Incorporating Substation and Switching Station Related Outages in Composite System Reliability Evaluation

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By

Rajesh U Nighot

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Abstract

This thesis presents the development of a new method for incorporating station related outages in composite or bulk system reliability analysis. Station related failures can cause multiple component outages that can propagate to other parts of the network resulting in severe damages. In order to minimize the effects of station related outages on the composite system performance it is necessary for the designer to assess their effects. This task can be achieved by including station related outages in the composite system evaluation.

Monte Carlo simulation is used in this research to assess composite system reliability. The new method described in this thesis is used to include station related outages in the reliability evaluation of two composite test systems. This new method is relatively simple and can be used to consider multiple component outages due to station related failures in composite system reliability evaluation. In this approach, the effects of station related outages are combined with the connected terminal failure parameters.

Reliability studies conducted on the two composite test systems demonstrates that station failures significantly affect the system performance. The system reliability can be improved by selecting appropriate station configurations. This is illustrated by application to the two composite test systems.

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List of Symbols and Abbreviations

HL	Hierarchical Level
S	System state
MECORE	Monte Carlo Enumeration Composite System Reliability
RBTS	Roy Billinton Test System
RTS	Reliability Test System
G	Generator
I/P	Input
EPRI	Electric Power Research Institute
BC	British Columbia
NARP	N-Area Reliability Program
ERCOT	Electric Reliability Council of Texas
ENEL	Ente Nazionale per l'Energia Elettrica
CREAM	Composite Reliability Evaluation and Management
EENS	Expected Energy Not Supplied
CPU	Central Processing Unit (Computer)
ENLC	Expected Number of Load Curtailment
PLC	Probability of Load Curtailment
ELC	Expected Load Curtailment
EENS	Expected Energy Not Supplied
ENLC	Expected Number of Load Curtailment
ADLC	Average Duration of Load Curtailment
EDLC	Expected Duration of Load Curtailment
EDC	Expected Damage Cost
BPII	Bulk Power Interruption Index
BECI	Bulk Power Energy Curtailment Index
BPACI	Bulk Power Supply Average Curtailment Index
MBECI	Modified Bulk Energy Curtailment Index
SI	Severity Index
IEAR	Interrupted Energy Assessment Rate
λ	Failure rate
$\mu, \mu_1, \mu_2, \mu_{12}$	Repair rate
m	Mean operating time
r	Mean repair time
T	System cycle time
MTTF	Mean Time To Fail
MTTR	Mean Time To Repair

MTBF	Mean Time Between Failures
P	Probability
λ_a	Active failure rate (circuit breaker)
μ_{sw}	Switching rate (circuit breaker)
λ_p	Passive failure rate (circuit breaker)
λ_b	Bus bar failure rate
μ_b	Bus bar repair rate
λ_t	Transformer failure rate
μ_t	Transformer repair rate
CB	Circuit Breaker
BB	Bus Bar
CB (A)	Active failure of a circuit breaker
CB (P)	Passive failure of a circuit breaker
T	Terminal
U	Unavailability
λ_{cs}	Failure rate of a minimal cut set
Ucs	Unavailability of a minimal cut set
n	Total number of independent minimal cut sets
CIGRE	International Council on Large Electric Systems
HV	High Voltage
GT	Generator and Transformer unit
CEA	Canadian Electric Association
PSS/E	Power System Simulator for Engineer
PTI	Power Technologies Inc
L	Transmission line
p.u	per unit
FOR	Forced Outage Rate
EDNS	Expected Demand Not Supplied
s	Switching time

Chapter 1

Introduction

1.1 Introduction

Modern society is highly dependent on the efficient operation of electric power systems and has developed in such a way that even a small interruption in electric power supply has a significant effect. Customers expect that electric power should be available 24 hours a day, 7 days a week without any interruption. The article *Power Cuts Can Wreck Business April 12, 1999: Fortune Magazine*, is ample evidence that illustrates the dependence of the world's advanced nations on electric power supply. In the early days of electricity supply, electric power was considered to be a luxury, but today it is a highly valued commodity. Although the number of electric power outages in developed nations has reduced considerably, developing nations are still coping with the problem of frequent power failures. The ability of a power system to provide customers with an adequate supply is usually designated by the term "reliability"[1].

Economic growth is highly dependent on the existence of reliable electricity supply at an affordable cost. Major electricity outages can occur due to incorrect planning and operation, equipment failures, vandalism, environmental conditions and adverse weather effects. The creation and operation of a completely reliable electric power system is technically and economically not viable. The practical way to avoid major power outages is to make a power system more reliable. This is usually accomplished by increasing the system redundancy and the capital investment. Increasing the capital investment will result in increased cost to the customer. Therefore there has to be a balance between the cost and reliability of an electric power system. Power system planners and designers sometimes find it difficult to achieve a balance between reliability and cost during the planning phase. Many electric power utilities use both deterministic and probabilistic techniques during the planning phase in order to assess power system reliability [2-12]. Probabilistic techniques can be used to incorporate a wide range of system behavior and are preferred over deterministic techniques [2]. Many probabilistic techniques are now available in the form of computer softwares for reliability analysis [5,12].

There are, however, still many unanswered problems particularly in the new deregulated environment and considerable research is in progress to address these issues. It is important to consider the vast amount of work that has been done over the last five decades [2-12], when considering the problems that face electric power utilities at the present time. Some of the basic concepts associated with power system reliability are briefly introduced in the following section.

1.2 Brief review of power system reliability evaluation

Adequacy and security:

Power system reliability assessment is primarily focused on an analysis of the healthy and failure states of a power system. Power system reliability can be subdivided in two classes as shown in Figure 1.1 [1,2].

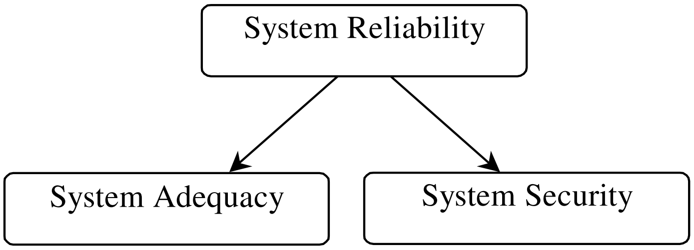


Figure 1.1: System reliability, adequacy and security

Adequacy assessment involves the determination of sufficient facilities within the system to satisfy the customer load and deals with static conditions in the power system. Power system security is the ability to respond to disturbance arising within the system and therefore deals with the dynamic conditions in the system.

A power system is a complex network and the reliability evaluation of the entire configuration is a difficult task. Despite the evaluation complexity, the need for reliability assessment is ever increasing and more utilities are investing time in reliability analysis. In order to reduce the complexity of an overall power system the network can be divided into three functional zones as shown in the Figure 1.2. These functional zones can be grouped to form three hierarchical levels (HL) for the purpose of reliability analysis. Figure 1.2 shows the three hierarchical levels.

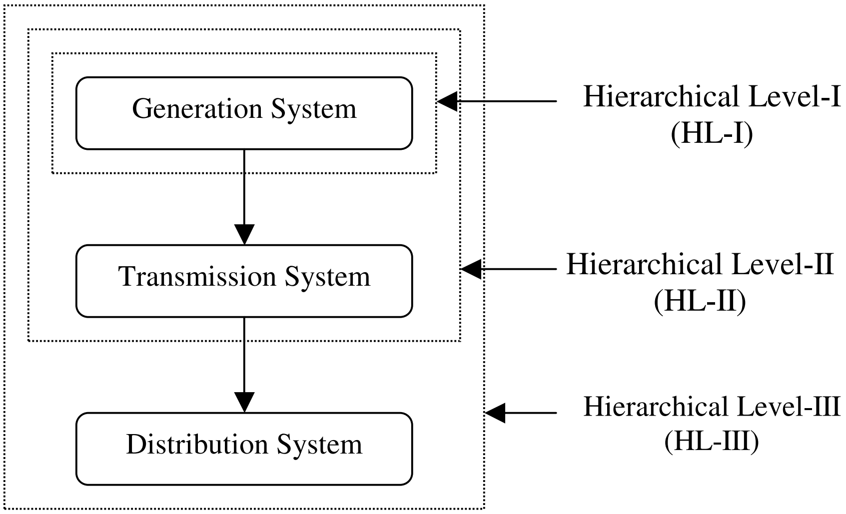


Figure 1.2: Power system hierarchical levels

Hierarchical Level-I involves the generation facilities and deals with the ability of these facilities to satisfy the total system load. Hierarchical Level-II involves the combination of generation facilities and the transmission system and is designated as the composite or bulk system. Reliability assessment at HL-II involves the ability of the composite system to satisfy the load requirements at the assigned load points. Hierarchical Level -III involves the combination of all the three functional zones. Reliability analysis at HL-III is very complex and is rarely done [2]. This thesis deals with adequacy assessment at HL-II. The basic concepts are presented in the following section.

1.3 Review of composite system reliability

Composite system (HL-II or bulk system) reliability evaluation considers both the generation and transmission facilities in the analysis and has been defined as follows.

> "Reliability is the degree of assurance of a bulk power supply in delivering electricity to major points of distribution."[1, page 297]

Reliability evaluation at HL-II is a complex task that involves the analysis of generation and transmission contingencies, the modeling of the operating polices necessary to order dispatch of generation units, assessment of power flows on transmission system components, the alleviation of network violations and load shedding if required [1,2].

Two basic tools i.e. analytical methods and Monte Carlo simulation have been extensively utilized for HL-I reliability evaluation. Similar techniques have been applied to HL-II evaluation and have been published [14]. The first fundamental developments in composite system reliability evaluation were associated with the analytical approach. In recent years, the focus has been on the utilization of Monte Carlo simulation in HL-II studies.

Monte Carlo methods were first introduced in the 1940's for solving mathematical problems. Monte Carlo methods simulate the behavior of the system by performing a series of experiments [3]. With the recent and rapid development of digital computers, Monte Carlo methods have been extensively used for simulating stochastic processes. These methods have many advantages over analytical methods in certain circumstances and their application to power system reliability is still developing. Considerable research is still required in the general area of HL-II evaluation due to difficulties encountered with data collection and modeling techniques.

There are a wide range of HL-II indices that can be calculated using the available reliability techniques. These indices can be used to assess the performance at the individual load points or for the overall system.

1.4 Predictive indices and past performance indices

HL-II reliability indices can be divided into the two categories of predictive indices and past performance indices [15,16]. Predictive indices provide information on the future performance of the system and are important planning parameters. Past performance indices indicate the actual system performance and are related to real time operation of the system. Most utilities collect past performance indices in order to assess their composite system performance.

Both analytical techniques and Monte Carlo techniques can be used to calculate predictive indices [4]. The concepts associated with Monte Carlo simulation are still developing and more research needs to be done to understand and deal with specific system problems. System outages can occur due to conditions created by multiple component failures.

These component outages can be categorized as follows [2,17]

1. independent outages,
2. dependent outages,
3. common cause or common mode outages and
4. station originated outages.

Data requirements for analyses depend on the kinds of outages considered in the analyses. In the real world, all types of component outages occur and therefore consideration should be given to them if they affect the system performance.

The following is a brief discussion on the four major outage types listed above.

Independent outages:

This outage event is related to individual component failures and is relatively easy to calculate. A simple two state model is usually used to represent a component. Most reliability evaluation techniques incorporate independent events in contingency evaluations.

Dependent outages:

These kinds of outage are dependent on the occurrence of one or more other outages and are not normally included in reliability studies.

Common mode outages:

These kinds of outage are due to the occurrence of an event that consists of two or more simultaneous outages [2]. Common mode outages have relatively high probabilities of occurrence and can have a severe effect on the system performance.

Station outages:

These outages are caused by the failure of one or more station components. Station component outages can have a significant effect on the system performance as they can result in the removal from service of generators, transmission lines, and other important components.

Evaluating all HL-II component outages can be a complex activity. A major task in HL-II reliability evaluation is the determination of the required outage depth when evaluating component outages.

The focus of this thesis is to improve the ability to conduct HL-II evaluation and is described in detail in the following section.

1.5 Objective of thesis

The basic objectives of this thesis are to examine the impact of station related failures on composite system reliability and to develop a relatively simple technique to include these outages in HL-II reliability evaluation.

Considerable attention has been given to the inclusion of station related outages in composite system reliability evaluation [18-29]. Stations are complicated networks and play a very important role in composite system operation. A station can connect many transmission lines, generators, reactors etc and is a node where power transfer takes place.

The basic functions of a station are listed below [30],

1. control the flow of current,
2. monitor the flow of current,
3. step up and step down voltage levels,
4. maintain voltage frequency and
5. protect system components.

Stations are also referred to as switching stations or substations in this thesis. In the initial stages of composite system reliability evaluation, stations were usually represented by a single bus bar. HL-II analysis was a daunting task during the initial stages of development due to the need for an exhaustive analytical technique and the availability of only minimal computational capability. Station related outages were normally not included in the analyses in the early stages of composite system reliability assessment.

A number of methods for station reliability have been published in the past two decades [1,3, 31- 33]. It is difficult to consider station outages within an evaluation of HL-II reliability due to station sizes and complexity. Methods have, however, been developed to evaluate stations individually and to combine these results in subsequent composite system analyses [31].

These studies clearly indicated the need for further work to accurately represent station related outages in composite system reliability assessment.

In spite of all the attention given to station reliability, stations are difficult to represent in an HL-II reliability evaluation. One of the objectives of this research is to develop a technique that provides the ability to consider station related outages in HL-II evaluation in a simple and realistic manner.

The HL-II reliability analyses shown in this thesis were conducted using the MECORE software. This software was jointly developed by BC-Hydro and the University of Saskatchewan and has been used extensively for reliability analysis.

The next section briefly describes the contents of the subsequent chapters in this thesis.

1.6 Thesis outline

This thesis contains five chapters. This introductory chapter introduces some of the basic concepts in power system reliability evaluation and the objectives of this thesis.

The basic concepts associated with Monte Carlo simulation are briefly explained in Chapter 2. The different types of Monte Carlo simulation and their advantages and disadvantages are discussed here. The MECORE software and its application to two composite test systems are presented.

Chapter 3 deals with the development of a new method to include station related outages in composite system reliability evaluation. The method is described in detail using an example. This method is then used to include station related outages in the analyses of the composite test systems. Different types of stations are included in these analyses and a range of studies are described in Chapter 3.

Sensitivity studies on the reliability of the composite test systems with the inclusion of station related outages are presented in Chapter 4. This chapter also shows the effect on the composite system reliability of varying the station component failure rates.

Chapter 5 presents the conclusions of this research.

Chapter 2

Monte Carlo Simulation Applied to Composite System Reliability

2.1. Introduction

As described in Chapter 1, the objectives of the research presented in this thesis are to investigate the ability to evaluate composite system reliability considering station related outages by utilizing Monte Carlo simulation. Monte Carlo simulation can be used to simulate the stochastic behavior of a system in situations where the problem is too complex to solve manually or with analytical methods. Monte Carlo simulation can be applied to processes that behave randomly e.g. tossing of coins, rolling of die etc. Monte Carlo simulations are used to solve a wide range of problems.

The application of Monte Carlo simulation started in North America. The use of Monte Carlo simulation is continually increasing and is becoming a widespread tool in system analysis. Monte Carlo simulation has been applied to various problems in nuclear engineering, statistical physics, medical sciences, power systems and other fields.

Monte Carlo simulation can be used to perform a series of experiments to simulate the behavior of a power system. The simulations utilize random number generators and probabilistic techniques to solve problems associated with stochastic processes. During the last two decades, many attempts have been made to apply Monte Carlo simulation to evaluate power system reliability. Power systems usually have very complex and large networks and in these situations reliability evaluation with Monte Carlo simulation can be a difficult task [1,2] and requires large amounts of computer storage and computing time. The recent development of high-speed computers with large storage has made the application of Monte Carlo simulation a much easier task. Monte Carlo simulation has been used successfully for reliability evaluation at HL-I and

HL-II. This chapter describes the basic concepts of Monte Carlo simulation and its application to reliability evaluation of composite power systems (HL-II).

2.2. Monte Carlo simulation process: A review

The basic task of a Monte Carlo simulation application is to examine and predict the real behavior patterns for a stochastic system [3]. In power system reliability evaluation, the output of a Monte Carlo simulation is usually the frequency or probability distributions of various reliability parameters. A vital part of Monte Carlo simulation is the random number generation [3]. Random numbers are created using digital computers and are usually normalized to lie between 0 and 1. These random numbers are called pseudo-random numbers because they would be repeated given a sufficiently long period. These random numbers can be converted using appropriate distribution functions before utilization in the simulation process. A Monte Carlo stimulation should be terminated when the results are sufficiently close to the actual values. The procedure for stopping a Monte Carlo simulation involves convergence analysis. Monte Carlo simulation creates a fluctuating convergence process as shown in Figure 2.1 [3].

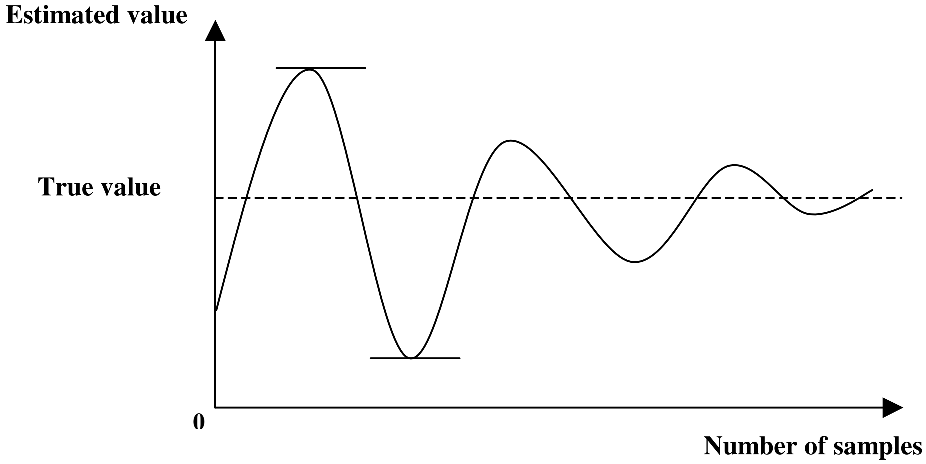


Figure 2.1: Fluctuating convergence

The stopping criteria for Monte Carlo simulation usually use the coefficient of variation of the output. Many different indices are obtained in a power system reliability evaluation using Monte Carlo stimulation. All indices have different speed of convergence characteristics and it is usual to select one index as an indicator for convergence. Based on past experience, the Expected Energy Not Supplied (EENS) index has the lowest speed of convergence and is usually used as the convergence indicator [33].

Monte Carlo simulation processes differ based on the techniques used for random number generation, the convergence criteria, the method used to achieve convergence and the different sampling approaches. Monte Carlo simulation techniques can be classified into the two categories of sequential and non-sequential methods. Sequential evaluation involves a chronological analysis of the system and component states. The chronology is absent in the case of non-sequential analysis. Non-sequential techniques are widely used for power system reliability evaluation and can be divided in the two categories of state sampling and state transition sampling. These techniques are described in the following sections.

Non-Sequential Methods: State Sampling Approach

In this approach, the system state is obtained by sampling all component states irrespective of the event chronologies [3]. A random number generator is used to determine the behavior of the component states [up, down]. The state sampling method is used to calculate the probability of occurrence of every system state in addition to the component states [3]. The following steps describe the process of this method.

1. Each system state is sampled using the component state sampling method. The component states are obtained by generating a random number and comparing it with the component forced unavailability. The component states are combined to determine the system state.
2. If the system state is predicted as an abnormal state, then load curtailment occurs; otherwise the next state is sampled.
3. If load curtailment is required, action is taken to determine the extent and the location.
4. The desired adequacy indices are calculated and stored and steps 1 to 3 are repeated until the coefficient of variation of a specified index is less than the criterion value.

A major disadvantage of this method is that it cannot be used to obtain a very accurate frequency index.

Non-Sequential Methods: State Transition Sampling Approach

This method can be used to calculate accurate frequency indices as it uses the system state transitions and not the component states to calculate the system indices. In this method the state transition of any component leads to a system state transition. The following steps describe the working process of this method [3].

1. The normal system is the first system state in the state transition sampling method. This is the state in which all the system components are in the up state.
2. The state transition of any component may lead to a system state transition. The state transition of any component is determined by random number generation. If the present system state is a contingency state in which at least one component is on outage, then load curtailment occurs. Otherwise the next sample is considered.
3. A long system state transition sequence is required to evaluate the indices of each system state.
4. The simulation is stopped when the coefficient of variation is less than the criterion value.

This procedure requires more time than the basic state sampling approach described earlier.

Sequential Methods: State Duration Sampling Approach

In this method, the process generates the chronological state transitions for all the components. The chronological system state transitions are generated from the component state sequences using their state duration distribution functions. All types of distribution functions can be used in the state duration sampling method. The procedure used for reliability evaluation is as follows [3]

1. The initial state of components (up or down) is assumed.
2. The chronological sequences of states for each component are determined.

3. The chronological sequence system state is obtained by combining the chronological component states.
4. System analysis is conducted on the obtained system states to produce the desired reliability indices.
5. Steps (1-5) are repeated until the coefficient of variation for a specified index is less than the criterion value.

This method can be used to obtain accurate frequency indices. A major disadvantage is that it requires more computation time and computer memory than the non-sequential techniques. This method requires all the parameters associated with the component state duration distributions as input.

2.3. Composite system (HL-II) adequacy evaluation using Monte Carlo simulation

The Monte Carlo simulation methods described above can be and have been applied to composite system reliability assessment. In these applications, load flow calculations, contingency analysis, generation rescheduling and overload alleviation involve considerable calculation time and hence non-sequential methods are preferred as they involve less computing time and memory. Monte Carlo simulation has been extensively applied to evaluate HL-II reliability.

Commercial softwares such as CREAM (Developed by EPRI, USA), MECORE (Developed at the University of Saskatchewan and then at BC Hydro, Canada) NARP (Developed by ERCOT, USA) SICRET (Developed by ENEL, Italy) and NH2 (developed by CEPEL, Brazil) use Monte Carlo simulation [44, 31] for evaluating composite power system reliability. The MECORE software was used in the research presented in this thesis and is described in the next section of this chapter.

MECORE software review

The MECORE software is based on a combination of Monte Carlo simulation and the enumeration technique. Monte Carlo simulation is conducted using the basic state sampling technique. [3,13]

The basic tasks involved in composite system reliability evaluation are

1. load flow calculations (DC load flow),
2. contingency analysis,
3. generation rescheduling and
4. overload alleviation.

The system states can be divided into the four subsets S1, S2, S3, and S4 and are displayed below [3].

$$S \begin{cases} S1 \\ \overline{S1} \begin{cases} S2 \\ \overline{S2} \begin{cases} S3 \\ S4 \end{cases} \end{cases} \end{cases}$$

Where,

S1 - Normal state subset with no contingencies

S2 - Subset composed of the contingency states which definitely have no load curtailment

S3 - Subset composed of contingency states, which have no load curtailment after rescheduling the generation

S4 - Subset composed of the contingency states, which still have load curtailment after rescheduling the generation

$\overline{S1}$ - Contingency subset

$\overline{S2}$ - Subset composed of the contingency states, which may have load curtailment.

The basic internal procedures in MECORE are shown in the Table 2.1, which shows that system states are evaluated further to segregate the unreliability subsets from the healthy system states.

Table 2.1: System state classification [3]

System State	Load curtailment	Contingency	Rescheduling of generators	Further steps
S1	No action	No action	No action	
$\overline{\text{S1}}$	No action	Action	No action	S2 or $\overline{\text{S2}}$
S2	No action	Action	No action	
$\overline{\text{S2}}$	Action	Action	No action	Reschedule generation and determine curtailed load, using minimization model
S3	No action	Action	Action	If the resulting load curtailed is 0 then go to state S3, else S4
S4	Action	Action	Action	Unreliability subset

Convergence of Monte Carlo simulation

As mentioned in Section 2.2, Monte Carlo simulation is a fluctuating process and the speed of convergence depends on the accuracy requirements and the computer CPU. The index Expected Energy Not Supplied (EENS) is often used as the convergence indicator. The EENS has the lowest convergence rate compared to other indices. The convergence criteria in these studies are the expected tolerance of ± 1 % in the variance of the EENS at the load buses and the system EENS coefficient of variation to be 0.02 to 0.1. The simulation proceeds until the desired convergence is achieved. As noted earlier, the rate of convergence is different for different indices. It also varies for the bus and the system index values.

MECORE capabilities

System Size:

The MECORE software is structured as follows [13].

Maximum buses: 1000

Maximum Branches: 2000

The MECORE installation guide recommends that a user should limit the size of the system to 200-300 buses for fast system solutions. Other capabilities of the MECORE software are as follows [13].

Component failure modes:

1. Independent failures of generators, lines and transformers
2. Common cause outages of transmission lines
3. Generating unit derated states

Component failure criteria:

1. Capacity deficiency of generators
2. Line overload
3. System separation-load loss
4. Bus isolation-load loss

Load models:

1. Annual, seasonal and monthly load curves.
2. Multi step models.
3. Bus load proportional scaling and flat level model.

Methods used to perform calculations:

1. Monte Carlo simulation and enumeration technique:
2. DC load flow:
3. Fast contingency analysis
4. Linear programming optimization model
5. Rescheduling/remedial action
6. Load curtailment philosophies
7. Reliability index evaluation

Task that can be performed using MECORE:

1. Power system reliability evaluation
2. System interruption cost assessment
3. Least cost probabilistic planning
4. Sensitivity analysis of generator location and size
5. Impact of Priority of loads or practices of load shedding
6. Reliability centered maintenance scheduling

Reliability indices evaluated by MECORE

The load bus and system indices evaluated by the MECORE software are abbreviated as follows [2,13].

Load Bus Indices:

ENLC	Expected Number of Load Curtailments (1/yr)
PLC	Probability of Load Curtailment
ELC	Expected Load Curtailment (MW/year)
EDNS	Expected Demand Not Supplied (MW)
EENS	Expected Energy Not Supplied (MWhr /year)

System Indices:

ENLC	Expected Number of Load Curtailments (1/year)
ADLC	Average Duration of Load Curtailment (hrs/disturbance)
EDLC	Expected Duration of Load Curtailment (hrs/year)
PLC	Probability of Load Curtailment
EDNS	Expected Demand Not Supplied (MW)
EENS	Expected Energy Not Supplied (MWhr /year)
EDC	Expected Damage Cost (k$/year)
BPII	Bulk Power Interruption Index (MW/MW-year)
BPECI	Bulk Power Energy Curtailment Index (MWhr/MW-year)
BPACI	Bulk Power supply Average Curtailment Index (MW/ disturbance)
MBECI	Modified Bulk Energy Curtailment Index (MW/disturbance)
SI	Severity Index (system minutes/year)

If these indices are calculated using a single load level expressed on a yearly basis then they are designated as annualized indices and if the indices are calculated using a load duration curve expressed on a yearly basis then they are designated as annual indices. The reliability indices are also calculated for the system and for the individual load points. The load or delivery point is the point of supply where the energy from the bulk electric system is transferred to the distribution system or to the retail customers [34]. This point is generally taken as the low voltage bus bar at step-down transformer stations. For customer owned stations supplied directly from the transmission system, this point is generally taken as the interface between the utility owned equipment (load transformer) and the customer's equipment [34]. The annual indices obtained from MECORE are used to evaluate composite system performance in this thesis.

Input data for MECORE

MECORE accepts formatted text files as an input and gives a formatted text file output. If there are any formatting errors in the input field format they can cause abnormal system conditions, and an interruption occurs in the simulation process. Data file processing done by MECORE is represented in Figure 2.2 [13].

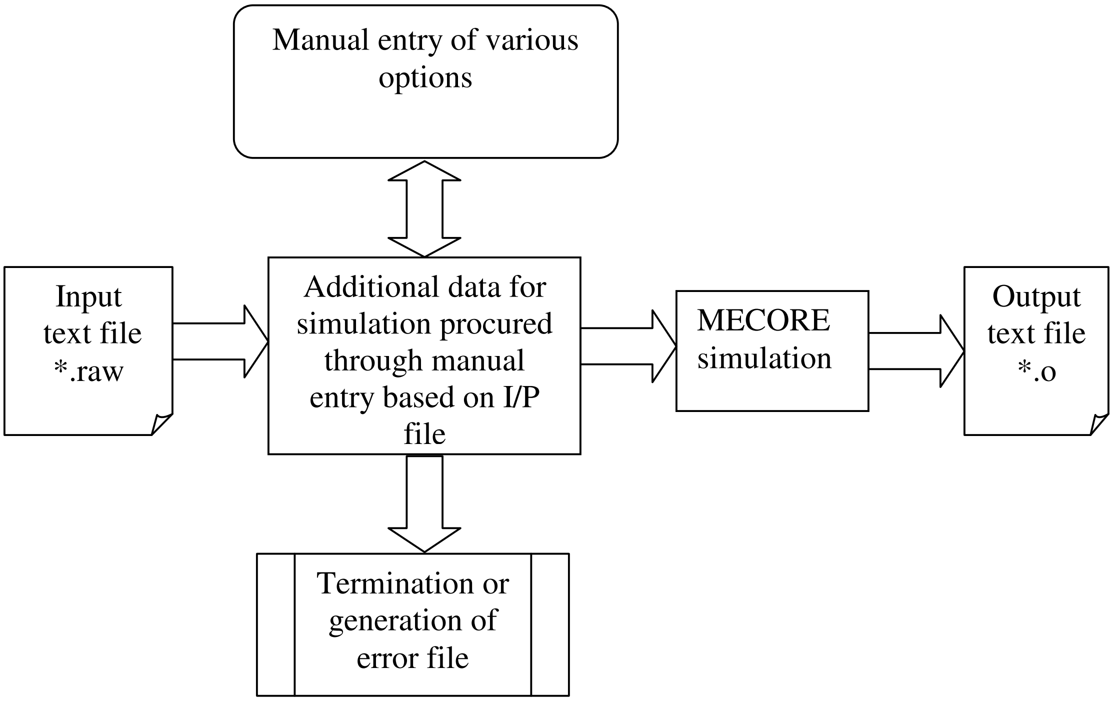


Figure 2.2: Data file processing for MECORE

The input file can be generated by PSS/E (PTI format) software or in the form of a specified text input known as the BC-Hydro format. The results obtained using the BC-Hydro and PTI format input files are similar. The analysis in this research was done using the BC-Hydro format input file.

2.4. Composite test systems

Two test systems have been utilized in this research. They are the Institution of Electrical and Electronics Engineers Reliability Test System-IEEE-RTS [35] and the Roy Billinton Test System-RBTS [36].The single line diagrams of the basic RBTS and the IEEE-RTS are shown in Figures 2.3 and 2.4 respectively.

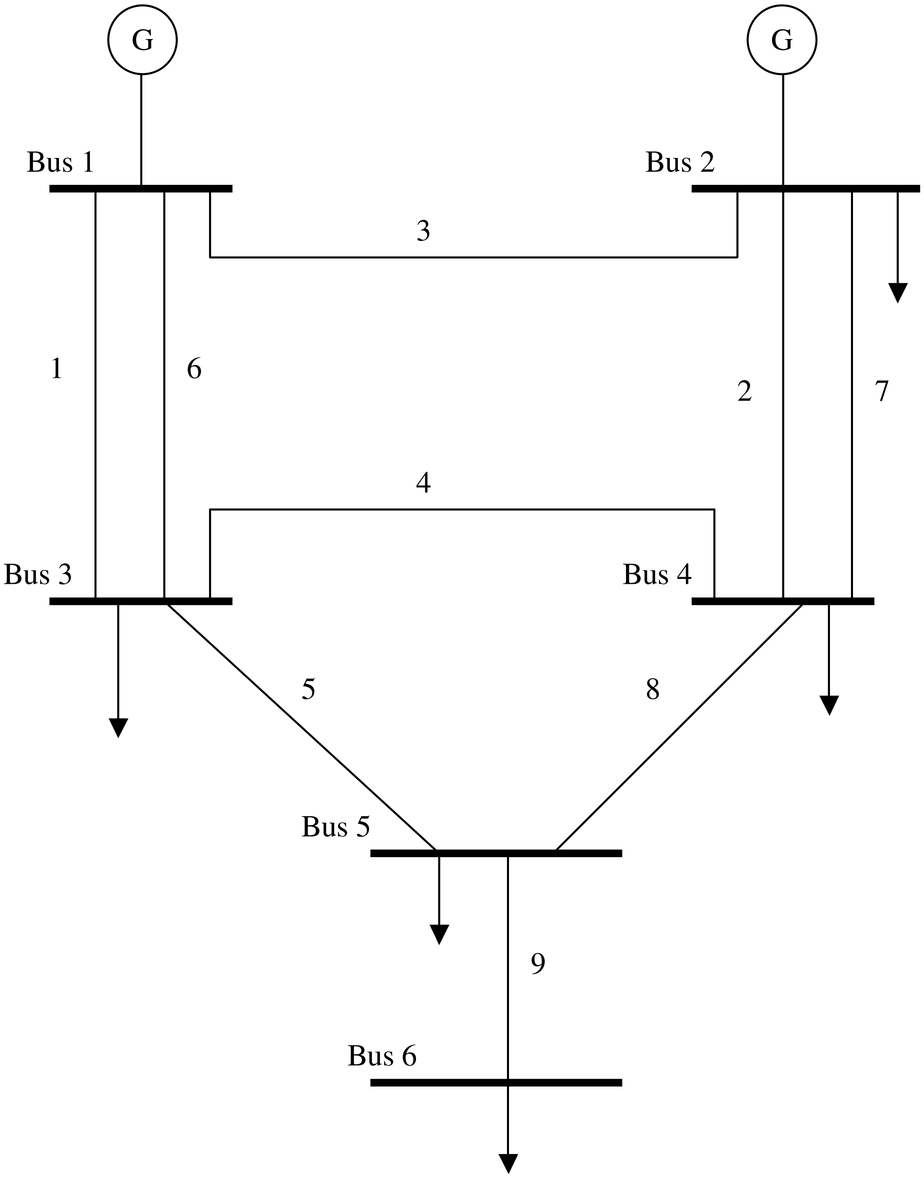


Figure 2.3: Single line diagram of the RBTS

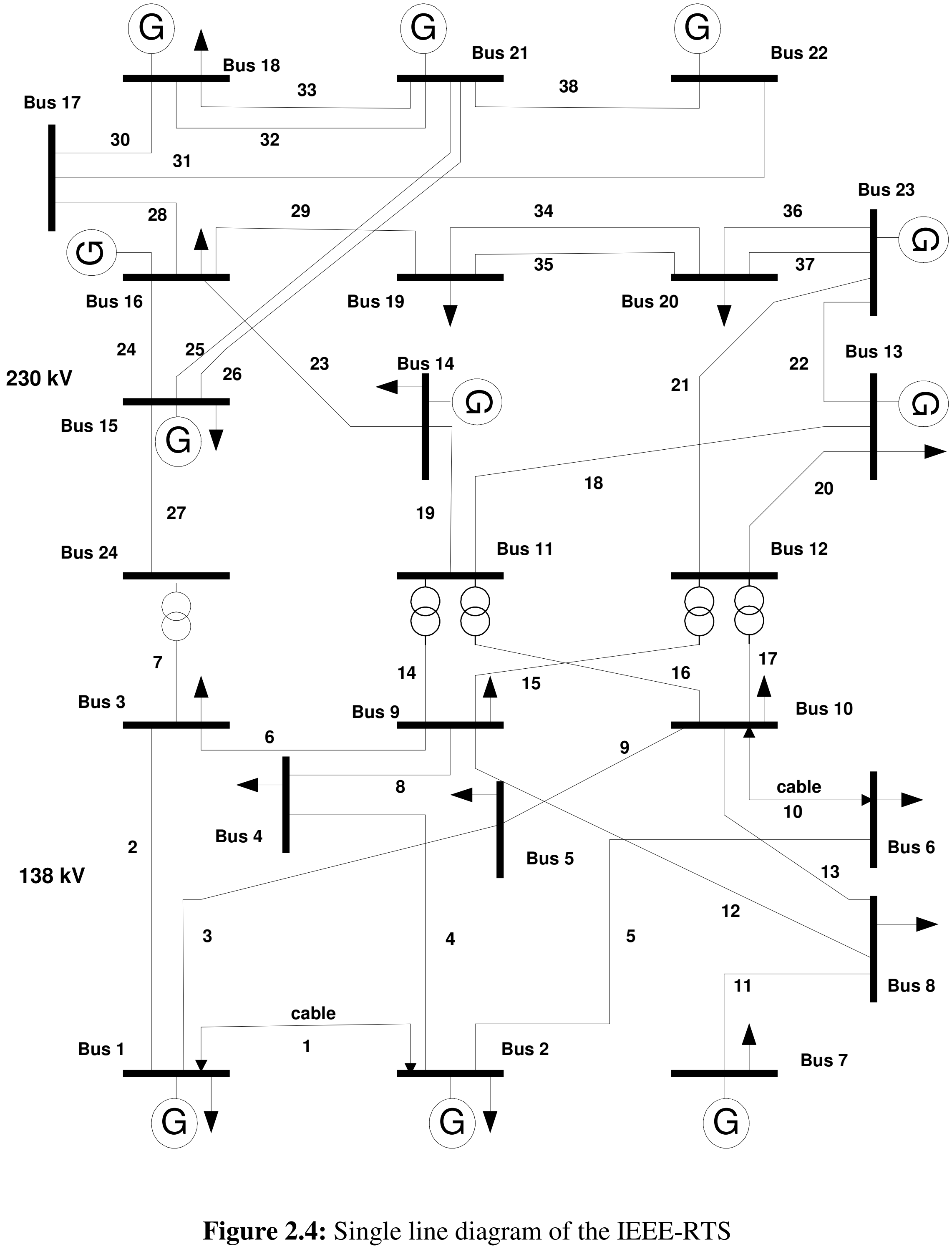


Figure 2.4: Single line diagram of the IEEE-RTS

The basic elements in the two test systems are shown in Table 2.2. The basic test system data are given in Appendix A (RBTS) and Appendix B (IEEE-RTS).

Table 2.2: Composite test systems composition

	RBTS[36]	**IEEE-RTS** [35]
No. of buses	6	24
No. of generators	11	32
No. of loads	5	17
No of generation buses	2	11
Installed generation	240 MW	3405 MW
Total load	185 MW	2850 MW
No. of circuits	9	38
No. of branches	7	34

The RBTS was developed at the University of Saskatchewan and is a small published test system developed for education and research purposes. The RBTS has been used to test the new method developed to include station related outages.

The IEEE-RTS is comparatively much bigger than the RBTS and has a strong transmission system and a weak generation system. The IEEE-RTS was first published in 1979 and since then has been extensively used for testing new reliability techniques and softwares. The IEEE-RTS is used as a secondary system to test the new method developed for including station related outages.

The basic single line diagrams of the RBTS and the IEEE-RTS shown in Figures 2.3 and 2.4 have been extended to include further detail and are shown in Figures 2.5 and 2.6 respectively. In these figures, each generating unit in a station is shown seperately with the associated step up transformer.

2.5. Convergence analysis of the RBTS and the IEEE-RTS

It is necessary to consider a sufficient number of samples in order to obtain accurate reliability indices using a simulation tool such as MECORE. The solution convergence is independent of the size of the system. The coefficient of variation of the output can also be used as a convergence indicator and should be between 0.02 and 0.1. [13] The coefficient of variation of the EENS is used in these studies in order to achieve acceptable accuracy.

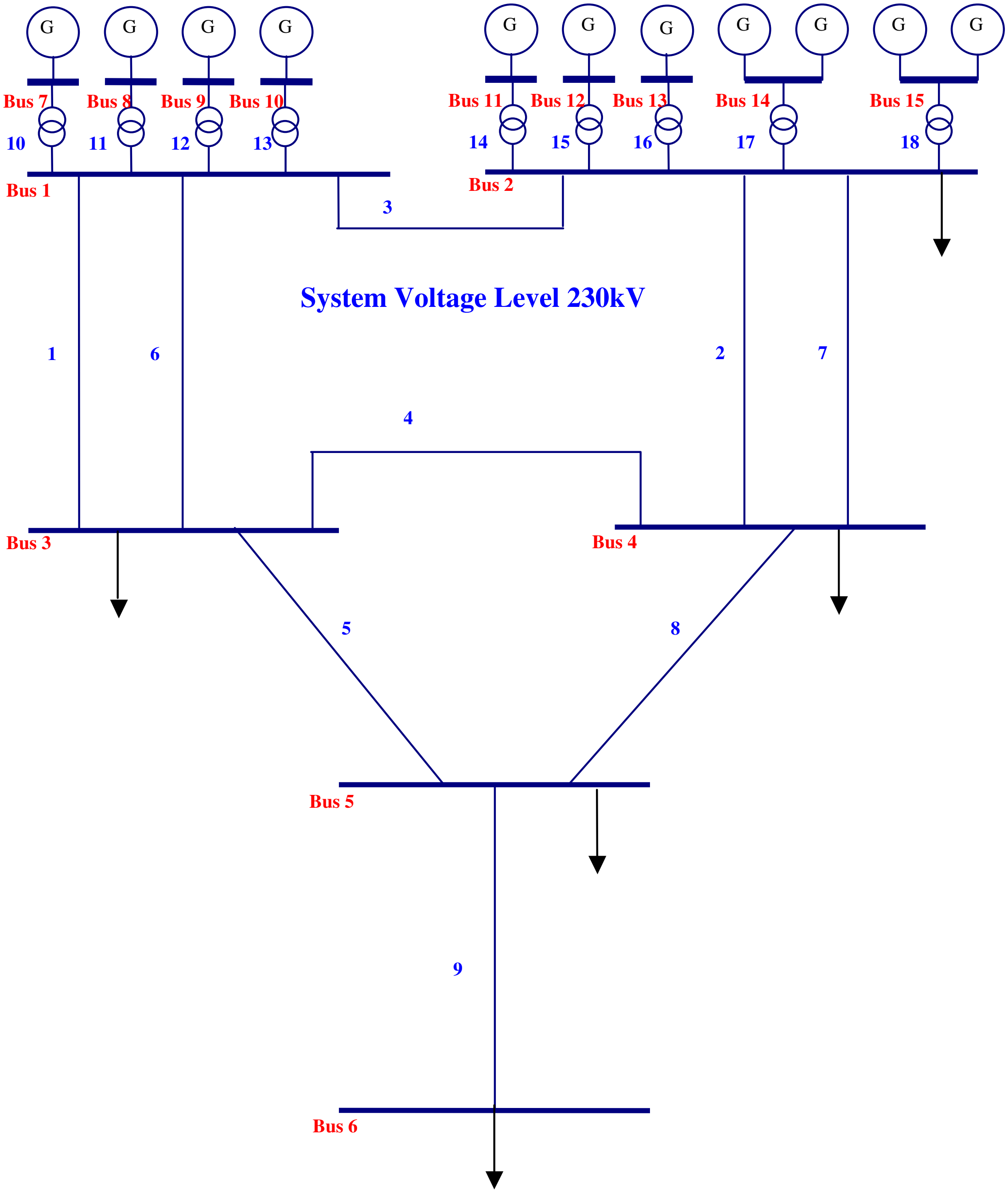


Figure 2.5: Extended single line diagram of the RBTS

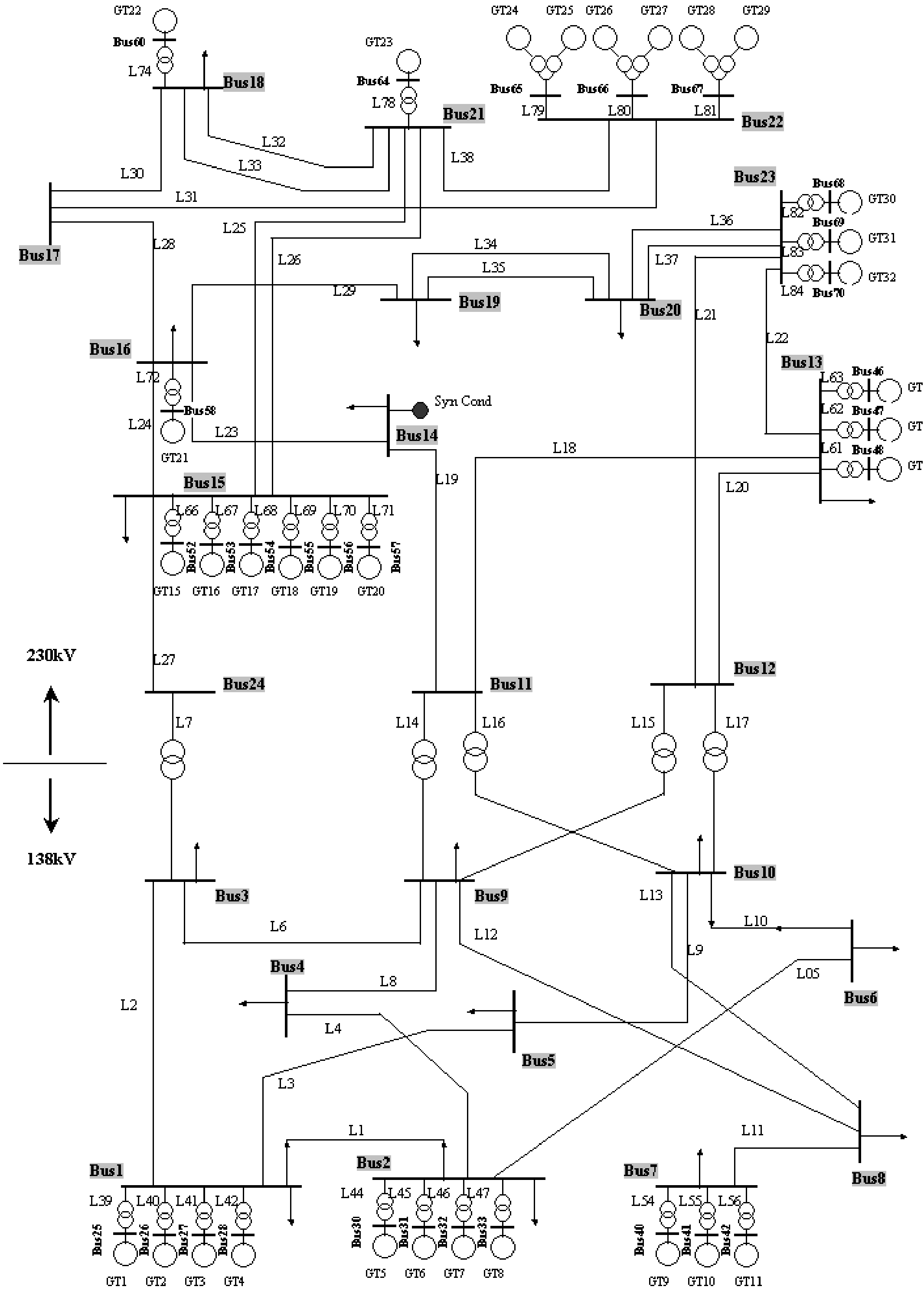


Figure 2.6: Extended single line diagram of the IEEE-RTS

The MECORE software calculates the coefficient of variation for the system EDNS. This index is directly related to the system EENS. The number of samples required for each MECORE simulation can also be decided from the variance in the EENS [3]. A 1% variance criterion was used to obtain the convergence. The next section illustrates the convergence characteristics of the RBTS (Figure 2.5) and the IEEE-RTS (Figure 2.6).

Convergence of the RBTS

A total number of 2,000,000 samples were required to obtain a variance of 1% or less in the EENS values at the selected load buses for the extended RBTS shown in Figure 2.5. It can be observed from Figure 2.7 that the selected load bus indices are below 1% at 2,000,000 simulations. Load buses 4 and 5 have a very low value of EENS and their rate of convergence is slow. The system indices converge faster compared to the load bus indices. The system EENS coefficient of variation is 0.082, which is less than 0.1.

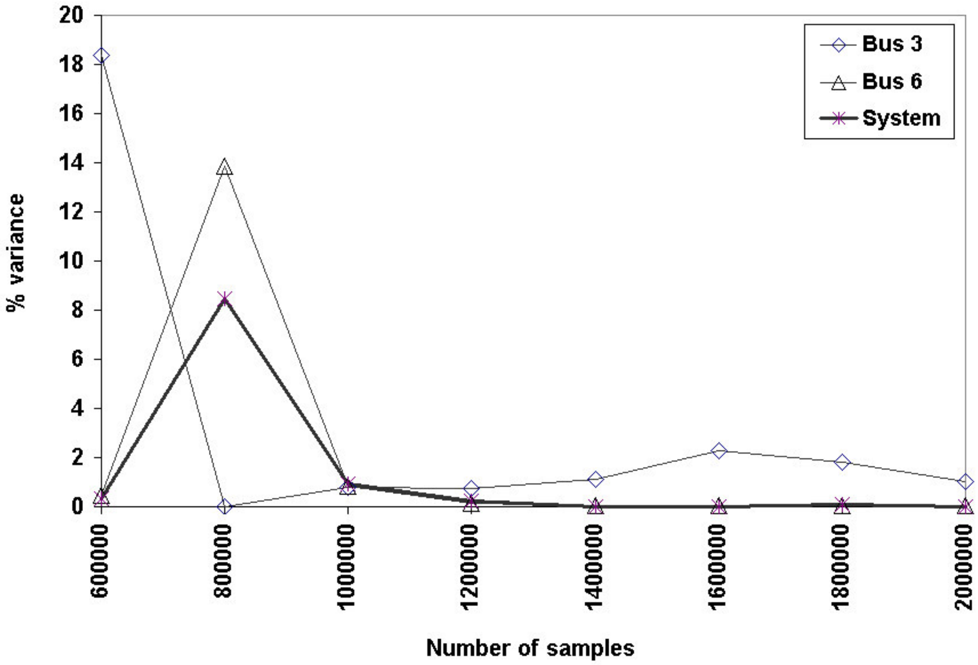


Figure 2.7 RBTS convergence

Convergence of the IEEE-RTS

A total of 500,000 samples were used to obtain a variance less than 1% for the extended IEEE-RTS shown in Figure 2.6. The variation in the EENS values at selected load buses is shown in Figure 2.8. In this case the coefficient of variation is 0.071, which is less than 0.1.

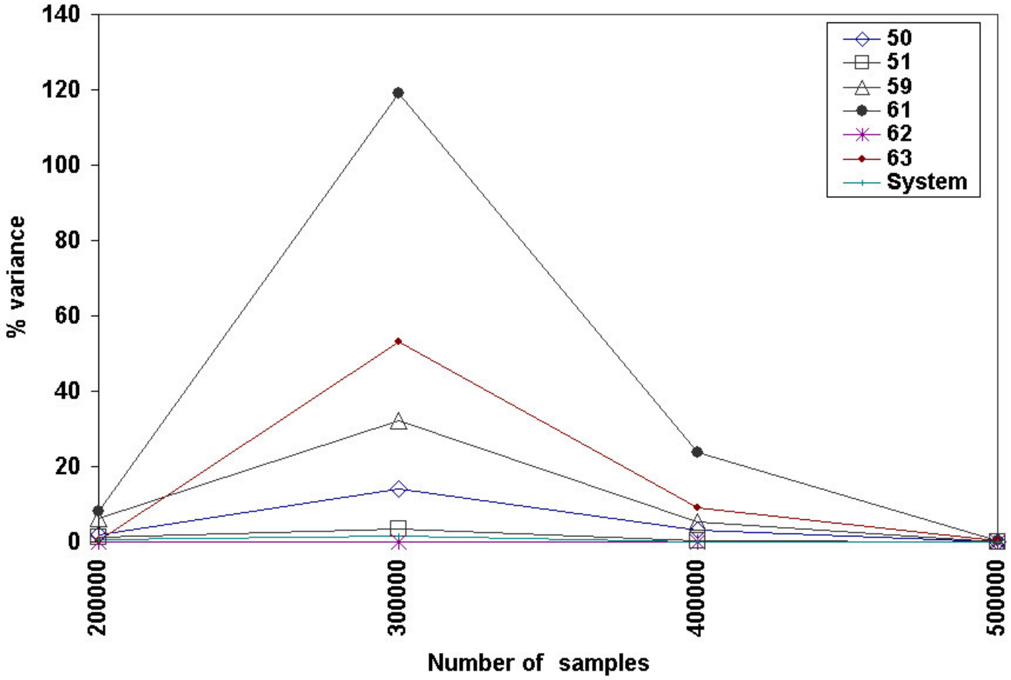


Figure 2.8: IEEE-RTS convergence

2.6. Base case reliability analysis

The test systems used for the reliability analyses discussed in this section are shown in Figures 2.5 and 2.6.

Analysis of the RBTS

The RBTS shown in Figure 2.5 is considered to be the base case representation in this research. Load curtailment due to overload conditions is based on the economic impact of these actions at various load buses [2,13].

IEAR values and priority order of load curtailment:

A priority order based on the IEAR (Interrupted Energy Assesment Rate) was used for load curtailment ranking. The IEAR is the average monetary impact on the customers at a load point, expressed in dollars per kW/h of unserved energy. The higher the IEAR the higher is the service priority at that bus. It can be observed from Tables 2.3 and 2.4 that load bus 2 has the highest priority as it has the highest IEAR. The overall system IEAR is 4.42$/kWh.

Table 2.3: Load bus IEAR for the RBTS

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

Table 2.4: Load bus priority order for the RBTS

Priority order	Load Bus
1	2
2	4
3	5
4	6
5	3

The RBTS reliability indices are shown in the following section.

RBTS reliability indices:

Tables 2.5 and 2.6 show the load bus and system indices for the RBTS. There is a wide range of reliability indices shown in Tables 2.5 and 2.6. Each index provides different information and some indices are more important than others. The load point indices are useful in assessing the load point impact of system modifications and provide input to reliability evaluation at the actual customer level. The system indices provide valuable information on the overall ability of the system to supply the customer load. The likelihood of a customer receiving uninterrupted power supply can be assessed from the indices of Table 2.5. The higher the value of the reliability indices the higher is the unreliability at the corresponding bus. Load bus 6 has the highest reliability indices as it is connected through a radial transmission line, making it relatively more unreliable. Load bus 3 has comparatively high reliability indices because it has the lowest load curtailment priority.

Table 2.5: Load bus indices for the RBTS

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
2	0.00000	0.00000	0.00000	0.00000	0.000	Bus 2
3	0.00019	0.10699	1.229	0.00212	18.580	Bus 3
4	0.00000	0.00103	0.00700	0.00000	0.031	Bus 4
5	0.00000	0.00549	0.05900	0.00003	0.289	Bus 5
6	0.00121	1.18785	15.1590	0.01538	134.744	Bus 6

Table 2.6: System indices for the RBTS

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.28996
Average duration of load curtailment (hrs/disturbance) ADLC	9.47
Expected duration of load curtailment (Hrs / year) EDLC	12.21
Probability of load curtailments (PLC)	0.00139
Expected demand not supplied (MW) EDNS	0.01754
Expected energy not supplied (MWhr / year) EENS	153.64
Expected Damage Cost (K$/ year) EDC	679.10
Bulk Power-interruption Index (MW/MW- year) BPII	0.08894
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.83051
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	12.76
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00009
Severity Index (system minutes/ year) SI	49.83

Analysis of the IEEE-RTS

The IEAR values used for the load buses of the IEEE-RTS are shown in Table 2.7 [2,33]. The corresponding priority orders used for load curtailment are shown in Table 2.8.

Table 2.7: Load bus IEAR for the IEEE -RTS

Load Bus	IEAR ($/kWh)
1	6.20
2	4.89
3	5.30
4	5.62
5	6.11
6	5.50
7	5.41
8	5.40
9	2.30
10	4.14
13	5.39
14	3.41
15	3.01
16	3.54
18	3.75
19	2.29
20	3.64

Table 2.8: Load bus priority order for the IEEE-RTS

Priority order	Load Bus
1	1
2	5
3	4
4	6
5	7
6	8
7	13
8	3
9	2
10	10
11	18
12	20
13	16
14	14
15	15
16	9
17	19

IEEE-RTS Reliability Indices:

This section deals with the analysis of the IEEE-RTS shown in Figure 2.6. The reliability indices shown are evaluated using the load curve given in [35]. The IEEE-RTS load bus and system indices are shown in Tables 2.9 and 2.10.

Load bus Indices:

It can be seen from Table 2.9 that the reliability indices at load bus 19 are relatively high as this load bus has the lowest load curtailment priority. The major contributions to the IEEE-RTS reliability indices are due to the weak generation system.

Table 2.9: Load bus indices for the IEEE-RTS

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
1	0.00000	0.00000	0.00000	0.00000	0.00000	Bus 1
2	0.00000	0.00131	0.047	0.00004	0.344	Bus 2
3	0.00000	0.00000	0.00000	0.00000	0.00000	Bus 3
4	0.00000	0.00000	0.00000	0.00000	0.00000	Bus 4
5	0.00000	0.00000	0.00000	0.00000	0.00000	Bus 5
6	0.00000	0.00000	0.00000	0.00000	0.00000	Bus 6
7	0.00000	0.00047	0.004	0.00000	0.020	Bus 7
8	0.00000	0.00009	0.001	0.00000	0.004	Bus 8
9	0.00111	0.91583	56.674	0.06865	601.401	Bus 9
10	0.00000	0.00496	0.276	0.00025	2.177	Bus 10
13	0.00000	0.00000	0.00000	0.00000	0.00000	Bus13
14	0.00020	0.18238	11.033	0.01217	106.585	Bus14
15	0.00066	0.54787	47.0245	0.05499	481.729	Bus15
16	0.00009	0.08377	3.190	0.00344	30.093	Bus16
18	0.00003	0.03012	2.315	0.00230	20.147	Bus18
19	0.00199	1.60393	101.608	0.12721	1114.373	Bus19
20	0.00006	0.05504	2.448	0.00252	22.086	Bus 20

Table 2.10: System indices for the IEEE-RTS

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.60450
Average duration of load curtailment (hrs/disturbance) ADLC	10.89
Expected duration of load curtailment (Hrs / year) EDLC	17.47
Probability of load curtailments (PLC)	0.00199
Expected demand not supplied (MW) EDNS	0.27157
Expected energy not supplied (MWhr / year) EENS	2378.95
Expected Damage Cost (K$/ year) EDC	10039.18
Bulk Power-interruption Index (MW/MW- year) BPII	0.07889
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.83472
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	140.13
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00010
Severity Index (system minutes/ year) SI	50.08

The EDC index in Table 2.10 is calculated using an IEAR of 4.22 $/kWh.

2.7. Composite test systems with load point transformers

Figure 2.9 shows a further extended RBTS that includes step down transformers at each load point. As noted earlier, Reference 34 states that the load or delivery points in a bulk system are the points of supply where the energy from the bulk system is transfered to the distribution system or to the retail customers. In the diagram shown in Figure 2.9, the transformers are assumed to be owned by the utility. The load point transformer failure data is given in Appendix B (Table B-7). It is assumed that only one transformer is present at every load bus. This may not be the case in practice and this assumption gives pessimistic results.

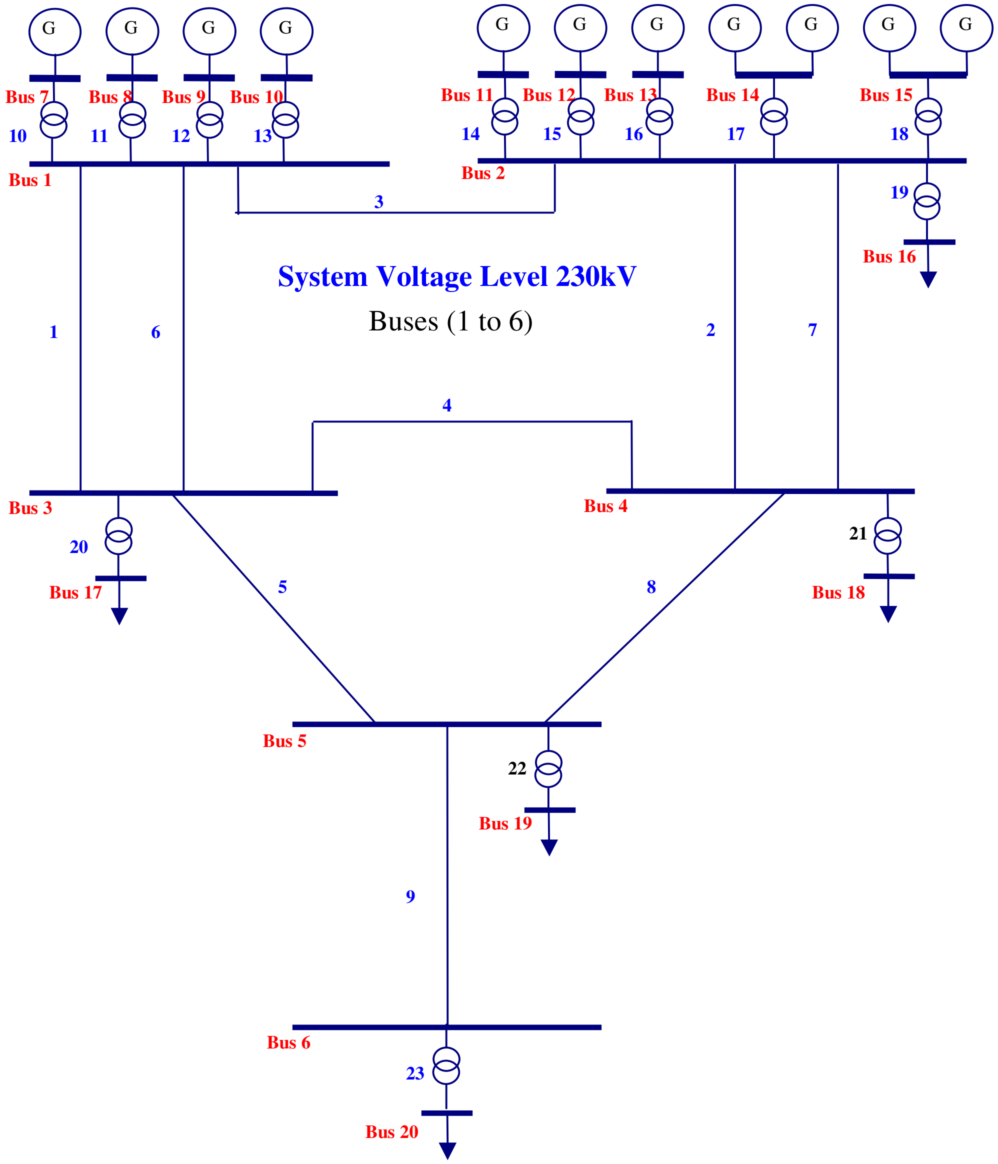


Figure 2.9: Extended single line diagram of the RBTS with load point transformers

The effect of including transformers is minimized by providing redundant or standby transformers.

Analysis of the RBTS with load point transformers

The single line diagram of the RBTS with load point transformers is shown in Figure 2.9. The load bus and system indices are shown in Tables 2.11 and 2.12. This analysis shows that load bus 17 has the maximum EENS. This load point has the maximum load and the lowest load curtailment priority. Load bus 20 has the second highest EENS because it is connected by a radial transmission line. The system indices show a significant increase from those in Table 2.6 due to the inclusion in the reliability analysis of the load point transformers.

Table 2.11: Load bus indices for the RBTS with load point transformers

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00175	0.21880	2.799	0.02240	196.224	Bus 16
17	0.00197	0.33909	13.887	0.09880	865.449	Bus 17
18	0.00178	0.23194	5.915	0.04558	399.315	Bus 18
19	0.00175	0.23431	2.986	0.02232	195.561	Bus 19
20	0.00300	1.41311	17.957	0.03829	335.433	Bus 20

Table 2.12: System indices for the RBTS with load point transformers

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.42
Average duration of load curtailment (hrs/disturbance) ADLC	37.00
Expected duration of load curtailment (Hrs / year) EDLC	89.40
Probability of load curtailments (PLC)	0.01021
Expected demand not supplied (MW) EDNS	0.22740
Expected energy not supplied (MWhr / year) EENS	1991.98
Expected Damage Cost (K$/ year) EDC	8804.56
Bulk Power-interruption Index (MW/MW- year) BPII	0.23537
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	10.77
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	18.02
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00123
Severity Index (system minutes/ year) SI	646.05

The extended single line diagram for the IEEE-RTS is shown in Figure 2.10

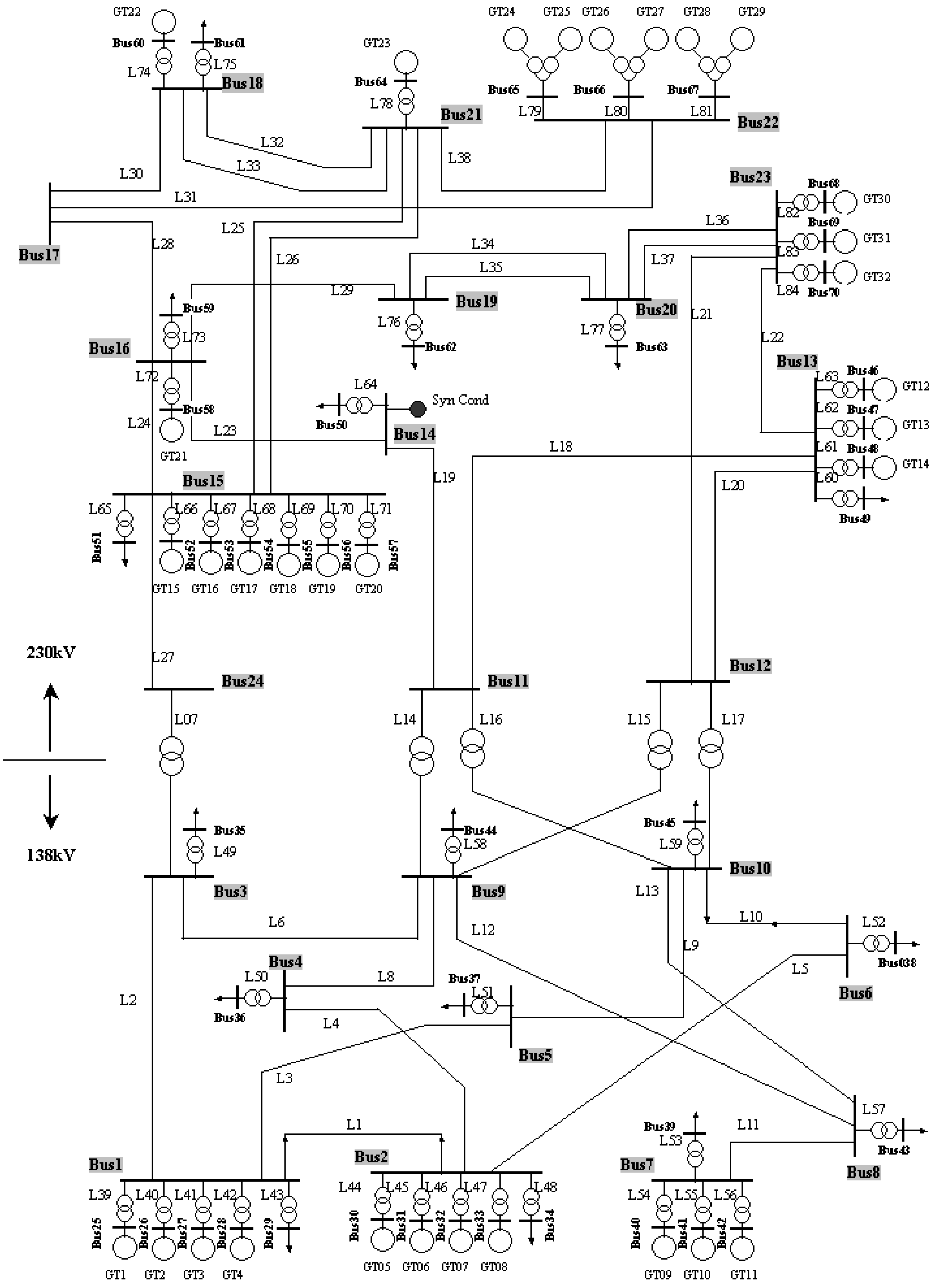


Figure 2.10: Extended single line diagram of the IEEE-RTS with load point transformers

Analysis of the IEEE-RTS with load point transformers

The IEEE-RTS with load point transformers is shown in Figure 2.10. The load bus indices and system indices shown in Tables 2.13 and 2.14 increase due to incorporating the load point transformers. Load bus 62 connected to bus 19 shows the highest value of the EENS as it has the lowest load curtailment priority.

Table 2.13: Load bus indices for the IEEE-RTS with load point transformers

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
29	0.00171	0.88195	60.926	.11785	1032.378	Bus29
34	0.00168	0.89028	54.966	0.10414	912.283	Bus34
35	0.00172	0.92045	105.975	0.19757	1730.717	Bus35
36	0.00181	0.94722	44.835	0.08558	749.663	Bus36
37	0.00168	0.90622	41.155	0.07648	669.941	Bus37
38	0.00173	0.90505	78.731	0.15084	1321.368	Bus38
39	0.00176	0.93253	74.526	0.14088	1234.126	Bus39
43	0.00185	0.98056	107.243	0.20213	1770.661	Bus43
44	0.00462	3.14052	236.220	0.36628	3208.585	Bus44
45	0.00179	0.94321	115.934	0.22168	1941.893	Bus45
49	0.00180	0.94842	160.761	0.30443	2666.787	Bus49
50	0.00238	1.45258	149.458	0.25761	2256.698	Bus50
51	0.00343	2.25026	305.643	0.50442	4418.740	Bus51
59	0.00202	1.16604	68.282	0.12203	1068.983	Bus59
61	0.00187	1.02702	205.371	0.38462	3369.313	Bus61
62	0.00656	4.55551	344.494	0.51841	4541.292	Bus62
63	0.00198	1.10042	83.488	0.15463	1354.596	Bus63

Table 2.14: System indices for the IEEE-RTS with load point transformers

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	18.97
Average duration of load curtailment (hrs/disturbance) ADLC	15.69
Expected duration of load curtailment (Hrs / year) EDLC	297.65
Probability of load curtailments (PLC)	0.03398
Expected demand not supplied (MW) EDNS	3.91
Expected energy not supplied (MWhr / year) EENS	34247.86
Expected Damage Cost (K$/ year) EDC	144525.97
Bulk Power-interruption Index (MW/MW- year) BPII	0.78527
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	12.02
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	117.96
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00137
Severity Index (system minutes/ year) SI	721.01

2.8 Summary

This chapter briefly illustrates the application of Monte Carlo simulation to composite system reliability evaluation. The various Monte Carlo methods used for reliability analysis are also briefly described.

The MECORE software used for composite system reliability analysis is briefly illustrated in this chapter. Details on the capabilities of the MECORE software and the various reliability indices obtained using the MECORE software are also presented.

The composite test systems (RBTS and IEEE-RTS) used for reliability studies in the research are also presented. The composite systems were modified to include the station transformers and are shown in the extended single line diagrams. The simulation convergence characteristics of the two test systems are illustrated and the convergence criteria applied in the studies described in this thesis are defined.

Base case reliability analyses of the composite test systems are also presented in this chapter. The base case indices are used for comparison purpose throughout this thesis.

Chapter 3

Composite System Evaluation with Station Related Outages

3.1 Introduction

A composite system normally has many stations within it and therefore the availability of power supply to the customer depends on the proper functioning of the station components. The influence of station failures on the power system performance can be appreciated from an event that was described on the BBC News, Monday October 14th, 2002*, Power cut: Most of the Oxfordshire in the dark as the Cowley substation went down on Sunday evening*. This event shows that the effect of faults that occur in a station can spread to other parts of a power system and can cause severe damages. Station faults can reduce the total system transfer capacity and affects the electricity supply to the customers. Minimizing the effects of station related outages on the composite system reliability is an important planning activity. Stations consist of components such as circuit breakers, bus bars, disconnects etc and have a range of possible configurations. A designer may decide to select a more reliable station configuration for a given set of components after assessing the effects of station related outages in an HL-II reliability study. This activity is a difficult task.

Collection of station component outages data is an important activity and is described in detail in this chapter. The composite test systems RBTS and IEEE-RTS presented in Chapter 2 are modified to include different station configurations in order to study the effects of station failures on the HL-II performance. This chapter describes a new technique that can be used to include station related outages in the analysis.

3.2 Station component failures and outages

Stations consist of components such as circuit breakers, bus bars, transformers and disconnects that are susceptible to failure when in operation. In order to understand the effects of station component failures on the system performance it is necessary to study the station component outage processes. In this research work the focus is on permanent outages of station components and maintenance outages are not considered. “A permanent outage is an outage whose cause if not self clearing, but must be corrected by eliminating the hazard or by repairing or by replacing the component before it can be returned to service” [31]. System components may be removed from service due to the outage of a station component. A failed station component is brought back to service by repair or by replacing the component. If a component is removed from service due to failures in other external devices then the time required to bring the component back into service is known as the switching time. The processes of component failure, repair and switching are used to model the component in discrete and identifiable states that are continuous in time. The usual method to represent a component in continuous discrete states is known as a continuous Markov process [38]. Important station components such as circuit breakers, bus bars and transformers are modeled using Markov processes. These models are then used to incorporate station related outages in the HL-II evaluation.

Basic Markov model for a single component

The continuous Markov process for a component with two states can be modeled as shown in Figure 3.1[38].

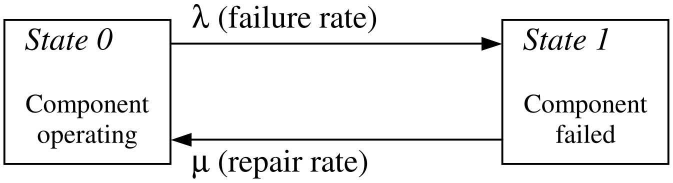


Figure 3.1: A component two state space diagram

A continuous Markov process is a specific stochastic process that is independent of all the past states except the immediately preceding one. The probability of failure or repair for a fixed interval of time is constant in a continuous Markov process. Power system components can be represented by discrete system states with constant transition rates between these states. In Figure 3.1, “State 0” represents the healthy state of the component and the component is in an operating condition. The component when it cannot perform its intended function is in “State 1” or the failed state. Transitions occur between “State 0” and “State 1”. The transition rates between the states are the failure rate “λ” and the repair rate “μ” and are shown in Figure 3.1. Figure 3.2 shows the two states in terms of the average residence time in each state.

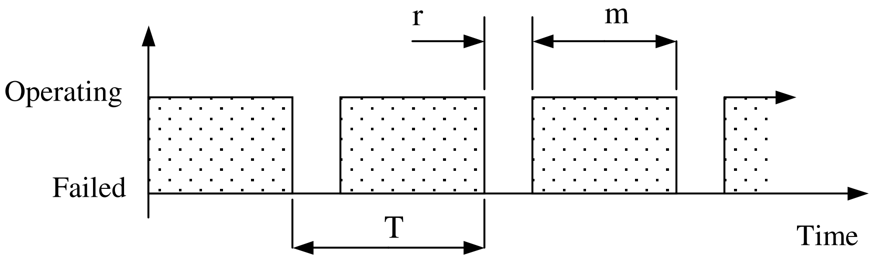


Figure 3.2: Mean time diagram for a two state component

Where,

m is the mean operating time of the component,

r is the mean repair time of the component,

T is the system cycle time.

In Figure 3.2, “m” is also known as the mean time to failure (MTTF) and “r” is the mean time to repair (MTTR). The summation of MTTF and MTTR is the mean time between failures (MTBF) or the cycle time “T”.

Equations 3.1 to 3.3 show the relationship between the transition rates and the transition times shown in Figures 3.1 and 3.2 respectively.

$$m = MTTF = 1/\lambda \tag{3.1}$$

$$r = MTTR = 1/\mu \tag{3.2}$$

$$T = MTBF = m + r = 1/\text{frequency} \tag{3.3}$$

The steady state probabilities of residing in the operating state (State 0) and the failed state (State 1) are designated as P_0 and P1 respectively. Equations 3.4 and 3.5 can be used to calculate these probabilities [38].

$$P_0 = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \tag{3.4}$$

$$P_1 = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \tag{3.5}$$

The component Markov representation shown in Figure 3.1 is used to model a number of station components. In some cases a component may have more than two states as shown in the following examples.

Markov model for a circuit breaker

Circuit breakers are switching devices that play an important role in power system operation. According to the American National Standards Association (ANSI) C37.100 a circuit breaker is defined as,

"A mechanical device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time and breaking currents under specified abnormal circuit conditions such as those of short circuit" [30].

A circuit breaker is intended for interrupting current. Breakers failures can result in severe damage to a power system and reduces its power transfer capacity. A model for a circuit breaker is shown in Figure 3.3. This Markov model includes both active and passive failures. These two modes of circuit breaker failures are defined as follows

Passive failure: A component failure mode that does not cause operation of a protection breaker and therefore does not have an impact on the remaining healthy components. Repairing or replacing the failed component restores the service [2].

Active failure: A component failure mode that causes the operation of the primary zone around the failed component and can therefore cause the removal of other healthy components and branches from service. After an active circuit breaker failure occurs the circuit breaker is isolated with the help of other protection breakers [2].

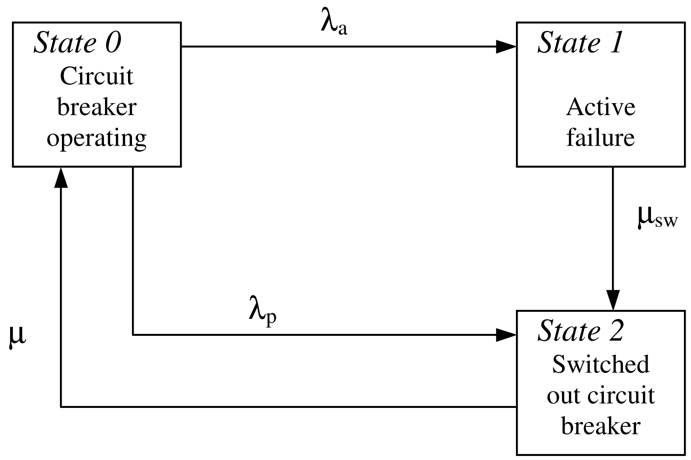


Figure 3.3: A circuit breaker state space diagram

The rate of transition from “State 0” to “State 1” is the active failure rate (λ_a) and the rate of transition from “State 0” to “State 2” is the passive failure rate (λ_p). The rate of transition from “State 1” to “State 2” is the switching rate (μ_{sw}) and is the reciprocal of the time required to switch out a circuit breaker with an active failure. The transition rate (μ) from “State 2” to “State 0” is the repair rate of a circuit breaker and is the reciprocal of the time required to bring a passively failed breaker into service.

Markov model for a bus section

Bus sections are used to connect system components. A bus section is defined as a set of conductors to which two or more components are electrically connected [40]. Generally the frequency of bus bar failures is relatively low when compared to circuit breaker failures, because their operation is independent of any switching actions. System operation can be severely affected by bus bar failures. A Markov model used to represent a bus bar is shown in Figure 3.4 and has the same structure as the model in Figure 3.1. The transition rate from “State 0” to “State 1” is known as the failure rate (λ_b) and the transition rate from “State 1” to “State 0” is known as the repair rate (μ_b).

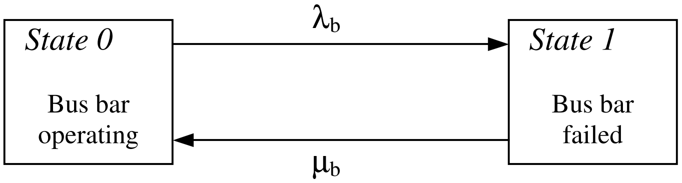


Figure 3.4: A bus bar state space diagram

Markov model for a transformer

A transformer is used to step up or step down the voltage levels in a power system network. Transformers are normally located at the generation or at the load points in a power system. The state space diagram for a transformer is shown in Figure 3.5 [31,40]. The terms λ_t designate the transformer failure rate and the term μ_t represents the repair rate. The average repair time for a transformer is usually very high compared to that of other station components.

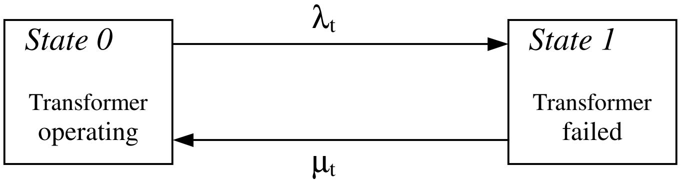


Figure 3.5: A transformer state space diagram

Markov model for station related multiple component outages

In some cases, station component failures can result in the simultaneous removal from service of two or more station connected devices. This event is designated as a station related outage. Figure 3.6 shows a Markov model of this type of event. This model is similar in form to that used to represent a common mode outage of two components. The rate of departure from “State 0”to “State 4” is the common failure rate (λ_{12}) and the rate of departure from “State 4” to “State 0” is the common repair rate (μ_{12}). The failure rates λ_1 and λ_2 and the repair rates μ_1 and μ_2 are related to the components 1 and 2 respectively. When the station failure causing a common outage (State 4) is removed, the two disconnected station connected components can be returned to service (State 0). The parameter μ_{12} in Figure 3.6 is the switching rate.

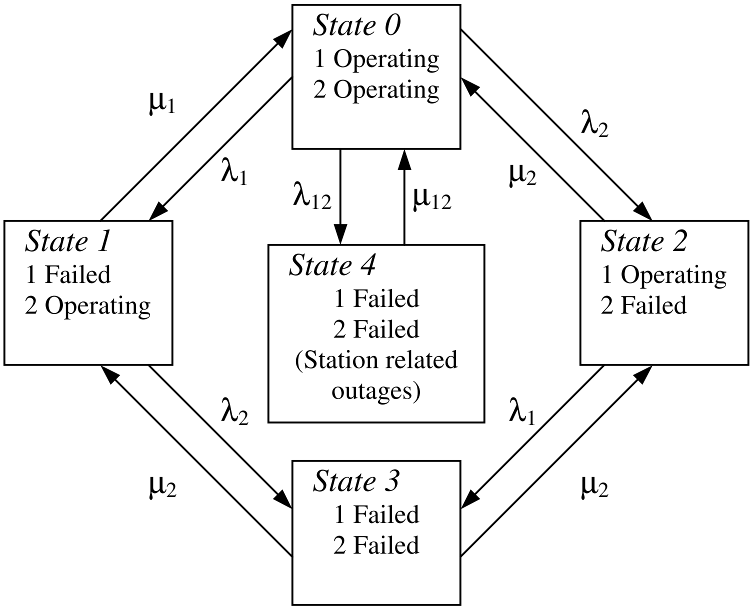
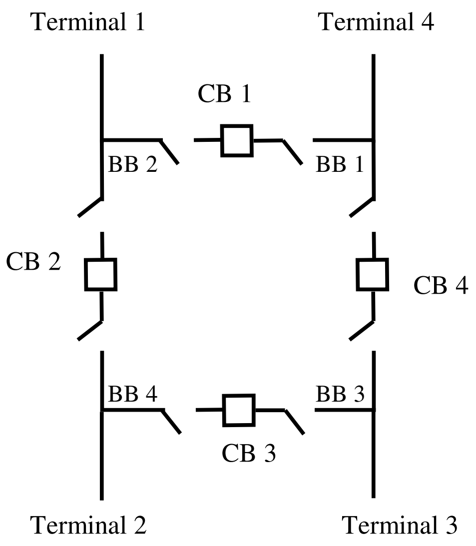


Figure 3.6: Outage of two system components caused by a station component failure

The Markov process can become complicated with increase in the number of station-connected components affected by a station component failure. The Markov models shown in Figure 3.3 to 3.6 for station components were used in the development of the new technique for including station outages in HL-II evaluation described in the next section.

3.3 A new method for representing station related outages

In order to assess the effects of station related outages on HL-II performance it is necessary to represent stations in detail. Station related outages can affect all the incoming and outgoing power system connections. One way to include the station related outages in an HL-II analysis is to incorporate station related effects into the failure parameters of the connected system components [32]. A new approach to accomplish this task using minimal cut sets is illustrated as follows using the ring bus scheme example shown in Figure 3.7.



Where,
CB- Circuit breaker
BB - Bus bar

Figure 3.7: Ring bus configuration

The terminals shown in the Figure 3.7 can be either load points, transmission lines or incoming feeders. The following steps explain the method.

Step 1: The minimal cut sets related to station component outages that cause failure of one terminal are determined. These minimal cut sets include both active and passive failure events of the station components. In this analysis, it is assumed that only circuit breakers have active and passive failures modes.

Step 2: Step 1 is repeated for all the station terminals.

Step 3: The minimal cut sets derived for all the terminals in Figure 3.7 are shown in Table 3.1.

Table 3.1: Minimal cut sets for station terminals
(A = active failure, P = passive failure)

	Terminal 1	**Terminal 2**	**Terminal 3**	**Terminal 4**
Minimal cut sets	CB1 (A)	CB3 (A)	CB3 (A)	CB1 (A)
	CB2 (A)	CB2 (A)	CB4 (A)	CB4 (A)
	BB1 + BB4	BB2 + BB3	BB1 + BB4	BB2 + BB3
	BB4 + CB1 (P)	BB2 + CB3 (P)	BB2 + CB1 (P)	BB2 + CB3 (P)
	BB4 + CB4 (A)	BB2 + CB4 (A)	BB1 + CB3 (A)	BB2 + CB4 (A)
	BB1 + CB3 (A)	BB3 + CB1 (A)	BB1 + CB2 (A)	BB3 + CB1 (A)
	BB1 + CB2 (P)	BB3 + CB2 (P)	BB2 + CB3 (P)	BB3 + CB2 (P)
	BB2	BB4	BB3	BB1
	CB1 (P) + CB2 (P)	CB2 (P) + CB3 (P)	CB3 (P) + CB4 (P)	CB1 (P) + CB4 (P)

Step 4: The minimal cut sets that result in the simultaneous outages of two or more terminals are extracted from Table 3.1 and are shown in Table 3.2. These minimal cut sets result in common terminal failures and are called common cut sets. The common terminal outage groups are marked with a similar subscript number.

Step 5: The individual failure groups that result in the outage of a single terminal are used to modify the failure parameters of the corresponding station terminals.

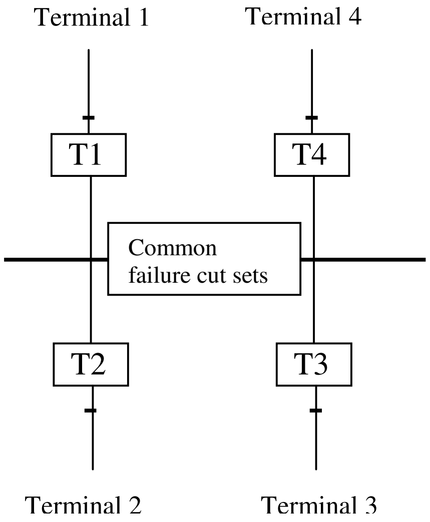
Table 3.2: Extracted minimal cut sets for station terminals
(Subscripts indicate common failure group)

Minimal cut sets type	**Terminal 1**	**Terminal 2**	**Terminal 3**	**Terminal 4**
Common terminal minimal cut sets	CB1 (A) $_{1}$	CB3 (A) $_{3}$	CB3 (A) $_{3}$	CB1 (A) $_{1}$
	CB2 (A) $_{2}$	CB2 (A) $_{2}$	CB4 (A) $_{4}$	CB4 (A) $_{4}$
	BB1 + BB4 $_{5}$	BB2 + BB3 $_{6}$	BB1 + BB4 $_{5}$	BB2 + BB3 $_{6}$
Independent minimal cut sets	BB4 + CB1 (P)	BB2 + CB3 (P)	BB2 + CB1 (P)	BB2 + CB3 (P)
	BB4 + CB4 (A)	BB2 + CB4 (A)	BB1 + CB3 (A)	BB2 + CB4 (A)
	BB1 + CB3 (A)	BB3 + CB1 (A)	BB1 + CB2 (A)	BB3 + CB1 (A)
	BB1 + CB2 (P)	BB3 + CB2 (P)	BB2 + CB3 (P)	BB3 + CB2 (P)
	BB2	BB4	BB3	BB1
	CB1 (P) + CB2 (P)	CB2 (P) + CB3 (P)	CB3 (P) + CB4 (P)	CB1 (P) + CB4 (P)
Group name of independent minimal cut sets	**T1**	**T2**	**T2**	**T3**

Step 6: If a transmission line has a station at each end, then the independent minimal cut sets derived from both stations are added in series with the line failure parameters.

Step 7: The failure parameters of the common terminal minimal cut sets causing the outage of the same terminals are combined.

The functional representation of the independent minimal cuts used to modify the failure parameters of the station terminals or the connections are shown in Figure 3.8. It should be noted that the common terminal failure group in Table 3.2 are not shown in detail in this representation.



Where,
T1, T2, T3 and T4 represent the individual minimal cut sets for terminals Terminal 1,2,3 and 4 respectively in Table 3.2

Figure 3.8: A functional representation for the ring bus configuration

The equations necessary to modify the terminal parameters are shown in the following section.

3.4 Equations for combining independent terminal failures

The equations necessary for adding the transmission line failure parameters to the failure parameters of the independent minimal cut sets shown in Table 3.2 are given in Equations 3.6 to 3.8.

$$\lambda_{new} = \lambda_{old} + \lambda_{set1} + \lambda_{set2} \tag{3.6}$$

$$U_{new} = U_{old} + U_{set1} + U_{set2} \tag{3.7}$$

$$r_{new} = \underline{U_{new}} \tag{3.8}$$

Where,

λ_{new} - Modified failure rate of the transmission line after combining the independent cut sets

λ_{old} - Failure rate of the transmission line

λ_{set1} – Total failure rate of the independent minimal cut sets on one end of the transmission line

λ_{set2} - Total failure rate of all the independent minimal cut sets on the other end of the transmission line

U_{new} - Modified unavailability of the transmission line after the inclusion of the independent cut sets

U_{old} - Unavailability of the transmission line

U_{set1} - Total unavailability of all the independent minimal cut sets on one end of line causing its failure

U_{set2} - Total unavailability of all the independent minimal cut sets on the other end of line causing its failure

r_{new} – Modified outage time of the transmission line after combining the independent cut sets

The independent cut set failure parameters are calculated as shown in Equations 3.9 to 3.11

$$\lambda_{set1} = \sum_{(K=1 \text{ to } n)} \lambda_{cs1}^{k} \tag{3.9}$$

$$U_{set1} = \sum_{(K=1 \text{ to } n)} U_{cs1}^{k} \tag{3.10}$$

$$r_{set1} = U_{set1} / \lambda_{set1} \tag{3.11}$$

Where,

λ_{cs1}^{k}- Failure rate of the k^{th} independent minimal cut set on one end of the transmission line

U_{cs1}^{k}- Unavailability of the k^{th} independent minimal cut set on one end of the transmission line

r_{set1} - Repair time of the independent minimal cut set on one end of the transmission line

n - Total number of the independent minimal cut set on one of the ends of the transmission line

The equations shown above are also used to include the failure parameters of the independent cut sets derived from the other end of the transmission line.

3.5 Ring bus station application

The new method described in Section 3.3 is applied to the ring bus example shown in Figure 3.7 using the equations presented in Section 3.4. The component failure data used are given in Table 3.3.

Table 3.3: Station component failure data (For the example)

	(F/yr) Active failure rate	(F/yr) Passive failure rate	(F/yr) Total failure rate	(Hr) Repair time	(Hr) Switching time
Circuit breaker	0.0066	0.0005	0.0071	72	1
Bus bar	-	-	0.022	10	-

The failure rate, average repair times and unavailability for the independent minimal cut sets associated with Terminal 1 given in Table 3.2 are shown in Table 3.4. The equations for the second order minimal cut sets are given in Appendix F [38].

Table 3.4: Independent minimal cut sets for Terminal 1

Event (T1)	Failure rate (F/yr)	Repair time (Hr)	Unavailability
BB4 + CB1 (P)	0.000001	8.78	0.000000
BB4 + CB4 (A)	0.000002	0.91	0.000000
BB1 + CB3 (A)	0.000002	0.91	0.000000
BB1 + CB2 (P)	0.000001	8.78	0.000000
BB2	0.022000	10.00	0.000025
CB1 (P) + CB2 (P)	0.000000	36.00	0.000000
Total	**0.022006**	**10.00**	**0.000025**

It can be seen from Table 3.2 that all the station terminals have the same contribution due to station related failures and therefore the values for T1 in Table 3.4 are applicable to all the station terminals. The common outage values are shown in Table 3.5.

Table 3.5: Common outage group corresponding to Terminal 1

Event	Failure rate (F/yr)	Repair time (Hr)	Unavailability
CB1 (A)	0.006600	1	0.000001
CB2 (A)	0.006600	1	0.000001
BB1 + BB4	0.000111	5	0.000000

It can be seen from Table 3.5, that circuit breaker active failures cause higher unavailability compared to the overlapping failure of two buses. The common terminal unavailability due to station component outages is directly dependent on their failure parameters. As in example, the unavailability due to bus bar failures will be higher if their failure parameters are very high compared to the active failure parameters of a circuit breaker. In the case of a ring bus scheme, all the terminals are equally affected by station related outages. This is not true, however for other station configurations in common use by utilities. The minimal cut sets shown in Tables 3.4 and 3.5 can be safely ignored if their unavailability is less than six decimal places. The assessment of station failures is highly dependent on the component outage data and therefore the collection of station component outage data is an important task. This is discussed in the following section.

3.6 Station component outage data

The significant components in station reliability analysis are as follows [44]

1. circuit breakers,
2. main bus bars (commonly referred as the bus bars) and
3. transformers.

The station component failure data used in these analyses were obtained from a number of different sources. The circuit breaker failure data were obtained from the Canadian Electric Association Equipment Reliability Information System [42]. The bus bar failure data were taken from published research work [18-21]. Different utilities may have relatively higher bus bar failure rates than those assumed [43]. The transformer failure data were taken from [3].

Active and passive failure rates of a circuit breaker

Determining the active and passive failure rates of a circuit breaker is a difficult task because these data cannot usually be directly obtained from the component outage data provided by a utility. Some utilities however do collect circuit breaker data in a detailed manner, which can be used to derive the percentage ratio of active, and passive failures. The ratio of the active failures to the passive failure rates was derived from data shown in the CIGRE report (Working Group 06/ Study Committee 13: Reliability of HV circuit breaker) [41]. An approximate analysis of the data can be used to calculate the ratio of active and passive failure rates. The important definitions of the terms used in the CIGRE report are given in the following section together with some relevant data.

CIGRE definitions and circuit breaker data

Major Failure (of a circuit breaker): Complete failure of a circuit breaker, which causes the lack of one or more of its fundamental functions [41].

Note: A major failure will result in an immediate change in the system operating condition (e.g. the back up protective equipment being required to remove the fault) or will result in mandatory removal from service for non scheduled maintenance. A major failure is also termed as the forced outage of a circuit breaker [41].

Minor Failure (of a circuit breaker): Failure of a circuit breaker other than a major failure [41].

The CIGRE data indicates that the bulk of the failures associated with circuit breakers can be designated as active failures. The component data [3,18-21,42] used for station analysis in the research work presented in this thesis is shown in Table 3.6.

Table 3.6: Station component data

Component	λ_a **(Failures/yr)**	λ_p **(Failures/yr)**	λ_T **(Failures/yr)**	**s (Hours)**	**r (Hours)**
Circuit breaker [42]	0.00963	0.00107	0.0107	1.00	93.62
Main Bus bar [18]	-	-	0.025	-	10.00

Reliability analyses of the composite test systems are presented in the following section.

3.7 Analysis of composite test systems with stations

The method described in Section 3.3 is used in this section to include station related outages in composite system reliability evaluation. The composite test systems, RBTS and IEEE-RTS shown in Figures 2.6 and 2.7 respectively are used for analysis. The station schemes listed below are included in the RBTS reliability studies [22].

1. ring bus,
2. double bus double breaker,
3. one and one half and
4. one and one third breaker

The single diagram of the RBTS becomes complicated when the load buses are replaced by stations. The single line diagrams of the RBTS with different station configurations are shown in Figures 3.9, 3.10, 3.11 and 3.12. The load point transformers shown in these diagrams are not used for the initial analyses shown in this section.

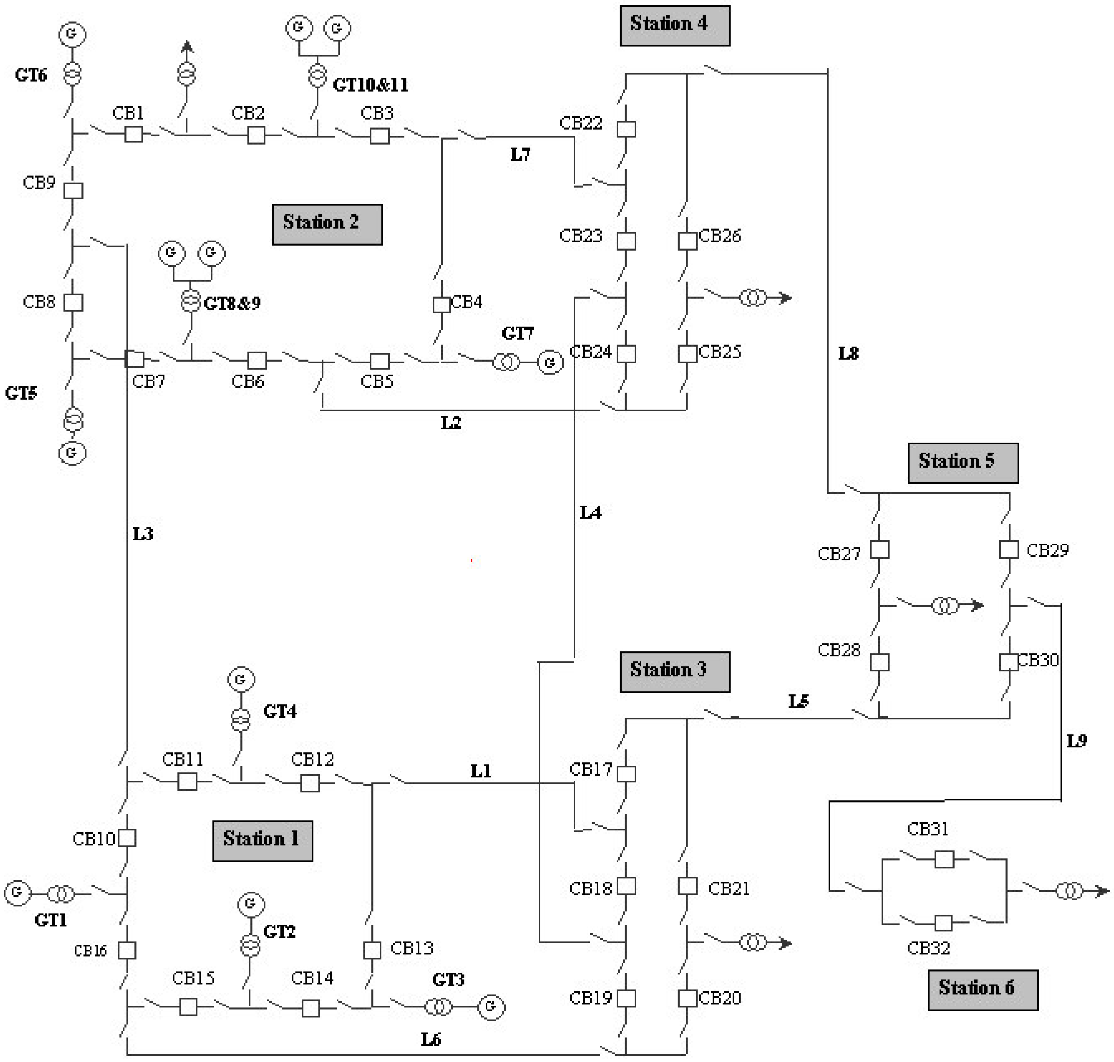


Figure 3.9: Single-line diagram of the RBTS with ring bus configurations

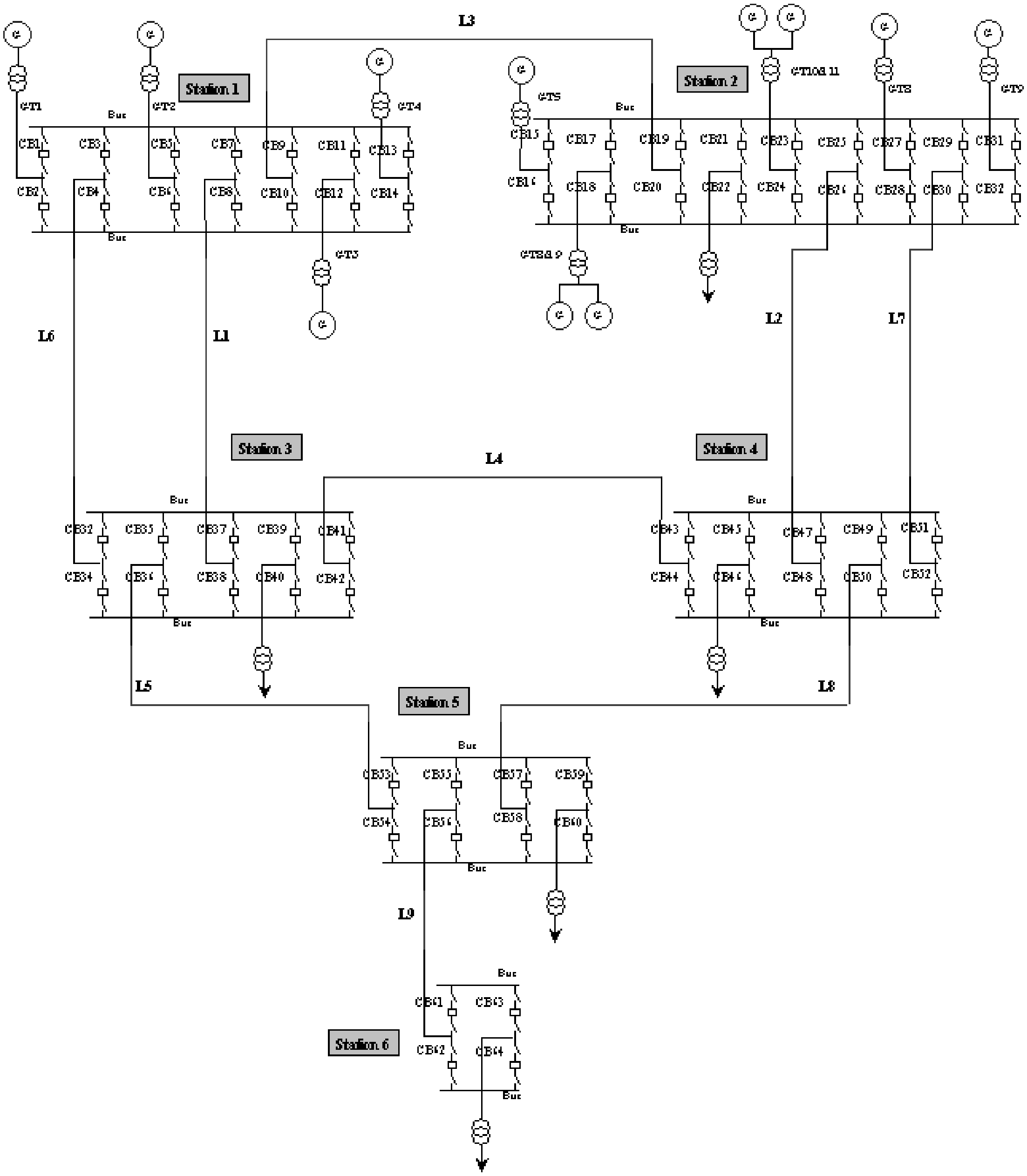


Figure 3.10: Single line diagram of the RBTS with double bus double breaker configurations

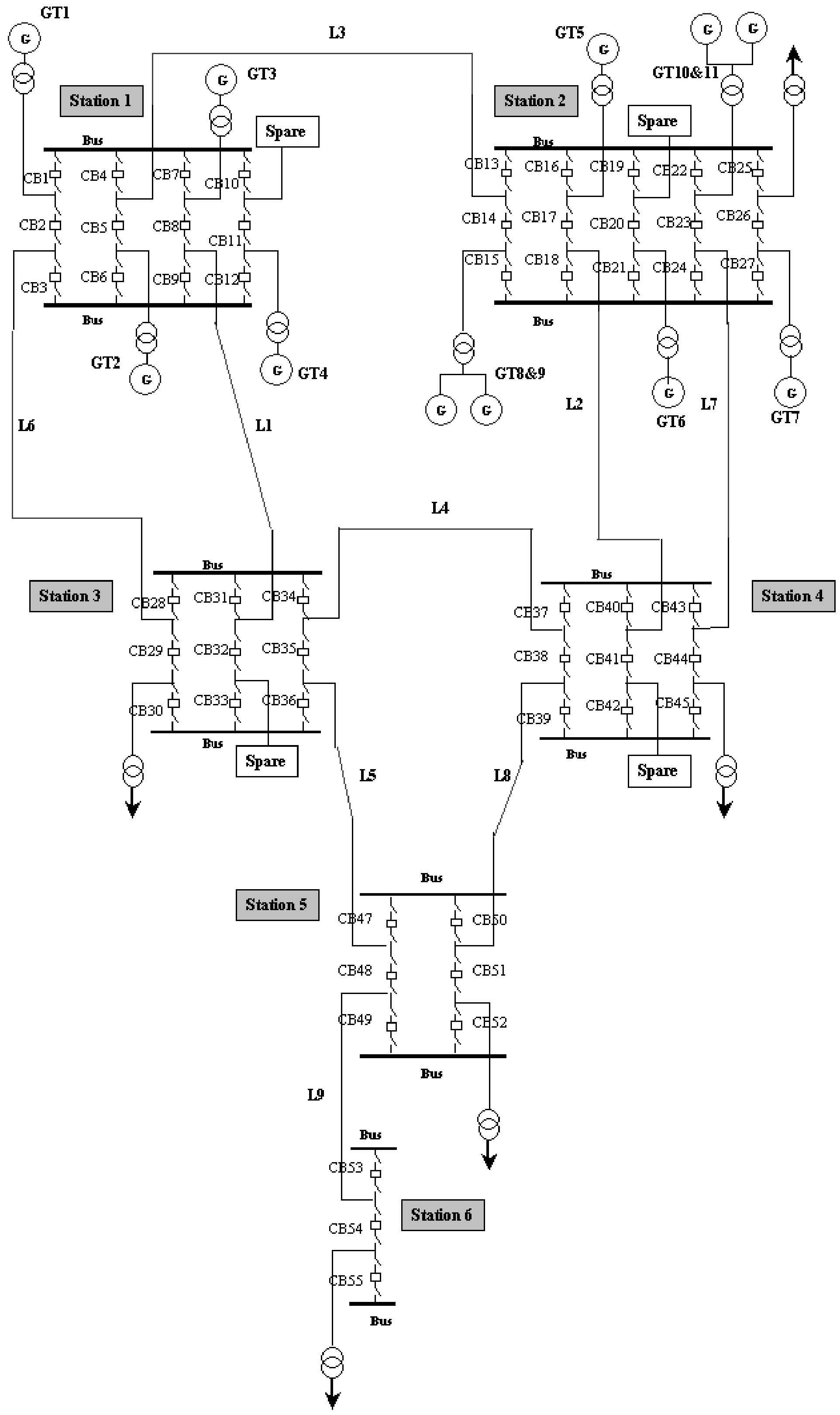


Figure 3.11: Single line diagram of the RBTS with one and one half breaker configurations

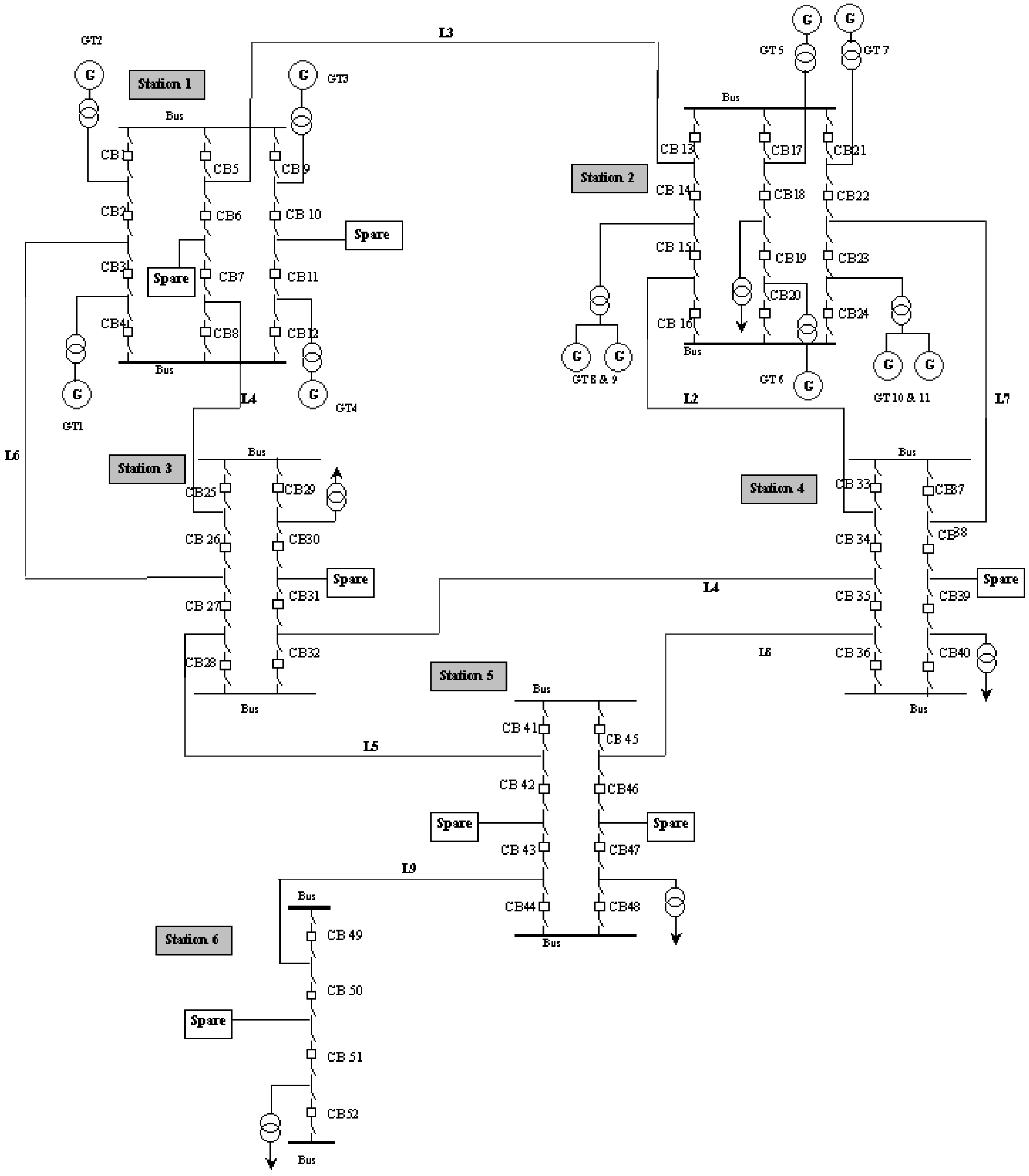


Figure 3.12: Single line diagram of the RBTS with one and one third circuit breaker configurations

RBTS reliability evaluation with station related outages

During the planning of a composite system it is necessary to select an appropriate station configuration. It is a difficult task to include and compare the performance of different station configurations in a large composite system. The RBTS shown in Figure 3.13 is a small composite system and can be relatively easily used to compare the system performance with different station configurations.

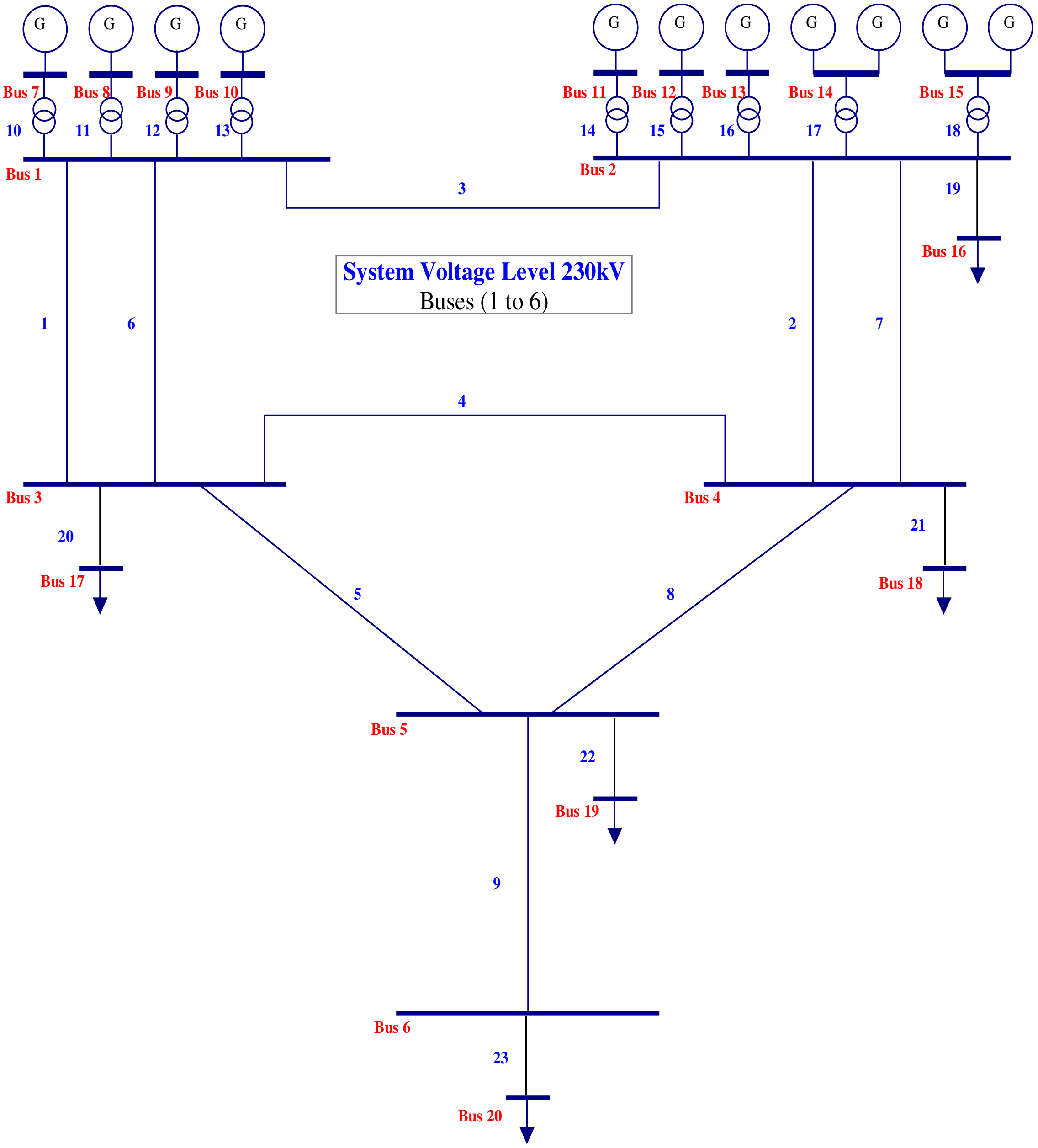


Figure 3.13: Extended single line diagram of the RBTS for including station related outages

The method in Section 3.3 is used for incorporating station related outages in composite system reliability evaluation and the single line diagrams shown in Figures 3.9, 3.10, 3.11 and 3.12 are reduced to that shown in Figure 3.13. The reliability results for the RBTS with different station configurations are given in the following sections.

RBTS with ring bus schemes

This section presents the reliability indices for the RBTS with ring bus station configurations. The load bus and the system indices for the system shown in Figure 3.13 are given in Tables 3.7 and 3.8. These indices can be compared with those shown in Tables 2.5 and 2.6. It can be seen that the load point and system indices show a significant increase due to the incorporation of station related outages.

Table 3.7: Load bus indices (RBTS with ring bus schemes)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00003	0.02521	0.323	0.00032	2.80	Bus 16
17	0.00022	0.13616	2.748	0.00362	31.73	Bus 17
18	0.00003	0.03243	0.811	0.00081	7.10	Bus 18
19	0.00004	0.03825	0.478	0.00046	3.99	Bus 19
20	0.00136	1.36287	17.301	0.01727	151.27	Bus 20

Table 3.8: System indices (RBTS with ring bus schemes)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.58347
Average duration of load curtailment (hrs/disturbance) ADLC	9.22
Expected duration of load curtailment (Hrs / year) EDLC	14.60
Probability of load curtailments (PLC)	0.00167
Expected demand not supplied (MW) EDNS	0.02247
Expected energy not supplied (MWhr / year) EENS	196.88
Expected Damage Cost (K$/ year) EDC	870.20
Bulk Power-interruption Index (MW/MW- year) BPII	0.11709
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	1.06421
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	13.68
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00012
Severity Index (system minutes/ year) SI	63.85

RBTS with double bus double breaker schemes

The detailed single line diagram for the RBTS with double bus double breaker station configurations is shown in Figure 3.10. This representation is reduced to that shown in Figure 3.13. The load bus and system indices are shown in Tables 3.9 and 3.10 and these indices again show an increase compared to the base case indices given in Tables 2.5 and 2.6. This increase is however is less than that for the RBTS with ring bus configurations.

Table 3.9: Load bus indices (RBTS with double bus double breaker schemes)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00000	0.00000	0.000	0.00000	0.000	Bus 16
17	0.00019	0.10787	1.238	0.00212	18.582	Bus 17
18	0.00000	0.00104	0.007	0.00000	0.031	Bus 18
19	0.00000	0.00564	0.061	0.00003	0.289	Bus 19
20	0.00121	1.23026	15.614	0.01536	134.744	Bus 20

Table 3.10: System indices (RBTS with double bus double breaker schemes)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.3332
Average duration of load curtailment (hrs/disturbance) ADLC	9.20
Expected duration of load curtailment (Hrs / year) EDLC	12.26
Probability of load curtailments (PLC)	0.0014
Expected demand not supplied (MW) EDNS	0.01752
Expected energy not supplied (MWhr / year) EENS	153.64
Expected Damage Cost (K$/ year) EDC	678.28
Bulk Power-interruption Index (MW/MW- year) BPII	0.09146
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.82949
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	12.69
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00009
Severity Index (system minutes/ year) SI	49.83

RBTS with one and one half breaker schemes

This section presents the reliability indices for the RBTS with one and one half circuit breaker configurations. The load bus and system indices are shown in Tables 3.11 and 3.12. The system and load bus indices are slightly higher than those obtained for the

RBTS with double bus double breaker stations. The ENLC values at the load buses are less than that of the RBTS with double bus double breaker configurations.

Table 3.11: Load bus indices (RBTS with one and one half breaker schemes)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00000	0.00892	0.114	0.00001	0.112	Bus 16
17	0.00019	0.11189	1.474	0.00215	18.818	Bus 17
18	0.00000	0.00103	0.007	0.00000	0.031	Bus 18
19	0.00000	0.01439	0.173	0.00005	0.401	Bus 19
20	0.00122	1.22000	15.484	0.01547	135.508	Bus 20

Table 3.12: System indices (RBTS with one and one half breaker schemes)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.34471
Average duration of load curtailment (hrs/disturbance) ADLC	9.19
Expected duration of load curtailment (Hrs / year) EDLC	12.35
Probability of load curtailments (PLC)	0.00141
Expected demand not supplied (MW) EDNS	0.01768
Expected energy not supplied (MWhr / year) EENS	154.87
Expected Damage Cost (K$/ year) EDC	684.53
Bulk Power-interruption Index (MW/MW- year) BPII	0.09326
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.83714
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	12.82964
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00010
Severity Index (system minutes/ year) SI	50.23

RBTS with one and one third breaker schemes

The load bus and system indices are shown in Tables 3.13 and 3.14 for the RBTS with one and one half breaker configurations. The indices are again slightly higher than those for the base case indices. The system indices for the four different station configurations are compared in the next section.

Table 3.13: Load bus indices (RBTS with one and one third breaker schemes)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00000	0.00000	0.00000	0.00000	0.000	Bus 16
17	0.00020	0.12092	1.960	0.00220	19.30	Bus 17
18	0.00000	0.00994	0.235	0.00003	0.031	Bus 18
19	0.00000	0.00557	0.060	0.00003	0.289	Bus 19
20	0.00121	1.21902	15.47	0.01533	134.74	Bus 20

Table 3.14: System indices (RBTS with one and one third breaker schemes)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	1.34393
Average duration of load curtailment (hrs/disturbance) ADLC	9.12
Expected duration of load curtailment (Hrs / year) EDLC	12.26
Probability of load curtailments (PLC)	0.0014
Expected demand not supplied (MW) EDNS	0.01760
Expected energy not supplied (MWhr / year) EENS	154.18
Expected Damage Cost (K$/ year) EDC	681.44
Bulk Power-interruption Index (MW/MW- year) BPII	0.09581
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.83336
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	13.19
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00010
Severity Index (system minutes/ year) SI	50.00

Comparison of the system reliability indices for the RBTS

The comparison is based on the percentage increase in a system index over that obtained in the base case shown in Table 2.6. Figure 3.14 presents a comparison of the increase in the system indices associated with the four station configurations considered. It can be seen that the RBTS with ring bus configuration has the highest percentage increase compared to the RBTS with other station configurations.

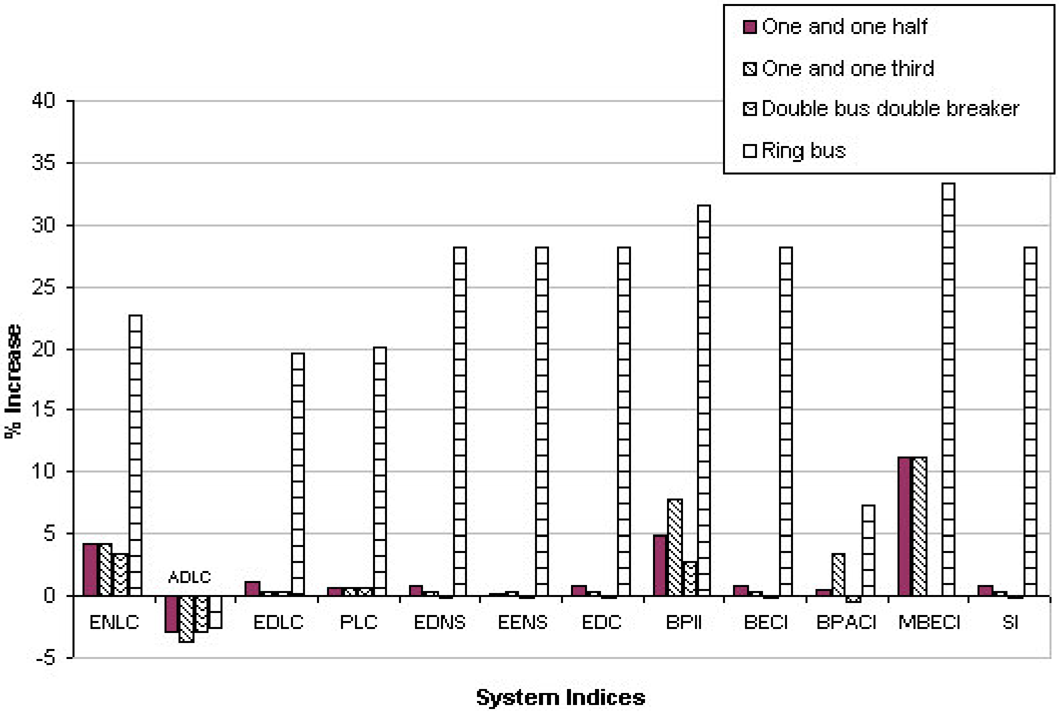


Figure 3.14: Relative impact on the system reliability indices for the RBTS due to station configurations

The comparisons shown in Figure 3.14 are based on the parameters shown in Table 3.6. Variation in the indices with changes in station component failure parameters are illustrated in Chapter 4. The most significant increase in the system indices is associated with the ring bus configuration. This is the least expensive configuration in terms of capital cost. The double bus double breaker configuration results in the lowest system ENLC and EENS and is the most expensive configuration.

IEEE-RTS with station related outages

The application of the proposed method for incorporating station configuration in composite system reliability analysis is further illustrated using the IEEE-RTS. The IEEE-RTS has 24 buses that require station models. The single line diagram of the IEEE-RTS becomes very complicated with the direct inclusion of stations. This can be seen from Figure 3.15. This complicated system is difficult to analyze directly. The method presented in Section 3.3 can be used to reduce the IEEE-RTS to the form shown in Figure 3.16.

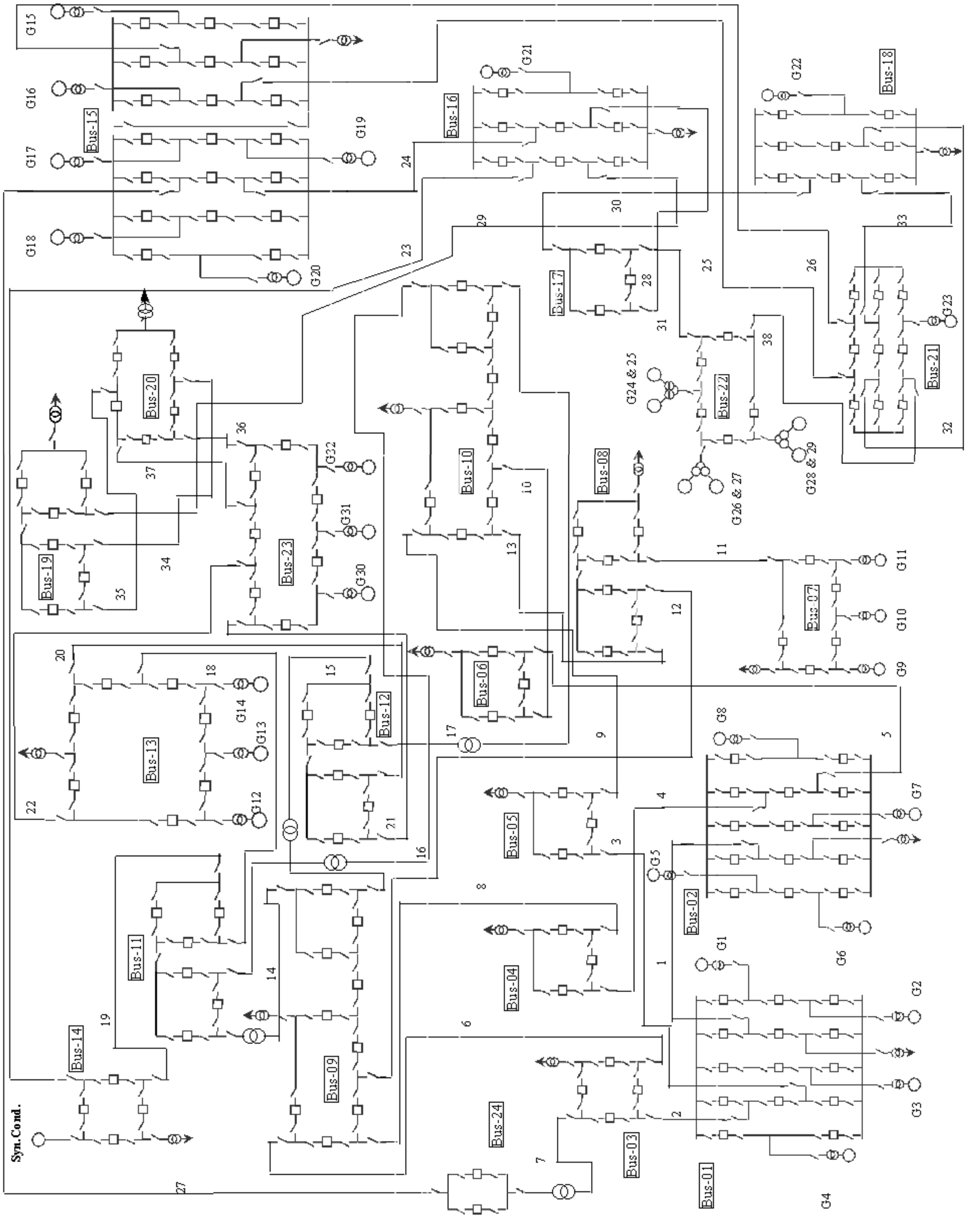


Figure 3.15: Single line diagram of the IEEE-RTS with stations

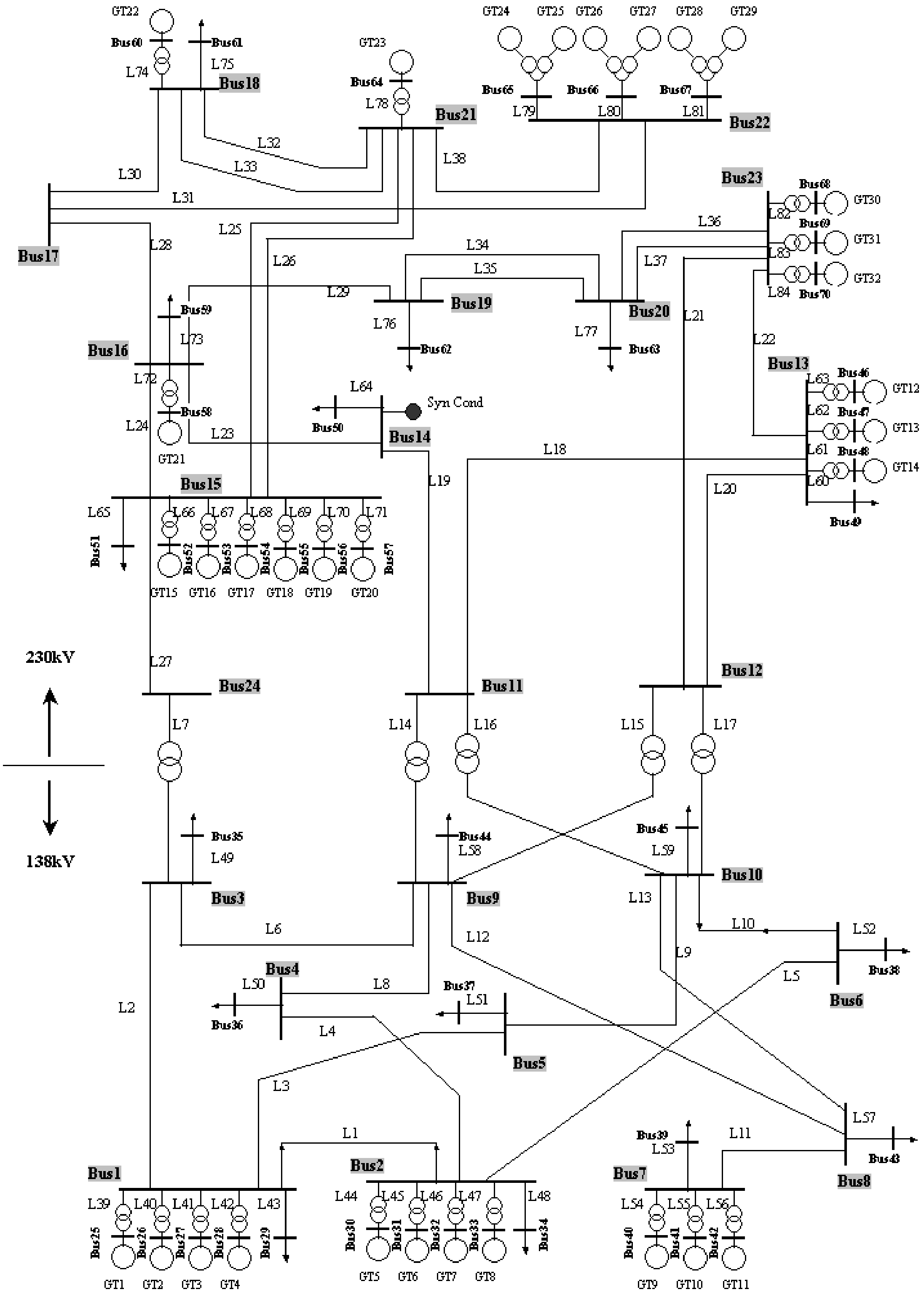


Figure 3.16: Extended single line diagram of the IEEE-RTS including station related outages

Load bus and system indices for the IEEE-RTS with stations:

The load bus and the system indices for the IEEE-RTS with stations are shown in Tables 3.15 and 3.16. There is an increase in the indices compared to the base case indices presented in Tables 2.9 and 2.10 due to the contributions made by station related outages.

Table 3.15: Load bus indices (IEEE-RTS with stations)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
29	0.00000	0.00000	0.000	0.00000	0.000	Bus29
34	0.00000	0.00131	0.047	0.00004	0.344	Bus34
35	0.00003	0.03811	4.387	0.00345	30.257	Bus35
36	0.00002	0.02301	1.089	0.00076	6.634	Bus36
37	0.00003	0.03651	1.658	0.00118	10.344	Bus37
38	0.00003	0.03854	3.352	0.00244	21.337	Bus38
39	0.00004	0.05081	4.029	0.00304	26.635	Bus39
43	0.00002	0.03210	3.502	0.00241	21.083	Bus43
44	0.00114	0.95978	61.301	0.07183	629.191	Bus44
45	0.00005	0.06753	8.078	0.00599	52.438	Bus45
49	0.00003	0.04036	6.842	0.00475	41.576	Bus49
50	0.00024	0.24968	19.310	0.01689	147.993	Bus50
51	0.00066	0.55107	47.537	0.05503	482.069	Bus51
59	0.00011	0.11368	5.092	0.00484	42.433	Bus59
61	0.00005	0.06400	9.513	0.00741	64.933	Bus61
62	0.00201	1.64274	105.593	0.12936	1133.161	Bus62
63	0.00008	0.08895	5.211	0.00449	39.317	Bus63

Table 3.16: System indices (IEEE-RTS with stations)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.16527
Average duration of load curtailment (hrs/disturbance) ADLC	9.64
Expected duration of load curtailment (Hrs / year) EDLC	20.87
Probability of load curtailments (PLC)	0.00238
Expected demand not supplied (MW) EDNS	0.31390
Expected energy not supplied (MWhr / year) EENS	2749.74
Expected Damage Cost (K$/ year) EDC	11603.90
Bulk Power-interruption Index (MW/MW- year) BPII	0.10054
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.96482
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	132.34
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00011
Severity Index (system minutes/ year) SI	57.89

3.8 Effect of including load point transformers

As discussed in Section 2.7, the presence of load point transformers in a composite system analysis can significantly impact the predicted system performance. The load point transformer failure data are given in Appendix B (Table B-7). The effects of including load point transformers are illustrated in the following section

RBTS with load point transformers and stations

A comparison of the reliability indices for the RBTS with different station configurations (Figures 3.9 to 3.12) and with load point transformers is shown in Figure 3.17. The RBTS configurations shown in Figure 3.9 to 3.12 are reduced to the representation shown in Figure 2.9 for composite system analysis. The reliability indices for the RBTS with load point transformers and stations are shown in Appendix C.

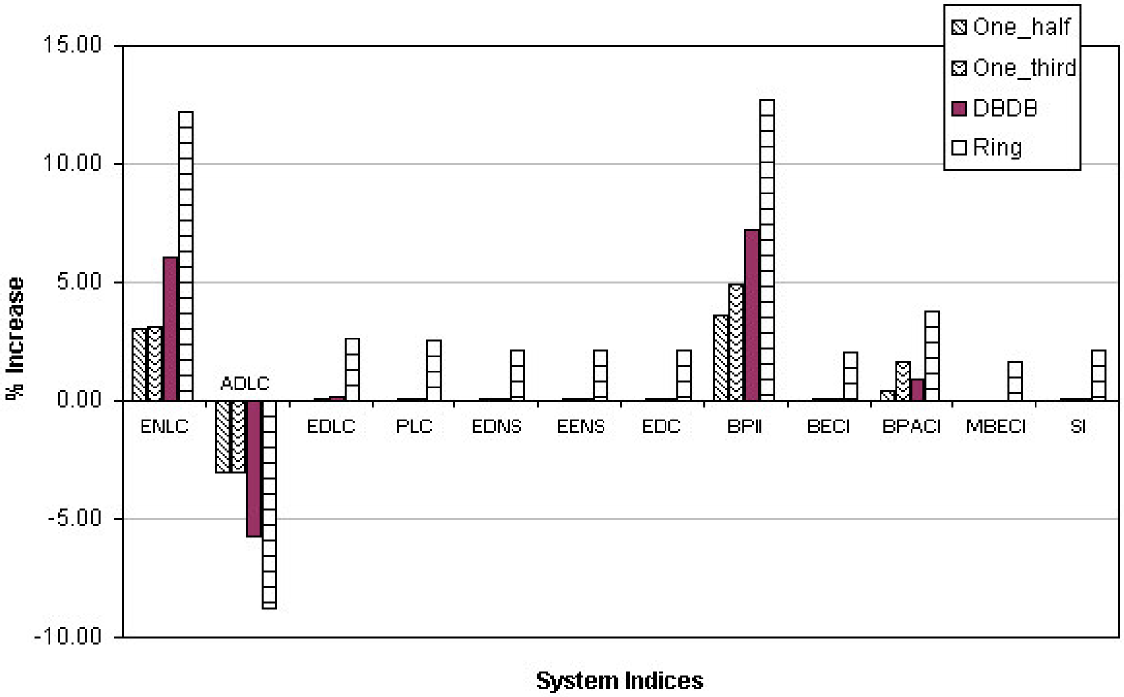


Figure 3.17: Relative impact on the system reliability indices for the RBTS due to station configurations and load point transformers

It can be seen from the Figure 3.17 that the RBTS with ring bus configurations has the maximum percentage increase compared to the base case indices presented in Tables 2.11 and 2.12. The percentage increase is less than that in the case of the RBTS without load point transformers. The specific impact can be seen from the numerical values in Appendix C. The RBTS analysis with one and one half breaker configurations and one and one third breaker configurations show a very similar performance when the EENS values are compared. The ENLC indices for the RBTS with the double bus double breaker configuration are relatively high in this case.

IEEE-RTS with load point transformers and stations

The complicated single line diagram of the IEEE-RTS with stations and load point transformers is reduced to the system shown in Figure 2.10. The load bus and system indices for the IEEE-RTS in this case are shown in Tables 3.17 and 3.18.

Table 3.17: Load bus indices
(IEEE-RTS with load point transformers and stations)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
29	0.00171	0.91241	63.030	0.117850	1032.378	Bus29
34	0.00168	0.92467	57.099	0.10414	912.283	Bus34
35	0.00175	0.98221	113.086	0.20149	1765.009	Bus35
36	0.00184	1.00243	47.448	0.08690	761.273	Bus36
37	0.00173	0.95989	43.593	0.07838	686.650	Bus37
38	0.00177	0.97482	84.800	0.15397	1348.802	Bus38
39	0.00180	1.00140	80.034	0.14360	1257.939	Bus39
43	0.00188	1.04214	113.978	0.20541	1799.405	Bus43
44	0.00463	3.21676	243.980	0.36812	3224.769	Bus44
45	0.00182	1.00164	123.215	0.22567	1976.858	Bus45
49	0.00183	1.01088	171.348	0.30985	2714.302	Bus49
50	0.00241	1.52448	158.224	0.26085	2285.040	Bus50
51	0.00343	2.29298	313.426	0.50447	4419.165	Bus51
59	0.00205	1.24607	73.372	0.12369	1083.537	Bus59
61	0.00187	1.07664	215.856	0.38462	3369.308	Bus61
62	0.00658	4.64346	353.556	0.52131	4566.651	Bus62
63	0.00202	1.16116	88.431	0.15791	1383.302	Bus63

The results shown in these tables can be compared with the values given in Tables 3.15 and 3.16. The inclusion of the load point transformers has a significant impact on the predicted indices. The impact will be reduced considerably if redundant transformer capacity is provided.

Table 3.18: System indices
(IEEE-RTS with load point transformers and stations)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	19.85
Average duration of load curtailment (hrs/disturbance) ADLC	15.16
Expected duration of load curtailment (Hrs / year) EDLC	301.034
Probability of load curtailments (PLC)	0.0344
Expected demand not supplied (MW) EDNS	3.9482
Expected energy not supplied (MWhr / year) EENS	34586.51
Expected Damage Cost (K$/ year) EDC	145955.071
Bulk Power-interruption Index (MW/MW- year) BPII	0.82263
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	12.13562
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	118.0894
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00139
Severity Index (system minutes/ year) SI	728.137

A comparison of the system reliability indices for the IEEE-RTS with and without load point transformers is shown in Figure 3.18.

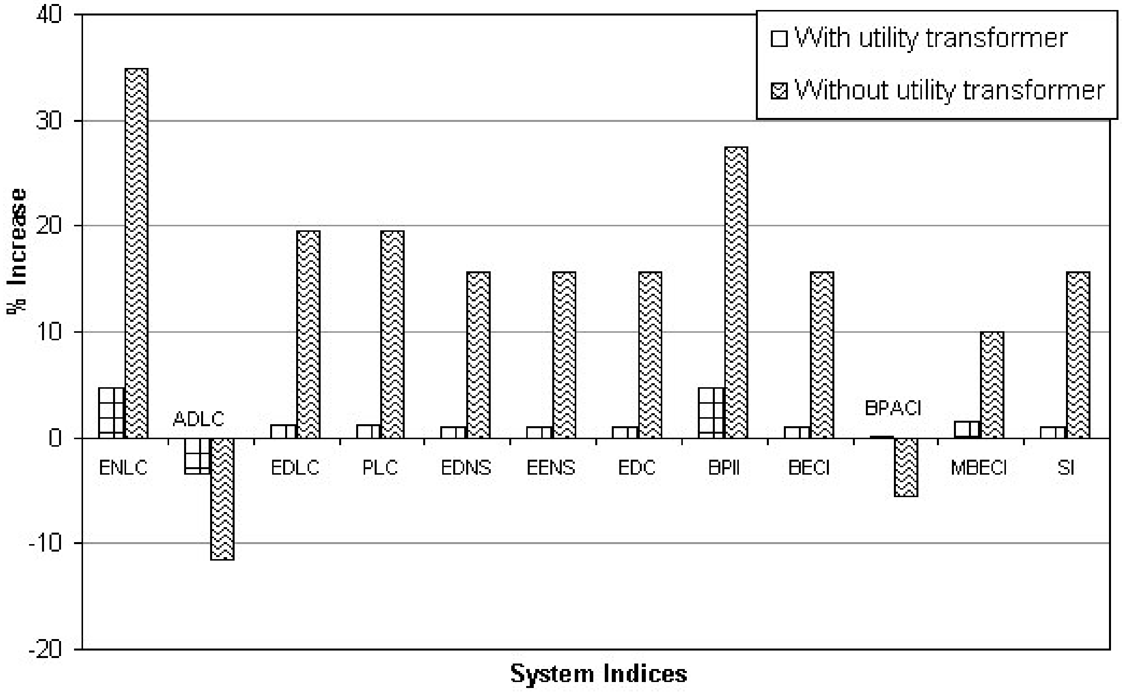


Figure 3.18: Relative impact on the system reliability indices of the IEEE-RTS with stations, with and without load point transformers

Figure 3.18 shows that the impact on the system indices of including station related outages is much less than that associated with including single load point transformers in the analysis. The numerical values used to create Figure 3.18 are given in Tables 3.16, 3.18, 2.6 and 2.10.

3.9 Summary

This chapter describes a method for including station related outages in composite system evaluation. This chapter also illustrates the basic state space models used for the various station components.

The method is presented using a ring bus configuration example. The necessary equations required to include station related outages in an HL-II reliability evaluation are also given.

Detailed RBTS reliability analyses are presented using different station configurations. The resulting load point and system indices are compared. The relative impact of the different station configurations on the system reliability indices can clearly be seen from the analyses. The effects of including stations in a composite system analysis are further illustrated in this chapter using the IEEE-RTS. The results show that station related outages are important factors in the system assessment and significantly affect the predicted indices.

Analyses were conducted on both the RBTS and the IEEE-RTS to examine the impact on the predicted system and load point indices of including load point transformers in the analysis. The use of single load point transformers results in a substantial increase in the predicted indices. These effects will be diminished if redundant transformer capacity is included in the evaluation.

Chapter 4

Sensitivity Studies on Composite Test Systems with Stations

4.1 Introduction

Assessing the effects of component failures on the system performance is an important composite system planning activity. As discussed in Chapter 3, the station components present in a composite system play a significant role in system performance. The new method described in Chapter 3, is used in this chapter to determine the effects of variations in selected station components failure rates on the composite system performance. The composite test systems and the station configurations analyzed in Chapter 3 are used in a series of sensitivity studies. Some of the station configurations have been modified in order to improve the composite system reliability. The analysis described in this chapter is done using the station component failure parameters shown in Chapter 3, as the base values. The failure parameters of the circuit breakers and bus bars are varied in order to observe this effect on the composite system reliability. The composite system sensitivity analyses conducted are described in the following sections. Load point transformers are not included in these studies.

4.2 Sensitivity analysis on the RBTS with stations

The RBTS is a small test system and is used extensively in this chapter for sensitivity analysis. The different station configurations presented in Chapter 3 are used in the sensitivity studies. The EENS index is an important indicator of system performance and is used for assessing the RBTS performance. Other indices could also be used if desired. The sensitivity studies done on the RBTS with ring bus schemes are as follows.

RBTS with ring bus schemes

The single line diagram of the RBTS with ring bus schemes is shown in Figure 3.9. The effect on the RBTS performance of varying the bus bar failure rate can be seen in Figure 4.1. The load bus and system indices increase with an increase in the bus bar failure rates. The effect is quite significant at all the buses and for the system, as the bus bars are important components in a ring bus configuration.

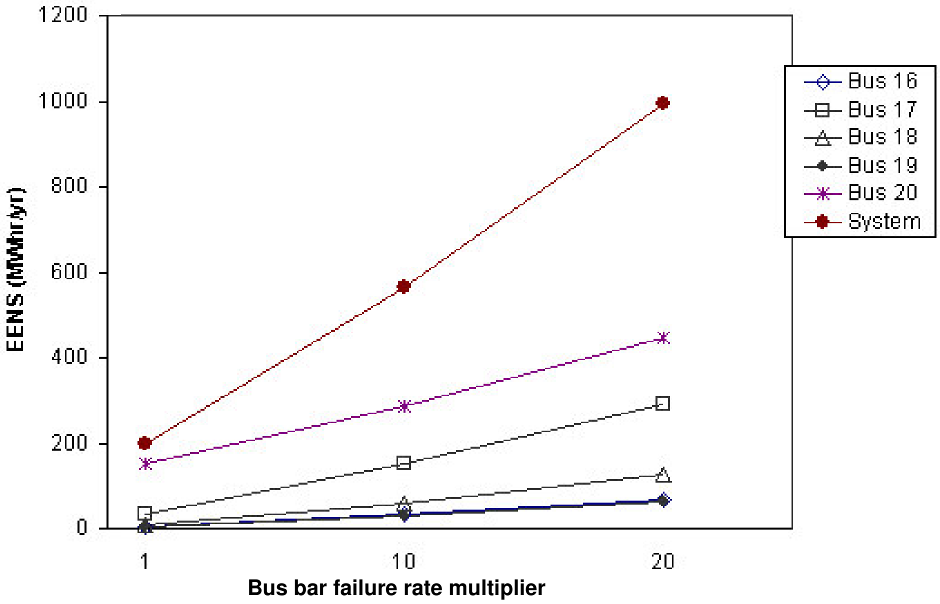


Figure 4.1: Effect of varying the bus bar failure rates in the RBTS with ring bus schemes

Other system and load bus indices show similar behavior with increase in the bus bar failure rate. The effect on the system performance of increasing the repair time of a bus bar is similar to the effect due to increasing the bus bar failure rate.

The effect on the EENS index of varying the circuit breaker failure rates can be observed from Figure 4.2. It can be seen that the system EENS of the RBTS with ring bus schemes is relatively less sensitive to increases in the circuit breaker failure rate as compared to that of varying the bus bar failure rate.

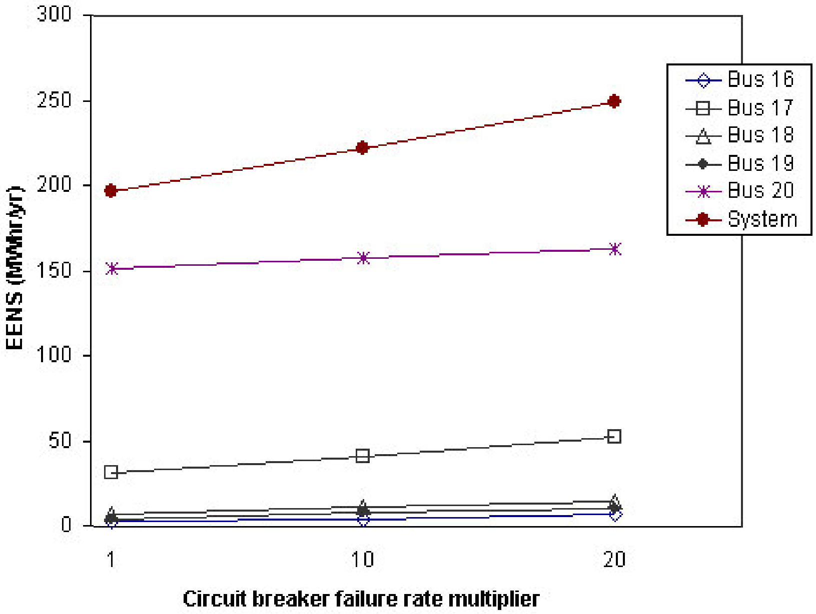


Figure 4.2: Effect of varying the circuit breaker failure rates in the RBTS with ring bus schemes

RBTS with double bus double breaker schemes

The single line diagram of the RBTS with double bus double breaker schemes is shown in Figure 3.10. The effect of varying the failure rates of the double bus double breaker station components can be observed from Figures 4.3 and 4.4. There is no significant increase in the EENS values at the load buses and for the system, when the bus bar failure rates are varied.

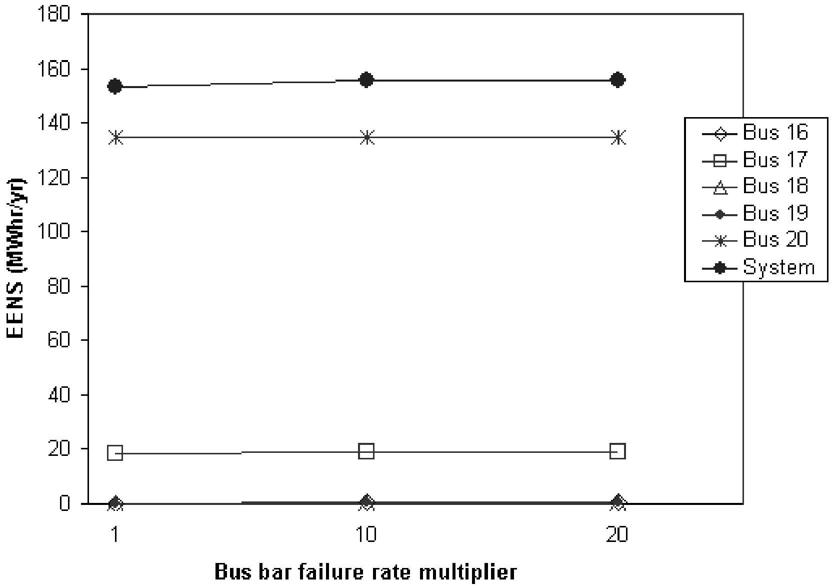


Figure 4.3: Effect of varying the bus bar failure rates in the RBTS with double bus double breaker schemes

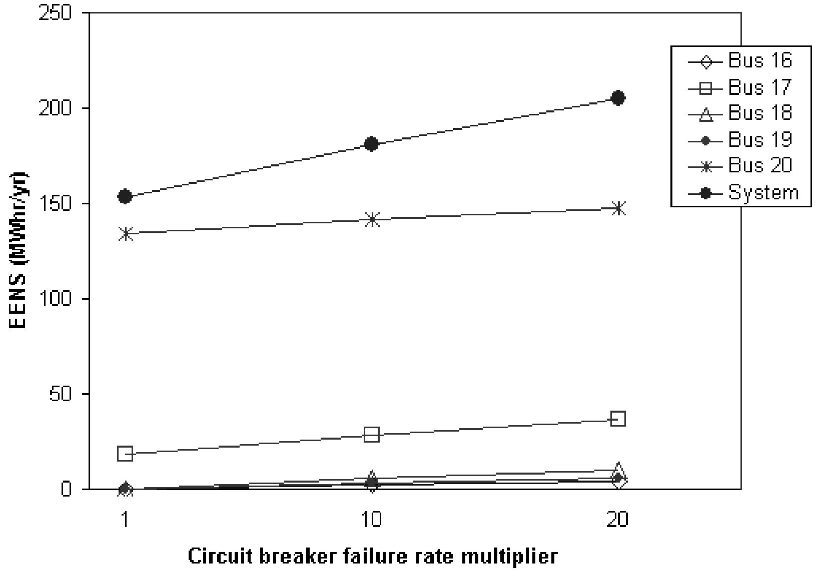


Figure 4.4: Effect of varying the circuit breaker failure rates in the RBTS with double bus double breaker schemes

The variation in the EENS with circuit breaker failure rate is very similar to that shown in Figure 4.2 for the RBTS with ring bus schemes.

RBTS with one and one half circuit breaker schemes

This station configuration is widely used in composite power systems [22]. The RBTS diagram for this case is shown in Figure 3.11. Figure 4.5 shows the response of the RBTS with one and one half breaker configurations to variations in the bus bar failure rates.

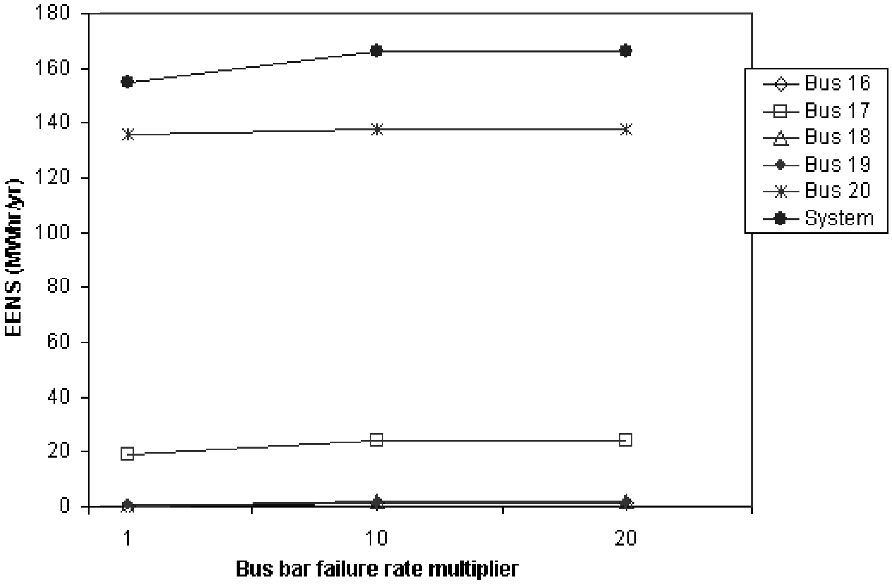


Figure 4.5: Effect of varying the bus bar failure rates in the RBTS with one and one half breaker schemes

It can be seen from Figure 4.5 that the RBTS with one and one half circuit breaker schemes is not very sensitive to variations in the bus bar failure rate.

Figure 4.6 shows the effect of varying the circuit breaker failure rates on the EENS index. It can be observed that the system EENS of the RBTS with one and one half breaker schemes is similar to that shown in Figure 4.4.

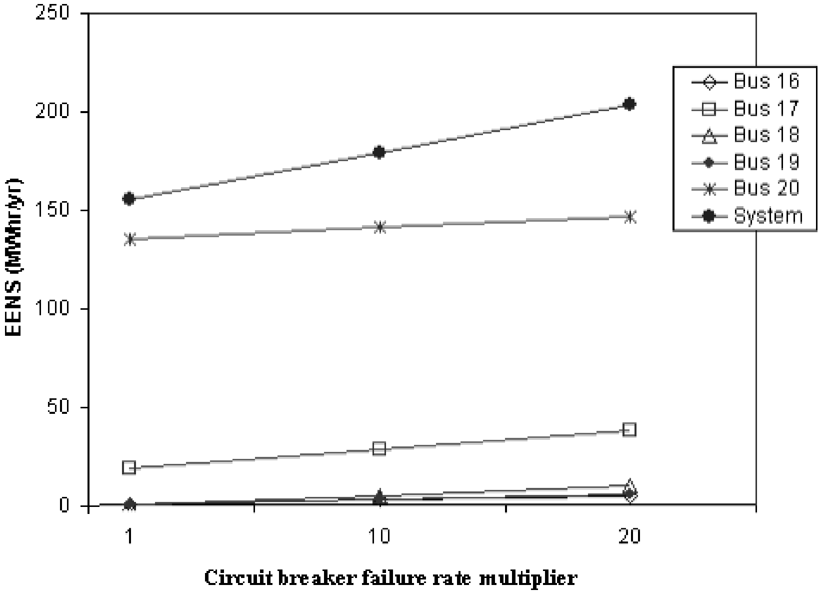


Figure 4.6: Effect of varying the circuit breaker failure rates in the RBTS with one and one half breaker schemes

RBTS with one and one third circuit breaker schemes

This configuration has fewer breakers per terminal compared to the one and one half breaker configuration and is shown in Figure 3.12. The effect on the performance of the RBTS with one and one third breaker configurations of varying the bus bar failure rate can be observed from Figure 4.7. It can be seen that the load bus and system EENS indices are relatively insensitive to variations in the bus bar failure rates.

The effect on the performance of the RBTS of varying the circuit breaker failure rates can be observed from Figure 4.8.

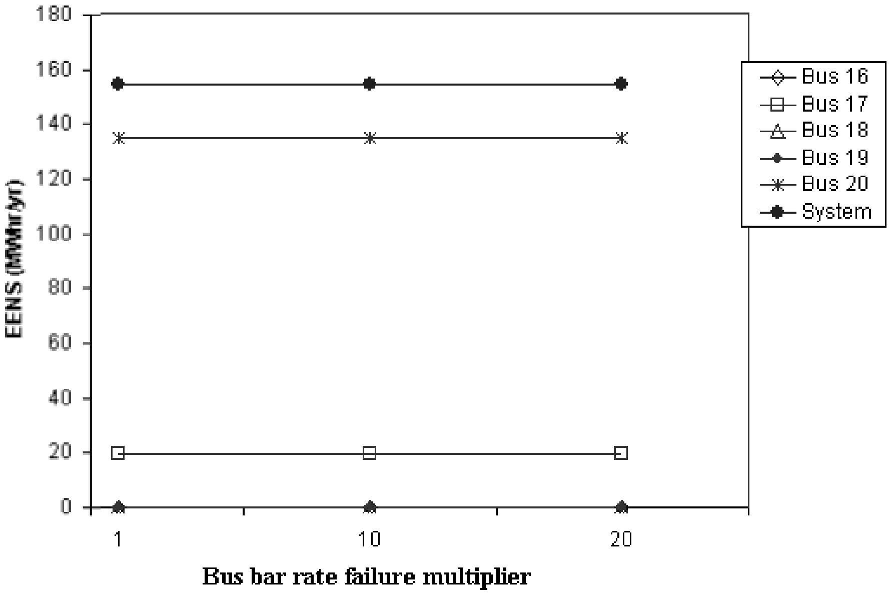


Figure 4.7: Effect of varying the bus bar failure rates in the RBTS with one and one third breaker schemes

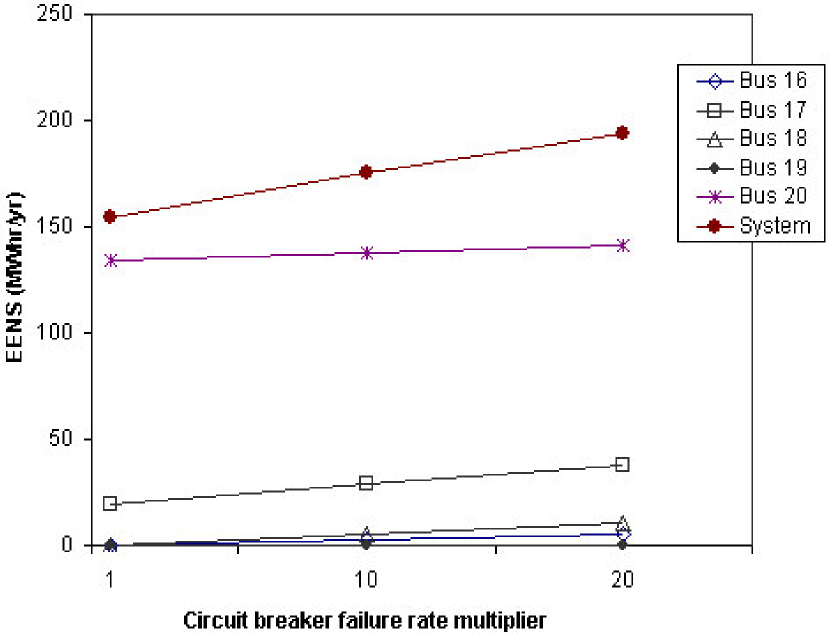


Figure 4.8: Effect of varying the circuit breaker failure rates in the RBTS with one and one third breaker schemes

The system EENS values are sensitive to variations in the circuit breaker failure rates and are similar to those shown in Figures 4.4 and 4.6. Load bus 17 is more sensitive to variations in the circuit breaker failure rates compared to the other load buses. The studies done on the RBTS with one and one third circuit breaker configurations shows that this configuration is more reliable than the ring bus scheme. The performance of the RBTS with one and one third stations is similar to that of the RBTS with one and one half circuit breaker stations and the RBTS with double bus double breaker configurations. It should be noted, however that the behavior of the RBTS with different station configurations could change with different station components failure parameters.

Comparison of variations in the circuit breaker failure rate

Figure 4.9 shows a comparison of the RBTS performance with different station configurations as a function of the circuit breaker failure rates. The variations in the system EENS index for all the configurations are very similar.

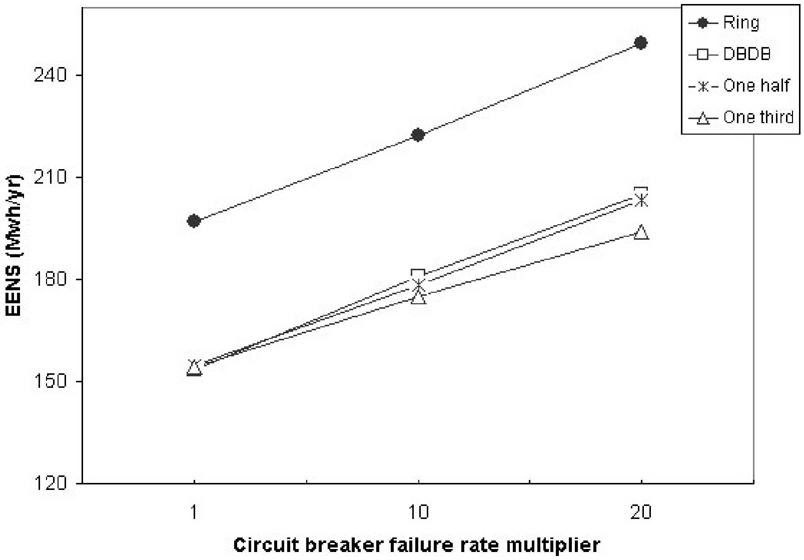


Figure 4.9: Station comparison of the impact of variations in the circuit breaker failure rates on the EENS index. (Note: DBDB- Double bus double breaker)

The RBTS with double bus double breaker configurations is slightly more sensitive to variations in the circuit breaker failure rates as compared to the RBTS with one and one half breaker configurations and one and one third breaker configurations.

4.3 Sensitivity analysis of the IEEE-RTS with stations

This section deals with sensitivity analysis of the IEEE-RTS with station related outages. It can be seen from the analysis in Chapter 3 that the IEEE-RTS reliability is highly influenced by generation outages and therefore station outages will not create a large increase in the system reliability indices. In order to examine the effect of station outages, the system was analyzed under the assumption that the generation facilities are completely reliable. The analysis in this case is shown in Table 4.1.

Table 4.1: Station related outage contributions to the IEEE-RTS transmission outages.

System Indices/Units	IEEE-RTS without stations	IEEE-RTS with stations
Expected number of load curtailments (1/ year) ENLC	0.00038	0.38010
Average duration of load curtailment (hrs/disturbance) ADLC	10.2406	8.95
Expected duration of load curtailment (Hrs / year) EDLC	0.00384	3.40029
Probability of load curtailments PLC	0.00	0.00039
Expected demand not supplied (MW) EDNS	0.00002	0.04128
Expected energy not supplied (MWhr / year) EENS	0.18975	369.54
Expected Damage Cost (K$/ year) EDC	0.80076	1559.45
Bulk Power-interruption Index (MW/MW- year) BPII	0.00001	0.01453
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	0.00007	0.12966
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	39.24	108.92
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00	0.00001
Severity Index (System minutes/ year) SI	0.004	7.77973

It can be observed from Table 4.1 that the EENS increases from 0.18975 MWhr/yr to 324.76 MWhr/yr with the inclusion of station outages. The load bus indices also show a comparable increase. This clearly illustrates that station outages can make a significant contribution to total transmission outages in the IEEE-RTS. The sensitivity analysis conducted on the IEEE-RTS with stations is described in the following sections.

Effect of circuit breaker failure rates on the IEEE-RTS performance

The failure rates of the circuit breakers in the IEEE-RTS were modified to examine the effect on the system reliability. The circuit breaker failure rates on the 138kV side of the system were modified first, followed by the circuit breaker failure rates on the 230kV side of the system.

138kV Circuit breaker failure rate variation:

The effect on the load bus indices of varying the 138kV circuit breaker failure rates can be seen in Figures 4.10 to 4.12.

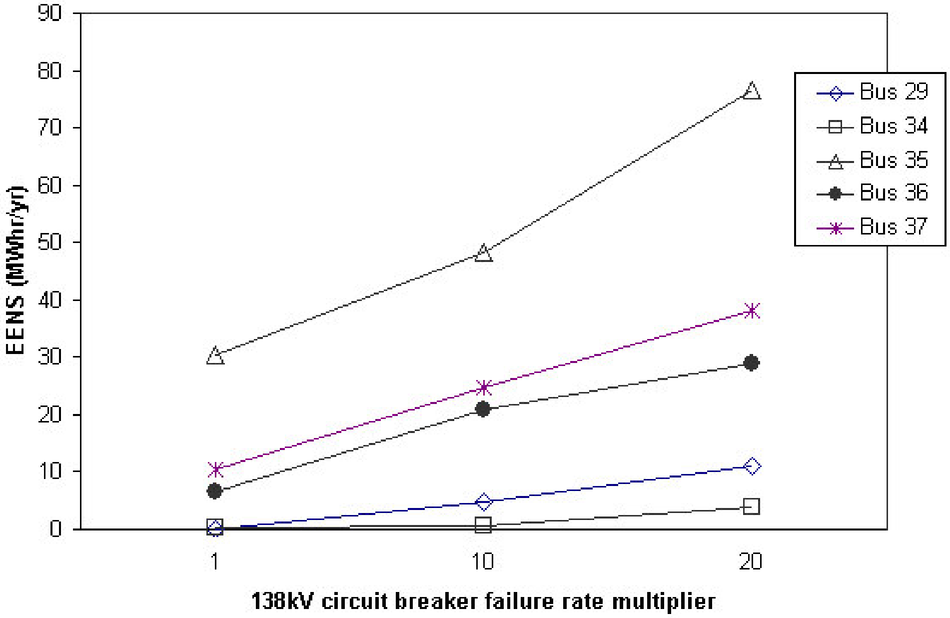


Figure 4.10: Effect of varying the138kV circuit breaker failure rates in the IEEE-RTS with stations (buses 29 to 37)

Figure 4.10 shows that the load bus indices on the 138kV side are sensitive to increases in the circuit breaker failure rates on the 138kV side of the system. The effect of these variations in the failure rate also depends on the station configuration (Appendix D) used at each load bus. Load buses 29 and 34 show a very small increase because they are connected to stations at buses 1 and 2 with one and one third breaker configurations. (Refer to Figures D-1 &D- 2 in Appendix D for bus 1 and 2, which supply load to buses 29 and 34 respectively). Figure 4.11 and 4.12 show the increase in the EENS at other load buses. Buses 35 and 36 are ring configurations and hence they show a higher increase with variations in the circuit breaker failure rate. The increase in this case is not linear and can be observed from Figure 4.10.

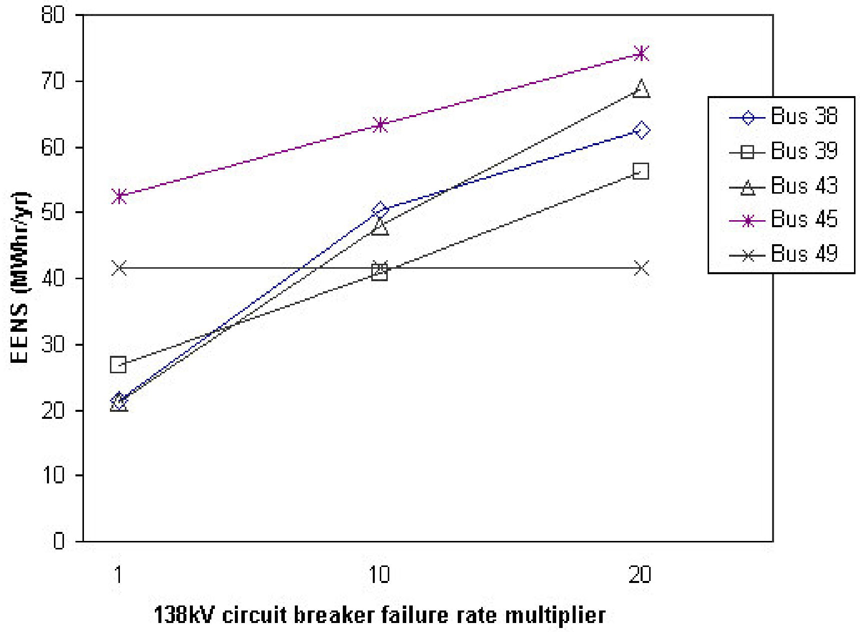


Figure 4.11: Effect of varying the 138kV circuit breaker failure rates in the IEEE-RTS with stations (buses 38 to 49)

The load point indices at buses 38, 39 and 43 (Figure 4.11) show an increase with increase in the 138kV circuit breaker failure rates. These buses have ring configurations, which are comparatively less reliable than the one and one third breaker configurations, or the one and one half breaker configurations. Figure 4.12 shows that the 230kV side of the IEEE-RTS is relatively insensitive to increases in the failure rates of the 138kV circuit breakers.

230kV Circuit breaker failure rate variation:

The effect of increasing the failure rates of the 230kV circuit breakers can be seen from Figure 4.13. It can be observed from this figure that the load bus indices on the 230kV side are sensitive to these increases in the circuit breaker failure rate. The actual increase in the EENS at the load buses depends on the station configuration used. Load buses 29, 34 to 39 and 43 to 45 are relatively less sensitive to variations in the 230kV circuit breaker failure rates.

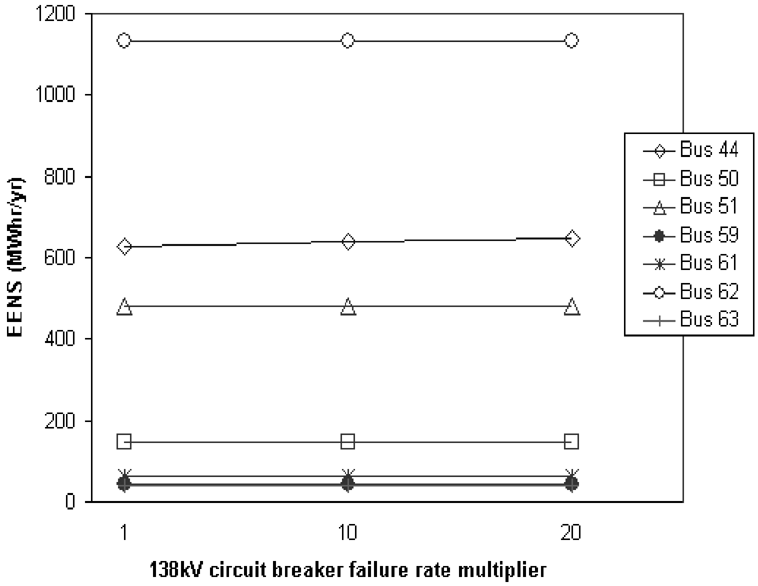


Figure 4.12: Effect of varying the138kV circuit breaker failure rates in the IEEE-RTS with stations (buses 44 to 63)

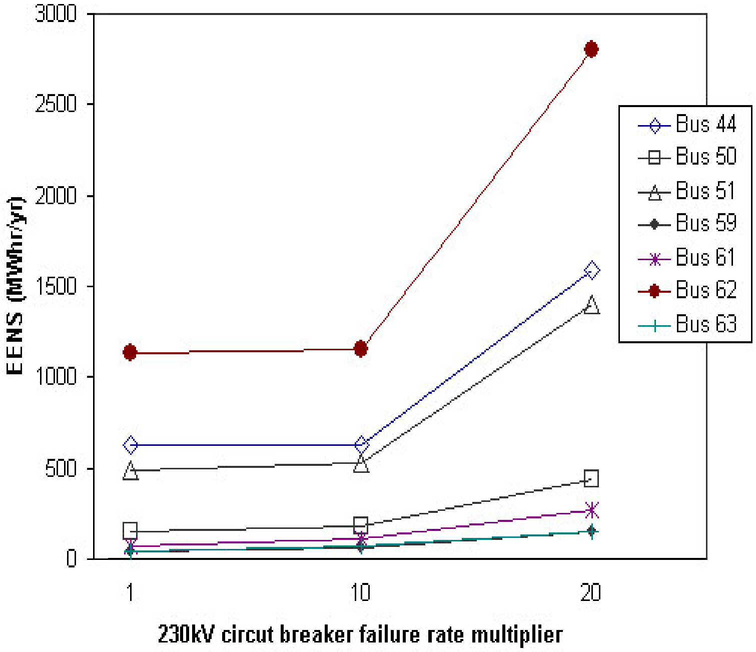


Figure 4.13: Effect of varying the 230kV circuit breaker failure rates in the IEEE-RTS with stations (buses 44 to 63)

Effect of varying the bus bar failure rates on the IEEE-RTS performance

The bus bar failure rate is assumed to be same for all the buses irrespective of the voltage level of the system and therefore changing the bus bar failure rate affects the performance of the load bus indices on both the 138kV and 230kV sides of the IEEE-RTS. Figure 4.14 shows that the increase in selected load bus indices is linear with respect to change in the bus bar failure rate.

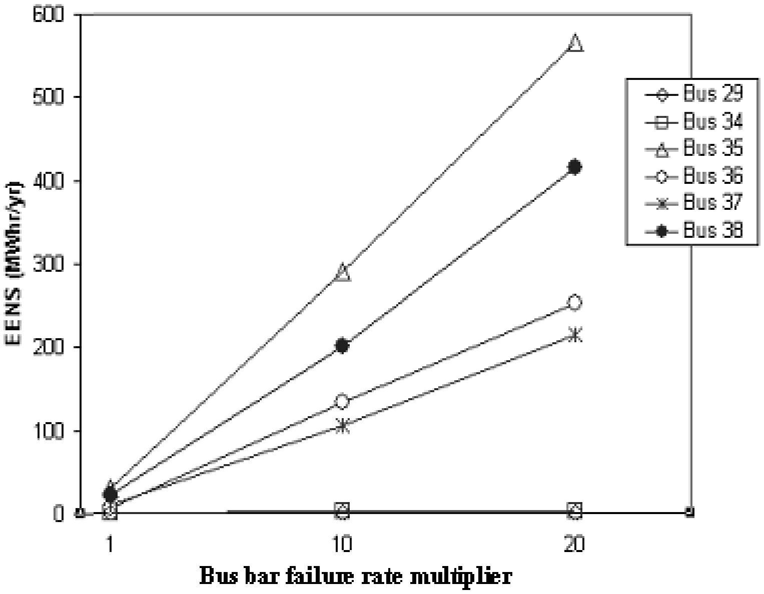


Figure 4.14: Effect of varying the bus bar failure rates in the IEEE-RTS with stations (buses 29 to 38)

Figures 4.15 and 4.16 show the effects of bus bar failures on the load bus indices at other load buses in the system. The actual increase depends on the station configuration at a bus and on the adjacent station configurations. In the case of load bus 29 there is a small increase in the indices because the station has a one and one third breaker configuration. This is also the case for bus 34. Load bus 35 is a ring type station configuration and therefore this bus shows a significant increase.

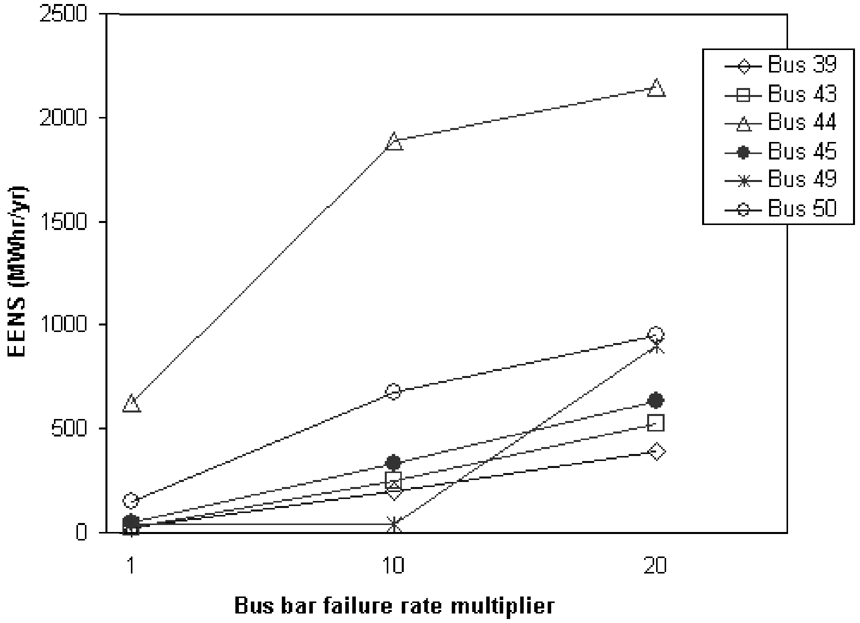


Figure 4.15: Effect of varying the bus bar failure rates in the IEEE-RTS with stations (buses 39 to 50)

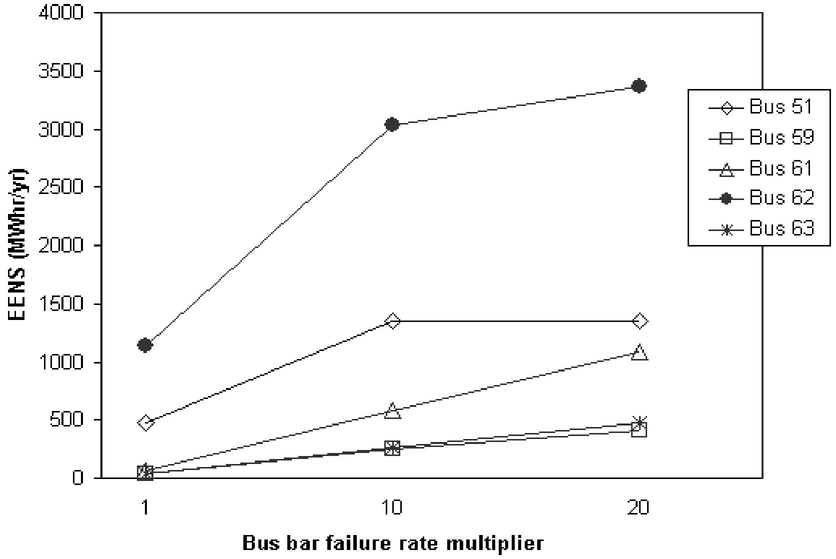


Figure 4.16: Effect of varying the bus bar failure rates in the IEEE-RTS with stations (buses 51 to 63)

The sensitivity analysis conducted on the IEEE-RTS supports the conclusions drawn from the RBTS analysis regarding the reliability effects of the different station configurations. The same conclusions can be applied to larger composite systems with the same component failure parameters. The studies described in this section have been used to modify the IEEE-RTS to improve the system performance. The station modifications used in the IEEE-RTS are described in the following section.

4.4 IEEE-RTS reliability improvements

The results in Section 4.3 clearly indicate the locations in the IEEE-RTS where reliability improvements can be made by changing the station configurations. The reliability improvements due to station modifications at selected buses are illustrated in the following sections.

Station modification at bus 19 (load bus 62):

This load bus has the highest EENS and therefore it is a candidate for modification. The increase in the EENS due to the inclusion of station outages is not particularly high when compared to the increase in the indices at other load buses. Bus 19 has a meshed ring configuration as seen from Figure D-19 (Appendix D). This configuration is influenced to a great extent by both bus bar failures and circuit breaker failures. This configuration was replaced with the one and one half breaker configuration shown in Figure E-1 (Appendix E). Table 4.2 shows that the EENS and PLC values at the connected load bus 62, after modifying the station at a bus 19 has decreased. The modified values of the EENS and PLC are similar to those of bus 19 without stations. In this case the indices at other associated load buses will also change slightly due to modification of load bus 19.

Table 4.2: Effects of station modification at bus 19

Bus 19 (Load bus 62)	**EENS (MWhr/yr)**	**PLC**
Without stations	1114.4	0.00199
Ring bus configuration	1133.2	0.00201
One and half breaker configuration	1114.9	0.00199

Station modification at bus 3 (load bus 35):

This load bus has the highest increase in reliability indices of all the load buses when stations are included in the analysis. The station configuration at bus 3 is a pure ring configuration with four terminals and is shown in Figure D-3 (Appendices D). This station was changed to the one and one half breaker configuration shown in Figure E-2 (Appendix E). It can be observed from Table 4.3 that using a one and half breaker configuration at bus 3 results in a considerable reduction in the EENS at load bus 35

Table 4.3: Effect of station modification at bus 3

Bus 3 (Load bus 35)	**EENS (MWhr/yr)**	**PLC**
Without stations	0.0	0.0
Ring configuration	30.3	0.00003
One and half breaker configuration	0.001	0.0

Figure 4.17 shows a comparison of the increase in the system indices due to the station modifications at buses 3 and 19.

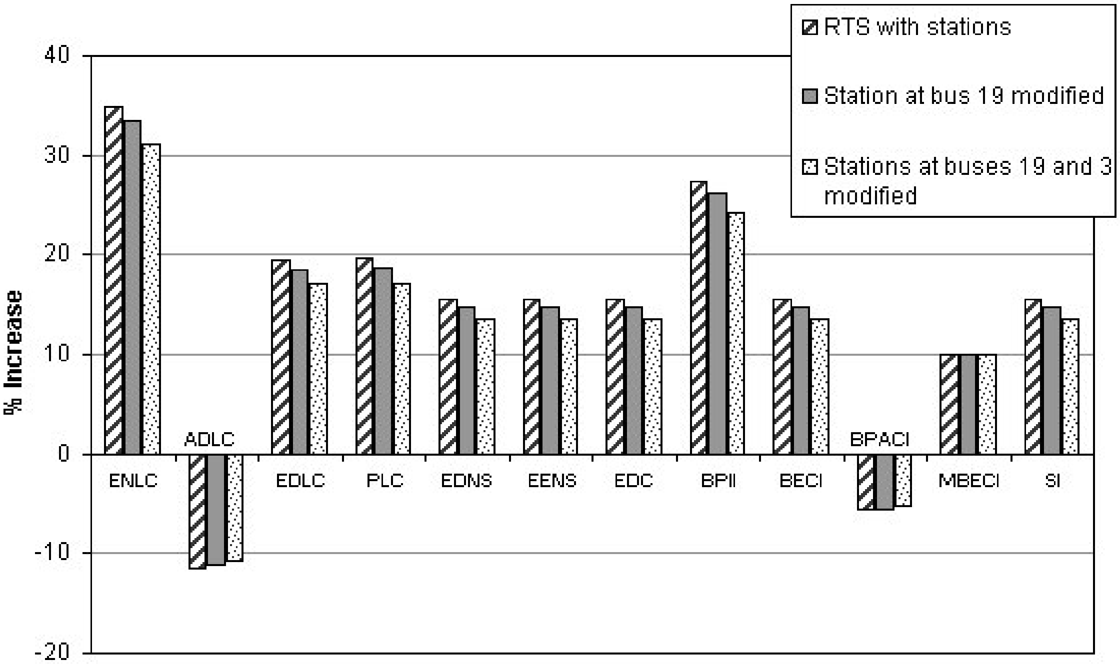


Figure 4.17: Effect of stations modification on reliability indices of the IEEE-RTS

Figure 4.17 shows that the modifications made at these two buses significantly improve the overall system reliability. Similar changes could be made at other stations to achieve higher levels of load point and system reliability. The resulting benefits should be compared with the cost associated with the modifications.

4.5 Summary

The new method presented in Chapter 3 for the inclusion of station related outages in HL-II evaluation was used to perform selective sensitivity studies on the RBTS and the IEEE- RTS. The EENS index is used to illustrate the system performance. The four different station configurations shown in Chapter 3 are used in the sensitivity studies presented in this chapter.

The RBTS with ring bus configurations is more sensitive to variations in the station component failure parameters than the RBTS with other station configurations. The RBTS with double bus double breaker configurations is relatively insensitive to variations in the bus bar failure rates.

In the case of the IEEE-RTS it was observed that the contributions due to station related outages to the system transmission outage events are significant. Selected stations in the IEEE-RTS were modified using more reliable configurations, in order to improve the system reliability. The load bus indices at the adjacent stations are slightly affected due to the modification of a station in the IEEE-RTS.

The sensitivity analysis conducted on the RBTS supports the conclusions drawn from the IEEE-RTS analysis regarding the reliability effects of different station configurations. The RBTS with ring bus configurations has the lowest reliability of the four configuration studied. It also uses the least number of circuit breakers and has the lowest capital cost. The RBTS with double bus double breaker configurations, one and one half breaker configurations and one and one third breaker configurations show a similar behavior due to variations in the circuit breaker failure rates. The RBTS with one and one half breaker configurations has a slightly higher reliability than the RBTS with one and one third breaker configurations and a slightly higher cost. The conclusions drawn from the sensitivity analysis presented in this chapter can be applied to larger composite systems with the same set of component failure parameters.

Chapter 5

Conclusions

The basic objective of the research described in this thesis, is to develop a method that can be used to include station related outages in composite system reliability analysis. The objective is described in detail in Chapter 1. Consideration of station related outages in composite system reliability analysis is a complex task and has received considerable attention from power system researchers in the past. The effects of station related outages can propagate to other parts of a system and cause severe damages. Stations are nodal points in a power system that control and monitor the flow of electric current and therefore failures in stations can significantly affect the load point supply.

Composite system reliability can be evaluated using both analytical methods and Monte Carlo simulation. A Monte Carlo simulation is a fluctuating convergence process that generates a series of experiments to assess power system reliability. This approach was used for composite system analysis in this research. A brief description of Monte Carlo simulation is given in Chapter 2, where different types of Monte Carlo methods are described. State sampling, which is a non-sequential method, is combined with enumeration techniques in the MECORE software used in this research. A brief review of the MECORE software is given in Chapter 2, in order to provide an appreciation of its structure and capabilities. The MECORE software is used to calculate a variety of reliability indices at the load point and system levels.

The RBTS and IEEE-RTS composite test systems used in this research are described in Chapter 2. The RBTS is a relatively small test system and was used for detailed study of the new method presented in this thesis for incorporating stations in composite system analysis. The IEEE-RTS is relatively larger test system and was used for some limited studies. The basic single diagrams of the composite test systems were extended to included station related outages in the reliability analysis. It was observed from the studies conducted that the RBTS requires more simulation samples for convergence than the IEEE-RTS.

The reliability analyses of the RBTS and the IEEE-RTS were done using the economic priority order for load curtailment. Predetermined IEAR values were used in the load curtailment philosophy for both test systems. The base case reliability indices for the two test systems are given in Chapter 2., The reliability indices at the load points and at the system level increase significantly when load point transformers are included in the analysis. The provision of standby or redundant transformers at a load point minimizes the effect of load point transformers. Chapter 2 describes the necessary concepts required to understand the new method used to include station related outages.

Stations are complex networks and their consideration in composite system analysis requires considerable effort. State space diagrams were used in order to understand the outage process and incorporate the effects of station component failures. Station components such as circuit breakers, bus bars and transformers are modeled using Markov processes. Common terminal failures due to station related outages causing failures of two or more station terminals are described in Chapter 3.

The published research indicates the difficulties and improvements required to represent station outages in HL-II reliability studies. A new method is presented in Chapter 3 to include the effects of common terminal outages caused by station component failures. This method is simple and easy to implement and considers station related outages in a straightforward manner. The minimal cut set approach is used to numerically incorporate station related outages [38]. This method is illustrated using a ring bus scheme example and the derived equations are given in Chapter 3. The equations required for incorporating station related outages in HL-II reliability studies are relatively simple.

A major problem in incorporating station related outages in composite system analyses is the availability of suitable station component data. These difficulties are discussed in Section 3.6. It was difficult to obtain suitable data on active and passive failures of circuit breakers from the CIGRE and CEA databases and some assumptions had to be made. Bus bar and transformer failure data were taken from published literature [18, 21].

The single line diagrams for the two test systems including station configurations are shown in Chapter 3. The reliability analysis conducted on the RBTS shows that the use of ring bus configurations results in significantly higher reliability indices than that found for the other station configurations. These analyses assume that the bus bar failure rates are the same for different station configurations. This may not be the case for all utilities. The IEEE-RTS has a strong transmission system and a weak generation system and therefore the major contributions to the load point and system indices are from the generation facilities.

When load point transformers are included with station related outages in a composite system reliability evaluation, the percentage increase due to station related outages is relatively less than that in a composite system without load point transformers and with stations. The presence of single load point transformers at all the load points dominates the station failure effects.

Selected sensitivities studies conducted on the composite test systems are presented in Chapter 4. It can be observed from these studies that the effect of variations in the station component failure rates is not the same for the RBTS with different station configurations. The reliability indices of the RBTS with ring bus schemes are sensitive to variations in the bus bar failure rates, and are relatively less sensitive to increases in the circuit breaker failure rates. The EENS index for the RBTS with double bus double breaker configurations, one and one half breaker configurations and one and one third breaker configurations are insensitive to variations in bus bar failure rates. The sensitivity studies presented in Chapter 4 are useful in power system planning.

The station related outages contribute in a significant way to the system related transmission outages of the IEEE-RTS. Variable failure rates for the 138kV and the 230kV circuit breakers were considered in the IEEE-RTS analysis. These changes in one side of the system affect that side only, with relatively slight effects in the other side. It was assumed that the bus bar failure rates for all the stations in the IEEE-RTS are the same. The load point indices of stations with ring bus configurations are sensitive to variations in the bus bar failure rates.

Selected station configurations were modified in order to improve the IEEE-RTS performance. As described in Chapter 4, the station modifications at the selected buses significantly improve the system performance. Slight changes are observed in the load point indices of the adjacent stations due to these modifications. The IEEE-RTS transmission system is relatively reliable and therefore an outage in a station does not affect the delivery point indices at the adjacent stations in a significant manner.

The new method presented in Chapter 3, has been successfully used for incorporating station related outages in composite system analysis. The research work presented in this thesis shows that importance should be given to the inclusion of station related outages in composite system studies. The incorporation of station related outages in the composite analysis is highly dependent on the availability of accurate component failure data. The conclusions drawn from the analysis presented in this thesis can be applied to larger composite systems. It is expected that the techniques and the concepts presented in this thesis should be useful to electric utility planners and decision makers.

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Appendices

Appendix A. Basic data for the RBTS

The data used for reliability analysis of the RBTS are given in Tables A-1, A-2 and A-3.

Table A-1: Generation data for the RBTS

Bus No.	Capacity (p.u)	Forced Outage Rate	MTTR (Hrs)
7	0.40	0.02825	41.38
8	0.40	0.02825	41.38
9	0.10	0.01825	40.17
10	0.20	0.02325	40.17
11	0.05	0.00825	36.50
12	0.05	0.00825	36.50
13	0.40	0.01825	53.65
14	0.20	0.01325	48.77
14	0.20	0.01325	48.77
15	0.20	0.01325	48.77
15	0.20	0.01325	48.77

Table A-2: Load bus data for the RBTS

Bus no.	Priority Code	Load (p.u)
2	1009	0.20
3	1005	0.85
4	1008	0.40
5	1007	0.20
6	1006	0.20

Table A-3: Transmission line or transformer data for the RBTS

No.	ID	From	To	Capacity (p.u)	1/Reactance (p.u)	FOR	MTTR (Hrs)
1	L1	Bus 1	Bus 3	0.85000	5.55556	0.00171	10.0
1	L2	Bus 1	Bus 3	0.85000	5.55556	0.00171	10.0
2	L3	Bus 2	Bus 4	0.71000	1.66667	0.00571	10.0
2	L4	Bus 2	Bus 4	0.71000	1.66667	0.00571	10.0
3	L5	Bus 1	Bus 2	0.71000	2.08883	0.00457	10.0
4	L6	Bus 3	Bus 4	0.71000	8.33333	0.00114	10.0
5	L7	Bus 3	Bus 5	0.71000	8.33333	0.00114	10.0
6	L8	Bus 4	Bus 5	0.71000	8.33333	0.00114	10.0
7	L9	Bus 5	Bus 6	0.71000	8.33333	0.00114	10.0
8	L10	Bus 1	Bus 7	0.48000	11.91900	0.00175	768.0
9	L11	Bus 1	Bus 8	0.48000	11.91900	0.00175	768.0
10	L12	Bus 1	Bus 9	0.12000	11.91900	0.00175	768.0
11	L13	Bus 1	Bus 10	0.24000	11.91900	0.00175	768.0
12	L14	Bus 2	Bus 11	0.06000	11.91900	0.00175	768.0
13	L15	Bus 2	Bus 12	0.06000	11.91900	0.00175	768.0
14	L16	Bus 2	Bus 13	0.48000	11.91900	0.00175	768.0
15	L17	Bus 2	Bus 14	0.48000	11.91900	0.00175	768.0
16	L18	Bus 2	Bus 15	0.48000	11.91900	0.00175	768.0

Appendix B. Basic data for the IEEE-RTS

This Appendix gives details about the IEEE-RTS (Figure 3.16) data (Table B-1 to B-3) and the load curve data (Tables B-4 to B-6). The IEEE-RTS transmission line data have been modified to exclude the bus bar failures. The load point transformer data is shown in Table B-7.

Table B-1: Generation data for the IEEE-RTS

Bus No.	**Capacity (p.u)**	**Forced Outage Rate**	**MTTR (Hrs)**
25	0.20	0.09825	44.26
26	0.20	0.09825	44.26
27	0.76	0.01825	35.92
28	0.76	0.01825	35.92
30	0.20	0.09825	44.26
31	0.20	0.09825	44.26
32	0.76	0.01825	35.92
33	0.76	0.01825	35.92
33	1.00	0.03825	46.02
40	1.00	0.03825	46.02
41	1.00	0.03825	46.02
42	1.97	0.03825	45.93
46	1.97	0.04825	45.93
47	1.97	45.9300	45.93
48	0.12	45.9300	54.01
52	0.12	54.0100	54.01
53	0.12	54.0100	54.01
54	0.12	54.0100	54.01
55	0.12	54.0100	54.01
56	0.12	54.0100	36.80
57	1.55	36.8000	36.80
58	1.55	36.8000	130.40
60	4.00	130.4000	130.40
64	4.00	130.4000	20.00
65	0.50	20.0000	20.00
65	0.50	20.0000	20.00
66	0.50	20.0000	20.00
66	0.50	20.0000	20.00
67	0.50	20.0000	20.00
67	0.50	20.0000	36.80
68	1.55	36.8000	36.80
69	1.55	36.8000	90.22
70	3.50	90.2200	44.26

Table B-2: Transmission line or transformer data for the IEEE-RTS

No.	ID	From	To	Capacity (p.u)	1/Reactance (p.u)	FOR	MTTR (Hrs)
1	L01	BUS001	BUS002	1.75	71.9424	0.00032	15.13
2	L02	BUS001	BUS003	1.75	4.7348	0.00047	8.93
3	L03	BUS001	BUS005	1.75	11.8343	0.00026	8.24
4	L04	BUS002	BUS004	1.75	7.8926	0.00033	8.55
5	L05	BUS002	BUS006	1.75	5.2083	0.00043	8.86
6	L06	BUS003	BUS009	1.75	8.4033	0.00032	8.51
7	L07	BUS003	BUS024	4.00	11.9189	0.00175	768.0
8	L08	BUS004	BUS009	1.75	9.6432	0.00029	8.41
9	L09	BUS005	BUS010	1.75	11.3250	0.00027	8.30
10	L10	BUS006	BUS010	1.75	16.5289	0.0012	38.13
11	L11	BUS007	BUS008	1.75	16.2866	0.00023	8.02
12	L12	BUS008	BUS009	1.75	6.0569	0.00039	8.74
13	L13	BUS008	BUS010	1.75	6.0569	0.00039	8.74
14	L14	BUS009	BUS011	4.00	11.9189	0.00175	768.0
15	L15	BUS009	BUS012	4.00	11.9189	0.00175	768.0
16	L16	BUS010	BUS011	4.00	11.9189	0.00175	768.0
17	L17	BUS010	BUS012	4.00	11.91895	0.00175	768.0
18	L18	BUS011	BUS013	5.00	21.0084	0.00044	10.77
19	L19	BUS011	BUS014	5.00	23.9234	0.00043	10.76
20	L20	BUS012	BUS013	5.00	21.0084	0.00044	10.77
21	L21	BUS012	BUS023	5.00	10.3519	0.00059	10.82
22	L22	BUS013	BUS023	5.00	11.5606	0.00055	10.81
23	L23	BUS014	BUS016	5.00	25.7069	0.00041	10.75
24	L24	BUS015	BUS016	5.00	57.8034	0.00035	10.71
25	L25	BUS015	BUS021	5.00	20.4081	0.00045	10.77
26	L26	BUS015	BUS021	5.00	20.4081	0.00045	10.77
27	L27	BUS015	BUS024	5.00	19.2678	0.00045	10.77
28	L28	BUS016	BUS017	5.00	38.6100	0.00038	10.73
29	L29	BUS016	BUS019	5.00	43.2900	0.00036	10.72
30	L30	BUS017	BUS018	5.00	69.4444	0.00034	10.70
31	L31	BUS017	BUS022	5.00	9.49668	0.00062	10.83
31	L32	BUS018	BUS021	5.00	38.6100	0.00038	10.73
32	L33	BUS018	BUS021	5.00	38.6100	0.00038	10.73
32	L34	BUS019	BUS020	5.00	25.2525	0.00041	10.75
33	L35	BUS019	BUS020	5.00	25.2525	0.00041	10.75
33	L36	BUS020	BUS023	5.00	46.2963	0.00036	10.72
34	L37	BUS020	BUS023	5.00	46.2963	0.00036	10.72
35	L38	BUS021	BUS022	5.00	14.74926	0.0005	10.79
36	L39	BUS001	BUS025	0.20	11.9190	0.00175	768.0
37	L40	BUS001	BUS026	0.20	11.9190	0.00175	768.0
38	L41	BUS001	BUS027	0.76	11.9190	0.00175	768.0

Table B-2 (continued)**:** Transmission line or transformer data for the IEEE-RTS

No.	ID	From	To	Capacity (p.u)	1/Reactance (p.u)	FOR	MTTR (Hrs)
39	L42	BUS001	BUS028	0.76	11.9190	0.00175	768.0
40	L43	BUS001	BUS029	1.08	11.9190	0	0
41	L44	BUS002	BUS030	0.20	11.9190	0.00175	768.0
50	L45	BUS002	BUS031	0.20	11.9190	0.00175	768.0
51	L46	BUS002	BUS032	0.76	11.9190	0.00175	768.0
59	L47	BUS002	BUS033	0.76	11.9190	0.00175	768.0
61	L48	BUS002	BUS034	0.97	11.9190	0	0
62	L49	BUS003	BUS035	1.80	11.9190	0	0
63	L50	BUS004	BUS036	0.74	11.9190	0	0

Table B-3: Load bus data for the IEEE-RTS

Bus no.	Priority Code	Load (p.u)
29	8021	1.08
34	1013	0.97
35	2014	1.8
36	6019	0.74
37	7020	0.71
38	5018	1.36
39	4017	1.25
43	3016	1.71
44	1005	1.75
45	1012	1.95
49	2015	2.65
50	1008	1.94
51	1007	3.17
59	1009	1
61	1011	3.33
62	1004	1.81
63	1010	1.28

Table B-4: Weekly peak load data for the IEEE-RTS and the RBTS in percentage of the 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 B-5: Daily peak load data for the IEEE-RTS and the RBTS in percent of the weekly peak

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

Table B-6: Hourly peak load in percentage of daily peak
(For the IEEE-RTS and the RBTS)

Hour	Winter Weeks 1-8 & 44-52		Summer Weeks 18-30		Spring/Fall Weeks 9-17 & 31-43	
	Week day	Week end	Week day	Week end	Week day	Week end
12-1 am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	53	65	58	66
4-5	59	64	53	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	85	86	99	89
10-11	96	90	99	91	100	92
11-Noon	85	91	100	93	99	94
Noon-1pm	85	90	99	93	93	91
1-2	85	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	919	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

Table B-7: Load point transformer failure data

Failure rate (f/yr)	0.02
Outage duration (hr)	768
Switching time (hr)	1

Appendix C. RBTS with load point transformers and stations

The effects of including load point transformers with stations on the IEEE-RTS load bus and system indices are shown in the next sections.

RBTS with ring bus schemes:

Table C.1.1: Load bus indices
(RBTS with ring bus schemes and load point tranformers)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00178	0.24899	3.185	0.02275	199.25	Bus 16
17	0.00199	0.37074	15.542	0.10002	876.22	Bus 17
18	0.00182	0.26481	6.756	0.04645	406.94	Bus 18
19	0.00177	0.26546	3.385	0.02269	198.76	Bus 19
20	0.00316	1.59110	20.221	0.04026	352.65	Bus 20

Table C.1.2: System indices (RBTS with ring bus schemes and load point tranformers)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.72
Average duration of load curtailment (hrs/disturbance) ADLC	33.76
Expected duration of load curtailment (Hrs / year) EDLC	91.71
Probability of load curtailments (PLC)	0.01047
Expected demand not supplied (MW) EDNS	0.23217
Expected energy not supplied (MWhr / year) EENS	2033.81
Expected Damage Cost (K$/ year) EDC	8989.42
Bulk Power-interruption Index (MW/MW- year) BPII	0.26535
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	10.99
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	18.07
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00125
Severity Index (system minutes/ year) SI	659.61

RBTS with double bus double breaker schemes

Table C.2.1: Load bus indices
(RBTS with double bus double breaker schemes and load point transformers)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00175	0.24018	3.072	0.00000	196.62	Bus 16
17	0.00197	0.36184	15.085	0.00212	865.93	Bus 17
18	0.00178	0.25364	6.470	0.00000	399.65	Bus 18
19	0.00175	0.25599	3.263	0.00003	195.79	Bus 19
20	0.00301	1.47797	18.783	0.01536	336.38	Bus 20

Table C.2.2: System indices
(RBTS with double bus double breaker schemes and load point transformers)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.57
Average duration of load curtailment (hrs/disturbance) ADLC	34.88
Expected duration of load curtailment (Hrs / year) EDLC	89.55
Probability of load curtailments (PLC)	0.01022
Expected demand not supplied (MW) EDNS	0.22767
Expected energy not supplied (MWhr / year) EENS	1994.36
Expected Damage Cost (K$/ year) EDC	8815.08
Bulk Power-interruption Index (MW/MW- year) BPII	0.25230
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	10.78
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	18.179
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00123
Severity Index (system minutes/ year) SI	646.82

RBTS with one and half breaker schemes

Table C.3.1: Load bus indices
(RBTS with one and one half breaker schemes and load point transformers)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00175	0.22947	2.935	0.02240	196.22	Bus 16
17	0.00197	0.35059	14.491	0.09880	865.45	Bus 17
18	0.00178	0.24286	6.195	0.04558	399.32	Bus 18
19	0.00175	0.24512	3.124	0.02232	195.56	Bus 19
20	0.00301	1.44664	18.384	0.03832	335.71	Bus 20

Table C.3.2: System indices
(RBTS with one and one half breaker schemes and load point transformers)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.49
Average duration of load curtailment (hrs/disturbance) ADLC	35.87
Expected duration of load curtailment (Hrs / year) EDLC	89.42
Probability of load curtailments (PLC)	0.01021
Expected demand not supplied (MW) EDNS	0.22743
Expected energy not supplied (MWhr / year) EENS	1992.26
Expected Damage Cost (K$/ year) EDC	8805.79
Bulk Power-interruption Index (MW/MW- year) BPII	0.24394
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	10.77
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	18.10
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00123
Severity Index (system minutes/ year) SI	646.14

RBTS with one and one third breaker schemes

Table C.4.1: Load bus indices
(RBTS with one and one third breaker schemes and load point transformers)

No. Bus	PLC	ENLC (1/yr)	ELC (MW/yr)	EDNS (MW)	EENS (MWhrs/yr)	Bus name
16	0.00175	0.22012	2.816	0.02240	196.22	Bus 16
17	0.00197	0.36081	15.042	0.09885	865.93	Bus 17
18	0.00178	0.25296	6.453	0.04562	399.65	Bus 18
19	0.00175	0.23612	3.009	0.02235	195.785	Bus 19
20	0.00301	1.44613	18.377	0.03837	336.16	Bus 20

Table C.4.2: System indices
(RBTS with one and one third breaker schemes and load point transformers)

System Indices/Units	
Expected number of load curtailments (1/ year) ENLC	2.49
Average duration of load curtailment (hrs/disturbance) ADLC	35.87603
Expected duration of load curtailment (Hrs / year) EDLC	89.50
Probability of load curtailments (PLC)	0.01022
Expected demand not supplied (MW) EDNS	0.22760
Expected energy not supplied (MWhr / year) EENS	1993.75
Expected Damage Cost (K$/ year) EDC	8812.36
Bulk Power-interruption Index (MW/MW- year) BPII	0.24701
Bulk Power/energy Curtailment Index (MWhr /MW- year) BECI	10.78
Bulk Power-supply average MW curtailment Index (MW/disturbance) BPACI	18.32
Modified Bulk/energy curtailment Index (MW/MW) MBECI	0.00123
Severity Index (system minutes/ year) SI	646.62

Appendix D. IEEE-RTS station configurations

The 24 station configurations shown in this section are with transformer at the load point. The same configurations are used for studies without load point transformers.

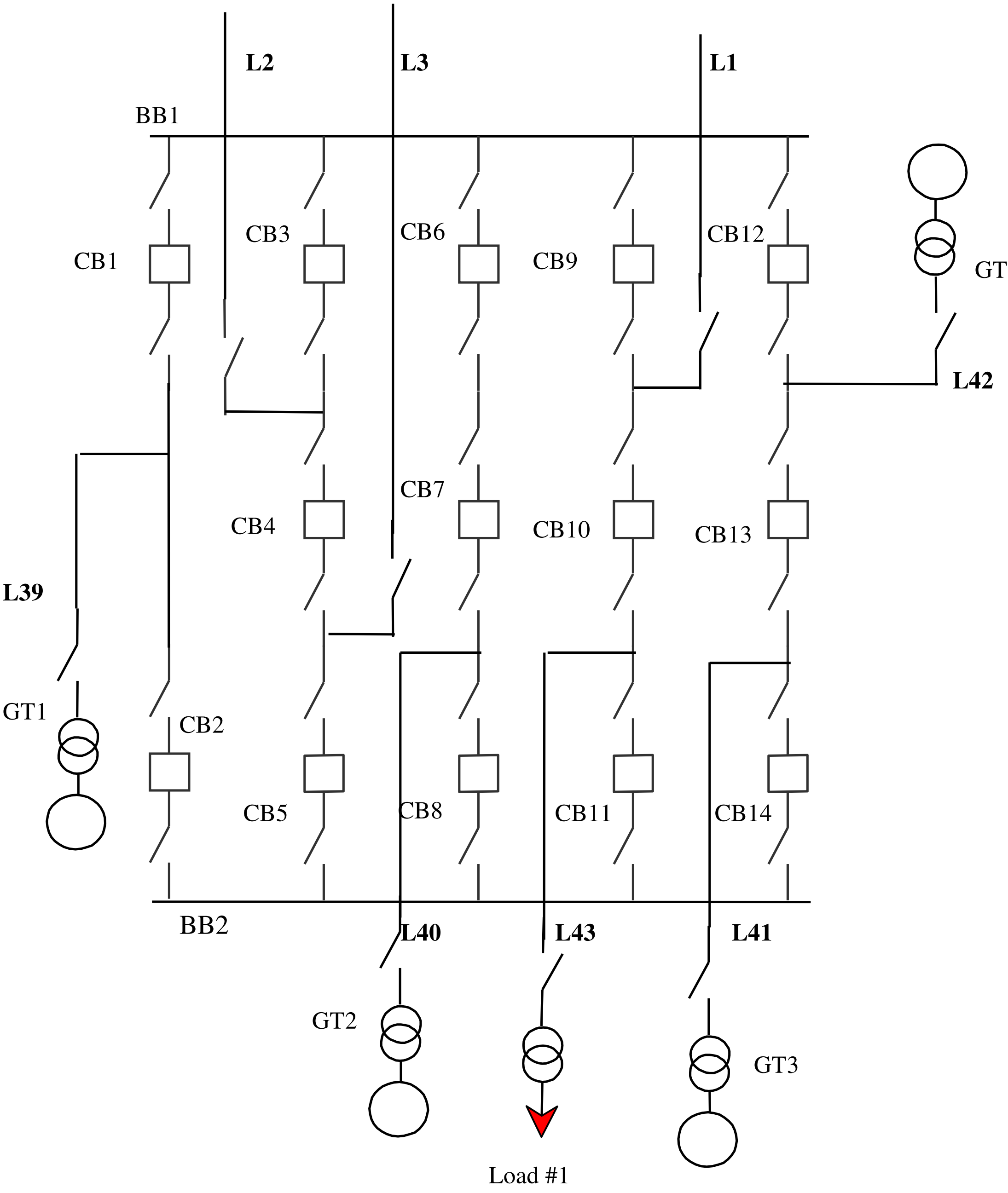

Figure D-1: Bus #1 (load bus 29)

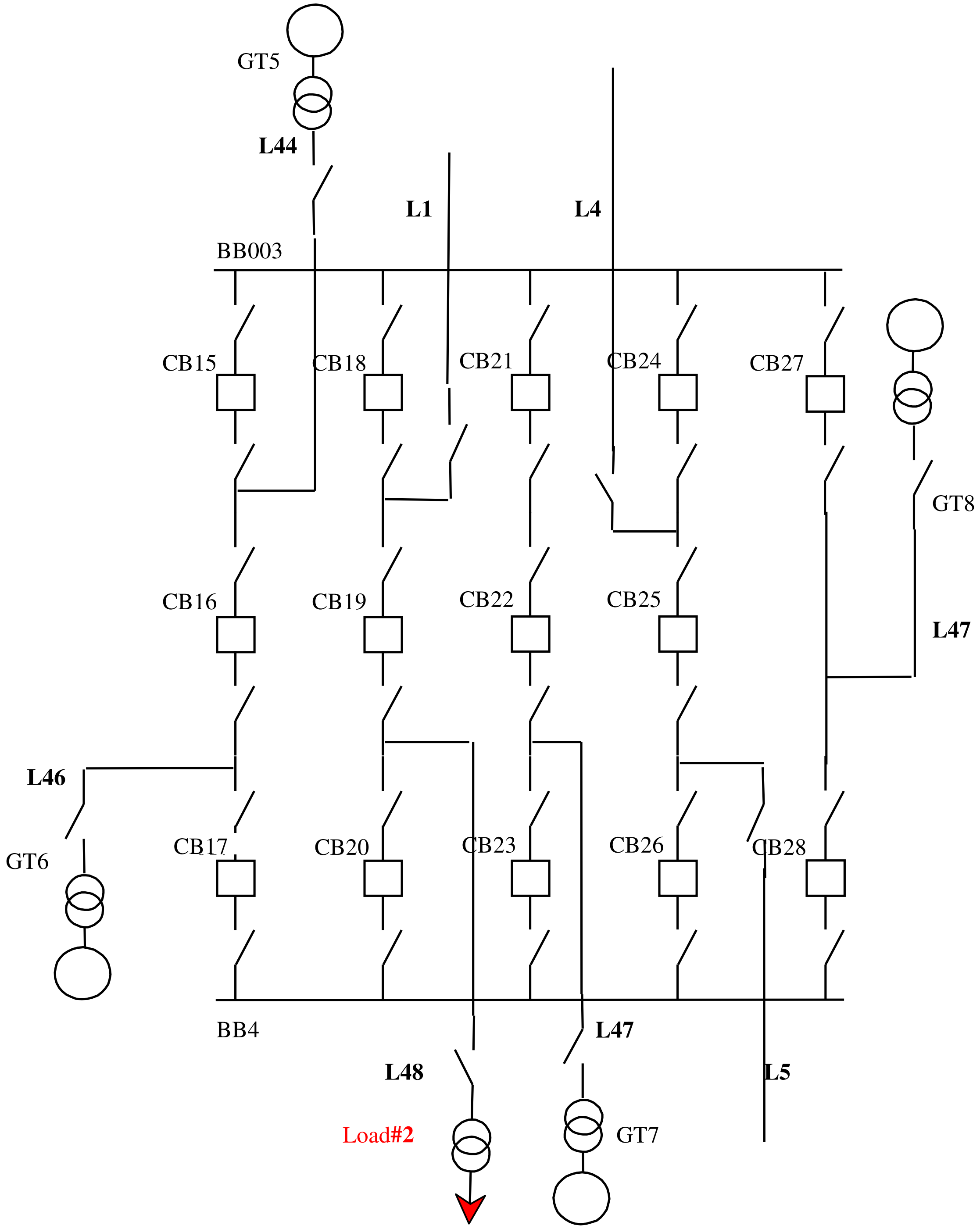

Figure D-2: Bus#2 (load bus 34)

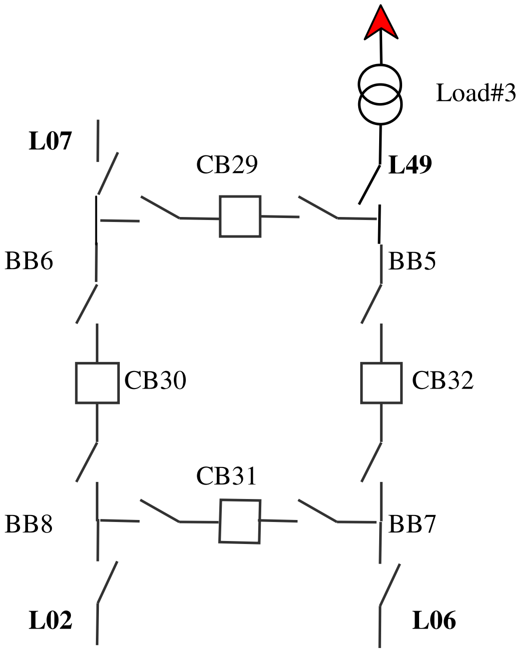

Figure D-3: Bus#3 (load bus 35)

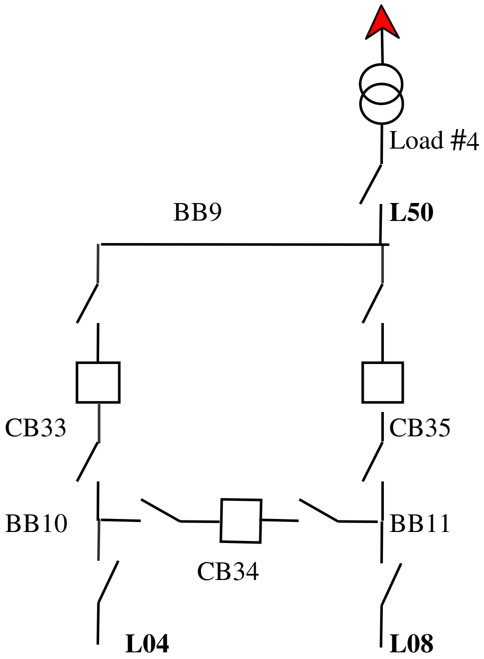

Figure D-4: Bus#4 (load bus 36)

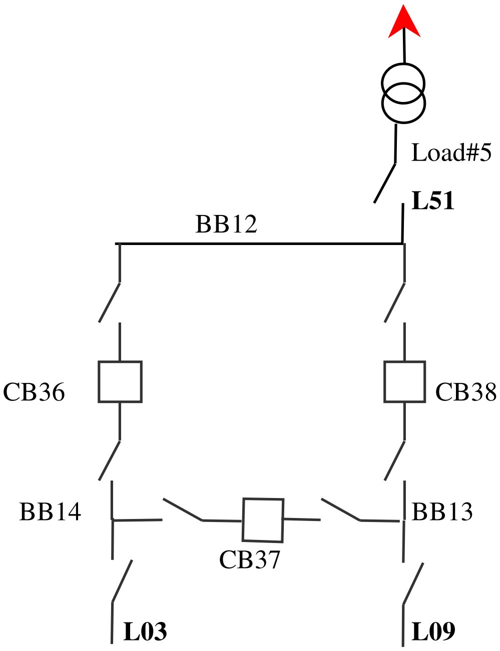

Figure D-5: Bus#5 (load bus 37)

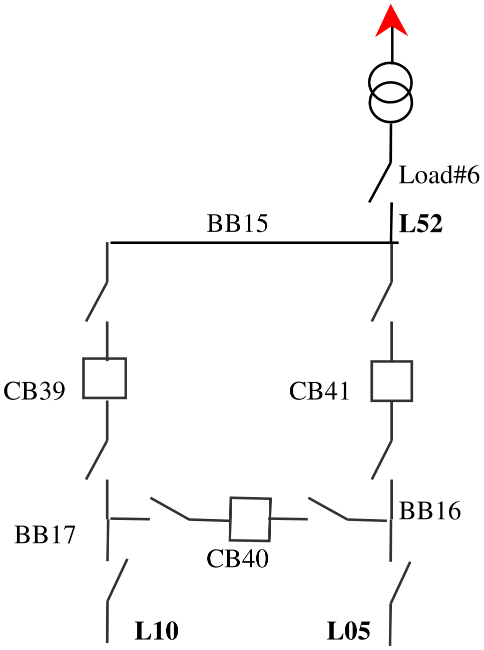

Figure D-6: Bus#6 (load bus 39)

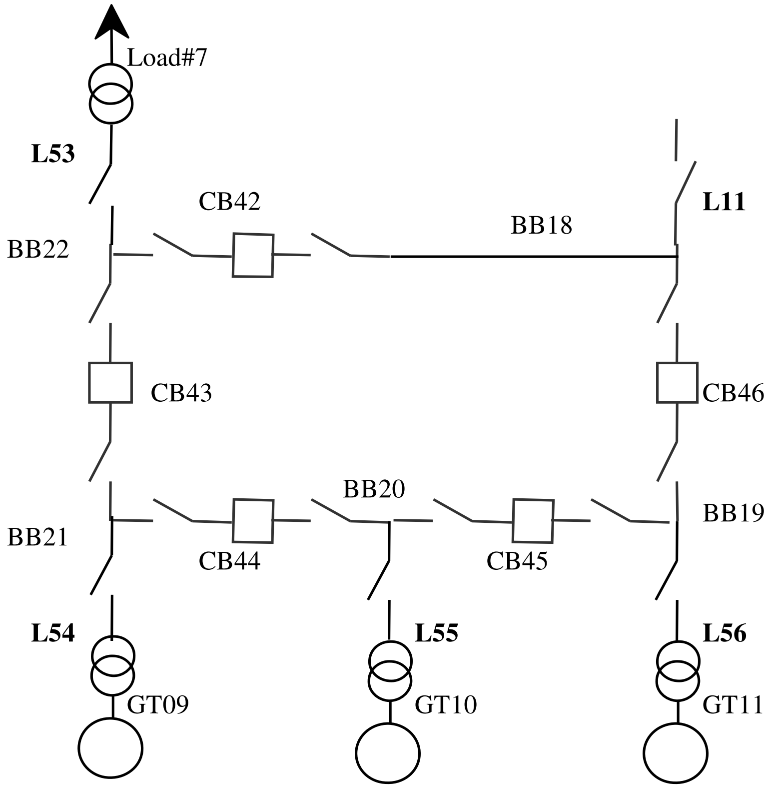

Figure D-7: Bus#7 (load bus 43)

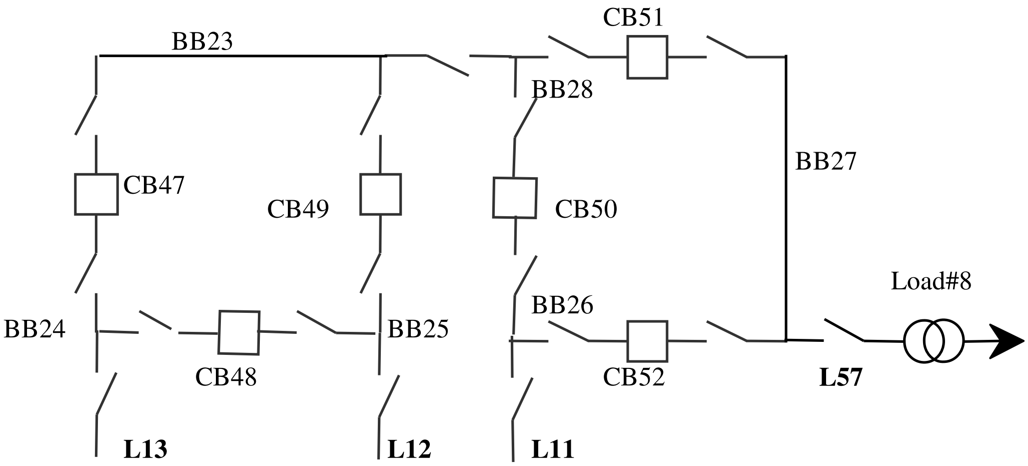

Figure D-8: Bus#8 (load bus 44)

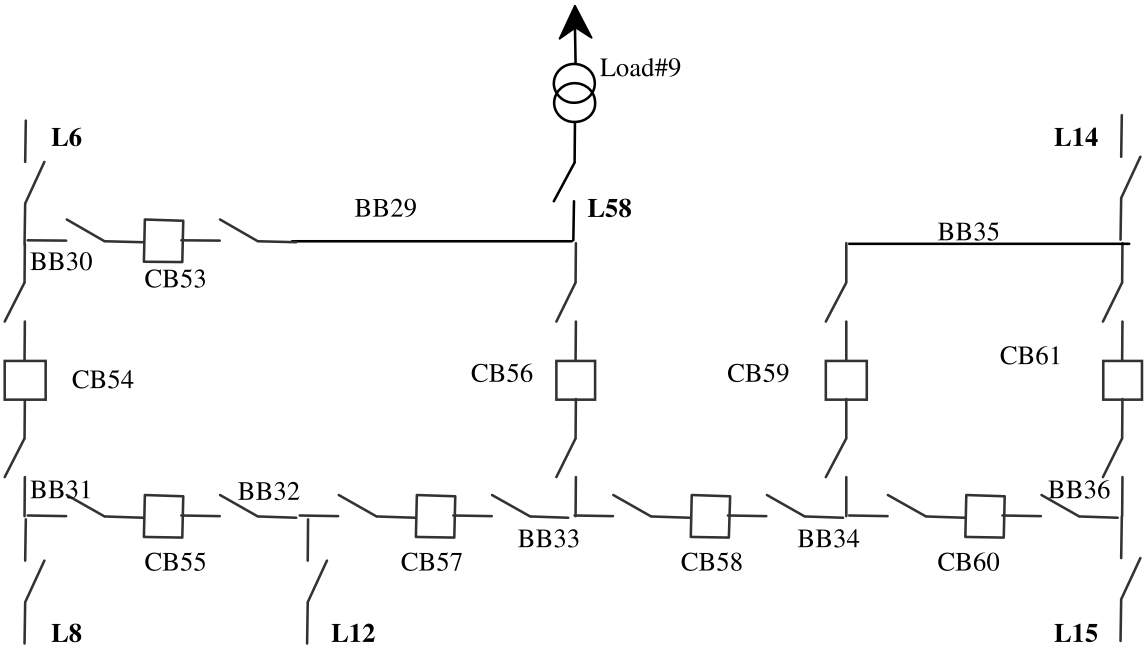

Figure D-9: Bus#9 (load bus 45)

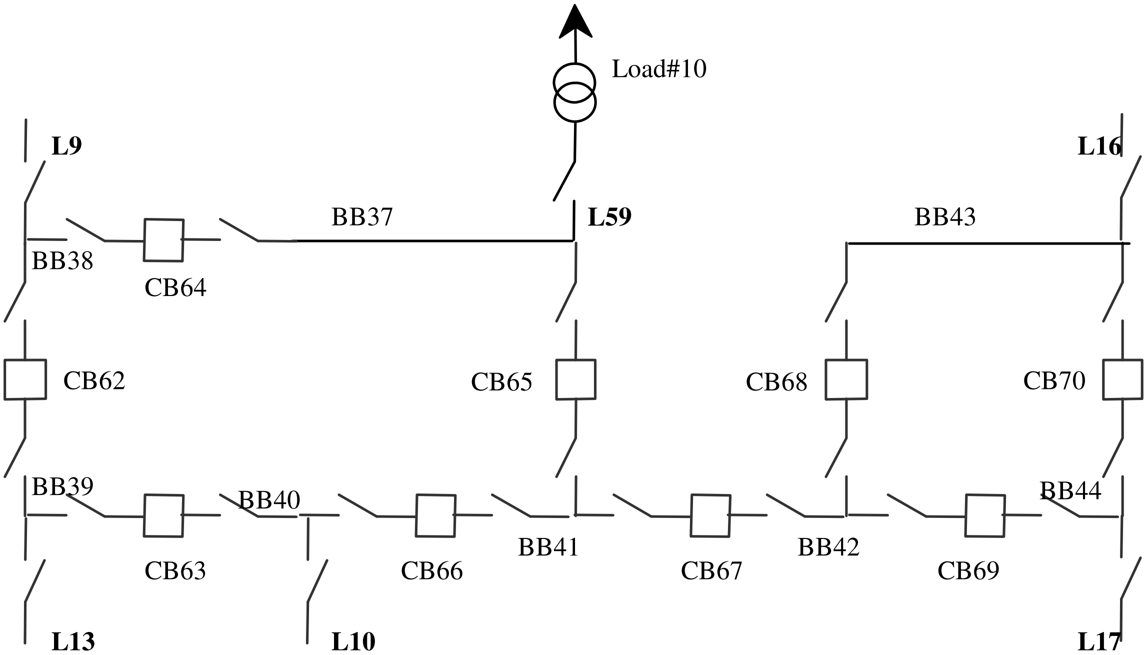

Figure D-10: Bus#10 (load bus 49)

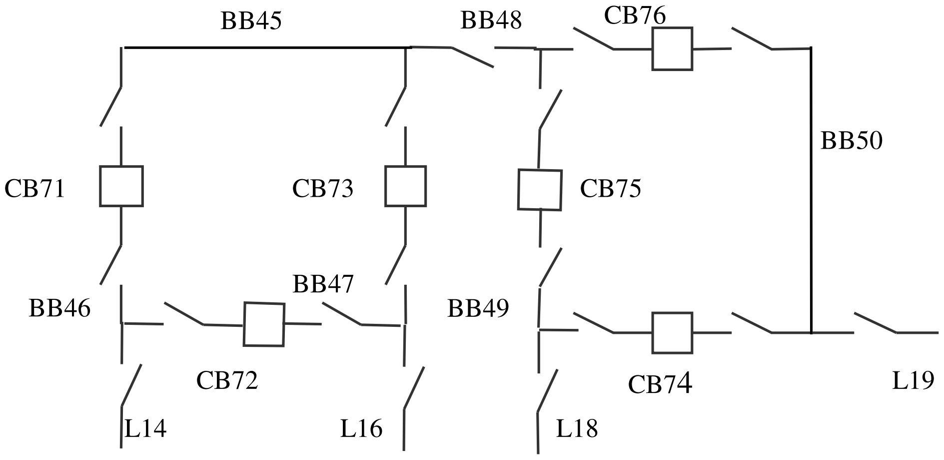

Figure D-11: Bus#11

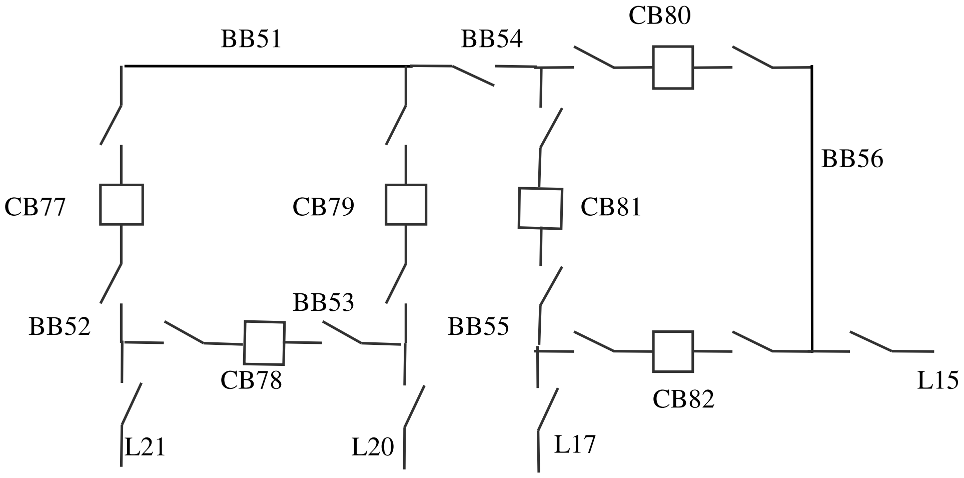

Figure D-12: Bus#12

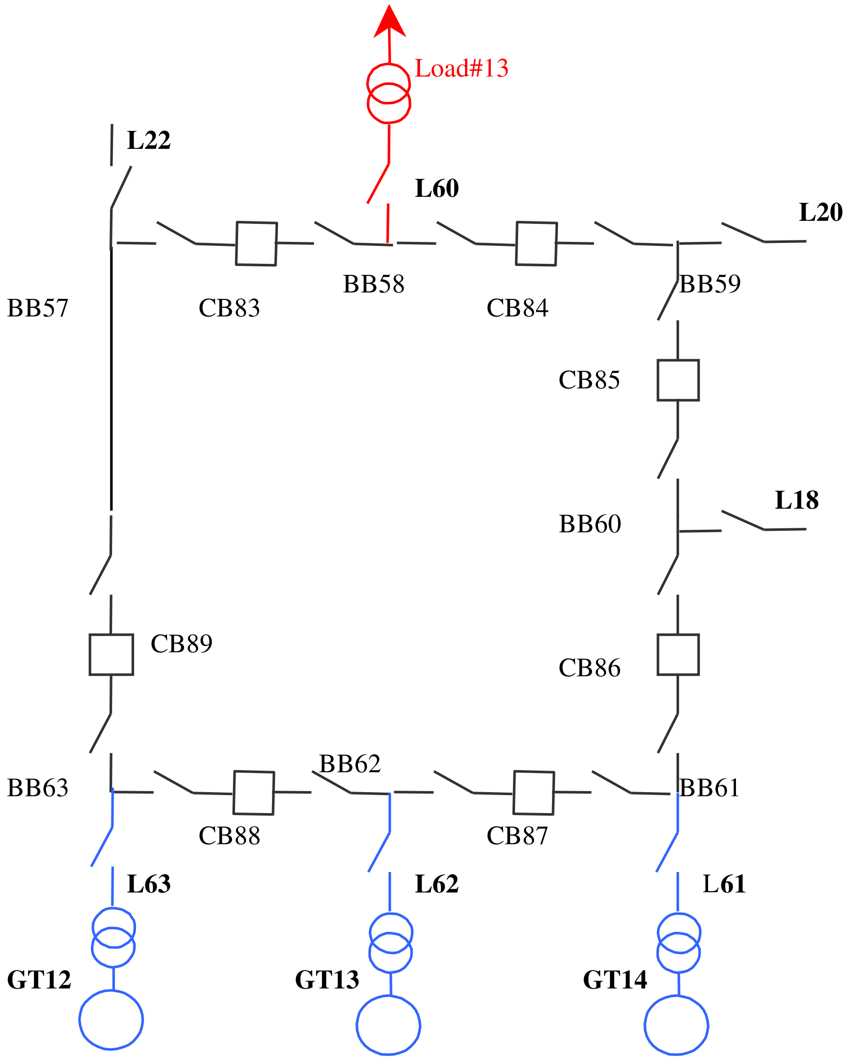

Figure D-13: Bus#13 (load bus 50)

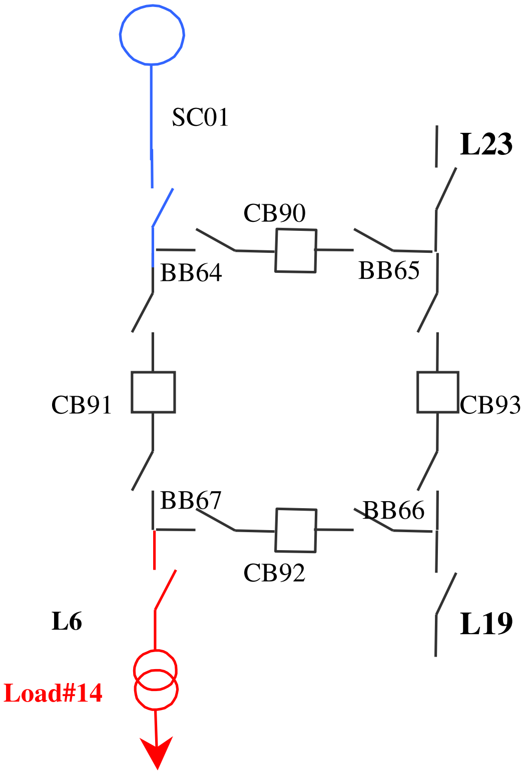

Figure D-14: Bus#14 (load bus 51)

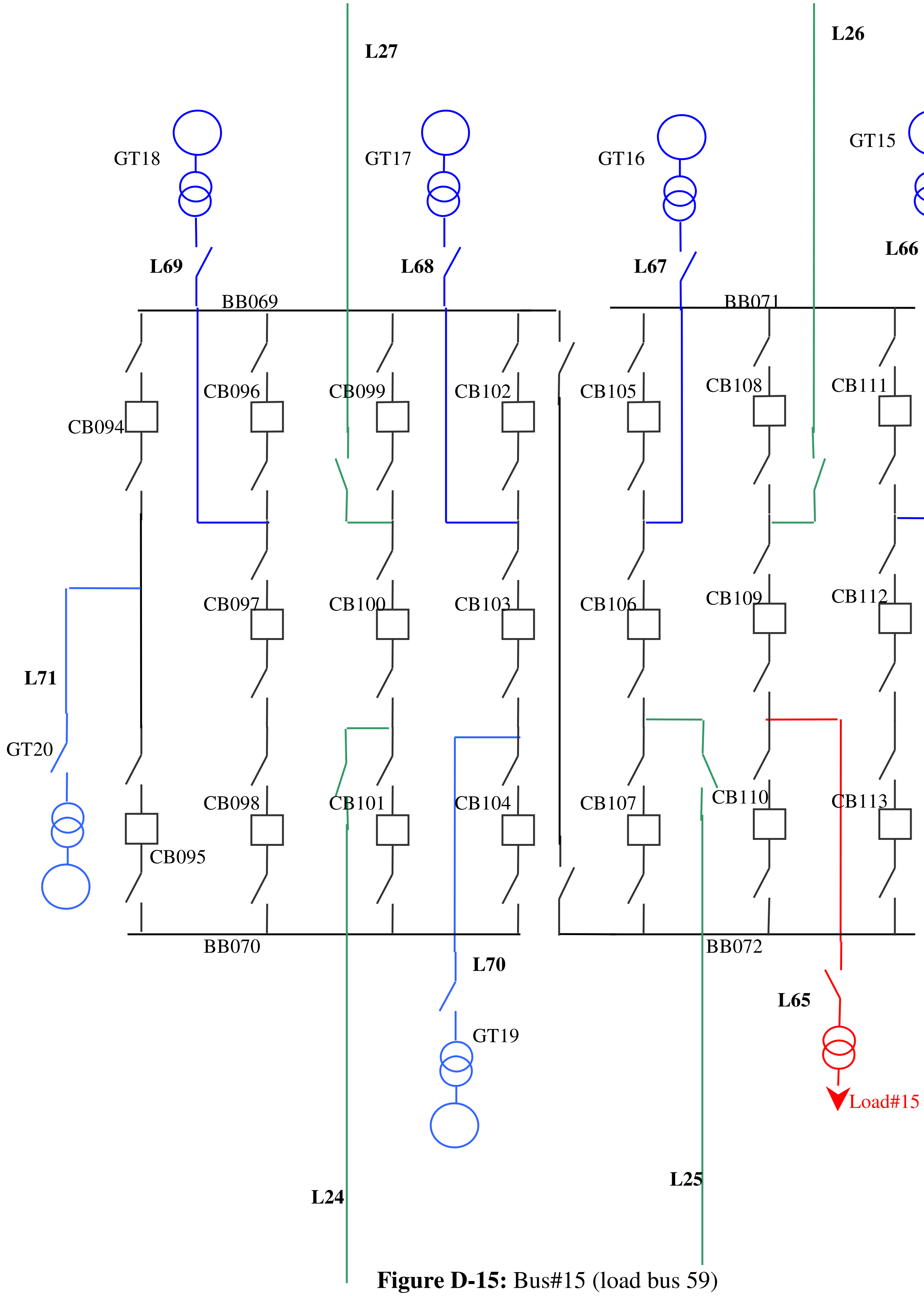

Figure D-15: Bus#15 (load bus 59)

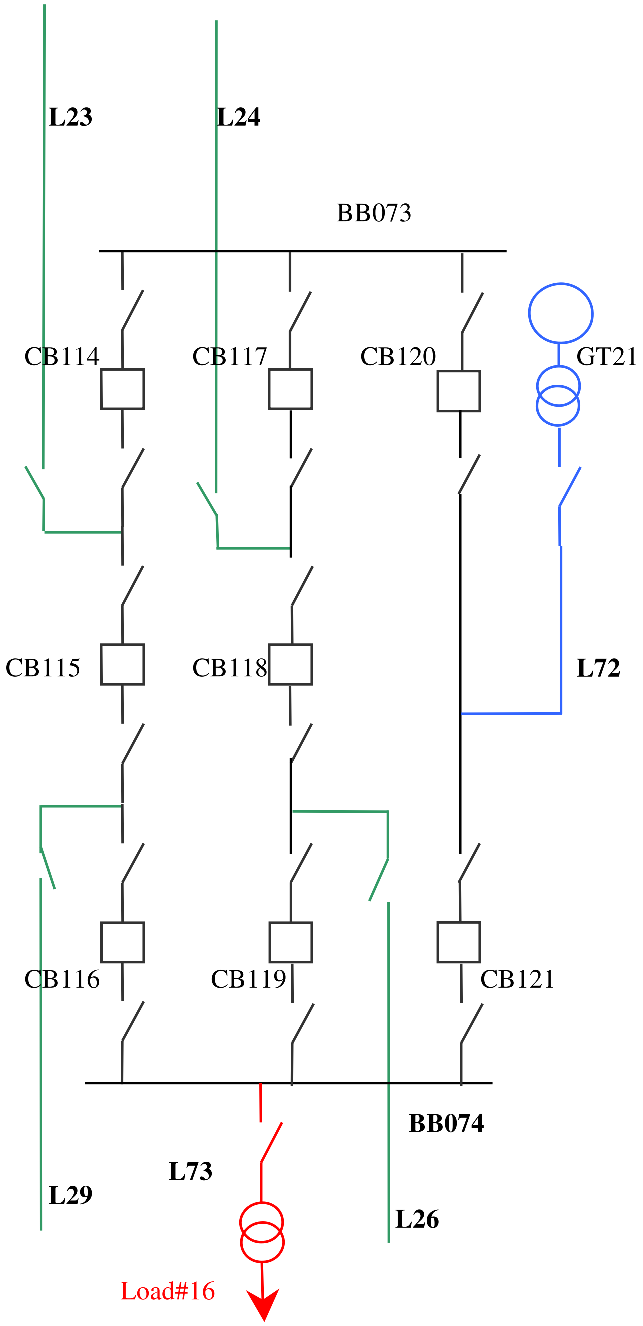

Figure D-16: Bus#16 (load bus 61)

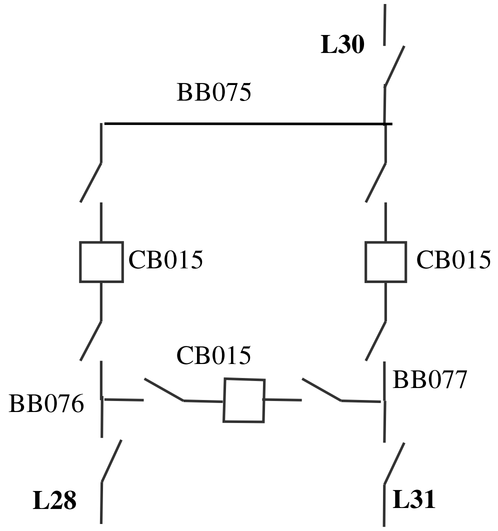

Figure D-17: Bus#17

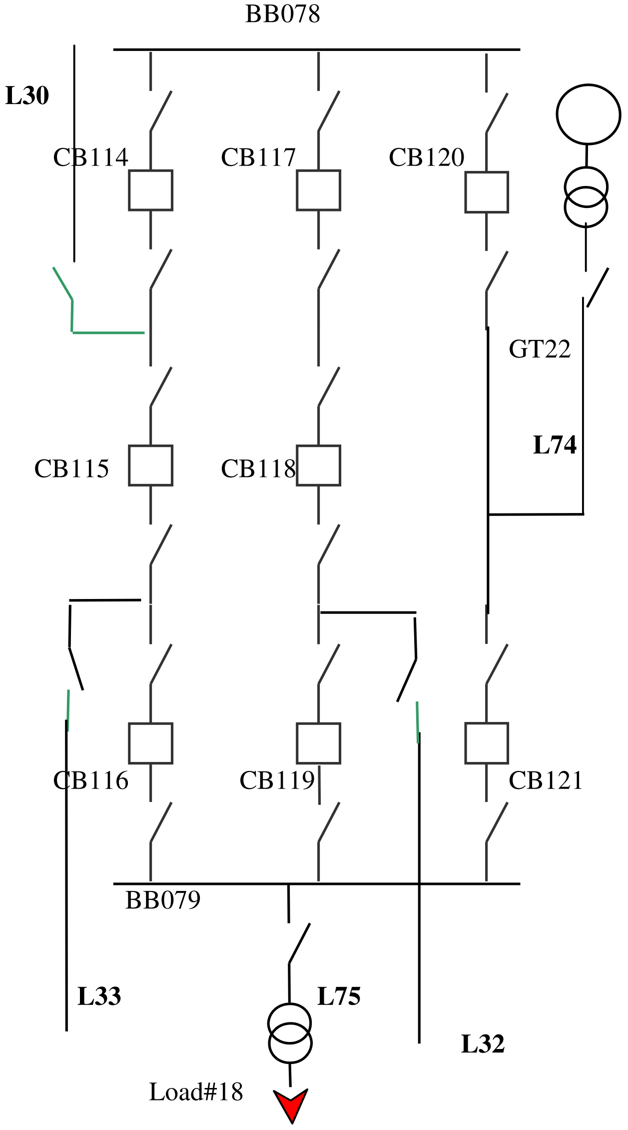

Figure D-18: Bus#18
(load bus 61)

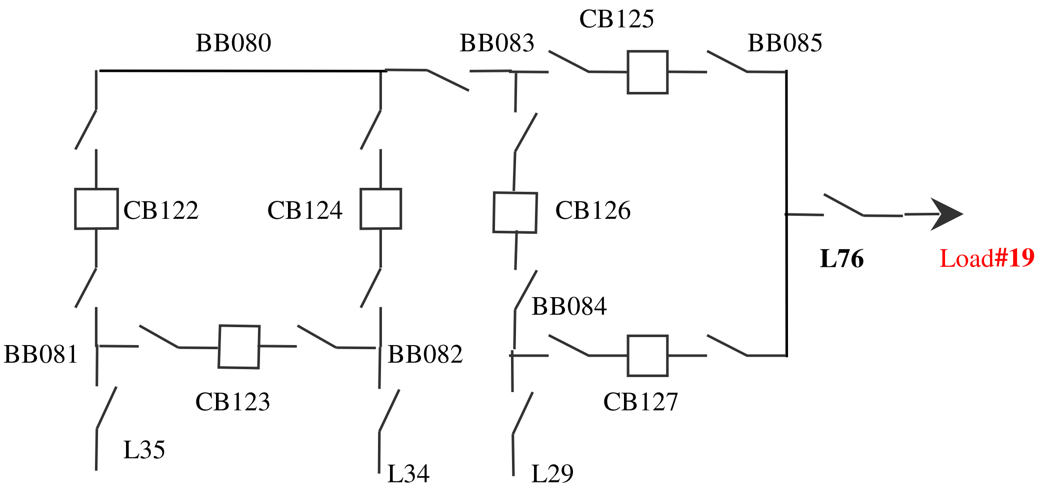

Figure D-19: Bus#19 (load bus 62)

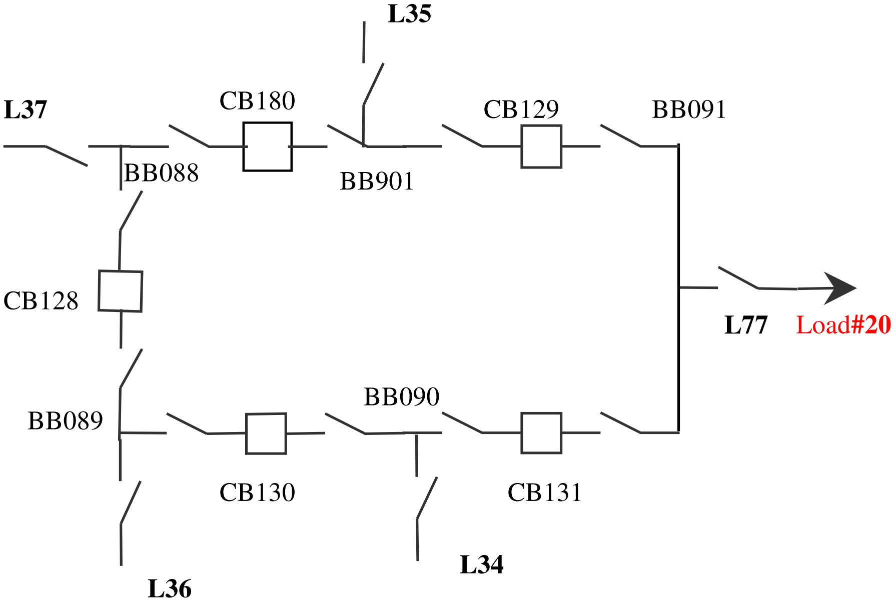

Figure D-20: Bus#20 (load bus 63)

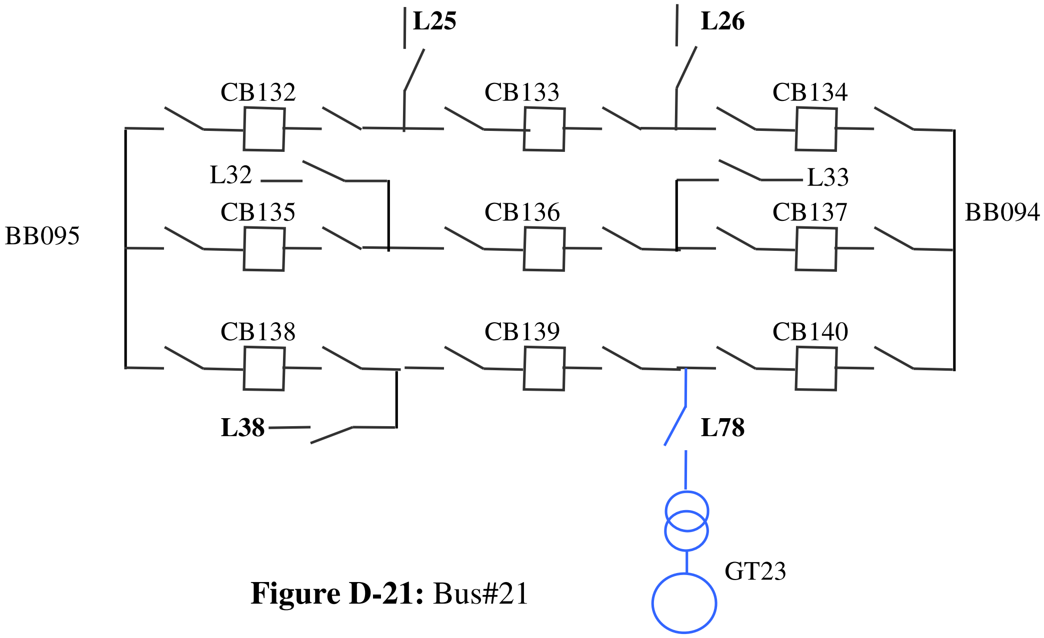

Figure D-21: Bus#21

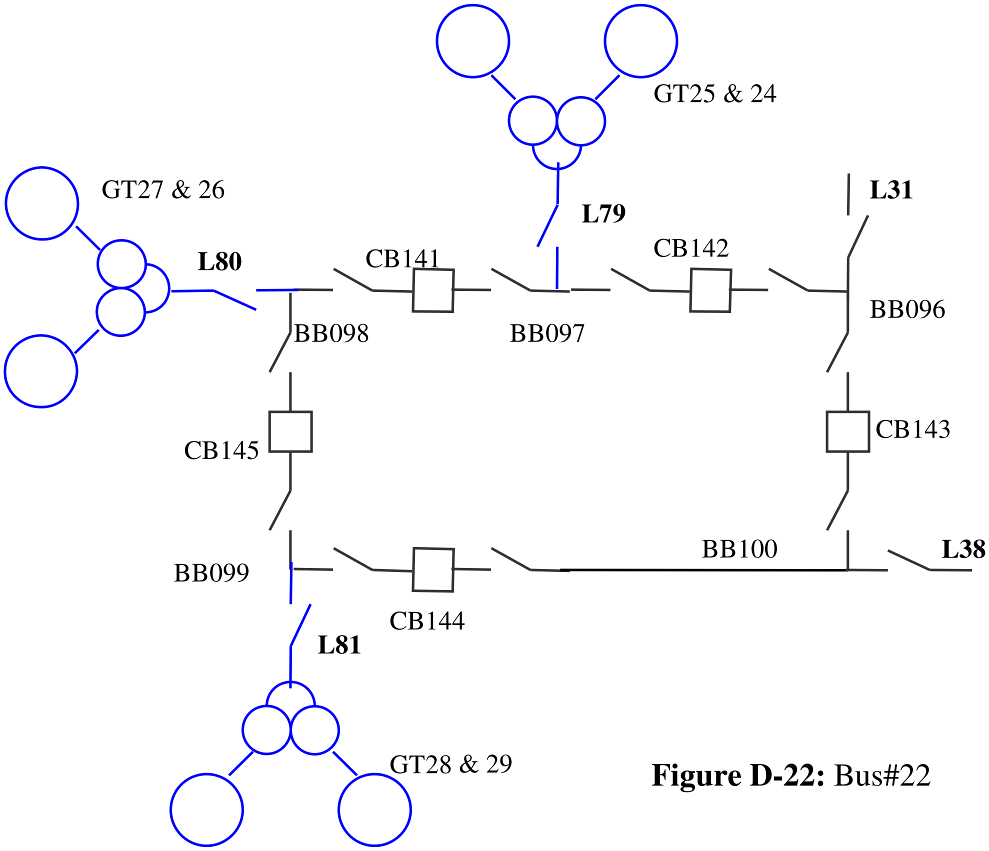

Figure D-22: Bus#22

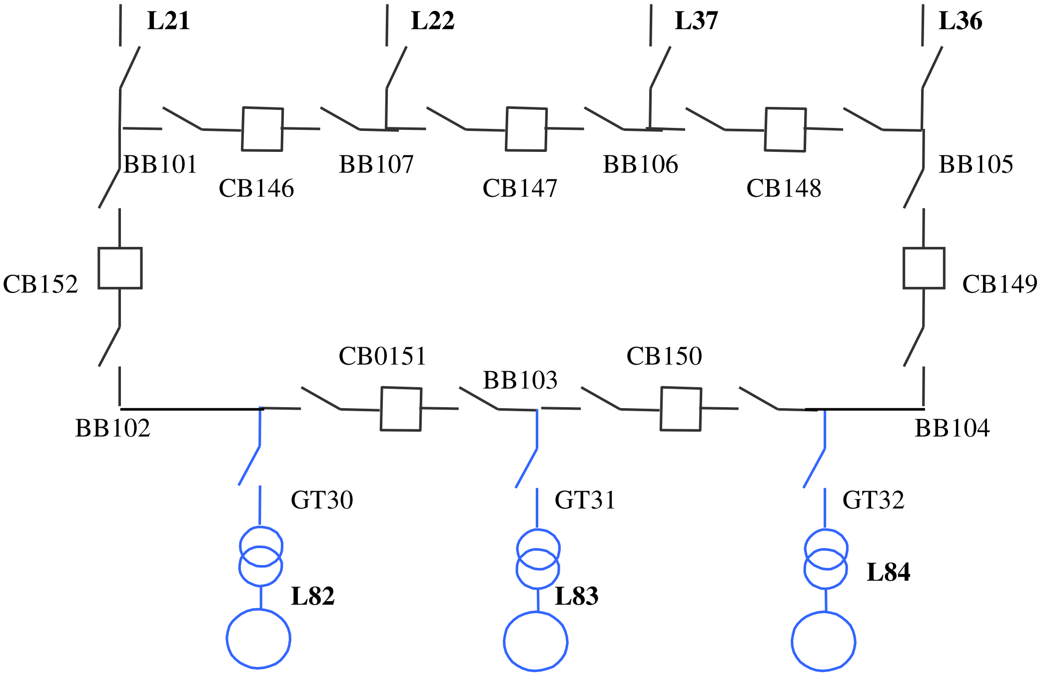

Figure D-23: Bus#23

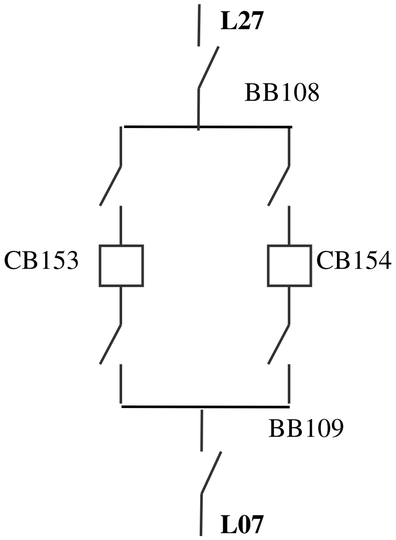

Figure D-24: Bus#24

Appendix E. Modified stations

Figures E-1 and E-2 show the modified stations for buses 19 and 3 in the IEEE-RTS respectively.

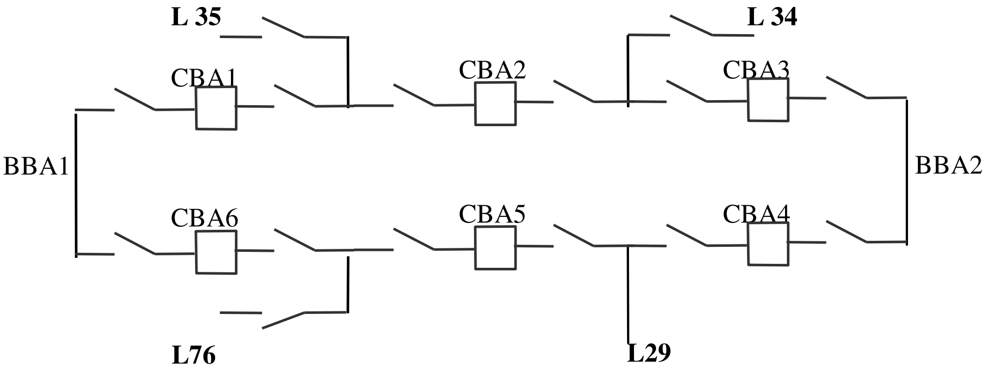

Figure E-1: Modified Bus#19 (load bus 62)

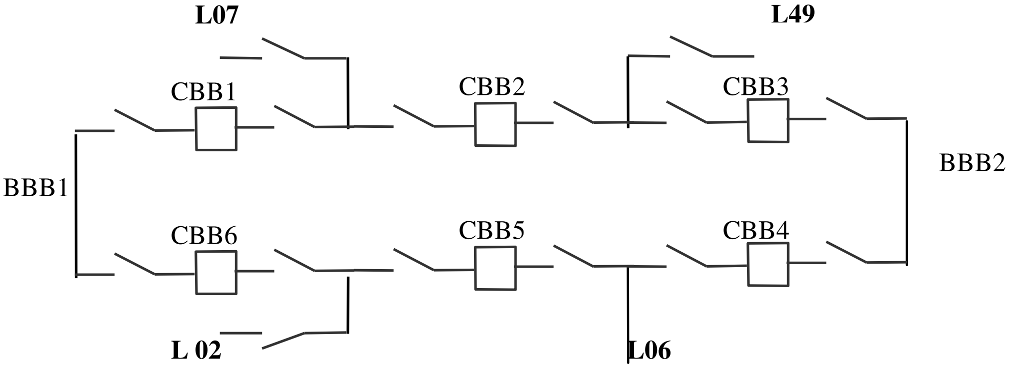

Figure E-2: Modified Bus#3 (load bus 35)

Appendix F. Equations for a second order minimal cut set

The failure rate, the repair time and the unavailability for a second order minimal cut set are calculated using Equations F.1 to F.3. It is assumed, that $\lambda_1 r_1$ and $\lambda_2 r_2$ are numerically very small [38].

$$\lambda_s = \lambda_1 \lambda_2 (r_1 + r_2) \tag{F.1}$$

$$U_s = \lambda_1 \lambda_2 r_1 r_2 \tag{F.2}$$

$$r_s = \frac{U_s}{\lambda_s} \tag{F.3}$$

Where,

λ_s – Failure rate of a second order minimal cut set (f/yr)
λ_1 – Failure rate of a component 1 (f/yr)
λ_2 – Failure rate of a component 2 (f/yr)
r_1 – Repair time of a component 1 (yr)
r_2 – Repair time of a component 2 (yr)
U_s – Unavailability for a second order minimal cut set

Equations for higher order minimal cut sets are given in [38].