and system indices considering generation failures only, transmission failures only and both generation and transmission failures, respectively. The effects on the EENS percentage change due to uncertainty are given in Tables 4.6 to 4.8.

Table 4.3 Effects of LFU on the RBTS$_{BPO1}$ Base Case Analysis
Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

		Generation Failures Only				
	LFU	System Peak Load Level (MW)				
Bus	(%)	170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020

Table 4.3 (Continued)

Bus	LFU (%)	Generation Failures Only				
		System Peak Load Level (MW)				
		170	180	185	190	200
3	0	2.8160	7.1450	12.0810	20.4650	44.1800
	2	3.0302	7.6245	12.8703	21.4771	46.8465
	5	3.8984	10.4660	17.2500	27.7892	66.0777
4	0	0.0010	0.0060	0.0110	0.0190	0.0440
	2	0.0017	0.0065	0.0117	0.0201	0.0466
	5	0.0026	0.0092	0.0163	0.0267	0.0653
5	0	0.0080	0.0210	0.0350	0.0580	0.1270
	2	0.0088	0.0222	0.0375	0.0608	0.1347
	5	0.0113	0.0302	0.0496	0.0792	0.1829
6	0	0.0280	0.0700	0.1130	0.1910	0.4010
	2	0.0301	0.0735	0.1212	0.1993	0.4150
	5	0.0380	0.0989	0.1573	0.2484	0.5552
System	0	2.8542	7.2421	12.2402	20.7340	44.7517
	2	3.0713	7.7267	13.0409	21.7577	47.4432
	5	3.9506	10.6046	17.4734	28.1444	66.8825

Table 4.4 Effects of LFU on the RBTS$_{\text{BPO1}}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

Bus	LFU (%)	Transmission Failures Only				
		System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.2280	0.2810	0.3270	0.4050	0.9610
	2	0.2286	0.2843	0.3351	0.4412	1.0869
	5	0.2316	0.3266	0.4494	0.7161	2.2508
4	0	0.0070	0.0130	0.0180	0.0250	0.0390
	2	0.0071	0.0132	0.0185	0.0256	0.0388
	5	0.0078	0.0150	0.0202	0.0265	0.0407
5	0	0.2230	0.2440	0.2560	0.2670	0.2870
	2	0.2232	0.2436	0.2557	0.2671	0.2881
	5	0.2232	0.2438	0.2556	0.2674	0.2903
6	0	126.7900	133.6870	137.8270	141.9700	148.8710
	2	126.7819	133.6872	137.8275	141.9696	148.8781
	5	126.4559	133.7812	137.8286	141.8763	149.2016
System	0	127.2476	134.2243	138.4281	142.6676	150.1575
	2	127.2403	134.2283	138.4371	142.7034	150.2917
	5	126.9184	134.3662	138.5537	142.8867	151.7831

Table 4.5 Effects of LFU on the RBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

		Generation and Transmission Failures				
	LFU	System Peak Load Level (MW)				
Bus	(%)	170	180	185	190	200
	0	0.0000	0.0000	0.0000	0.0000	0.0010
2	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
	0	3.0800	7.5090	12.5610	21.1640	45.9150
3	2	3.2955	8.0009	13.3754	22.2361	48.7490
	5	4.1795	10.9396	17.9595	28.9517	69.3835
	0	0.0080	0.0190	0.0290	0.0450	0.0830
4	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
	0	0.2320	0.2650	0.2910	0.3260	0.4150
5	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2744	0.3057	0.3478	0.4753
	0	126.8180	133.7570	137.9420	142.1640	149.2780
6	2	126.8118	133.7616	137.9505	142.1719	149.2986
	5	126.4944	133.8809	137.9882	142.1283	149.7631
	0	130.1384	141.5507	150.8225	163.6990	195.6910
System	2	130.3486	142.0483	151.6495	164.7829	198.5585
	5	130.9188	145.1196	156.2897	171.4818	219.7299

Table 4.6 EENS Percentage Change (%) due to LFU for the RBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

			Generation Failures Only				
	LFU (%)		System Peak Load Level (MW)				
Bus	From	To	170	180	185	190	200
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.6	6.7	6.5	4.9	6.0
	0	5	38.4	46.5	42.8	35.8	49.6
4	0	2	70.0	8.3	6.4	5.8	5.9
	0	5	160.0	53.3	48.2	40.5	48.4
5	0	2	10.0	5.7	7.1	4.8	6.1
	0	5	41.3	43.8	41.7	36.6	44.0
6	0	2	7.5	5.0	7.3	4.3	3.5
	0	5	35.7	41.3	39.2	30.1	38.5
System	0	2	7.6	6.7	6.5	4.9	6.0
	0	5	38.4	46.4	42.8	35.7	49.5

Table 4.7 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

			Transmission Failures Only				
	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	–
	0	5	–	–	–	–	–
3	0	2	0.3	1.2	2.5	8.9	13.1
	0	5	1.6	16.2	37.4	76.8	134.2
4	0	2	1.4	1.5	2.8	2.4	-0.5
	0	5	11.4	15.4	12.2	6.0	4.4
5	0	2	0.1	-0.2	-0.1	0.0	0.4
	0	5	0.1	-0.1	-0.2	0.1	1.1
6	0	2	0.0	0.0	0.0	0.0	0.0
	0	5	-0.3	0.1	0.0	-0.1	0.2
System	0	2	0.0	0.0	0.0	0.0	0.1
	0	5	-0.3	0.1	0.1	0.2	1.1

Table 4.8 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

			Generation and Transmission Failures				
	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.0	6.6	6.5	5.1	6.2
	0	5	35.7	45.7	43.0	36.8	51.1
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	0.3	0.5	0.8	0.8	2.2
	0	5	1.2	3.5	5.1	6.7	14.5
6	0	2	0.0	0.0	0.0	0.0	0.0
	0	5	-0.3	0.1	0.0	0.0	0.3
System	0	2	0.2	0.4	0.5	0.7	1.5
	0	5	0.6	2.5	3.6	4.8	12.3

Table 4.3 presents the load point and system EENS values attributable to generation failures. It can be seen that the Bus 3 values are the highest load point indices and are more strongly affected by LFU. The Bus 6 values are only slightly affected. Table 4.4 show the load point and system EENS attributable to transmission failures. In this case, the Bus 3 values are relatively small and are impacted by LFU, while the Bus 6 values are high and are virtually unaffected by LFU. The relative changes in the risk

index are shown in Tables 4.6 and 4.7. The results indicate that in general, load points which are associated with generation deficiencies are more influenced by LFU while load points which are associated with transmission deficiencies are less influenced by LFU. As noted earlier, the load point risk impacts are related to the system topology and parameters and the system load curtailment philosophy. The overall indices attributable to both generation and transmission failures are illustrated in Tables 4.5 and are shown earlier in Table 3.5. The percentage changes due to LFU are shown in Table 4.8 which illustrates that the relative impact of LFU is different at each load point and for the overall system.

4.3 The MRBTS$_{BPO1}$ Base Case Analysis Considering LFU

Table 4.9 shows the EENS load bus and system indices with and without uncertainty for the MRBTS$_{BPO1}$. Table 4.10 shows the EENS percentage changes due to uncertainty. Figure 4.2 shows the system EENS as a function of the peak load including LFU.

Table 4.9 Effects of LFU on the MRBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	3.0810	7.5120	12.5660	21.174	45.9400
	2	3.2962	8.0037	13.3809	22.2471	48.7764
	5	4.1806	10.9446	17.9683	28.9672	69.4287
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	0.2320	0.2650	0.2910	0.3260	0.4150
	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2743	0.3057	0.3478	0.4753
6	0	0.5310	0.6070	0.6740	0.7770	1.0280
	2	0.5333	0.6113	0.6827	0.7855	1.0406
	5	0.5396	0.6389	0.7202	0.8338	1.1809
System	0	3.8520	8.4029	13.5593	22.3228	47.4669
	2	4.0707	8.9008	14.3869	23.4074	50.3281
	5	4.9653	11.8820	19.0301	30.2032	71.1934

Table 4.10 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1}$ Base Case Analysis

	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.0	6.5	6.5	5.1	6.2
	0	5	35.7	45.7	43.0	36.8	51.1
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	0.3	0.5	0.8	0.8	2.2
	0	5	1.2	3.5	5.1	6.7	14.5
6	0	2	0.4	0.7	1.3	1.1	1.2
	0	5	1.6	5.3	6.9	7.3	14.9
System	0	2	5.7	5.9	6.1	4.9	6.0
	0	5	28.9	41.4	40.3	35.3	50.0

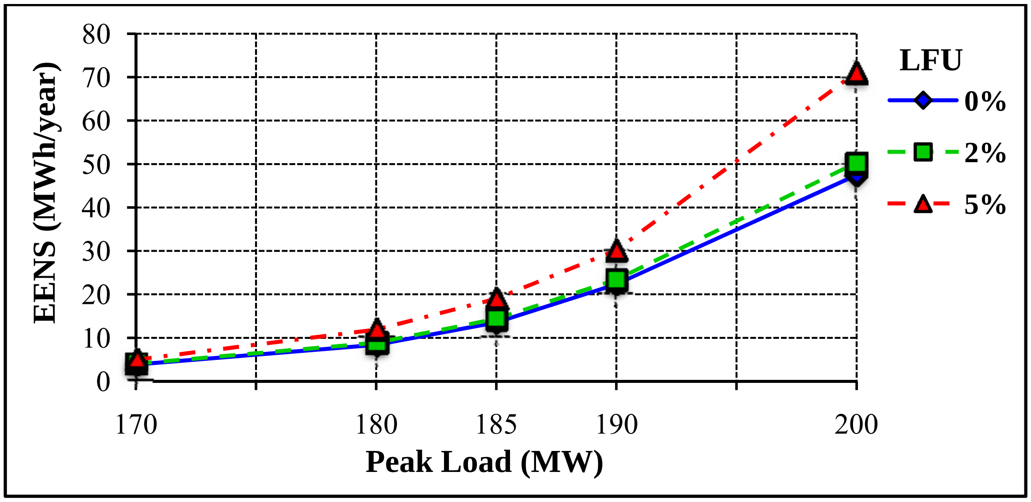


Figure 4.2 System EENS for the MRBTS$_{BPO1}$ as a Function of the Peak Load Including LFU

The addition of line 10 in the MRBTS$_{BPO1}$ puts Bus 6 in a similar class to other buses in the system and it cannot be considered to be transmission deficient. It is now a highly reliable bus and its percentage changes are similar to those at Bus 5. Bus 3 has the largest percentage change and receives the bulk of generation deficiencies due to the load curtailment philosophy.

4.3.1 Factor Analysis of the MRBTS$_{BPO1}$ Base Case Considering LFU

Tables 4.11 to 4.13 show the EENS load bus and system index considering generation failures only, transmission failures only and both generation and transmission failures, respectively. The effects in the EENS percentage change due to uncertainty are given in Tables 4.14 to 4.16.

Table 4.11 Effects of LFU on the MRBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

Bus	LFU (%)	Generation Failures Only				
		System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	2.8160	7.1450	12.0810	20.4650	44.1800
	2	3.0302	7.6245	12.8703	21.4771	46.8465
	5	3.8984	10.4660	17.2500	27.7892	66.0776
4	0	0.0010	0.0060	0.0110	0.0190	0.0440
	2	0.0017	0.0065	0.0117	0.0201	0.0466
	5	0.0026	0.0092	0.0162	0.0267	0.0653
5	0	0.0080	0.0210	0.0350	0.0580	0.1270
	2	0.0088	0.0222	0.0375	0.0608	0.1347
	5	0.0113	0.0302	0.0496	0.0792	0.1829
6	0	0.0280	0.0700	0.1130	0.1910	0.4010
	2	0.0301	0.0735	0.1212	0.1993	0.4150
	5	0.0380	0.0989	0.1573	0.2484	0.5552
System	0	2.8542	7.2421	12.2402	20.7340	44.7517
	2	3.0713	7.7267	13.0409	21.7577	47.4432
	5	3.9506	10.6046	17.4734	28.1444	66.8825

Table 4.12 Effects of LFU on the MRBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

Bus	LFU (%)	Transmission Failures Only				
		System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000

Table 4.12 (Continued)

Bus	LFU (%)	Transmission Failures Only				
		System Peak Load Level (MW)				
		170	180	185	190	200
3	0	0.2280	0.2810	0.3270	0.4050	0.9610
	2	0.2285	0.2843	0.3351	0.4412	1.0871
	5	0.2316	0.3266	0.4495	0.7162	2.2514
4	0	0.0070	0.0130	0.0180	0.0250	0.0390
	2	0.0071	0.0132	0.0185	0.0256	0.0388
	5	0.0078	0.0150	0.0202	0.0265	0.0407
5	0	0.2230	0.2440	0.2560	0.2670	0.2870
	2	0.2232	0.2436	0.2557	0.2671	0.2881
	5	0.2232	0.2438	0.2556	0.2674	0.2903
6	0	0.5030	0.5360	0.5590	0.5830	0.6210
	2	0.5029	0.5366	0.5592	0.5829	0.6201
	5	0.5014	0.5386	0.5603	0.5816	0.6193
System	0	0.9608	1.0741	1.1598	1.2813	1.9079
	2	0.9618	1.0781	1.1689	1.3171	2.0339
	5	0.9638	1.1240	1.2855	1.5925	3.2019

Table 4.13 Effects of LFU on the MRBTS$_{BPO1}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year) (Factor Analysis)

Bus	LFU (%)	Generation and Transmission Evaluations				
		System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	3.0810	7.5120	12.5660	21.174	45.9400
	2	3.2962	8.0037	13.3809	22.2471	48.7764
	5	4.1806	10.9446	17.9683	28.9672	69.4287
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	0.2320	0.2650	0.2910	0.3260	0.4150
	2	0.2326	0.2664	0.2934	0.3286	0.4242
	5	0.2348	0.2743	0.3057	0.3478	0.4753
6	0	0.5310	0.6070	0.6740	0.7770	1.0280
	2	0.5333	0.6113	0.6827	0.7855	1.0406
	5	0.5396	0.6389	0.7202	0.8338	1.1809
System	0	3.8520	8.4029	13.5593	22.3228	47.4669
	2	4.0707	8.9008	14.3869	23.4074	50.3281
	5	4.9653	11.8820	19.0301	30.2032	71.1934

Table 4.14 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

Bus	LFU (%)		Generation Failures Only				
			System Peak Load Level (MW)				
	From	To	170	180	185	190	200
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.6	6.7	6.5	4.9	6.0
	0	5	38.4	46.5	42.8	35.8	49.6
4	0	2	70.0	8.3	6.4	5.8	5.9
	0	5	160.0	53.3	47.3	40.5	48.4
5	0	2	10.0	5.7	7.1	4.8	6.1
	0	5	41.3	43.8	41.7	36.6	44.0
6	0	2	7.5	5.0	7.3	4.3	3.5
	0	5	35.7	41.3	39.2	30.1	38.5
System	0	2	7.6	6.7	6.5	4.9	6.0
	0	5	38.4	46.4	42.8	35.7	49.5

Table 4.15 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

Bus	LFU (%)		Transmission Failures Only				
			System Peak Load Level (MW)				
	From	To	170	180	185	190	200
2	0	2	–	–	–	–	–
	0	5	–	–	–	–	–
3	0	2	0.2	1.2	2.5	8.9	13.1
	0	5	1.6	16.2	37.5	76.8	134.3
4	0	2	1.4	1.5	2.8	2.4	-0.5
	0	5	11.4	15.4	12.2	6.0	4.4
5	0	2	0.1	-0.2	-0.1	0.0	0.4
	0	5	0.1	-0.1	-0.2	0.1	1.1
6	0	2	0.0	0.1	0.0	0.0	-0.1
	0	5	-0.3	0.5	0.2	-0.2	-0.3
System	0	2	0.1	0.4	0.8	2.8	6.6
	0	5	0.3	4.6	10.8	24.3	67.8

Table 4.16 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1}$ Base Case Analysis (Factor Analysis)

Bus	LFU (%)		Generation and Transmission Evaluations				
			System Peak Load Level (MW)				
	From	To	170	180	185	190	200
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	7.0	6.5	6.5	5.1	6.2
	0	5	35.7	45.7	43.0	36.8	51.1
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	0.3	0.5	0.8	0.8	2.2
	0	5	1.2	3.5	5.1	6.7	14.5
6	0	2	0.4	0.7	1.3	1.1	1.2
	0	5	1.6	5.3	6.9	7.3	14.9
System	0	2	5.7	5.9	6.1	4.9	6.0
	0	5	28.9	41.4	40.3	35.3	50.0

Table 4.11 shows that generation failures dictates the EENS at Bus 3 and for the system, and have relatively little effect at the other buses. The percentage changes shown in Table 4.14 due to LFU are similar at all the load points. Table 4.12 shows that the effects on LFU in the indices at Bus 4, Bus 5 and Bus 6 are relatively minor due to the transmission topology.

4.4 The RBTS$_{BPO2}$ Base Case Analysis Considering LFU

Table 4.17 shows the effects of changing the load bus priority order considering load forecast uncertainty. Table 4.18 shows the percentage change in the EENS due to LFU.

Table 4.17 Effects of LFU on the RBTS$_{BPO2}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020

Table 4.17 (Continued)

	LFU	System Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
3	0	0.6230	1.2760	2.0360	3.3410	7.8960
	2	0.6489	1.3574	2.1660	3.5716	8.4288
	5	0.7667	1.8452	3.0121	4.9704	12.7445
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	2.0050	4.8280	7.9730	13.2380	27.3670
	2	2.1426	5.1226	8.4574	13.8064	29.0805
	5	2.7009	6.8514	11.0795	17.5476	41.1675
6	0	127.5020	135.4280	140.7850	147.0750	160.3450
	2	127.5487	135.5490	140.9961	147.3590	160.9631
	5	127.4408	136.3992	142.1620	148.9098	165.7104
System	0	130.1384	141.5507	150.8225	163.6990	195.6912
	2	130.3486	142.0483	151.6495	164.7829	198.5587
	5	130.9188	145.1196	156.2897	171.4819	219.7303

Table 4.18 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO2}$ Base Case Analysis

	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	4.2	6.4	6.4	6.9	6.7
	0	5	23.1	44.6	47.9	48.8	61.4
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	6.9	6.1	6.1	4.3	6.3
	0	5	34.7	41.9	39.0	32.6	50.4
6	0	2	0.0	0.1	0.1	0.2	0.4
	0	5	0.0	0.7	1.0	1.2	3.3
System	0	2	0.2	0.4	0.5	0.7	1.5
	0	5	0.6	2.5	3.6	4.8	12.3

It can be seen from Table 4.17 that the change in the load curtailment philosophy has a considerable effect on the individual load bus indices. In the RBTS$_{BPO1}$, Bus 3 and Bus 6 are the least reliable buses. In the RBTS$_{BPO2}$, Bus 5 has the lowest priority order and Bus 3 has the third lowest priority order. Table 4.17 shows that the reliability indices at Bus 3 are considerable lower than those for the RBTS$_{BPO1}$. The load bus indices at Bus 5 are much higher in the $\text{RBTS}_{\text{BPO2}}$ and increase rapidly as the system peak load level increases. The reliability indices calculated at Bus 6 are slightly higher than in the $\text{RBTS}_{\text{BPO1}}$. The peak load at Bus 5 is *20 MW* and this may not be large enough to accommodate all the required curtailments due to generation and transmission outages. The results show that some of these events may result in curtailments at Bus 3 and Bus 6. Table 4.17 also shows that due to this condition, the LFU makes a distinct contribution to the EENS values at Bus 3 and Bus 6 in addition to that at Bus 5. Factor analysis could be used to determine the contributing factors in the $\text{RBTS}_{\text{BPO2}}$.

4.5 The $\text{MRBTS}_{\text{BPO2}}$ Base Case Analysis Considering LFU

Tables 4.19 and 4.20 show the effects of changing the load bus priority order considering load forecast uncertainty. Table 4.20 shows the percentage changes in the EENS due to LFU.

Table 4.19 Effects of LFU on the $\text{MRBTS}_{\text{BPO2}}$ Base Case Analysis Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	System Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0010
	2	0.0000	0.0000	0.0000	0.0001	0.0010
	5	0.0000	0.0001	0.0002	0.0005	0.0020
3	0	0.6230	1.2780	2.0390	3.3460	7.9060
	2	0.6489	1.3591	2.1688	3.5764	8.4389
	5	0.7672	1.8475	3.0158	4.9762	12.7568
4	0	0.0080	0.0190	0.0290	0.0450	0.0830
	2	0.0088	0.0197	0.0304	0.0461	0.0855
	5	0.0102	0.0241	0.0364	0.0539	0.1064
5	0	2.0060	4.8290	7.9750	13.2430	27.3790
	2	2.1430	5.1239	8.4596	13.8116	29.0940
	5	2.7017	6.8535	11.0837	17.5555	41.1933
6	0	1.2150	2.2780	3.5170	5.6890	12.0990
	2	1.2702	2.3988	3.7284	5.9736	12.7091
	5	1.4859	3.1574	4.8947	7.6175	17.1359
System	0	3.8520	8.4029	13.5593	22.3228	47.4671
	2	4.0707	8.9008	14.3869	23.4074	50.3283
	5	4.9653	11.8820	19.0301	30.2033	71.1938

Table 4.20 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO2}$ Base Case Analysis

	LFU (%)		System Peak Load Level (MW)				
Bus	**From**	**To**	**170**	**180**	**185**	**190**	**200**
2	0	2	–	–	–	–	0.0
	0	5	–	–	–	–	100.0
3	0	2	4.2	6.3	6.4	6.9	6.7
	0	5	23.1	44.6	47.9	48.7	61.4
4	0	2	10.0	3.7	4.8	2.4	3.0
	0	5	27.5	26.8	25.5	19.8	28.2
5	0	2	6.8	6.1	6.1	4.3	6.3
	0	5	34.7	41.9	39.0	32.6	50.5
6	0	2	4.5	5.3	6.0	5.0	5.0
	0	5	22.3	38.6	39.2	33.9	41.6
System	0	2	5.7	5.9	6.1	4.9	6.0
	0	5	28.9	41.4	40.3	35.3	50.0

Table 4.19 shows that Bus 5 has the highest EENS value followed by those at Bus 3 and Bus 6. These values are dominated by generation deficiencies and therefore the EENS values are highly influence by the LFU. Factor analysis could be used to determine the contributions to these indices.

4.6 Generation Expansion Analysis for the RBTS$_{BPO1}$ and MRBTS$_{BPO1}$ Considering LFU

As noted earlier, the time period required to expand a system by adding generation can be quite extensive, *e.g.* from 2 to 10 years depending on the type of unit, regulatory process and environmental requirements. It is therefore necessary to evaluate the system requirements considerably in advance of the actual unit-in-service date [1]. This section illustrates the concept of generation expansion analysis incorporating LFU. Base case studies and factor analysis have been performed on the two systems to identify their least reliable buses and the causes of problems. In the case of the RBTS$_{BPO1}$, it was concluded that its least reliable load buses are Bus 3 and Bus 6. The reliability indices using factor analysis showed that generation outages are dominant at Bus 3 and transmission outages are dominant at Bus 6. The addition of a transmission line between Bus 5 and Bus 6 was incorporated as a remedial modification to improve the reliability at Bus 6. The system with this modification was designated as the $\mathrm{MRBTS}_{\mathrm{BPO1}}$.

In the $\mathrm{MRBTS}_{\mathrm{BPO1}}$, the base cases analysis showed that Bus 3 is the least reliable load bus and the factor analysis concluded that generation outages make a larger contribution to the EENS than do transmission deficiencies. It is assumed that three generation expansion scenarios have been proposed as shown in Table 4.21. Three cases considering different generation connection points are included in each scenario. The object in this analysis is not to determine the best scenario but to investigate the effects of LFU on generation additions at different points in the system.

Table 4.21 Generation Expansion Analysis for the $\mathbf{RBTS}_{\mathbf{BPO1}}$ and $\mathbf{MRBTS}_{\mathbf{BPO1}}$

Generation Expansion	Addition Units × (MW)	Designated Systems		Case Analysis	Added at Bus
E-1	1 × 20	$\mathbf{RBTS}_{\mathbf{BPO1\text{-}E1}}$	$\mathbf{MRBTS}_{\mathbf{BPO1\text{-}E1}}$	Case 1	1
				Case 2	5
				Case 3	6
E-2	2 × 20	$\mathbf{RBTS}_{\mathbf{BPO1\text{-}E2}}$	$\mathbf{MRBTS}_{\mathbf{BPO1\text{-}E2}}$	Case 1	1
				Case 2	5
				Case 3	6
E-3	1 × 40	$\mathbf{RBTS}_{\mathbf{BPO1\text{-}E3}}$	$\mathbf{MRBTS}_{\mathbf{BPO1\text{-}E3}}$	Case 1	1
				Case 2	5
				Case 3	6

In the generation expansion scenarios shown in Table 4.21, the designated generation is added at either Bus 1, Bus 5 or Bus 6 of the $\mathrm{RBTS}_{\mathrm{BPO1}}$ and $\mathrm{MRBTS}_{\mathrm{BPO1}}$. The *20 MW* and *40 MW* generating units are assumed to have the reliability data given in Table 4.22 [40, 29], respectively.

Table 4.22 Generation Unit Rating and Reliability Data

Generating Unit	Rating (MW)	Failure Rate (occ/year)	Repair Time (hrs)	Failure Prob.
1	20.0	20.0	23.0	0.05
2	40.0	6.0	45.0	0.03

It is assumed that the system peak load level for the $\text{RBTS}_{\text{BPO1-E1}}$ and $\text{MRBTS}_{\text{BPO1-E1}}$ increases from *190 MW* to *220 MW* in steps of *10 MW*. In the case of the $\text{RBTS}_{\text{BPO1-E2}}$, $\text{MRBTS}_{\text{BPO1-E2}}$, $\text{RBTS}_{\text{BPO1-E3}}$ and $\text{MRBTS}_{\text{BPO1-E3}}$, the system peak level was increased from *210 MW* to *240 MW* in steps of *10 MW*. The load ranges recognize the largest unit reserve criterion. The same generation expansion analysis described in this section was conducted on the $\text{RBTS}_{\text{BPO2}}$ and $\text{MRBTS}_{\text{BPO2}}$ and is presented in Appendix E.

4.6.1 $\text{RBTS}_{\text{BPO1-E1}}$ Generation Expansion 1 Case Analysis

The addition of a *20 MW* generating unit at three different buses is examined as a function of the system peak load considering *2%* and *5%* uncertainty of the forecast peak load. Tables 4.23, 4.25 and 4.27 show the effects of LFU as generation is added to the $\text{RBTS}_{\text{BPO1-E1}}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case addition are given in Tables 4.24, 4.26 and 4.28, respectively.

Table 4.23 Effects of LFU on the $\text{RBTS}_{\text{BPO1-E1}}$: Case 1 Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	(%)	190	200	210	220
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0006
3	0	3.2250	8.2450	25.2010	58.2190
	2	3.4739	8.9716	25.9059	62.1105
	5	5.1362	14.4053	36.9100	88.7884
4	0	0.0010	0.0030	0.0110	0.0250
	2	0.0008	0.0035	0.0110	0.0268
	5	0.0018	0.0059	0.0156	0.0366
5	0	0.1810	0.1990	0.2330	0.2810
	2	0.1818	0.1997	0.2325	0.2853
	5	0.1841	0.2067	0.2447	0.3148
6	0	131.2210	137.6180	145.3330	151.8400
	2	131.2224	137.6280	144.9418	151.8550
	5	131.1443	137.9498	144.9869	151.9709
System	0	134.6280	146.0651	170.7787	210.3651
	2	134.8790	146.8028	171.0919	214.2780
	5	136.4663	152.5679	182.1576	241.1115

Table 4.24 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO1-E1}}$: Case 1

			1 × 20 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.7	8.8	2.8	6.7
	0	5	59.3	74.7	46.5	52.5
4	0	2	-20.0	16.7	0.0	7.2
	0	5	80.0	96.7	41.8	46.4
5	0	2	0.4	0.4	-0.2	1.5
	0	5	1.7	3.9	5.0	12.0
6	0	2	0.0	0.0	-0.3	0.0
	0	5	-0.1	0.2	-0.2	0.1
System	0	2	0.2	0.5	0.2	1.9
	0	5	1.4	4.5	6.7	14.6

Table 4.25 Effects of LFU on the RBTS$_{\text{BPO1-E1}}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 5			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	3.1180	7.4400	21.2080	47.0500
	2	3.3196	8.0363	21.6623	50.1113
	5	4.6519	12.2723	30.3475	72.5648
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	0.0260	0.0410	0.0730	0.1220
	2	0.0262	0.0417	0.0730	0.1265
	5	0.0287	0.0492	0.0863	0.1591
6	0	131.1070	137.5030	145.2210	151.7370
	2	131.1080	137.5133	144.8303	151.7538
	5	131.0309	137.8370	144.8787	151.8726
System	0	134.2501	144.9852	166.5083	198.9276
	2	134.4536	145.5931	166.5723	202.0116
	5	135.7118	150.1617	175.3236	224.6267

**Table 4.26 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO1-E1}$: Case 2**

			1 × 20 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	6.5	8.0	2.1	6.5
	0	5	49.2	65.0	43.1	54.2
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	0.8	1.7	0.0	3.7
	0	5	10.4	20.0	18.2	30.4
6	0	2	0.0	0.0	-0.3	0.0
	0	5	-0.1	0.2	-0.2	0.1
System	0	2	0.2	0.4	0.0	1.6
	0	5	1.1	3.6	5.3	12.9

**Table 4.27 Effects of LFU on the RBTS$_{BPO1-E1}$: Case 3
Annual Load Bus and System EENS (MWh/year)**

		1 × 20 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
	0	0.0000	0.0000	0.0000	0.0000
2	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
	0	3.1210	7.4490	21.2320	47.0980
3	2	3.3231	8.0461	21.6865	50.1614
	5	4.6570	12.2858	30.3783	72.6295
	0	0.0000	0.0010	0.0060	0.0180
4	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
	0	0.0260	0.0410	0.0730	0.1220
5	2	0.0262	0.0417	0.0730	0.1265
	5	0.0287	0.0492	0.0863	0.1592
	0	7.6700	8.1080	8.8150	9.7450
6	2	7.6744	8.1198	8.8041	9.8029
	5	7.6950	8.2286	8.9849	10.1492
	0	10.8176	15.5996	30.1262	56.9844
System	2	11.0239	16.2093	30.5706	60.1111
	5	12.3816	20.5674	39.4609	82.9681

Table 4.28 EENS Percentage Change (%)
due to LFU for the RBTS$_{\mathbf{BPO1\text{-}E1}}$: Case 3

			1 × 20 MW Generating Unit Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	6.5	8.0	2.1	6.5
	0	5	49.2	64.9	43.1	54.2
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	0.8	1.7	0.0	3.7
	0	5	10.4	20.0	18.2	30.5
6	0	2	0.1	0.1	-0.1	0.6
	0	5	0.3	1.5	1.9	4.1
System	0	2	1.9	3.9	1.5	5.5
	0	5	14.5	31.8	31.0	45.6

Table 4.23 shows the EENS values for Case 1 in which the *20 MW* unit is added at Bus 1. The effects of LFU as shown in Table 4.24 are similar in form to those noted for the base case. The injection of *20 MW* of generation at Bus 5 in Case 2 results in a general decrease in the bus and the system EENS as shown in Table 4.25. The EENS at Bus 6 is basically unchanged due to the radial supply. In both cases, the LFU has considerable influence at Bus 3 and on the system index and relatively little influence at the other buses.

The percentage change at Bus 3 due to LFU as shown in Table 4.26, is very similar to that in Case 1. The addition of 20 *MW* at Bus 6 in Case 3 has a considerable affect on the system and Bus 3 EENS as shown in Table 4.27. The Bus 3 values shown in Table 4.27 for Case 3 are very similar to those in Table 4.25 for Case 2. The percentage changes in the EENS at Bus 3 due to LFU are basically the same for all the three cases.

The addition of the *20 MW* unit at Bus 6 in Case 3, tends to compensate for the transmission deficiency that previously existed at this load point. The percentage changes at Bus 6 due to LFU are observable but very small in this case. The EENS values for the three cases show that the system reliability improvement with the addition of *20 MW* is greater when the generating unit is added in the southern portion of the system (Cases 2 and 3). This indicates that the system is becoming transmission deficient in regard to north-south power transfer. Factor analysis could be used to further study these conditions.

4.6.2 MRBTS$_{BPO1\text{-}E1}$ Generation Expansion 1 Case Analysis

Tables 4.29, 4.31 and 4.33 show the effects of LFU as generation is added to the MRBTS$_{BPO1\text{-}E1}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables 4.30, 4.32 and 4.34, respectively.

Table 4.29 Effects of LFU on the MRBTS$_{BPO1\text{-}E1}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 1			
	LFU	**System Peak Load Level (MW)**			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0006
3	0	3.2280	8.2530	25.2270	58.2780
	2	3.4771	8.9804	25.9321	62.1737
	5	5.1412	14.4198	36.9475	88.8788
4	0	0.0010	0.0030	0.0110	0.0250
	2	0.0008	0.0035	0.0110	0.0268
	5	0.0018	0.0059	0.0156	0.0366
5	0	0.1810	0.1990	0.2330	0.2810
	2	0.1818	0.1997	0.2325	0.2853
	5	0.1841	0.2067	0.2447	0.3148
6	0	0.4960	0.5470	0.6480	0.8090
	2	0.4975	0.5497	0.6486	0.8240
	5	0.5043	0.5721	0.6938	0.9398
System	0	3.9062	9.0027	26.1186	59.3933
	2	4.1574	9.7335	26.8248	63.3101
	5	5.8315	15.2046	37.9018	90.1708

Table 4.30 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO1-E1}$: Case 1

			1 × 20 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.7	8.8	2.8	6.7
	0	5	59.3	74.7	46.5	52.5
4	0	2	-20.0	16.7	0.0	7.2
	0	5	80.0	96.7	41.8	46.4
5	0	2	0.4	0.4	-0.2	1.5
	0	5	1.7	3.9	5.0	12.0
6	0	2	0.3	0.5	0.1	1.9
	0	5	1.7	4.6	7.1	16.2
System	0	2	6.4	8.1	2.7	6.6
	0	5	49.3	68.9	45.1	51.8

Table 4.31 Effects of LFU on the MRBTS$_{BPO1-E1}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	3.1210	7.4490	21.2350	47.1120
	2	3.3228	8.0459	21.6901	50.1765
	5	4.6569	12.2876	30.3862	72.6554
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	0.0260	0.0410	0.0730	0.1220
	2	0.0262	0.0417	0.0730	0.1265
	5	0.0287	0.0492	0.0863	0.1591
6	0	0.3820	0.4330	0.5360	0.7050
	2	0.3833	0.4355	0.5371	0.7224
	5	0.3913	0.4596	0.5856	0.8413
System	0	3.5285	7.9237	21.8505	47.9583
	2	3.7322	8.5248	22.3072	51.0457
	5	5.0775	12.7995	31.0693	73.6863

Table 4.32 EENS Percentage Change (%)
due to LFU for the $\mathrm{MRBTS}_{\mathrm{BPO1\text{-}E1}}$: Case 2

			1 × 20 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	6.5	8.0	2.1	6.5
	0	5	49.2	65.0	43.1	54.2
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	0.8	1.7	0.0	3.7
	0	5	10.4	20.0	18.2	30.4
6	0	2	0.3	0.6	0.2	2.5
	0	5	2.4	6.1	9.3	19.3
System	0	2	5.8	7.6	2.1	6.4
	0	5	43.9	61.5	42.2	53.6

Table 4.33 Effects of LFU on the $\mathrm{MRBTS}_{\mathrm{BPO1\text{-}E1}}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	3.1210	7.4490	21.2350	47.1120
	2	3.3228	8.0459	21.6901	50.1765
	5	4.6569	12.2876	30.3862	72.6554
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	0.0260	0.0410	0.0730	0.1220
	2	0.0280	0.0417	0.0730	0.1265
	5	0.0305	0.0496	0.0863	0.1591
6	0	0.0860	0.1220	0.2080	0.3650
	2	0.0907	0.1248	0.2104	0.3821
	5	0.0988	0.1490	0.2593	0.5017
System	0	3.2323	7.6132	21.5232	47.6176
	2	3.4414	8.2143	21.9808	50.7052
	5	4.7867	12.4896	30.7434	73.3464

Table 4.34 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1-E1}$: Case 3

			1 × 20 MW Generating Unit Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	190	200	210	220
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	6.5	8.0	2.1	6.5
	0	5	49.2	65.0	43.1	54.2
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	7.7	1.7	0.0	3.7
	0	5	17.3	21.0	18.2	30.4
6	0	2	5.5	2.3	1.2	4.7
	0	5	14.9	22.1	24.7	37.5
System	0	2	6.5	7.9	2.1	6.5
	0	5	48.1	64.1	42.8	54.0

The EENS values at Buses 2, 3, 4 and 5 shown in Table 4.29 are very similar to those in Table 4.23 for the RBTS$_{BPO1-E1}$. The Bus 6 and system EENS are reduced considerably with the addition of line 10. The Bus 3 and the system EENS are responsive to LFU as shown in Table 4.30. When the *20 MW* unit is added at Bus 6 in Case 3, the system EENS results are very similar to those obtained in Case 2. The system indices are basically determined by the Bus 3 values and are responsive to LFU.

4.6.3 RBTS$_{BPO1-E2}$ Generation Expansion 2 Case Analysis

As shown in Table 4.21, Generation Expansion E-2 considers the addition of *40 MW* of generation in two *20 MW* units at each of the selected buses in the RBTS$_{BPO1-E2}$. Tables 4.35, 4.37 and 4.39 show the effects of LFU for the three cases. The EENS percentage changes for each case are given in Tables 4.36, 4.38 and 4.40.

Table 4.35 Effects of LFU on the $\text{RBTS}_{\text{BPO1-E2}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 1			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	8.6050	21.9080	49.7270	113.6360
	2	8.9811	23.5579	54.7424	115.5612
	5	13.4982	33.6682	74.3090	149.0875
4	0	0.0000	0.0000	0.0010	0.0040
	2	0.0000	0.0001	0.0011	0.0043
	5	0.0001	0.0006	0.0027	0.0095
5	0	0.3250	0.3410	0.3610	0.4030
	2	0.3241	0.3413	0.3642	0.4050
	5	0.3251	0.3453	0.3775	0.4403
6	0	150.5930	157.2150	163.8660	171.9530
	2	150.1853	157.2181	164.2083	171.6526
	5	150.1935	157.2443	164.3680	171.8441
System	0	159.5229	179.4635	213.9552	285.9948
	2	159.4903	181.1174	219.3160	287.6225
	5	164.0169	191.2582	239.0574	321.3805

Table 4.36 EENS Percentage Change (%)
due to LFU for the $\text{RBTS}_{\text{BPO1-E2}}$: Case 1

			2 × 20 MW Generating Units Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	4.4	7.5	10.1	1.7
	0	5	56.9	53.7	49.4	31.2
4	0	2	–	–	10.0	7.5
	0	5	–	–	170.0	137.5
5	0	2	-0.3	0.1	0.9	0.5
	0	5	0.0	1.3	4.6	9.3
6	0	2	-0.3	0.0	0.2	-0.2
	0	5	-0.3	0.0	0.3	-0.1
System	0	2	0.0	0.9	2.5	0.6
	0	5	2.8	6.6	11.7	12.4

Table 4.37 Effects of LFU on the RBTS$_{\text{BPO1-E2}}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	3.2560	7.9120	18.5860	47.7250
	2	3.3643	8.5619	21.0499	50.1316
	5	5.0963	13.2969	33.0388	76.1588
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0047	0.0115
5	0	0.0140	0.0210	0.0320	0.0610
	2	0.0144	0.0213	0.0344	0.0624
	5	0.0159	0.0253	0.0441	0.0853
6	0	150.2970	156.9080	163.5420	171.5620
	2	149.8899	156.9104	163.8778	171.2537
	5	149.8966	156.9280	164.0033	171.3457
System	0	153.5672	164.8408	182.1607	219.3534
	2	153.2683	165.4939	184.9636	221.4537
	5	155.0092	170.2514	197.0909	247.6016

Table 4.38 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO1-E2}}$: Case 2

			2 × 20 MW Generating Units Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	8.2	13.3	5.0
	0	5	56.5	68.1	77.8	59.6
4	0	2	–	–	60.0	14.0
	0	5	–	–	370.0	130.0
5	0	2	2.9	1.4	7.5	2.3
	0	5	13.6	20.5	37.8	39.8
6	0	2	-0.3	0.0	0.2	-0.2
	0	5	-0.3	0.0	0.3	-0.1
System	0	2	-0.2	0.4	1.5	1.0
	0	5	0.9	3.3	8.2	12.9

Table 4.39 Effects of LFU on the RBTS$_{BPO1-E2}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	3.2810	7.9610	18.6790	47.9190
	2	3.3892	8.6129	21.1507	50.3302
	5	5.1279	13.3631	33.1730	76.4209
4	0	0.0000	0.0000	0.0010	0.0060
	2	0.0000	0.0001	0.0016	0.0061
	5	0.0001	0.0008	0.0039	0.0120
5	0	0.0140	0.0210	0.0320	0.0620
	2	0.0144	0.0213	0.0344	0.0631
	5	0.0159	0.0254	0.0453	0.0866
6	0	0.6490	0.7350	0.8770	1.1610
	2	0.6488	0.7410	0.8979	1.1682
	5	0.6683	0.7803	0.9725	1.3004
System	0	3.9443	8.7166	19.5891	49.1473
	2	4.0523	9.3754	22.0848	51.5679
	5	5.8123	14.1696	34.1945	77.8197

Table 4.40 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO1-E2}$: Case 3

			2 × 20 MW Generating Units Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	8.2	13.2	5.0
	0	5	56.3	67.9	77.6	59.5
4	0	2	–	–	60.0	1.7
	0	5	–	–	290.0	100.0
5	0	2	2.9	1.4	7.5	1.8
	0	5	13.6	21.0	41.6	39.7
6	0	2	0.0	0.8	2.4	0.6
	0	5	3.0	6.2	10.9	12.0
System	0	2	2.7	7.6	12.7	4.9
	0	5	47.4	62.6	74.6	58.3

The EENS values shown in Table 4.35 when *40 MW* of generation is added at Bus 1 are basically composed of two components, the EENS at Bus 3 and the EENS at

Bus 6. The Bus 3 value is highly influenced by the LFU while the Bus 6 value is basically due to failures of line 10. The Bus 3 results for the three cases clearly show the benefits of adding the units in the southern portion of the system which suggests the further influence of deficiencies in the north-south transmission. The Bus 3 indices decrease considerably in Case 2 compared to those in Case 1. The Bus 3 EENS values are basically identical in Cases 2 and 3 and are highly influenced by LFU. The system EENS is dominant by the Bus 3 values and the Bus 6 EENS is a relatively small component of the system value in Case 3.

4.6.4 MRBTS$_{\text{BPO1-E2}}$ Generation Expansion 2 Case Analysis

Tables 4.41, 4.43 and 4.45 show the effects of LFU as generation is added to the MRBTS$_{\text{BPO1-E2}}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables 4.42, 4.44 and 4.46, respectively.

Table 4.41 Effects of LFU on the MRBTS$_{\text{BPO1-E2}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	8.6100	21.9210	49.7610	113.7170
	2	8.9857	23.5726	54.7798	115.6439
	5	13.5065	33.6902	74.3614	149.1975
4	0	0.0000	0.0000	0.0010	0.0040
	2	0.0000	0.0001	0.0011	0.0043
	5	0.0001	0.0006	0.0027	0.0095
5	0	0.3250	0.3410	0.3610	0.4030
	2	0.3241	0.3413	0.3642	0.4050
	5	0.3251	0.3453	0.3775	0.4403
6	0	0.4010	0.4350	0.4990	0.6810
	2	0.4002	0.4382	0.5144	0.6995
	5	0.4084	0.4644	0.5940	0.8988
System	0	9.3348	22.6970	50.6217	114.8038
	2	9.7096	24.3522	55.6596	116.7522
	5	14.2396	34.5007	75.3359	150.5455

Table 4.42 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1\text{-}E2}$: Case 1

			2 × 20 MW Generating Units Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	4.4	7.5	10.1	1.7
	0	5	56.9	53.7	49.4	31.2
4	0	2	–	–	10.0	7.5
	0	5	–	–	170.0	137.5
5	0	2	-0.3	0.1	0.9	0.5
	0	5	0.0	1.3	4.6	9.3
6	0	2	-0.2	0.7	3.1	2.7
	0	5	1.8	6.8	19.0	32.0
System	0	2	4.0	7.3	10.0	1.7
	0	5	52.5	52.0	48.8	31.1

Table 4.43 Effects of LFU on the MRBTS$_{BPO1\text{-}E2}$: Case 2 Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 5			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	3.2600	7.9230	18.6120	47.7890
	2	3.3685	8.5740	21.0792	50.1986
	5	5.1031	13.3150	33.0826	76.2556
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0039	0.0115
5	0	0.0140	0.0210	0.0320	0.0610
	2	0.0144	0.0213	0.0344	0.0624
	5	0.0159	0.0253	0.0449	0.0853
6	0	0.1040	0.1280	0.1750	0.2900
	2	0.1045	0.1306	0.1840	0.3004
	5	0.1113	0.1483	0.2293	0.4007
System	0	3.3790	8.0724	18.8202	48.1453
	2	3.4874	8.7263	21.2994	50.5674
	5	5.2308	13.4900	33.3606	76.7532

Table 4.44 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO1-E2}$: Case 2

			2 × 20 MW Generating Units Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	8.2	13.3	5.0
	0	5	56.5	68.1	77.7	59.6
4	0	2	–	–	60.0	14.0
	0	5	–	–	290.0	130.0
5	0	2	2.9	1.4	7.5	2.3
	0	5	13.6	20.5	40.3	39.8
6	0	2	0.5	2.0	5.1	3.6
	0	5	7.0	15.9	31.0	38.2
System	0	2	3.2	8.1	13.2	5.0
	0	5	54.8	67.1	77.3	59.4

Table 4.45 Effects of LFU for the MRBTS$_{BPO1-E2}$: Case 3 Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 6			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	3.2600	7.9230	18.6120	47.7890
	2	3.3685	8.5740	21.0792	50.1986
	5	5.1031	13.3150	33.0826	76.2556
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0039	0.0115
5	0	0.0140	0.0210	0.0320	0.0610
	2	0.0144	0.0213	0.0344	0.0624
	5	0.0159	0.0253	0.0449	0.0853
6	0	0.0390	0.0600	0.1040	0.2150
	2	0.0392	0.0624	0.1127	0.2257
	5	0.0462	0.0801	0.1580	0.3262
System	0	3.3135	8.0040	18.7489	48.0706
	2	3.4220	8.6579	21.2279	50.4927
	5	5.1654	13.4215	33.2891	76.6786

Table 4.46 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO1\text{-}E2}$: Case 3

			2 × 20 MW Generating Units Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	8.2	13.3	5.0
	0	5	56.5	68.1	77.7	59.6
4	0	2	–	–	60.0	14.0
	0	5	–	–	290.0	130.0
5	0	2	2.9	1.4	7.5	2.3
	0	5	13.6	20.5	40.3	39.8
6	0	2	0.5	4.0	8.4	5.0
	0	5	18.5	33.5	51.9	51.7
System	0	2	3.3	8.2	13.2	5.0
	0	5	55.9	67.7	77.6	59.5

The EENS values at Buses 2, 3, 4 and 5 shown in Table 4.41 are very similar to those in Table 4.35 for the RBTS$_{BPO1\text{-}E2}$. The Bus 6 and system EENS are reduced considerably with the addition of line 10. The Bus 3 and system EENS are responsive to LFU as shown in Table 4.41. When the second *20 MW* unit is added at Bus 6 in Case 3, the EENS results are very similar to those obtained in Case 2. The system indices are basically determined by the Bus 3 values and are responsive to LFU.

4.6.5 RBTS$_{BPO1\text{-}E3}$ Generation Expansion 3 Case Analysis

As shown in Table 4.21, Generation Expansion E-3 considers the addition of *40 MW* of generation in a *40 MW* unit at each of the selected buses in the RBTS$_{BPO1\text{-}E3}$. Tables 4.47, 4.49 and 4.51 show the effects of LFU for the three cases. The EENS percentage changes for each case are given in Tables 4.48, 4.50 and 4.52.

Table 4.47 Effects of LFU on the $\text{RBTS}_{\text{BPO1-E3}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 1			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0001
3	0	9.9100	24.6320	55.4150	125.9500
	2	10.3137	26.4553	60.9586	127.8116
	5	15.2971	37.5723	82.1263	163.2427
4	0	0.0000	0.0010	0.0040	0.0150
	2	0.0001	0.0014	0.0051	0.0156
	5	0.0007	0.0030	0.0100	0.0266
5	0	0.1980	0.2140	0.2390	0.2980
	2	0.1978	0.2149	0.2435	0.3015
	5	0.2006	0.2224	0.2647	0.3516
6	0	145.2300	151.6320	158.0800	165.9570
	2	144.8374	151.6368	158.4163	165.6714
	5	144.8505	151.6749	158.5954	165.8936
System	0	155.3382	176.4793	213.7376	292.2198
	2	155.3487	178.3082	219.6230	293.8001
	5	160.3490	189.4728	240.9964	329.5149

Table 4.48 EENS Percentage Change (%)
due to LFU for the $\text{RBTS}_{\text{BPO1-E3}}$: Case 1

			1 × 40 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	4.1	7.4	10.0	1.5
	0	5	54.4	52.5	48.2	29.6
4	0	2	–	40.0	27.5	4.0
	0	5	–	200.0	150.0	77.3
5	0	2	-0.1	0.4	1.9	1.2
	0	5	1.3	3.9	10.8	18.0
6	0	2	-0.3	0.0	0.2	-0.2
	0	5	-0.3	0.0	0.3	0.0
System	0	2	0.0	1.0	2.8	0.5
	0	5	3.2	7.4	12.8	12.8

Table 4.49 Effects of LFU on the RBTS$_{BPO1\text{-}E3}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 5			
	LFU (%)	System Peak Load Level (MW)			
Bus		210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	5.0090	11.5190	25.7030	62.1820
	2	5.1462	12.3549	28.7343	64.4937
	5	7.4287	18.1720	42.3456	92.3359
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328
5	0	0.0060	0.0150	0.0320	0.0810
	2	0.0065	0.0158	0.0360	0.0843
	5	0.0092	0.0232	0.0558	0.1257
6	0	145.0380	151.4330	157.8700	165.7010
	2	144.6458	151.4375	158.2016	165.4073
	5	144.6583	151.4690	158.3533	165.5442
System	0	150.0548	162.9698	183.6127	227.9849
	2	149.8001	163.8116	186.9815	230.0076
	5	152.0984	169.6700	200.7692	258.0390

Table 4.50 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO1\text{-}E3}$: Case 2

			1 × 40 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	2.7	7.3	11.8	3.7
	0	5	48.3	57.8	64.7	48.5
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	8.3	5.3	12.5	4.1
	0	5	53.3	54.7	74.4	55.2
6	0	2	-0.3	0.0	0.2	-0.2
	0	5	-0.3	0.0	0.3	-0.1
System	0	2	-0.2	0.5	1.8	0.9
	0	5	1.4	4.1	9.3	13.2

Table 4.51 Effects of LFU for the $\text{RBTS}_{\text{BPO1-E3}}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	5.0350	11.5730	25.8080	62.4060
	2	5.1727	12.4113	28.8488	64.7224
	5	7.4629	18.2461	42.4977	92.6323
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0145	0.0329
5	0	0.0060	0.0150	0.0320	0.0810
	2	0.0065	0.0158	0.0360	0.0846
	5	0.0092	0.0233	0.0562	0.1266
6	0	5.4010	5.6710	5.9830	6.4650
	2	5.3870	5.6753	6.0111	6.4678
	5	5.3996	5.7073	6.0884	6.6119
System	0	10.4434	17.2617	31.8317	68.9738
	2	10.5676	18.1059	34.9060	71.2976
	5	12.8738	23.9822	48.6569	99.4049

Table 4.52 EENS Percentage Change (%)
due to LFU for the $\text{RBTS}_{\text{BPO1-E3}}$: Case 3

			1 × 40 MW Generating Unit Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	2.7	7.2	11.8	3.7
	0	5	48.2	57.7	64.7	48.4
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	81.3	56.7
5	0	2	8.3	5.3	12.5	4.4
	0	5	53.3	55.3	75.6	56.3
6	0	2	-0.3	0.1	0.5	0.0
	0	5	0.0	0.6	1.8	2.3
System	0	2	1.2	4.9	9.7	3.4
	0	5	23.3	38.9	52.9	44.1

The EENS values in this expansion scenario (E-3) can be compared directly with those in E-2 as the total installed capacity and the load are the same. The addition of a *40 MW* unit at Bus 1 (Case 1) does not provide the same benefits to the system as the addition of two *20 MW* generating units. This can be seen by comparing Table 4.47 with Table 4.35. This effect is also seen in Tables 4.49 and 4.51, where the EENS values at Bus 3 are higher than those in Tables 4.37 and 4.39, respectively.

The actual percentage increase at Bus 3 due to LFU is larger for E-2 than it is for E-3, and the percentage increase for the system is slightly lower for Cases 1 and 2 and higher for Case 3. The *40 MW* generating unit is added to the system at Bus 6 in Case 3 and while it removes the effect of a single supply at this bus, it does not provide the same benefit as the two *20 MW* units in E-2, Case 3.

4.6.6 MRBTS$_{BPO1-E3}$ Generation Expansion 3 Case Analysis

Tables 4.53, 4.55 and 4.57 show the effects of LFU as generation is added to the MRBTS$_{BPO1-E3}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables 4.54, 4.56 and 4.58, respectively.

Table 4.53 Effects of LFU on the MRBTS$_{BPO1-E3}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0001
3	0	9.9160	24.6510	55.4630	126.0650
	2	10.3198	26.4760	61.0117	127.9276
	5	15.3084	37.6039	82.1993	163.3915
4	0	0.0000	0.0010	0.0040	0.0150
	2	0.0001	0.0014	0.0051	0.0156
	5	0.0007	0.0030	0.0100	0.0266
5	0	0.1980	0.2140	0.2390	0.2980
	2	0.1978	0.2149	0.2435	0.3015
	5	0.2006	0.2224	0.2647	0.3516

Table 4.53 (Continued)

		1 × 40 MW Generating Unit Added at Bus 1			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
6	0	0.5440	0.6010	0.7020	0.9650
	2	0.5439	0.6057	0.7240	0.9865
	5	0.5572	0.6435	0.8257	1.2164
System	0	10.6584	25.4668	56.4085	127.3419
	2	11.0617	27.2975	61.9844	129.2310
	5	16.0669	38.4730	83.3000	164.9860

Table 4.54 EENS Percentage Change (%)
due to LFU for the $\text{MRBTS}_{\text{BPO1-E3}}$: Case 1

			1 × 40 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	4.1	7.4	10.0	1.5
	0	5	54.4	52.5	48.2	29.6
4	0	2	–	40.0	27.5	4.0
	0	5	–	200.0	150.0	77.3
5	0	2	-0.1	0.4	1.9	1.2
	0	5	1.3	3.9	10.8	18.0
6	0	2	0.0	0.8	3.1	2.2
	0	5	2.4	7.1	17.6	26.1
System	0	2	3.8	7.2	9.9	1.5
	0	5	50.7	51.1	47.7	29.6

Table 4.55 Effects of LFU on the $\text{MRBTS}_{\text{BPO1-E3}}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 5			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	5.0130	11.5320	25.7350	62.2590
	2	5.1507	12.3691	28.7700	64.5740
	5	7.4364	18.1934	42.3977	92.4488
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328

Table 4.55 (Continued)

		1 × 40 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
5	0	0.0060	0.0150	0.0320	0.0810
	2	0.0065	0.0158	0.0360	0.0843
	5	0.0092	0.0232	0.0558	0.1257
6	0	0.3530	0.4020	0.4920	0.7080
	2	0.3528	0.4062	0.5095	0.7221
	5	0.3654	0.4380	0.5838	0.8666
System	0	5.3738	11.9514	26.2674	63.0702
	2	5.5115	12.7943	29.3251	65.4030
	5	7.8129	18.6602	43.0519	93.4748

Table 4.56 EENS Percentage Change (%)
due to LFU for the MRBTS$_{\text{BPO1-E3}}$: Case 2

			1 × 40 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	2.7	7.3	11.8	3.7
	0	5	48.3	57.8	64.7	48.5
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	8.3	5.3	12.5	4.1
	0	5	53.3	54.7	74.4	55.2
6	0	2	-0.1	1.0	3.6	2.0
	0	5	3.5	9.0	18.7	22.4
System	0	2	2.6	7.1	11.6	3.7
	0	5	45.4	56.1	63.9	48.2

Table 4.57 Effects of LFU on the MRBTS$_{\text{BPO1-E3}}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	5.0130	11.5320	25.7350	62.2590
	2	5.1507	12.3691	28.7700	64.5740
	5	7.4364	18.1934	42.3977	92.4488

Table 4.57 (Continued)

		1 × 40 MW Generating Unit Added at Bus 6			
	LFU	**System Peak Load Level (MW)**			
Bus	**(%)**	**210**	**220**	**230**	**240**
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328
5	0	0.0060	0.0150	0.0320	0.0810
	2	0.0065	0.0158	0.0360	0.0843
	5	0.0092	0.0232	0.0558	0.1257
6	0	0.0320	0.0660	0.1430	0.3350
	2	0.0328	0.0706	0.1597	0.3516
	5	0.0466	0.1025	0.2316	0.4959
System	0	5.0525	11.6161	25.9180	62.6964
	2	5.1911	12.4590	28.9749	65.0321
	5	7.4944	18.3247	42.6993	93.1039

**Table 4.58 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO1-E3}$: Case 3**

			1 × 40 MW Generating Unit Added at Bus 6			
	LFU (%)		**System Peak Load Level (MW)**			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	2.7	7.3	11.8	3.7
	0	5	48.3	57.8	64.7	48.5
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	8.3	5.3	12.5	4.1
	0	5	53.3	54.7	74.4	55.2
6	0	2	2.5	7.0	11.7	5.0
	0	5	45.6	55.3	62.0	48.0
System	0	2	2.7	7.3	11.8	3.7
	0	5	48.3	57.8	64.7	48.5

The effects of adding a *40 MW* generating unit rather than adding two *20 MW* generating units to the MRBTS$_{BPO1-E3}$ are similar to those seen for the RBTS$_{BPO1-E3}$. The Bus 6 and system EENS are reduced considerably with the addition of line 10. The effects of LFU on the EENS are largely seen at Bus 3 and for the system. When the *40 MW* unit is added at Bus 6 in Case 3, the EENS results are slightly lower than those obtained in Case 2. The system indices are basically determined by the Bus 3 values and are responsive to LFU.

4.7 Summary

This chapter illustrates the effects of load forecast uncertainty in a generation expansion framework. A base case analysis is performed on the $\text{RBTS}_{\text{BPO1}}$ and the $\text{MRBTS}_{\text{BPO1}}$ to obtain the load bus and system reliability indices and to identify the least reliable load buses. The load point and system results were used as base case analyses including *2%* and *5%* uncertainty in the forecast load. Factor analyses is performed on the two systems to indicate the relative contributions to the load point and system EENS of generation and transmission failures. Capacity expansion analysis is considered in three generation expansion scenarios designated as E-1, E-2 and E-3 and each scenario includes three cases in which the generation is added at either Bus 1, Bus 5 or Bus 6. The base case systems and the three scenarios, each with three case additions provide a total of twenty different power system configurations.

The studies illustrate the effect of LFU on the system and load bus adequacy in the form of the EENS. The studies show that the system EENS is very responsive to LFU. The individual load point EENS is very dependent on the topology of the system and the load curtailment philosophy. Bus three has the lowest priority in regard to load curtailment and therefore is interrupted whenever there are generation deficiencies in the system. The EENS at this bus is therefore very sensitive to LFU. Bus 6 in the RBTS is transmission deficient and therefore is generally insensitive to LFU. This condition is corrected in the MRBTS and the adequacy is improved considerably. The EENS at this bus is affected by LFU in a similar manner to that at Buses 4 and 5.

The actual magnitude of the changes due to LFU in the load bus and system risk indices and in the percentage change values are different for each generation expansion scenario and their cases. The topology and parameters of the system are different in each of the twenty power system configurations.

The studies shown in this chapter illustrate that the effect of LFU on the system and load point adequacy can be quantified and therefore utilized in the decision-making process associated with system generation and transmission planning. The results show that the LFU has important impacts on the system and load point indices that can only be appreciated by conducting comprehensive bulk system adequacy assessment. The actual effects are a complicated function of the system topology and parameters, and the system load curtailment philosophy. The capacity expansion analysis including LFU considerations described in this chapter can be extended to larger systems.

5. SUMMARY AND CONCLUSIONS

Composite or bulk system assessment involves the integrated generation and transmission system and focuses on the ability of the system to transport the energy produced by the generating system to the major load points. Composite system adequacy assessment is an important aspect in system reinforcement and/or expansion planning. The continuing growth in size and complexity of bulk electrical systems require careful study of the uncertainty associated with the growing demand for electrical energy. The primary focus of the research described in this thesis is to examine the effects and implications of load forecast uncertainty on the load point and system adequacy indices of composite generation and transmission systems. The research was conducted using a computer program based on Monte Carlo simulation and designated as MECORE. The research described in this thesis should prove useful to engineers and managers engaged in comparing different alternatives and in system development. The research presented, illustrates the application of the proposed concepts and techniques using a well known composite reliability test system.

Chapter 1 provides a brief introduction of the overall area of power system reliability assessment including, the definition and comparison of absolute and relative reliability indices, the concepts of adequacy and security, and the power system functional zones in the form of hierarchical levels. A brief description of the power industry in a deregulated market environment is presented. The basic definition of analytical and simulation techniques as used in the adequacy assessment of composite systems and the two sets of load point and system reliability indices used in the adequacy assessment of composite systems are briefly discussed. The importance and recognition of load forecast uncertainty in predicting future generation and transmission requirements is stressed in this chapter.

Chapter 2 briefly discusses the basic objectives of power system planning, provides background information on composite system analysis and defines the main tasks in composite system reliability evaluation. The definition and application of analytical and simulation techniques are described in detail. The two basic indices of probability and frequency of an outage event are extended to create a range of additional indices to describe the load point and system adequacy. Load bus indices indicate the reliability at individual load points and can be used to identify weak points in the system and to assess the local effects of capital investment. Overall system indices provide a general appraisal of the total system reliability and are valuable information when comparing different alternatives in bulk electrical system planning. The basic adequacy indices including past performance and predictive parameters are briefly introduced. Chapter 2 also emphasises that both analytical and Monte Carlo simulation techniques can be applied to composite system reliability assessment and that the Monte Carlo simulation approach is used in this research work. The three Monte Carlo methods designated as state sampling, state transition sampling and sequential sampling, and the advantages and limitations are briefly discussed.

A computer software designated as MECORE, which is a Monte Carlo based composite generation and transmission system reliability evaluation tool designed to perform reliability and reliability worth assessment of bulk electrical systems, is also described in Chapter 2. The MECORE program utilizes the state sampling technique and was initially developed at the University of Saskatchewan and subsequently enhanced by BC Hydro. It can be used to perform a wide range of composite system studies. MECORE produces eight basic indices and five IEEE-proposed indices and can provide both annualized and annual load bus and system indices. The basic indices can be obtained for each load point or for an overall system. The IEEE-proposed indices are determined for an overall system. Both load point and system indices have different functions but complement each other. They can be obtained on an annualized or annual basis. Annualized indices are calculated at the system peak load level and expressed on a one-year basis. Annual indices are obtained by incorporating the variations in the load level throughout a given period. Both sets of indices are important reliability parameters in the decision making-process of overall development and energy system management as they provide valuable input data on the reliability performance of bulk generation and transmission systems.

A discrete 20 step-load model was used to calculate annual reliability indices in all the studies conducted in this thesis. The educational test system designated as the *Roy Billinton Test System* (RBTS) was used to conduct the research work in this thesis and is introduced in Chapter 2. The calculated annual values, which are used as a base case reference for comparison purposes in the subsequent studies and the corresponding assumptions for the RBTS are presented in this chapter. A brief case study based on this composite system is also illustrated.

A load curtailment philosophy in the form of a load bus priority order (BPO) is utilized in the adequacy assessment of the RBTS in this chapter and later extended in Chapter 4. Individual load points in an actual power system have different priority orders which are usually based on economic factors as some loads are more important than others. The MECORE program was designed to incorporate a load bus priority order. The Interrupted Energy Assessment Rate (IEAR) which recognizes the customer cost associated with power outage is used to establish an initial load bus priority order (BPO1) in this chapter. A load bus priority order has considerable impact on the load bus indices and almost negligible effects on the overall system reliability as the total amount of load curtailment for a given contingency system state is minimized. The least reliable load buses are curtailed first followed by the more important loads. Two different load bus priority orders designated as BPO1 and BPO2 are applied to the RBTS in this chapter.

A quantitative adequacy assessment approach for composite system expansion and reinforcement planning is described in Chapter 2. A procedure known as factor analysis used to identify generation and transmission deficiencies is presented in this chapter and was applied to the $\mathrm{RBTS}_{\mathrm{BPO1}}$ and $\mathrm{MRBTS}_{\mathrm{BPO1}}$. The composite system reliability techniques described in this chapter are used to assess the adequacy of four systems designated as the $\mathrm{RBTS}_{\mathrm{BPO1}}$, $\mathrm{MRBTS}_{\mathrm{BPO1}}$, $\mathrm{RBTS}_{\mathrm{BPO2}}$, and $\mathrm{MRBTS}_{\mathrm{BPO2}}$. The system results were used as base case analyses in the load forecast uncertainty and system expansion scenarios presented in Chapter 4.

The prediction of future energy requirement is a continuous operational and planning task in an electric power utility. Chapter 3 proposes two methods to incorporate the inherent uncertainty associated with future load forecast in the adequacy assessment of composite generation and transmission systems. These two techniques are designated as the Load Forecast Probability Distribution (LFPD) method and the Load Forecast Modified Load Curve (LFMLC) approach.

The Load Forecast Probability Distribution (LFPD) method is directly related to the basic technique used to calculate the system reliability indices at a single load level. The load levels associated with the uncertainty distribution are used to calculate a group of reliability indices which are then weighted and aggregated using the associated probabilities to produce a set of expected indices that include the uncertainty parameter.

The LFMLC method develops a modified load duration curve model that incorporates the load forecast uncertainty probability distribution. The application of the modified load model results in a set of reliability indices that directly includes the uncertainty in the load forecast. The concept of using the load forecast uncertainty distribution to create a modified load duration is a useful approach which can be used to conduct a wide range of repetitive studies with considerable savings in computer time.

The two methods are applied to the $\text{RBTS}_{\text{BPO1}}$ to evaluate the Expected Duration of Load Curtailment (EDLC), Expected Number of Load Curtailment (ENLC) and Expected Energy Not Supplied (EENS) system indices using the MECORE program and a simple step-load model. The results obtained, show that the two methods provide virtually identical system reliability indices. The basic advantage of the LFMLC approach is that it requires less computer time to produce practically the same reliability indices than the time required using the LFPD method. This could be of great importance in large system analysis. The preliminary load forecast uncertainty studies conducted using these two methods show that the EENS index is very responsive to load forecast uncertainty.

The modified load duration curve obtained using a *20* step-load duration model and the LFMLC method in Section 3.4 is composed of *140* step-load levels. The MECORE software as introduced in Chapter 2, can handle up to *100* step-load levels in a multi-step load duration curve model. This capability limits the application of the LFMLC approach in the reliability evaluation of composite systems. In order to use the modified load duration model as input data to MECORE, it was concluded that the final load model would have to be reduced to one containing *100* or less step-load levels. This involves creating an approximate model which will reduce the accuracy associated with the analysis. It was therefore decided to utilize the LFPD approach in the subsequent studies.

Chapter 4 illustrates the effects of load forecast uncertainty in a generation expansion scenario using the LDPF method. The most common reliability index in an assessment of a composite system is the EENS index which indicates the expected energy not supplied due to generation and/or transmission failures. The EENS index is used to study the impacts of load forecast uncertainty in this chapter. A base case analysis was performed on the $\text{RBTS}_{\text{BPO1}}$ and the $\text{MRBTS}_{\text{BPO1}}$ to obtain the load bus and system reliability indices and to identify the least reliable load buses. The load point and system results were used as base case analyses including *2%* and *5%* uncertainty in the forecast load. Factor analyses were conducted on the two systems to indicate the relative contribution of generation and transmission failures to the load point and system EENS.

Capacity expansion analysis considering three generation expansion scenarios, each scenario with three cases in which the generation is added at either Bus 1, Bus 5 or Bus 6 is also presented in Chapter 4. The base case systems and the three scenarios, each with three case additions provided a total of twenty different power system configurations. The studies illustrate the effects of load forecast uncertainty on the system and load bus adequacy in the form of the EENS. The studies also show that the system EENS is very responsive to load forecast uncertainty. It is observed in this chapter that the individual load point EENS is very dependent on the topology of the system and the load curtailment philosophy. Bus 3 has the lowest priority in regard to load curtailment and is therefore interrupted whenever there are generation deficiencies in the system. The EENS at this bus is therefore very sensitive to load forecast uncertainty. Bus 6 in the RBTS is transmission deficient and is therefore generally insensitive to load forecast uncertainty. This condition is corrected in the MRBTS and the adequacy is improved considerably. It was noticed that the EENS at this bus is affected by load forecast uncertainty in a similar manner to that at Buses 4 and 5.

The actual magnitude of the changes due to load forecast uncertainty in the load bus and system risk indices and in the percentage change values as obtained in Chapter 4 are different for each generation expansion scenario and their cases. The topology and parameters of the system are different in each of the twenty power system configurations. The studies shown in Chapter 4 illustrate that the effect of load forecast uncertainty on the system and load point adequacy can be quantified and therefore utilized in the decision-making process associated with system generation and transmission planning. The results in this chapter also show that the load forecast uncertainty has important impacts on the system and load point indices that can only be appreciated by conducting comprehensive bulk system adequacy assessment. The actual effects are a complicated function of the system topology and parameters, and the system load curtailment philosophy. The capacity expansion analysis including load forecast uncertainty considerations presented in this chapter can be extended to larger systems.

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APPENDIX A. BASIC DATA FOR THE RBTS

A.1 Bus, Transmission Line and Generation Data

The bus and transmission line data for the RBTS are given in Tables A.1 and A.2, respectively. Table A.3 shows the reliability data for the transmission system, and Table A.4 displays the generation unit rating and reliability data for the RBTS.

Table A.1 Bus Data for the RBTS

Bus No.	Load (p.u.)							
	Active	Reactive	P_g	Q_{max}	Q_{min}	V_0	V_{max}	V_{min}
1	0.00	0.0	1.0	0.50	-0.40	1.05	1.05	0.97
2	0.20	0.0	1.2	0.75	-0.40	1.05	1.05	0.97
3	0.85	0.0	0.0	0.00	0.00	1.00	1.05	0.97
4	0.40	0.0	0.0	0.00	0.00	1.00	1.05	0.97
5	0.20	0.0	0.0	0.00	0.00	1.00	1.05	0.97
6	0.20	0.0	0.0	0.00	0.00	1.00	1.05	0.97

Table A.2 Transmission Line Impedance and Rating Data for the RBTS

Line	Buses		Impedance (p.u.)			Tap	Current Rating (p.u.)
	From	To	R	X	B/2		
1,6	1	3	0.0342	0.18	0.0106	1.0	0.85
2,7	2	4	0.1140	0.60	0.0352	1.0	0.71
3	1	2	0.0912	0.48	0.0282	1.0	0.71
4	3	4	0.0228	0.12	0.0071	1.0	0.71
5	3	5	0.0228	0.12	0.0071	1.0	0.71
8	4	5	0.0228	0.12	0.0071	1.0	0.71
9	5	6	0.0228	0.12	0.0071	1.0	0.71

Table A.3 Transmission Line Reliability Data for the RBTS

Line	Buses		Failure Rate (occ/year)	Repair Time (hrs)	Failure Prob.
	From	To			
1,6	1	3	1.50	10.0	0.00171
2,7	2	4	5.00	10.0	0.00568
3	1	2	4.00	10.0	0.00455
4	3	4	1.00	10.0	0.00114
5	3	5	1.00	10.0	0.00114
8	4	5	1.00	10.0	0.00114
9	5	6	1.00	10.0	0.00114

Table A.4 Generation Unit Rating and Reliability Data for the RBTS

Unit No.	Bus No.	Rating (MW)	Failure Rate (occ/year)	Repair Time (hrs)	Failure Prob.
1	1	40.0	6.0	45.0	0.03
2	1	40.0	6.0	45.0	0.03
3	1	10.0	4.0	45.0	0.02
4	1	20.0	5.0	45.0	0.025
5	2	5.0	2.0	45.0	0.01
6	2	5.0	2.0	45.0	0.01
7	2	40.0	3.0	60.0	0.02
8	2	20.0	2.4	55.0	0.015
9	2	20.0	2.4	55.0	0.015
10	2	20.0	2.4	55.0	0.015
11	2	20.0	2.4	55.0	0.015

A.2 Per-unit Weekly, Daily and Hourly Peak Load Data

Tables A.5 to A.7 show the per-unit load model for the RBTS.

Table A.5 Weekly Peak Load as a Percent of Annual Peak

Week	Peak Load	Week	Peak Load	Week	Peak Load	Week	Peak Load
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	87.8	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 A.6 Daily Peak Load as a Percentage of Weekly Load

Day	Peak Load
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Table A.7 Hourly Peak Load as a Percentage of Daily Peak

Hour	Winter Weeks 1-8 & 44-52		Summer Weeks 18-30		Spring/Fall Weeks 9-17 & 31-43	
	Wkd	Wkend	Wkd	Wkend	Wkd	Wkend
12-1am	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-1pm	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

Note: Wkd-Weekday; Wkend-Weekend

A.3 RBTS Per-unit 20 Step-Load Data and Model

Table A.8 and Figure A.1, respectively, show the per-unit *20* step-load data and model used for the RBTS analysis.

Table A.8 20 Step-Load Duration Curve Data for the RBTS

Step	Step-Load Level (p.u)	Probability	Cumulative Probability
1	1.0000	0.000228	0.000228
2	0.9900	0.000114	0.000342
3	0.9830	0.000571	0.000913
4	0.9660	0.001712	0.002626
5	0.9490	0.001712	0.004338
6	0.9320	0.003311	0.007648
7	0.9150	0.006164	0.013813
8	0.8980	0.009703	0.023516
9	0.8810	0.011530	0.035046
10	0.8640	0.016096	0.051142
11	0.8470	0.023630	0.074772
12	0.8300	0.025457	0.100228
13	0.8130	0.023858	0.124087
14	0.8000	0.033105	0.157192
15	0.7800	0.034589	0.191781
16	0.7600	0.016324	0.208105
17	0.7500	0.082192	0.290297
18	0.7000	0.231621	0.521918
19	0.6000	0.215525	0.737443
20	0.5000	0.262557	1.000000

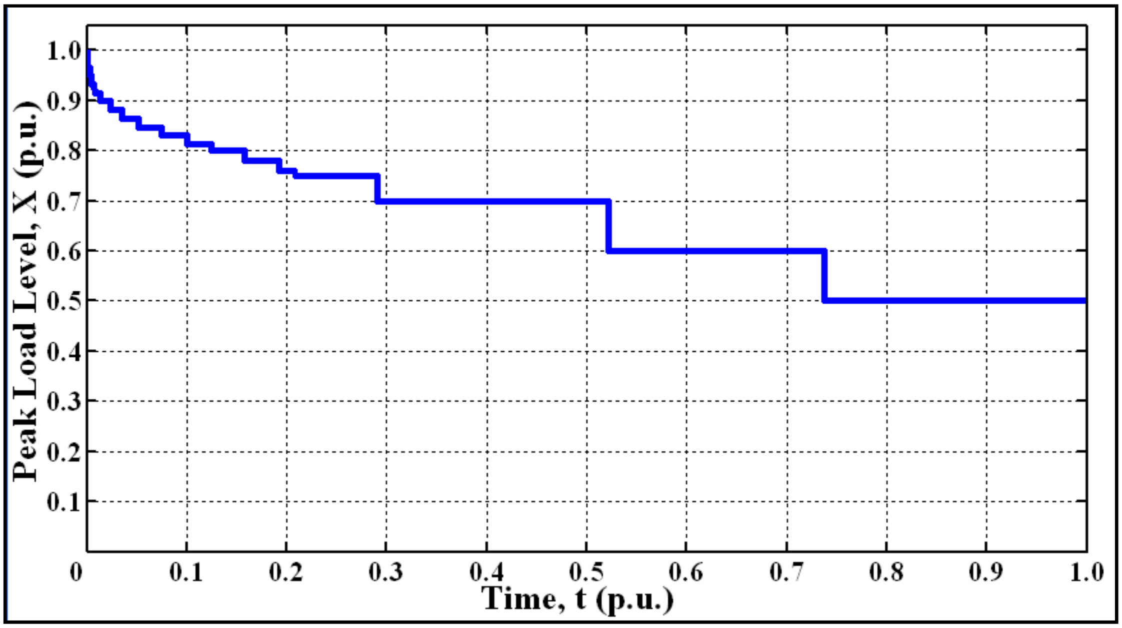

Figure A.1 20 Step-Load Duration Curve for the RBTS

APPENDIX B. ANALYSIS RESULTS FOR THE RBTS$_{\text{BPO1}}$ AND MRBTS$_{\text{BPO1}}$

B.1 The RBTS$_{\text{BPO1}}$ Base Case Analysis

Tables B.1 and B.2, respectively, show the annual load bus and system indices as a function of the system peak load level for the RBTS$_{\text{BPO1}}$ base case analysis.

Table B.1 Annual Load Bus Indices for the RBTS$_{\text{BPO1}}$ Base Case Analysis

Reliability Indices	Bus	Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0005
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0012	0.0012	0.0012	0.0012	0.0012
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.8760	1.2264	2.2776	3.9420
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0876
	6	10.5120	10.5120	10.5120	10.5120	10.5996
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0253	0.0557	0.0787	0.1396	0.2380
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0048	0.0053	0.0055	0.0062	0.0076
	6	1.1797	1.1808	1.1822	1.1832	1.1855
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2780	0.5750	0.8910	1.4090	2.8670
	4	0.0020	0.0040	0.0060	0.0090	0.0150
	5	0.0490	0.0560	0.0600	0.0650	0.0750
	6	14.2400	15.0190	15.4890	15.9620	16.7550
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0004	0.0009	0.0014	0.0024	0.0052
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
	6	0.0145	0.0153	0.0158	0.0162	0.0170
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	3.0800	7.5090	12.5610	21.1640	45.9150
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	0.2320	0.2650	0.2910	0.3260	0.4150
	6	126.8180	133.7570	137.9420	142.1640	149.2780

Table B.2 System Indices for the $\text{RBTS}_{\text{BPO1}}$ Base Case Analysis

Reliability Indices	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	1.2034	1.2338	1.2568	1.3176	1.4160
ADLC (hrs/disturbance)	8.9946	9.1870	9.3198	9.7062	10.2071
EDLC (hrs/year)	10.8237	11.3348	11.7130	12.7892	14.4536
PLC	0.0012	0.0013	0.0013	0.0015	0.0017
EDNS (MW)	0.0149	0.0162	0.0172	0.0187	0.0223
EENS (MWh/year)	130.1384	141.5507	150.8225	163.6990	195.6910
EDC (k$/year)	575.2116	625.6540	666.6355	723.5494	864.9544
BPII (MW/MW-year)	0.0788	0.0846	0.0889	0.0943	0.1066
BECI (MWh/MW-year)	0.7035	0.7651	0.8153	0.8849	1.0578
BPACI (MW/disturbance)	12.1078	12.6884	13.0859	13.2390	13.9208
MBECI (MW/MW)	0.0001	0.0001	0.0001	0.0001	0.0001
SI (system minutes/year)	45.9312	47.1836	48.9154	51.6944	58.7073

B.2 Factor Analysis of the $\text{RBTS}_{\text{BPO1}}$ Base Case Analysis

Tables B.3 to B.5 and B.6 to B.8, respectively, show the annual load bus and system indices for the $\text{RBTS}_{\text{BPO1}}$ assuming generation outages only, transmission outages only and both generation and transmission outages.

Table B.3 Annual Load Bus Indices for the $\text{RBTS}_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Bus	Generation Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0004
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0000
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.7884	1.1388	2.1900	3.7668
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0876
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0195	0.0459	0.0645	0.1157	0.1871
	4	0.0000	0.0001	0.0002	0.0003	0.0005
	5	0.0002	0.0003	0.0005	0.0009	0.0020
	6	0.0004	0.0009	0.0016	0.0025	0.0046

Table B.3 (Continued)

Reliability Indices	Bus	Generation Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1860	0.4380	0.7080	1.1460	2.3350
	4	0.0000	0.0000	0.0010	0.0020	0.0030
	5	0.0010	0.0020	0.0030	0.0040	0.0090
	6	0.0020	0.0050	0.0080	0.0140	0.0280
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0003	0.0008	0.0014	0.0023	0.0050
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0001
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	2.8160	7.1450	12.0810	20.4650	44.1800
	4	0.0010	0.0060	0.0110	0.0190	0.0440
	5	0.0080	0.0210	0.0350	0.0580	0.1270
	6	0.0280	0.0700	0.1130	0.1910	0.4010

Table B.4 Annual Load Bus Indices for the RBTS$_{BPO1}$ Base Case: Factor Analysis

Reliability Indices	Bus	Transmission Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0000
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0012	0.0012	0.0012	0.0012	0.0012
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0876
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	10.5120	10.5120	10.5120	10.5120	10.5120
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0034	0.0040	0.0047	0.0073	0.0193
	4	0.0003	0.0005	0.0009	0.0010	0.0012
	5	0.0045	0.0047	0.0048	0.0050	0.0053
	6	1.0930	1.0935	1.0941	1.0941	1.0941

Table B.4 (Continued)

Reliability Indices	Bus	Transmission Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0690	0.0830	0.0940	0.1120	0.1960
	4	0.0020	0.0040	0.0050	0.0080	0.0120
	5	0.0470	0.0520	0.0550	0.0570	0.0620
	6	13.1950	13.9140	14.3460	14.7790	15.4990
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0001	0.0001
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0145	0.0153	0.0157	0.0162	0.0170
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2280	0.2810	0.3270	0.4050	0.9610
	4	0.0070	0.0130	0.0180	0.0250	0.0390
	5	0.2230	0.2440	0.2560	0.2670	0.2870
	6	126.7900	133.6870	137.8270	141.9700	148.8710

Table B.5 Annual Load Bus Indices for the RBTS$_{BPO1}$ Base Case: Factor Analysis

Reliability Indices	Bus	Both Generation and Transmission Failures				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0005
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0012	0.0012	0.0012	0.0012	0.0012
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.8760	1.2264	2.2776	3.9420
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0876
	6	10.5120	10.5120	10.5120	10.5120	10.5996
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0253	0.0557	0.0787	0.1396	0.2380
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0048	0.0053	0.0055	0.0062	0.0076
	6	1.1797	1.1808	1.1822	1.1832	1.1855

Table B.5 (Continued)

Reliability Indices	Bus	Both Generation and Transmission Failures				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2780	0.5750	0.8910	1.4090	2.8670
	4	0.0020	0.0040	0.0060	0.0090	0.0150
	5	0.0490	0.0560	0.0600	0.0650	0.0750
	6	14.2400	15.0190	15.4890	15.9620	16.7550
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0004	0.0009	0.0014	0.0024	0.0052
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
	6	0.0145	0.0153	0.0158	0.0162	0.0170
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	3.0800	7.5090	12.5610	21.1640	45.9150
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	0.2320	0.2650	0.2910	0.3260	0.4150
	6	126.8180	133.7570	137.9420	142.1640	149.2780

Table B.6 System Indices for the RBTS $_{BPO1}$ Base Case: Factor Analysis

Reliability Indices	Generation Failures Only				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	0.0195	0.0459	0.0645	0.1157	0.1871
ADLC (hrs/disturbance)	16.1053	17.7683	18.2250	19.2168	19.9929
EDLC (hrs/year)	0.3143	0.8153	1.1756	2.2224	3.7396
PLC	0.0000	0.0001	0.0001	0.0003	0.0004
EDNS (MW)	0.0003	0.0008	0.0014	0.0024	0.0051
EENS (MWh/year)	2.8542	7.2421	12.2402	20.7340	44.7517
EDC (k$/year)	12.6156	32.0101	54.1015	91.6443	197.8023
BPII (MW/MW-year)	0.0010	0.0024	0.0039	0.0063	0.0129
BECI (MWh/MW-year)	0.0154	0.0392	0.0662	0.1121	0.2419
BPACI (MW/disturbance)	9.6883	9.7161	11.1555	10.0829	12.7055
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	1.0074	2.4140	3.9698	6.5476	13.4255

Table B.7 System Indices for the RBTS $_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Transmission Failures Only				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	1.0951	1.0958	1.0964	1.0991	1.1111
ADLC (hrs/disturbance)	9.5934	9.5906	9.5879	9.5798	9.5607
EDLC (hrs/year)	10.5058	10.5091	10.5123	10.5288	10.6227
PLC	0.0012	0.0012	0.0012	0.0012	0.0012
EDNS (MW)	0.0145	0.0153	0.0158	0.0163	0.0171
EENS (MWh/year)	127.2476	134.2243	138.4281	142.6676	150.1575
EDC (k$/year)	562.4344	593.2713	611.8522	630.5907	663.6962
BPII (MW/MW-year)	0.0720	0.0760	0.0784	0.0808	0.0852
BECI (MWh/MW-year)	0.6878	0.7255	0.7483	0.7712	0.8117
BPACI (MW/disturbance)	12.1563	12.8247	13.2255	13.6077	14.1926
MBECI (MW/MW)	0.0001	0.0001	0.0001	0.0001	0.0001
SI (system minutes/year)	44.9109	44.7414	44.8956	45.0529	45.0473

Table B.8 System Indices for the RBTS $_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Both Generation and Transmission Failures				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	1.2034	1.2338	1.2568	1.3176	1.4160
ADLC (hrs/disturbance)	8.9946	9.1870	9.3198	9.7062	10.2071
EDLC (hrs/year)	10.8237	11.3348	11.7130	12.7892	14.4536
PLC	0.0012	0.0013	0.0013	0.0015	0.0017
EDNS (MW)	0.0149	0.0162	0.0172	0.0187	0.0223
EENS (MWh/year)	130.1384	141.5507	150.8225	163.6990	195.6910
EDC (k$/year)	575.2116	625.6540	666.6355	723.5494	864.9544
BPII (MW/MW-year)	0.0788	0.0846	0.0889	0.0943	0.1066
BECI (MWh/MW-year)	0.7035	0.7651	0.8153	0.8849	1.0578
BPACI (MW/disturbance)	12.1078	12.6884	13.0859	13.2390	13.9208
MBECI (MW/MW)	0.0001	0.0001	0.0001	0.0001	0.0001
SI (system minutes/year)	45.9312	47.1836	48.9154	51.6944	58.7073

B.3 The MRBTS$_{BPO1}$ Base Case Analysis

Tables B.9 and B.10, respectively, show the annual load bus and system indices as a function of the system peak load level for the MRBTS$_{BPO1}$ base case analysis.

Table B.9 Annual Load Bus Indices for the MRBTS$_{BPO1}$ Base Case Analysis

Reliability Indices	Bus	Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0005
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0000
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.8760	1.2264	2.2776	3.9420
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0876
	6	0.0876	0.0876	0.0876	0.0876	0.0876
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0254	0.0561	0.0792	0.1405	0.2395
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0053	0.0057	0.0060	0.0066	0.0081
	6	0.0104	0.0115	0.0128	0.0139	0.0162
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2790	0.5780	0.8950	1.4160	2.8840
	4	0.0020	0.0040	0.0060	0.0090	0.0160
	5	0.0550	0.0610	0.0660	0.0700	0.0810
	6	0.1150	0.1270	0.1360	0.1480	0.1740
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0004	0.0009	0.0014	0.0024	0.0052
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
	6	0.0001	0.0001	0.0001	0.0001	0.0001
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	3.0810	7.5120	12.5660	21.1740	45.9400
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	0.2320	0.2650	0.2910	0.3260	0.4150
	6	0.5310	0.6070	0.6740	0.7770	1.0280

Table B.10 System Indices for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ Base Case Analysis

Reliability Indices	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	0.0341	0.0647	0.0879	0.1492	0.2482
ADLC (hrs/disturbance)	10.8120	13.5972	14.3227	15.6590	16.1213
EDLC (hrs/year)	0.3687	0.8802	1.2586	2.3356	4.0014
PLC	0.0000	0.0001	0.0001	0.0003	0.0005
EDNS (MW)	0.0004	0.0010	0.0016	0.0026	0.0054
EENS (MWh/year)	3.8520	8.4029	13.5593	22.3228	47.4669
EDC (k$/year)	17.0260	37.1406	59.9322	98.6666	209.8039
BPII (MW/MW-year)	0.0024	0.0042	0.0060	0.0089	0.0171
BECI (MWh/MW-year)	0.0208	0.0454	0.0733	0.1207	0.2566
BPACI (MW/disturbance)	13.2325	11.9000	12.5530	11.0225	12.7083
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	1.3595	2.8010	4.3976	7.0493	14.2401

B.4 Factor Analysis of the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ Base Case Analysis

Tables B.11 to B.13 and B.14 to B.16, respectively, show the annual load bus and system indices for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ assuming generation outages only, transmission outages only and both generation and transmission outages.

Table B.11 Annual Load Bus Indices for the $\mathrm{MRBTS}_{\mathrm{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Bus	Generation Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0004
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0000
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.7884	1.1388	2.1900	3.7668
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0876
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0195	0.0459	0.0645	0.1157	0.1871
	4	0.0000	0.0001	0.0002	0.0003	0.0005
	5	0.0002	0.0003	0.0005	0.0009	0.0020
	6	0.0004	0.0009	0.0016	0.0025	0.0046

Table B.11 (Continued)

Reliability Indices	Bus	Generation Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1860	0.4380	0.7080	1.1460	2.3350
	4	0.0000	0.0000	0.0010	0.0020	0.0030
	5	0.0010	0.0020	0.0030	0.0040	0.0090
	6	0.0020	0.0050	0.0080	0.0140	0.0280
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0003	0.0008	0.0014	0.0023	0.0050
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0001
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	2.8160	7.1450	12.0810	20.4650	44.1800
	4	0.0010	0.0060	0.0110	0.0190	0.0440
	5	0.0080	0.0210	0.0350	0.0580	0.1270
	6	0.0280	0.0700	0.1130	0.1910	0.4010

Table B.12 Annual Load Bus Indices for the MRBTS$_{BPO1}$ Base Case: Factor Analysis

Reliability Indices	Bus	Transmission Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0000
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0000
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0876
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0876	0.0876	0.0876	0.0876
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0034	0.0040	0.0047	0.0073	0.0194
	4	0.0003	0.0005	0.0009	0.0010	0.0012
	5	0.0049	0.0052	0.0052	0.0054	0.0057
	6	0.0097	0.0102	0.0108	0.0108	0.0108

Table B.12 (Continued)

Reliability Indices	Bus	Transmission Failures Only				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0690	0.0830	0.0940	0.1120	0.1960
	4	0.0020	0.0040	0.0050	0.0080	0.0120
	5	0.0520	0.0570	0.0600	0.0630	0.0680
	6	0.1100	0.1170	0.1230	0.1290	0.1380
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0001	0.0001
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0001	0.0001	0.0001	0.0001	0.0001
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2280	0.2810	0.3270	0.4050	0.9610
	4	0.0070	0.0130	0.0180	0.0250	0.0390
	5	0.2230	0.2440	0.2560	0.2670	0.2870
	6	0.5030	0.5360	0.5590	0.5830	0.6210

Table B.13 Annual Load Bus Indices for the $\text{MRBTS}_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Bus	Both Generation and Transmission Failures				
		Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0001	0.0001	0.0003	0.0005
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.0000
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3504	0.8760	1.2264	2.2776	3.9420
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0876
	6	0.0876	0.0876	0.0876	0.0876	0.0876
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0254	0.0561	0.0792	0.1405	0.2395
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0053	0.0057	0.0060	0.0066	0.0081
	6	0.0104	0.0115	0.0128	0.0139	0.0162

Table B.13 (Continued)

Reliability Indices	Bus	Both Generation and Transmission Failures				
		Peak Load Level (MW)				
		170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2790	0.5780	0.8950	1.4160	2.8840
	4	0.0020	0.0040	0.0060	0.0090	0.0160
	5	0.0550	0.0610	0.0660	0.0700	0.0810
	6	0.1150	0.1270	0.1360	0.1480	0.1740
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0004	0.0009	0.0014	0.0024	0.0052
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
	6	0.0001	0.0001	0.0001	0.0001	0.0001
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	3.0810	7.5120	12.5660	21.1740	45.9400
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	0.2320	0.2650	0.2910	0.3260	0.4150
	6	0.5310	0.6070	0.6740	0.7770	1.0280

Table B.14 System Indices for the MRBTS$_{BPO1}$ Base Case: Factor Analysis

Reliability Indices	Generation Failures Only				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	0.0195	0.0459	0.0645	0.1157	0.1871
ADLC (hrs/disturbance)	16.1053	17.7683	18.2250	19.2168	19.9929
EDLC (hrs/year)	0.3143	0.8153	1.1756	2.2224	3.7396
PLC	0.0000	0.0001	0.0001	0.0003	0.0004
EDNS (MW)	0.0003	0.0008	0.0014	0.0024	0.0051
EENS (MWh/year)	2.8542	7.2421	12.2402	20.7340	44.7517
EDC (k$/year)	12.6156	32.0101	54.1015	91.6443	197.8023
BPII (MW/MW-year)	0.0010	0.0024	0.0039	0.0063	0.0129
BECI (MWh/MW-year)	0.0154	0.0392	0.0662	0.1121	0.2419
BPACI (MW/disturbance)	9.6883	9.7161	11.1555	10.0829	12.7055
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	1.0074	2.4140	3.9698	6.5476	13.4255

Table B.15 System Indices for the $\text{MRBTS}_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Transmission Failures Only				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	0.0118	0.0124	0.0131	0.0157	0.0278
ADLC (hrs/disturbance)	4.3091	4.3435	4.3739	4.6860	6.0372
EDLC (hrs/year)	0.0507	0.0540	0.0573	0.0737	0.1677
PLC	0.0000	0.0000	0.0000	0.0000	0.0000
EDNS (MW)	0.0001	0.0001	0.0001	0.0002	0.0002
EENS (MWh/year)	0.9608	1.0741	1.1598	1.2813	1.9079
EDC (k$/year)	4.2468	4.7474	5.1265	5.6633	8.4330
BPII (MW/MW-year)	0.0013	0.0014	0.0015	0.0017	0.0022
BECI (MWh/MW-year)	0.0052	0.0058	0.0063	0.0069	0.0103
BPACI (MW/disturbance)	19.7087	21.0382	21.6231	19.7944	14.9080
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	0.3391	0.3580	0.3762	0.4046	0.5724

Table B.16 System Indices for the $\text{MRBTS}_{\text{BPO1}}$ Base Case: Factor Analysis

Reliability Indices	Both Generation and Transmission Failures				
	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	0.0341	0.0647	0.0879	0.1492	0.2482
ADLC (hrs/disturbance)	10.8120	13.5972	14.3227	15.6590	16.1213
EDLC (hrs/year)	0.3687	0.8802	1.2586	2.3356	4.0014
PLC	0.0000	0.0001	0.0001	0.0003	0.0005
EDNS (MW)	0.0004	0.0010	0.0016	0.0026	0.0054
EENS (MWh/year)	3.8520	8.4029	13.5593	22.3228	47.4669
EDC (k$/year)	17.0260	37.1406	59.9322	98.6666	209.8039
BPII (MW/MW-year)	0.0024	0.0042	0.0060	0.0089	0.0171
BECI (MWh/MW-year)	0.0208	0.0454	0.0733	0.1207	0.2566
BPACI (MW/disturbance)	13.2325	11.9000	12.5530	11.0225	12.7083
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	1.3595	2.8010	4.3976	7.0493	14.2401

APPENDIX C. ANALYSIS RESULTS FOR THE RBTS$_{BPO2}$ AND MRBTS$_{BPO2}$: CHANGE IN THE LOAD BUS PRIORITY ORDER

C.1 The RBTS$_{BPO2}$ Case Analysis

Tables C.1 and C.2, respectively, show the annual load bus and system indices as a function of the system peak load level for the RBTS$_{BPO2}$ case analysis.

Table C.1 Annual Load Bus Indices for the RBTS$_{BPO2}$ Case Analysis

Reliability Indices	Bus	Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0001
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0001	0.0001	0.0003	0.0004
	6	0.0012	0.0012	0.0013	0.0013	0.0014
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0876	0.0876	0.1752	0.3504	0.8760
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.3504	0.8760	1.2264	2.2776	3.7668
	6	10.5996	10.8624	11.1252	11.3880	12.1764
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0071	0.0126	0.0203	0.0335	0.0719
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0287	0.0576	0.0783	0.1348	0.2148
	6	1.1913	1.2030	1.2188	1.2364	1.2826
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0830	0.1440	0.2120	0.3240	0.7010
	4	0.0020	0.0040	0.0060	0.0090	0.0150
	5	0.1870	0.3610	0.5410	0.8320	1.5870
	6	14.2980	15.1450	15.6870	16.2790	17.4090
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0001	0.0002	0.0002	0.0004	0.0009
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0002	0.0006	0.0009	0.0015	0.0031
	6	0.0146	0.0155	0.0161	0.0168	0.0183
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	0.6230	1.2760	2.0360	3.3410	7.8960
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	2.0050	4.8280	7.9730	13.2380	27.3670
	6	127.5020	135.4280	140.7850	147.0750	160.3450

Table C.2 Annual System Indices for the $\mathrm{RBTS_{BPO2}}$ Case Analysis

Reliability Indices	Peak Load Level (MW)				
	170	180	185	190	200
ENLC (1/year)	1.2034	1.2338	1.2568	1.3176	1.4160
ADLC (hrs/disturbance)	8.9946	9.1870	9.3198	9.7062	10.2071
EDLC (hrs/year)	10.8237	11.3348	11.7130	12.7892	14.4536
PLC	0.0012	0.0013	0.0013	0.0015	0.0017
EDNS (MW)	0.0149	0.0162	0.0172	0.0187	0.0223
EENS (MWh/year)	130.1384	141.5507	150.8225	163.6990	195.6912
EDC (k$/year)	575.2116	625.6540	666.6355	723.5495	864.9550
BPII (MW/MW-year)	0.0788	0.0846	0.0889	0.0943	0.1066
BECI (MWh/MW-year)	0.7035	0.7651	0.8153	0.8849	1.0578
BPACI (MW/disturbance)	12.1078	12.6884	13.0859	13.2390	13.9208
MBECI (MW/MW)	0.0001	0.0001	0.0001	0.0001	0.0001
SI (system minutes/year)	45.9312	47.1836	48.9154	51.6944	58.7074

C.2 The $\mathrm{MRBTS_{BPO2}}$ Case Analysis

Tables C.3 and C.4, respectively, show the annual load bus and system indices as a function of the system peak load level for the $\mathrm{MRBTS_{BPO2}}$ case analysis.

Table C.3 Annual Load Bus Indices for the $\mathrm{MRBTS_{BPO2}}$ Case Analysis

Reliability Indices	Bus	Peak Load Level (MW)				
		170	180	185	190	200
PLC	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0000	0.0000	0.0000	0.0000	0.0001
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0001	0.0001	0.0003	0.0004
	6	0.0000	0.0000	0.0001	0.0001	0.0002
EDLC (hrs/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0876	0.0876	0.1752	0.3504	0.8760
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.3504	0.8760	1.2264	2.2776	3.7668
	6	0.1752	0.3504	0.6132	0.9636	1.7520
ENLC (1/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0071	0.0127	0.0204	0.0337	0.0723
	4	0.0004	0.0006	0.0011	0.0013	0.0018
	5	0.0293	0.0583	0.0791	0.1360	0.2166
	6	0.0219	0.0337	0.0496	0.0673	0.1138

Table C.3 (Continued)

Reliability Indices	Bus	Peak Load Level (MW) 170	180	185	190	200
ELC (MW/year)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0830	0.1450	0.2130	0.3260	0.7050
	4	0.0020	0.0040	0.0060	0.0090	0.0160
	5	0.1930	0.3680	0.5490	0.8420	1.6030
	6	0.1730	0.2530	0.3340	0.4670	0.8310
EDNS (MW)	2	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.0001	0.0002	0.0002	0.0004	0.0009
	4	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0002	0.0006	0.0009	0.0015	0.0031
	6	0.0001	0.0003	0.0004	0.0007	0.0014
EENS (MWh/year)	2	0.0000	0.0000	0.0000	0.0000	0.0010
	3	0.6230	1.2780	2.0390	3.3460	7.9060
	4	0.0080	0.0190	0.0290	0.0450	0.0830
	5	2.0060	4.8290	7.9750	13.2430	27.3790
	6	1.2150	2.2780	3.5170	5.6890	12.0990

Table C.4 Annual System Indices for the MRBTS$_{BPO2}$ Case Analysis

Reliability Indices	Peak Load Level (MW) 170	180	185	190	200
ENLC (1/year)	0.0341	0.0647	0.0879	0.1492	0.2482
ADLC (hrs/disturbance)	10.8120	13.5972	14.3227	15.6590	16.1213
EDLC (hrs/year)	0.3687	0.8802	1.2586	2.3356	4.0014
PLC	0.0000	0.0001	0.0001	0.0003	0.0005
EDNS (MW)	0.0004	0.0010	0.0016	0.0026	0.0054
EENS (MWh/year)	3.8520	8.4029	13.5593	22.3228	47.4671
EDC (k$/year)	17.0260	37.1406	59.9322	98.6667	209.8046
BPII (MW/MW-year)	0.0024	0.0042	0.0060	0.0089	0.0171
BECI (MWh/MW-year)	0.0208	0.0454	0.0733	0.1207	0.2566
BPACI (MW/disturbance)	13.2325	11.9000	12.5530	11.0226	12.7084
MBECI (MW/MW)	0.0000	0.0000	0.0000	0.0000	0.0000
SI (system minutes/year)	1.3595	2.8010	4.3976	7.0493	14.2401

APPENDIX D. EFFECTS OF LOAD FORECAST UNCERTAINTY ON THE RBTS$_{BPO1}$ AND MRBTS$_{BPO1}$ USING THE LFPD APPROACH

D.1 Effects of LFU on the RBTS$_{BPO1}$

The effects of load forecast uncertainty for the RBTS$_{BPO1}$ are shown in Tables D.1 to D.4. These tables show the annual load bus and system PLC, ELC, EDNS and SI indices as a function of the system peak load.

Table D.1 Effects of LFU on the RBTS$_{BPO1}$
Annual Load Bus and System PLC

Bus	LFU (%)	Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0000	0.0001	0.0001	0.0003	0.0005
	2	0.0000	0.0001	0.0002	0.0003	0.0005
	5	0.0001	0.0001	0.0002	0.0003	0.0007
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
5	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
6	0	0.0012	0.0012	0.0012	0.0012	0.0012
	2	0.0012	0.0012	0.0012	0.0012	0.0012
	5	0.0012	0.0012	0.0012	0.0012	0.0012
System	0	0.0012	0.0013	0.0013	0.0015	0.0017
	2	0.0012	0.0013	0.0014	0.0015	0.0017
	5	0.0013	0.0013	0.0014	0.0015	0.0019

Table D.2 Effects of LFU on the RBTS$_{BPO1}$ Annual Load Bus ELC (MW/year)

Bus	LFU (%)	Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
3	0	0.2780	0.5750	0.8910	1.4090	2.8670
	2	0.2915	0.6033	0.9376	1.4698	3.0216
	5	0.3435	0.7723	1.1969	1.8412	4.0695
4	0	0.0020	0.0040	0.0060	0.0090	0.0150
	2	0.0023	0.0044	0.0064	0.0094	0.0157
	5	0.0025	0.0050	0.0074	0.0101	0.0173
5	0	0.0490	0.0560	0.0600	0.0650	0.0750
	2	0.0493	0.0560	0.0600	0.0648	0.0759
	5	0.0495	0.0564	0.0609	0.0664	0.0804
6	0	14.2400	15.0190	15.4890	15.9620	16.7550
	2	14.2391	15.0195	15.4896	15.9623	16.7566
	5	14.2033	15.0324	15.4926	15.9553	16.8021

Table D.3 Effects of LFU on the RBTS$_{BPO1}$ Annual Load Bus and System EDNS (MW)

Bus	LFU (%)	Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0004	0.0009	0.0014	0.0024	0.0052
	2	0.0004	0.0009	0.0015	0.0025	0.0056
	5	0.0005	0.0012	0.0020	0.0033	0.0079
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
5	0	0.0000	0.0000	0.0000	0.0000	0.0001
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
6	0	0.0145	0.0153	0.0158	0.0162	0.0170
	2	0.0145	0.0153	0.0158	0.0162	0.0170
	5	0.0144	0.0153	0.0158	0.0162	0.0171
System	0	0.0149	0.0162	0.0172	0.0187	0.0223
	2	0.0149	0.0162	0.0173	0.0188	0.0227
	5	0.0149	0.0166	0.0178	0.0196	0.0251

Table D.4 Effects of LFU on the RBTS$_{BPO1}$
Annual System SI (system minutes/year)

LFU (%)	Peak Load Level (MW)				
	170	180	185	190	200
0	45.9312	47.1836	48.9154	51.6944	58.7073
2	46.0054	47.3494	49.1836	52.0367	59.5676
5	46.2066	48.3732	50.6886	54.1521	65.9190

D.2 Effects of LFU on the MRBTS$_{BPO1}$

The effects of load forecast uncertainty for the MRBTS$_{BPO1}$ are shown in Tables D.5 to D.8. These tables show the annual load bus and system PLC, ELC, EDNS and SI indices as a function of the system peak load.

Table D.5 Effects of LFU on the MRBTS$_{BPO1}$
Annual Load Bus and System PLC

Bus	LFU (%)	Peak Load Level (MW)				
		170	180	185	190	200
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0000	0.0001	0.0001	0.0003	0.0004
	2	0.0000	0.0001	0.0001	0.0003	0.0005
	5	0.0001	0.0001	0.0002	0.0003	0.0007
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
5	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
6	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
System	0	0.0000	0.0001	0.0001	0.0003	0.0005
	2	0.0000	0.0001	0.0002	0.0003	0.0005
	5	0.0001	0.0001	0.0002	0.0003	0.0008

Table D.6 Effects of LFU on the $\text{MRBTS}_{\text{BPO1}}$
Annual Load Bus ELC (MW/year)

	LFU	Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
3	0	0.2790	0.5780	0.8950	1.4160	2.8840
	2	0.2925	0.6061	0.9420	1.4774	3.0397
	5	0.3448	0.7762	1.2031	1.8515	4.0952
4	0	0.0020	0.0040	0.0060	0.0090	0.0160
	2	0.0023	0.0044	0.0064	0.0094	0.0161
	5	0.0025	0.0050	0.0074	0.0103	0.0177
5	0	0.0550	0.0610	0.0660	0.0700	0.0810
	2	0.0548	0.0611	0.0660	0.0704	0.0819
	5	0.0550	0.0620	0.0666	0.0721	0.0861
6	0	0.1150	0.1270	0.1360	0.1480	0.1740
	2	0.1156	0.1272	0.1366	0.1485	0.1744
	5	0.1156	0.1298	0.1396	0.1518	0.1838

Table D.7 Effects of LFU on the $\text{MRBTS}_{\text{BPO1}}$
Annual Load Bus and System EDNS (MW)

	LFU	Peak Load Level (MW)				
Bus	**(%)**	**170**	**180**	**185**	**190**	**200**
2	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
3	0	0.0004	0.0009	0.0014	0.0024	0.0052
	2	0.0004	0.0009	0.0015	0.0025	0.0056
	5	0.0005	0.0012	0.0020	0.0033	0.0079
4	0	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0000
5	0	0.0000	0.0000	0.0000	0.0000	0.0001
	2	0.0000	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000	0.0001
6	0	0.0001	0.0001	0.0001	0.0001	0.0001
	2	0.0001	0.0001	0.0001	0.0001	0.0001
	5	0.0001	0.0001	0.0001	0.0001	0.0001
System	0	0.0004	0.0010	0.0016	0.0026	0.0054
	2	0.0004	0.0010	0.0017	0.0027	0.0057
	5	0.0006	0.0014	0.0022	0.0034	0.0081

Table D.8 Effects of LFU on the MRBTS$_{BPO1}$
Annual System SI (system minutes/year)

LFU (%)	Peak Load Level (MW)				
	170	180	185	190	200
0	1.3595	2.8010	4.3976	7.0493	14.2401
2	1.4367	2.9669	4.6660	7.3918	15.0984
5	1.7525	3.9607	6.1719	9.5379	21.3580

APPENDIX E. GENERATION EXPANSION ANALYSIS FOR THE RBTS$_{BPO2}$ AND MRBTS$_{BPO2}$: CHANGE IN THE LOAD BUS PRIORITY ORDER

E.1 RBTS$_{BPO2-E1}$ Generation Expansion 1 Case Analysis

As shown in Table 4.21, Generation Expansion E-1 considers the addition of 20 *MW* of generation in a *20 MW* unit at each of the selected buses in the RBTS$_{BPO2-E1}$. Tables E.1, E.3 and E.5 show the effects of LFU for the three cases. The EENS percentage changes for each case addition are given in Tables E.2, E.4 and E.6.

Table E.1 Effects of LFU on the RBTS$_{BPO2-E1}$: Case 1 Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 1			
	LFU	**System Peak Load Level (MW)**			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0006
3	0	0.6880	2.1010	7.4180	18.7410
	2	0.7662	2.3159	7.7607	20.1205
	5	1.2952	4.1714	11.5340	28.2323
4	0	0.0010	0.0030	0.0110	0.0250
	2	0.0008	0.0035	0.0110	0.0268
	5	0.0018	0.0059	0.0156	0.0366
5	0	2.0680	4.7630	13.5420	29.2620
	2	2.1938	5.1563	13.7157	31.0953
	5	3.0364	7.8069	18.9977	44.9280
6	0	131.8710	139.1980	149.8070	162.3380
	2	131.9179	139.3273	149.6041	163.0358
	5	132.1327	140.5835	151.6103	167.9147
System	0	134.6280	146.0651	170.7788	210.3655
	2	134.8790	146.8028	171.0920	214.2783
	5	136.4663	152.5679	182.1578	241.1118

Table E.2 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO2-E1}}$: Case 1

			1 × 20 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	11.4	10.2	4.6	7.4
	0	5	88.3	98.5	55.5	50.6
4	0	2	-20.0	16.7	0.0	7.2
	0	5	80.0	96.7	41.8	46.4
5	0	2	6.1	8.3	1.3	6.3
	0	5	46.8	63.9	40.3	53.5
6	0	2	0.0	0.1	-0.1	0.4
	0	5	0.2	1.0	1.2	3.4
System	0	2	0.2	0.5	0.2	1.9
	0	5	1.4	4.5	6.7	14.6

Table E.3 Effects of LFU on the RBTS$_{\text{BPO2-E1}}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	0.4090	1.0160	2.9250	6.9450
	2	0.4398	1.0864	3.0363	7.5168
	5	0.6266	1.7237	4.5202	11.5107
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	2.0700	4.8200	13.7480	29.4830
	2	2.1954	5.2255	13.8976	31.3021
	5	3.0445	7.8888	19.1455	45.0621
6	0	131.7710	139.1480	149.8290	162.4810
	2	131.8185	139.2794	149.6319	163.1729
	5	132.0400	140.5458	151.6470	168.0242
System	0	134.2501	144.9852	166.5085	198.9277
	2	134.4536	145.5931	166.5724	202.0118
	5	135.7118	150.1618	175.3238	224.6271

Table E.4 EENS Percentage Change (%) due to LFU for the $\text{RBTS}_{\text{BPO2-E1}}$: Case 2

			1 × 20 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.5	6.9	3.8	8.2
	0	5	53.2	69.7	54.5	65.7
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	6.1	8.4	1.1	6.2
	0	5	47.1	63.7	39.3	52.8
6	0	2	0.0	0.1	-0.1	0.4
	0	5	0.2	1.0	1.2	3.4
System	0	2	0.2	0.4	0.0	1.6
	0	5	1.1	3.6	5.3	12.9

Table E.5 Effects of LFU on the $\text{RBTS}_{\text{BPO2-E1}}$: Case 3 Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	0.4100	1.0190	2.9330	6.9630
	2	0.4406	1.0895	3.0445	7.5352
	5	0.6284	1.7284	4.5314	11.5355
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	2.0720	4.8270	13.7640	29.5140
	2	2.1981	5.2326	13.9136	31.3338
	5	3.0480	7.8981	19.1655	45.1023
6	0	8.3350	9.7530	13.4220	20.4900
	2	8.3849	9.8861	13.6055	21.2226
	5	8.7044	10.9374	15.7530	26.3009
System	0	10.8176	15.5997	30.1264	56.9845
	2	11.0239	16.2093	30.5707	60.1113
	5	12.3816	20.5674	39.4610	82.9684

Table E.6 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO2-E1}}$: Case 3

			1 × 20 MW Generating Unit Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.5	6.9	3.8	8.2
	0	5	53.3	69.6	54.5	65.7
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	6.1	8.4	1.1	6.2
	0	5	47.1	63.6	39.2	52.8
6	0	2	0.6	1.4	1.4	3.6
	0	5	4.4	12.1	17.4	28.4
System	0	2	1.9	3.9	1.5	5.5
	0	5	14.5	31.8	31.0	45.6

E.2 MRBTS$_{\text{BPO2-E1}}$ Generation Expansion 1 Case Analysis

Tables E.7, E.9 and E.11 show the effects of LFU as generation is added to the MRBTS$_{\text{BPO2-E1}}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables E.8, E.10 and E.12, respectively.

Table E.7 Effects of LFU on the MRBTS$_{\text{BPO2-E1}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0006
3	0	0.6880	2.1020	7.4230	18.7570
	2	0.7662	2.3167	7.7663	20.1381
	5	1.2958	4.1743	11.5435	28.2580
4	0	0.0010	0.0030	0.0110	0.0250
	2	0.0008	0.0035	0.0110	0.0268
	5	0.0018	0.0059	0.0156	0.0366
5	0	2.0700	4.7690	13.5570	29.2920
	2	2.1959	5.1624	13.7304	31.1270
	5	3.0398	7.8155	19.0177	44.9734

Table E.7 (Continued)

		1 × 20 MW Generating Unit Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	(%)	190	200	210	220
6	0	1.1470	2.1290	5.1280	11.3200
	2	1.1939	2.2511	5.3171	12.0186
	5	1.4942	3.2092	7.3255	16.9029
System	0	3.9062	9.0028	26.1187	59.3936
	2	4.1574	9.7335	26.8249	63.3104
	5	5.8315	15.2047	37.9019	90.1712

Table E.8 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO2-E1}$: Case 1

			1 × 20 MW Generating Unit Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	190	200	210	220
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	11.4	10.2	4.6	7.4
	0	5	88.3	98.6	55.5	50.7
4	0	2	-20.0	16.7	0.0	7.2
	0	5	80.0	96.7	41.8	46.4
5	0	2	6.1	8.2	1.3	6.3
	0	5	46.9	63.9	40.3	53.5
6	0	2	4.1	5.7	3.7	6.2
	0	5	30.3	50.7	42.9	49.3
System	0	2	6.4	8.1	2.7	6.6
	0	5	49.3	68.9	45.1	51.8

Table E.9 Effects of LFU on the MRBTS$_{BPO2-E1}$: Case 2 Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	(%)	190	200	210	220
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	0.4090	1.0160	2.9270	6.9510
	2	0.4398	1.0871	3.0384	7.5229
	5	0.6267	1.7247	4.5237	11.5208
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295

Table E.9 (Continued)

		1 × 20 MW Generating Unit Added at Bus 5			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**190**	**200**	**210**	**220**
5	0	2.0720	4.8260	13.7670	29.5230
	2	2.1977	5.2323	13.9164	31.3439
	5	3.0479	7.8991	19.1707	45.1183
6	0	1.0470	2.0790	5.1500	11.4660
	2	1.0945	2.2035	5.3455	12.1591
	5	1.4015	3.1716	7.3635	17.0176
System	0	3.5285	7.9237	21.8506	47.9584
	2	3.7322	8.5248	22.3073	51.0460
	5	5.0775	12.7996	31.0695	73.6867

Table E.10 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO2\text{-}E1}$: Case 2

			1 × 20 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**190**	**200**	**210**	**220**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.5	7.0	3.8	8.2
	0	5	53.2	69.8	54.6	65.7
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	6.1	8.4	1.1	6.2
	0	5	47.1	63.7	39.3	52.8
6	0	2	4.5	6.0	3.8	6.0
	0	5	33.9	52.6	43.0	48.4
System	0	2	5.8	7.6	2.1	6.4
	0	5	43.9	61.5	42.2	53.6

Table E.11 Effects of LFU on the MRBTS$_{BPO2\text{-}E1}$: Case 3 Annual Load Bus and System EENS (MWh/year)

		1 × 20 MW Generating Unit Added at Bus 6			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**190**	**200**	**210**	**220**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0002
3	0	0.4090	1.0160	2.9270	6.9510
	2	0.4398	1.0871	3.0384	7.5229
	5	0.6267	1.7247	4.5237	11.5208

Table E.11 (Continued)

Bus	LFU (%)	1 × 20 MW Generating Unit Added at Bus 6 System Peak Load Level (MW) 190	200	210	220
4	0	0.0000	0.0010	0.0060	0.0180
	2	0.0001	0.0014	0.0066	0.0195
	5	0.0006	0.0032	0.0107	0.0295
5	0	2.0720	4.8260	13.7670	29.5230
	2	2.1995	5.2323	13.9164	31.3439
	5	3.0497	7.8995	19.1707	45.1183
6	0	0.7510	1.7690	4.8230	11.1260
	2	0.8019	1.8935	5.0195	11.8191
	5	1.1093	2.8618	7.0379	16.6777
System	0	3.2323	7.6132	21.5234	47.6178
	2	3.4414	8.2143	21.9809	50.7054
	5	4.7867	12.4897	30.7435	73.3468

Table E.12 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO2-E1}$: Case 3

Bus	LFU (%) From	To	1 × 20 MW Generating Unit Added at Bus 6 System Peak Load Level (MW) 190	200	210	220
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	7.5	7.0	3.8	8.2
	0	5	53.2	69.8	54.6	65.7
4	0	2	–	40.0	10.0	8.3
	0	5	–	220.0	78.3	63.9
5	0	2	6.2	8.4	1.1	6.2
	0	5	47.2	63.7	39.3	52.8
6	0	2	6.8	7.0	4.1	6.2
	0	5	47.7	61.8	45.9	49.9
System	0	2	6.5	7.9	2.1	6.5
	0	5	48.1	64.1	42.8	54.0

E.3 RBTS$_{BPO2-E2}$ Generation Expansion 2 Case Analysis

As shown in Table 4.21, Generation Expansion E-2 considers the addition of *40 MW* of generation in two *20 MW* units at each of the selected buses in the RBTS$_{BPO2-E2}$. Tables E.13, E.15 and E.17 show the effects of LFU for the three cases. The EENS percentage changes for each case are given in Tables E.14, E.16 and E.18.

Table E.13 Effects of LFU on the RBTS$_{\text{BPO2-E2}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	5.5100	14.5200	32.7440	71.1780
	2	5.7931	15.5985	35.6143	71.0393
	5	8.7589	21.5766	44.9149	82.4054
4	0	0.0000	0.0000	0.0010	0.0040
	2	0.0000	0.0001	0.0011	0.0043
	5	0.0001	0.0006	0.0027	0.0095
5	0	2.6810	5.9070	13.1330	32.1530
	2	2.7392	6.3315	14.7653	33.7522
	5	3.9049	9.4368	22.4377	50.3928
6	0	151.3320	159.0370	168.0780	182.6600
	2	150.9579	159.1874	168.9355	182.8269
	5	151.3532	160.2443	171.7023	188.5731
System	0	159.5229	179.4635	213.9553	285.9949
	2	159.4903	181.1174	219.3161	287.6226
	5	164.0169	191.2582	239.0575	321.3807

Table E.14 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO2-E2}}$: Case 1

			2 × 20 MW Generating Units Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	7.4	8.8	-0.2
	0	5	59.0	48.6	37.2	15.8
4	0	2	–	–	10.0	7.5
	0	5	–	–	170.0	137.5
5	0	2	2.2	7.2	12.4	5.0
	0	5	45.7	59.8	70.8	56.7
6	0	2	-0.2	0.1	0.5	0.1
	0	5	0.0	0.8	2.2	3.2
System	0	2	0.0	0.9	2.5	0.6
	0	5	2.8	6.6	11.7	12.4

Table E.15 Effects of LFU on the RBTS$_{\text{BPO2-E2}}$: Case 2
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 5			
		System Peak Load Level (MW)			
Bus	**LFU (%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	0.3460	0.8930	2.2270	6.4060
	2	0.3632	0.9784	2.5882	6.7315
	5	0.5835	1.6455	4.3990	10.6736
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0039	0.0115
5	0	2.2530	5.3410	12.3900	31.0000
	2	2.3088	5.7612	13.9849	32.6139
	5	3.4464	8.8189	21.5737	49.1301
6	0	150.9680	158.6060	167.5430	181.9410
	2	150.5963	158.7539	168.3892	182.1019
	5	150.9790	159.7857	171.1142	187.7860
System	0	153.5672	164.8408	182.1607	219.3534
	2	153.2683	165.4939	184.9636	221.4537
	5	155.0092	170.2514	197.0909	247.6016

Table E.16 EENS Percentage Change (%)
due to LFU for the RBTS$_{\text{BPO2-E2}}$: Case 2

			2 × 20 MW Generating Units Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.0	9.6	16.2	5.1
	0	5	68.6	84.3	97.5	66.6
4	0	2	–	–	60.0	14.0
	0	5	–	–	290.0	130.0
5	0	2	2.5	7.9	12.9	5.2
	0	5	53.0	65.1	74.1	58.5
6	0	2	-0.2	0.1	0.5	0.1
	0	5	0.0	0.7	2.1	3.2
System	0	2	-0.2	0.4	1.5	1.0
	0	5	0.9	3.3	8.2	12.9

Table E.17 Effects of LFU on the RBTS$_{BPO2\text{-}E2}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	0.3550	0.9120	2.2650	6.4870
	2	0.3721	0.9985	2.6298	6.8145
	5	0.5955	1.6720	4.4536	10.7794
4	0	0.0000	0.0000	0.0010	0.0060
	2	0.0000	0.0001	0.0016	0.0061
	5	0.0001	0.0008	0.0039	0.0120
5	0	2.2690	5.3710	12.4440	31.1140
	2	2.3248	5.7921	14.0438	32.7308
	5	3.4659	8.8584	21.6535	49.2875
6	0	1.3210	2.4330	4.8780	11.5410
	2	1.3555	2.5844	5.4093	12.0168
	5	1.7510	3.6379	8.0833	17.7411
System	0	3.9443	8.7166	19.5891	49.1473
	2	4.0523	9.3754	22.0848	51.5679
	5	5.8123	14.1696	34.1946	77.8197

Table E.18 EENS Percentage Change (%)
due to LFU for the RBTS$_{BPO2\text{-}E2}$: Case 3

			2 × 20 MW Generating Units Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	4.8	9.5	16.1	5.0
	0	5	67.7	83.3	96.6	66.2
4	0	2	–	–	60.0	1.7
	0	5	–	–	290.0	100.0
5	0	2	2.5	7.8	12.9	5.2
	0	5	52.8	64.9	74.0	58.4
6	0	2	2.6	6.2	10.9	4.1
	0	5	32.6	49.5	65.7	53.7
System	0	2	2.7	7.6	12.7	4.9
	0	5	47.4	62.6	74.6	58.3

E.4 MRBTS$_{\text{BPO2-E2}}$ Generation Expansion 2 Case Analysis

Tables E.19, E.21 and E.23 show the effects of LFU as generation is added to the MRBTS$_{\text{BPO2-E2}}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables E.20, E.22 and E.24, respectively.

Table E.19 Effects of LFU on the MRBTS$_{\text{BPO2-E2}}$: Case 1
Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	2 × 20 MW Generating Units Added at Bus 1			
		System Peak Load Level (MW)			
		210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	5.5120	14.5270	32.7610	71.2180
	2	5.7956	15.6061	35.6337	71.0795
	5	8.7629	21.5881	44.9397	82.4518
4	0	0.0000	0.0000	0.0010	0.0040
	2	0.0000	0.0001	0.0011	0.0043
	5	0.0001	0.0006	0.0027	0.0095
5	0	2.6830	5.9120	13.1450	32.1830
	2	2.7412	6.3368	14.7788	33.7833
	5	3.9079	9.4450	22.4579	50.4395
6	0	1.1400	2.2580	4.7140	11.3990
	2	1.1729	2.4090	5.2459	11.8854
	5	1.5687	3.4669	7.9350	17.6451
System	0	9.3348	22.6970	50.6218	114.8038
	2	9.7096	24.3522	55.6596	116.7523
	5	14.2396	34.5008	75.3359	150.5456

Table E.20 EENS Percentage Change (%)
due to LFU for the MRBTS$_{\text{BPO2-E2}}$: Case 1

Bus	LFU (%)		2 × 20 MW Generating Units Added at Bus 1			
			System Peak Load Level (MW)			
	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	7.4	8.8	-0.2
	0	5	59.0	48.6	37.2	15.8
4	0	2	–	–	10.0	7.5
	0	5	–	–	170.0	137.5
5	0	2	2.2	7.2	12.4	5.0
	0	5	45.7	59.8	70.8	56.7

Table E.20 (Continued)

			2 × 20 MW Generating Units Added at Bus 1			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
6	0	2	2.9	6.7	11.3	4.3
	0	5	37.6	53.5	68.3	54.8
System	0	2	4.0	7.3	10.0	1.7
	0	5	52.5	52.0	48.8	31.1

Table E.21 Effects of LFU on the MRBTS$_{BPO2\text{-}E2}$: Case 2 Annual Load Bus and System EENS (MWh/year)

		2 × 20 MW Generating Units Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	0.3460	0.8940	2.2280	6.4130
	2	0.3635	0.9791	2.5902	6.7388
	5	0.5839	1.6470	4.4031	10.6846
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0039	0.0115
5	0	2.2560	5.3490	12.4080	31.0400
	2	2.3119	5.7698	14.0045	32.6559
	5	3.4510	8.8311	21.6020	49.1908
6	0	0.7760	1.8290	4.1820	10.6870
	2	0.8116	1.9768	4.7025	11.1666
	5	1.1949	3.0106	7.3512	16.8662
System	0	3.3790	8.0724	18.8202	48.1453
	2	3.4874	8.7263	21.2994	50.5674
	5	5.2308	13.4900	33.3606	76.7532

Table E.22 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO2\text{-}E2}$: Case 2

			2 × 20 MW Generating Units Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	9.5	16.3	5.1
	0	5	68.8	84.2	97.6	66.6

Table E.22 (Continued)

Bus	LFU (%) From	LFU (%) To	2 × 20 MW Generating Units Added at Bus 5 System Peak Load Level (MW) 210	220	230	240
4	0	2	–	–	60.0	14.0
	0	5	–	–	290.0	130.0
5	0	2	2.5	7.9	12.9	5.2
	0	5	53.0	65.1	74.1	58.5
6	0	2	4.6	8.1	12.4	4.5
	0	5	54.0	64.6	75.8	57.8
System	0	2	3.2	8.1	13.2	5.0
	0	5	54.8	67.1	77.3	59.4

Table E.23 Effects of LFU on the MRBTS$_{BPO2-E2}$: Case 3 Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	2 × 20 MW Generating Units Added at Bus 6 System Peak Load Level (MW) 210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0000
3	0	0.3460	0.8940	2.2280	6.4130
	2	0.3635	0.9791	2.5902	6.7388
	5	0.5839	1.6470	4.4031	10.6846
4	0	0.0000	0.0000	0.0010	0.0050
	2	0.0000	0.0001	0.0016	0.0057
	5	0.0001	0.0008	0.0039	0.0115
5	0	2.2560	5.3490	12.4080	31.0400
	2	2.3119	5.7698	14.0045	32.6559
	5	3.4510	8.8311	21.6020	49.1908
6	0	0.7110	1.7610	4.1110	10.6120
	2	0.7464	1.9085	4.6312	11.0919
	5	1.1299	2.9423	7.2799	16.7918
System	0	3.3135	8.0040	18.7489	48.0706
	2	3.4220	8.6579	21.2279	50.4927
	5	5.1654	13.4215	33.2891	76.6786

Table E.24 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO2\text{-}E2}$: Case 3

			2 × 20 MW Generating Units Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	9.5	16.3	5.1
	0	5	68.8	84.2	97.6	66.6
4	0	2	–	–	60.0	14.0
	0	5	–	–	290.0	130.0
5	0	2	2.5	7.9	12.9	5.2
	0	5	53.0	65.1	74.1	58.5
6	0	2	5.0	8.4	12.7	4.5
	0	5	58.9	67.1	77.1	58.2
System	0	2	3.3	8.2	13.2	5.0
	0	5	55.9	67.7	77.6	59.5

E.5 RBTS$_{BPO2\text{-}E3}$ Generation Expansion 3 Case Analysis

As shown in Table 4.21, Generation Expansion E-3 considers the addition of *40 MW* of generation in a *40 MW* unit at each of the selected buses in the RBTS$_{BPO2\text{-}E3}$. Tables E.25, E.27 and E.29 show the effects of LFU for the three cases. The EENS percentage changes for each case are given in Tables E.26, E.28 and E.30.

Table E.25 Effects of LFU on the RBTS$_{BPO2\text{-}E3}$: Case 1
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 1			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0001
3	0	5.7010	14.9280	33.5490	73.0500
	2	5.9895	16.0240	36.5132	72.9768
	5	9.0189	22.1615	46.2021	85.0737
4	0	0.0000	0.0010	0.0040	0.0150
	2	0.0001	0.0014	0.0051	0.0156
	5	0.0007	0.0030	0.0100	0.0266
5	0	3.3130	7.4730	16.6190	39.3670
	2	3.3937	8.0116	18.5380	40.8222
	5	4.8748	11.6931	26.8629	58.0016

Table E.25 (Continued)

Bus	LFU (%)	1 × 40 MW Generating Unit Added at Bus 1 System Peak Load Level (MW) 210	220	230	240
6	0	146.3240	154.0770	163.5650	179.7890
	2	145.9654	154.2712	164.5666	179.9856
	5	146.4544	155.6148	167.9214	186.4134
System	0	155.3382	176.4794	213.7378	292.2200
	2	155.3488	178.3083	219.6232	293.8003
	5	160.3490	189.4729	240.9966	329.5151

Table E.26 EENS Percentage Change (%) due to LFU for the RBTS$_{BPO2\text{-}E3}$: Case 1

	LFU (%)		1 × 40 MW Generating Unit Added at Bus 1 System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	7.3	8.8	-0.1
	0	5	58.2	48.5	37.7	16.5
4	0	2	–	40.0	27.5	4.0
	0	5	–	200.0	150.0	77.3
5	0	2	2.4	7.2	11.5	3.7
	0	5	47.1	56.5	61.6	47.3
6	0	2	-0.2	0.1	0.6	0.1
	0	5	0.1	1.0	2.7	3.7
System	0	2	0.0	1.0	2.8	0.5
	0	5	3.2	7.4	12.8	12.8

Table E.27 Effects of LFU on the RBTS$_{BPO2\text{-}E3}$: Case 2 Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	1 × 40 MW Generating Unit Added at Bus 5 System Peak Load Level (MW) 210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	0.7630	1.7710	3.8410	9.3850
	2	0.7881	1.8861	4.2988	9.7475
	5	1.1228	2.7484	6.4450	14.2411
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328

Table E.27 (Continued)

		1 × 40 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
5	0	3.1480	7.2890	16.3690	39.0140
	2	3.2238	7.8221	18.2834	40.4736
	5	4.6947	11.4802	26.5850	57.5875
6	0	146.1420	153.9070	163.3940	179.5650
	2	145.7868	154.0998	164.3899	179.7643
	5	146.2789	155.4359	167.7246	186.1768
System	0	150.0548	162.9698	183.6127	227.9849
	2	149.8001	163.8116	186.9815	230.0076
	5	152.0984	169.6700	200.7692	258.0390

Table E.28 EENS Percentage Change (%) due to LFU for the RBTS$_{BPO2\text{-}E3}$: Case 2

			1 × 40 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	6.5	11.9	3.9
	0	5	47.2	55.2	67.8	51.7
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	2.4	7.3	11.7	3.7
	0	5	49.1	57.5	62.4	47.6
6	0	2	-0.2	0.1	0.6	0.1
	0	5	0.1	1.0	2.7	3.7
System	0	2	-0.2	0.5	1.8	0.9
	0	5	1.4	4.1	9.3	13.2

Table E.29 Effects of LFU on the RBTS$_{BPO2\text{-}E3}$: Case 3 Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	0.7710	1.7890	3.8800	9.4710
	2	0.7964	1.9057	4.3412	9.8359
	5	1.1343	2.7751	6.5032	14.3579

Table E.29 (Continued)

Bus	LFU (%)	1 × 40 MW Generating Unit Added at Bus 6 System Peak Load Level (MW) 210	220	230	240
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0145	0.0329
5	0	3.1660	7.3240	16.4350	39.1520
	2	3.2421	7.8586	18.3552	40.6142
	5	4.7173	11.5272	26.6793	57.7685
6	0	6.5050	8.1450	11.5080	20.3290
	2	6.5279	8.3378	12.1997	20.8248
	5	7.0201	9.6738	15.4595	27.2448
System	0	10.4434	17.2617	31.8317	68.9738
	2	10.5676	18.1059	34.9060	71.2976
	5	12.8738	23.9822	48.6569	99.4049

Table E.30 EENS Percentage Change (%) due to LFU for the RBTS$_{\text{BPO2-E3}}$: Case 3

	LFU (%)		1 × 40 MW Generating Unit Added at Bus 6 System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	6.5	11.9	3.9
	0	5	47.1	55.1	67.6	51.6
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	81.3	56.7
5	0	2	2.4	7.3	11.7	3.7
	0	5	49.0	57.4	62.3	47.5
6	0	2	0.4	2.4	6.0	2.4
	0	5	7.9	18.8	34.3	34.0
System	0	2	1.2	4.9	9.7	3.4
	0	5	23.3	38.9	52.9	44.1

E.6 MRBTS$_{\text{BPO2-E3}}$ Generation Expansion 3 Case Analysis

Tables E.31, E.33 and E.35 show the effects of LFU as generation is added to the MRBTS$_{\text{BPO2-E3}}$ at either Bus 1, Bus 5 or Bus 6, respectively. The EENS percentage changes for each case are given in Tables E.32, E.34 and E.36, respectively.

Table E.31 Effects of LFU on the MRBTS$_{BPO2\text{-}E3}$: Case 1
Annual Load Bus and System EENS (MWh/year)

Bus	LFU (%)	1 × 40 MW Generating Unit Added at Bus 1 System Peak Load Level (MW) 210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000
	5	0.0000	0.0000	0.0000	0.0001
3	0	5.7040	14.9410	33.5800	71.2180
	2	5.9931	16.0376	36.5475	71.0795
	5	9.0259	22.1818	46.2452	85.1538
4	0	0.0000	0.0010	0.0040	0.0040
	2	0.0001	0.0014	0.0051	0.0043
	5	0.0007	0.0030	0.0100	0.0266
5	0	3.3150	7.4780	16.6320	32.1830
	2	3.3959	8.0172	18.5525	33.7833
	5	4.8781	11.7019	26.8850	58.0514
6	0	1.6380	3.0470	6.1920	11.3990
	2	1.6722	3.2415	6.8796	11.8854
	5	2.1617	4.5863	10.1597	21.7547
System	0	10.6585	25.4670	56.4087	127.3421
	2	11.0618	27.2976	61.9846	129.2312
	5	16.0669	38.4731	83.3002	164.9861

Table E.32 EENS Percentage Change (%)
due to LFU for the MRBTS$_{BPO2\text{-}E3}$: Case 1

Bus	LFU (%) From	LFU (%) To	1 × 40 MW Generating Unit Added at Bus 1 System Peak Load Level (MW) 210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	5.1	7.3	8.8	-0.2
	0	5	58.2	48.5	37.7	19.6
4	0	2	–	40.0	27.5	7.5
	0	5	–	200.0	150.0	565.0
5	0	2	2.4	7.2	11.5	5.0
	0	5	47.2	56.5	61.6	80.4
6	0	2	2.1	6.4	11.1	4.3
	0	5	32.0	50.5	64.1	90.8
System	0	2	3.8	7.2	9.9	1.5
	0	5	50.7	51.1	47.7	29.6

Table E.33 Effects of LFU on the MRBTS$_{BPO2\text{-}E3}$: Case 2 Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 5			
	LFU	System Peak Load Level (MW)			
Bus	(%)	210	220	230	240
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	0.7630	1.7710	3.8420	9.3910
	2	0.7881	1.8864	4.3005	9.7539
	5	1.1230	2.7495	6.4489	14.2522
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328
5	0	3.1520	7.2980	16.3920	39.0640
	2	3.2276	7.8322	18.3080	40.5258
	5	4.7003	11.4950	26.6194	57.6593
6	0	1.4570	2.8780	6.0250	14.5940
	2	1.4943	3.0713	6.7067	15.1006
	5	1.9869	4.4095	9.9689	21.5300
System	0	5.3738	11.9514	26.2674	63.0702
	2	5.5115	12.7943	29.3251	65.4030
	5	7.8129	18.6602	43.0519	93.4748

Table E.34 EENS Percentage Change (%) due to LFU for the MRBTS$_{BPO2\text{-}E3}$: Case 2

			1 × 40 MW Generating Unit Added at Bus 5			
	LFU (%)		System Peak Load Level (MW)			
Bus	From	To	210	220	230	240
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	6.5	11.9	3.9
	0	5	47.2	55.3	67.9	51.8
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	2.4	7.3	11.7	3.7
	0	5	49.1	57.5	62.4	47.6
6	0	2	2.6	6.7	11.3	3.5
	0	5	36.4	53.2	65.5	47.5
System	0	2	2.6	7.1	11.6	3.7
	0	5	45.4	56.1	63.9	48.2

Table E.35 Effects of LFU on the $\text{MRBTS}_{\text{BPO2-E3}}$: Case 3
Annual Load Bus and System EENS (MWh/year)

		1 × 40 MW Generating Unit Added at Bus 6			
	LFU	System Peak Load Level (MW)			
Bus	**(%)**	**210**	**220**	**230**	**240**
2	0	0.0000	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0001
	5	0.0000	0.0000	0.0001	0.0005
3	0	0.7630	1.7710	3.8420	9.3910
	2	0.7881	1.8864	4.3005	9.7539
	5	1.1230	2.7495	6.4489	14.2522
4	0	0.0010	0.0030	0.0080	0.0210
	2	0.0013	0.0035	0.0094	0.0222
	5	0.0019	0.0057	0.0144	0.0328
5	0	3.1520	7.2980	16.3920	39.0640
	2	3.2276	7.8322	18.3080	40.5258
	5	4.7003	11.4950	26.6194	57.6593
6	0	1.1360	2.5430	5.6750	14.2200
	2	1.1739	2.7362	6.3565	14.7298
	5	1.6686	4.0744	9.6159	21.1590
System	0	5.0525	11.6161	25.9180	62.6964
	2	5.1911	12.4590	28.9749	65.0321
	5	7.4944	18.3247	42.6993	93.1039

Table E.36 EENS Percentage Change (%)
due to LFU for the $\text{MRBTS}_{\text{BPO2-E3}}$: Case 3

			1 × 40 MW Generating Unit Added at Bus 6			
	LFU (%)		System Peak Load Level (MW)			
Bus	**From**	**To**	**210**	**220**	**230**	**240**
2	0	2	–	–	–	–
	0	5	–	–	–	–
3	0	2	3.3	6.5	11.9	3.9
	0	5	47.2	55.3	67.9	51.8
4	0	2	30.0	16.7	17.5	5.7
	0	5	90.0	90.0	80.0	56.2
5	0	2	2.4	7.3	11.7	3.7
	0	5	49.1	57.5	62.4	47.6
6	0	2	3.3	7.6	12.0	3.6
	0	5	46.9	60.2	69.4	48.8
System	0	2	2.7	7.3	11.8	3.7
	0	5	48.3	57.8	64.7	48.5