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Reliability and Maintenance of Power System Substations

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Reliability and Maintenance of Power System Substations submitted by Suresh C. Sharma in partial fulfilment of the requirements for the degree of Master of Science.

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Supervisor

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Date 17 April 86

To my parents

and

To my wife

ABSTRACT

The methodology for reliability analysis of power system substations has been developed in this thesis. The impact of various modes of component outages on load point interruptions has been studied. The various modes of component outages considered are passive failures and overlapping passive failures, passive failures overlapping maintenance, active failures, active failures overlapping passive failures and maintenance, active failures with stuck breakers, active failures with stuck breakers with overlapping passive failures and maintenance activities, common mode failures, common mode failures overlapping passive failures and maintenance outages. The impact of switching actions and reserve supply considerations on load point reliability levels has also been studied.

The Markov modelling and cut set modelling techniques have been discussed. The limitations of presently available dual component models have been discussed and two new models have been proposed and illustrated with various practical case studies.

The algorithms for reliability evaluation of a general substation configuration has been described and applied to ten published substation configurations being used by electric utilities. The reliability analysis of British Columbia Hydro and Power Authority's George Dickie

substation has been performed. The limitations of presently available techniques of reliability analysis of substation configurations have been discussed.

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CHAPTER 1

INTRODUCTION

The modern discipline of reliability had its origin in the military and space technology areas. Its influence has been spreading into many other engineering applications(e.g., power systems, communication networks, etc.).

Reliability of electric service has always been a prime concern of utility engineers and managers and is becoming even more crucial in system planning, design and operation of today's complex systems. The cost of failures in modern power systems goes much beyond the cost of repairs or replacement of faulty electrical eqipment. The inconvenience to consumers, lost products, crime and decreased productivity costs are much more than the price of immediate repairs.

An electrical power system substation forms an important link within any power system configuration and any failures occurring in a substation configuration can lead to cascading failures which will result in a significant number of interruptions to a utility's customers. From Federal Power Commission reports [1] of 200 disturbances, 39 were associated with equipment difficulties in substations and 12 were associated with errors in operation (i.e., human error). Statistics such as these serve to point out the relative frequency of occurrence of disturbances initiating in certain portions of an electric power system and, in particular, their significance for substations.

It is therefore very essential to evaluate the effectiveness of any substation operating scheme and assess the impact of component modes of failure and their effect on the overall substation reliability levels. The choice of substation scheme is a very complex task involving the assessment of many economic and technical considerations. Reliability analysis of alternative substation variants provide the substation designer with useful information in assessing the future short term and long term operating behaviour of the designs under consideration.

The methodology required to evaluate the reliability levels of various substation configurations has been developed in this thesis. Some of the commonly used substation schemes presently used in utilities have been analysed in some detail and are presented in this thesis.

The various technical definitions used in the thesis have been presented in Appendix A. The Markov modelling technique [2] used for reliability analysis of substations is discussed in some detail in Chapter 2 of the thesis. Chapter 3 deals with the Cut Set technique[3] and has been used for the analysis of substation schemes presented in the thesis. The substation reliability evaluation algorithms have been presented and applied to several substation configurations in Chapter 4. Two of the schemes, one fully automated i.e., breaker and half scheme and a semi-automated scheme i.e., main bus with auxilliary bus system have been discussed in some detail in this Chapter. The substation load point indices evaluated by the cut set approach for ten published substation configurations have been presented in Appendix C. For the purposes of comparing reliability techniques a simple substation configuration was selected from reference [4]. The reliability levels have been evaluated by the classical Markov modelling approach and the cut set approach and have been presented and discussed in Chapters 2 and 4, respectively.

An actual substation configuration obtained from B.C. Hydro and Power Authority has been analysed in Chapter 5. The conclusions and a list of references have been provided in Chapters 6 and 7 respectively.

CHAPTER 2

MARKOV MODELLING OF SUBSTATION CONFIGURATIONS

2.1 Introduction:

Central to the theory of Markov process models are the concepts of state and state transition [5].

The State Concept: For example, a chemical process can often be specified by the values of temperature, pressure and volume, which are called "state variables". Thus, the state of a system represents all we need to know (i.e., based on our theoretical models) to describe the system at any instant in time.

The Transition Concept: In the course of time a system passes from state to state and thus exhibits dynamic behaviour. Such changes of state are called "state transitions" or simply "transitions".

An example of a system that resides in two mutually exclusive states is shown below in the state space diagram shown in Figure 2.1.

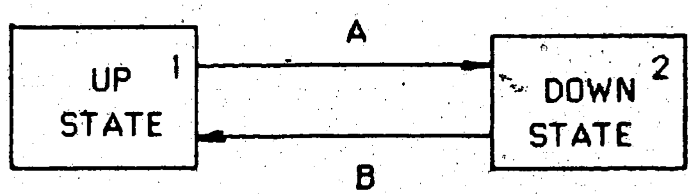


Figure 2.1: State space diagram

where:

A - is the probability of the system transiting from state 1 to 2

B - is the probability of the system transiting from state 2 to 1

2.2 Classical Two Component Model

The state space diagram for a two component model is shown in Figure 2.2

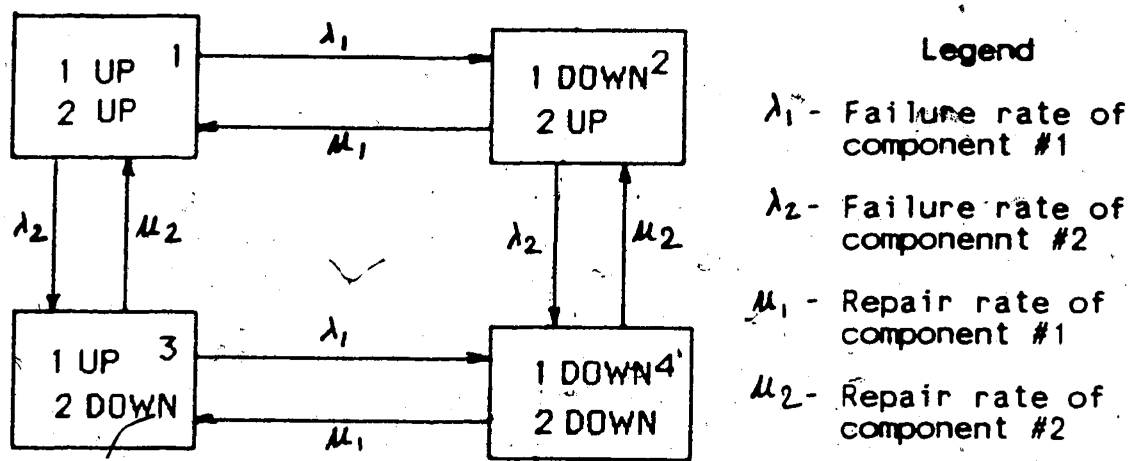


Figure 2.2: Two component state space diagram

The steady state solution for the probabilities of occupying various states of a space diagram is obtained by a frequency balance approach technique [6]. The frequency of departure from a given state is defined as the product of the probability of the state and the sum of the transition rates departing from the state. Similarly, the frequency of entry from a group of states to a given state is defined as the sum of products of the probability of each of the states and its transition rate into the given state. The underlying principle of the frequency balance approach is the frequency of departure from a given state or a given set of states is equal to the frequency of entry from another set of states under <u>steady state conditions</u>.

With reference to Figure 2.2, the various steady state frequencies are:

$$f1 = P1(\lambda_1+\lambda_2) = P2\,\mu_1 + P3\,\mu_2 \quad (2.1)$$

$$f2 = P2(\mu_1+\lambda_2) = P1\,\lambda_1 + P4\,\mu_2 \quad (2.2)$$

$$f3 = P3(\lambda_1+\mu_2) = P1\,\lambda_2 + P4\,\mu_1 \quad (2.3)$$

$$f4 = P4(\mu_1+\mu_2) = P2\,\lambda_2 + P3\,\lambda_1 \quad (2.4)$$

And,

$$P1 + P2 + P3 + P4 = 1.0 \quad (2.5)$$

By solving the above set of simultaneous equations, the steady state probability of occupying each state is :

$$P1 = \mu_1\,\mu_2 / (\lambda_1+\mu_1)(\lambda_2+\mu_2) \quad (2.6)$$

$$P2 = \mu_2\,\lambda_1 / (\lambda_1+\mu_1)(\lambda_2+\mu_2) \quad (2.7)$$

$$P3 = \mu_1\,\lambda_2 / (\lambda_1+\mu_1)(\lambda_2+\mu_2) \quad (2.8)$$

$$P4 = \lambda_1\,\lambda_2 / (\lambda_1+\mu_1)(\lambda_2+\mu_2) \quad (2.9)$$

The classical model shown in Figure 2.2 is extensively used in literature[2,7,8]. The failure rates of components used in this model are equal to the average failure rates of each component. The four state model assumes that the individual components can reside in four different states as shown in Figure 2.2. However, a more comprehensive model has been proposed[9] which removes the limitations of the classical model.

2.3 Proposed Model

The state space diagram of a 2 component (i.e., a transformer bank) redundant configuration of the proposed model is shown in Figure 2.3 and the definitions of the symbols used in the model are listed in Table 2.1.

If a component or a group of components can replace a component or a group of other components without affecting the defined successful operation of the system, then the component or the group of components is called a *redundant* unit, otherwise, it is called the *non-redundant* unit.

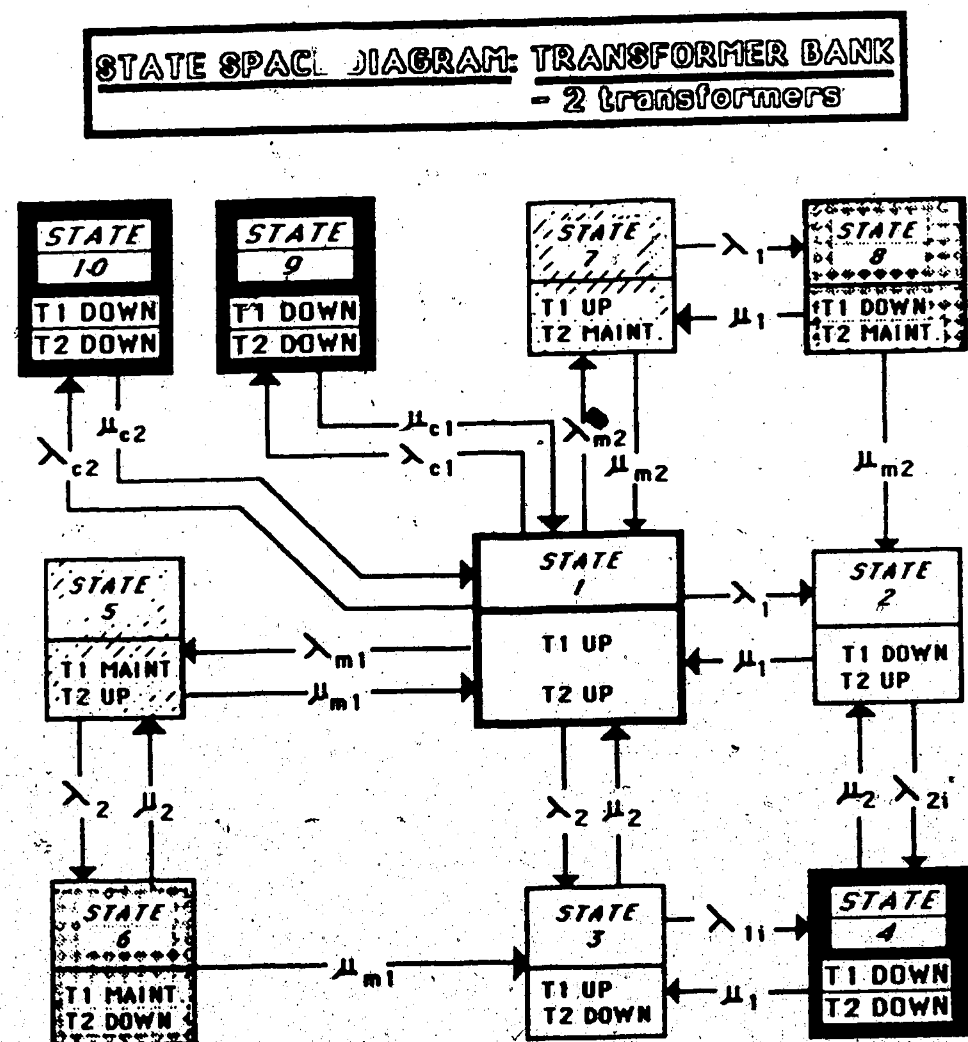


Figure 2.3: State space diagram: 2 transformers bank

Table 2.1: Definitions of Figure 2.3 symbols

SYMBOL	DESCRIPTION
λ_1	- Average failure rate Transformer #1
λ_2	- Average failure rate Transformer #2
λ_{11}	- Increased failure rate Transformer #1
λ_{12}	- Increased failure rate Transformer #2
λ_{m1}	- Maintenance rate Transformer #1
λ_{m2}	- Maintenance rate Transformer #2
λ_{c1}	- Common mode failure rate of bank due to external system failures
λ_{c2}	- Common mode failure rate of bank due to internal system failures
μ_1	- Restoration rate of Transformer #1
μ_2	- Restoration rate of Transformer #2
μ_{m1}	- Maintenance restoration rate Transformer #1
μ_{m2}	- Maintenance restoration rate Transformer #2
μ_{c1}	- Restoration rate of common mode failures due to external system failures
μ_{c2}	- Restoration rate of common mode failures due to internal system failures

The proposed model alters the failure rates of the components when they are forced to carry the additional load of the system because a redundant component has been forced out of service. The proposed model defines two maintenance states (i.e. 5 and 7) and two failure states (i.e. from the perspective of the system, numbered 6 and 8) when the in-service component fails during the maintenance period of the other component. Two common mode failure states (i.e. 9 and 10) are included in the model to account for external and internal system faults or failures. For example, the failure of the common bus feeding both transformers can be classified as the internal fault and the failure of both components in a heavy snow storm, for example, could be categorized as the external fault.

2.3.1 State Probabilities

The steady state probabilities of occupying each state in Figure 2.3 can be solved by the frequency balance approach[6]. The closed form steady state equations for occupying each state are defined as follows:

$$Pi = P1 * Ai \qquad (2.10)$$

where:

Pi = Steady State Probability of occupying state i

Ai = Constant associated with state i

The probability of occupying the fully operational state (i.e. P1) is defined as follows:

$$P1 = 1.0/(1.0 + A2 + A3 + . . . +A10) \qquad (2.11)$$

The definition of constants A2 to A10 are listed in Table 2.2

Table 2.2: Definition of constants

CONSTANT	MATHEMATICAL DESCRIPTION
A2.1	$(\{\lambda_1 + A8 \cdot \mu_{m2}\}\{\mu_1 + \mu_2\} + A3 \cdot \mu_2 \lambda_{11})$
A2.2	$(\{\lambda_{21} + \mu_1\}\{\mu_1 + \mu_2\} - \mu_2 \lambda_{21})$
A2.3	$\{\lambda_1 + A8 \cdot \mu_{m2}\}\{\mu_1 + \mu_2\}$
A2	A2.1/A2.2
A3.1	$\{\lambda_1 + \lambda_2 + \lambda_{m1} + \lambda_{m2} - A5 \cdot \mu_{m1} - A7 \mu_{m2}\}$
A3	$(\{A3.1 \cdot A2.2\} - \mu_1 \cdot A2.3)$
A4	$(\{A2 \cdot \lambda_{21} + A3 \cdot \lambda_{11}\}/\{\mu_1 + \mu_2\})$
A5.1	$(\{\mu_2 + \mu_{m1}\}\{\lambda_{21} + \mu_{m1}\} - \mu_2 \lambda_{21})$
A5	$\lambda_{m1}\{\mu_2 + \mu_{m1}\}/A5.1$
A6	$\lambda_{21} \lambda_{m1}/A5.1$
A7.1	$(\{\mu_1 + \mu_{m1}\}\{\lambda_{11} + \mu_{m2}\} - \lambda_{11} \mu_1)$
A7	$\lambda_{m2}\{\mu_1 + \mu_{m2}\}/A7.1$
A8	$\{\lambda_{m2} \lambda_{11}\}/A7.1$
A9	λ_{c1}/μ_{c1}
A10	λ_{c2}/μ_{c2}

2.3.2 *Case Study 2.1: Fully redundant system*

A transformer bank consisting of two redundant transformers will be used to illustrate the proposed model. The basic reliability data selected for the studies presented in this Chapter are listed in Table 2.3. The increased failure rates of one transformer (i.e., due to increased stress levels) when the other has been forced out of service is assumed to be ten times the average failure rate of the in-service transformer unit. Considerably more research is required to accurately estimate the multiplier for the large pieces of electrical apparatus that has been developed in the microelectronic industry (e.g. MIL-HDBK-217 D). The failure rates and restoration rates were selected from the literature and are typical failure rates for transformers in the power industry.

Table 2.3: Case study reliability data

SYMBOL	CASE STUDY VALUES
λ_1	0.00000107 failures per hour
λ_2	0.00000107 failures per hour
λ_{11}	10 times λ_1
λ_{21}	10 times λ_2
λ_{m1}	VARIABLE 0.5 to 4 times per year
λ_{m2}	VARIABLE 0.5 to 4 times per year
λ_{c1}	0.312 failures per year
λ_{c2}	0.250 failures per year

SYMBOL	CASE STUDY VALUES
μ_1	0.00456621 repairs per hour
μ_2	0.00456621 repairs per hour
μ_{m1}	1.0/r where r varies from 4 to 72 hours
μ_{m2}	1.0/r where r varies from 4 to 72 hours
μ_{c1}	1.923076 repairs per hour
μ_{c2}	0.833333 repairs per hour

For the transformer bank consisting of two redundant transformers the system load can be carried by one of the transformers during the period when the other transformer has been isolated from the system for the scheduled preventive maintenance. But when the other transformer has been forced out of service, the in-service transformer will experience increased stress levels which will increase its failure rate. The system availability as a function of the frequency and duration of maintenance activities is shown in Figure 2.4.

It can be clearly seen from Figure 2.4 that for a fixed maintenance duration, the system availability increases with increasing frequencies of maintenance. Also, if the total annual duration of maintenance is fixed, then the system availability remains fairly constant for various combinations of the frequency of maintenance whose total annual duration equals the fixed value.

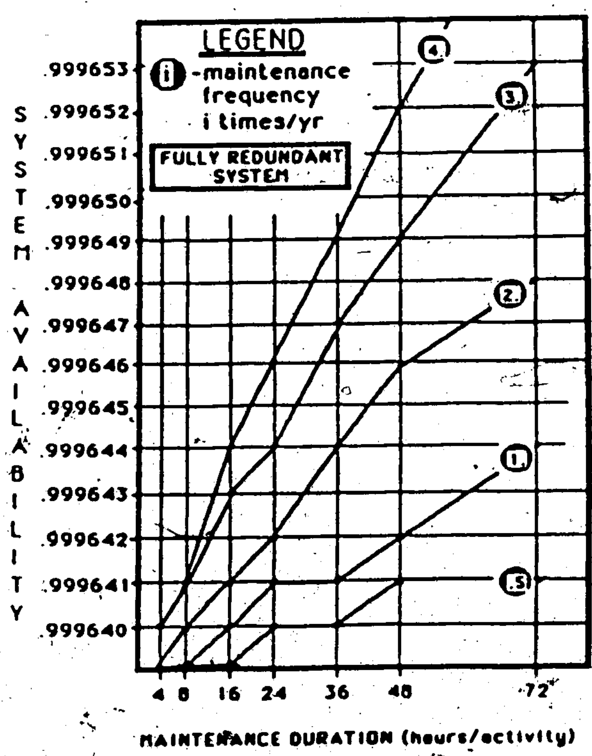


Figure 2.4: System availability vs maintenance frequency

For many processes one of the key indicators of system performance is the mean duration the system is in the operational state as illustrated in Figure 2.5. It can be clearly seen from Figure 2.5 that for a fixed maintenance duration the mean duration in the system operational state increases significantly with increasing maintenance frequency. Which values of maintenance frequency and duration are utilized in practice is an economic decision in which the cost benefits associated with incremental operational durations must be balanced by the increased costs associated with increased maintenance activities.

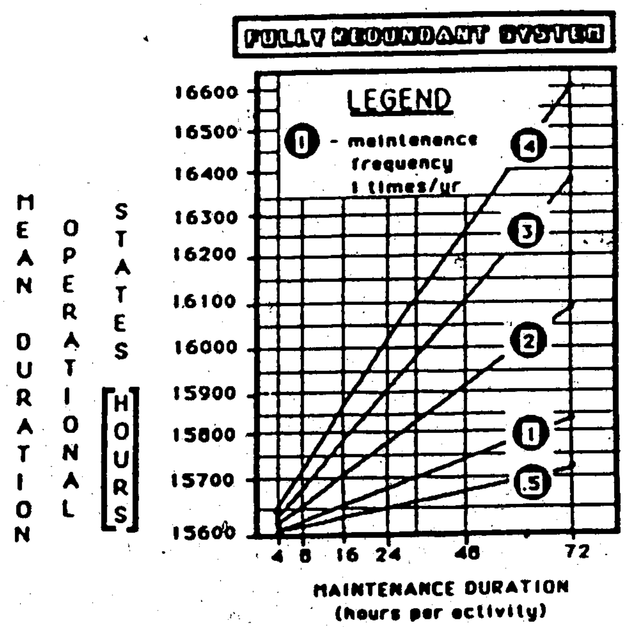


Figure 2.5: Mean duration of operational states vs maintenance duration

2.3.3 Case Study 2.2: Non-redundant system

The system availability for a non-redundant system as a function of the frequency and duration of the maintenance activities is shown in Figure 2.6. The assumption of a fully redundant system can often be violated in practice. When a system of fixed capacity is installed to satisfy a given load at one point in time, the system operation criteria of the fully redundant mode will erode as the system load increases. A critical time period may be reached in the history of a system whereby the single in-service transformer can no longer safely carry the total system load. At this point in time, the system can be considered as a non-redundant system (i.e., an extreme constraint).

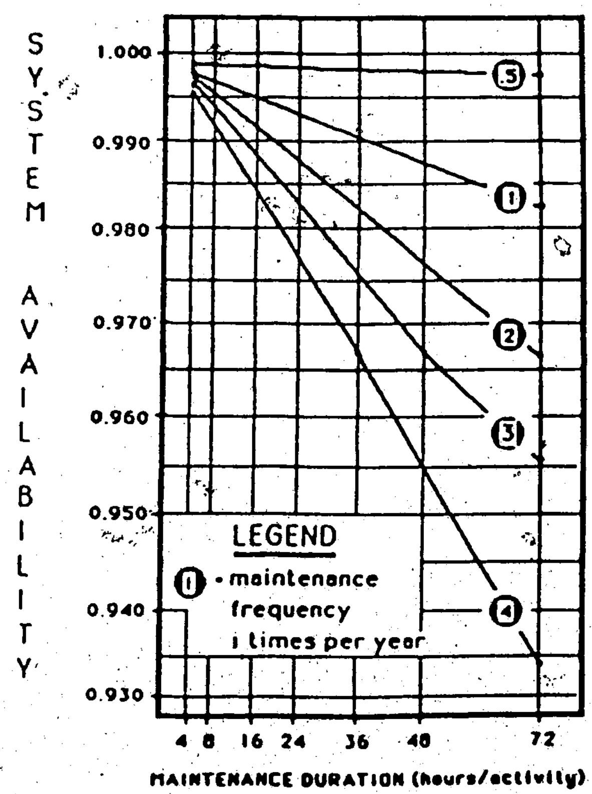


Figure 2.6: Non-Redundant system availability

It can be clearly seen from Figure 2.6 for a non-redundant system that if a particular piece of equipment requires frequent and lengthy maintenance activities, then the overall system availability deteriorates quite rapidly.

2.3.3.1 System Risk During Maintenance Periods

During the maintenance activities on a fully redundant transformer bank configuration, there is a probability that when a unit has been removed from service for maintenance, the in-service unit may fail resulting in a system outage. The risk to the system during maintenance periods can be significant as shown in Figure 2.7.

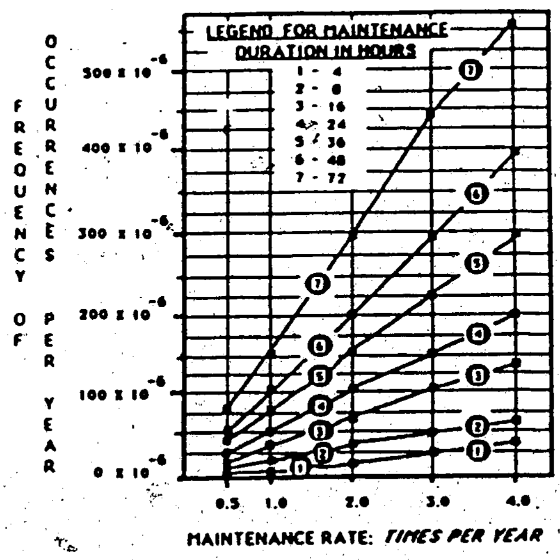


Figure 2.7: System risk during maintenance periods

It is evident that the frequency of occurrences of system outages during maintenance periods increases significantly with the duration of these maintenance activities. The risk to the overall system operation can be quite significant during the duration of maintenance activities if the stress levels imposed on the in-service equipment are high resulting in a higher in-service equipment failure rate.

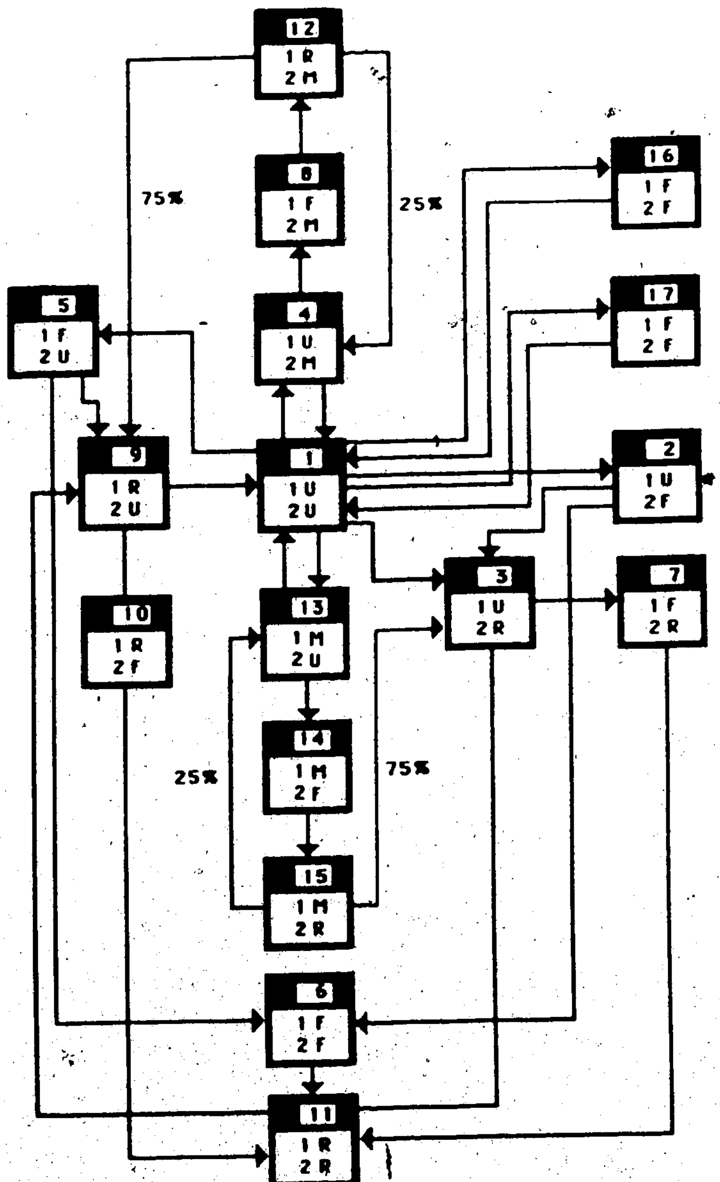
It can also be seen from Figure 2.7 that the risk of a system outage varies approximately linearly with the annual rate of maintenance. The maintenance rate is usually determined by the manufacturers of the transformers and the stress levels imposed on the equipment during its life cycle. In many systems the rate of maintenance activities is fixed. However, depending upon the stress levels experienced by the transformers in service, the rates may be inadequate (i.e., too low or high), a subject of future research.

The results of this case study suggest that for most "redundant" systems, the system availability can be improved with increased maintenance activities. However, if the original design or the increased system load violates the "redundancy" assumption then, for the resulting non-redundant system, the system availability decreases significantly for increased maintenance activities.

2.4 Another Proposed Model

Another dual component redundant system Markov model has been presented in Reference [10] and is shown in Figure 2.8. The definitions of symbols used in the model are listed in Table 2.4.

LEGEND : Symbolic Transition Rates



DEFINITION OF STATE SPACE TRANSITION SYMBOLS

STATE TRANSITIONS FROM	TO	SYMBOL
1	2	λ_2
1	4	λ_{m2}
1	5	λ_1
1	13	λ_{m1}
1	16	λ_{c1}
1	17	λ_{c2}
2	3	μ_{L2}
3	1	μ_{r2}
3	7	λ_1
4	1	μ_{m2}
4	8	λ_1
5	6	λ_2
5	9	μ_{L1}
6	11	$\mu_{L1}+\mu_{L2}$
7	11	μ_{L1}
8	12	μ_{L1}
9	1	μ_{r1}
9	10	λ_2
10	11	μ_{L2}
11	3	μ_{r1}
11	9	μ_{r2}
12	4	25%
12	9	75%
13	14	λ_2
14	15	λ_{L2}
15	3	25%
15	13	75%
16	1	λ_{c1}
17	1	λ_{c2}

Figure 2.8: Markov model of a dual component redundant system

The proposed Markov model is an extension of the model presented in reference [4]. Two additional states are added (i.e. state 16 and 17) to the model. These additional states account for common mode failures due to internal and external system failures. A single subsystem or component is assumed to reside in the following basic states:

1. operational
2. subsystem or component failed and isolated.
3. time required for fault localization
4. under repair
5. being maintained
6. subjected to common mode failures

Table 2.4: Definitions of Figure 2.8 symbols

SYMBOL	DESCRIPTION
λ_1	AVERAGE FAILURE RATE OF SUBSYSTEM #1
λ_2	AVERAGE FAILURE RATE OF SUBSYSTEM #2
λ_{e1}	COMMON MODE FAILURE RATE OF THE SYSTEM DUE TO INTERNAL SYSTEM FAILURES
λ_{e2}	COMMON MODE FAILURE RATE OF THE SYSTEM DUE TO EXTERNAL SYSTEM FAILURES
λ_{m1}	MAINTENANCE RATE OF SUBSYSTEM #1
λ_{m2}	MAINTENANCE RATE OF SUBSYSTEM #2
μ_{L1}	FAULT LOCALIZATION RATE OF SUBSYSTEM #1
μ_{L2}	FAULT LOCALIZATION RATE OF SUBSYSTEM #2
μ_{r1}	RESTORATION RATE OF SUBSYSTEM #1
μ_{r2}	RESTORATION RATE OF SUBSYSTEM #2
μ_{m1}	MAINTENANCE RESTORATION RATE OF SUBSYSTEM #1
μ_{m2}	MAINTENANCE RESTORATION RATE OF SUBSYSTEM #2
μ_{e1}	RESTORATION RATE OF COMMON MODE FAILURES DUE TO INTERNAL SYSTEM FAILURES
μ_{e2}	RESTORATION RATE OF COMMON MODE FAILURES DUE TO EXTERNAL SYSTEM FAILURES

The referenced and the proposed model deviate from the classical redundant models by introducing states for fault localization. The total repair time is the addition of fault identification time i.e., fault localization and the actual repair time. In the proposed and the referenced models both the fault localization and the actual repair activities are treated separately whereas these activities are grouped together in the classical models making it difficult to analyse the individual contribution of the activities to the reliability performance of the scheme.

The steady state probabilities of occupying each state in Figure 2.8 can be solved by the frequency balance approach. The closed form steady state equations for occupying each state are defined as follows:

$$Pi = P1*Ai \qquad (2.12)$$

where:

Pi = Steady state probability of occupying state i

Ai = Constant associated with state i

The probability of occupying the fully operational state (i.e., state 1 defined as P1) is defined as follows:

$$P1 = 1.0/(1 + \sum_{i=1}^{n} Ai) \qquad (2.13)$$

where:

ni = the number of states.

The definitions of constants A2 to A17 are listed in Table 2.5

Table 2.5: Definition of constants associated with Figure 2.8's state space probabilities

CONSTANT	MATHEMATICAL DESCRIPTION
A_2	$\lambda_2 \backslash [\mu_{t2} + \lambda_1]$
A_3	$\dfrac{[A_2 \mu_{t2} + .75 A_{15} + \mu_{r1} A_{11}]}{[\mu_{r2} + \lambda_1]}$
A_4	$\lambda_{m2} \backslash [\mu_{m2} + .75 \lambda_1]$
A_5	$\lambda_1 \backslash [\mu_{t1} + \lambda_2]$
A_6	$[A_5 \lambda_2 + A_2 \lambda_1] \backslash [\mu_{t1} + \mu_{t2}]$
A_7	$\lambda_1 A_3 \backslash \mu_{t1}$
A_8	$\lambda_1 A_4 \backslash \mu_{t1}$
A_9	$\dfrac{[A_5 \mu_{t1} + .75 A_{12} + \mu_{r2} A_{11}]}{[\mu_{r1} + \lambda_2]}$
A_{10}	$\lambda_2 A_9 \backslash \mu_{t2}$
$A_{11.1}$	$\lambda_2 [\mu_{r2} + \lambda_1][\mu_{t1} A_5 + .75 A_{12}] + \lambda_1 [\mu_{r1} + \lambda_2][\mu_{t2} A_2 + .75 A_{15}] + A_6 [\mu_{t1} + \mu_{t2}][\mu_{r1} + \lambda_2][\mu_{r2} + \lambda_1]$
$A_{11.2}$	$[\mu_{r1} + \mu_{r2}][\mu_{r1} + \lambda_2][\mu_{r2} + \lambda_1] - \lambda_2 \mu_{r2} [\mu_{r2} + \lambda_1] - \lambda_1 \mu_{r1} [\mu_{r1} + \lambda_2]$
A_{11}	$A_{11.1} \backslash A_{11.2}$
A_{12}	$A_8 \mu_{t1}$
A_{13}	$[\lambda_{m1} + .25 A_{15}] \backslash [\mu_{m1} + .75 \lambda_2]$
A_{14}	$A_{13} \lambda_2 \backslash \lambda_{t2}$
A_{15}	$\lambda_2 \lambda_{m1} \backslash [\mu_{m1} + .75 \lambda_2]$
A_{16}	$\lambda_{e1} \backslash \mu_{e1}$
A_{17}	$\lambda_{e2} \backslash \mu_{e2}$

2.4.1 Case Study 2.3

The basic reliability data used for the case studies presented here are listed in Table 2.6. The majority of the case study parameters were assumed to be fixed at the levels presented in the literature [11]. However, the frequency and duration of maintenance activities were allowed to vary within the boundaries defined in the literature for the purposes of comparison.

Table 2.6: Case study parameters

DEFINITION OF TRANSITION RATES
CASE STUDY PARAMETERS
FAILURE AND MAINTENANCE RATES

SYMBOL	CASE STUDY VALUES
λ_1	0.71917776429 x 10^{-6} failures/hr
λ_2	0.71917776429 x 10^{-6} failures/hr
λ_{c1}	0.312 failures per year
λ_{c2}	0.250 failures per year
λ_{m1}	VARIABLE 0.5 to 5.0 actions per year
λ_{m2}	VARIABLE 0.5 to 5.0 actions per year

DEFINITION OF TRANSITION RATES
CASE STUDY PARAMETERS:
RESTORATION AND MAINTENANCE RATES

SYMBOL	CASE STUDY VALUES
μ_{L1}	0.5 localizations per hour
μ_{L2}	0.5 localizations per hour
μ_{r1}	0.10003054141988829 repairs per hour
μ_{r2}	0.10003054141988829 repairs per hour
μ_{m1}	1.0/r where: r varies from 12.6 to 48.0 hrs
μ_{m2}	1.0/r where: r varies from 12.6 to 48.0 hrs
μ_{c1}	1.923076 repairs per hour
μ_{c2}	0.833333 repairs per hour

For the dual component system configuration the probability of the system being operational is defined as:

$$P(\text{Operational}) = P1+P3+P4+P9+P13 \qquad (2.14)$$

The probability of the system failure is simply given by the following expression:

$$P(\text{System failure}) = 1.-P(\text{Operational}) \qquad (2.15)$$

The availability or the probability of the system being operational in the long term i.e., independent of time for the fully redundant system was evaluated as a function of the frequency and duration of maintenance activities including and excluding the common mode failures. The results are listed in Table 2.7.

Table 2.7: System availability vs maintenance activity

DURATION OF MAINTENANCE HOURS PER ACTIVITY	RATE OF MAINTENANCE PER YEAR	AVAILABILITY OF OPERATIONAL STATES: EXCLUDING COMMON MODE FAILURES	AVAILABILITY OF OPERATIONAL STATES: INCLUDING COMMON MODE FAILURES
48.0 hours	0.5	0.999997	0.999638
	1.0	0.999997	0.999640
	2.0	0.999997	0.999644
	3.0	0.999997	0.999648
	4.0	0.999997	0.999651
	5.0	0.999997	0.999655
24.0 hours	0.5	0.999997	0.999637
	1.0	0.999997	0.999638
	2.0	0.999997	0.999640
	3.0	0.999997	0.999642
	4.0	0.999997	0.999644
	5.0	0.999997	0.999648
12.6 hours	0.5	0.999997	0.999637
	1.0	0.999997	0.999637
	2.0	0.999997	0.999638
	3.0	0.999997	0.999639
	4.0	0.999997	0.999640
	5.0	0.999997	0.999641

With reference to Table 2.7, the following conclusions can be made:

1. When common mode failures are excluded from the proposed model (i.e., the published model [4]) the following observations may be made:

   a. the system availability is high;

   b. the frequency and duration of maintenance activities have no significant impact on the availability of the system. It remains almost constant (i.e., 6 decimal places).

2. When common mode failures are included in the proposed model the following observations may be made:
   a. the system availability is lowered considerably;
   b. the system availability is affected by the frequency and duration of maintenance activities. It increases with increasing rates and durations of maintenance activities.

For the dual component system configuration, the frequency of departure (Fup) from the non-operational states is given by the following equation:

$$Fup = P2\,\mu_{L2} + P15 + P5\,\mu_{L1} + P11(\mu_{r1} + \mu_{r2}) + P12 + P16\,\mu_{C1} + P17\,\mu_{C2} \qquad (2.16)$$

The mean duration in hours in the operational states (Mup) of the proposed dual component system is given by the following equation:

$$Mup \text{ (in hours)} = P(\text{operational})/Fup \qquad (2.17)$$

The mean duration in the operational state was evaluated as a function of the frequency and duration of maintenance activities. The results are shown in Table 2.8.

Table 2.8: Mean duration of operational states vs. maintenance activity

MEAN DURATION OF OPERATIONAL STATES
FULLY REDUNDANT SYSTEM

DURATION OF MAINTENANCE HOURS PER ACTIVITY	RATE OF MAINTENANCE PER YEAR	MEAN DURATION OF OPERATIONAL STATES: EXCLUDING COMMON MODE FAILURES	MEAN DURATION OF OPERATIONAL STATES: INCLUDING COMMON MODE FAILURES
48.0 hours	0.5	698813.5	15329.0
	1.0	702381.2	15412.5
	2.0	709509.1	15579.3
	3.0	726627.4	15746.1
	4.0	723735.9	15912.9
	5.0	730834.7	16079.8
24.0 hours	0.5	697028.8	15287.3
	1.0	698813.6	15329.0
	2.0	702381.3	15412.5
	3.0	705946.5	15495.9
	4.0	709509.3	15579.3
	5.0	713069.7	15662.7
12.6 hours	0.5	696180.8	15267.5
	1.0	697118.0	15289.4
	2.0	698992.0	15333.2
	3.0	700865.3	15377.0
	4.0	702737.9	15420.8
	5.0	704609.9	15464.6

The impact of common mode failures on the mean duration in the operational states is significant. When common mode failures were excluded from the model, the mean duration in the operational states is quite high and increases with increased frequency and duration of maintenance activities.

When common mode failures are included in the proposed model, the duration in the operational states is considerably lower due to the frequency of occurrences of common mode failures being significantly higher than the overlapping forced outages of the two subsystems. The mean duration in the operational states increases with increasing rates and durations of maintenance activities.

2.5 Case Study 2.4: Reliability analysis of a simple substation scheme [4] by Markov modelling technique

The reliability analysis of a simple substation scheme selected from reference [4] by Markov modelling is presented in this case study. The results of this analysis will be compared in Chapter 4 with those obtained by the cut set technique (see Chapter 3). The substation scheme is shown in Figure 2.9:

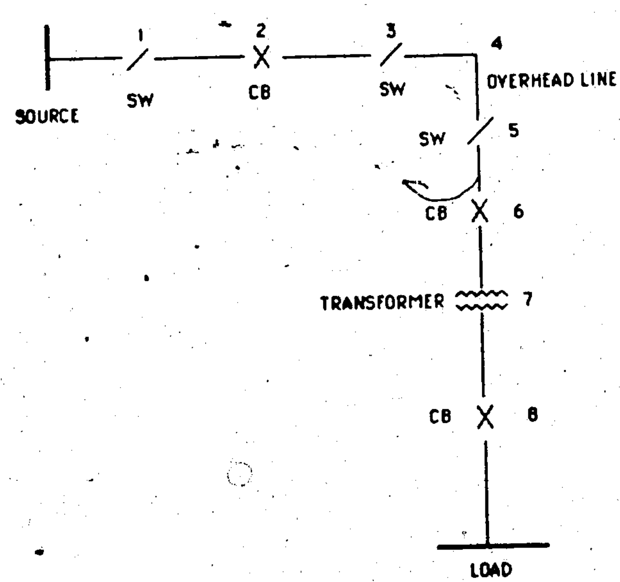


Figure 2.9: Simple substation configuration

The data given in the reference[4] is reproduced in Table 2.9.

Table 2.9: Reliability data for case study 2.4

1. Failure rates and Repair Times

Component	Failure Rate	Repair Time
Disconnector	.002/Yr.	6.00 Hours
Circuit Breaker	.0043/Yr.	12.00 Hours
Transformer	.0088/Yr.	27.95 Hours
Overhead line	2.7/100 Km-Yr.	5.50 Hours

2. Maintenance Rate and Duration

Maintenance Rate	Duration
1.0/Yr.	12.60 Hours

The Markov model of the substation scheme shown in Figure 2.9 is shown in Figure 2.10.

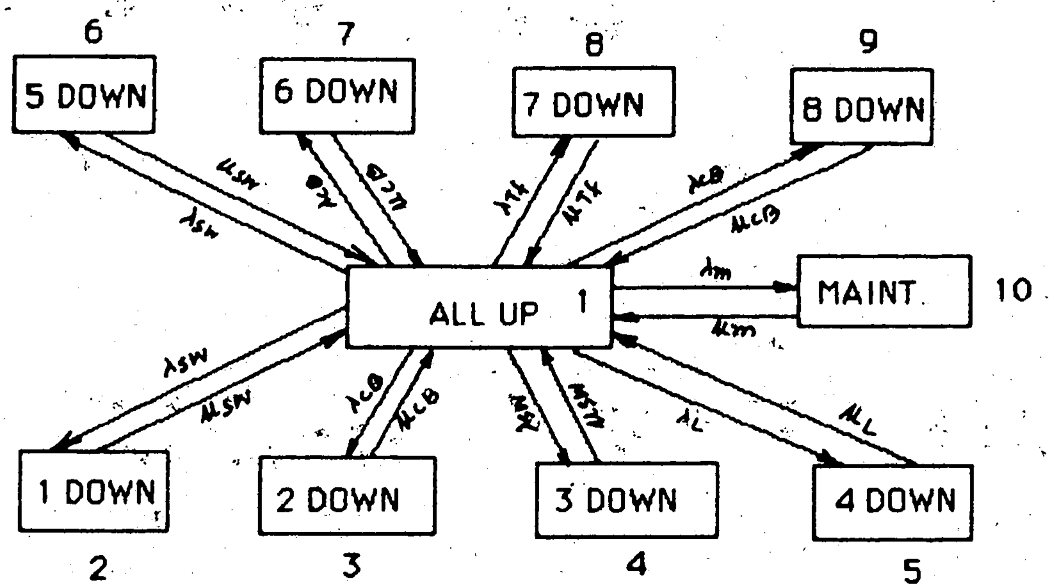


Figure 2.10: Markov model of substation scheme

By the frequency balance approach, the following equations can be generated:

$$P1(\lambda_{sw} + \lambda_{cB} + \lambda_{sw} + \lambda_{L} + \lambda_{sw} + \lambda_{cB} + \lambda_{Tf} + \lambda_{cB} + \lambda_{m})$$

$$= P2\,\mu_{sw} + P3\,\mu_{cB} + P4\,\mu_{sw} + P5\,\mu_{L} + P6\,\mu_{sw} + P7\,\mu_{cB} + P8\,\mu_{Tf} + P9\,\mu_{cB} + P10\,\mu_{m} \qquad (2.18)$$

$$P2\,\mu_{sw} = P1\,\lambda_{sw} \qquad (2.19)$$

$$P3\,\mu_{cB} = P1\,\lambda_{cB} \qquad (2.20)$$

$$P4\,\mu_{sw} = P1\,\lambda_{sw} \qquad (2.21)$$

$$P5\,\mu_{L} = P1\,\lambda_{L} \qquad (2.22)$$

$$P6\,\mu_{sw} = P1\,\lambda_{cB} \qquad (2.23)$$

$$P7\,\mu_{cB} = P1\,\lambda_{cB} \quad (2.24)$$

$$P8\,\mu_{Tf} = P1\,\lambda_{Tf} \quad (2.25)$$

$$P9\,\mu_{cB} = P1\,\lambda_{cB} \quad (2.26)$$

$$P10\,\mu_{m} = P1\,\lambda_{m} \quad (2.27)$$

$$P1[1 + P2/P1 + P3/P1 + P4/P1 + P5/P1 + P6/P1 + P7/P1 + P8/P1 + P9/P1 + P10/P1] = 1.0 \quad (2.28)$$

By substituting various values of failure, repair and maintenance rates, the state probabilities are obtained and are shown in Table 2.10

Table 2.10: Probabilities of various states

State Probability	Value
P1	.9983281126
P2	.1367576 E-05
P3	.5880576 E-05
P4	.1367576 E-05
P5	.1861613 E-03
P6	.1367576 E-03
P7	.5880576 E-05
P8	.2803076 E-04
P9	.5880576 E-05
P10	.1435956 E-02

The following reliability indices are evaluated as follows:

$$Pup = P1 = .998328113 \quad (2.29)$$

$$Pdown = P2+P3+P4+P5+P6+P7+P8+P9+P10 \quad (2.30)$$

$$= .001671851$$

$$Fup = P10\mu_m + P9\mu_{CB} + P8\mu_{Tf} + P7\mu_{CB} + P6\mu_{SW} + P5\mu_L + P4\mu_{SW} + P3\mu_{CB} + P2\mu_{SW} \quad (2.31)$$

= 1.025981796 occ/yr.

$$Fdown = P1*(\lambda_{SW} + \lambda_{CB} + \lambda_{SW} + \lambda_L + \lambda_{SW} + \lambda_{CB} + \lambda_{Tf} + \lambda_{CB} + \lambda_m) \quad (2.32)$$

= 1.322485177 occ/yr.

where:

Pup = Probability of system being in the up state

Pdown = Probability of system being in the down state

Fup = Frequency of occurences of the system in the up state

Fdown = Frequency of occurences of the system in the down state

The system mean down time = (Pdown/Fdown)*8760. hours (2.33)

= 11.074402475 hours

The system failure rate = Fdown / Availability (2.34)

= 1.322485177 / .998328113

= 1.324699926 failures / year

The system down time/year = Failure rate * Mean down time (2.35)

= 1.324699926 * 11.074402475

= 14.670260144 hours / year

The results of the substation scheme shown in Figure 2.9 are summarized in Table 2.11.

Table 2.11: Summary of substation reliability levels

System Availability	=	.998328113
System mean down time	=	11.074402475 hours
System down time per year	=	14.670260144 hrs/Yr
System failure rate	=	1.324699926 f/Yr

2.6 Conclusions

The Markov approach is a general approach whose results are accurate provided the underlying assumptions of the scheme are not violated. The application of this scheme becomes cumbersome in a practical network configuration. For example, in a system containing n components, each of which can reside in two states, there are 2 raised to the power n possible system states. When the components can reside in more than two states (i.e., multimodes of failure) which often is the case for power system components, the complexity of the problem increases. The application of this technique is therefore limited by computer storage, solution time requirements and rounding errors incurred in the solution [15].

CHAPTER 3

CUT SET MODELLING TECHNIQUE

3.1 *Introduction*

The cut set approach is becoming increasingly popular in reliability evaluation of transmission and distribution systems. In Chapter 2, it was shown that the Markov modelling approach is limited to comparatively simple systems. The cut set approach is suitable for simple and as well as complex systems [3,12,13,14]. Since the cut set technique has been extensively used in this thesis, it is therefore appropriate to discuss the technique in some detail.

A few definitions and explanations are offered first as follows:

3.1.1 *Tie Set*

A tie is a set of interconnected components whose working condition assures system operation. In other words, a tie set (i.e., success path) is a directed path from input nodes (i.e., source) to the output nodes (i.e., sink).

3.1.2 *Minimal Tie Set*

A tie set is a minimal tie set if the set remaining after the removal of any of its components is no longer a tie.

3.1.3 Cut Set

A cut set is a set of elements which literally cuts all success paths, that is, it severs the line of communication between input and output nodes of a system configuration. Hence, it is a set of components whose failure results in system failure.

3.1.4 Minimal Cut Set

A minimal cut set is a cut where the set of elements remaining after the removal of any of its elements is no longer a cut. A minimal cut has no proper subset of components whose failure alone will cause system failure.

If all the components in a cut set fail, the system will fail regardless of the condition of the other components in the system. A system may have a large number of cut sets and a particular component may be in more than one of them. The general approach can be seen in the following simple examples taken from references [8] and [15].

3.1.5 Example 1

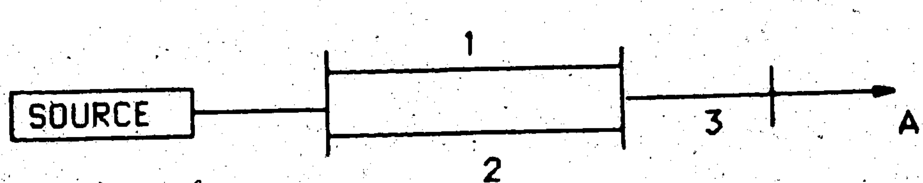


Figure 3.1: Network configuration

The cut sets for load point A in Figure 3.1 are shown in Table 3.1.

Table 3.1: Cut sets for network configuration shown in Figure 3.1

Cut Set	Components in Cut
1	3
2	1,2
3	1,3
4	1,2,3
5	2,3

The definition of a minimal cut set as a cut set in which there is no subset of components whose failure alone will cause the system to fail, implies that a minimal cut set corresponds to no more component failures than are required to cause system failure. The minimal cut sets for the load point A are shown in Table 3.2.

Table 3.2: Minimal cut sets for the network configuration shown in Figure 3.1

Minimal Cut Set	Components in Minimal Cut Set
1	3

3.1.6 *Example 2*

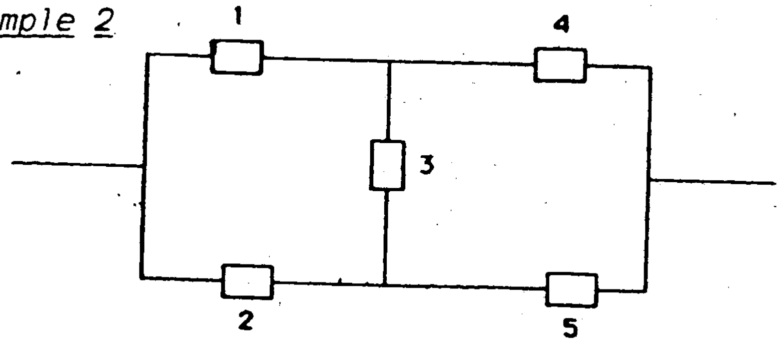


Figure 3.2: Bridge circuit configuration

From the bridge circuit shown in Figure 3.2, the following sets can be identified:

Ties:

14,25,135,234,124,134,154,125,235,245,
1235,1245,1234,1345,2345,12345

Cuts:

12,45,135,234,123,124,125,145,245,345,
1235,1245,1234,1345,2345,12345

Minimal Ties:

14,25,135,234.

Minimal Cuts:

12,45,135,234.

To illustrate the difference between minimal and non-minimal sets, the set 1345, for example, is a cut, but is not a minimal cut because after the removal of component 4 the remaining set 135 is still a cut. The cut 135 is a minimal cut set because the sets remaining after any further reduction(13,15,35) are no longer cuts (i.e., will not cause the system to fail). The component blocks in a minimal cut are considered to be in parallel for reliability calculations because all of them must fail in order to disconnect the input and output node. The minimal cuts themselves are connected in series, as failure of any single cut ensures the system failure.

3.2 Generation of cut sets

The first step in the generation of cut sets is to find the tie sets (success paths) between the source and the load point being considered by the algorithm published in Reference [25]. The paths are converted to a Boolean array of zeros (i.e., indicating no physical component) and ones (i.e., component present). The simple Boolean logic is then applied for identifying the cut sets [3]. With reference to Figure 3.2, the minimal tie sets are shown in Table 3.3.

Table 3.3: Minimal tie sets for the bridge circuit configuration

P 1	1 - 4
P 2	2 - 5
P 3	1 - 3 -5
P 4	2 - 3 -4

The Minimal path matrix in binary form is:

$$[P] = \begin{bmatrix} P\ 1 \\ P\ 2 \\ P\ 3 \\ P\ 4 \end{bmatrix} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \end{array} \begin{array}{c} 1\ 2\ 3\ 4\ 5 \\ \begin{bmatrix} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{bmatrix} \end{array}$$

Minimal path matrix in binary form

The Minimal path matrix has the dimensions M * N

M = Rows of the matrix

= No. of success paths

N = Columns of the matrix

= No. of components in the system

In the present example, there are 4 success paths and 5 elements in the system so the dimensions of the Minimal Path Matrix is 4 * 5.

To deduce the first order minimal cuts, the computer program searches for columns in which every element is unity and then the column elements are replaced by zeroes to prevent non minimal cuts which contain first order minimal cuts from being detected. The maximum order of a minimal cut is equal to the number of minimal paths i.e., 4th order in the present example. Since none of the column vectors in the matrix is a unit vector then there is no first order cut in the system.

The second order minimal cuts are calculated by adding logically (.OR. operation) two columns at a time. The logical OR operation for two components is defined below:

0 + 0 = 0

0 + 1 = 1

1 + 0 = 1

1 + 1 = 1

If any of the resulting vectors has every element equal to unity, the combined columns (i.e., components) form a second order minimal cut.

The logical addition of column 1 & 2 and 4 & 5 results in unit vectors, hence components 1-2 & 3-4 are second order cuts for the bridge network configuration.

The process is continued by logically adding three columns at a time to detect the third order cuts and so on until cuts of all required orders are found. Each time a cut of order 3 or greater, say order n is found, it is necessary to check whether it includes any minimal cut sets of order between 2 and n-1. If it does, the cut is rejected as a non minimal cut. To do this the following computer technique is utilized.

Consider two cuts, I and J; I being a minimal cut set of order i and J a cut set of order j where i is less than j. Consider the following sets:

[I] = [Ai, Bi, Ci..]; where i is the number of elememts in the set.

[J] = [Aj, Bj, Cj..]; where j is the number of elements in the set.

Each element of cut set J is compared with the elements of cut set I. Each time the same element is found in I, then a flag (e.g., score) is incremented by one. If the score equals i, then [J] is a non minimal cut and is rejected.

For example, the logical addition of columns 1, 2, 4 produces a unit vector and is detected as a third order cut. But when it is compared with a minimal cut 1, 2 the score becomes 2 which is equal to the number of elements in the second order minimal cut 1, 2; hence, cut 1, 2, 4 is discarded as non minimal cut. Similarly, the other third or fourth order cuts except 1, 3, 5 and 2, 3, 4 are rejected as non minimal cuts.

Hence, the computer program determined the following minimal cuts.

Order	Number	Elements
First	0	nil
Second	2	1,2 and 4,5
Third	2	1,3,5 and 2,3,4

3.3 *Availability of Cut Sets*[12, 13, 14]

In the minimal cut set approach the components of the system configuration are assumed to be connected in parallel for evaluating the availability since all of them must fail in order to produce a flow cut between the source and the sink. The minimal cuts themselves are, however, in series as even a single minimal cut ensures system failure. The cut set availability expression can be derived as follows:

Let Ti denote the ith tie set.

Let Cj denote the jth cut set.

The reliability R of the system can be expressed as follows:

$$R = Pr[\ T1 \cup T2 \cup \ldots Ti\ ] \qquad (3.1)$$

$$= Pr[\text{ At least one tie set is good }]$$

The reliability (R) of the system can also be expressed in terms of cut sets as follows:

$$R = Pr[C1 \cdot C2 \cdot C3 \ldots \cdot Cj] \qquad (3.2)$$

= Pr[All minimal cut sets are good, viz. contains at least one element of the set which is operative].

Equivalently, the unreliability is expressed as:

$$1 - R = Pr[\overline{T1} \cdot \overline{T2} \ldots \overline{Ti}] \qquad (3.3)$$

$$= Pr[\text{All tie sets have a failure}]$$

Or.

$$1 - R = Pr[\ \overline{C1} \cup \overline{C2} \cup \ldots \overline{Cj}] \qquad (3.4)$$

$$= Pr[\text{ At least one cut occurs }]$$

The events $\overline{Ti}$ and $\overline{Cj}$ are the compliments of the events Ti and Cj, respectively. Thus, $\overline{Ti}$ denotes failure of at least one item in the ith tie set and $\overline{Cj}$ denotes failure of all items of the jth cut. These are the exact equations for the system reliability and unreliability levels. The general equation for system failure (i.e., Pf) can be written as:

$$Pf = Pr(\overline{Ci})+Pr(\overline{C2})+....+Pr(\overline{Cj})$$
$$-[Pr(\overline{C1}\cap \overline{C2})+...+Pr(\overline{Ci}\cap \overline{Cj})]$$
$$+[Pr(\overline{C1}\cap\overline{C2}\cap \overline{C3})+...+Pr(\overline{Ci}\cap \overline{Cj}\cap \overline{Ck})]$$
$$.$$
$$.$$
$$+(-1)^{m-1}[Pr(\overline{C1}\cap \overline{C2}\cap \; .\cap.\overline{Cm})] \quad (3.5)$$

3.3.1 <u>Bridge circuit reliability evaluation</u>

Refer to Figure 3.2 for the bridge circuit. The probability of system failure for the bridge circuit is expressed as follows:

$$Pf = Pr(\overline{C1} \cup \overline{C2} \cup \overline{C3} \cup \overline{C4})$$
$$= Pr(\overline{C1})+Pr(\overline{C2})+Pr(\overline{C3})+Pr(\overline{C4})$$
$$-Pr(\overline{C1}\cap \overline{C2})-Pr(\overline{C1}\cap \overline{C3})-Pr(\overline{C1}\cap \overline{C4})$$
$$-Pr(\overline{C2}\cap \overline{C3})-Pr(\overline{C2}\cap \overline{C4})-Pr(\overline{C3}\cap \overline{C4})$$
$$+Pr(\overline{C1}\cap\overline{C2}\cap\overline{C3})+Pr(\overline{C1}\cap \overline{C2}\cap \overline{C4})$$
$$+Pr(\overline{C1}\cap\overline{C3}\cap \overline{C4})+Pr(\overline{C2}\cap\overline{C3}\cap\overline{C4})$$
$$-Pr(\overline{C1}\cap \overline{C2}\cap\overline{C3}\cap \overline{C4}) \quad (3.6)$$

If Pi is the reliability of a component in a cut and Qi its unreliability, then based on the assumption that the components are independent, the following equations for the probabilities of cut sets failing can be written:

$$Pr(\overline{C1}) = Q1.Q2 \quad (3.7)$$
$$Pr(\overline{C2}) = Q3.Q4 \quad (3.8)$$
$$Pr(\overline{C3}) = Q1.Q4.Q5 \quad (3.9)$$
$$Pr(\overline{C4}) = Q2.Q3.Q5 \quad (3.10)$$
$$Pr(\overline{C1}\cap \overline{C2}) = Q1.Q2.Q3.Q4 \quad (3.11)$$

$$Pr(\overline{C1} \cap \overline{C3}) = Q1.Q2.Q4.Q5 \quad (3.12)$$

$$Pr(\overline{C1} \cap \overline{C4}) = Q1.Q2.Q3.Q5 \quad (3.13)$$

$$Pr(\overline{C2} \cap \overline{C3}) = Q1.Q3.Q4.Q5 \quad (3.14)$$

$$Pr(\overline{C2} \cap \overline{C4}) = Q2.Q3.Q4.Q5 \quad (3.15)$$

$$Pr(\overline{C3} \cap \overline{C4}) = Q1.Q2.Q3.Q4.Q5 \quad (3.16)$$

$$Pr(\overline{C1} \cap \overline{C2} \cap \overline{C3}) = Q1.Q2.Q3.Q4.Q5 \quad (3.17)$$

$$Pr(\overline{C1} \cap \overline{C2} \cap \overline{C4}) = Q1.Q2.Q3.Q4.Q5 \quad (3.18)$$

$$Pr(\overline{C1} \cap \overline{C3} \cap \overline{C4}) = Q1.Q2.Q3.Q4.Q5 \quad (3.19)$$

$$Pr(\overline{C2} \cap \overline{C3} \cap \overline{C4}) = Q1.Q2.Q3.Q4.Q5 \quad (3.20)$$

$$Pr(\overline{C1} \cap \overline{C2} \cap \overline{C3} \cap \overline{C4}) = Q1.Q2.Q3.Q4.Q5 \quad (3.21)$$

Therefore, the probability of system failure can be expressed as follows:

$$\begin{aligned} Pf = {} & Q1.Q2 + Q3.Q4 + Q1.Q4.Q5 + Q2.Q3.Q5 \\ & - [Q1.Q2.Q3.Q4 + Q1.Q2.Q4.Q5 + Q1.Q2.Q3.Q5 \\ & + Q2.Q3.Q4.Q5 + Q1.Q2.Q3.Q4.Q5] \\ & + Q1.Q2.Q3.Q4.Q5 + Q1.Q2.Q3.Q4.Q5 \\ & + Q1.Q2.Q3.Q4.Q5 + Q1.Q2.Q3.Q4.Q5 \\ & - Q1.Q2.Q3.Q4.Q5 \end{aligned} \quad (3.22)$$

If Q1 = Q2 = Q3 = Q4 = Q5 = Q (i.e. all components are identical), then the probability of system failure is given by the following expression:

$$Pf = 2Q^2 + 2Q^3 - 5Q^4 + 2Q^5 \quad (3.23)$$

In order to show that the equation obtained for unreliability is exact, the unreliability of the bridge network will be calculated by Baye's theorem.

3.4 *Baye's Theorem*[5]

Baye's theorem states that if A is an event which depends on one of the two mutually exclusive events Bi and Bj of which one must necessarily occur, then the probability of occurrence of A is given by the following equation:

P(A) = P(A,given Bi).P(Bi) + P(A,given Bj).P(Bj) (3.24)

Applying Baye's theorem to the bridge circuit shown in Figure 3.2, the probability of system failure can be written as:

Pf = P(System failure if component 3 is good).R3

+

P(System failure if component 3 is bad).Q3

The system can be decomposed as shown in Figure 3.3

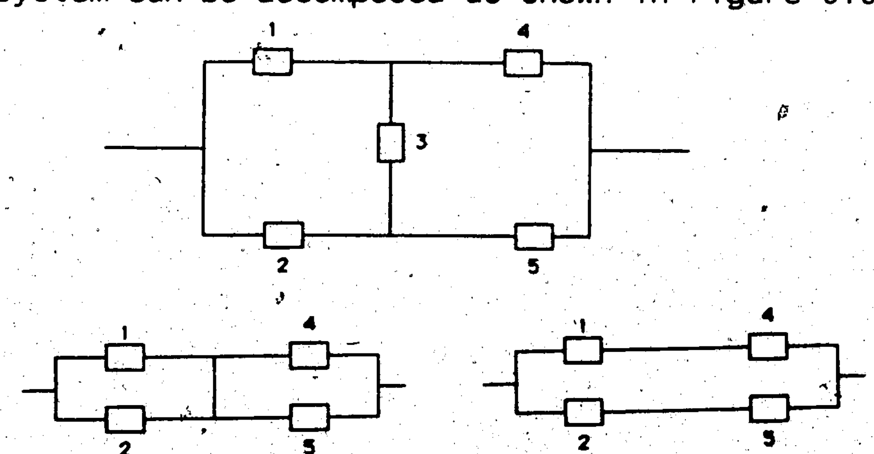


Figure 3.3: Decomposed bridge network

P(System failure if 3 is good) = Q1.Q2 + Q4.Q5

- Q1.Q2.Q4.Q5 (3.25)

P(System failure if 3 is bad) = 1.-(R1.R4 +R2.R5

- R1.R2.R4.R5)(3.26)

Therefore, the probability of system failure is:

$$
\begin{aligned}
Pf &= (Q1.Q2 + Q4.Q5 - Q1.Q2.Q4.Q5).R3 \\
&\quad +[1. - (R1.R4 + R2.R5 - R1.R2.R4.R5)].Q3 \\
&= (Q1.Q2 + Q4.Q5 - Q1.Q2.Q4.Q5)(1.-Q3) \\
&\quad + Q3 - (1-Q1).(1-Q4).Q3 - (1-Q2).(1-Q5).Q3 \\
&\quad +(1-Q1).(1-Q2).(1-Q4).(1-Q5).Q3 \qquad (3.27)
\end{aligned}
$$

Assuming all components are identical, the probability of system failure is given by the following expression:

$$Pf = 2Q^{2} + 2Q^{3} - 5Q^{4} + 2Q^{5} \qquad (3.28)$$

Equation (3.28) agrees with the results obtained by the cut set method (i.e., equation 3.23)

Hence, if <u>all</u> the minimal cuts of a system are taken into consideration, the exact values of the reliability can be obtained, but in practice [3, 6, 12] the contributions by the terms beyond the third order are assumed to be negligible and the computations are usually truncated at this point.

It may be noted that the expansion formula 3.5 does not apply when components are dependent. The assumption of independence can, however, yield close results for the dependent case if component reliabilities are sufficiently high which is the case usually for the power system components.

3.5 *Frequency of System Failure*[17]

In order to understand the derivation of the failure frequency equation the relationship between the minimal cut sets and the system state space diagram should be understood. Consider a minimal cut set Ci which has components l and m as its members. By the very definition of minimal cut set, if components l and m fail, the system will fail irrespective of the states of the other components of the system. The failure of the members of Ci is equivalent to the system being in the subset Si of the state space S,

where:

Si = [Components l and m are failed and the other components exist in a particular state i.e., either up or down]

Let Siv be called the vertex state of the subset Si in which l and m are failed and all of the other components are functioning.

The system can transit from the vertex state either upwards i.e., less components in the failed state by repair of the failed components l and/or m or it can transit downwards i.e., more components in the failed state by the successive failures of more components. Subset Si is constituted by the states generated by the downward transitions from Siv. The system could transit out of Si by the repair of l or m and therefore the frequency of encountering subset Si is:

$$F_i = \sum_{S_j \in S_i} P(S_j) \sum_{k \in C_i} \mu_K$$

$$= P(\bar{C}_i) . \bar{\mu}_i \qquad (3.29)$$

where:

$$\bar{\mu}_i = \sum_{k \in C_i} \mu_K$$

The relationship between the cut set and its equivalent state space subset can be more clearly understood with reference to Figure 3.4 where the cut C1 of Figure 3.2 and the equivalent subset S1 are shown.

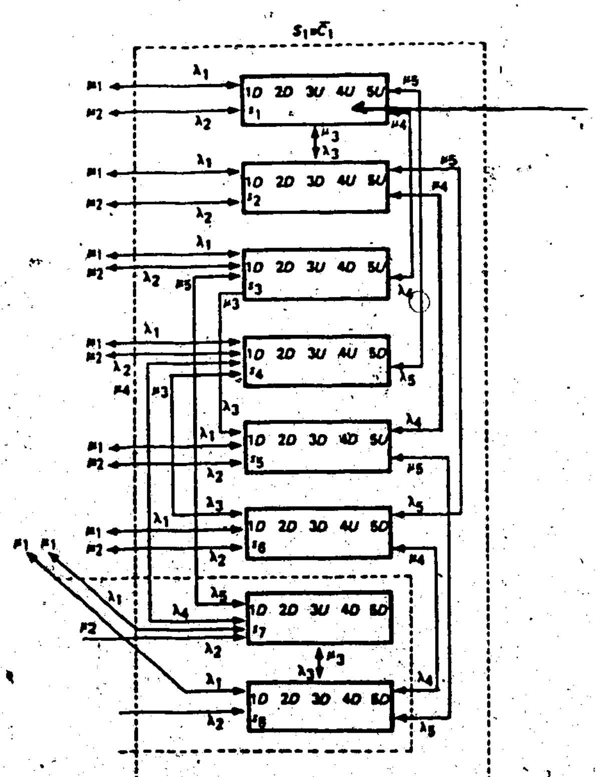


Figure 3.4: Equivalence between cut sets and state space

With reference to Figure 3.4:

the members of C1 = 1, 2

S1 = [s1,s2,s3,s4,s5,s6,s7,s8]

The states which are elements of S1 are generated by successive failures of components 3, 4, and 5 from the vertex state s1. From any state which belongs to S1, the system could transit out of S1 by repair of component 1 or 2 which are members of C1.

The frequency of encountering S1 is:

$$F1 = (\mu_1+\mu_2)[\sum_{i=1}^{8} P(Si)]$$

$$= (\mu_1+\mu_2)P(\overline{C1})$$

$$= (\mu_1+\mu_2).(Q1.Q2) \qquad (3.31)$$

Now consider another minimal cut set Ck and the equivalent subset Sk of state space S. If Si and Sk are mutually exclusive events, then there will not be any transitions between states Si and Sk. In such a case the frequency contribution due to Si and Sk is Fi+Fk [15]. In practice, however, the state space subsets minimal cut sets overlap and the frequency equation for system failures for this case can be derived by referring to the Venn diagram in Figure 3.5.

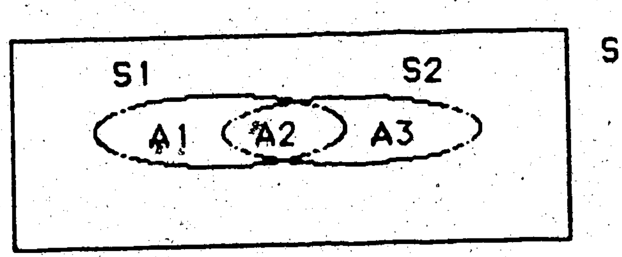


Figure 3.5: Venn diagram

Define: event Si = A1 U A2

event S2 = A3 U A2

Then,

$$F(Si \cup Sk) = F(Si) + F(Sk) - F(Si \cap Sk)$$
$$= Pr(\overline{Ci})\overline{\mu}_i + Pr(\overline{Ck})\overline{\mu}_k$$
$$- Pr(\overline{Ci} \cap \overline{Ck})\overline{\mu}_{i+k} \qquad (3.32)$$

where:

$\overline{\mu}_{i+k}$ = Sum of the repair rates of components which belong to cut sets Ci and Ck

In general for m cuts, the frequency of system failures is given by:

$$Ff = F[S1 \cup S2 \cup S3 \cup \ldots \cup Sm]$$
$$= [Pr(\overline{C1})\overline{\mu}_1 + Pr(\overline{C2})\overline{\mu}_2 + \ldots + Pr(\overline{Cm})\overline{\mu}_m]$$
$$-[Pr(\overline{C1} \cap \overline{C2})\overline{\mu}_{1+2} + Pr(\overline{C1} \cap \overline{C3})\overline{\mu}_{1+3} +$$
$$\ldots Pr(\overline{Ci} \cap \overline{Cj})\overline{\mu}_{i+j}] +$$
$$\ldots$$
$$(-1)^{m-1} Pr(\overline{C1} \cap \overline{C2} \cap \overline{C3} \ldots \cap \overline{Cm})\overline{\mu}_{1+2+3+\ldots m} \qquad (3.33)$$

The probabilities of the frequency of encountering higher order contingencies become increasingly smaller. The application of frequency equation (3.33) can be demonstrated on the bridge circuit shown in Figure 3.2. For convenience the various minimal cuts with its members are reproduced as follows:

C1 = 1, 2   C3 = 1, 3, 5

C2 = 4, 5   C4 = 2, 3, 4

The frequency of bridge circuit failure (i.e., Ff) is given by:

$$
\begin{aligned}
Ff = & [P(\overline{C1})\overline{\mu}_1 + P(\overline{C2})\overline{\mu}_2 + P(C3)\overline{\mu}_3 + P(C4)\overline{\mu}_4] \\
& -[P(\overline{C1} \cap \overline{C2})(\overline{\mu}_{1+2}) + P(\overline{C1} \cap \overline{C3})(\overline{\mu}_{1+3}) \\
& + P(\overline{C1} \cap \overline{C4})(\overline{\mu}_{1+4}) + P(\overline{C2} \cap \overline{C3})(\overline{\mu}_{2+3}) \\
& + P(\overline{C3} \cap \overline{C4})(\overline{\mu}_{3+4}) + P(\overline{C2} \cap \overline{C4})(\overline{\mu}_{2+4})] \\
& +[P(\overline{C1} \cap \overline{C2} \cap \overline{C3})(\overline{\mu}_{1+2+3}) \\
& + P(\overline{C2} \cap \overline{C3} \cap \overline{C4})(\overline{\mu}_{2+3+4}) \\
& + P(\overline{C1} \cap \overline{C3} \cap \overline{C4})(\overline{\mu}_{1+3+4})] \\
& - [P(\overline{C1} \cap \overline{C2} \cap \overline{C3} \cap \overline{C4})(\overline{\mu}_{1+2+3+4})]
\end{aligned}
\quad (3.34)
$$

If each component is assumed identical with a failure rate λ (i.e., failures per year) and a repair rate μ (i.e., repairs per year) then the probability of the failure of that component is given by the following equation:

$$Q = \frac{\lambda}{\lambda + \mu} \quad (3.35)$$

Since cut sets C1 and C2 of the bridge network configuration have two components each, then

$$P(\overline{C1}) = P(\overline{C2}) = Q^2 \quad (3.36)$$

$$P(\overline{C3}) = P(\overline{C4}) = Q^3 \quad (3.37)$$

$$
\begin{aligned}
P(\overline{C1} \cap \overline{C2}) &= P(\overline{C1} \cap \overline{C3}) = P(\overline{C1} \cap \overline{C4}) \\
&= P(\overline{C2} \cap \overline{C3}) = P(\overline{C2} \cap \overline{C4}) \\
&= Q^4
\end{aligned}
\quad (3.38)
$$

$$P(\overline{C3} \cap \overline{C4}) = Q^5 \quad (3.39)$$

Similarly,

$$P(\overline{C1} \cap \overline{C2} \cap \overline{C3}) = P(\overline{C1} \cap \overline{C2} \cap \overline{C4})$$
$$= P(\overline{C2} \cap \overline{C3} \cap \overline{C4})$$
$$P(\overline{C1} \cap \overline{C2} \cap \overline{C3}) = P(\overline{C1} \cap \overline{C3} \cap \overline{C4})$$
$$= Q^5 \qquad (3.40)$$

Also,

$$\bar{\mu}_1 = \bar{\mu}_2 = 2\mu \,; \quad \bar{\mu}_3 = \bar{\mu}_4 = 3\mu$$
$$\bar{\mu}_{1+2} = \bar{\mu}_{1+3} = \bar{\mu}_{1+4} = 4\mu$$

$$\bar{\mu}_{1+2+3} = \bar{\mu}_{1+2+4} = \bar{\mu}_{2+3+4} = \bar{\mu}_{1+3+4} = 5\mu \qquad (3.41)$$

$$\bar{\mu}_{1+2+3+4} = 5\mu \qquad (3.42)$$

Substituting the values from equations (3.36) to (3.42) into equation (3.34), the frequency of system failure is given by the following equation:

$$Ff = (4\,Q^2 + 6\,Q^3 - 20\,Q^4 + 10\,Q^5)\,\mu \qquad (3.43)$$

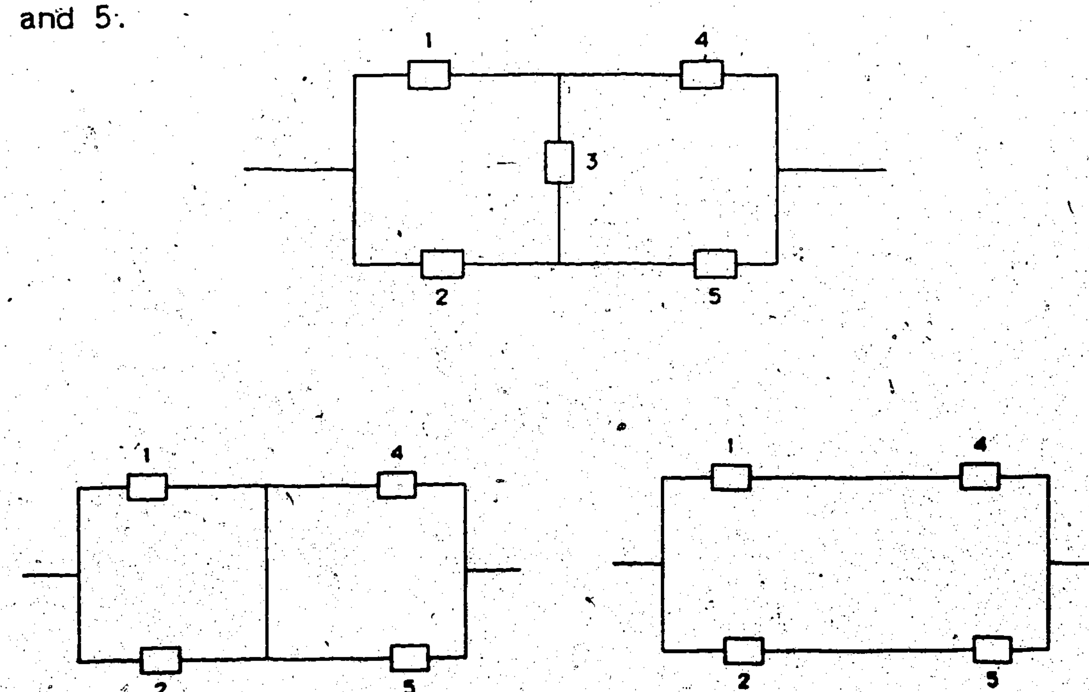
The frequency of system failure by the decomposition method i.e., Baye's theorem, can also be calculated [16]. If x is the selected key component, and P(x) and Q(x) are the probabilities of its being in up and down state respectively, then the frequency of the system failure i.e., Ff is given by:

$$
\begin{aligned}
Ff = \; & F(\text{System failure} / x \text{ is good})P(x) \\
& + F(\text{System failure}/x \text{ is bad})Q(x) \\
& + P(\text{System failure}/x \text{ is bad}) \\
& - P(\text{System failure}/x \text{ is good})P(x) \qquad (3.44)
\end{aligned}
$$

where:

= The failure rate of X

Referring to Figure 3.6, the selected key component is #3. When component 3 is good, the components 1 and 2 form a parallel block which is in series with the parallel block of components 4 and 5. Similarly, when component 3 is assumed to have failed, then the component 1 and 4 are in series and form a parallel block with the series block of components 2 and 5.



a) Component 3 is good   b) Component 3 is bad

Figure 3.6: Decomposed bridge network

The following equations are based on the assumption that all the components in the bridge network are identical.

Given component 3 is good:

$$P12d = \text{Probability of 1 and 2 down} = Q * Q \qquad (3.45)$$

$$P12u = \text{Probability of 1 and 2 up} = 1 - Q^2 \qquad (3.46)$$

$$\text{Frequency of failure of 1 and 2} = P12d\ (\mu_1 + \mu_2)$$

$$= Q^2 (2\mu) \qquad (3.47)$$

The block containing components 5 and 4 is similar to that of 1 and 2, hence the frequency of failure of components 5 and 4 failing simultaneously (i.e., F54) is given by the following equation:

$$F54 = F12 = 2\mu Q^2 \qquad (3.48)$$

Since the blocks are assumed to be connected in series in order to evaluate system reliability,

$$P(\text{System failure / 3 is good}) = P1245d$$

$$= 1 - P12u \, . \, P34u$$

$$= 1 - (1 - Q^2).(1 - Q^2)$$

$$= 2Q^2 - Q^4 \qquad (3.49)$$

$$F(\text{System failure / 3 is good}) = P1234u(\lambda_{12} + \lambda_{45})$$

The equivalent failure rate of block containing 1 and 2 is:

$$\lambda_{12} = F12 / P12u$$

$$= 2\mu Q^2 / (1 - Q^2) \quad (3.50)$$

Similarly;

$$\lambda_{45} = 2\mu Q^2 / (1 - Q^2) \quad (3.51)$$

The equivalent repair rate (i.e., μ_{12}) is:

$$\mu_{12} = F12 / P12d$$

$$= 2\mu \quad (3.52)$$

Also;

$$\mu_{45} = 2\mu \quad (3.53)$$

$$F(\text{System failure} / 3 \text{ is good}) = P1234u(\lambda_{12} + \lambda_{45})$$

$$= 4\mu Q^2 (1 - Q^2) \quad (3.54)$$

Given 3 is bad:

$$P14u = P1u * P4u$$

$$= (1 - Q)^2 \quad (3.55)$$

$$P14d = 1 - P14u$$

$$= 2Q - Q^2 \quad (3.56)$$

$$F14 = P14u(\lambda_1 + \lambda_4)$$

$$= (1 - Q)^2 . 2\lambda$$

$$\mu_{14} = F14 / P14d$$

$$= 2\lambda(1 - Q)^2 / (2Q - Q^2) \quad (3.57)$$

$$P(\text{System failure} / 3 \text{ is bad}) = P1425d$$
$$= P14d \,.\, P25d$$
$$= (2Q - Q^2)^2 \qquad (3.58)$$

$$F(\text{System failure} / 3 \text{ is bad}) = P1425d(\mu_{14}+\mu_{25})$$

$$F(\text{System failure} / 3 \text{ is bad}) = 4\mu Q(1-Q)(2Q-Q^2) \qquad (3.59)$$

Now, the frequency of system failure is:

$$Ff = F(\text{System failure}/3 \text{ good})P(3 \text{ good})$$
$$+$$
$$F(\text{System failure}/3 \text{ bad})P(3 \text{ bad})$$
$$+$$
$$P(\text{System failure}/3 \text{ bad})$$
$$-$$
$$P(\text{System failure}/3 \text{ good}) * P(3 \text{ good}) . \lambda_3$$

$$Ff = 4 \;\; Q(1-Q^2)(1- Q)+4 \;\; Q^2 (2Q-Q^2)(1-Q)$$
$$+[(2Q-Q^2)^2 -2Q^2 +Q^4]\mu Q$$
$$= (4Q^2 +6Q^3 - 20 Q^4 + 10 Q^5)\mu \qquad (3.60)$$

This equation is the same as obtained by the cut set method.

3.6 *Second Method of finding Frequency of System Failure*

Another method [17] also uses cut sets in finding the failure frequency of a system. It is claimed in the referenced paper [17] that the results obtained using this technique are in agreement with those obtained by Markov system model.

As per the referenced paper, if K is the cut set and k is an element (i.e., component) of the cut set, then the frequency of system failure is given by the following equation:

$$F_{system} = \sum_{k \in K} f_k \, . \, Pr[f = f_k] \qquad (3.61)$$

where:

$$Pr[f = f_k] = Pr[M_k \cup N_k] - Pr[N_k] \qquad (3.62)$$

$Pr[M_k \cup N_k]$ = Non availability of cut set K when component k is omitted

and, $Pr[N_k]$ = Non availability of cut sets not containing component k

The non availabilities of the cut sets can be calculated from equation 3.5.

Let us apply this procedure to the cut sets of the bridge network. The cut sets are again listed here for convenience as follows:

C1 = 1, 2

C2 = 4, 5

C3 = 1, 3, 5

C4 = 2, 3, 4

The components contained in the cut sets are 1, 2, 3, 4 and 5. By setting k equal to 1 in equation (3.61), the non availability of cut sets when component 1 is omitted and the non availability of cut sets not containing component 1 can be evaluated as follows:

P_{f1} = Non availability of cuts when component 1 is omitted

$$P_{f1} = (Q + Q^2 + Q^2 + Q^3) - (Q^3 + Q^3 + Q^3 + Q^3 + Q^4 + Q^4)$$
$$+ (Q^4 + Q^4 + Q^4 + Q^4) - Q^4 \qquad (3.63)$$

P_{f1n} = Non availability of cuts not containing component 1

$$= Q^2 + Q^3 - Q^4 \qquad (3.64)$$

$$Pr(f = f_1) = P_{f1} - P_{f1n}$$

$$= Q + Q^2 - 4Q^3 + 2Q^4 \qquad (3.65)$$

Similarly;

$$Pr(f = f_2) = Q + Q^2 - 4Q^3 + 2Q^4 \qquad (3.66)$$

$$Pr(f = f_3) = Q + Q^2 - 4Q^3 + 2Q^4 \qquad (3.67)$$

$$Pr(f = f_4) = Q + Q^2 - 4Q^3 + 2Q^4 \qquad (3.68)$$

$$Pr(f = f_5) = Q + Q^2 - 4Q^3 + 2Q^4 \qquad (3.69)$$

And,

$$f_K = f_1 = f_2 = f_3 = f_4 = \frac{\lambda}{\lambda + \mu} \cdot \mu \qquad (3.70)$$
$$= Q \cdot \mu$$

Therefore, the frequency of system failure is:

$$f_{system} = \sum_{k=1}^{5} f_K \, Pr(f = f_K) \qquad (3.71)$$

$$f_{system} = f_1 \, Pr(f = f_1) + f_2 \, Pr(f = f_2)$$
$$+ f_3 \, Pr(f = f_3) + f_4 \, Pr(f = f_4)$$
$$+ f_5 \, Pr(f = f_5)$$
$$= (4 Q^2 + 6 Q^3 - 20 Q^4 + 11 Q^5) . \mu \qquad (3.72)$$

The numerical values for the failure frequency can be evaluated by the two methods and compared. Let the repair rate be equal to 438 repairs per year (i.e., the mean down time of a component is equal to 20 hours) and the failure rate varied from 2 failures per year to 219 failures per year. These results are shown in Table 3.4

Table 3.4: Frequency of system failures for the bridge circuit

Failures/yr	Frequency of Failure		Percentage
	Method 1	Method 2	Error
2.0	.03644142301	.036441423	4.665 E-08
4.0	.145375288	.145375315	1.794 E-05
8.0	.577963221	.577964034	1.406 E-04
16.0	2.277773988	2.277797800	1.045 E-03
32.0	8.769140832	8.769781650	7.307 E-03
219.0	201.876543200	203.679012300	0.89285713

As can be seen from Table 3.4 the percentage error in the calculation of frequency of failure by the two methods is negligibly small but when the second method was applied to the substation configuration shown in Figure 2.9, it failed to yield accurate results.

The error in the second method can be explained as follows. The system shown in Figure 2.9 has 8 first order cuts only i.e., 1, 2, 3, 4, 5, 6, 7 and 8. The non availability of cut sets when component k is omitted equals the non availability of cut sets not containing component k and hence the net frequency turns out to be zero, which is incorrect. Hence, the second method is not suitable for systems containing first order cuts only.

3.7 *Conclusion*

This chapter has introduced the various concepts relating to the cut set modelling technique. The algorithm for generation of cut sets has been explained. The equations for system availability and system failure frequency have been described.

It has been shown that if all the cut sets of the system are considered the results obtained are exact. This has been shown by application of the technique to the bridge circuit configuration. The equivalence between the minimal cut set and the state space has also been shown in this Chapter.

Another published method of finding the system failure frequency has been illustrated and compared with the first method. The limitations of the second method have been shown and discussed.

CHAPTER 4

SUBSTATION RELIABILITY EVALUATION

4.1 *Introduction*

The electrical components in a power system can fail in various modes. The component outage may or may not cause load point interruptions depending upon the configuration of the substation. The impact of various modes of component failures on the load point reliability indices of a given configuration are presented in this chapter. Also, the algorithms for the calculation of load point reliability indices for a general substation configuration are presented and applied to several substation configurations.

4.2 *Load-Point Failure Modes*

All electrical component faults which result in the removal of other operating components from service are classified as active failures. All component outages which do not remove any other operating components from service are classified as passive failures. If a component is being maintained, then the component is classified as being on maintenance outage. Each of the failure modes of individual electrical components may or may not cause load point interruptions depending upon the configuration of the substation. If the single failure of an electrical component does not cause a load point interruption but the failures of more than one component cause a load point interruption then, the failure mode is called an <u>overlapping failure</u>.

The above modes of component failures can be demonstrated with a simple substation configuration [18] as shown in Figure 4.1 below:

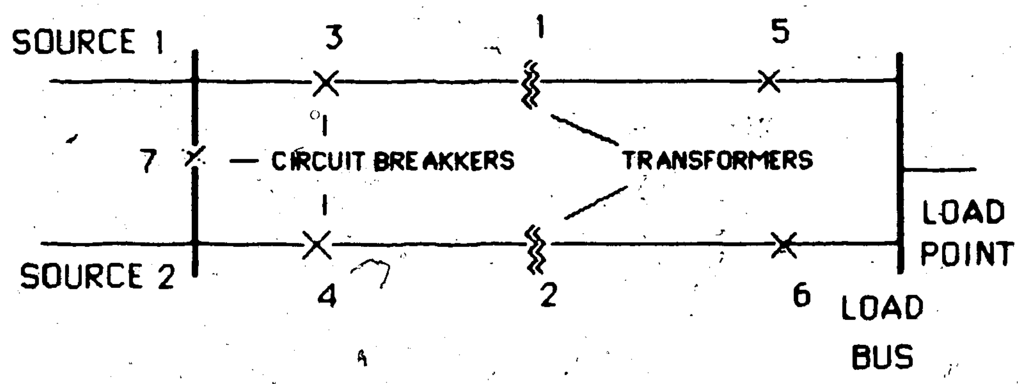


Figure 4.1: Simple Substation Configuration

The above substation configuration shows two electrical sources feeding the load point bus via:

i) source 1, transformer 1, circuit breakers 3 and 5.

ii) source 1, transformer 2, circuit breakers 7, 4 and 6

iii) source 2, transformer 2, circuit breakers 4 and 6.

iv) source 2, transformer 1, circuit breakers 7, 3 and 5

The following initial assumptions are made:

1. The load bus and the sources are assumed 100% reliable.
2. Each transformer has the capacity to meet the load requirements.
3. The circuit breaker ratings are not exceeded for all system normal operating conditions.

The following discussion will be directed at describing the various modes of failure which lead to load point interruptions in the simple substation configuration shown in Figure 4.1. Based on initial assumptions previously listed, the passive failures of none of the components will cause a load point interruption. The maintenance outages for all components except the load bus will not cause a load point interruption. However, passive failures of transformer 1 or breaker 3 or breaker 5 overlapping the passive failures of transformer 2 or breaker 4 or breaker 6 can cause a load point interruption. Such combinations of failure events are called overlapping passive failures.

If transformer 1 or breaker 3 or breaker 5 is out of service due to a scheduled maintenance outage and if transformer 2 or breaker 4 or breaker 6 fails passively during the maintenance period, then it will cause a load point interruption. Such failures are called passive failures overlapping maintenance activities. If an outage in the system occurs, then scheduled maintenance activities on components which can cause a load point interruption are assumed to be deferred. For example, if line 1 or breaker 3 or breaker 5, has failed then the maintenance on line 2 or breaker 4 or breaker 6 will not be started.

When the active failure of breaker 5 occurs, its failure trips breaker 3 and 6 (assuming an ideal protection coordination scheme) and isolates the sources and the load point resulting in a load point interruption. Similarly, the active failures of breakers 6 or 7 also cause a load point interruption.

Considering the case of an active failure of breaker 3 when breaker 5 is stuck i.e., breaker 5 fails to operate when required to do so. In order to clear the active failure of breaker 3, breakers 5 and 7 and the breaker at the far end of source 1 have to operate. Since breaker 5 is stuck it is assumed that breaker 6 will operate in order to stop feeding the fault via the second source and resulting in a load point interruption. Also, if breaker 7 is stuck and breaker 3 is actively failed, then breakers at the far end of sources 1 and 2 will operate to clear the fault resulting in a load point interruption.

Similarly, the active failure of breaker 4 when breaker 6 or 7 is stuck causes a load point interruption. Also, the active failure of transformer 1 when breaker 5 is stuck and active failure of transformer 2 when breaker 6 is stuck result in a load point interruption.

If the two sources can fail in common mode for example, if the two sources are dual transmission lines approaching the substation on a common tower then the mechanical failure of the tower can cause both the circuits to fail, then such outages are called common mode outages.

All combinations of components failing in various modes of failure and leading to load point interruption of simple substation configuration shown in figure 4.1 are tabulated in Table 4.1.

Table 4.1: Load point interruption table

1. Passive failure of transformer 1 or breaker 3 or breaker 5 overlapping the passive failure of transformer 2 or breaker 4 or breaker 6 and vice versa.
2. Passive failure of transformer 1 or breaker 3 or breaker 5 overlapping the maintenance outage of transformer 2 or breaker 4 or breaker 6 and vice versa.
3. Active failures of breaker 5 or 6 or 7.
4. Active failure of breaker 3 when breaker 5 or 7 is stuck.
5. Active failure of breaker 4 when breaker 6 or 7 is stuck.
6. Active failure of transformer 1 when breaker 5 is stuck.
7. Active failure of transformer 2 when breaker 6 is stuck.
8. Common mode outage of sources 1 and 2.

Often substation configurations have normally open branches which are used to reconfigure the substation during outage periods. When an outage occurs, the fault first is identified, then the faulty components are isolated by switching operations and if it is possible to establish the continuity of service between the load point and the source by closing the normally open branches, then these branches are closed (i.e., the durations of certain outages of components can be reduced by closing the normally open branches).

The following outage events which significantly affect the substation reliability levels are considered in this thesis:

1. Passive failures and overlapping passive failures of substation components.
2. Maintenance outages and maintenance outages overlapping passive failures.
3. Passive failures and overlapping passive failures which can be eliminated by closing normally open (N/O) branches.
4. Passive failures overlapping maintenance outages which can be eliminated by closing normally open branches.
5. Active failures and active failures overlapping passive failures.
6. Active failures overlapping maintenance outages
7. Active failures with stuck breaker condition
8. Active failure with stuck breaker condition overlapping maintenance.
9. Common cause outages.
10. Common cause outages overlapping maintenance outages.

4.3 *Limitations of present literature*

Considerable literature has been published which describes many techniques for the reliability evaluation of substations. Reference [19] requires construction of logic diagrams [8, page 32] from the physical diagram of the system. Often the construction of the logic diagram for a complex substation configuration may not be possible. In the logic diagram approach, only the passive failures of components are considered. Reference [4] makes use of Markov modelling and is limited to simple substation configurations where the passive and maintenance outage modes of failure are only considered. The reference [17] takes into account various failure modes but not common mode failures. Also, the impact of active failures is evaluated only for the circuit breakers in reference [17]. The active failures of other components may also have a significant impact and hence can not be ignored. The computer program described in reference [20] does not appear to be applicable when :

1. Normally open breakers or switches are present in the system.
2. All circuit breaker faults are not ground faults.
3. The protective system is not perfectly reliable.

The program described in reference [18] takes into account all the realistic failure modes of components but does not include the common cause outages which may have a significant impact [10, 21, 22, 23] on the reliability of a substation. All the above limitations have been considered in the reliability evaluation of substation configurations presented in this thesis. The algorithm for evaluation of substation reliability and the equations for calculation of reliability indices are presented in Appendices B and G, respectively.

The reliability indices of ten basic substation configurations reported in reference [26] have been analysed by this algorithm. The configurations and the results of analysis are presented in Appendix C. The analysis of two of these designs i.e., design 10 and 4 (from the perspective of the referenced paper) have been presented in detail later in this chapter. The design 4 represents the conventional "Main Bus and Transfer Bus" arrangement and the design 10 the "Breaker and Half" scheme.

4.4 *Case Study 4.1: Simple substation configuration*

The reliability indices for the system shown in Figure 2.9 of Chapter 2 are calculated by the cut set technique. It may be recalled that in Chapter 2 the system indices for the same system were calculated by Markov modelling and only two modes of failure i.e., the component passive and overlapping passive failures and component passive failures overlapping maintenance outages were considered. The results are tabulated in Table 4.3. The first column in Table 4.3 refers to the event numbers. The correspondence between the event numbers and their definitions are shown in Table 4.2. It can be clearly seen from the results obtained in case study 2.4 and in Table 4.3 that the results obtained by the cut set technique are in agreement with those obtained by Markov modelling.

Table 4.2: Correspondence between event numbers and their definitions

Event Number	Definition
1	Passive failures and overlapping passive failures
2	Maintenance outages overlapping passive failures of components
3	Passive failures and overlapping passive failures which can be avoided by closing N/O branches
4	Maintenance outages overlapping passive failures which can be avoided by closing N/O branches
5	Active failures and active failures overlapping passive outages
6	Active failures overlapping maintenance outages
7	Active failures with stuck breaker condition overlapping passive failures
8	Active failures with stuck breaker condition overlapping maintenance outages
9	Common mode outages and common mode outages overlapping passive failures.
10	Common mode outages overlapping maintenance outages.

Table 4.3: Load point indices of reliability for system shown in Figure 2.9 by cut set method.

***** SINGLE TRANSFORMER SCHEME *****

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.3246999	6.3759146	2.0702581
2	1.0000000	12.5999985	12.5999985
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0
8	0.0	0.0	0.0
9	0.0	0.0	0.0
10	0.0	0.0	0.0
TOTAL	1.3246994	11.0744038	14.6702557

LOAD POINT AVAILABILITY = 0.99832779169

4.5 Case study 4.2: Breaker and half scheme[26]

The arrangement of components in this scheme is shown in Figure 4.2

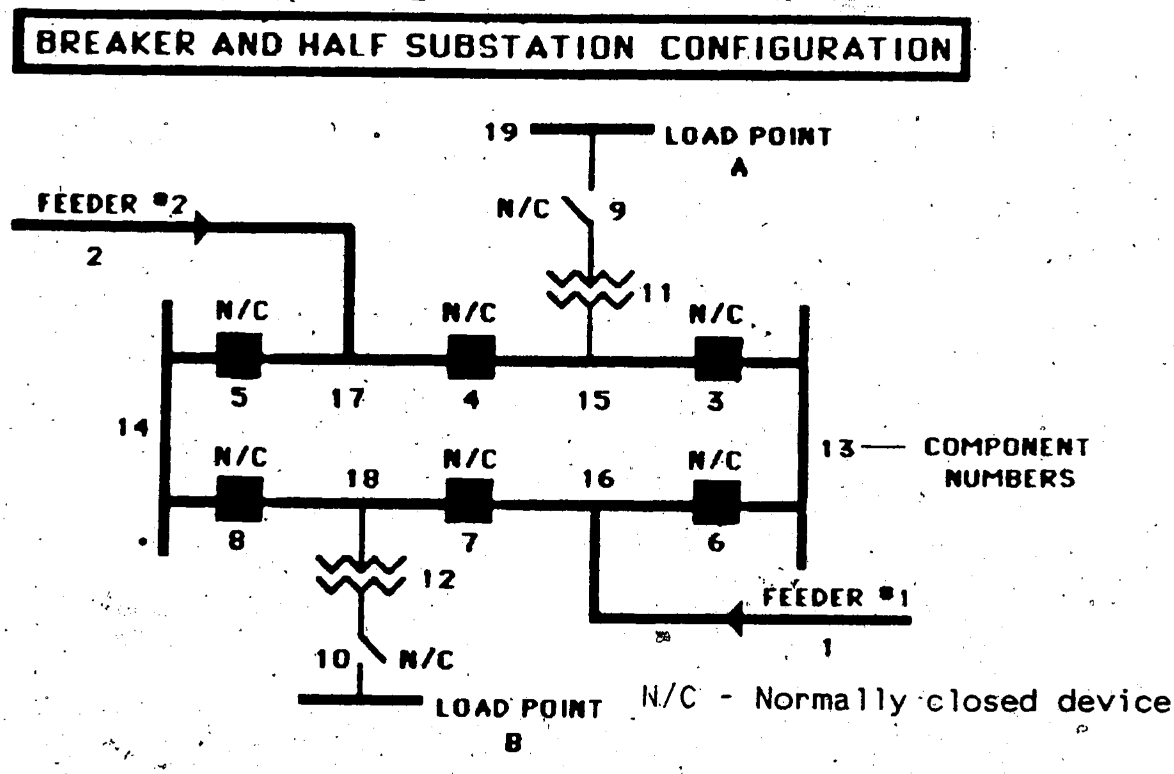


Figure 4.2: Breaker and half scheme

Lines 1 and 2 are the input sources for the substation scheme and has 6 circuit breakers labeled as 3, 4, 5, 6, 7 and 8 as shown in Figure 4.2. Elements 13 and 14 are the substation buses. Elements 11 and 12 are the transformers. The secondary ends of each of these transformers feed loads A and B, respectively. Elements 9 and 10 are the disconnect switches. Elements 15, 16, 17, 18 are termination nodes which have been labelled for the formulation method of determining the paths between the sources nodes and the various load points.

The criteria of successful system operation is the continuity of service between any of the sources and any of the load points. It is assumed that each transformer and all components in the system have capacity to meet the system load requirements. The load point reliability indices are defined as the continuity of service to either load point A or B or both.

The input data for this case study and its explanation are given in Appendix D. The various paths between the sources and the load point being considered are shown and discussed in Appendix D.

The load point reliability results obtained for the breaker and half substation configuration are presented in Table 4.4.

Table 4.4: Load point reliability indices of breaker and half scheme

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0073596	156.5519714	1.1521568
2	0.0019933	14.2033005	0.0283109
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0014196	1.9941425	0.0028310
6	0.0004935	1.9996061	0.0009868
7	0.0001329	2.7119865	0.0003605
8	0.0000144	0.2950544	0.0000043
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.5734133	7.4564791	4.2756433

LOAD POINT AVAILABILITY=0.99951225519

4.5.1 *Discussion of results of case study 4.2*

Table 4.4 lists the contributions to the load point indices of reliability due to the various failure events. The correspondence between the event numbers and their definitions are shown in Table 4.2.

It can be clearly seen from Table 4.4 that the contribution to the load point reliability indices by common mode outages i.e., event 9 is the highest because all other listed events have contributions either by second order cut sets or by the third order cut sets. The next highest contributions are from event 1 and then from event 2 which reflect the passive failures and the maintenance outages overlapping passive failures. The components contributing to these events are those feeding the two loads and the two sources. In other words, any failures of components 9 and 11 overlapping with components 10 and 12 causes a load point interruption. Also, the simultaneous outages of the two transmission lines cause a load point interruption. The next highest interruptions are due to events 5 and 6 i.e., the impact of active failures and the active failures overlapping the maintenance outages. The next highest contributions to the load point reliability indices are by events 7 and 8 (i.e., the effects of active failures with stuck breakers and the maintenance outages overlapping the active failures with stuck breakers).

The contributions by events 3 and 4 are zero because there are no normally open components present in the system.

4.6 Case Study 4.3: Main bus and transfer bus configuration [26]

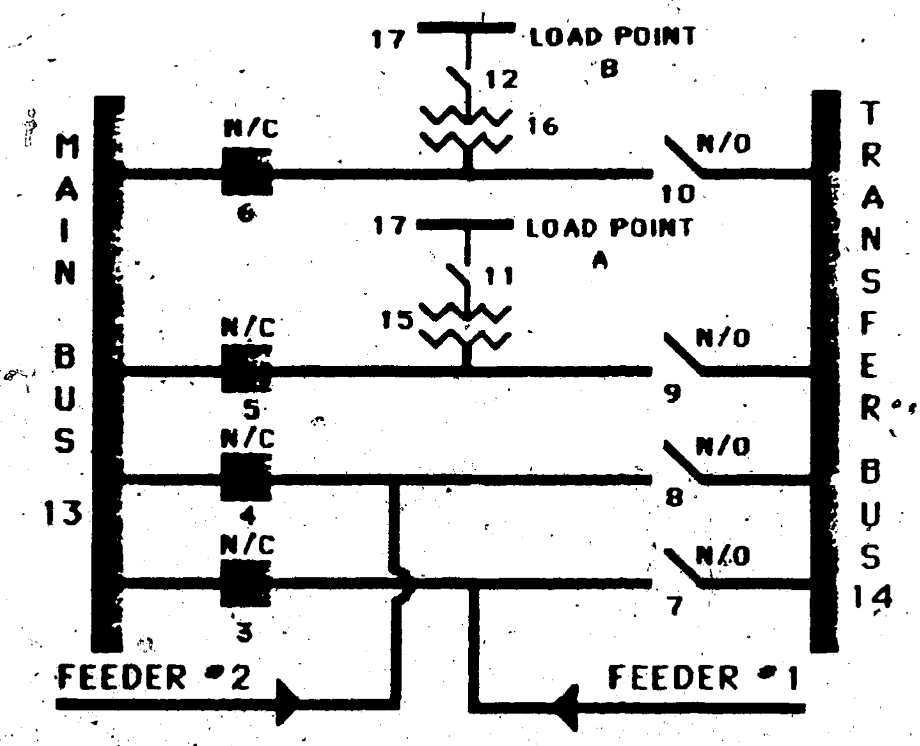


Figure 4.3: Main bus and transfer bus configuration

Figure 4.3 shows the main bus and transfer bus substation configuration. The elements 1 and 2 are the two electrical sources. They energize the main bus 13 through the circuit breakers 3 and 4, respectively. The main bus feeds the two transformers 15 and 16 through the S & C interrupters 5 and 6, respectively. The transformers in turn feed the load A and B, respectively. In Reference [26] elements 7, 8, 9 and 10 have been shown as normally open switches. If any of the two loads has to be switched to the transfer bus because of outages on the substation main bus (e.g. node 13), then the transfer bus can be energized by closing either or both switches 7 and 8 and then by closing switches 9 or 10, the load A or B can be switched to the transfer bus. But it can be argued that in that case any faults on the load feeders will be seen by the far end breakers of transmission lines 1 and 2, which is a poor operating practice. Hence, in order that all feeder faults be cleared within the substation, either the disconnect switches 7 and 8 should be replaced by breakers or the disconnect switches 9 and 10 should be replaced by breakers. In this study N/O switches 7 and 8 have been replaced by N/O breakers.

As in the previous case study, it has been assumed that the criteria of successful system operation is the continuity of service between any of the sources to at least one of the load points.

The various tie sets between the sources and the load point being considered and the respective cut sets for different events are presented in the Appendix E. The load point reliability indices for this substation configuration are shown in Table 4.5

Table 4.5: Load point indices of reliability for main bus and transfer bus configuration

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0073532	156.6836853	1.1521225
2	0.0019910	14.2140570	0.0282997
3	0.0293319	3.0000000	0.0879955
4	0.0029248	3.0000000	0.0087743
5	0.1199999	1.9999990	0.2399998
6	0.0	0.0	0.0
7	0.0030000	1.4333315	0.0043000
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7266006	6.3480349	4.6124859

LOAD POINT AVAILABILITY=0.99947386980

4.6.1 *Discussion of results of case study 4.3*

As can be seen from Table 4.5, the contribution to the load point reliability indices is the highest for the common mode failures. The contribution to the failure rate by the active failures (i.e., event 5) is considerably higher in this case than the previous case study because the active failures of breakers 3, 4, 5 and 6 individually cause a load point interruption to occur since each component failure causes a main bus fault. However, these failure events can be terminated by closing normally open components (deferring repair activities) and the contributions to the down time per year is comparatively small since in general the duration of switching activities is usually less than the duration of repair activities.

The effect of including the normally open branches in the configuration model is discussed below. The average duration of the K type cuts,i.e., events which can be terminated by repair is about 156.68 hours and that of H type cuts i.e., events which can be terminated by switching is 3.0 hours, hence the contribution to the total outage time per year is smaller for H type cuts than the K type cuts.

CHAPTER 5

RELIABILITY ANALYSIS OF AN ACTUAL SUBSTATION CONFIGURATION

5.1 *Introduction*

Reliability analysis of British Columbia Hydro and Power Authority's George Dickie substation has been performed in this Chapter. The cut-set technique and the Markov modelling technique have been used for the analysis. The single line diagram of the substation configuration is shown in Figure 5.1.

5.2 *Description of elements*

The description of the elements contained in the George Dickie substation is presented in Table 5.1.

Table 5.1: Description of elements of George Dickie substation

Description	Substation elements
Sources	1,2
Load Point	52
H V Buses	19,20,21
L V Buses	22,23,24,38,39,40,41
Disconnecting Switches	3,4,5,6,7,8,11,12,17,18 25,26,27,28,30,31,32,33, 36,37,42,43,46,50,51,53, 58 to 94,102,116,130, 137,141,156

Table 5.1 (continued): Description of elements of George Dickie substation

Description	Substation elements
Circuit Breakers	9,10,15,16,29,47,54, 123 to 129,131 to 136
Voltage Regulators	49,95 to 101,103 to 108
Reactors	48,55,109 to 115, 117 to 122
Cables	34,35,44,45
Lightning Arrestors	145,146
H.V. Potential Transformers	149,150
L.V. Potential Transformers	154,155
Station Transformers	140,144
Earthing Switches	147,148,151,152,153
Transfer Bays	4F56 and 4F65
Feeder Bays	4F51 to 4F55 and 4F57 to 4F64

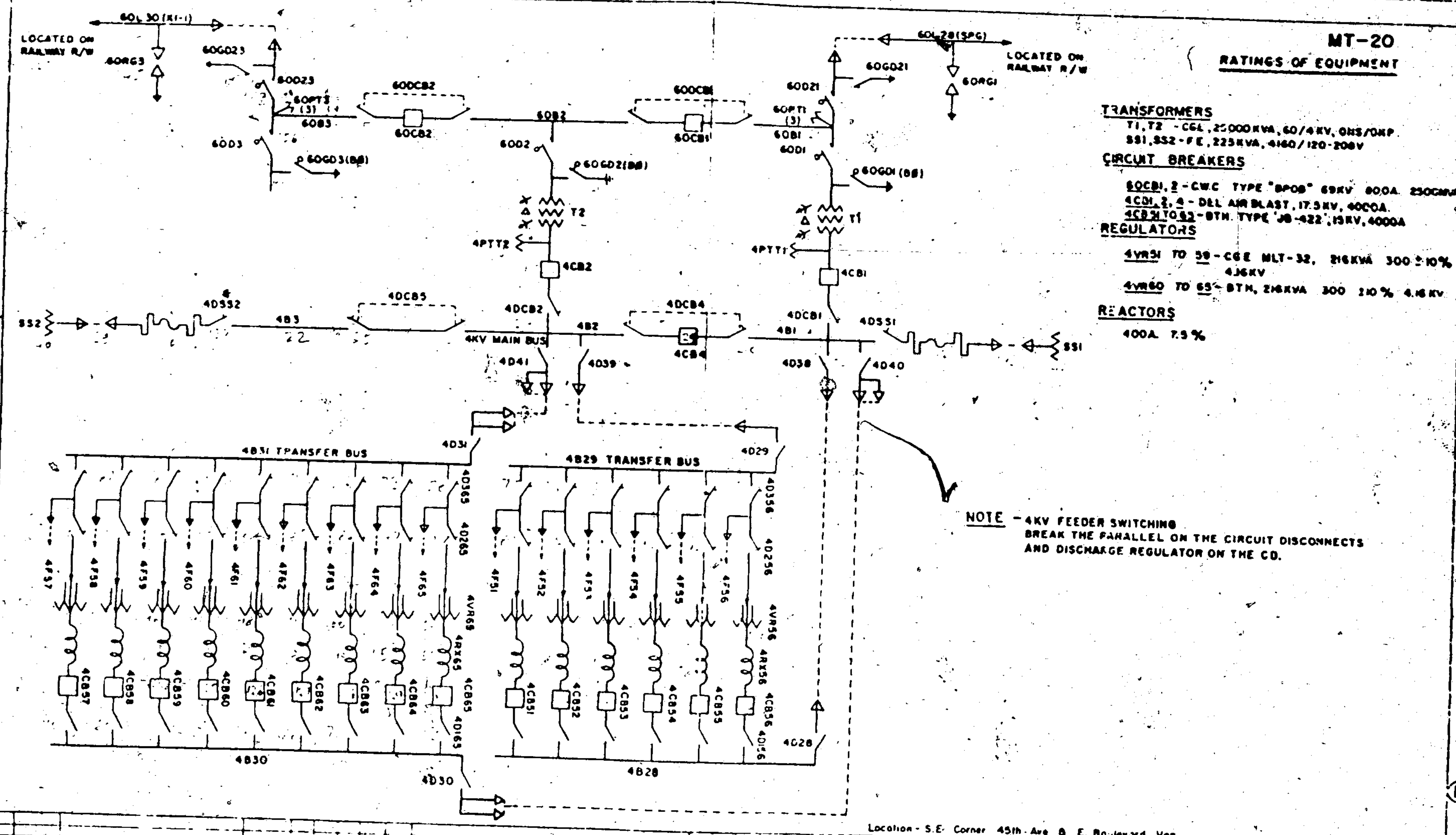


Figure 5.1: B.C. Hydro and Power Authority's George Dickie Substation

5.3 *Criteria of Successful System Operation*

The criteria of successful substation operation is defined as the continuity of service between either or both sources 1 and 2 and the load point 52 which was selected to illustrate the reliability methodology proposed in this thesis.

5.4 *Operating Procedure*

With reference to Figure 5.1, and considering load point 52, the following discussion describes the operating procedures for the substation configuration. The disconnecting switches 30, 31, 36, 37, 51, 67 to 73 and 75 to 79 are normally open. The transfer bus 38 and 39 are kept charged by closing the disconnecting switches 53, 58 and circuit breaker 54 and disconnecting switches 66 and 80 and circuit breaker 136, respectively. In the event of active failures of components 46 and 47, breakers 16 and 29 operate to isolate the fault. However, for active failures of components 48, 49, 50 and 52, the fault is cleared by the breaker 47. It is assumed that the normally open components are fully reliable. In the event of an outage of components in the feeder bay 4F57 or any other component in the normally closed tie set, the faulty component is identified and isolated for repair. It is then ascertained whether continuity of service between the load point and any of the sources can be established by closing the normally open components or not. If so, the normally open components are closed and the supply resumed. It may be noted that in the event of failure of the main bus and the components in the feeder and transfer bays, the supply to the feeder e.g., 4F57 can be restored by closing the normally open disconnecting switches 30, 36 and 51 and hence transferring the protection to the main bus breakers 15 and 29 instead of the breaker 47. In practice, the feeder loads may be transferred to the adjacent feeders (e.g., the feeder 4F57 can be fed by feeder bay of 4F58 by closing disconnecting switches 67 and 51, provided the components in the feeder bay 4F58 have enough capacity margin). This activity is similar to transferring the feeder load to the transfer bay. In this study the bays for feeders 4F65 and 4F56 have been considered as transfer feeder bays and the activity of transferring the load to adjacent feeders has been restricted in this study.

5.5 *System analysis*

The input data for the George Dickie substation configuration is presented in Appendix F. The paths or tie sets between the sources and the load point by considering the normally open components open are formulated and the corresponding cut sets are deduced. These tie sets and the cut sets are presented in Appendix F. Similarly, the tie sets and the cut sets by closing the normally open components are also deduced. Next, the K type and H type cuts which represent the events which can be terminated by repair and switching respectively are calculated. All the above tie sets and the cut sets are presented in the Appendix F.

The contributions to the reliability indices i.e. failure rate, mean duration of repair and the annual interruption time for the designated load point are calculated for the passive failures, overlapping passive failures and passive failures overlapping maintenance by the appropriate equations presented in Appendix G. The impact of each component failure in an active mode, active failures overlapping passive failures and active failures overlapping maintenance are also calculated by the appropriate equations. Next, the impact of active failures with stuck breakers present in the system is analysed and finally the impact of common mode failures is studied. The load point reliability indices of the George Dickie substation configuration are presented in Table 5.2

Table 5.2: Load point reliability indices of George Dickie substation configuration

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	OUTAGE TIME HOURS/YR
1	0.0194475	60.5544739	1.1776333
2	0.0075107	5.4066353	0.0406073
3	0.7600482	3.0000000	2.2801418
4	1.2500000	3.0000000	3.7500000
5	0.2668599	1.9455576	0.5191913
6	0.0035169	2.0538054	0.0072230
7	0.0990719	2.3328838	0.2311233
8	0.0000358	2.1325779	0.0000765
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	2.9684868	3.7382651	11.0969896

LOAD POINT AVAILABILITY = 0.99873435497

5.6 *Discussion of results*

The weakest link between the sources of supply and the load point is that formed by elements 24, 33, 45, 42, 40, 46, 47, 48, 49 and 50. The failure of any of these components cause a load point interruption and hence they constitute first order cuts. But these events can be terminated by switching i.e., by closing normally open disconnecting switches 30, 36 and 51. Hence, the first order cuts detected by the program are the H type cuts i.e., the events which can be terminated by reconfiguration. Since these are the first order events, their contribution to the load point failure rate is the highest. The overlapping passive failures with maintenance outages which can be terminated by switching i.e., event 4 has the next highest contribution to the load point failure rate. This is followed by event 3 (i.e., the passive failures and overlapping passive failures which can be terminated by switching). The next highest contribution to the load point reliability indices is due to common mode failures.

The contribution to the reliability indices to the load point by active failures can be clearly seen from the results for event 5. The contribution to the reliability indices to the load point by active failures overlapping passive failures is considerably higher than event 1 i.e., the passive failures and the overlapping passive failures because there are numerous components which are not on the direct path between the sources and the load point (e.g., adjacent feeders) and their failure in active mode cause interruptions to the load point being considered.

5.7 *Impact of Reserve Supply*

Often a reserve supply (e.g., generator, UPS, etc.) is available or there are adjacent distribution links (i.e., another substation) present which can have a significant impact on the reliability levels of the load point. This aspect can be studied by a Markov model [4] shown in Figure 5.2.

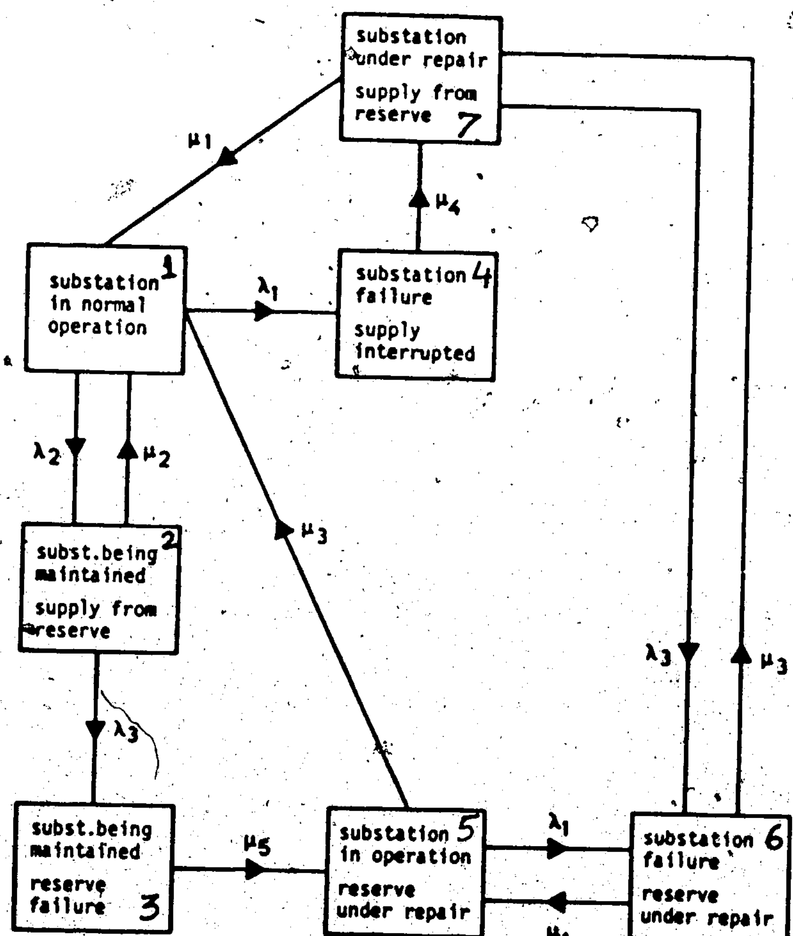


Figure 5.2: Markov model for reserve supply considerations

Under normal operating conditions, the electrical supply to the load is fed by the substation. In case of a substation failure the supply is fed by the reserve system. After the repair process has been completed the substation configuration is returned to its normal operating configuration. When the substation is undergoing maintenance, the load is again fed by the reserve system.

The definitions of symbols used for the Markov model presented in Figure 5.2 are listed in Table 5.3.

Table 5.3: Definitions of symbols used in Markov model

Symbol	Description
λ_1	Failure rate of substation based on random events
λ_2	Maintenance outage rate of substation
λ_3	Failure rate of reserve supply
μ_1	Restoration rate of substation based on random events
μ_2	Maintenance restoration rate
$\mu_3 = 1/\lambda_3$	Restoration rate of reserve supply
$\mu_4 = 1/\lambda_4$	Switching rate of system reserve
$\mu_5 = 1/\lambda_5$	Rate of time lapse required to return substation to service

Referring to Table 4.2, it can be clearly seen that all odd numbered events are random events and the even numbered events are maintenance oriented and hence represent scheduled activities. λ_1 and μ_1 are random events and are defined in Table 5.3. λ_2 and μ_2 are based on maintenance events. Referring to Table 5.2, the substation random event failure rate and its mean duration (i.e., λ_1 and r1) and the substation maintenance failure rate and its mean duration (i.e., λ_2 and r2) can be calculated as follows :

$$\lambda_1 = \lambda \text{ event } 1 + \lambda \text{ event } 3 + \lambda \text{ event } 5 + \lambda \text{ event } 7 + \lambda \text{ event } 9 \quad (5.1)$$

$$r_1 = (\lambda \text{ event } 1 \times r \text{ event } 1 + \ldots + \lambda \text{ event } 9 \times r \text{ event } 9)/\lambda_1 \quad (5.2)$$

Similarly,

$$\lambda_2 = \lambda \text{ event } 2 + \lambda \text{ event } 4 + \lambda \text{ event } 6 + \lambda \text{ event } 8 + \lambda \text{ event } 10 \quad (5.3)$$

$$r_2 = (\lambda \text{ event } 2 \times r \text{ event } 2 + \ldots + \lambda \text{ event } 10 \times r \text{ event } 10)/\lambda_2 \quad (5.4)$$

The system reserve reliability data was selected from reference [4] and is listed in Table 5.4 below:

Table 5.4: Data for system reserve

Symbol	Value
λ_3	1.0 failure/year
r3	4.0 hours
r4	15 minutes
r5	1 hour

If P1, P2, P3, P4, P5, P6 and P7 are the probabilities of occupying the states 1, 2, 3, 4, 5, 6 and 7, respectively in the Markov model shown in Figure 5.2, then the following equations can be generated by frequency balance approach:

$$P1(\lambda_1+\lambda_2) = P2\,\mu_2 + P7\,\mu_1 + P5\,\mu_3 \quad (5.5)$$

$$P2(\mu_2+\lambda_3) = P1\,\lambda_2 \quad (5.6)$$

$$P3\,\mu_5 = P2\,\lambda_3 \quad (5.7)$$

$$P4\,\mu_4 = P1\,\lambda_1 \quad (5.8)$$

$$P5(\lambda_1+\mu_3) = P3\,\mu_5 + P6\,\mu_1 \quad (5.9)$$

$$P6(\mu_1+\mu_3) = P5\,\lambda_1 + P7\,\lambda_3 \quad (5.10)$$

and,

$$P1(1+P2/P1+P3/P1+P4/P1+P5/P1+P6/P1+P7/P1) = 1.0 \quad (5.11)$$

The evaluation of the above set of simultaneous equations leads to the indices of reliability shown in Table 5.5.

Table 5.5: Load point indices of reliability by considering reserve supply

LOAD POINT FAILURE RATE = 1.7082615 f/yr.

LOAD POINT MEAN DOWN TIME = 0.2478783 hours

LOAD POINT DOWN TIME PER YEAR = 0.4234409 hours/yr.

LOAD POINT AVAILABILITY = 0.9999517

The impact of consideration of system reserve on the load point indices of reliability can be clearly seen from Table 5.5. All three indices i.e., load point failure rate, mean duration of an outage and the annual outage time are significantly lowered.

CHAPTER 6

CONCLUSIONS

The methodology for reliability analysis of power system substations has been developed in this thesis. The various concepts regarding state space and cut set modelling has been introduced.

It was pointed out that the results obtained by Markov modelling are accurate provided the underlying assumptions of the failure processes associated with a given substation configuration are not violated. But this approach becomes unmanageable as the number of components in a given system increase. The complexity of the problem increases significantly if the components can occupy various failure states.

The cut set technique is quite useful in analysing complex and as well as simple systems. It identifies the weak points in the system in terms of the order and the number of cut sets. The results obtained by cut set modelling are exact if all the cut sets of the system are taken into consideration. The larger the system configuration in terms of number of components, the larger is the order of cut sets and it becomes computationally inefficient to analyse the cut sets beyond third order. In practice, the contributions to the indices of reliability by higher order cut sets than third order may be negligible [3, 6, 12]. Thus, complex systems can be analysed accurately by considering all the cut sets up to third order.

The impact of various modes of component outages on load point interruptions has been studied. The modes of component outages considered in this thesis are listed as follows:

1. passive failures and overlapping passive failures;
2. passive failures overlapping maintenance;
3. passive failures and overlapping passive failures which can be terminated by switching;
4. passive failures overlapping maintenance which can be terminated by switching;
5. active failures and active failures overlapping passive failures;
6. active failures overlapping maintenance outages;
7. active failures with stuck breakers and active failures with stuck breakers and active failures with stuck breakers overlapping passive failures;
8. active failures with stuck breakers overlapping maintenance;
9. common mode outages and common mode outages overlapping passive failures;
10. common mode outages overlapping maintenance outage;

Each mode of above failure events has a distinct impact on the frequency and duration of load point interruptions.

The contribution and their net effect on the reliability indices of each of these events was studied in detail for ten basic substation configurations being used by the electric utilities. The single line diagrams and a discussion of the results of the ten published substation configurations is shown in Appendix C.

Each mode of component failures has a distinct impact on the reliability levels of a load point. Based on the need and the quality of service desired, the effects of failure modes of components can be studied for different substation configurations. The most suitable configuration can then be selected by selecting the best load point reliability level configuration from these.

The computer program described in the thesis is very general in nature. It is suitable for predicting the load point reliability indices of any general substation configuration. Many other relevant failure modes and their effects can also be easily added to the program. The effects of varying the system configuration on the load point indices have been illustrated. This form of analysis provides a quantitative basis for the judicious selection of a reliable and economical substation design.

CHAPTER 7

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APPENDIX A

Definition of Terms and Reliability Indices

The following definitions have been used in the thesis [18, 27, 28, 29]:

Component: A component is a piece of equipment, a line, a section of line or a group of items which is viewed as an entity for the purpose of reporting, analyzing and predicting outages.

System: A system is a group of components which are interconnected to form a fixed system configuration to perform a specified function.

Reliability: Reliability is the probability of a system or a component performing its intended function (i.e., purpose) adequately for the period of time intended under the operating conditions encountered [5].

Power System Substation: An assembly of switchgear components used to direct the flow of electrical energy in a power system, and to ensure the security of the system by providing a point at which automatic protective devices, and means for diverting the flow of energy along alternative routes can be installed.

A substation may be associated with a generating station, directly controlling the flow of power into the power system, or with power transformers converting the voltage of supply to a higher or lower level, or it may connect a number of supply routes at the same voltage level. Basically, any substation consists of a number of incoming and outgoing circuits connected to a common bus bar system, the main components of each circuit being a circuit breaker, instrument transformers and one or more disconnecting switches.

Circuit Breaker: A circuit breaker is defined in IEC Publication 50, Section 15 as "a device capable of making, carrying and breaking normal load currents, and also making and breaking (under predetermined conditions) abnormal currents such as short circuit currents", a description making clear its two fold function. The first use is in switching circuits in and out to control the flow of energy, and disconnecting circuits, or part of power system, to allow maintenance work or extensions to be effected. In performing its second duty, a circuit breaker is part of a scheme of protection that automatically disconnects any part of the system on which a fault occurs.

Outage Terms

Outage: An outage describes the state of a component when it is not available to perform its intended function due to some event directly associated with that or any other component.

Failure: A failure describes the state of a component when it is not available to perform its intended function due to the malfunction of that component. A component failure results in a component outage but a component outage can occur without a component failure.

Switching Time: Switching time is the period from the time a switching operation is required due to an outage until that switching operation is performed. For example, switching operations include successfully reclosing a circuit breaker after a trip out, opening or closing a sectionalizing switch or circuit breaker, or replacing a fuse link.

Exposure Time: Exposure time is the time during which a component is performing its intended function and there is a probability that this component may fail during this time period.

Outage Rate: The outage rate for a particular classification of outage and type of component is the mean number of outages per unit exposure time per component. For example, a 10 Km. section of line averaging one outage every 10 years has an annual outage rate of .01 failures/Km/year.

Outage Duration: Outage duration is the period from the initiation of an outage until the affected component is repaired or replaced and becomes available to perform its intended function.

Interruption: An interruption is the loss of service to one or more customers (load points) and is the result of one or more component outages or component outages overlapping maintenance activity.

Interruption Duration: Interruption duration is the period from the initiation of an interruption to a customer until service has been restored to that customer.

Measures of Reliability or Reliability Indices

Many different measures of service reliability are possible and useful. Measures of reliability usually relate to the frequency or duration of interruptions or both. Useful measures of reliability should have two properties:

1. be calculable from the operating history of the system;

2. be calculable from component data using system reliability calculation techniques.

Measures of reliability which have been used in this thesis are as follows:

Outage Rate: This has been defined above.

Outage Duration: This has been defined above.

Reliability: This has been defined above.

However, it can be added that the relationship between reliability, R(t) and outage rate exists for all distributions i.e.,

$$R(t) = \exp\left[-\int_0^t \lambda(t)\,dt\right]$$

in the special case when is constant and independent of time

$$R(t) = \exp(-\lambda t)$$

Availability (A): This is the ratio of mean up time of the component to the total cycle time (i.e., m+r)

$$A = \frac{m}{m + r} = \frac{\mu}{\lambda + \mu}$$

where:

m = mean up time of the system
r = mean down time of the system
λ = failure rate of the system
μ = restoration rate of the system

Unavailability: The ratio of mean down time of the system to the cycle time is called the unavailability of the system.

Outage frequency: This is the ratio of the availability of the system to the outage duration.

Outage duration per year: This is the mean outage time of the system in one year.

All these indices are related through the following equations :

$$\bar{A} = f \cdot r$$

$$\bar{A} = 1 - A;\ \lambda = f/A$$

$$r = A \cdot T$$

where: T is the basic period of analysis (e.g., one year)

The total outage rate of the system when all outage modes are taken into account may be evaluated as follows:

$$\lambda_T = \sum_{i=1}^{n} \lambda_i$$

The total availability of the system as follows:

$$A_T = \prod_{i}^{n} A_i$$

where: λ_i and Ai being reliability indices for the outage mode involved, n is the total number of outage modes and i is the ith outage mode.

APPENDIX B

The Algorithm for Evaluation of Substation Reliability [17, 18, 23]

The algorithm described here performs the failure modes and effects analysis and computes system reliability indices. The criteria of success is the continuity between any source nodes and a load point by at least one path. It is assumed that each source and the path are capable of meeting the load requirements. In other words, the failure of any circuit between the source and the sink (load point) does not cause overloading of other circuits.

The following are the steps for the evaluation of load point reliability of a substation configuration :

1. Read the input data. It consists of a number of components in the system, the substation graph (configuration) in terms of predecessors of each component, the reliability data i.e., the passive failure rate, passive repair rate, maintenance outage rate, maintenance restoration rate, active failure rate, switching time and the stuck probability. The stuck probability of a breaker or a switch represents the probability of its being stuck i.e., not operating when required to do so. The stuck breaker probability is estimated from the ratio of the number of times the breaker fails to operate when called upon to do so to the total number of times the breaker is called upon to operate. The effects of failures of components in active mode on other components of the system are read. The unfaulted components which are isolated as a result of the fault on the component under consideration are identifeid. Similarly the combined effects of a component active failure and the stuck breaker condition present in the system are also read. All those breakers which operate during the active failure of the component under consideration are considered stuck one at a time and the effects on all other healty components are recognized.

   There are certain components in the system which are not on a direct path between the source and the sink, hence their passive failure will not cause any effect on the system outage indices but their active failures may do so. Such components are assigned zero values (i.e., zero to six significant decimal places) for the passive failure and restoration rates. The maintenance outage of such components will also not affect the load point outages. The active failure and restoration rates are assigned the actual values.

The components which can fail in common mode are also recognized and their respective failure and repair rates are specified.

2. The minimal paths between the source and the designated load point are established [25] with the normally open branches open.

3. The minimal cut sets [3] corresponding to minimal paths for N/O branches are deduced. Let us refer to these cut sets as G.

4. The minimal paths are also formed by closing the N/O branches.

5. The minimal cut sets for above paths are also deduced.

6. Some of the cut sets deduced in step 5 obtain additional elements than those deduced in step 3. Let us denote these cut sets as H. Let us denote the remaining cut sets of G as K. It can be seen that the H type cuts are those which can be eliminated by closing the normally open branches.

7. Calculate the outage rate, average duration and total outage time due to passive failures for K type cut sets by using the appropriate equations. Once the failure rate and the average outage duration of a particular event are known the non-availability of the system due to that event can be easily calculated. The event in this case is passive failures. If is the outage rate and "r" the average repair time or the average outage duration, then

$$\text{Non-availability} = \frac{\lambda r}{1+\lambda r}$$

8. Calculate the contribution to above indices for the event passive failures overlapping maintenance outage for K type cuts.

9. The substation outage frequency for H type cuts is evaluated by the formula (3.5) described in Chapter 3. The switching time S is assumed equal for all components and is the time period starting from the active failure of a component and lasting up to the time for disconnecting the faulty component from service and reconnecting all other healthy components back to service. The fault identification time is included in

the switching time.

Let the frequency of failure for these cuts be denoted as f, then the Non-availability due to this event, $\bar{A}$=fs

Having known the availability and the frequency, the failure rate contribution due to an event can be calculated as follows:

System failure rate = frequency/availability

System average down time/yr = failure rate*average repair time

10. The above indices of reliability for overlapping of passive failures and maintenance outages for H type cuts are evaluated in the same way as K type cuts as shown in step 8.

11. Consider the active failure of each component. Interrupt all those paths containing the actively failed component and the healthy components which are switched out as the effect of the faulted component. If all the paths between the source and the load point are interrupted, then the faulted component forms the first order cut. If there are some paths available between the source and the load point then deduce the cut sets out of these paths. The first order cuts thus obtained will form the second order cuts for the system when considered with the actively failed component under consideration. That is, if the actively failed component is i and there are n paths still remaining connected or unaffected between the source and the load point and if j, k, l . . etc. are the first ordered cuts deduced out of paths n, then, for the complete outage to occur between the source and the load point the following cut sets are involved:

1) i, j
2) i, k
3) i, l
4) i, . .

where: i is the actively failed component and the other components may fail in passive mode or can be on maintenance outage mode.
The probability of two active failures in the system is assumed zero.

Since all component faults are included in the passive failures i.e., it is only a particular fraction of total component failures which form the active failure, therefore, if component passive failures or overlapping passive failures can cause an interruption at the load point, then the contributions due to active failures need not be considered. Hence, from the cut sets obtained by considering active failures, those cut sets are dropped which have been evaluated in K type or H type cuts.

If the cut sets can be eliminated by switching i.e., by closing the normally open branches the repair time for that component is replaced by the switching time, otherwise, the repair time is used for the calculation of reliability indices due to this mode of failure.

12. The contributions to the load point reliability indices due to combined active failures and the stuck breaker condition are also done in the same way as in step 11. All those breakers are considered stuck one at a time along with the actively failed component which take part in clearing the fault of the component under consideration. The probability of two stuck breakers is assumed to be zero. The contributions due to this failure mode overlapping passive outages and the maintenance outages are evaluated by the appropriate equations presented in the Appendix G.

13. The overall indices of reliability are evaluated as follows:
If $\lambda_1, \lambda_2, \lambda_3 \ldots\ldots \lambda_n$ are the failure rate contributions due to each failure mode, and r1, r2, r3 . . rn, the average outage duration and $\bar{A}1$, $\bar{A}2$, $\bar{A}3$, . . , $\bar{A}n$, the non availability contributions then, the following reliability parameters can be calculated:

overall failure rate, $\lambda = \sum_{i=1}^{n} \lambda_i$ failures/year

overall outage duration, $r = \sum_{i=1}^{n} \lambda_i r_i / \lambda$ hours

overall down time/yr, $\tau = \lambda r$ hours/year

overall non-availability $= \bar{A} \simeq \sum_{i=1}^{n} \bar{A}_i$

or

overall availability, $A = 1. - \bar{A}$

APPENDIX C

C.1 Single Line Diagrams:

Figures C.1 and C.2 represent the single line diagrams of the ten published substation configurations and their load point indices of reliability are presented in Tables C.1 to C.10. The reliability data has been selected from reference [18] and is the same as used for case studies 4.1 and 4.2 in Chapter 4.

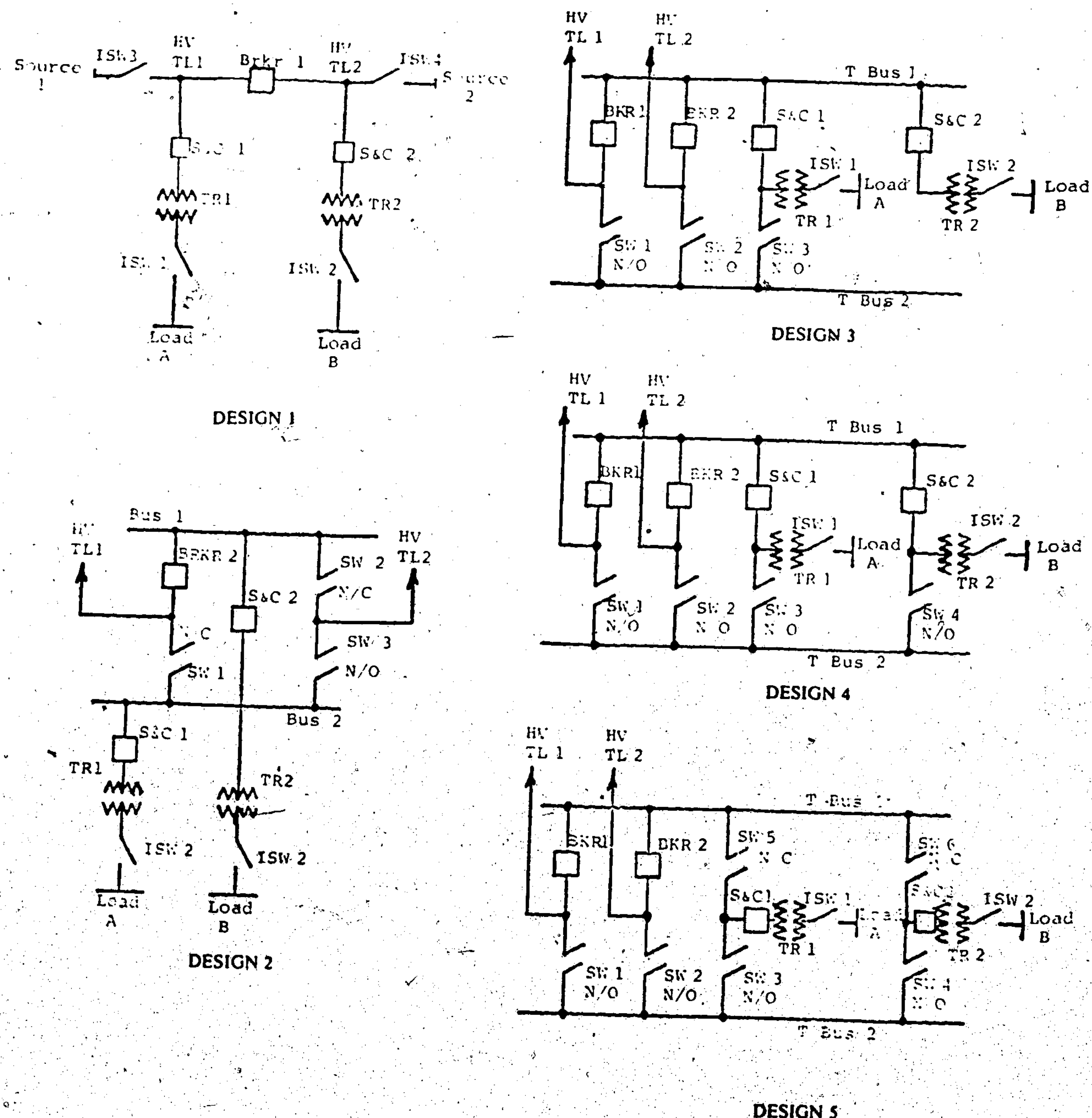

Figure C.1: Single line diagrams of designs 1 to 5

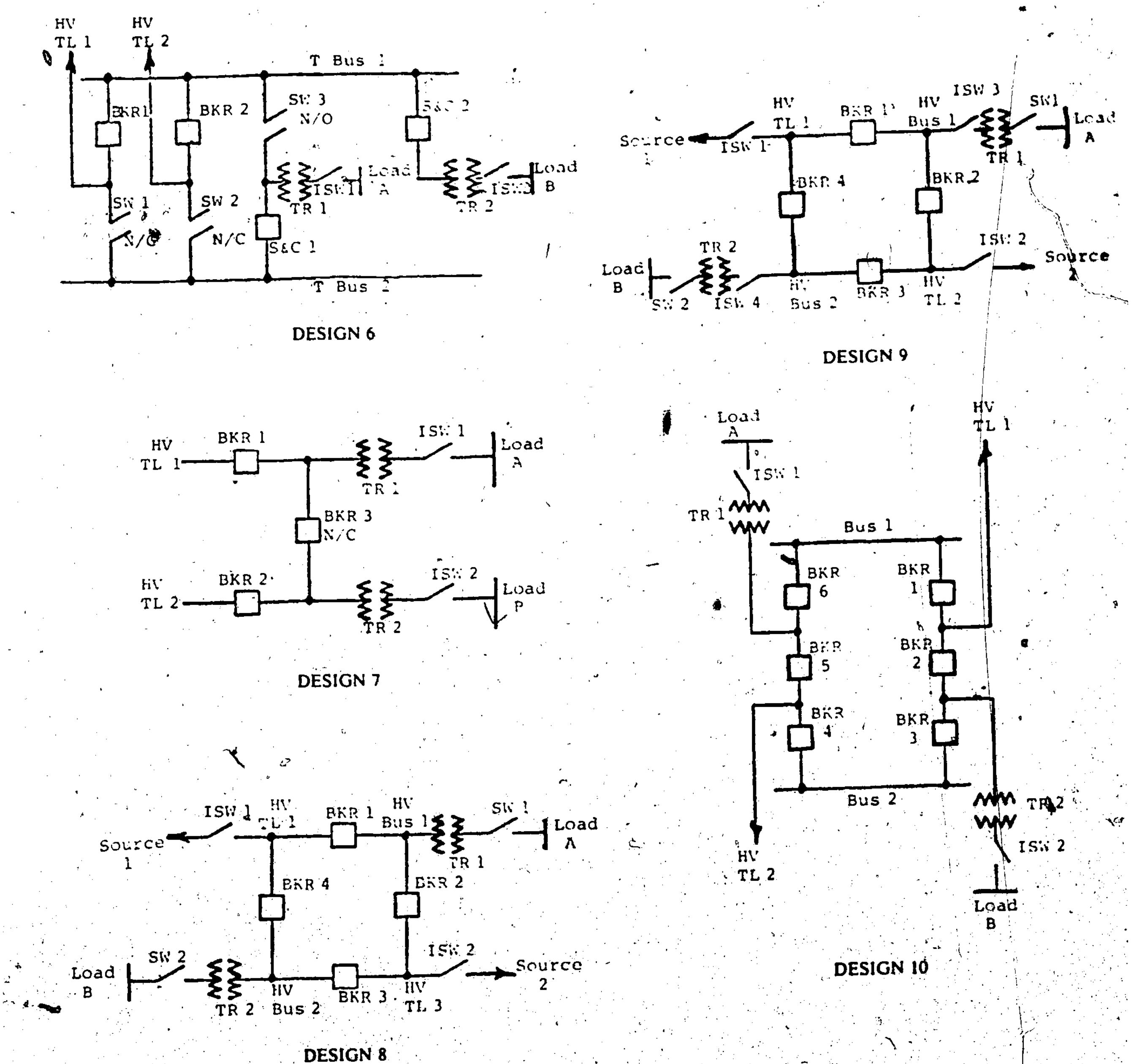

Figure C.2: Single line diagrams of designs 6 to 10

Table C.1: Load Point Reliability Indices of Design #1

************* DESIGN NO. 1 **********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS			
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0129590	93.4931335	1.2115726
2	0.0041045	11.1485033	0.0457588
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0313090	1.9736452	0.0617928
6	0.0004201	1.4103251	0.0005925
7	0.0008501	1.5882168	0.0013501
8	0.0000006	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6116432	7.2134562	4.4120607

LOAD POINT AVAILABILITY=0.99949663877

Table C.2: Load Point Reliability Indices of Design #2

************* DESIGN NO. 2 **********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS			
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0135215	89.6880951	1.2127151
2	0.0042273	10.9638662	0.0463476
3	0.0026129	3.0000000	0.0078386
4	0.0010778	3.0000000	0.0032333
5	0.0302601	2.0077639	0.0607551
6	0.0001765	2.4062052	0.0004247
7	0.0016402	1.5731382	0.00[illegible]5802
8	0.0000012	1.1043758	0.0000013
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6155173	7.1888952	4.4248886

LOAD POINT AVAILABILITY=0.99949526787

Table C.3: Load Point Reliability Indices of Design #3

************ DESIGN NO. 3 **********

LOAD POINT INDICES OF RELIABILITY

		CONTRIBUTIONS	
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0340842	36.0718079	1.2294788
2	0.0028665	12.5465918	0.0359653
3	0.0030537	3.0000000	0.0091611
4	0.0020491	3.0000000	0.0061473
5	0.1199999	1.9999990	0.2399998
6	0.0	0.0	0.0
7	0.0028500	1.4035072	0.0040000
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7269034	6.3498764	4.6157465

LOAD POINT AVAILABILITY=0.99947357178

Table C.4: Load Point Reliability Indices of Design #4

************ DESIGN NO. 4 ***********

LOAD POINT INDICES OF RELIABILITY

		CONTRIBUTIONS	
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0073532	156.6836853	1.1521225
2	0.0019910	14.2140570	0.0282997
3	0.0293319	3.0000000	0.0879956
4	0.0029248	3.0000000	0.0087743
5	0.1199999	1.9999990	0.2399998
6	0.0	0.0	0.0
7	0.0030000	1.4333315	0.0043000
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7266006	6.3480349	4.6124859

LOAD POINT AVAILABILITY=0.99947386980

Table C.5: Load Point Reliability Indices of Design #5

************* DESIGN NO. 5 **********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS			
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0129498	93.5601044	1.2115850
2	0.0040571	11.3447628	0.0460265
3	0.0292784	3.0000000	0.0878351
4	0.0025914	3.0000000	0.0077743
5	0.1599999	2.2499962	0.3599992
6	0.0	0.0	0.0
7	0.0029500	1.7118626	0.0050500
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7738265	6.2149124	4.8092632

LOAD POINT AVAILABILITY=0.99945139885

Table C.6: Load Point Reliability Indices of Design #6

************ DESIGN NO. 6 *********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS			
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0103698	113.9890289	1.1820450
2	0.0029517	12.2393322	0.0361265
3	0.0031157	3.0000000	0.0093471
4	0.0012761	3.0000000	0.0038284
5	0.3339998	1.5808372	0.5279993
6	0.0000000	0.5739490	0.0000000
7	0.0006001	1.3333797	0.0008002
8	0.0000006	0.8724269	0.0000005
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.9143137	5.3057737	4.8511410

LOAD POINT AVAILABILITY=0.99944663048

Table C.7: Load Point Reliability Indices of Design #7

*********** DESIGN NO. 7 **********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0075789	152.1700439	1.1532774
2	0.0028507	11.6987009	0.0333493
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0307924	1.9979944	0.0615229
6	0.0005548	1.5390921	0.0008539
7	0.0016626	1.5124254	0.0025146
8	0.0000000	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6054444	7.1724386	4.3425121

LOAD POINT AVAILABILITY=0.99950468540

Table C.8: Load Point Reliability Indices of Design #8

*********** DESIGN NO. 8 **********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0079762	144.5971069	1.1533337
2	0.0026018	11.2818251	0.0293533
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0014531	1.9906425	0.0028927
6	0.0005481	1.9997864	0.0010962
7	0.0012275	1.9858694	0.0024376
8	0.0000125	0.3319820	0.0000042
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.5758193	7.4330845	4.2801123

LOAD POINT AVAILABILITY=0.99951171875

Table C.9: Load Point Reliability Indices of Design #9

************* DESIGN NO. 9 **********

LOAD POINT INDICES OF RELIABILITY

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
	CONTRIBUTIONS		
1	0.0130838	88.9582825	1.1639090
2	0.0039864	8.0455503	0.0320730
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0214655	2.9310932	0.0629172
6	0.0005619	1.9997873	0.0011236
7	0.0012298	1.9860315	0.0024423
8	0.0000144	0.4192657	0.0000060
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6023416	7.2275677	4.3534641

LOAD POINT AVAILABILITY=0.99950337410

Table C.10: Load Point Reliability Indices of Design #10

************* DESIGN NO. 10 **********

LOAD POINT INDICES OF RELIABILITY

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
	CONTRIBUTIONS		
1	0.0073596	156.5519714	1.1521568
2	0.0019933	14.2033005	0.0283109
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0014196	1.9941425	0.0028310
6	0.0004935	1.9996061	0.0009868
7	0.0001329	2.7119856	0.0003605
8	0.0000144	0.2950544	0.0000043
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.5734133	7.4564791	4.2756433

LOAD POINT AVAILABILITY=0.99951225519

C.2 *Discussion of substation designs 1 and 2*

The design 1 and 2 have been designated as "1" breaker designs. The only difference between the two is the addition of a transfer bus in design 2. The load point reliability indices of the two designs are approximately the same and there is no improvement to reliability levels of the load point by addition of the transfer bus because there are 24 second order and 12 third order cuts for the first design and 23 second order and 13 third order cuts for the second design. However out of the cuts mentioned above for the second design, there are 6 H type second order cuts and 7 H type third order cuts in design 2 i.e., those events which can be terminated by switching instead of repair. But based on domains of the data, there is no improvement in load point reliability levels of design 2 than over design 1.

C.3 *Discussion of substation designs 3 to 6*

The designs 3 to 6 have been designated as "2" breaker stations in reference [26]. No circuit breaker has been provided for transferring the load to the transfer bus. Hence, if the load is transferred to the transfer bus by closing the normally open switches e.g., switches 7, 8 and 9 in design 3, then any active faults on the tie sets between the sources and the load point, the far end breakers of sources 1 and 2 operate to clear the fault and the faults within the substation are cleared by the components outside the substation, which is not a good operating procedure. Hence, for making the designs practical, either the normally open switches 7 and 8 or the normally open switch 9 be replaced by a normally open circuit breaker. The similar reasoning holds for normally open switches 7, 8, 9 and 10 for designs 4 and 5. For the studies presented in this thesis, the normally open switches 7 and 8 were treated as normally open breakers.

The overall contribution to load point reliability indices by designs 3 and 4 are approximately the same. In design 3, only the load point A can be switched to the transfer bus but in design 4, both load points A and B can be switched to the transfer bus. Consequently, the contributions to the reliability levels of load point by event 1 (i.e., those events which are terminated by repair) is significantly higher in design 3 than those in design 4 and vice versa for event 4 (i.e., those events which can be terminated by switching).

The impact of active failures on load point reliability levels in case of designs 3 and 4 is significantly higher than those in designs 1 and 2. It is because there is only one single contingency event each in design 1 and 2 which leads to a load point interruption. In design 1 this event is active failure of bus coupler breaker 9 and in design 2 it is bus side breaker 3, the active failure of which leads to load point interruption. In designs 3 and 4 there are 5 single contingency events each which lead to load point interruption. These events are the active failures of breakers 3 and 4 and S&C interrupters 5 and 6 and the main bus. Similarly since the number of events leading to load point interruption are more in designs 3 and 4 and also the number of circuit breakers taking part are more, therefore, the load point due to event 7 i.e., the impact of active failures with stuck breakers present in the system is higher than those for designs 1 and 2. Hence, it is the impact of active failures which causes the load point failure rate to be 18% higher in designs 3 and 4 than those in designs 1 and 2.

Substation designs 5 and 6 fare even worse. The design 5 relocates the position of the S&C interrupter in design 4 and an additional normally closed switch is added in the tie set and this causes the load point failure rate to rise. Also, there are 7 active failures of the components alone which cause a load point interruption resulting in a higher failure rate.

C.4 Discussion of substation designs 7 to 10

The load point reliability indices of design 7 are better than substation designs 1 to 6 because of reduced number of components and consequently, lesser events leading to load point interruption.

Substation designs 8 and 9 represent a traditional ring bus arrangement. The only difference between substation designs 8 and 9 is the inclusion of two additional bus components in design 9. Consequently, the load point indices of design 8 are slightly better than design 9. The main advantage of a ring bus system is that there is no single contingency event that can lead to load point interruption. This is particularly important if even momentary interruptions can cause problems. This is frequently the case for large petro-chemical plants and other important loads e.g., digital equipmemts. One of the disadvantages of the ring bus configuration is that from a construction stand point it is not easily expandable to more than 4 to 6 lines.

The load point reliability indices of substation design 10 i.e., breaker and a half scheme, are quite comparable to the ring bus. Its main advantage over the ring bus is that it can easily be expanded to accommodate more lines. Many generating switching stations use this design in practice.

APPENDIX D

D.1 Input data for case study 4.2 : (Breaker and half scheme)

The input data for case study 4.2 is shown and explained below in Table D.1.

Table D.1: Input data for case study 4.2

Line No.	Data
1	19 1
2	19 19
3	0
4	5 15 16 17 18 19
5	6 3 4 5 6 7 8
6	1 -1
7	2 -1
8	3 13 15
9	4 15 17
10	5 17 14
11	6 13 16
12	7 16 18
13	8 18 14
14	9 11
15	10 12
16	11 15
17	12 18
18	13 3 6
19	14 5 8
20	15 3 4
21	16 1 6 7
22	17 2 4 5
23	18 7 8
24	19 9 10
25	499 19
26	14
27	.09,7.33,1.,8.,.09,1.,.000
28	.09,7.33,1.,8.,.09,1.,.000
29	.23,11.13,.25,24.,.03,2.0,.005
30	.23,11.13,.25,24.,.03,2.0,.005
31	.23,11.13,.25,24.,.03,2.0,.005
32	.23,11.13,.25,24.,.03,2.0,.005
33	.23,11.13,.25,24.,.03,2.0,.005
34	.23,11.13,.25,24.,.03,2.0,.005
35	.22,2.09,.25,4.,.02,3.0,.000
36	.22,2.09,.25,4.,.02,3.0,.000
37	.10,1000.,.50,48.,.10,1.,.000
38	.10,1000.,.50,48.,.10,1.,.000
39	.024,2.,.0000001,.0000001,.024,2.,.000
40	.024,2.,.0000001,.0000001,.024,2.,.000

Table D.1(continued): Input data for case study 4.2

Line No.	Data					
41			3.0			
42	1	2	6	7		
43	2	2	4	5		
44	3	2	4	6		
45	4	3	2	3	5	
46	5	3	2	4	8	
47	6	3	1	3	7	
48	7	3	1	6	8	
49	8	2	5	7		
50	9	2	3	4		
51	10	2	7	8		
52	11	2	3	4		
53	12	2	7	8		
54	13	2	3	6		
55	14	2	5	8		
56	499	0	.0	0	0	0
57	1	6	2	7	3	
58	1	7	2	6	8	
59	2	4	2	5	3	
60	2	5	2	4	8	
61	3	4	3	6	2	5
62	3	6	3	4	1	7
63	4	3	3	2	5	6
64	4	5	3	2	3	8
65	5	4	3	2	8	3
66	5	8	3	2	7	4
67	6	3	3	1	7	4
68	6	7	3	1	3	8
69	7	6	3	1	8	3
70	7	8	3	1	6	5
71	8	5	3	2	7	4
72	8	7	3	1	5	6
73	9	4	3	5	3	1
74	9	3	2	4	6	
75	9	4	3	2	3	5
76	10	7	3	8	1	6
77	11	3	2	4	6	
78	11	4	3	3	5	2
79	12	7	3	8	6	1
80	12	8	2	7	5	
81	13	3	2	6	4	
82	13	6	3	1	7	3
83	14	5	3	2	4	8
84	14	8	2	7	5	
85	499					
86	1	2	.562		5.5	
87	499	0	.0		.0	

D.2 *Explanation of input data*

The input data as reported in references [18] and [9] has been used for the analysis. The first block in the input data (i.e., from line 1 to 25 in Table D.1) is the information about the connections of the configuration. The first line of the data means that there are 19 number of components in the system and there is one load point. However, there are two load points in the system but they have been labled by a common name 19 because the criteria of successful operation is the continuity between any of the sources to at least one load point. The second line specifies the output node i.e, number 19. Since the program requires any integer number for an output node to start with, hence, the number 19 has been specified twice. The third line specifies the number and then the labels of normally open components. Since there are no N/O components in this particular example and hence zero value has been specified. The fourth line of the data specifies the number and then the labels of those node points which have been labeled just for the ease of specifying the predecessors of the components. After formulation of the paths between the sources and the load points these nodes are deleted because these are assumed as 100% reliable and their inclusion in the further analysis unnecessarily adds to the computer time. However, if these are not 100% reliable then they can be retained as other components in the system. The fifth line is used for specifying any restraints on the paths. For example, if power could be routed through a limited number of components only (e.g., each path must contain a circuit breaker) then these could be specified here.

The lines 6 to 25 specify the predecessors of each component. The predecessors for the sources have been specified as -1. Some of the components have more than one predecessors. This means that power could flow from all of those components to that particular component. For example the component or node 17 can get feed from line 2, breaker 4 or breaker 5. A fictitious number 499 has been incorporated to specify the end of the predecessor matrix and the predecessor of the label 499 is the label of the load point.

The next block is the reliability data for each component. The first line of the block i.e., line 26 in this case, specifies the number of components for which the data is to be read. The next line of the block, i.e., line 27 is the data for the first component and next the second and so on. Each line in the block specifies the passive failure rate in failures per year, repair time in hours, maintenance outage rate in actions per year, maintenance restoration time in hours per activity, active failure rate in failures per year, switching time in hours and the stuck probability. The stuck probability of circuit breakers is defined quantitatively and in case of other components it is meaningless and is therefore specified a zero value. The next line i.e., number 41 specifies the switching time required to identify the fault, disconnecting the faulty components and closing the normally open components.

The next block i.e., line 42 to 56 represents the effects of actively failed components, the number and the lables of healthy components switched out as the effect of the actively failed components. For example, line 42 means that component 1 is actively failed and as a result, components 6 and 7 are switched out. As before line 56 specifies the arbitrary number 499 to indicate the end of the block.

The next block i.e., lines 57 to 85 specifies the effects of the actively actively failed components and the stuck breaker conditions. For example, line 57 means that component 1 is actively failed and the breaker number 6 is stuck and as a result 2 healthy components i.e., number 7 and 3 are switched out of service.

The next block i.e., lines 86 and 87 specify the components failed in common mode, their failure rate and the repair time.

D.3 Tie sets and Cut sets of Case Study 4.2 : Breaker and half scheme

********* BREAKER AND HALF SCHEME *********

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (8)

PATH NUMBER	ELEMENT NUMBERS												
1	1	16	7	18	12	10	19						
2	2	17	4	15	11	9	19						
3	1	16	6	13	3	15	11	9	19				
4	2	17	5	14	8	18	12	10	19				
5	2	17	4	15	3	13	6	16	7	18	12	10	19
6	1	16	7	18	8	14	5	17	4	15	11	9	19
7	2	17	5	14	8	18	7	16	6	13	3	15	11
	9	19											
8	1	16	6	13	3	15	4	17	5	14	8	18	12
	11	19											

CUTSETS AFTER DELETING 100% RELIABLE NODES

First Order Cuts = NIL
Second Order Cuts = 5. These are:

Number	Elememts		Number	Elements	
1	1	2	4	10	11
2	9	10	5	11	12
3	9	12			

Third Order Cuts = 18. These are:

Number	Elements		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12

Cut sets for tie sets with N/O components open continued:

Number	Elements in the Cut		
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

b) WITH NORMALLY OPEN COMPONENTS CLOSED
TIE SET OR SUCCESS PATHS (8)

PATH NUMBER	ELEMENT NUMBERS													
1	1	16	7	18	12	10	19							
2	2	17	4	15	11	9	19							
3	1	16	6	13	3	15	11	9	19					
4	2	17	5	14	8	18	12	10	19					
5	2	17	4	15	3	13	6	16	7	18	12	10	19
6	1	16	7	18	8	14	5	17	4	15	11	9	19
7	2	17	5	14	8	18	7	16	6	13	3	15	11
	9	19											
8	1	16	6	13	3	15	4	17	5	14	8	18	12
	10	19											

CUT SETS AFTER DELETING 100% RELIABLE NODES

First Order Cuts = NIL
Second Order Cuts = 5. These are:

Number	Elememts		Number	Elements	
1	1	2	4	10	11
2	9	10	5	11	12
3	9	12			

Third Order Cuts = 18. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

Fourth Order Cuts = 49. These are:

Number	Elememts in the Cut			
1	1	3	5	9
2	1	3	5	11
3	1	3	8	9
4	1	3	8	11
5	1	3	9	14
6	1	3	11	14
7	1	4	7	10
8	1	4	7	12
9	1	5	6	9
10	1	5	6	11
11	1	5	9	13
12	1	5	11	13
13	1	6	8	9
14	1	6	8	11
15	1	6	9	14
16	1	6	11	14
17	1	8	9	13
18	1	8	11	13
19	1	9	13	14
20	1	11	13	14
21	2	3	5	10

Fourth order cut sets for case study 4.2
(Breaker and half scheme) continued:

Number	Elements			
22	2	3	5	12
23	2	3	8	10
24	2	3	8	12
25	2	3	10	14
26	2	3	12	14
27	2	4	7	9
28	2	4	7	11
29	2	5	6	10
30	2	5	6	12
31	2	5	10	13
32	2	5	12	13
33	2	6	8	10
34	2	6	8	12
35	2	6	10	14
36	2	6	12	14
37	2	8	10	13
38	2	8	12	13
39	2	10	13	14
40	2	12	13	14
41	3	4	5	7
42	3	4	7	8
43	3	4	7	14
44	4	5	6	7
45	4	5	7	13
46	4	6	7	8
47	4	6	7	14
48	4	7	8	13
49	4	7	13	14

c) K TYPE CUTS

First Order Cuts = Nil
Second Order Cuts = 5. These are:

Number	Elements in the Cut	
1	1	2
2	9	10
3	9	12
4	10	11
5	11	12

Third Order Cuts = 18. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

d) H TYPE CUTS
First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES
ACTIVELY FAILED COMPONENT= 1

REMAINING PATHS

Path Number	Elements								
1	2	17	4	15	11	9	19		
2	2	17	5	14	8	18	12	10	19

Cuts because of above event after deleting 100% reliable nodes

First Order Cuts = Nil
Second Order Cuts = 1. This is:

Number	Elements in the Cut	
1	1	2

Third Order Cuts = 15
These are :

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	10
11	1	9	12
12	1	9	14
13	1	10	11
14	1	11	12
15	1	11	14

CUTS WHICH HAVE BEEN EVALUATED BEFORE ARE DELETED

REMAINING CUTS TO BE EVALUATED

First Order Cuts = Nil

Second Order Cuts = Nil

Third Order Cuts = 8. These are:

Number	Elements in the Cut		
1	1	4	10
2	1	4	12
3	1	5	9
4	1	5	11
5	1	8	9
6	1	8	11
7	1	9	14
8	1	11	14

The active failures of other components are treated in the same way as shown for component number 1. The cut sets obtained after considering the active failures of all the components are tabulated below in Table D.2:

Table D.2: Cut sets due to Active Failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
1	nil	nil	1 4 10
			1 4 12
			1 5 9
			1 5 11
			1 8 9
			1 8 11
			1 9 14
			1 11 14
2	nil	nil	2 3 10
			2 3 12
			2 6 10
			2 6 12
			2 7 9
			2 7 11
			2 10 13
			2 12 13
3	nil	nil	3 1 5
			3 1 8
			3 1 14
			3 5 7
			3 7 8
			3 7 14
4	nil	4 1	nil
		4 7	
		4 10	
		4 12	
5	nil	5 1	5 3 7
			5 3 10
			5 3 12
			5 6 7
			5 6 10
			5 6 12
			5 7 13
			5 10 13
			5 12 13
6	nil	6 2	6 4 5
			6 4 8
			6 4 10
			6 4 12
			6 4 14
			6 5 9

Table D.2 (continued): Cut sets due to active failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
			6 5 11
			6 8 9
			6 8 11
			6 9 10
			6 9 12
			6 9 14
			6 10 11
			6 11 12
			6 11 14
7	nil	7 2	nil
		7 4	
		7 9	
		7 11	
8	nil	8 9	8 1 2
		8 11	8 1 4
			8 2 3
			8 2 6
			8 2 13
			8 3 4
			8 4 6
			8 4 13
9	nil	nil	9 1 5
			9 1 8
			9 1 14
			9 2 7
10	nil	nil	10 1 4
			10 2 3
			10 2 6
			10 2 13
11	nil	nil	11 1 5
			11 1 8
			11 1 14
			11 2 7
12	nil	nil	12 1 4
			12 2 3
			12 2 6
			12 2 13
13	nil	nil	nil
14	nil	nil	nil

f) IMPACT OF ACTIVE FAILURES AND STUCK BREAKERS

ACTIVELY FAILED COMPONENT= 1

STUCK BREAKER= 6

REMAINING SUCCESS PATHS

Path Number	Elements								
1	2	17	4	15	11	9	19		
2	2	17	5	14	8	18	12	10	19

Cut sets because of above events
after deleting 100% reliable nodes

First Order Cuts = Nil
Second Order Cut = 1
That is:

Number	Elements	
1	1	2

Third Order Cuts = 15
These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	10
11	1	9	12
12	1	9	14
13	1	10	11
14	1	11	12
15	1	11	14

CUTS WHICH HAVE BEEN EVALUATED BEFORE ARE DELETED.

REMAINING CUTS

First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = 11. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	14
11	1	11	14

The cut sets for the remaining components are formulated as shown above for component one and are tabulated below in Table D.3

Table D.3: Cut sets due to active failures and stuck breakers

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
1	7	nil	1 4	nil
			1 9	
			1 11	
2	4	nil	2 7	nil
			2 10	
			2 12	
2	5	nil	nil	2 3 10
				2 3 12
				2 6 10
				2 6 12
				2 7 9
				2 7 11
				2 10 13
				2 12 13

Table D.3 (continued): cut sets due to active failures and stuck breakers

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
3	4	nil	3 1	nil
			3 7	
			3 10	
			3 12	
3	6	nil	3 2	nil
			3 5	
			3 8	
			3 10	
			3 12	
			3 14	
4	3	nil	4 1	nil
			4 7	
			4 10	
			4 12	
4	5	nil	4 1	nil
			4 7	
			4 10	
			4 12	
5	4	nil	5 1	nil
			5 7	
			5 10	
			5 12	
5	8	nil	5 1	nil
			5 3	
			5 6	
			5 9	
			5 11	
			5 13	
6	3	nil	6 2	nil
			6 5	
			6 8	
			6 10	
			6 12	
			6 14	
6	7	nil	6 2	nil
			6 4	

Table D.3 (continued): cut sets due to active failures and stuck breakers.

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
			6 9 6 11	
7	6	nil	7 2 7 4 7 9 7 11	nil
7	8	nil	7 2 7 4 7 9 7 11	nil
8	5	nil	8 1 8 3 8 6 8 9 8 11 8 13	nil
8	7	nil	8 2 8 4 8 9 8 11	nil
9	4	9	nil	nil
9	3	nil	nil	9 1 5 9 1 8 9 1 14 9 2 7
9	4	nil	9 1 9 7	nil
10	7	nil	10 2 10 4	nil
11	3	nil	nil	11 1 5 11 1 8 11 1 14 11 2 7

Table D.3 (continued): cut sets because of active failures and stuck breakers.

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
11	4	nil	11 1	nil
			11 7	
			11 10	
			11 12	
12	7	nil	12 2	nil
			12 4	
12	8	nil	nil	12 1 4
				12 2 3
				12 2 6
				12 2 13
13	3	nil	13 10	13 1 5
			13 12	13 1 8
				13 1 14
				13 5 7
				13 7 8
				13 7 14
13	6	nil	13 2	13 4 5
				13 4 8
				13 4 14
				13 5 9
				13 5 11
				13 8 9
				13 8 11
				13 9 14
				13 11 14
14	5	nil	14 1	14 3 7
				14 3 10
				14 3 12
				14 6 7
				14 6 10
				14 6 12
				14 7 13
				14 10 13
				14 12 13
14	8	nil	14 9	14 2 3
			14 11	14 2 6
				14 2 13
				14 3 4
				14 4 6
				14 4 13

APPENDIX E

Tie sets and cut sets of case study 4.3: Main bus and transfer bus system

********** DESIGN NO. 4 **********
*** MAIN BUS AND TRANSFER BUS SYSTEM ***

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (4)

PATH NUMBER	ELEMENTS								
1	1	18	3	13	5	20	15	11	17
2	1	18	3	13	6	21	16	12	17
3	2	19	4	13	5	20	15	11	17
4	2	19	4	13	6	21	16	12	17

CUTSETS FOR NORMALLY CLOSED PATHS

First Order Cuts = 2
These are element number 13 and 17

Second Order Cuts = 25. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	10	5	12	19	12	15
2	1	4	11	5	16	20	12	20
3	1	19	12	5	21	21	15	16
4	2	3	13	6	11	22	15	21
5	2	18	14	6	15	23	16	20
6	3	4	15	6	20	24	18	19
7	3	19	16	11	12	25	20	21
8	4	18	17	11	16			
9	5	6	18	11	21			

Third Order Cuts = Nil

b) WITH NORMALLY OPEN COMPONENTS CLOSED

TIE SET OR SUCCESS PATHS (24)

PATH NUMBER	ELEMENTS								
1	1	18	3	13	5	20	15	11	17
2	1	18	3	13	6	21	16	12	17
3	1	18	7	14	9	20	15	11	17
4	1	18	7	14	10	21	16	12	17
5	2	19	4	13	5	20	15	11	17
6	2	19	4	13	6	21	16	12	17
7	2	19	8	14	9	20	15	11	17

Tie sets (continued) with N/O components closed for case study 4.3 (main bus and transfer bus scheme)

PATH NUMBER	ELEMENTS												
8	2	19	8	14	10	21	16	12	17				
9	1	18	7	14	10	21	6	13	5	20	15	11	17
10	1	18	3	13	6	21	10	14	9	20	15	11	17
11	1	18	7	14	9	20	5	13	6	21	16	12	17
12	1	18	3	13	5	20	9	14	10	21	16	12	17
13	2	19	8	14	7	18	3	13	5	20	15	11	17
14	2	19	8	14	7	18	3	13	6	21	16	12	17
15	2	19	4	13	3	18	7	14	9	20	15	11	17
16	2	19	4	13	3	18	7	14	10	21	16	12	17
17	1	18	7	14	8	19	4	13	5	20	15	11	17
18	1	18	7	14	8	19	4	13	6	21	16	12	17
19	1	18	3	13	4	19	8	14	9	20	15	11	17
20	1	18	3	13	4	19	8	14	10	21	16	12	17
21	2	19	8	14	10	21	6	13	5	20	15	11	17
22	2	19	8	14	9	20	5	13	6	21	16	12	17
23	2	19	4	13	6	21	10	14	9	20	15	11	17
24	2	19	4	13	5	20	9	14	10	21	16	12	17

CUTSETS FOR NORMALLY OPEN COMPONENTS CLOSED

First Order Cut = 1 ; i.e., element 17
Second Order Cuts = 14; These are :

Number	Elements		Number	Elements		Number	Elements	
1	1	2	6	11	21	11	15	21
2	1	19	7	12	15	12	16	20
3	2	18	8	12	20	13	18	19
4	11	12	9	13	14	14	20	21
5	11	16	10	15	16			

Third Order Cuts = 34. These are:

Number	Elements			Number	Elements			Number	Elements		
1	1	4	8	13	5	9	12	25	7	8	13
2	1	4	14	14	5	9	16	26	7	13	19
3	1	8	13	15	5	9	21	27	8	13	18
4	2	3	7	16	5	12	14	28	9	10	13
5	2	3	14	17	5	14	16	29	9	12	13
6	2	7	13	18	5	14	21	30	9	13	16
7	3	4	14	19	6	10	11	31	9	13	21
8	3	7	19	20	6	10	15	32	10	11	13
9	3	14	19	21	6	10	20	33	10	13	15
10	4	8	18	22	6	11	14	34	10	13	20
11	4	14	18	23	6	14	15				
12	5	6	14	24	6	14	20				

Fourth Order Cuts = 20. These are:

Number	Elements				Number	Elements			
1	3	4	7	8	11	5	6	7	8
2	3	4	9	10	12	5	6	7	19
3	3	4	9	21	13	5	6	8	18
4	3	4	10	20	14	5	6	9	10
5	3	9	10	19	15	5	7	8	21
6	3	9	19	21	16	5	7	19	21
7	3	10	19	20	17	5	8	18	21
8	4	9	10	18	18	6	7	8	20
9	4	9	18	21	19	6	7	19	20
10	4	10	18	20	20	6	8	18	20

c) K TYPE CUTS

First Order Cut = 1
It is element number 17

Second Order Cuts = 13. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	6	11	21	11	16	20
2	1	19	7	12	15	12	18	19
3	2	18	8	12	20	13	20	21
4	11	12	9	15	16			
5	11	16	10	15	21			

Third Order Cuts = Nil

d) H TYPE CUTS
First Order Cuts = 1
It is element number 13

Second Order Cuts = 12. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	4	5	4	18	9	5	21
2	2	3	6	5	6	10	6	11
3	3	4	7	5	12	11	6	15
4	3	19	8	5	16	12	6	20

Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES
ACTIVE FAILURE OF COMPONENT= 1
REMAINING SUCCESS PATHS

PATH	ELEMENTS								
1	2	19	4	13	5	20	15	11	17
2	2	19	4	13	6	21	16	12	17

CUTSETS BECAUSE OF ABOVE EVENT
First Order Cuts = Nil
Second Order Cuts = 5; These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	3	1	13	5	1	19
2	1	4	4	1	17			

Third Order Cuts = 16. These are:

Number	Elements			Number	Elements			Number	Elements		
1	1	5	6	7	1	6	20	13	1	15	16
2	1	5	12	8	1	11	12	14	1	15	21
3	1	5	16	9	1	11	16	15	1	16	20
4	1	5	21	10	1	11	21	16	1	20	21
5	1	6	11	11	1	12	15				
6	1	6	15	12	1	12	20				

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE.
REMAINING CUTS TO BE EVALUATED:

First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = Nil

The active failures of other components are also treated in the same way as the component number 1. The cut sets obtained this way are tabulated below in Table E.1.

Table E.1: Cut sets because of Active Failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
2	nil	nil	nil
3	3	nil	nil
4	4	nil	nil
5	5	nil	nil
6	6	nil	nil
11	nil	nil	nil
12	nil	nil	nil
13	nil	nil	nil
15	nil	nil	nil
16	nil	nil	nil

f) Cut sets due to active failures and stuck breakers

ACTIVE FAILURE OF COMPONENTS = 1
STUCK BREAKER = 3

SUCCESS PATHS REMAINING AFTER ABOVE EVENT

NO SUCCESS PATH TO LOAD POINT

CUTS WITH STUCK BREAKER

First Order Cut = 1 i.e., element 1
Second Order Cuts = Nil
Third Order Cuts = Nil

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS

First Order Cut = 1 i.e., element 1
Second Order Cuts = Nil
Third Order Cuts = Nil

The active failures with stuck breakers for other cases are done the same way as done for component 1 actively failed and breaker 3 stuck. These are tabulated below in Table E.2.

Table E.2: Cut sets because of active failures and stuck breakers

Actively failed component	Stuck breaker	order of cuts		
		First	Second	Third
2	4	2	nil	nil
3	4	3	nil	nil
4	3	4	nil	nil
5	3	5	nil	nil
6	3	6	nil	nil
6	4	6	nil	nil
11	5	11	nil	nil
12	6	12	nil	nil
13	3	nil	nil	nil
13	4	nil	nil	nil
15	5	15	nil	nil
16	6	16	nil	nil

APPENDIX F

<u>Input data, tie sets and cut sets for George Dickie Substation (Figure 5.1)</u>

F.1 <u>Input Data</u>: The input data is shown below in Table F.1.

Table F.1: Input Data for George Dickie Substation Configuration

```
            ***** B.C. HYDRO GEORGE DICKIE SUBSTATION ****
156  1
 52 52
 17 30 31 36 37 51 67 68 69 70 71 72 73 75 76 77 78 79
  1 52
  2  1  2
   1 -1
   2 -1
   3  1
   4  2
   5 19
   6  9
   7 20 10
   8 10 21
   9  5
  10  7  8
  11 20
  12 21
  13 11
  14 12
  15 13
  16 14
  17 15
  18 16
  19  3
  20  6  7
  21  8  4
  22 25
  23 17 27
  24 18 28
  25 26
  26 23
  27 23 29
  28 29 24
  29 27 28
  30 23
  31 23
  32 24
```

Table F.1 (contd.) Input Data George Dickie Substation

33	24	
34	30	
35	31	
36	34	
37	35	
38	36	58
39	37	80
40	42	
41	43	
42	45	
43	44	
44	32	
45	33	
46	40	
47	46	
48	47	
49	48	
50	49	
51	38	
52	50	51
53	40	
54	53	
55	54	
56	55	
57	56	
58	57	
59	40	
60	40	
61	41	
62	41	
63	41	
64	41	
65	41	
66	41	
67	38	
68	38	
69	38	
70	38	
71	38	
72	38	
73	38	
74	40	
75	39	
76	39	
77	39	
78	39	
79	39	
80	94	
81	95	
82	96	

Table F.1 (contd.) Input Data - George Dickie Substation

83	97
84	98
85	99
86	100
87	101
88	40
89	103
90	104
91	105
92	106
93	107
94	108
95	109
96	110
97	111
98	112
99	113
100	114
101	115
102	40
103	117
104	118
105	119
106	120
107	121
108	122
109	123
110	124
111	125
112	126
113	127
114	128
115	129
116	40
117	131
118	132
119	133
120	134
121	135
122	136
123	60
124	130
125	116
126	102
127	57
128	58
129	59
130	40
131	61
132	62

Table F.1 (contd.) Input Data - George Dickie Substation

```
 133 63
 134 64
 135 65
 136 66
 137 22
 138 137
 139 138
 140 139
 141 24
 142 141
 143 142
 144 143
 145  1
 146  2
 147  1
 148  2
 149 19
 150 21
 151 156
 152 11
 153 12
 154 13
 155 14
 156 19
 499 52
   156
.09,7.33,1.0,8.,.09,1.,.000
.09,7.33,1.0,8.,.09,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.23,11.13,.25,24.,.03,2.,.005
.23,11.13,.25,24.,.03,2.,.005
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.10,1000.,.5,48.,.10,1.,.000
.10,1000.,.5,48.,.10,1.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.22,2.09,.25,4.,.02,3.,.000
.02,3.,.25,12.,.01,1.,.06
.004,10.,.0000001,.0000001,.004,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.22,2.09,.25,4.,.02,3.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.008,10.,.00000001,.0000001,.008,1.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.008,10.,.00000001,.0000001,.008,1.,.000
.007,10.,.007,1.,.00000001,.0000001,.000
.007,10.,.007,1.,.00000001,.0000001,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
3.0
  1  1  9
  2  1 10
  3  2  1  9
  4  2  2 10
  5  2  1  9
  6  2  9 10
  7  2  9 10
  8  2 10  2
  9  2  1 10
 10  2  2  9
 11  2  9 10
 12  2  2 10
 13  2  9 10
 14  2  2 10
 15  2  9 10
 16  2 10  2
 17  2 15 29
 18  2 16 29
 19  2  1  9
```

Table F.1 (contd.) Input Data - George Dickie Substation

20	2	9	10
21	2	10	2
22	2	15	29
23	2	15	29
24	2	16	29
25	2	15	29
26	2	15	29
27	2	15	29
28	2	16	29
29	2	15	16
32	2	16	29
33	2	16	29
34	2	15	29
35	2	15	29
38	1	54	
39	1	136	
40	2	16	29
41	2	16	29
42	2	16	29
43	2	16	29
44	2	16	29
45	2	16	29
46	2	16	29
47	2	16	29
48	1	47	
49	1	47	
50	1	47	
52	1	47	
53	2	16	29
54	2	16	29
55	1	54	
56	1	54	
57	1	54	
58	1	54	
59	2	16	29
60	2	16	29
61	2	16	29
62	2	16	29
63	2	16	29
64	2	16	29
65	2	16	29
66	2	16	29
74	2	16	29
80	1	136	
81	1	123	
82	1	124	
83	1	125	
84	1	126	
85	1	127	

Table F.1 (contd.) Input Data - George Dickie Substation

86	1	128	
87	1	129	
88	2	16	29
89	1	131	
90	1	132	
91	1	133	
92	1	134	
93	1	135	
94	1	136	
95	1	123	
96	1	124	
97	1	125	
98	1	126	
99	1	127	
100	1	128	
101	1	129	
102	2	16	29
103	1	131	
104	1	132	
105	1	133	
106	1	134	
107	1	135	
108	1	136	
109	1	123	
110	1	124	
111	1	125	
112	1	126	
113	1	127	
114	1	128	
115	1	129	
116	2	16	29
117	1	131	
118	1	132	
119	1	133	
120	1	134	
121	1	135	
122	1	136	
123	2	16	29
124	2	16	29
125	2	16	29
126	2	16	29
127	2	16	29
128	2	16	29
129	2	16	29
130	2	16	29
131	2	16	29
132	2	16	29
133	2	16	29
134	2	16	29

Table F.1 (contd.) Input Data - George Dickie Substation

135	2	16	29	
136	2	16	29	
137	2	15	29	
138	2	15	29	
139	2	15	29	
140	2	15	29	
141	2	16	29	
142	2	16	29	
143	2	16	29	
144	2	16	29	
145	2	1	9	
146	2	2	10	
147	2	1	9	
148	2	2	10	
149	2	1	9	
150	2	2	10	
151	2	1	9	
152	2	9	10	
153	2	2	10	
154	2	9	10	
155	2	2	10	
156	2	1	9	
499	0	0	0	
1	9	1	10	
2	10	1	9	
3	9	2	10	1
4	10	2	9	2
5	9	2	1	10
6	9	2	1	10
6	10	2	9	2
7	9	2	1	10
8	10	2	9	2
9	10	2	1	2
10	9	2	2	1
11	9	2	1	10
11	10	2	2	9
12	10	2	2	9
13	9	2	1	10
13	10	2	2	9
14	10	2	2	9
15	9	2	1	10
15	10	2	2	9
16	10	2	2	9
17	15	2	9	10
18	16	2	2	10
19	9	2	1	10
20	9	2	1	10
20	10	2	2	9
21	10	2	2	9

Table F.1 (contd.) Input Data - George Dickie Substation

22	15	2	9	10	
22	29	2	15	16	
23	15	2	9	10	
23	29	2	15	16	
24	16	2	2	10	
24	29	2	15	16	
25	15	2	9	10	
25	29	2	15	16	
26	15	3	9	10	29
26	29	2	15	16	
27	15	3	29	9	10
27	29	2	15	16	
28	16	3	29	10	2
28	29	2	15	16	
29	15	3	16	9	10
32	16	3	29	2	10
32	29	2	15	16	
33	16	3	29	2	10
34	15	3	29	9	10
34	29	2	15	16	
35	15	3	29	9	10
35	29	2	15	16	
38	54	2	16	29	
39	136	2	16	29	
40	16	3	29	10	2
40	29	2	16	15	
41	16	3	29	2	10
41	29	2	16	15	
42	16	3	29	10	2
42	29	2	15	16	
43	16	3	29	2	10
43	29	2	15	16	
44	16	3	29	10	2
44	29	2	15	16	
45	16	3	29	2	10
45	29	2	16	15	
46	16	3	29	2	10
46	29	2	16	15	
47	16	3	29	2	10
47	29	2	15	16	
48	47	2	16	29	
49	47	2	16	29	
50	47	2	16	29	
53	16	3	29	10	2
53	29	2	15	16	
54	16	3	29	10	2
54	29	2	15	16	
55	54	2	16	29	
56	54	2	16	29	

Table F.1 (contd.) Input Data - George Dickie Substation

57	54	2	16	29	
58	54	2	16	29	
59	16	3	29	10	2
59	29	2	15	16	
60	16	3	29	10	2
60	29	2	15	16	
61	16	3	29	10	2
61	29	2	15	16	
62	16	3	29	10	2
62	29	2	15	16	
63	16	3	29	10	2
63	29	2	15	16	
64	16	3	29	10	2
64	29	2	15	16	
65	16	3	29	10	2
65	29	2	15	16	
66	16	3	29	2	10
66	29	2	15	16	
74	16	3	29	2	10
74	29	2	16	15	
80	136	2	16	29	
81	123	2	16	29	
82	124	2	16	29	
83	125	2	16	29	
84	126	2	16	29	
85	127	2	16	29	
86	128	2	16	29	
87	129	2	16	29	
88	16	3	29	2	10
88	29	2	16	15	
89	131	2	16	29	
90	132	2	16	29	
91	133	2	16	29	
92	134	2	16	29	
93	135	2	16	29	
94	136	2	16	29	
95	123	2	16	29	
96	124	2	16	29	
97	125	2	16	29	
98	126	2	16	29	
99	127	2	16	29	
100	128	2	16	29	
101	129	2	16	29	
102	16	3	29	2	10
102	29	2	16	15	
103	131	2	16	29	
104	132	2	16	29	
105	133	2	16	29	
106	134	2	16	29	

Table F.1 (contd.) Input Data - George Dickie Substation

107	135	2	16	29	
108	136	2	16	29	
109	123	2	16	29	
110	124	2	16	29	
111	125	2	16	29	
112	126	2	16	29	
113	127	2	16	29	
114	128	2	16	29	
115	129	2	16	29	
116	16	3	29	2	10
116	29	2	16	15	
117	131	2	16	29	
118	132	2	16	29	
119	133	2	16	29	
120	134	2	16	29	
121	135	2	16	29	
122	136	2	16	29	
123	16	3	29	2	10
123	29	2	16	15	
124	16	3	29	2	10
124	29	2	15	16	
125	16	3	29	2	10
125	29	2	15	16	
126	16	3	29	2	10
126	29	2	15	16	
127	16	3	29	2	10
127	29	2	15	16	
128	16	3	29	2	10
128	29	2	15	16	
129	16	3	29	2	10
129	29	2	15	16	
130	16	3	29	2	10
130	29	2	15	16	
131	16	3	29	2	10
131	29	2	15	16	
132	16	3	29	2	10
132	29	2	15	16	
133	16	3	29	2	10
133	29	2	15	16	
134	16	3	29	2	10
134	29	2	15	16	
135	16	3	29	2	10
135	29	2	15	16	
136	16	3	29	2	10
136	29	2	15	16	
137	15	3	9	10	29
137	29	2	15	16	
138	15	3	9	10	29
138	29	2	15	16	

Table F.1 (contd.) Input Data - George Dickie Substation

139	15	3	9	10	29
139	29	2	15	16	
140	15	3	9	10	29
140	29	2	15	16	
141	16	3	29	10	2
141	29	2	16	15	
142	16	3	29	10	2
142	29	2	16	15	
143	16	3	29	10	2
143	29	2	16	15	
144	16	3	29	10	2
144	29	2	16	15	
145	9	2	1	10	
146	10	2	2	9	
147	9	2	1	10	
148	10	2	2	9	
149	9	2	1	10	
150	10	2	2	9	
151	9	2	1	10	
152	9	2	10	1	
152	10	2	9	2	
153	10	2	2	9	
154	9	2	10	1	
154	10	2	9	2	
155	10	2	9	2	
156	9	2	1	10	
499					

1,2,.562,5.5

499,0,.0,.0

F.2 *Tie sets and cut sets of George Dickie Substation*

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (4)

PATH NUMBER	ELEMENTS											
1	2	4	21	12	14	16	18	24	33	45	42	40
	46	47	48	49	50	52						
2	1	3	19	5	9	6	20	11	13	15	17	23
	27	29	28	24	33	45	42	40	46	47	48	49
	50	52										
3	1	3	19	5	9	6	20	7	10	8	21	12
	14	16	18	24	33	45	42	40	46	47	48	49
	50	52										
4	2	4	21	8	10	7	20	11	13	15	17	23
	27	29	28	24	33	45	42	40	46	47	48	49
	50	52										

Component 52 i.e., load point assumed 100% reliable and therefore deleted from cuts

b) CUTSETS FOR NORMALLY CLOSED PATHS

First Order Cuts = 10
These are element numbers shown below:

24 33 40 42 45 46 47 48 49 50

Second Order Cuts = 65
These are given below:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	23	11	18	45	15	18
2	1	4	24	11	21	46	15	21
3	1	21	25	12	13	47	16	17
4	2	3	26	12	15	48	16	20
5	2	5	27	12	17	49	16	23
6	2	6	28	12	20	50	16	27
7	2	9	29	12	23	51	16	28
8	2	19	30	12	27	52	16	29
9	2	20	31	12	28	53	17	18
10	3	4	32	12	29	54	17	21
11	3	21	33	13	14	55	18	20
12	4	5	34	13	16	56	18	27
13	4	6	35	13	18	57	18	28

Second order cuts (contd.) with N/O branches open - George Dickie Substation

Number	Elements		Number	Elements		Number	Elements	
14	4	9	36	13	21	58	18	29
15	4	19	37	14	15	59	19	21
16	4	20	38	14	17	60	20	21
17	5	21	39	14	20	61	21	23
18	6	21	40	14	23	62	21	27
19	9	21	41	14	27	63	21	28
20	11	12	42	14	28	64	21	29
21	11	14	43	14	29	65	18	23
22	11	16	44	15	16			

Third Order Cuts = 120. These are:

Number	Element			Number	Element			Number	Element		
1	1	7	12	41	3	8	12	81	5	10	12
2	1	7	14	42	3	8	14	82	5	10	14
3	1	7	16	43	3	8	16	83	5	10	16
4	1	7	18	44	3	8	18	84	5	10	18
5	1	8	12	45	3	10	12	85	6	7	12
6	1	8	14	46	3	10	14	8	6	7	14
7	1	8	16	47	3	10	16	87	6	7	16
8	1	8	18	48	3	10	18	88	6	7	18
9	1	10	12	49	4	7	11	89	6	8	12
10	1	10	14	50	4	7	13	90	6	8	14
11	1	10	16	51	4	7	15	91	6	8	16
12	1	10	18	52	4	7	17	92	6	8	18
13	2	7	11	53	4	7	23	93	6	10	12
14	2	7	13	54	4	7	27	94	6	10	14
15	2	7	15	55	4	7	28	95	6	10	16
16	2	7	17	56	4	7	29	96	6	10	18
17	2	7	23	57	4	8	11	97	7	9	12
18	2	7	27	58	4	8	13	98	7	9	14
19	2	7	28	59	4	8	15	99	7	9	16
20	2	7	29	60	4	8	17	100	7	9	18
21	2	8	11	61	4	8	23	101	7	12	19
22	2	8	13	62	4	8	27	102	7	14	19
23	2	8	15	63	4	8	28	103	7	16	19
24	2	8	17	63	4	8	29	104	7	18	19
25	2	8	23	65	4	10	11	105	8	9	12
26	2	8	27	66	4	10	13	106	8	9	14
27	2	8	28	67	4	10	15	107	8	9	16
28	2	8	29	68	4	10	17	108	8	9	18
29	2	10	11	69	4	10	23	109	8	12	19
30	2	10	13	70	4	10	27	110	8	14	19
31	2	10	15	71	4	10	28	111	8	16	19

Third order cuts(contd.) with N/O branches open
- George Dickie Substation

Number	Element			Number	Element			Number	Element		
32	2	10	17	72	4	10	29	112	8	18	19
33	2	10	23	73	5	7	12	113	9	10	12
34	2	10	27	74	5	7	14	114	9	10	14
35	2	10	28	75	5	7	16	115	9	10	16
36	2	10	29	76	5	7	18	116	9	10	18
37	3	7	12	77	5	8	12	117	10	12	19
38	3	7	14	78	5	8	14	118	10	14	19
39	3	7	16	79	5	8	16	119	10	16	19
40	3	7	18	80	5	8	18	120	10	18	19

WITH NORMALLY OPEN COMPONENTS CLOSED
TIE SET OR SUCCESS PATHS (12)

PATH	ELEMENT NUMBERS										
1	1	3	19	5	9	6	20	11	13	15	17
	23	30	34	36	38	51	52				
2	2	4	21	8	10	7	20	11	13	15	17
	23	30	34	36	38	51	52				
3	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				
4	2	4	21	12	14	16	18	24	28	29	27
	23	30	34	36	38	51	52				
5	2	4	21	12	14	16	18	24	33	45	42
	40	53	54	55	56	57	58	38	51	52	
6	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	33	45	42	40	46	47
	48	49	50	52							
7	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	28	29	27	23	30	34
	36	38	51	52							
8	1	3	19	5	9	6	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							
9	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							
10	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				
11	1	3	19	5	9	6	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				
12	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				

c) K TYPE CUTS

First Order Cuts = Nil

Second Order Cuts = 65
These are the same as the second order cuts shown above.

Third Order Cuts = 120
These are same as the third order cuts shown above.

d) H TYPE CUTS

First Order Cuts = 10
These are the following element numbers :
24 33 40 42 45 46 47 48 49 50

Second Order Cuts= Nil

Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES

ACTIVE FAILURE OF COMPONENT= 1

REMAINING SUCCESS PATHS

PATH NUMBER	ELEMENTS										
1	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				
2	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							

CUTSETS BECAUSE OF ABOVE EVENT

First Order Cuts = Nil

Second Order Cuts = 13;.These are:

Number	Element		Number	Element		Number	Element	
1	1	2	6	1	40	11	1	48
2	1	4	7	1	42	12	1	49
3	1	21	8	1	45	13	1	50
4	1	24	9	1	46			
5	1	33	10	1	47			

Third Order Cuts = 48. These are:

Number	Element			Number	Element			Number	Element		
1	1	7	12	17	1	12	13	33	1	14	28
2	1	7	14	18	1	12	15	34	1	14	29
3	1	7	16	19	1	12	17	35	1	15	16
4	1	7	18	20	1	12	20	36	1	15	18
5	1	8	12	21	1	12	23	37	1	16	17
6	1	8	14	22	1	12	27	38	1	16	20
7	1	8	16	23	1	12	28	39	1	16	23
8	1	8	18	24	1	12	29	40	1	16	27
9	1	10	12	25	1	13	14	41	1	16	28
10	1	10	14	26	1	13	16	42	1	16	29
11	1	10	16	27	1	13	18	43	1	17	18
12	1	10	18	28	1	14	15	44	1	18	20
13	1	11	12	29	1	14	17	45	1	18	23
14	1	11	14	30	1	14	20	46	1	18	27
15	1	11	16	31	1	14	23	47	1	18	28
16	1	11	18	32	1	14	27	48	1	18	29

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS TO BE EVALUATED

First Order Cuts = Nil

Second Order Cuts = Nil

Third Order Cuts = Nil

The cut sets for active failures of other components are also calculated in the same way. The count and order of cuts because of active failures of other components are tabulated below in Table F.2:

Table F.2: Cut sets due to Active Failures

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
2	nil	8	nil
3	nil	nil	nil
4	nil	7	nil
5	nil	12	nil
6	nil	13	nil
7	1	nil	nil
8	nil	15	nil
9	nil	12	nil
10	nil	15	nil
11	1	nil	nil
12	nil	6	nil
13	nil	2	nil
14	nil	6	nil
15	nil	2	nil
16	nil	6	nil
17	nil	nil	nil
18	nil	nil	nil
19	nil	nil	nil
20	nil	nil	nil
21	nil	nil	nil
22	nil	5	6
23	nil	nil	nil
24	nil	nil	nil
25	nil	5	6
26	nil	5	6
27	nil	nil	nil
28	28	nil	nil
29	nil	nil	nil
32	nil	9	18
33	nil	nil	nil
34	nil	5	6
35	nil	5	6
38	nil	nil	nil
39	nil	nil	nil
40	nil	nil	nil
41	nil	9	18
42	nil	nil	nil
43	nil	9	18
44	nil	9	18

Table F.2 (contd.) cut sets due to active failures - George Dickie Substation

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
45	nil	nil	nil
46	nil	nil	nil
47	nil	nil	nil
48	nil	nil	nil
49	nil	nil	nil
50	nil	nil	nil
52	1	nil	nil
53	nil	9	18
54	nil	9	18
55	nil	nil	nil
56	nil	nil	nil
57	nil	nil	nil
58	nil	nil	nil
59	nil	9	18
60	nil	9	18
61	nil	9	18
62	nil	9	18
63	nil	9	18
64	nil	9	18
65	nil	9	18
66	nil	9	18
74	nil	9	18
80	nil	nil	nil
81	nil	nil	nil
82	nil	nil	nil
83	nil	nil	nil
84	nil	nil	nil
85	nil	nil	nil
86	nil	nil	nil
87	nil	nil	nil
88	1	nil	nil
89	nil	nil	nil
90	nil	nil	nil
91	nil	nil	nil
92	nil	nil	nil
93	nil	nil	nil
94	nil	nil	nil
95	nil	nil	nil
96	nil	nil	nil
97	nil	nil	nil
98	nil	nil	nil
99	nil	nil	nil
100	nil	nil	nil
101	nil	nil	nil
102	nil	15	nil

Table F.2 (contd.) cut sets due to active failures - George Dickie Substation.

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
103	nil	nil	nil
104	nil	nil	nil
105	nil	nil	nil
⋮	⋮	⋮	⋮
115	nil	nil	nil
116	1	nil	nil
117	nil	nil	nil
⋮			⋮
122	nil	nil	nil
123	1	nil	nil
124	1	nil	nil
⋮	⋮	⋮	⋮
136	1	nil	nil
137	nil	5	6
138	nil	5	6
139	nil	5	6
140	nil	5	6
141	1	nil	nil
142	1	nil	nil
143	1	nil	nil
144	1	nil	nil
145	nil	3	12
146	nil	15	nil
147	nil	3	12
148	nil	15	nil
149	nil	3	12
150	nil	15	nil
151	nil	3	12
152	nil	7	nil
153	nil	15	nil
154	nil	7	nil
155	nil	15	nil
156	nil	3	12

f) *Cut sets with active failures and stuck breakers*

ACTIVE FAILURE OF COMPONENT= 1
STUCK BREAKER= 9

SUCCESS PATHS REMAINING AFTER ABOVE EVENT

PATH NUMBER	ELEMENTS										
1	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				

CUTS WITH STUCK BREAKER

First Order Cuts = Nil

Second Order Cuts = 17. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	7	1	21	13	1	46
2	1	4	8	1	24	14	1	47
3	1	12	9	1	33	15	1	48
4	1	14	10	1	40	16	1	49
5	1	16	11	1	42	17	1	50
6	1	18	12	1	45			

Third Order Cuts = Nil

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS

First Order Cuts = Nil

Second Order Cuts = 4
These are :

Number	Elements		Number	Elements	
1	1	12	3	1	16
2	1	14	4	1	18

Third Order Cuts = Nil

The cut sets for other combinations of active failures of components and the stuck breakers present in the system are calculated in the same way as demonstrated above for active failure of component 1 and stuck breaker 9. The order and count of cut sets thus obtained are listed in the table F.3

Table F.3: Cut sets due to active failures and stuck breakers

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
2	10	1	nil	nil
3	9	nil	4	nil
4	10	1	nil	nil
5	9	nil	4	nil
6	9	nil	4	nil
6	10	1	nil	nil
7	9	nil	7	nil
8	10	1	nil	nil
9	10	1	nil	nil
10	9	1	nil	nil
11	9	nil	2	nil
11	10	1	nil	nil
12	10	1	nil	nil
13	9	nil	2	nil
13	10	1	nil	nil
14	10	1	nil	nil
15	9	nil	2	nil
15	10	1	nil	nil
16	10	1	nil	nil
17	15	nil	2	nil
18	16	nil	6	nil
19	9	nil	4	nil
20	9	nil	nil	nil
20	10	1	nil	nil
21	10	1	nil	nil
22	15	nil	7	nil
22	29	1	nil	nil
23	15	nil	2	nil
23	29	1	nil	nil
24	16	1	nil	nil
24	29	nil	nil	nil
25	15	nil	7	nil
25	29	1	nil	nil
26	15	nil	7	nil
26	29	1	nil	nil
27	15	nil	2	nil
27	29	1	nil	nil
28	16	1	nil	nil
28	29	1	nil	nil
29	15	1	nil	nil
32	16	1	nil	nil
32	29	1	nil	nil
33	16	nil	nil	nil

Table F.3 (contd.) Cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
34	15	nil	7	nil
34	29	1	nil	nil
35	15	nil	7	nil
35	29	1	nil	nil
38	54	1	nil	nil
39	136	1	nil	nil
40	16	nil	nil	nil
40	29	nil	nil	nil
41	16	1	nil	nil
41	29	1	nil	nil
42	16	nil	nil	nil
42	29	nil	nil	nil
43	16	1	nil	nil
43	29	1	nil	nil
44	16	1	nil	nil
44	29	1	nil	nil
45	16	nil	nil	nil
45	29	nil	nil	nil
46	16	nil	nil	nil
46	29	nil	nil	nil
47	16	nil	nil	nil
47	29	nil	nil	nil
48	47	nil	nil	nil
49	47	nil	nil	nil
50	47	nil	nil	nil
53	16	1	nil	nil
53	29	1	nil	nil
54	16	1	nil	nil
54	29	1	nil	nil
55	54	1	nil	nil
56	54	1	nil	nil
57	54	1	nil	nil
58	54	1	nil	nil
59	16	1	nil	nil
59	29	1	nil	nil
60	16	1	nil	nil
60	29	1	nil	nil
61	16	1	nil	nil
61	29	1	nil	nil
62	16	1	nil	nil
62	29	1	nil	nil
63	16	1	nil	nil
63	29	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
64	16	1	nil	nil
64	29	1	nil	nil
65	16	1	nil	nil
65	29	1	nil	nil
66	16	1	nil	nil
66	29	1	nil	nil
74	16	1	nil	nil
74	29	1	nil	nil
80	136	1	nil	nil
81	123	1	nil	nil
82	124	1	nil	nil
83	125	1	nil	nil
84	126	1	nil	nil
85	127	1	nil	nil
86	128	1	nil	nil
87	129	1	nil	nil
88	16	1	nil	nil
88	29	1	nil	nil
89	131	1	nil	nil
90	132	1	nil	nil
91	133	1	nil	nil
92	134	1	nil	nil
93	135	1	nil	nil
94	136	1	nil	nil
95	123	1	nil	nil
96	124	1	nil	nil
97	125	1	nil	nil
98	126	1	nil	nil
99	127	1	nil	nil
100	128	1	nil	nil
101	129	1	nil	nil
102	16	1	nil	nil
102	29	1	nil	nil
103	131	1	nil	nil
104	132	1	nil	nil
105	133	1	nil	nil
106	134	1	nil	nil
107	135	1	nil	nil
108	136	1	nil	nil
109	123	1	nil	nil
110	124	1	nil	nil
111	125	1	nil	nil
112	126	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
113	127	1	nil	nil
114	128	1	nil	nil
115	129	1	nil	nil
116	16	1	nil	nil
116	29	1	nil	nil
117	131	1	nil	nil
118	132	1	nil	nil
119	133	1	nil	nil
120	134	1	nil	nil
121	135	1	nil	nil
122	136	1	nil	nil
123	16	1	nil	nil
123	29	1	nil	nil
124	16	1	nil	nil
124	29	1	nil	nil
125	16	1	nil	nil
125	29	1	nil	nil
126	16	1	nil	nil
126	29	1	nil	nil
127	16	1	nil	nil
127	29	1	nil	nil
128	16	1	nil	nil
128	29	1	nil	nil
129	16	1	nil	nil
129	29	1	nil	nil
130	16	1	nil	nil
130	29	1	nil	nil
131	16	1	nil	nil
131	29	1	nil	nil
132	16	1	nil	nil
132	29	1	nil	nil
133	16	1	nil	nil
133	29	1	nil	nil
134	16	1	nil	nil
134	29	1	nil	nil
135	16	1	nil	nil
135	29	1	nil	nil
136	16	1	nil	nil
136	29	1	nil	nil
137	15	nil	7	nil
137	29	1	nil	nil
138	15	nil	7	nil
138	29	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
139	15	nil	7	nil
139	29	1	nil	nil
140	15	nil	7	nil
141	16	1	nil	nil
141	29	1	nil	nil
142	16	1	nil	nil
142	29	1	nil	nil
143	16	1	nil	nil
143	29	1	nil	nil
144	16	1	nil	nil
144	29	1	nil	nil
145	9	nil	7	nil
146	10	1	nil	nil
147	9	nil	7	nil
148	10	1	nil	nil
149	9	nil	7	nil
150	10	1	nil	nil
151	9	nil	7	nil
152	9	nil	7	nil
152	10	1	nil	nil
153	10	1	nil	nil
154	9	nil	7	nil
154	10	1	nil	nil
155	10	1	nil	nil
156	9	nil	7	nil

APPENDIX G

EQUATIONS FOR EVALUATION OF CUT SETS

The assumptions made in the formulation of these equations are as follows:

1. Component failure and repair events are independent of each other.
2. Component repair rates are much larger than their failure rates
3. Preventive maintenance is not performed if there is some outage existing in a related portion of the system.
4. The probability of two or more active failures is approximately equal to zero.
5. Probability of two or more stuck breakers in the system is approximately equal to zero.

In the following section the equations contributing to load point failure rate and duration are developed and all failures are referred to as a load point failures.

a) Passive failures and overlapping passive failures

i) First Order Cutset

Let i be the component in the cutset, then

Contribution to the failure rate = λ_i

Duration = r_i

ii) Second Order Cutset

Components in the cutset = i, j

The components of the cutset are in parallel and the Markov model of a two component parallel system is shown in Figure G.1

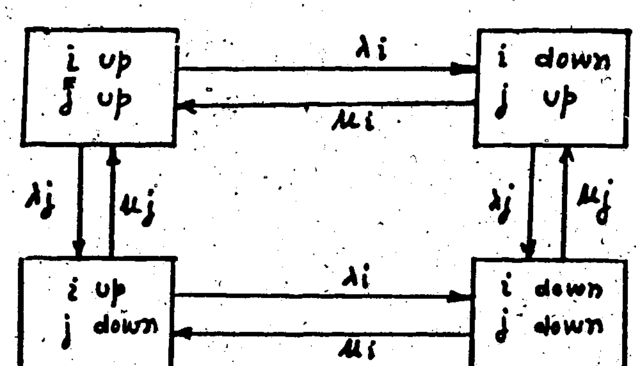

Figure G.1: Markov model of a two component parallel system

where:

λ_i = Failure rate of component i

λ_j = Failure rate of component j

μ_i = Repair rate of component i

μ_j = Repair rate of component j

r_i = Mean repair time of component i

r_j = Mean repair time of component j

$\mu_i \equiv 1/r_i$

$\mu_j \equiv 1/r_j$

P_1, P_2, P_3 and P_4 are the probabilities of state 1, 2, 3 and 4 respectively. As has been described in Chapter 2 the steady state probabilities of occupying each state can be found by using frequency balance approach resulting in the following :

$$P_1 = \frac{\mu_i \cdot \mu_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \qquad (8.1)$$

$$P_2 = \frac{\mu_j \cdot \lambda_i}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \qquad (8.2)$$

$$P_3 = \frac{\mu_i \cdot \lambda_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \qquad (8.3)$$

$$P_4 = \frac{\lambda_i \cdot \lambda_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \qquad (8.4)$$

The system availability is defined as $= P_1 + P_2 + P_3$

$$= \frac{\mu_i\mu_j + \mu_j\lambda_i + \mu_i\lambda_j}{(\mu_i + \lambda_i)(\mu_j + \lambda_j)}$$

$$= \frac{1/r_i 1/r_j + \lambda_i/r_j + \lambda_j/r_j}{(1/r_i + \lambda_i)(1/r_j + \lambda_j)}$$

$$= \frac{1 + \lambda_i r_i + \lambda_j r_j}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)} \qquad (8.5)$$

The probability of system failure (i.e., P_f) is the probability of residing in state 4 and is defined as follows:

$$P_f = \lambda_i \lambda_j r_i r_j / (1 + \lambda_i r_i)(1 + \lambda_j r_j)$$

The frequency of failure = Probability of system failure x Rate of departure from the failed state

$$= P_f (\mu_i + \mu_j)$$

$$= \frac{\lambda_i \lambda_j (r_i + r_j)}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)} \qquad (8.6)$$

The failure rate, λ = Frequency of failure / Availability

$$= \frac{\lambda_i \lambda_j (r_i + r_j)(1 + \lambda_i r_i)(1 + \lambda_j r_j)}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)(1 + \lambda_i r_i + \lambda_j r_j)}$$

$$= \frac{\lambda_i \lambda_j (r_i + r_j)}{(1 + \lambda_i r_i + \lambda_j r_j)}$$

In many practical studies the following assumptions can be made:

If $\lambda_i << \mu_i$ and $\lambda_j << \mu_j$, then,

$1 + \lambda_i r_i + \lambda_j r_j \approx 1$

and therefore,

the load point failure rate $\lambda = \lambda_i \lambda_j (r_i + r_j)$ (8.7)

and,

the load point average duration of repair, $r = P_f / f_f$

Substituting values of P_f and f_f, we get

$$r = r_i \cdot r_j / (r_i + r_j) \quad (8.8)$$

where:

λ and r are the load point failure rate and mean duration of repair time.

The same results can be obtained by the following procedure:
The load point is in the down state when both components have failed. Assuming that no simultaneous or common mode failure can occur, the system failure state can occur with the components failing sequentially in one of the two different combinations. These are:

combination	order of failure
i)	i j
ii)	j i

Since the events are mutually exclusive, the total load point failure rate is the addition of the contributions to failure rate by each of above combinations.
The contribution to load point failure rate by the first combination,

λ_1 = Failure rate of component i x (probability component j fails while i is failed)

$$= \lambda_i(\lambda_j r_i)/(1 + \lambda_j r_i) \quad (8.9)$$

Since it has been assumed that repair rates of components are much larger than their respective failure rates, hence the denominator term in equation 8.9 equals unity approximately.
Therefore, $\lambda_1 = \lambda_i(\lambda_j r_i)$
Similarly, the contribution to failure rate by second combination

λ_2 = Failure rate of component j x (Probability component i fails while j is failed)

$= \lambda_j(\lambda_i r_j)$

Total contribution to load point failure rate $= \lambda_1 + \lambda_2$

$= \lambda_i \lambda_j (r_i + r_j)$

iii) Third order cutset

Let the components in the third order cut be i, j, and k. Since the components in the third order cut are in parallel, hence the load point is in failed state when all three components have failed. This state can occur with the components failing in one of six different combinations. These are :-

Combination	order of failure
1)	i j k
2)	i k j
3)	j k i
4)	k j i
5)	j i k
6)	k i j

The total failure rate is the addition of the contributions to failure rate by each of the six combinations

The contribution to the failure rate by the first combination is

= Failure rate of component i x (Probability component j fails while i is failed) x (Probability component k fails while i and j are failed)

$$= \lambda_i \lambda_j r_i \cdot \lambda_k r_i r_j / (r_i + r_j)$$

$$= \lambda_i \lambda_j \lambda_k (r_i^2 r_j)/(r_i + r_j)$$

The contributions to the failure rate due to rest of the combinations can also be written in the same fashion.

The total contribution to load point failure rate,

$$\lambda = \lambda_i \lambda_j \lambda_k (r_i^2 r_j / r_i + r_j) + \lambda_i \lambda_j \lambda_k (r_i^2 r_k)/(r_i + r_k)$$
$$+ \lambda_i \lambda_j \lambda_k (r_j^2 r_k)/(r_j + r_k) + \lambda_i \lambda_j \lambda_k (r_j^2 r_i)/(r_i + r_k)$$
$$+ \lambda_i \lambda_j \lambda_k (r_k^2 r_i)/(r_i + r_k) + \lambda_i \lambda_j \lambda_k (r_j r_k^2)/(r_j + r_k)$$
$$= \lambda_i \lambda_j \lambda_k (r_i r_j + r_i r_k + r_j r_k) \qquad (8.10)$$

b) Maintenance Outages and maintenance outages overlapping passive failures

I) First order cut

Let the component in the cut be i and let its maintenance outage rate be defined as λ_i'' and the maintenance restoration rate as r_i''. Then,

Load point failure rate contribution = λ_i''

Mean outage Duration = r_i''

There can not be any contribution by maintenance outages overlapping passive failures because of the assumption that if there exists an outage in the system the maintenance activity is not started

II) Second order cut

The contribution to the reliability indices due to the maintenance outages overlapping the passive failures can be obtained by the same logic as explained for the overlapping passive outages.

Let the components in the cut be i and j. Since maintenance activities are not started when there exists an outage in the system, only two combinations are possible which lead to the load point outages. They are:

1. component i in maintenance outage and component j in passive outage mode.
2. component j in maintenance outage mode and component i in passive outage mode.

The contribution to load point failure rate and mean duration indices by the first combination is given by:

$$\lambda_1 = \lambda_i'' (\lambda_j r_i'')$$

$$r_1 = \frac{r_i'' r_j}{r_i'' + r_j}$$

Similarly,

$$\lambda_2 = \lambda_j'' (\lambda_i r_j'')$$

$$r_2 = r_j'' r_i / (r_j'' + r_i)$$

Total failure rate = $\lambda = \lambda_1 + \lambda_2 = \lambda_i''(\lambda_j r_i'') + \lambda_j''(\lambda_i r_j'')$ (8.11)

Mean outage duration = $r = \dfrac{r_1\lambda_1 + r_2\lambda_2}{\lambda_1 + \lambda_2}$

If

$\upsilon_i \equiv \lambda_i r_i$; $\upsilon_i'' \equiv \lambda_i'' r_i''$; $\upsilon_j'' \equiv \lambda_j'' r_j''$

and,

$\nu_{ij} \equiv r_i'' / (r_i'' + r_j)$

where:

υ_i is the total annual passive outage duration of component i.

υ_i'' is the total annual maintenance outage duration of component i.

υ_j'' is the total annual maintenance outage duration of component j.

ν_{ij} is the mean outage duration when component i is on maintenance outage and the component j fails passively.

Then,

the mean outage duration, $r = (\upsilon_i''\upsilon_i\nu_{ij} + \upsilon_j''\upsilon_i\nu_{ji}) / \lambda$ (8.12)

III) Third order cut set

Let the components in the cut set be i, j and k. The three events which lead to the load point interruptions are as follows:

1. component i in maintenance, j and k in passive outage mode;
2. component j in maintenance, i and k in passive outage mode;
3. component k in maintenance, i and j in passive outage mode.

Each of above events can have can have 2 subevents because of the order of failure of passive failures. For example, event 1 can have the following subevents:

1. subevent 1, i in maintenance, j fails and then k fails;
2. subevent 2, i in maintenance, k fails and then j fails;

The outage rate resulting from event 1 is defined as:

$$\lambda_1 = \lambda_i''(\lambda_j r_i'')(\lambda_k r_i'' r_j/(r_i''+r_j)) + \lambda_i''(\lambda_k r_i'')(\lambda_j)(r_i'' r_k)/(r_i''+r_k)$$

where:

λ_i'' = maintenance outage rate of component i

$\lambda_j r_i''$ = probability that component j fails while i in maintenance outage

$\lambda_k r_i'' r_j / (r_i'' + r_j)$ = probability that component k fails during the maintenance outage of component i and repair duration of component k

It may be noted that the above two terms are numerically equal to the respective probabilities because the denominator terms have been ignored (Refer equation 8.9).

The outage duration due to above event is given by the following equations

$$1/r_1 = 1/r_i'' + 1/r_j'' + 1/r_k''$$

$$r_1 = r_i'' r_j r_k \ / \ (r_i'' r_j + r_j r_k + r_i'' r_k)$$

Similarly, the indices resulting from events 2 and 3 are given by:

$$\lambda_2 = \lambda_j''(\lambda_i r_j'')(\lambda_k)(r_i r_j'')/(r_i + r_j'') + \lambda_j''(\lambda_k r_j'')(\lambda_i)(r_j'' r_k)/(r_j'' + r_k)$$

$$r_2 = r_j'' r_i r_k \ / \ (r_j'' r_i + r_j'' r_k + r_i r_k)$$

$$\lambda_3 = \lambda_k''(\lambda_i r_k'')(\lambda_j)(r_i r_k'')/(r_i + r_k'') + \lambda_k''(\lambda_j r_k'')(\lambda_i)(r_j r_k'')/(r_j + r_k'')$$

$$r_3 = r_k'' r_i r_j \ / (r_k'' r_i + r_k'' r_j + r_i r_j)$$

The total contribution to the load point reliability indices is given by the following equations:

Load point failure rate $\lambda = \lambda_1 + \lambda_2 + \lambda_3$ (8.13)

Mean outage duration = $r = (\lambda_1 r_1 + \lambda_2 r_2 + \lambda_3 r_3)/\lambda$ (8.14)

c) Active failures and active failures overlapping passive failures:

Let:

λ_{ig} = Active failure rate of component i

S_i = Switching duration of component i

λ_i = Passive failure rate of component i

r_i = Mean repair duration of component i

λ = Equivalent failure rate of the cutset

r = Equivalent mean repair duration of the cutset

i) First order cut set

Let the component in the cut set be i, then:

Load point failure rate contribution = λ_{ig}. (8.15)

Load point mean outage duration = S_i (8.16)

If the component can not be switched, then:

the load point mean outage duration = r_i

ii) Second order cut set

Let the components in the cut set be i and j, where i is the actively failed component.

Load point failure rate = Active failure rate of component i .(Probability j fails passively while i is actively failed)

+

passive failure rate of component j .(Probability i fails actively while j is failed passively)

$$= \lambda_{ig}\lambda_j S_i + \lambda_j \lambda_{ig} r_j \quad (8.17)$$

If the failed component can not be switched then,

the mean outage repair time is given by:

$$r = S_i r_j / (S_i + r_j) \quad (8.18)$$

If the component can be switched then the event can be terminated by the mean duration of S_i.

iii) Third order cut set

Let the components in the cutset be i, j and k and let i be the actively failed component.

Load point failure rate = Active failure rate of i(Probability j fails passively while i is actively failed) .(Probability k fails passively while i is actively failed and j is passively failed)

+

Active failure rate of i.(Probability k fails passively while i is actively failed) .(Probability j fails passively while i is actively failed and k is passively failed)

+

Passive failure rate of j.(Probability i fails actively while j is passively failed) .(Probability k fails passively while j is passively failed and i is actively failed)

+

Passive failure of j.(Probability k fails passively while j is passively failed) .(Probability i fails actively while j and k are passively failed)

+

Passive failure of k.(Probability i fails actively while k is passively failed) .(Probability j fails passively while k is passively failed and i is actively failed)

+

Passive failure rate of k.(Probability j fails passively while k is passively failed)

.(Probability i fails actively while j and k are passively failed)

Load point failure rate, $\lambda = \lambda_{ig}\lambda_j S_i \lambda_k S_i r_j/(S_i+r_j) + \lambda_{ig}\lambda_k S_i \lambda_j S_i r_k/(S_i+r_k)$

$$+ \lambda_j\lambda_{ig} r_j \lambda_k r_j S_i/(r_j+S_i) + \lambda_j\lambda_k r_j \lambda_{ig} r_j r_k/(r_j+r_k)$$

$$+ \lambda_k\lambda_{ig} r_k \lambda_j r_k S_i/(r_k+S_i) + \lambda_k\lambda_j r_k \lambda_{ig} r_k r_j/(r_k+r_j) \qquad (8.19)$$

If the event can not be terminated by switching then the mean repair duration is given by the following equations:

$$1/r = 1/S_i + 1/r_j + 1/r_k$$

$$r = S_i r_j r_k/(r_j r_k + S_i r_k + S_i r_j) \qquad (8.20)$$

Otherwise, if the event can be terminated by switching, then the mean repair time is given by the following equation:

$$r = S_i \qquad (8.21)$$

d) Active failures overlapping Maintenance Activity

i) First Order Cut Set

There can not be any contribution by maintenance outages overlapping active failures because of the assumption that if there exists an outage in the system the maintenance activity is not started.

ii) Second Order Cut Set

Let the components in the cut set be i and j, where i fails actively while j is on maintenance outage.

Load point failure rate = Maintenance outage of j.(Probability i fails actively when j is on maintenance outage)

Load point failure rate, $\lambda = \lambda_j''(\lambda_{ig} r_j'')$ (8.22)

If the event can not be terminated by switching, then

the mean outage duration = $S_i r_j'' / (S_i + r_j'')$ (8.23)

If the event can be terminated by switching, then

the mean outage duration = S_i (8.24)

iii) Third Order Cut Set

Let the components in the cut set be i, j and k, where i fails actively, j can be on maintenance outage and k can fail passively.

Load point failure rate = Maintenance outage rate of j.(Probability i fails actively when j is on maintenance outage).(Probability k fails passively while j is on maintenance outage and i is failed actively)

+

Maintenance outage rate of j.(Probability k fails passively when j is on maintenance outage).(Probability i fails actively while j is on maintenance outage and k is failed passively)

+

Similar terms when component k is on maintenance outage and component j fails passively.

Let the event when component i fails actively, j on maintenance outage and k fails passively be termed as event 1 and the event when component i fails actively, k on maintenance outage and j fails passively be termed as event 2. And also let the failure rate and mean repair duration contributions be called λ_1, r_1 and λ_2, r_2 respectively for event 1 and 2. Then:

$$\lambda_1 = \lambda_j'' \lambda_{ig} r_j'' \lambda_k \{ r_j'' S_i / (r_j'' + S_i) + r_j'' r_k / (r_j'' + r_k) \}$$

$$\lambda_2 = \lambda_k'' \lambda_{ig} r_k'' \lambda_j \{ r_k'' S_i / (r_k'' + S_i) + r_k'' r_j / (r_k'' + r_j) \}$$

Total load point contribution = $\lambda_1 + \lambda_2$ (8.25)

If the event can not be terminated by switching, then

$$r_1 = r_j'' S_i r_k / (S_i r_k + r_j'' r_k + S_i r_j'')$$

and

$$r_2 = r_k'' S_i r_j / (S_i r_j + r_k'' r_j + r_k'' S_i)$$

The equivalent load point failure duration = $r = (\lambda_1 r_1 + \lambda_2 r_2)/(\lambda_1 + \lambda_2)$ (8.26)

If the event can be terminated by switching, then the load point failure duration, $r = S_i$

(8.27)

Active failures with stuck breakers and overlapping passive failures

) First Order Cut Set

Let i be the actively failed component and j be the stuck breaker present in the system, then the load point failure rate = $\lambda_{ig} Pr(j)$ (8.28)
where: Pr(j) is the probability of the stuck breaker.

If the component can not be switched, then the load point mean duration of repair = r_i (8.29)

If the component can be switched, then the load point mean duration of repair = S_i (8.30)

) Second Order Cut Set

Let i be the actively failed component and let j be the stuck breaker.

A) If the components in the cut set are i and j, then the load point failure rate = $\lambda_{ig} Pr(j)$ (8.31)

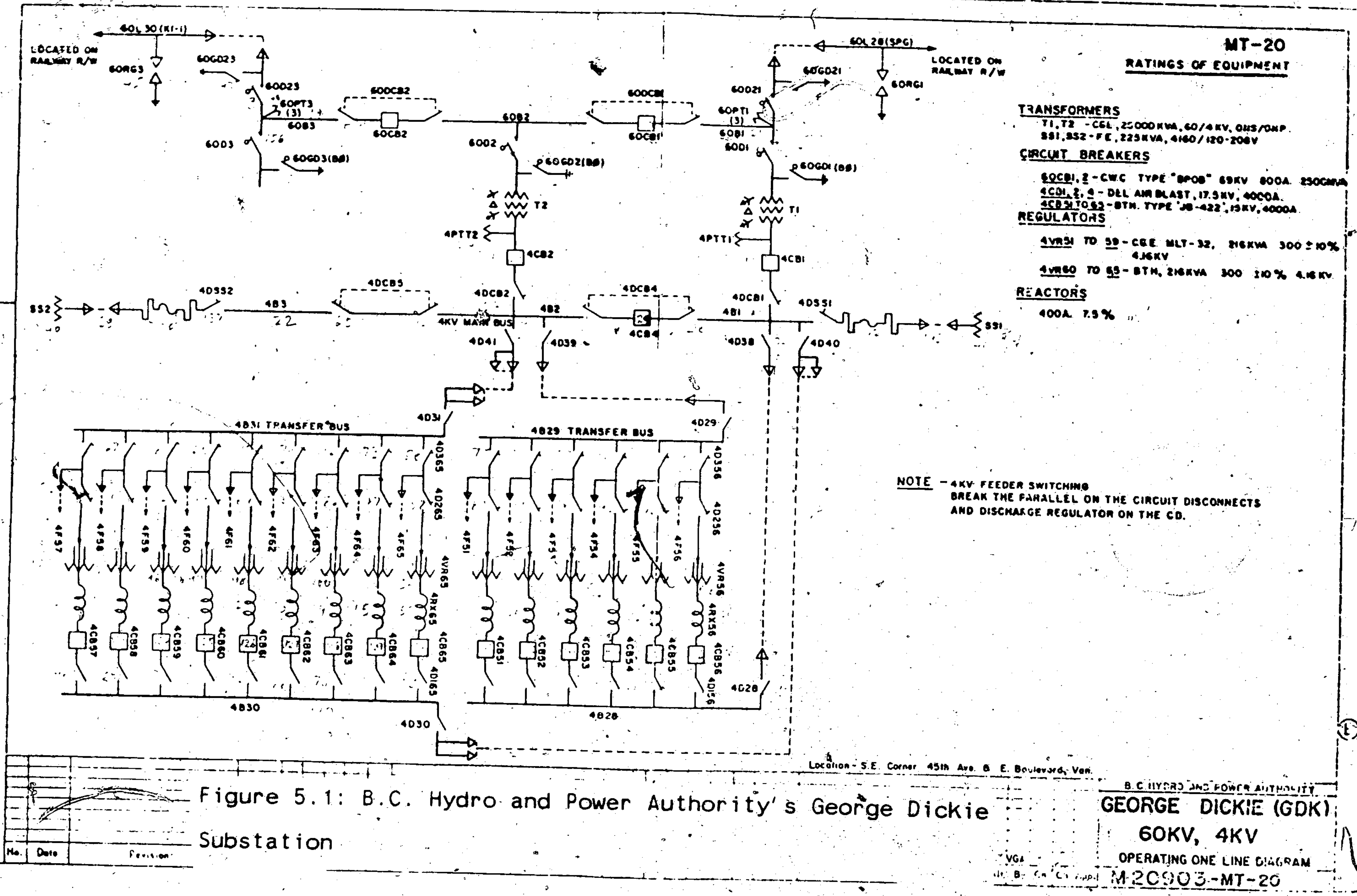

Figure 5.1: B.C. Hydro and Power Authority's George Dickie Substation

5.3 *Criteria of Successful System Operation*

The criteria of successful substation operation is defined as the continuity of service between either or both sources 1 and 2 and the load point 52 which was selected to illustrate the reliability methodology proposed in this thesis.

5.4 *Operating Procedure*

With reference to Figure 5.1, and considering load point 52, the following discussion describes the operating procedures for the substation configuration. The disconnecting switches 30, 31, 36, 37, 51, 67 to 73 and 75 to 79 are normally open. The transfer bus 38 and 39 are kept charged by closing the disconnecting switches 53, 58 and circuit breaker 54 and disconnecting switches 66 and 80 and circuit breaker 136, respectively. In the event of active failures of components 46 and 47, breakers 16 and 29 operate to isolate the fault. However, for active failures of components 48, 49, 50 and 52, the fault is cleared by the breaker 47. It is assumed that the normally open components are fully reliable. In the event of an outage of components in the feeder bay 4F57 or any other component in the normally closed tie set, the faulty component is identified and isolated for repair. It is then ascertained whether continuity of service between the load point and any of the sources can be established by closing the normally open components or not. If so, the normally open components are closed and the supply resumed. It may be noted that in the event of failure of the main bus and the components in the feeder and transfer bays; the supply to the feeder e.g., 4F57 can be restored by closing the normally open disconnecting switches 30, 36 and 51 and hence transferring the protection to the main bus breakers 15 and 29 instead of the breaker 47. In practice, the feeder loads may be transferred to the adjacent feeders (e.g., the feeder 4F57 can be fed by feeder bay of 4F58 by closing disconnecting switches 67 and 51, provided the components in the feeder bay 4F58 have enough capacity margin). This activity is similar to transferring the feeder load to the transfer bay. In this study the bays for feeders 4F65 and 4F56 have been considered as transfer feeder bays and the activity of transferring the load to adjacent feeders has been restricted in this study.

5.5 *System analysis*

The input data for the George Dickie substation configuration is presented in Appendix F. The paths or tie sets between the sources and the load point by considering the normally open components open are formulated and the corresponding cut sets are deduced. These tie sets and the cut sets are presented in Appendix F. Similarly, the tie sets and the cut sets by closing the normally open components are also deduced. Next, the K type and H type cuts which represent the events which can be terminated by repair and switching respectively are calculated. All the above tie sets and the cut sets are presented in the Appendix F.

The contributions to the reliability indices i.e., failure rate, mean duration of repair and the annual interruption time for the designated load point are calculated for the passive failures, overlapping passive failures and passive failures overlapping maintenance by the appropriate equations presented in Appendix G. The impact of each component failure in an active mode, active failures overlapping passive failures and active failures overlapping maintenance are also calculated by the appropriate equations. Next, the impact of active failures with stuck breakers present in the system is analysed and finally the impact of common mode failures is studied. The load point reliability indices of the George Dickie substation configuration are presented in Table 5.2

Table 5.2: Load point reliability indices of George Dickie substation configuration

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS			
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	OUTAGE TIME HOURS/YR
1	0.0194475	60.5544739	1.1776333
2	0.0075107	5.4066353	0.0406073
3	0.7600482	3.0000000	2.2801418
4	1.2500000	3.0000000	3.7500000
5	0.2668599	1.9455576	0.5191913
6	0.0035169	2.0538054	0.0072230
7	0.0990719	2.3328838	0.2311233
8	0.0000358	2.1325779	0.0000765
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	2.9684868	3.7382651	11.0969896

LOAD POINT AVAILABILITY = 0.99873435497

5.6 Discussion of results

The weakest link between the sources of supply and the load point is that formed by elements 24, 33, 45, 42, 40, 46, 47, 48, 49 and 50. The failure of any of these components cause a load point interruption and hence they constitute first order cuts. But these events can be terminated by switching i.e., by closing normally open disconnecting switches 30, 36 and 51. Hence, the first order cuts detected by the program are the H type cuts i.e., the events which can be terminated by reconfiguration. Since these are the first order events, their contribution to the load point failure rate is the highest. The overlapping passive failures with maintenance outages which can be terminated by switching i.e., event 4 has the next highest contribution to the load point failure rate. This is followed by event 3 (i.e., the passive failures and overlapping passive failures which can be terminated by switching). The next highest contribution to the load point reliability indices is due to common mode failures.

The contribution to the reliability indices to the load point by active failures can be clearly seen from the results for event 5. The contribution to the reliability indices to the load point by active failures overlapping passive failures is considerably higher than event 1 i.e., the passive failures and the overlapping passive failures because there are numerous components which are not on the direct path between the sources and the load point (e.g., adjacent feeders) and their failure in active mode cause interruptions to the load point being considered.

5.7 *Impact of Reserve Supply*

Often a reserve supply (e.g., generator, UPS, etc.) is available or there are adjacent distribution links (i.e., another substation) present which can have a significant impact on the reliability levels of the load point. This aspect can be studied by a Markov model [4] shown in Figure 5.2.

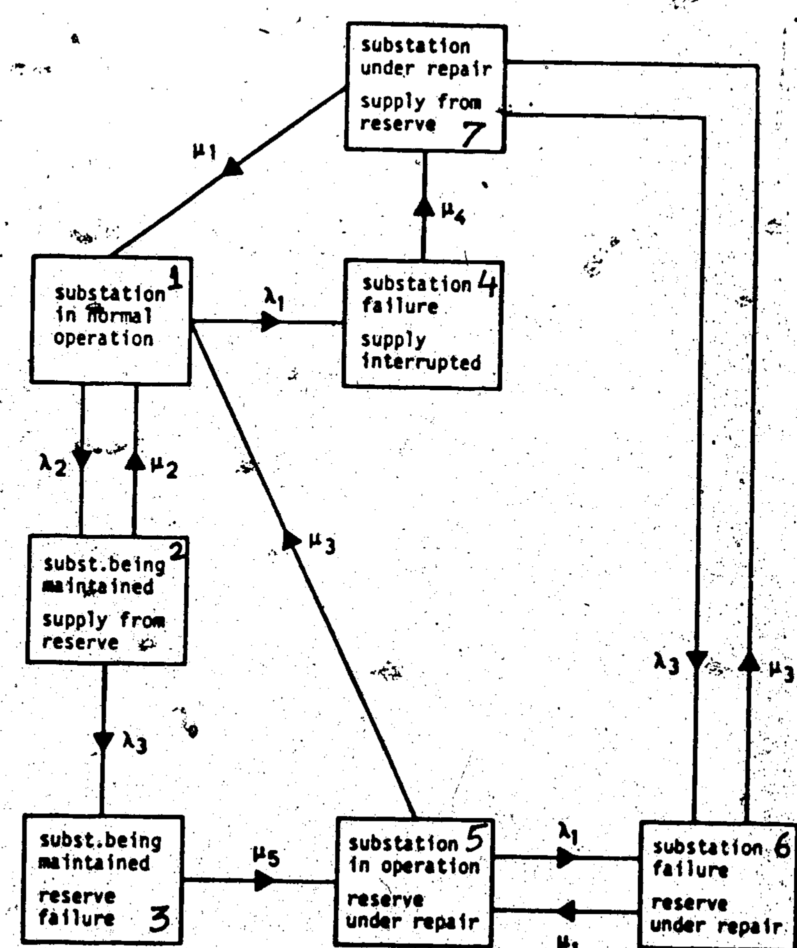

Figure 5.2: Markov model for reserve supply considerations

Under normal operating conditions, the electrical supply to the load is fed by the substation. In case of a substation failure the supply is fed by the reserve system. After the repair process has been completed the substation configuration is returned to its normal operating configuration. When the substation is undergoing maintenance, the load is again fed by the reserve system.

The definitions of symbols used for the Markov model presented in Figure 5.2 are listed in Table 5.3.

Table 5.3: Definitions of symbols used in Markov model

Symbol	Description
λ_1	Failure rate of substation based on random events
λ_2	Maintenance outage rate of substation
λ_3	Failure rate of reserve supply
μ_1	Restoration rate of substation based on random events
μ_2	Maintenance restoration rate
$\mu_3 = 1/\lambda_3$	Restoration rate of reserve supply
$\mu_4 = 1/\lambda_4$	Switching rate of system reserve
$\mu_5 = 1/\lambda_5$	Rate of time lapse required to return substation to service

Referring to Table 4.2, it can be clearly seen that all odd numbered events are random events and the even numbered events are maintenance oriented and hence represent scheduled activities. λ_1 and μ_1 are random events and are defined in Table 5.3. λ_2 and μ_2 are based on maintenance events. Referring to Table 5.2, the substation random event failure rate and its mean duration (i.e., λ_1 and r1) and the substation maintenance failure rate and its mean duration (i.e., λ_2 and r2) can be calculated as follows :

$$\lambda_1 = \lambda \text{ event } 1 + \lambda \text{ event } 3 + \lambda \text{ event } 5 + \lambda \text{ event } 7 + \lambda \text{ event } 9 \quad (5.1)$$

$$r_1 = (\lambda \text{ event } 1 \times r \text{ event } 1 + \ldots + \lambda \text{ event } 9 \times r \text{ event } 9)/\lambda_1 \quad (5.2)$$

Similarly,

$$\lambda_2 = \lambda \text{ event } 2 + \lambda \text{ event } 4 + \lambda \text{ event } 6 + \lambda \text{ event } 8 + \lambda \text{ event } 10 \quad (5.3)$$

$$r_2 = (\lambda \text{ event } 2 \times r \text{ event } 2 + \ldots + \lambda \text{ event } 10 \times r \text{ event } 10)/\lambda_2 \quad (5.4)$$

The system reserve reliability data was selected from reference [4] and is listed in Table 5.4 below:

Table 5.4: Data for system reserve

Symbol	Value
λ_3	1.0 failure/year
r3	4.0 hours
r4	15 minutes
r5	1 hour

If P1, P2, P3, P4, P5, P6 and P7 are the probabilities of occupying the states 1, 2, 3, 4, 5, 6 and 7, respectively in the Markov model shown in Figure 5.2, then the following equations can be generated by frequency balance approach:

$$P1(\lambda_1+\lambda_2) = P2\,\mu_2 + P7\,\mu_1 + P5\,\mu_3 \qquad (5.5)$$

$$P2(\mu_2+\lambda_3) = P1\,\lambda_2 \qquad (5.6)$$

$$P3\,\mu_5 = P2\,\lambda_3 \qquad (5.7)$$

$$P4\,\mu_4 = P1\,\lambda_1 \qquad (5.8)$$

$$P5(\lambda_1+\mu_3) = P3\,\mu_5 + P6\,\mu_1 \qquad (5.9)$$

$$P6(\mu_1+\mu_3) = P5\,\lambda_1 + P7\,\lambda_3 \qquad (5.10)$$

and,

$$P1(1+P2/P1+P3/P1+P4/P1+P5/P1+P6/P1+P7/P1) = 1.0 \qquad (5.11)$$

The evaluation of the above set of simultaneous equations leads to the indices of reliability shown in Table 5.5.

Table 5.5: Load point indices of reliability by considering reserve supply

LOAD POINT FAILURE RATE = 1.7082615 f/yr.

LOAD POINT MEAN DOWN TIME = 0.2478783 hours

LOAD POINT DOWN TIME PER YEAR = 0.4234409 hours/yr.

LOAD POINT AVAILABILITY = 0.9999517

The impact of consideration of system reserve on the load point indices of reliability can be clearly seen from Table 5.5. All three indices i.e., load point failure rate, mean duration of an outage and the annual outage time are significantly lowered.

CHAPTER 6

CONCLUSIONS

The methodology for reliability analysis of power system substations has been developed in this thesis. The various concepts regarding state space and cut set modelling has been introduced.

It was pointed out that the results obtained by Markov modelling are accurate provided the underlying assumptions of the failure processes associated with a given substation configuration are not violated. But this approach becomes unmanageable as the number of components in a given system increase. The complexity of the problem increases significantly if the components can occupy various failure states.

The cut set technique is quite useful in analysing complex and as well as simple systems. It identifies the weak points in the system in terms of the order and the number of cut sets. The results obtained by cut set modelling are exact if all the cut sets of the system are taken into consideration. The larger the system configuration in terms of number of components, the larger is the order of cut sets and it becomes computationally inefficient to analyse the cut sets beyond third order. In practice, the contributions to the indices of reliability by higher order cut sets than third order may be negligible [3, 6, 12]. Thus, complex systems can be analysed accurately by considering all the cut sets up to third order.

The impact of various modes of component outages on load point interruptions has been studied. The modes of component outages considered in this thesis are listed as follows:

1. passive failures and overlapping passive failures;
2. passive failures overlapping maintenance;
3. passive failures and overlapping passive failures which can be terminated by switching;
4. passive failures overlapping maintenance which can be terminated by switching;
5. active failures and active failures overlapping passive failures;
6. active failures overlapping maintenance outages;
7. active failures with stuck breakers and active failures with stuck breakers and active failures with stuck breakers overlapping passive failures;
8. active failures with stuck breakers overlapping maintenance;
9. common mode outages and common mode outages overlapping passive failures;
10. common mode outages overlapping maintenance outage;

Each mode of above failure events has a distinct impact on the frequency and duration of load point interruptions.

The contribution and their net effect on the reliability indices of each of these events was studied in detail for ten basic substation configurations being used by the electric utilities. The single line diagrams and a discussion of the results of the ten published substation configurations is shown in Appendix C.

Each mode of component failures has a distinct impact on the reliability levels of a load point. Based on the need and the quality of service desired, the effects of failure modes of components can be studied for different substation configurations. The most suitable configuration can then be selected by selecting the best load point reliability level configuration from these.

The computer program described in the thesis is very general in nature. It is suitable for predicting the load point reliability indices of any general substation configuration. Many other relevant failure modes and their effects can also be easily added to the program. The effects of varying the system configuration on the load point indices have been illustrated. This form of analysis provides a quantitative basis for the judicious selection of a reliable and economical substation design.

CHAPTER 7

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APPENDIX A

Definition of Terms and Reliability Indices

The following definitions have been used in the thesis [18, 27, 28, 29]:

Component: A component is a piece of equipment, a line, a section of line or a group of items which is viewed as an entity for the purpose of reporting, analyzing and predicting outages.

System: A system is a group of components which are interconnected to form a fixed system configuration to perform a specified function.

Reliability: Reliability is the probability of a system or a component performing its intended function (i.e., purpose) adequately for the period of time intended under the operating conditions encountered [5].

Power System Substation: An assembly of switchgear components used to direct the flow of electrical energy in a power system, and to ensure the security of the system by providing a point at which automatic protective devices, and means for diverting the flow of energy along alternative routes can be installed.

A substation may be associated with a generating station, directly controlling the flow of power into the power system, or with power transformers converting the voltage of supply to a higher or lower level, or it may connect a number of supply routes at the same voltage level. Basically, any substation consists of a number of incoming and outgoing circuits connected to a common bus bar system, the main components of each circuit being a circuit breaker, instrument transformers and one or more disconnecting switches.

Circuit Breaker: A circuit breaker is defined in IEC Publication 50, Section 15 as "a device capable of making, carrying and breaking normal load currents, and also making and breaking (under predetermined conditions) abnormal currents such as short circuit currents", a description making clear its two fold function. The first use is in switching circuits in and out to control the flow of energy, and disconnecting circuits, or part of power system, to allow maintenance work or extensions to be effected. In performing its second duty, a circuit breaker is part of a scheme of protection that automatically disconnects any part of the system on which a fault occurs.

Outage Terms

Outage: An outage describes the state of a component when it is not available to perform its intended function due to some event directly associated with that or any other component.

Failure: A failure describes the state of a component when it is not available to perform its intended function due to the malfunction of that component. A component failure results in a component outage but a component outage can occur without a component failure.

Switching Time: Switching time is the period from the time a switching operation is required due to an outage until that switching operation is performed. For example, switching operations include successfully reclosing a circuit breaker after a trip out, opening or closing a sectionalizing switch or circuit breaker, or replacing a fuse link.

Exposure Time: Exposure time is the time during which a component is performing its intended function and there is a probability that this component may fail during this time period.

Outage Rate: The outage rate for a particular classification of outage and type of component is the mean number of outages per unit exposure time per component. For example, a 10 Km. section of line averaging one outage every 10 years has an annual outage rate of .01 failures/km/year.

Outage Duration: Outage duration is the period from the initiation of an outage until the affected component is repaired or replaced and becomes available to perform its intended function.

Interruption: An interruption is the loss of service to one or more customers (load points) and is the result of one or more component outages or component outages overlapping maintenance activity.

Interruption Duration: Interruption duration is the period from the initiation of an interruption to a customer until service has been restored to that customer.

Measures of Reliability or Reliability Indices

Many different measures of service reliability are possible and useful. Measures of reliability usually relate to the frequency or duration of interruptions or both. Useful measures of reliability should have two properties:

1. be calculable from the operating history of the system;

2. be calculable from component data using system reliability calculation techniques.

Measures of reliability which have been used in this thesis are as follows:

Outage Rate: This has been defined above.

Outage Duration: This has been defined above.

Reliability: This has been defined above.

However, it can be added that the relationship between reliability, R(t) and outage rate exists for all distributions i.e.,

$$R(t) = \exp\left[-\int_0^t \lambda(t)\,dt\right]$$

in the special case when is constant and independent of time

$$R(t) = \exp(-\lambda t)$$

Availability (A): This is the ratio of mean up time of the component to the total cycle time (i.e., m+r)

$$A = \frac{m}{m + r} = \frac{\mu}{\lambda + \mu}$$

where:

m = mean up time of the system
r = mean down time of the system
λ = failure rate of the system
μ = restoration rate of the system

Unavailability: The ratio of mean down time of the system to the cycle time is called the unavailability of the system.

Outage frequency: This is the ratio of the availability of the system to the outage duration.

Outage duration per year: This is the mean outage time of the system in one year.

All these indices are related through the following equations :

$$\bar{A} = f.r$$

$$\bar{A} = 1 - A; \lambda = f/A$$

$$\Gamma = A . T$$

where: T is the basic period of analysis (e.g., one year)

The total outage rate of the system when all outage modes are taken into account may be evaluated as follows:

$$\lambda_T = \sum_{i=1}^{n} \lambda_i$$

The total availability of the system as follows:

$$A_T = \prod_{i}^{n} A_i$$

where: λ_i and Ai being reliability indices for the outage mode involved, n is the total number of outage modes and i is the ith outage mode.

APPENDIX B

The Algorithm for Evaluation of Substation Reliability [17, 18, 23]

The algorithm described here performs the failure modes and effects analysis and computes system reliability indices. The criteria of success is the continuity between any source nodes and a load point by at least one path. It is assumed that each source and the path are capable of meeting the load requirements. In other words, the failure of any circuit between the source and the sink (load point) does not cause overloading of other circuits.

The following are the steps for the evaluation of load point reliability of a substation configuration :

1. Read the input data. It consists of a number of components in the system, the substation graph (configuration) in terms of predecessors of each component, the reliability data i.e., the passive failure rate, passive repair rate, maintenance outage rate, maintenance restoration rate, active failure rate, switching time and the stuck probability. The stuck probability of a breaker or a switch represents the probability of its being stuck i.e., not operating when required to do so. The stuck breaker probability is estimated from the ratio of the number of times the breaker fails to operate when called upon to do so to the total number of times the breaker is called upon to operate. The effects of failures of components in active mode on other components of the system are read. The unfaulted components which are isolated as a result of the fault on the component under consideration are identifeid. Similarly the combined effects of a component active failure and the stuck breaker condition present in the system are also read. All those breakers which operate during the active failure of the component under consideration are considered stuck one at a time and the effects on all other healty components are recognized.

   There are certain components in the system which are not on a direct path between the source and the sink, hence their passive failure will not cause any effect on the system outage indices but their active failures may do so. Such components are assigned zero values (i.e., zero to six significant decimal places) for the passive failure and restoration rates. The maintenance outage of such components will also not affect the load point outages. The active failure and restoration rates are assigned the actual values.

The components which can fail in common mode are also recognized and their respective failure and repair rates are specified.

2. The minimal paths between the source and the designated load point are established [25] with the normally open branches open.

3. The minimal cut sets [3] corresponding to minimal paths for N/O branches are deduced. Let us refer to these cut sets as G.

4. The minimal paths are also formed by closing the N/O branches.

5. The minimal cut sets for above paths are also deduced.

6. Some of the cut sets deduced in step 5 obtain additional elements than those deduced in step 3. Let us denote these cut sets as H. Let us denote the remaining cut sets of G as K. It can be seen that the H type cuts are those which can be eliminated by closing the normally open branches.

7. Calculate the outage rate, average duration and total outage time due to passive failures for K type cut sets by using the appropriate equations. Once the failure rate and the average outage duration of a particular event are known the non-availability of the system due to that event can be easily calculated. The event in this case is passive failures. If is the outage rate and "r" the average repair time or the average outage duration, then:

$$\text{Non-availability} = \frac{\lambda r}{1+\lambda r}$$

8. Calculate the contribution to above indices for the event passive failures overlapping maintenance outage for K type cuts.

9. The substation outage frequency for H type cuts is evaluated by the formula (3.5) described in Chapter 3. The switching time S is assumed equal for all components and is the time period starting from the active failure of a component and lasting up to the time for disconnecting the faulty component from service and reconnecting all other healthy components back to service. The fault identification time is included in

the switching time.

Let the frequency of failure for these cuts be denoted as f, then the Non-availability due to this event, $\bar{A}$=fs

Having known the availability and the frequency, the failure rate contribution due to an event can be calculated as follows:

System failure rate = frequency/availability

System average down time/yr = failure rate*average repair time

10. The above indices of reliability for overlapping of passive failures and maintenance outages for H type cuts are evaluated in the same way as K type cuts as shown in step 8.

11. Consider the active failure of each component. Interrupt all those paths containing the actively failed component and the healthy components which are switched out as the effect of the faulted component. If all the paths between the source and the load point are interrupted, then the faulted component forms the first order cut. If there are some paths available between the source and the load point then deduce the cut sets out of these paths. The first order cuts thus obtained will form the second order cuts for the system when considered with the actively failed component under consideration. That is, if the actively failed component is i and there are n paths still remaining connected or unaffected between the source and the load point and if j, k, l . . . etc. are the first ordered cuts deduced out of paths n, then, for the complete outage to occur between the source and the load point the following cut sets are involved:

    1) i, j
    2) i, k
    3) i, l
    4) i, . .

where: i is the actively failed component and the other components may fail in passive mode or can be on maintenance outage mode.
The probability of two active failures in the system is assumed zero.

Since all component faults are included in the passive failures i.e., it is only a particular fraction of total component failures which form the active failure, therefore, if component passive failures or overlapping passive failures can cause an interruption at the load point, then the contributions due to active failures need not be considered. Hence, from the cut sets obtained by considering active failures, those cut sets are dropped which have been evaluated in K type or H type cuts.

If the cut sets can be eliminated by switching i.e., by closing the normally open branches the repair time for that component is replaced by the switching time, otherwise, the repair time is used for the calculation of reliability indices due to this mode of failure.

12. The contributions to the load point reliability indices due to combined active failures and the stuck breaker condition are also done in the same way as in step 11. All those breakers are considered stuck one at a time along with the actively failed component which take part in clearing the fault of the component under consideration. The probability of two stuck breakers is assumed to be zero. The contributions due to this failure mode overlapping passive outages and the maintenance outages are evaluated by the appropriate equations presented in the Appendix G.

13. The overall indices of reliability are evaluated as follows:
If $\lambda_1, \lambda_2, \lambda_3 \cdots\cdots \lambda_n$ are the failure rate contributions due to each failure mode, and r1, r2, r3 . . rn, the average outage duration and $\bar{A}1$, $\bar{A}2$, $\bar{A}3$, . . ., $\bar{A}n$, the non availability contributions then, the following reliability parameters can be calculated:

overall failure rate, $\lambda = \sum_{i=1}^{n} \lambda_i$ failures/year

overall outage duration, $r = \sum_{i=1}^{n} \lambda_i r_i / \lambda$ hours

overall down time/yr, $\tau = \lambda r$ hours/year

overall non availability $= \bar{A} = \sum_{i=1}^{n} \bar{A}_i$

or

overall availability, $A = 1. - \bar{A}$

APPENDIX C

C.1 Single Line Diagrams:

Figures C.1 and C.2 represent the single line diagrams of the ten published substation configurations and their load point indices of reliability are presented in Tables C.1 to C.10. The reliability data has been selected from reference [18] and is the same as used for case studies 4.1 and 4.2 in Chapter 4.

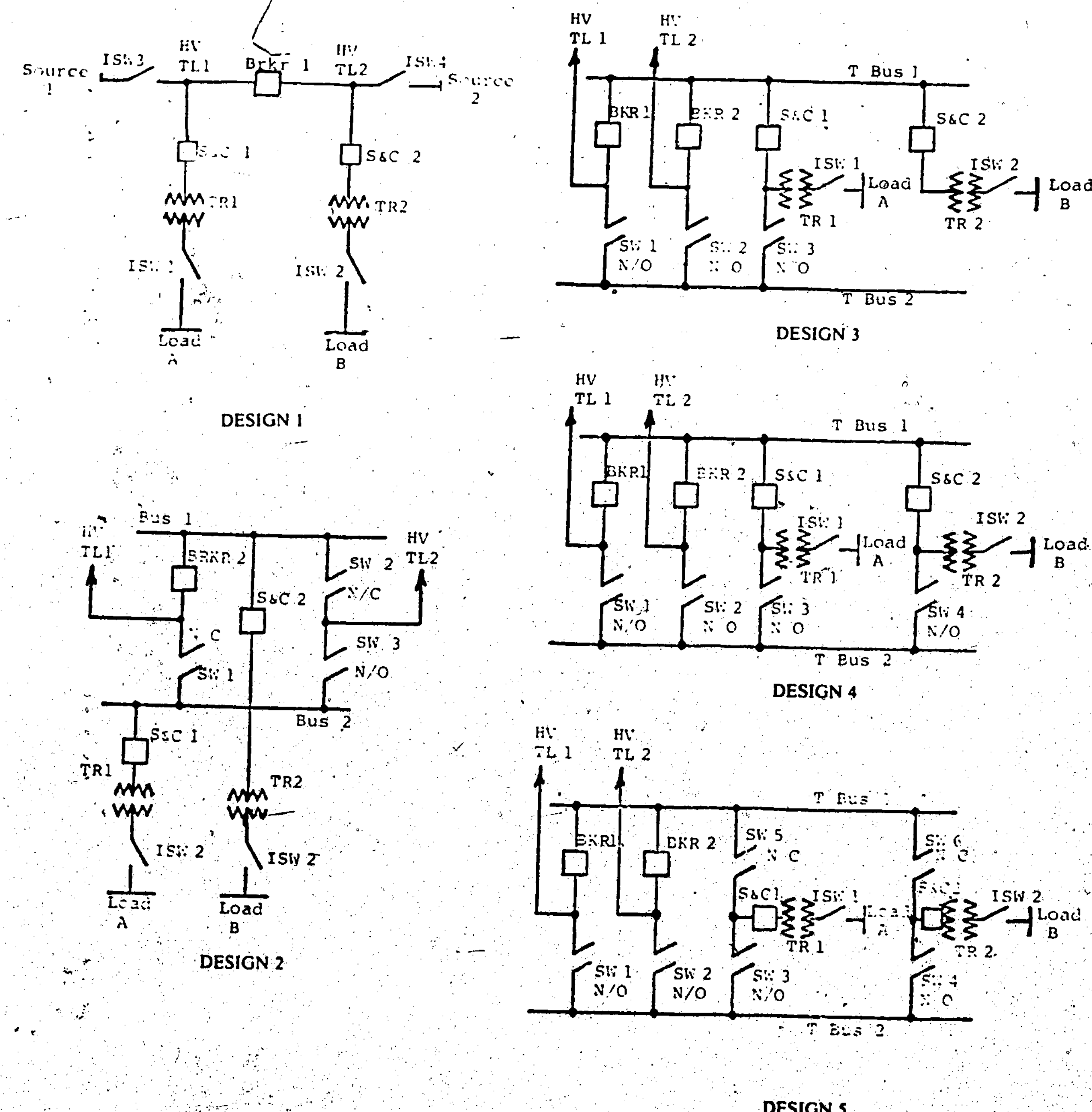
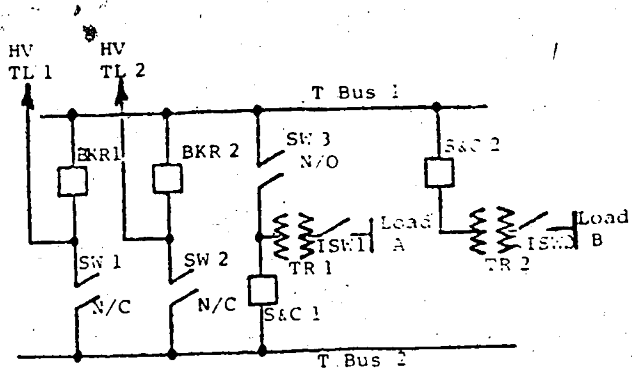
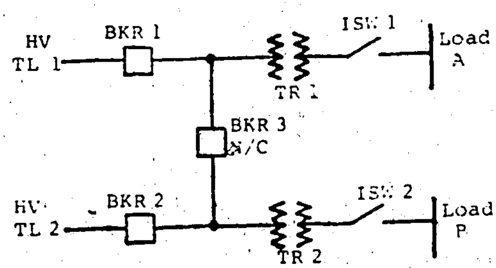


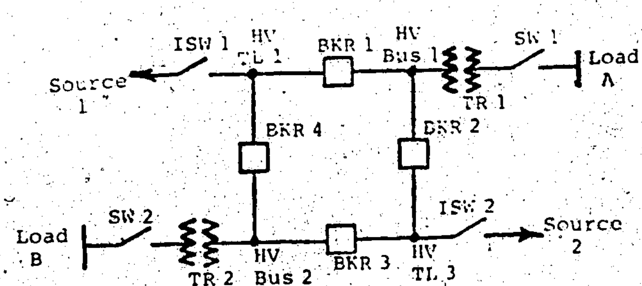
Figure C.1: Single line diagrams of designs 1 to 5



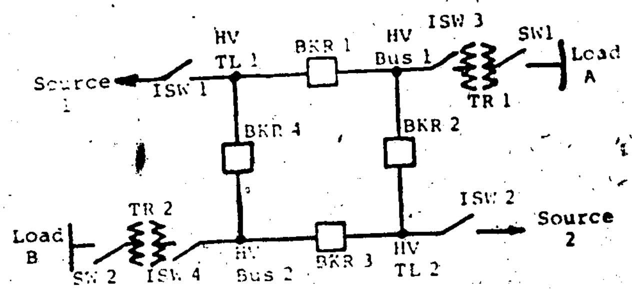
DESIGN 6



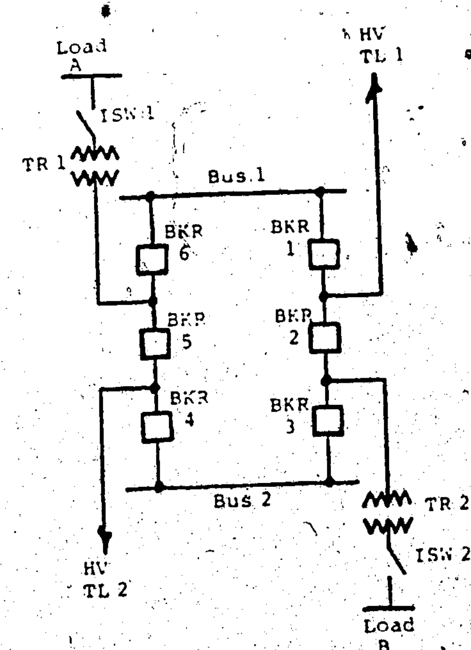
DESIGN 7



DESIGN 8



DESIGN 9



DESIGN 10

Figure C.2: Single line diagrams of designs 6 to 10

Table C.1: Load Point Reliability Indices of Design #1

************ DESIGN NO. 1 **********
LOAD POINT INDICES OF RELIABILITY

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
		CONTRIBUTIONS	
1	0.0129590	93.4931335	1.2115726
2	0.0041045	11.1485033	0.0457588
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0313090	1.9736452	0.0617928
6	0.0004201	1.4103251	0.0005925
7	0.0008501	1.5882168	0.0013501
8	0.0000006	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6116432	7.2134562	4.4120607

LOAD POINT AVAILABILITY=0.99949663877

Table C.2: Load Point Reliability Indices of Design #2

************ DESIGN NO. 2 **********
LOAD POINT INDICES OF RELIABILITY

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
		CONTRIBUTIONS	
1	0.0135215	89.6880951	1.2127151
2	0.0042273	10.9638662	0.0463476
3	0.0026129	3.0000000	0.0078386
4	0.0010778	3.0000000	0.0032333
5	0.0302601	2.0077639	0.0607551
6	0.0001765	2.4062052	0.0004247
7	0.0016402	1.5731382	0.0025802
8	0.0000012	1.1043758	0.0000013
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6155173	7.1888952	4.4248886

LOAD POINT AVAILABILITY=0.99949526787

Table C.3: Load Point Reliability Indices of Design #3

************ DESIGN NO. 3 **********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0340842	36.0718079	1.2294788
2	0.0028665	12.5465918	0.0359653
3	0.0030537	3.0000000	0.0091611
4	0.0020491	3.0000000	0.0061473
5	0.1199999	1.9999990	0.2399998
6	0.0	0.0	0.0
7	0.0028500	1.4035072	0.0040000
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7269034	6.3498764	4.6157465

LOAD POINT AVAILABILITY=0.99947357178

Table C.4: Load Point Reliability Indices of Design #4

************ DESIGN NO. 4 ***********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0073532	156.6836853	1.1521225
2	0.0019910	14.2140570	0.0282997
3	0.0293319	3.0000000	0.0879956
4	0.0029248	3.0000000	0.0087743
5	0.1199999	1.9999990	0.2399998
6	0.0	0.0	0.0
7	0.0030000	1.4333315	0.0043000
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7266006	6.3480349	4.6124859

LOAD POINT AVAILABILITY=0.99947386980

Table C.5: Load Point Reliability Indices of Design #5

************* DESIGN NO. 5 **********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0129498	93.5601044	1.2115850
2	0.0040571	11.3447628	0.0460265
3	0.0292784	3.0000000	0.0878351
4	0.0025914	3.0000000	0.0077743
5	0.1599999	2.2499962	0.3599992
6	0.0	0.0	0.0
7	0.0029500	1.7118626	0.0050500
8	0.0	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.7738265	6.2149124	4.8092632

LOAD POINT AVAILABILITY=0.99945139885

Table C.6: Load Point Reliability Indices of Design #6

************ DESIGN NO. 6 *********

LOAD POINT INDICES OF RELIABILITY

CONTRIBUTIONS

EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0103698	113.9890289	1.1820450
2	0.0029517	12.2393322	0.0361265
3	0.0031157	3.0000000	0.0093471
4	0.0012761	3.0000000	0.0038284
5	0.3339998	1.5808372	0.5279993
6	0.0000000	0.5739490	0.0000000
7	0.0006001	1.3333797	0.0008002
8	0.0000006	0.8724269	0.0000005
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.9143137	5.3057737	4.8511410

LOAD POINT AVAILABILITY=0.99944663048

Table C.7: Load Point Reliability Indices of Design #7

*********** DESIGN NO. 7 **********

LOAD POINT INDICES OF RELIABILITY

EVENT	CONTRIBUTIONS OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0075789	152.1700439	1.1532774
2	0.0028507	11.6987009	0.0333493
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0307924	1.9979944	0.0615229
6	0.0005548	1.5390921	0.0008539
7	0.0016626	1.5124254	0.0025146
8	0.0000000	0.0	0.0
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6054444	7.1724386	4.3425121

LOAD POINT AVAILABILITY=0.99950468540

Table C.8: Load Point Reliability Indices of Design #8

*********** DESIGN NO. 8 **********

LOAD POINT INDICES OF RELIABILITY

EVENT	CONTRIBUTIONS OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0079762	144.5971069	1.1533337
2	0.0026018	11.2818251	0.0293533
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0014531	1.9906425	0.0028927
6	0.0005481	1.9997864	0.0010962
7	0.0012275	1.9858694	0.0024376
8	0.0000125	0.3319820	0.0000042
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.5758193	7.4330845	4.2801123

LOAD POINT AVAILABILITY=0.99951171875

Table C.9: Load Point Reliability Indices of Design #9

************ DESIGN NO. 9 **********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0130838	88.9582825	1.1639090
2	0.0039864	8.0455503	0.0320730
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0214655	2.9310932	0.0629172
6	0.0005619	1.9997873	0.0011236
7	0.0012298	1.9860315	0.0024423
8	0.0000144	0.4192657	0.0000060
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.6023416	7.2275677	4,3534641

LOAD POINT AVAILABILITY=0.99950337410

Table C.10: Load Point Reliability Indices of Design #10

************ DESIGN NO. 10 **********

LOAD POINT INDICES OF RELIABILITY

	CONTRIBUTIONS		
EVENT	OUTAGE RATE FL/YR	AVG DURATION HOURS	TOTAL OUTAGE TIME HOURS/YR
1	0.0073596	156.5519714	1.1521568
2	0.0019933	14.2033005	0.0283109
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0014196	1.9941425	0.0028310
6	0.0004935	1.9996061	0.0009868
7	0.0001329	2.7119856	0.0003605
8	0.0000144	0.2950544	0.0000043
9	0.5620000	5.4999952	3.0909967
10	0.0	0.0	0.0
TOTAL	0.5734133	7.4564791	4.2756433

LOAD POINT AVAILABILITY=0.99951225519

C.2 Discussion of substation designs 1 and 2

The design 1 and 2 have been designated as "1" breaker designs. The only difference between the two is the addition of a transfer bus in design 2. The load point reliability indices of the two designs are approximately the same and there is no improvement to reliability levels of the load point by addition of the transfer bus because there are 24 second order and 12 third order cuts for the first design and 23 second order and 13 third order cuts for the second design. However out of the cuts mentioned above for the second design, there are 6 H type second order cuts and 7 H type third order cuts in design 2 i.e., those events which can be terminated by switching instead of repair. But based on domains of the data, there is no improvement in load point reliability levels of design 2 than over design 1.

C.3 Discussion of substation designs 3 to 6

The designs 3 to 6 have been designated as "2" breaker stations in reference [26]. No circuit breaker has been provided for transferring the load to the transfer bus. Hence, if the load is transferred to the transfer bus by closing the normally open switches e.g., switches 7, 8 and 9 in design 3, then any active faults on the tie sets between the sources and the load point, the far end breakers of sources 1 and 2 operate to clear the fault and the faults within the substation are cleared by the components outside the substation, which is not a good operating procedure. Hence, for making the designs practical, either the normally open switches 7 and 8 or the normally open switch 9 be replaced by a normally open circuit breaker. The similar reasoning holds for normally open switches 7, 8, 9 and 10 for designs 4 and 5. For the studies presented in this thesis, the normally open switches 7 and 8 were treated as normally open breakers.

The overall contribution to load point reliability indices by designs 3 and 4 are approximately the same. In design 3, only the load point A can be switched to the transfer bus but in design 4, both load points A and B can be switched to the transfer bus. Consequently, the contributions to the reliability levels of load point by event 1 (i.e., those events which are terminated by repair) is significantly higher in design 3 than those in design 4 and vice versa for event 4 (i.e., those events which can be terminated by switching).

The impact of active failures on load point reliability levels in case of designs 3 and 4 is significantly higher than those in designs 1 and 2. It is because there is only one single contingency event each in design 1 and 2 which leads to a load point interruption. In design 1 this event is active failure of bus coupler breaker 9 and in design 2 it is bus side breaker 3, the active failure of which leads to load point interruption. In designs 3 and 4 there are 5 single contingency events each which lead to load point interruption. These events are the active failures of breakers 3 and 4 and S&C interrupters 5 and 6 and the main bus. Similarly since the number of events leading to load point interruption are more in designs 3 and 4 and also the number of circuit breakers taking part are more, therefore, the load point due to event 7 i.e., the impact of active failures with stuck breakers present in the system is higher than those for designs 1 and 2. Hence, it is the impact of active failures which causes the load point failure rate to be 18% higher in designs 3 and 4 than those in designs 1 and 2.

Substation designs 5 and 6 fare even worse. The design 5 relocates the position of the S&C interrupter in design 4 and an additional normally closed switch is added in the tie set and this causes the load point failure rate to rise. Also, there are 7 active failures of the components alone which cause a load point interruption resulting in a higher failure rate.

C.4 Discussion of substation designs 7 to 10

The load point reliability indices of design 7 are better than substation designs 1 to 6 because of reduced number of components and consequently, lesser events leading to load point interruption.

Substation designs 8 and 9 represent a traditional ring bus arrangement. The only difference between substation designs 8 and 9 is the inclusion of two additional bus components in design 9. Consequently, the load point indices of design 8 are slightly better than design 9. The main advantage of a ring bus system is that there is no single contingency event that can lead to load point interruption. This is particularly important if even momentary interruptions can cause problems. This is frequently the case for large petro-chemical plants and other important loads e.g., digital equipmemts. One of the disadvantages of the ring bus configuration is that from a construction stand point it is not easily expandable to more than 4 to 6 lines.

The load point reliability indices of substation design 10 i.e., breaker and a half scheme, are quite comparable to the ring bus. Its main advantage over the ring bus is that it can easily be expanded to accommodate more lines. Many generating switching stations use this design in practice.

APPENDIX D

D.1 Input data for case study 4.2 : (Breaker and half scheme)

The input data for case study 4.2 is shown and explained below in Table D.1.

Table D.1: Input data for case study 4.2

Line No.	Data
1	19 1
2	19 19
3	0
4	5 15 16 17 18 19
5	6 3 4 5 6 7 8
6	1 -1
7	2 -1
8	3 13 15
9	4 15 17
10	5 17 14
11	6 13 16
12	7 16 18
13	8 18 14
14	9 11
15	10 12
16	11 15
17	12 18
18	13 3 6
19	14 5 8
20	15 3 4
21	16 1 6 7
22	17 2 4 5
23	18 7 8
24	19 9 10
25	499 19
26	14
27	.09,7.33,1.,8.,.09,1.,.000
28	.09,7.33,1.,8.,.09,1.,.000
29	.23,11.13,.25,24.,.03,2.0,.005
30	.23,11.13,.25,24.,.03,2.0,.005
31	.23,11.13,.25,24.,.03,2.0,.005
32	.23,11.13,.25,24.,.03,2.0,.005
33	.23,11.13,.25,24.,.03,2.0,.005
34	.23,11.13,.25,24.,.03,2.0,.005
35	.22,2.09,.25,4.,.02,3.0,.000
36	.22,2.09,.25,4.,.02,3.0,.000
37	.10,1000.,.50,48.,.10,1.,.000
38	.10,1000.,.50,48.,.10,1.,.000
39	.024,2.,.0000001,.0000001,.024,2.,.000
40	.024,2.,.0000001,.0000001,.024,2.,.000

Table D.1(continued): Input data for case study 4.2

Line No.	Data					
41		3.0				
42	1	2	6	7		
43	2	2	4	5		
44	3	2	4	6		
45	4	3	2	3	5	
46	5	3	2	4	8	
47	6	3	1	3	7	
48	7	3	1	6	8	
49	8	2	5	7		
50	9	2	3	4		
51	10	2	7	8		
52	11	2	3	4		
53	12	2	7	8		
54	13	2	3	6		
55	14	2	5	8		
56	499	0	0	0	0	0
57	1	6	2	7	3	
58	1	7	2	6	8	
59	2	4	2	5	3	
60	2	5	2	4	8	
61	3	4	3	6	2	5
62	3	6	3	4	1	7
63	4	3	3	2	5	6
64	4	5	3	2	3	8
65	5	4	3	2	8	3
66	5	8	3	2	7	4
67	6	3	3	1	7	4
68	6	7	3	1	3	8
69	7	6	3	1	8	3
70	7	8	3	1	6	5
71	8	5	3	2	7	4
72	8	7	3	1	5	6
73	9	4	3	5	3	1
74	9	3	2	4	6	
75	9	4	3	2	3	5
76	10	7	3	8	1	6
77	11	3	2	4	6	
78	11	4	3	3	5	2
79	12	7	3	8	6	1
80	12	8	2	7	5	
81	13	3	2	6	4	
82	13	6	3	1	7	3
83	14	5	3	2	4	8
84	14	8	2	7	5	
85	499					
86	1	2	.562	5.5		
87	499	0	.0	.0		

D.2 *Explanation of input data*

The input data as reported in references [18] and [9] has been used for the analysis. The first block in the input data (i.e., from line 1 to 25 in Table D.1) is the information about the connections of the configuration. The first line of the data means that there are 19 number of components in the system and there is one load point. However, there are two load points in the system but they have been labled by a common name 19 because the criteria of successful operation is the continuity between any of the sources to at least one load point. The second line specifies the output node i.e, number 19. Since the program requires any integer number for an output node to start with, hence, the number 19 has been specified twice. The third line specifies the number and then the labels of normally open components. Since there are no N/O components in this particular example and hence zero value has been specified. The fourth line of the data specifies the number and then the labels of those node points which have been labeled just for the ease of specifying the predecessors of the components. After formulation of the paths between the sources and the load points these nodes are deleted because these are assumed as 100% reliable and their inclusion in the further analysis unnecessarily adds to the computer time. However, if these are not 100% reliable then they can be retained as other components in the system. The fifth line is used for specifying any restraints on the paths. For example, if power could be routed through a limited number of components only (e.g., each path must contain a circuit breaker) then these could be specified here.

The lines 6 to 25 specify the predecessors of each component. The predecessors for the sources have been specified as -1. Some of the components have more than one predecessors. This means that power could flow from all of those components to that particular component. For example the component or node 17 can get feed from line 2, breaker 4 or breaker 5. A fictitious number 499 has been incorporated to specify the end of the predecessor matrix and the predecessor of the label 499 is the label of the load point.

The next block is the reliability data for each component. The first line of the block i.e., line 26 in this case, specifies the number of components for which the data is to be read. The next line of the block, i.e., line 27 is the data for the first component and next the second and so on. Each line in the block specifies the passive failure rate in failures per year, repair time in hours, maintenance outage rate in actions per year, maintenance restoration time in hours per activity, active failure rate in failures per year, switching time in hours and the stuck probability. The stuck probability of circuit breakers is defined quantitatively and in case of other components it is meaningless and is therefore specified a zero value. The next line i.e., number 41 specifies the switching time required to identify the fault, disconnecting the faulty components and closing the normally open components.

The next block i.e., line 42 to 56 represents the effects of actively failed components, the number and the lables of healthy components switched out as the effect of the actively failed components. For example, line 42 means that component 1 is actively failed and as a result, components 6 and 7 are switched out. As before line 56 specifies the arbitrary number 499 to indicate the end of the block.

The next block i.e., lines 57 to 85 specifies the effects of the actively actively failed components and the stuck breaker conditions. For example, line 57 means that component 1 is actively failed and the breaker number 6 is stuck and as a result 2 healthy components i.e., number 7 and 3 are switched out of service.

The next block i.e., lines 86 and 87 specify the components failed in common mode, their failure rate and the repair time.

D.3 *Tie sets and Cut sets of Case Study 4.2 : Breaker and half scheme*

*********   BREAKER AND HALF SCHEME   *********

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (8)

PATH NUMBER	ELEMENT NUMBERS												
1	1	16	7	18	12	10	19						
2	2	17	4	15	11	9	19						
3	1	16	6	13	3	15	11	9	19				
4	2	17	5	14	8	18	12	10	19				
5	2	17	4	15	3	13	6	16	7	18	12	10	19
6	1	16	7	18	8	14	5	17	4	15	11	9	19
7	2	17	5	14	8	18	7	16	6	13	3	15	11
	9	19											
8	1	16	6	13	3	15	4	17	5	14	8	18	12
	11	19											

CUTSETS AFTER DELETING 100% RELIABLE NODES

First Order Cuts = NIL
Second Order Cuts = 5. These are:

Number	Elememts		Number	Elements	
1	1	2	4	10	11
2	9	10	5	11	12
3	9	12			

Third Order Cuts = 18. These are:

Number	Elements		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12

Cut sets for tie sets with N/O components open continued:

Number	Elements in the Cut		
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

b) WITH NORMALLY OPEN COMPONENTS CLOSED
TIE SET OR SUCCESS PATHS (8)

PATH NUMBER	ELEMENT NUMBERS													
1	1	16	7	18	12	10	19							
2	2	17	4	15	11	9	19							
3	1	16	6	13	3	15	11	9	19					
4	2	17	5	14	8	18	12	10	19					
5	2	17	4	15	3	13	6	16	7	18	12	10	19	
6	1	16	7	18	8	14	5	17	4	15	11	9	19	
7	2	17	5	14	8	18	7	16	6	13	3	15	11	
	9	19												
8	1	16	6	13	3	15	4	17	5	14	8	18	12	
	10	19												

CUT SETS AFTER DELETING 100% RELIABLE NODES

First Order Cuts = NIL
Second Order Cuts = 5. These are:

Number	Elememts		Number	Elements	
1	1	2	4	10	11
2	9	10	5	11	12
3	9	12			

Third Order Cuts = 18. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

Fourth Order Cuts = 49. These are:

Number	Elememts in the Cut			
1	1	3	5	9
2	1	3	5	11
3	1	3	8	9
4	1	3	8	11
5	1	3	9	14
6	1	3	11	14
7	1	4	7	10
8	1	4	7	12
9	1	5	6	9
10	1	5	6	11
11	1	5	9	13
12	1	5	11	13
13	1	6	8	9
14	1	6	8	11
15	1	6	9	14
16	1	6	11	14
17	1	8	9	13
18	1	8	11	13
19	1	9	13	14
20	1	11	13	14
21	2	3	5	10

Fourth order cut sets for case study 4.2 (Breaker and half scheme) continued:

Number	Elements			
22	2	3	5	12
23	2	3	8	10
24	2	3	8	12
25	2	3	10	14
26	2	3	12	14
27	2	4	7	9
28	2	4	7	11
29	2	5	6	10
30	2	5	6	12
31	2	5	10	13
32	2	5	12	13
33	2	6	8	10
34	2	6	8	12
35	2	6	10	14
36	2	6	12	14
37	2	8	10	13
38	2	8	12	13
39	2	10	13	14
40	2	12	13	14
41	3	4	5	7
42	3	4	7	8
43	3	4	7	14
44	4	5	6	7
45	4	5	7	13
46	4	6	7	8
47	4	6	7	14
48	4	7	8	13
49	4	7	13	14

c) K TYPE CUTS

First Order Cuts = Nil
Second Order Cuts = 5. These are:

Number	Elements in the Cut	
1	1	2
2	9	10
3	9	12
4	10	11
5	11	12

Third Order Cuts = 18. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	14
4	2	3	7
5	2	6	7
6	2	7	13
7	3	4	10
8	3	4	12
9	4	6	10
10	4	6	12
11	4	10	13
12	4	12	13
13	5	7	9
14	5	7	11
15	7	8	9
16	7	8	11
17	7	9	14
18	7	11	14

d) H TYPE CUTS
First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES
ACTIVELY FAILED COMPONENT= 1

REMAINING PATHS.

Path Number	Elements								
1	2	17	4	15	11	9	19		
2	2	17	5	14	8	18	12	10	19

Cuts because of above event after deleting 100% reliable nodes

First Order Cuts = Nil
Second Order Cuts = 1. This is:

Number	Elements in the Cut	
1	1	2

Third Order Cuts = 15
These are :

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	10
11	1	9	12
12	1	9	14
13	1	10	11
14	1	11	12
15	1	11	14

CUTS WHICH HAVE BEEN EVALUATED BEFORE ARE DELETED

REMAINING CUTS TO BE EVALUATED

First Order Cuts = Nil

Second Order Cuts = Nil

Third Order Cuts = 8. These are:

Number	Elements in the Cut		
1	1	4	10
2	1	4	12
3	1	5	9
4	1	5	11
5	1	8	9
6	1	8	11
7	1	9	14
8	1	11	14

The active failures of other components are treated in the same way as shown for component number 1. The cut sets obtained after considering the active failures of all the components are tabulated below in Table D.2:

Table D.2: Cut sets due to Active Failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
1	nil	nil	1 4 10 1 4 12 1 5 9 1 5 11 1 8 9 1 8 11 1 9 14 1 11 14
2	nil	nil	2 3 10 2 3 12 2 6 10 2 6 12 2 7 9 2 7 11 2 10 13 2 12 13
3	nil	nil	3 1 5 3 1 8 3 1 14 3 5 7 3 7 8 3 7 14
4	nil	4 1 4 7 4 10 4 12	nil
5	nil	5 1	5 3 7 5 3 10 5 3 12 5 6 7 5 6 10 5 6 12 5 7 13 5 10 13 5 12 13
6	nil	6 2	6 4 5 6 4 8 6 4 10 6 4 12 6 4 14 6 5 9

Table D.2 (continued): Cut sets due to active failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
			6 5 11
			6 8 9
			6 8 11
			6 9 10
			6 9 12
			6 9 14
			6 10 11
			6 11 12
			6 11 14
7	nil	7 2	nil
		7 4	
		7 9	
		7 11	
8	nil	8 9	8 1 2
		8 11	8 1 4
			8 2 3
			8 2 6
			8 2 13
			8 3 4
			8 4 6
			8 4 13
9	nil	nil	9 1 5
			9 1 8
			9 1 14
			9 2 7
10	nil	nil	10 1 4
			10 2 3
			10 2 6
			10 2 13
11	nil	nil	11 1 5
			11 1 8
			11 1 14
			11 2 7
12	nil	nil	12 1 4
			12 2 3
			12 2 6
			12 2 13
13	nil	nil	nil
14	nil	nil	nil

f) IMPACT OF ACTIVE FAILURES AND STUCK BREAKERS

ACTIVELY FAILED COMPONENT= 1

STUCK BREAKER= 6

REMAINING SUCCESS PATHS

Path Number	Elements								
1	2	17	4	15	11	9	19		
2	2	17	5	14	8	18	12	10	19

Cut sets because of above events
after deleting 100% reliable nodes

First Order Cuts = Nil
Second Order Cut = 1
That is:

Number	Elements
1	1 2

Third Order Cuts = 15
These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	10
11	1	9	12
12	1	9	14
13	1	10	11
14	1	11	12
15	1	11	14

CUTS WHICH HAVE BEEN EVALUATED BEFORE ARE DELETED

REMAINING CUTS

First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = 11. These are:

Number	Elements in the Cut		
1	1	4	5
2	1	4	8
3	1	4	10
4	1	4	12
5	1	4	14
6	1	5	9
7	1	5	11
8	1	8	9
9	1	8	11
10	1	9	14
11	1	11	14

The cut sets for the remaining components are formulated as shown above for component one and are tabulated below in Table D.3

Table D.3: Cut sets due to active failures and stuck breakers

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
1	7	nil	1 4 1 9 1 11	nil
2	4	nil	2 7 2 10 2 12	nil
2	5	nil	nil	2 3 10 2 3 12 2 6 10 2 6 12 2 7 9 2 7 11 2 10 13 2 12 13

Table D.3 (continued): cut sets due to active failures and stuck breakers

		Elements in the Cut		
Actively failed component	Stuck breaker	First order	Second order	Third order
3	4	nil	3 1	nil
			3 7	
			3 10	
			3 12	
3	6	nil	3 2	nil
			3 5	
			3 8	
			3 10	
			3 12	
			3 14	
4	3	nil	4 1	nil
			4 7	
			4 10	
			4 12	
4	5	nil	4 1	nil
			4 7	
			4 10	
			4 12	
5	4	nil	5 1	nil
			5 7	
			5 10	
			5 12	
5	8	nil	5 1	nil
			5 3	
			5 6	
			5 9	
			5 11	
			5 13	
6	3	nil	6 2	nil
			6 5	
			6 8	
			6 10	
			6 12	
			6 14	
6	7	nil	6 2	nil
			6 4	

Table D.3 (continued): cut sets due to active failures and stuck breakers.

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
			6 9	
			6 11	
7	6	nil	7 2	nil
			7 4	
			7 9	
			7 11	
7	8	nil	7 2	nil
			7 4	
			7 9	
			7 11	
8	5	nil	8 1	nil
			8 3	
			8 6	
			8 9	
			8 11	
			8 13	
8	7	nil	8 2	nil
			8 4	
			8 9	
			8 11	
9	4	9	nil	nil
9	3	nil	nil	9 1 5
				9 1 8
				9 1 14
				9 2 7
9	4	nil	9 1	nil
			9 7	
10	7	nil	10 2	nil
			10 4	
11	3	nil	nil	11 1 5
				11 1 8
				11 1 14
				11 2 7

Table D.3 (continued): cut sets because of active failures and stuck breakers.

Actively failed component	Stuck breaker	Elements in the Cut: First order	Second order	Third order
11	4	nil	11 1	nil
			11 7	
			11 10	
			11 12	
12	7	nil	12 2	nil
			12 4	
12	8	nil	nil	12 1 4
				12 2 3
				12 2 6
				12 2 13
13	3	nil	13 10	13 1 5
			13 12	13 1 8
				13 1 14
				13 5 7
				13 7 8
				13 7 14
13	6	nil	13 2	13 4 5
				13 4 8
				13 4 14
				13 5 9
				13 5 11
				13 8 9
				13 8 11
				13 9 14
				13 11 14
14	5	nil	14 1	14 3 7
				14 3 10
				14 3 12
				14 6 7
				14 6 10
				14 6 12
				14 7 13
				14 10 13
				14 12 13
14	8	nil	14 9	14 2 3
			14 11	14 2 6
				14 2 13
				14 3 4
				14 4 6
				14 4 13

APPENDIX E

Tie sets and cut sets of case study 4.3: Main bus and transfer bus system

********** DESIGN NO. 4 **********
*** MAIN BUS AND TRANSFER BUS SYSTEM ***

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (4)

PATH NUMBER	ELEMENTS								
1	[illegible]	18	3	13	5	20	15	11	17
2	1	18	3	13	6	21	16	12	17
3	2	19	4	13	5	20	15	11	17
4	2	19	4	13	6	21	16	12	17

CUTSETS FOR NORMALLY CLOSED PATHS

First Order Cuts = 2
These are element number 13 and 17

Second Order Cuts = 25. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	10	5	12	19	12	15
2	1	4	11	5	16	20	12	20
3	1	19	12	5	21	21	15	16
4	2	3	13	6	11	22	15	21
5	2	18	14	6	15	23	16	20
6	3	4	15	6	20	24	18	19
7	3	19	16	11	12	25	20	21
8	4	18	17	11	16			
9	5	6	18	11	21			

Third Order Cuts = Nil

b) WITH NORMALLY OPEN COMPONENTS CLOSED

TIE SET OR SUCCESS PATHS (24)

PATH NUMBER	ELEMENTS								
1	1	18	3	13	5	20	15	11	17
2	1	18	3	13	6	21	16	12	17
3	1	18	7	14	9	20	15	11	17
4	1	18	7	14	10	21	16	12	17
5	2	19	4	13	5	20	15	11	17
6	2	19	4	13	6	21	16	12	17
7	2	19	8	14	9	20	15	11	17

Tie sets (continued) with N/O components closed for case study 4.3 (main bus and transfer bus scheme)

PATH NUMBER	ELEMENTS												
8	2	19	8	14	10	21	16	12	17				
9	1	18	7	14	10	21	6	13	5	20	15	11	17
10	1	18	3	13	6	21	10	14	9	20	15	11	17
11	1	18	7	14	9	20	5	13	6	21	16	12	17
12	1	18	3	13	5	20	9	14	10	21	16	12	17
13	2	19	8	14	7	18	3	13	5	20	15	11	17
14	2	19	8	14	7	18	3	13	6	21	16	12	17
15	2	19	4	13	3	18	7	14	9	20	15	11	17
16	2	19	4	13	3	18	7	14	10	21	16	12	17
17	1	18	7	14	8	19	4	13	5	20	15	11	17
18	1	18	7	14	8	19	4	13	6	21	16	12	17
19	1	18	3	13	4	19	8	14	9	20	15	11	17
20	1	18	3	13	4	19	8	14	10	21	16	12	17
21	2	19	8	14	10	21	6	13	5	20	15	11	17
22	2	19	8	14	9	20	5	13	6	21	16	12	17
23	2	19	4	13	6	21	10	14	9	20	15	11	17
24	2	19	4	13	5	20	9	14	10	21	16	12	17

CUTSETS FOR NORMALLY OPEN COMPONENTS CLOSED

First Order Cut = 1 ; i.e., element 17
Second Order Cuts = 14; These are :

Number	Elements		Number	Elements		Number	Elements	
1	1	2	6	11	21	11	15	21
2	1	19	7	12	15	12	16	20
3	2	18	8	12	20	13	18	19
4	11	12	9	13	14	14	20	21
5	11	16	10	15	16			

Third Order Cuts = 34. These are:

Number	Elements			Number	Elements			Number	Elements		
1	1	4	8	13	5	9	12	25	7	8	13
2	1	4	14	14	5	9	16	26	7	13	19
3	1	8	13	15	5	9	21	27	8	13	18
4	2	3	7	16	5	12	14	28	9	10	13
5	2	3	14	17	5	14	16	29	9	12	13
6	2	7	13	18	5	14	21	30	9	13	16
7	3	4	14	19	6	10	11	31	9	13	21
8	3	7	19	20	6	10	15	32	10	11	13
9	3	14	19	21	6	10	20	33	10	13	15
10	4	8	18	22	6	11	14	34	10	13	20
11	4	14	18	23	6	14	15				
12	5	6	14	24	6	14	20				

Fourth Order Cuts = 20. These are:

Number	Elements				Number	Elements			
1	3	4	7	8	11	5	6	7	8
2	3	4	9	10	12	5	6	7	19
3	3	4	9	21	13	5	6	8	18
4	3	4	10	20	14	5	6	9	10
5	3	9	10	19	15	5	7	8	21
6	3	9	19	21	16	5	7	19	21
7	3	10	19	20	17	5	8	18	21
8	4	9	10	18	18	6	7	8	20
9	4	9	18	21	19	6	7	19	20
10	4	10	18	20	20	6	8	18	20

c) K TYPE CUTS

First Order Cut = 1
It is element number 17

Second Order Cuts = 13. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	6	11	21	11	16	20
2	1	19	7	12	15	12	18	19
3	2	18	8	12	20	13	20	21
4	11	12	9	15	16			
5	11	16	10	15	21			

Third Order Cuts = Nil

d) H TYPE CUTS
First Order Cuts = 1
It is element number 13

Second Order Cuts = 12. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	4	5	4	18	9	5	21
2	2	3	6	5	6	10	6	11
3	3	4	7	5	12	11	6	15
4	3	19	8	5	16	12	6	20

Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES
ACTIVE FAILURE OF COMPONENT= 1
REMAINING SUCCESS PATHS

PATH	ELEMENTS								
1	2	19	4	13	5	20	15	11	17
2	2	19	4	13	6	21	16	12	17

CUTSETS BECAUSE OF ABOVE EVENT
First Order Cuts = Nil
Second Order Cuts = 5; These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	3	1	13	5	1	19
2	1	4	4	1	17			

Third Order Cuts = 16; These are:

Number	Elements			Number	Elements			Number	Elements		
1	1	5	6	7	1	6	20	13	1	15	16
2	1	5	12	8	1	11	12	14	1	15	21
3	1	5	16	9	1	11	16	15	1	16	20
4	1	5	21	10	1	11	21	16	1	20	21
5	1	6	11	11	1	12	15				
6	1	6	15	12	1	12	20				

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE.
REMAINING CUTS TO BE EVALUATED:

First Order Cuts = Nil
Second Order Cuts = Nil
Third Order Cuts = Nil

The active failures of other components are also treated in the same way as the component number 1. The cut sets obtained this way are tabulated below in Table E.1.

Table E.1: Cut sets because of Active Failures

Actively failed component	First order cuts	Second order cuts	Third order cuts
2	nil	nil	nil
3	3	nil	nil
4	4	nil	nil
5	5	nil	nil
6	6	nil	nil
11	nil	nil	nil
12	nil	nil	nil
13	nil	nil	nil
15	nil	nil	nil
16	nil	nil	nil

f) Cut sets due to active failures and stuck breakers

ACTIVE FAILURE OF COMPONENTS = 1
STUCK BREAKER = 3

SUCCESS PATHS REMAINING AFTER ABOVE EVENT

NO SUCCESS PATH TO LOAD POINT

CUTS WITH STUCK BREAKER

First Order Cut = 1 i.e., element 1
Second Order Cuts = Nil
Third Order Cuts = Nil

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS

First Order Cut = 1 i.e., element 1
Second Order Cuts = Nil
Third Order Cuts = Nil

The active failures with stuck breakers for other cases are done the same way as done for component 1 actively failed and breaker 3 stuck. These are tabulated below in Table E.2.

Table E.2: Cut sets because of active failures and stuck breakers

Actively failed component	Stuck breaker	order of cuts: First	Second	Third
2	4	2	nil	nil
3	4	3	nil	nil
4	3	4	nil	nil
5	3	5	nil	nil
6	3	6	nil	nil
6	4	6	nil	nil
11	5	11	nil	nil
12	6	12	nil	nil
13	3	nil	nil	nil
13	4	nil	nil	nil
15	5	15	nil	nil
16	6	16	nil	nil

APPENDIX F

Input data, tie sets and cut sets for George Dickie Substation (Figure 5.1)

F.1 *Input Data*: The input data is shown below in Table F.1.

Table F.1: Input Data for George Dickie Substation Configuration

```
          ***** B.C. HYDRO GEORGE DICKIE SUBSTATION ****
156   1
 52  52
 17  30  31  36  37  51  67  68  69  70  71  72  73  75  76  77  78  79
  1  52
  2   1   2
   1  -1
   2  -1
   3   1
   4   2
   5  19
   6   9
   7  20  10
   8  10  21
   9   5
  10   7   8
  11  20
  12  21
  13  11
  14  12
  15  13
  16  14
  17  15
  18  16
  19   3
  20   6   7
  21   8   4
  22  25
  23  17  27
  24  18  28
  25  26
  26  23
  27  23  29
  28  29  24
  29  27  28
  30  23
  31  23
  32  24
```

Table F.1 (contd.) Input Data - George Dickie Substation

33	24	
34	30	
35	31	
36	34	
37	35	
38	36	58
39	37	80
40	42	
41	43	
42	45	
43	44	
44	32	
45	33	
46	40	
47	46	
48	47	
49	48	
50	49	
51	38	
52	50	51
53	40	
54	53	
55	54	
56	55	
57	56	
58	57	
59	40	
60	40	
61	41	
62	41	
63	41	
64	41	
65	41	
66	41	
67	38	
68	38	
69	38	
70	38	
71	38	
72	38	
73	38	
74	40	
75	39	
76	39	
77	39	
78	39	
79	39	
80	94	
81	95	
82	96	

Table F.1 (contd.) Input Data - George Dickie Substation

83	97
84	98
85	99
86	100
87	101
88	40
89	103
90	104
91	105
92	106
93	107
94	108
95	109
96	110
97	111
98	112
99	113
100	114
101	115
102	40
103	117
104	118
105	119
106	120
107	121
108	122
109	123
110	124
111	125
112	126
113	127
114	128
115	129
116	40
117	131
118	132
119	133
120	134
121	135
122	136
123	60
124	130
125	116
126	102
127	57
128	58
129	59
130	40
131	61
132	62

Table F.1 (contd.) Input Data - George Dickie Substation

```
133 63
134 64
135 65
136 66
137 22
138 137
139 138
140 139
141 24
142 141
143 142
144 143
145   1
146   2
147   1
148   2
149 19
150 21
151 156
152 11
153 12
154 13
155 14
156 19
499 52
  156
.09,7.33,1.0,8.,.09,1.,.000
.09,7.33,1.0,8.,.09,1.,.000
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.22,2.09,.25,4.,.02,3.,.000
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.02,3.,.25,12.,.01,1.,.06
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.024,2.,.0000001,.0000001,.024,2.,.000
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.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
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.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
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.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
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.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.024,2.,.0000001,.0000001,.024,2.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.22,2.09,.25,4.,.02,3.,.000
.02,3.,.25,12.,.01,1.,.06
.004,10.,.0000001,.0000001,.004,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
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.22,2.09,.25,4.,.02,3.,.000
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.008,10.,.0000001,.0000001,.008,1.,.000
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.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
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.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
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.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
.22,2.09,.25,4.,.02,3.,.000
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.008,10.,.0000001,.0000001,.008,1.,.000
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.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
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.008,10.,.0000001,.0000001,.008,1.,.000
.008,10.,.0000001,.0000001,.008,1.,.000
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.004,10.,.0000001,.0000001,.004,1.,.000
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.004,10.,.0000001,.0000001,.004,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.004,10.,.0000001,.0000001,.004,1.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
```

Table F.1 (contd.) Input Data - George Dickie Substation

```
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.22,2.09,.25,4.,.02,3.,.000
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.02,3.,.25,12.,.01,1.,.06
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
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.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
.008,10.,.00000001,.0000001,.008,1.,.000
.007,10.,.007,1.,.00000001,.0000001,.000
.007,10.,.007,1.,.00000001,.0000001,.000
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.22,2.09,.25,4.,.02,3.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.008,10.,.00000001,.0000001,.008,1.,.000
.22,2.09,.25,4.,.02,3.,.000
.0000001,.0000001,.0000001,.0000001,.0000001,.0000001,.0
3.0
  1  1  9
  2  1 10
  3  2  1  9
  4  2  2 10
  5  2  1  9
  6  2  9 10
  7  2  9 10
  8  2 10  2
  9  2  1 10
 10  2  2  9
 11  2  9 10
 12  2  2 10
 13  2  9 10
 14  2  2 10
 15  2  9 10
 16  2 10  2
 17  2 15 29
 18  2 16 29
 19  2  1  9
```

Table F.1 (contd.) Input Data - George Dickie Substation

20	2	9	10
21	2	10	2
22	2	15	29
23	2	15	29
24	2	16	29
25	2	15	29
26	2	15	29
27	2	15	29
28	2	16	29
29	2	15	16
32	2	16	29
33	2	16	29
34	2	15	29
35	2	15	29
38	1	54	
39	1	136	
40	2	16	29
41	2	16	29
42	2	16	29
43	2	16	29
44	2	16	29
45	2	16	29
46	2	16	29
47	2	16	29
48	1	47	
49	1	47	
50	1	47	
52	1	47	
53	2	16	29
54	2	16	29
55	1	54	
56	1	54	
57	1	54	
58	1	54	
59	2	16	29
60	2	16	29
61	2	16	29
62	2	16	29
63	2	16	29
64	2	16	29
65	2	16	29
66	2	16	29
74	2	16	29
80	1	136	
81	1	123	
82	1	124	
83	1	125	
84	1	126	
85	1	127	

Table F.1 (contd.) Input Data - George Dickie Substation

86	1	128	
87	1	129	
88	2	16	29
89	1	131	
90	1	132	
91	1	133	
92	1	134	
93	1	135	
94	1	136	
95	1	123	
96	1	124	
97	1	125	
98	1	126	
99	1	127	
100	1	128	
101	1	129	
102	2	16	29
103	1	131	
104	1	132	
105	1	133	
106	1	134	
107	1	135	
108	1	136	
109	1	123	
110	1	124	
111	1	125	
112	1	126	
113	1	127	
114	1	128	
115	1	129	
116	2	16	29
117	1	131	
118	1	132	
119	1	133	
120	1	134	
121	1	135	
122	1	136	
123	2	16	29
124	2	16	29
125	2	16	29
126	2	16	29
127	2	16	29
128	2	16	29
129	2	16	29
130	2	16	29
131	2	16	29
132	2	16	29
133	2	16	29
134	2	16	29

Table F.1 (contd.) Input Data - George Dickie Substation

135	2	16	29	
136	2	16	29	
137	2	15	29	
138	2	15	29	
139	2	15	29	
140	2	15	29	
141	2	16	29	
142	2	16	29	
143	2	16	29	
144	2	16	29	
145	2	1	9	
146	2	2	10	
147	2	1	9	
148	2	2	10	
149	2	1	9	
150	2	2	10	
151	2	1	9	
152	2	9	10	
153	2	2	10	
154	2	9	10	
155	2	2	10	
156	2	1	9	
499	0	0	0	
1	9	1	10	
2	10	1	9	
3	9	2	10	1
4	10	2	9	2
5	9	2	1	10
6	9	2	1	10
6	10	2	9	2
7	9	2	1	10
8	10	2	9	2
9	10	2	1	2
10	9	2	2	1
11	9	2	1	10
11	10	2	2	9
12	10	2	2	9
13	9	2	1	10
13	10	2	2	9
14	10	2	2	9
15	9	2	1	10
15	10	2	2	9
16	10	2	2	9
17	15	2	9	10
18	16	2	2	10
19	9	2	1	10
20	9	2	1	10
20	10	2	2	9
21	10	2	2	9

Table F.1 (contd.) Input Data - George Dickie Substation

22	15	2	9	10	
22	29	2	15	16	
23	15	2	9	10	
23	29	2	15	16	
24	16	2	2	10	
24	29	2	15	16	
25	15	2	9	10	
25	29	2	15	16	
26	15	3	9	10	29
26	29	2	15	16	
27	15	3	29	9	10
27	29	2	15	16	
28	16	3	29	10	2
28	29	2	15	16	
29	15	3	16	9	10
32	16	3	29	2	10
32	29	2	15	16	
33	16	3	29	2	10
34	15	3	29	9	10
34	29	2	15	16	
35	15	3	29	9	10
35	29	2	15	16	
38	54	2	16	29	
39	136	2	16	29	
40	16	3	29	10	2
40	29	2	16	15	
41	16	3	29	2	10
41	29	2	16	15	
42	16	3	29	10	2
42	29	2	15	16	
43	16	3	29	2	10
43	29	2	15	16	
44	16	3	29	10	2
44	29	2	15	16	
45	16	3	29	2	10
45	29	2	16	15	
46	16	3	29	2	10
46	29	2	16	15	
47	16	3	29	2	10
47	29	2	15	16	
48	47	2	16	29	
49	47	2	16	29	
50	47	2	16	29	
53	16	3	29	10	2
53	29	2	15	16	
54	16	3	29	10	2
54	29	2	15	16	
55	54	2	16	29	
56	54	2	16	29	

Table F.1 (contd.) Input Data - George Dickie Substation

57	54	2	16	29	
58	54	2	16	29	
59	16	3	29	10	2
59	29	2	15	16	
60	16	3	29	10	2
60	29	2	15	16	
61	16	3	29	10	2
61	29	2	15	16	
62	16	3	29	10	2
62	29	2	15	16	
63	16	3	29	10	2
63	29	2	15	16	
64	16	3	29	10	2
64	29	2	15	16	
65	16	3	29	10	2
65	29	2	15	16	
66	16	3	29	2	10
66	29	2	15	16	
74	16	3	29	2	10
74	29	2	16	15	
80	136	2	16	29	
81	123	2	16	29	
82	124	2	16	29	
83	125	2	16	29	
84	126	2	16	29	
85	127	2	16	29	
86	128	2	16	29	
87	129	2	16	29	
88	16	3	29	2	10
88	29	2	16	15	
89	131	2	16	29	
90	132	2	16	29	
91	133	2	16	29	
92	134	2	16	29	
93	135	2	16	29	
94	136	2	16	29	
95	123	2	16	29	
96	124	2	16	29	
97	125	2	16	29	
98	126	2	16	29	
99	127	2	16	29	
100	128	2	16	29	
101	129	2	16	29	
102	16	3	29	2	10
102	29	2	16	15	
103	131	2	16	29	
104	132	2	16	29	
105	133	2	16	29	
106	134	2	16	29	

Table F.1 (contd.) Input Data - George Dickie Substation

107	135	2	16	29	
108	136	2	16	29	
109	123	2	16	29	
110	124	2	16	29	
111	125	2	16	29	
112	126	2	16	29	
113	127	2	16	29	
114	128	2	16	29	
115	129	2	16	29	
116	16	3	29	2	10
116	29	2	16	15	
117	131	2	16	29	
118	132	2	16	29	
119	133	2	16	29	
120	134	2	16	29	
121	135	2	16	29	
122	136	2	16	29	
123	16	3	29	2	10
123	29	2	16	15	
124	16	3	29	2	10
124	29	2	15	16	
125	16	3	29	2	10
125	29	2	15	16	
126	16	3	29	2	10
126	29	2	15	16	
127	16	3	29	2	10
127	29	2	15	16	
128	16	3	29	2	10
128	29	2	15	16	
129	16	3	29	2	10
129	29	2	15	16	
130	16	3	29	2	10
130	29	2	15	16	
131	16	3	29	2	10
131	29	2	15	16	
132	16	3	29	2	10
132	29	2	15	16	
133	16	3	29	2	10
133	29	2	15	16	
134	16	3	29	2	10
134	29	2	15	16	
135	16	3	29	2	10
135	29	2	15	16	
136	16	3	29	2	10
136	29	2	15	16	
137	15	3	9	10	29
137	29	2	15	16	
138	15	3	9	10	29
138	29	2	15	16	

Table F.1 (contd.) Input Data - George Dickie Substation

139	15	3	9	10	29
139	29	2	15	16	
140	15	3	9	10	29
140	29	2	15	16	
141	16	3	29	10	2
141	29	2	16	15	
142	16	3	29	10	2
142	29	2	16	15	
143	16	3	29	10	2
143	29	2	16	15	
144	16	3	29	10	2
144	29	2	16	15	
145	9	2	1	10	
146	10	2	2	9	
147	9	2	1	10	
148	10	2	2	9	
149	9	2	1	10	
150	10	2	2	9	
151	9	2	1	10	
152	9	2	10	1	
152	10	2	9	2	
153	10	2	2	9	
154	9	2	10	1	
154	10	2	9	2	
155	10	2	9	2	
156	9	2	1	10	
499					

1,2,.562,5.5
499,0,.0,.0

F.2 *Tie sets and cut sets of George Dickie Substation*

a) WITH NORMALLY OPEN COMPONENTS OPEN

TIE SET OR SUCCESS PATHS (4)

PATH NUMBER	ELEMENTS											
1	2	4	21	12	14	16	18	24	33	45	42	40
	46	47	48	49	50	52						
2	1	3	19	5	9	6	20	11	13	15	17	23
	27	29	28	24	33	45	42	40	46	47	48	49
	50	52										
3	1	3	19	5	9	6	20	7	10	8	21	12
	14	16	18	24	33	45	42	40	46	47	48	49
	50	52										
4	2	4	21	8	10	7	20	11	13	15	17	23
	27	29	28	24	33	45	42	40	46	47	48	49
	50	52										

Component 52 i.e., load point assumed 100%
reliable and therefore deleted from cuts

b) CUTSETS FOR NORMALLY CLOSED PATHS

First Order Cuts = 10
These are element numbers shown below:

24 33 40 42 45 46 47 48 49 50

Second Order Cuts = 65
These are given below:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	23	11	18	45	15	18
2	1	4	24	11	21	46	15	21
3	1	21	25	12	13	47	16	17
4	2	3	26	12	15	48	16	20
5	2	5	27	12	17	49	16	23
6	2	6	28	12	20	50	16	27
7	2	9	29	12	23	51	16	28
8	2	19	30	12	27	52	16	29
9	2	20	31	12	28	53	17	18
10	3	4	32	12	29	54	17	21
11	3	21	33	13	14	55	18	20
12	4	5	34	13	16	56	18	27
13	4	6	35	13	18	57	18	28

Second order cuts (contd.) with N/O branches open - George Dickie Substation

Number	Elements		Number	Elements		Number	Elements	
14	4	9	36	13	21	58	18	29
15	4	19	37	14	15	59	19	21
16	4	20	38	14	17	60	20	21
17	5	21	39	14	20	61	21	23
18	6	21	40	14	23	62	21	27
19	9	21	41	14	27	63	21	28
20	11	12	42	14	28	64	21	29
21	11	14	43	14	29	65	18	23
22	11	16	44	15	16			

Third Order Cuts = 120. These are:

Number	Element			Number	Element			Number	Element		
1	1	7	12	41	3	8	12	81	5	10	12
2	1	7	14	42	3	8	14	82	5	10	14
3	1	7	16	43	3	8	16	83	5	10	16
4	1	7	18	44	3	8	18	84	5	10	18
5	1	8	12	45	3	10	12	85	6	7	12
6	1	8	14	46	3	10	14	8	6	7	14
7	1	8	16	47	3	10	16	87	6	7	16
8	1	8	18	48	3	10	18	88	6	7	18
9	1	10	12	49	4	7	11	89	6	8	12
10	1	10	14	50	4	7	13	90	6	8	14
11	1	10	16	51	4	7	15	91	6	8	16
12	1	10	18	52	4	7	17	92	6	8	18
13	2	7	11	53	4	7	23	93	6	10	12
14	2	7	13	54	4	7	27	94	6	10	14
15	2	7	15	55	4	7	28	95	6	10	16
16	2	7	17	56	4	7	29	96	6	10	18
17	2	7	23	57	4	8	11	97	7	9	12
18	2	7	27	58	4	8	13	98	7	9	14
19	2	7	28	59	4	8	15	99	7	9	16
20	2	7	29	60	4	8	17	100	7	9	18
21	2	8	11	61	4	8	23	101	7	12	19
22	2	8	13	62	4	8	27	102	7	14	19
23	2	8	15	63	4	8	28	103	7	16	19
24	2	8	17	63	4	8	29	104	7	18	19
25	2	8	23	65	4	10	11	105	8	9	12
26	2	8	27	66	4	10	13	106	8	9	14
27	2	8	28	67	4	10	15	107	8	9	16
28	2	8	29	68	4	10	17	108	8	9	18
29	2	10	11	69	4	10	23	109	8	12	19
30	2	10	13	70	4	10	27	110	8	14	19
31	2	10	15	71	4	10	28	111	8	16	19

Third order cuts(contd.) with N/O branches open
- George Dickie Substation

Number	Element			Number	Element			Number	Element		
32	2	10	17	72	4	10	29	112	8	18	19
33	2	10	23	73	5	7	12	113	9	10	12
34	2	10	27	74	5	7	14	114	9	10	14
35	2	10	28	75	5	7	16	115	9	10	16
36	2	10	29	76	5	7	18	116	9	10	18
37	3	7	12	77	5	8	12	117	10	12	19
38	3	7	14	78	5	8	14	118	10	14	19
39	3	7	16	79	5	8	16	119	10	16	19
40	3	7	18	80	5	8	18	120	10	18	19

WITH NORMALLY OPEN COMPONENTS CLOSED
TIE SET OR SUCCESS PATHS (12)

PATH	ELEMENT NUMBERS										
1	1	3	19	5	9	6	20	11	13	15	17
	23	30	34	36	38	51	52				
2	2	4	21	8	10	7	20	11	13	15	17
	23	30	34	36	38	51	52				
3	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				
4	2	4	21	12	14	16	18	24	28	29	27
	23	30	34	36	38	51	52				
5	2	4	21	12	14	16	18	24	33	45	42
	40	53	54	55	56	57	58	38	51	52	
6	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	33	45	42	40	46	47
	48	49	50	52							
7	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	28	29	27	23	30	34
	36	38	51	52							
8	1	3	19	5	9	6	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							
9	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							
10	1	3	19	5	9	6	20	7	10	8	21
	12	14	16	18	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				
11	1	3	19	5	9	6	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				
12	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	53	54
	55	56	57	58	38	51	52				

c) K TYPE CUTS

First Order Cuts = Nil

Second Order Cuts = 65
These are the same as the second order cuts shown above.

Third Order Cuts = 120
These are same as the third order cuts shown above.

d) H TYPE CUTS

First Order Cuts = 10
These are the following element numbers :
24 33 40 42 45 46 47 48 49 50

Second Order Cuts= Nil

Third Order Cuts = Nil

e) SUCCESS PATHS CONSIDERING ACTIVE FAILURES

ACTIVE FAILURE OF COMPONENT= 1

REMAINING SUCCESS PATHS

PATH NUMBER	ELEMENTS										
1	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				
2	2	4	21	8	10	7	20	11	13	15	17
	23	27	29	28	24	33	45	42	40	46	47
	48	49	50	52							

CUTSETS BECAUSE OF ABOVE EVENT

First Order Cuts = Nil

Second Order Cuts = 13; These are:

Number	Element		Number	Element		Number	Element	
1	1	2	6	1	40	11	1	48
2	1	4	7	1	42	12	1	49
3	1	21	8	1	45	13	1	50
4	1	24	9	1	46			
5	1	33	10	1	47			

Third Order Cuts = 48. These are:

Number	Element			Number	Element			Number	Element		
1	1	7	12	17	1	12	13	33	1	14	28
2	1	7	14	18	1	12	15	34	1	14	29
3	1	7	16	19	1	12	17	35	1	15	16
4	1	7	18	20	1	12	20	36	1	15	18
5	1	8	12	21	1	12	23	37	1	16	17
6	1	8	14	22	1	12	27	38	1	16	20
7	1	8	16	23	1	12	28	39	1	16	23
8	1	8	18	24	1	12	29	40	1	16	27
9	1	10	12	25	1	13	14	41	1	16	28
10	1	10	14	26	1	13	16	42	1	16	29
11	1	10	16	27	1	13	18	43	1	17	18
12	1	10	18	28	1	14	15	44	1	18	20
13	1	11	12	29	1	14	17	45	1	18	23
14	1	11	14	30	1	14	20	46	1	18	27
15	1	11	16	31	1	14	23	47	1	18	28
16	1	11	18	32	1	14	27	48	1	18	29

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS TO BE EVALUATED

First Order Cuts = Nil

Second Order Cuts = Nil

Third Order Cuts = Nil

The cut sets for active failures of other components are also calculated in the same way. The count and order of cuts because of active failures of other components are tabulated below in Table F.2:

Table F.2: Cut sets due to Active Failures

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
2	nil	8	nil
3	nil	nil	nil
4	nil	7	nil
5	nil	12	nil
6	nil	13	nil
7	1	nil	nil
8	nil	15	nil
9	nil	12	nil
10	nil	15	nil
11	1	nil	nil
12	nil	6	nil
13	nil	2	nil
14	nil	6	nil
15	nil	2	nil
16	nil	6	nil
17	nil	nil	nil
18	nil	nil	nil
19	nil	nil	nil
20	nil	nil	nil
21	nil	nil	nil
22	nil	5	6
23	nil	nil	nil
24	nil	nil	nil
25	nil	5	6
26	nil	5	6
27	nil	nil	nil
28	28	nil	nil
29	nil	nil	nil
32	nil	9	18
33	nil	nil	nil
34	nil	5	6
35	nil	5	6
38	nil	nil	nil
39	nil	nil	nil
40	nil	nil	nil
41	nil	9	18
42	nil	nil	nil
43	nil	9	18
44	nil	9	18

Table F.2 (contd.) cut sets due to active failures
- George Dickie Substation

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
45	nil	nil	nil
46	nil	nil	nil
47	nil	nil	nil
48	nil	nil	nil
49	nil	nil	nil
50	nil	nil	nil
52	1	nil	nil
53	nil	9	18
54	nil	9	18
55	nil	nil	nil
56	nil	nil	nil
57	nil	nil	nil
58	nil	nil	nil
59	nil	9	18
60	nil	9	18
61	nil	9	18
62	nil	9	18
63	nil	9	18
64	nil	9	18
65	nil	9	18
66	nil	9	18
74	nil	9	18
80	nil	nil	nil
81	nil	nil	nil
82	nil	nil	nil
83	nil	nil	nil
84	nil	nil	nil
85	nil	nil	nil
86	nil	nil	nil
87	nil	nil	nil
88	1	nil	nil
89	nil	nil	nil
90	nil	nil	nil
91	nil	nil	nil
92	nil	nil	nil
93	nil	nil	nil
94	nil	nil	nil
95	nil	nil	nil
96	nil	nil	nil
97	nil	nil	nil
98	nil	nil	nil
99	nil	nil	nil
100	nil	nil	nil
101	nil	nil	nil
102	nil	15	nil

Table F.2 (contd.) cut sets due to active failures - George Dickie Substation.

Actively failed component	#First order cuts	#Second order cuts	#Third order cuts
103	nil	nil	nil
104	nil	nil	nil
105	nil	nil	nil
.	.	.	.
.	.	.	.
115	nil	nil	nil
116	1	nil	nil
117	nil	nil	nil
.	.	.	.
122	nil	nil	nil
123	1	nil	nil
124	1	nil	nil
.	.	.	.
.	.	.	.
136	1	nil	nil
137	nil	5	6
138	nil	5	6
139	nil	5	6
140	nil	5	6
141	1	nil	nil
142	1	nil	nil
143	1	nil	nil
144	1	nil	nil
145	nil	3	12
146	nil	15	nil
147	nil	3	12
148	nil	15	nil
149	nil	3	12
150	nil	15	nil
151	nil	3	12
152	nil	7	nil
153	nil	15	nil
154	nil	7	nil
155	nil	15	nil
156	nil	3	12

f) *Cut sets with active failures and stuck breakers*
ACTIVE FAILURE OF COMPONENT= 1
STUCK BREAKER= 9

SUCCESS PATHS REMAINING AFTER ABOVE EVENT

PATH NUMBER	ELEMENTS										
1	2	4	21	12	14	16	18	24	33	45	42
	40	46	47	48	49	50	52				

CUTS WITH STUCK BREAKER

First Order Cuts = Nil

Second Order Cuts = 17. These are:

Number	Elements		Number	Elements		Number	Elements	
1	1	2	7	1	21	13	1	46
2	1	4	8	1	24	14	1	47
3	1	12	9	1	33	15	1	48
4	1	14	10	1	40	16	1	49
5	1	16	11	1	42	17	1	50
6	1	18	12	1	45			

Third Order Cuts = Nil

DROP THOSE CUTS WHICH HAVE BEEN EVALUATED BEFORE

REMAINING CUTS :

First Order Cuts = Nil

Second Order Cuts = 4
These are :

Number	Elements		Number	Elements	
1	1	12	3	1	16
2	1	14	4	1	18

Third Order Cuts = Nil

The cut sets for other combinations of active failures of components and the stuck breakers present in the system are calculated in the same way as demonstrated above for active failure of component 1 and stuck breaker 9. The order and count of cut sets thus obtained are listed in the table F.3

Table F.3: Cut sets due to active failures and stuck breakers

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
2	10	1	nil	nil
3	9	nil	4	nil
4	10	1	nil	nil
5	9	nil	4	nil
6	9	nil	4	nil
6	10	1	nil	nil
7	9	nil	7	nil
8	10	1	nil	nil
9	10	1	nil	nil
10	9	1	nil	nil
11	9	nil	2	nil
11	10	1	nil	nil
12	10	1	nil	nil
13	9	nil	2	nil
13	10	1	nil	nil
14	10	1	nil	nil
15	9	nil	2	nil
15	10	1	nil	nil
16	10	1	nil	nil
17	15	nil	2	nil
18	16	nil	6	nil
19	9	nil	4	nil
20	9	nil	nil	nil
20	10	1	nil	nil
21	10	1	nil	nil
22	15	nil	7	nil
22	29	1	nil	nil
23	15	nil	2	nil
23	29	1	nil	nil
24	16	1	nil	nil
24	29	nil	nil	nil
25	15	nil	7	nil
25	29	1	nil	nil
26	15	nil	7	nil
26	29	1	nil	nil
27	15	nil	2	nil
27	29	1	nil	nil
28	16	1	nil	nil
28	29	1	nil	nil
29	15	1	nil	nil
32	16	1	nil	nil
32	29	1	nil	nil
33	16	nil	nil	nil

Table F.3 (contd.) Cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
34	15	nil	7	nil
34	29	1	nil	nil
35	15	nil	7	nil
35	29	1	nil	nil
38	54	1	nil	nil
39	136	1	nil	nil
40	16	nil	nil	nil
40	29	nil	nil	nil
41	16	1	nil	nil
41	29	1	nil	nil
42	16	nil	nil	nil
42	29	nil	nil	nil
43	16	1	nil	nil
43	29	1	nil	nil
44	16	1	nil	nil
44	29	1	nil	nil
45	16	nil	nil	nil
45	29	nil	nil	nil
46	16	nil	nil	nil
46	29	nil	nil	nil
47	16	nil	nil	nil
47	29	nil	nil	nil
48	[illegible]	nil	nil	nil
49	47	nil	nil	nil
50	47	nil	nil	nil
53	16	1	nil	nil
53	29	1	nil	nil
54	16	1	nil	nil
54	29	1	nil	nil
55	54	1	nil	nil
56	54	1	nil	nil
57	54	1	nil	nil
58	54	1	nil	nil
59	16	1	nil	nil
59	29	1	nil	nil
60	16	1	nil	nil
60	29	1	nil	nil
61	16	1	nil	nil
61	29	1	nil	nil
62	16	1	nil	nil
62	29	1	nil	nil
63	16	1	nil	nil
63	29	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
64	16	1	nil	nil
64	29	1	nil	nil
65	16	1	nil	nil
65	29	1	nil	nil
66	16	1	nil	nil
66	29	1	nil	nil
74	16	1	nil	nil
74	29	1	nil	nil
80	136	1	nil	nil
81	123	1	nil	nil
82	124	1	nil	nil
83	125	1	nil	nil
84	126	1	nil	nil
85	127	1	nil	nil
86	128	1	nil	nil
87	129	1	nil	nil
88	16	1	nil	nil
88	29	1	nil	nil
89	131	1	nil	nil
90	132	1	nil	nil
91	133	1	nil	nil
92	134	1	nil	nil
93	135	1	nil	nil
94	136	1	nil	nil
95	123	1	nil	nil
96	124	1	nil	nil
97	125	1	nil	nil
98	126	1	nil	nil
99	127	1	nil	nil
100	128	1	nil	nil
101	129	1	nil	nil
102	16	1	nil	nil
102	29	1	nil	nil
103	131	1	nil	nil
104	132	1	nil	nil
105	133	1	nil	nil
106	134	1	nil	nil
107	135	1	nil	nil
108	136	1	nil	nil
109	123	1	nil	nil
110	124	1	nil	nil
111	125	1	nil	nil
112	126	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
113	127	1	nil	nil
114	128	1	nil	nil
115	129	1	nil	nil
116	16	1	nil	nil
116	29	1	nil	nil
117	131	1	nil	nil
118	132	1	nil	nil
119	133	1	nil	nil
120	134	1	nil	nil
121	135	1	nil	nil
122	136	1	nil	nil
123	16	1	nil	nil
123	29	1	nil	nil
124	16	1	nil	nil
124	29	1	nil	nil
125	16	1	nil	nil
125	29	1	nil	nil
126	16	1	nil	nil
126	29	1	nil	nil
127	16	1	nil	nil
127	29	1	nil	nil
128	16	1	nil	nil
128	29	1	nil	nil
129	16	1	nil	nil
129	29	1	nil	nil
130	16	1	nil	nil
130	29	1	nil	nil
131	16	1	nil	nil
131	29	1	nil	nil
132	16	1	nil	nil
132	29	1	nil	nil
133	16	1	nil	nil
133	29	1	nil	nil
134	16	1	nil	nil
134	29	1	nil	nil
135	16	1	nil	nil
135	29	1	nil	nil
136	16	1	nil	nil
136	29	1	nil	nil
137	15	nil	7	nil
137	29	1	nil	nil
138	15	nil	7	nil
138	29	1	nil	nil

Table F.3 (continued) cut sets due to active failures and stuck breakers - George Dickie Substation.

Actively failed component	Stuck breaker	#First order cuts	#Second order cuts	#Third order cuts
139	15	nil	7	nil
139	29	1	nil	nil
140	15	nil	7	nil
141	16	1	nil	nil
141	29	1	nil	nil
142	16	1	nil	nil
142	29	1	nil	nil
143	16	1	nil	nil
143	29	1	nil	nil
144	16	1	nil	nil
144	29	1	nil	nil
145	9	nil	7	nil
146	10	1	nil	nil
147	9	nil	7	nil
148	10	1	nil	nil
149	9	nil	7	nil
150	10	1	nil	nil
151	9	nil	7	nil
152	9	nil	7	nil
152	10	1	nil	nil
153	10	1	nil	nil
154	9	nil	7	nil
154	10	1	nil	nil
155	10	1	nil	nil
156	9	nil	7	nil

APPENDIX G

EQUATIONS FOR EVALUATION OF CUT SETS

The assumptions made in the formulation of these equations are as follows:

1. Component failure and repair events are independent of each other.
2. Component repair rates are much larger than their failure rates
3. Preventive maintenance is not performed if there is some outage existing in a related portion of the system.
4. The probability of two or more active failures is approximately equal to zero.
5. Probability of two or more stuck breakers in the system is approximately equal to zero.

In the following section the equations contributing to load point failure rate and duration are developed and all failures are referred to as a load point failures.

a) Passive failures and overlapping passive failures

i) First Order Cutset

Let i be the component in the cutset, then

Contribution to the failure rate = λ_i

Duration = r_i

ii) Second Order Cutset

Components in the cutset = i, j

The components of the cutset are in parallel and the Markov model of a two component parallel system is shown in Figure G.1

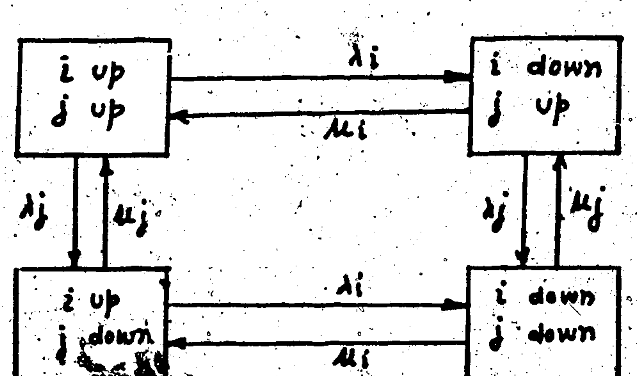

Figure G.1: Markov model of a two component parallel system

where:

λ_i = Failure rate of component i

λ_j = Failure rate of component j

μ_i = Repair rate of component i

μ_j = Repair rate of component j

r_i = Mean repair time of component i

r_j = Mean repair time of component j

$\mu_i \equiv 1/r_i$

$\mu_j \equiv 1/r_j$

P_1, P_2, P_3 and P_4 are the probabilities of state 1, 2, 3 and 4 respectively. As has been described in Chapter 2 the steady state probabilities of occupying each state can be found by using frequency balance approach resulting in the following :

$$P_1 = \frac{\mu_i \cdot \mu_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \quad (8.1)$$

$$P_2 = \frac{\mu_j \cdot \lambda_i}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \quad (8.2)$$

$$P_3 = \frac{\mu_i \cdot \lambda_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \quad (8.3)$$

$$P_4 = \frac{\lambda_i \cdot \lambda_j}{\{\mu_i + \lambda_i\}\{\mu_j + \lambda_j\}} \quad (8.4)$$

The system availability is defined as $= P_1 + P_2 + P_3$

$$= \frac{\mu_i\mu_j + \mu_j\lambda_i + \mu_i\lambda_j}{(\mu_i + \lambda_i)(\mu_j + \lambda_j)}$$

$$= \frac{1/r_i 1/r_j + \lambda_i/r_j + \lambda_j/r_j}{(1/r_i + \lambda_i)(1/r_j + \lambda_j)}$$

$$= \frac{1 + \lambda_i r_i + \lambda_j r_j}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)} \qquad (8.5)$$

The probability of system failure (i.e., P_f) is the probability of residing in state 4 and is defined as follows:

$$P_f = \lambda_i \lambda_j r_i r_j / (1 + \lambda_i r_i)(1 + \lambda_j r_j)$$

The frequency of failure = Probability of system failure x Rate of departure from the failed state

$$= P_f (\mu_i + \mu_j)$$

$$= \frac{\lambda_i \lambda_j (r_i + r_j)}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)} \qquad (8.6)$$

The failure rate, λ = Frequency of failure / Availability

$$= \frac{\lambda_i \lambda_j (r_i + r_j)(1 + \lambda_i r_i)(1 + \lambda_j r_j)}{(1 + \lambda_i r_i)(1 + \lambda_j r_j)(1 + \lambda_i r_i + \lambda_j r_j)}$$

$$= \frac{\lambda_i \lambda_j (r_i + r_j)}{(1 + \lambda_i r_i + \lambda_j r_j)}$$

In many practical studies the following assumptions can be made:

If $\lambda_i << \mu_i$ and $\lambda_j << \mu_j$, then,

$1 + \lambda_i r_i + \lambda_j r_j \approx 1$

and therefore,

the load point failure rate $\lambda = \lambda_i \lambda_j (r_i + r_j)$ (8.7)

and,

the load point average duration of repair, $r = P_f / f_f$

Substituting values of P_f and f_f, we get

$$r = r_i \cdot r_j / (r_i + r_j) \qquad (8.8)$$

where:

λ and r are the load point failure rate and mean duration of repair time.

The same results can be obtained by the following procedure:
The load point is in the down state when both components have failed. Assuming that no simultaneous or common mode failure can occur, the system failure state can occur with the components failing sequentially in one of the two different combinations. These are:

combination	order of failure	
i)	i	j
ii)	j	i

Since the events are mutually exclusive, the total load point failure rate is the addition of the contributions to failure rate by each of above combinations.
The contribution to load point failure rate by the first combination,

λ_1 = Failure rate of component i x (probability component j fails while i is failed)

$$= \lambda_i(\lambda_j r_i)/(1 + \lambda_j r_i) \qquad (8.9)$$

Since it has been assumed that repair rates of components are much larger than their respective failure rates, hence the denominator term in equation 8.9 equals unity approximately.
Therefore, $\lambda_1 = \lambda_i(\lambda_j r_i)$
Similarly, the contribution to failure rate by second combination

λ_2 = Failure rate of component j x (Probability component i fails while j is failed)

$= \lambda_j(\lambda_i r_j)$

Total contribution to load point failure rate $= \lambda_1 + \lambda_2$

$$= \lambda_i \lambda_j (r_i + r_j)$$

iii) Third order cutset

Let the components in the third order cut be i, j, and k. Since the components in the third order cut are in parallel, hence the load point is in failed state when all three components have failed. This state can occur with the components failing in one of six different combinations. These are :-

Combination	order of failure
1)	i j k
2)	i k j
3)	j k i
4)	k j i
5)	j i k
6)	k i j

The total failure rate is the addition of the contributions to failure rate by each of the six combinations

The contribution to the failure rate by the first combination is

= Failure rate of component i x (Probability component j fails while i is failed) x (Probability component k fails while i and j are failed)

$$= \lambda_i \lambda_j r_i . \lambda_k r_i r_j / (r_i + r_j)$$

$$= \lambda_i \lambda_j \lambda_k (r_i^2 r_j)/(r_i + r_j)$$

The contributions to the failure rate due to rest of the combinations can also be written in the same fashion.

The total contribution to load point failure rate,

$$\lambda = \lambda_i \lambda_j \lambda_k (r_i^2 r_j / r_i + r_j) + \lambda_i \lambda_j \lambda_k (r_i^2 r_k)/(r_i + r_k)$$

$$+ \lambda_i \lambda_j \lambda_k (r_j^2 r_k)/(r_j + r_k) + \lambda_i \lambda_j \lambda_k (r_j^2 r_i)/(r_i + r_k)$$

$$+ \lambda_i \lambda_j \lambda_k (r_k^2 r_i)/(r_i + r_k) + \lambda_i \lambda_j \lambda_k (r_j r_k^2)/(r_j + r_k)$$

$$= \lambda_i \lambda_j \lambda_k (r_i r_j + r_i r_k + r_j r_k) \qquad (8.10)$$

b) <u>Maintenance Outages and maintenance outages overlapping passive failures</u>

I) <u>First order cut</u>

Let the component in the cut be i and let its maintenance outage rate be defined as λ_i'' and the maintenance restoration rate as r_i''. Then,

Load point failure rate contribution = λ_i''

Mean outage Duration = r_i''

There can not be any contribution by maintenance outages overlapping passive failures because of the assumption that if there exists an outage in the system the maintenance activity is not started

II) <u>Second order cut</u>

The contribution to the reliability indices due to the maintenance outages overlapping the passive failures can be obtained by the same logic as explained for the overlapping passive outages

Let the components in the cut be i and j. Since maintenance activities are not started when there exists an outage in the system, only two combinations are possible which lead to the load point outages. They are:

1. component i in maintenance outage and component j in passive outage mode.
2. component j in maintenance outage mode and component i in passive outage mode.

The contribution to load point failure rate and mean duration indices by the first combination is given by:

$$\lambda_1 = \lambda_i'' (\lambda_j r_i'')$$

$$r_1 = \frac{r_i'' r_j}{r_i'' + r_j}$$

Similarly,

$$\lambda_2 = \lambda_j'' (\lambda_i r_j'')$$

$$r_2 = r_i r_j'' / (r_j'' + [illegible])$$

Total failure rate = $\lambda = \lambda_1 + \lambda_2 = \lambda_i''(\lambda_j r_i'') + \lambda_j''(\lambda_i r_j'')$ (8.11)

Mean outage duration = $r = \dfrac{r_1\lambda_1 + r_2\lambda_2}{\lambda_1 + \lambda_2}$

If

$\upsilon_i \equiv \lambda_i r_i; \quad \upsilon_i'' \equiv \lambda_i'' r_i''; \quad \upsilon_j'' \equiv \lambda_j'' r_j''$

and,

$\nu_{ij} \equiv r_i'' / (r_i'' + r_j)$

where:

υ_i is the total annual passive outage duration of component i.

υ_i'' is the total annual maintenance outage duration of component i.

υ_j'' is the total annual maintenance outage duration of component j.

ν_{ij} is the mean outage duration when component i is on maintenance outage and the component j fails passively.

Then,

the mean outage duration, $r = (\upsilon_i''\upsilon_i\nu_{ij} + \upsilon_j''\upsilon_i\nu_{ji}) / \lambda$. (8.12)

III) <u>Third order cut set</u>

Let the components in the cut set be i, j and k.

The three events which lead to the load point interruptions are as follows:

1. component i in maintenance, j and k in passive outage mode;
2. component j in maintenance, i and k in passive outage mode;
3. component k in maintenance, i and j in passive outage mode.

Each of above events can have can have 2 subevents because of the order of failure of passive failures. For example, event 1 can have the following subevents:

1. subevent 1, i in maintenance, j fails and then k fails;
2. subevent 2, i in maintenance, k fails and then j fails;

The outage rate resulting from event 1 is defined as:

$$\lambda_1 = \lambda_i''(\lambda_j r_i'')(\lambda_k r_i'' r_j/(r_i''+r_j)) + \lambda_i''(\lambda_k r_i'')(\lambda_j)(r_i'' r_k)/(r_i''+r_k)$$

where:

λ_i'' = maintenance outage rate of component i

$\lambda_j r_i''$ = probability that component j fails while i in maintenance outage

$\lambda_k r_i'' r_j / (r_i'' + r_j)$ = probability that component k fails during the maintenance outage of component i and repair duration of component k

It may be noted that the above two terms are numerically equal to the respective probabilities because the denominator terms have been ignored (Refer equation 8.9).

The outage duration due to above event is given by the following equations

$$1/r_1 = 1/r_i'' + 1/r_j'' + 1/r_k''$$

$$r_1 = r_i'' r_j r_k / (r_i'' r_j + r_j r_k + r_i'' r_k)$$

Similarly, the indices resulting from events 2 and 3 are given by:

$$\lambda_2 = \lambda_j''(\lambda_i r_j'')(\lambda_k)(r_i r_j'')/(r_i + r_j'') + \lambda_j''(\lambda_k r_j'')(\lambda_i)(r_j'' r_k)/(r_j'' + r_k)$$

$$r_2 = r_j'' r_i r_k / (r_j'' r_i + r_j'' r_k + r_i r_k)$$

$$\lambda_3 = \lambda_k''(\lambda_i r_k'')(\lambda_j)(r_i r_k'')/(r_i + r_k'') + \lambda_k''(\lambda_j r_k'')(\lambda_i)(r_j r_k'')/(r_j + r_k'')$$

$$r_3 = r_k'' r_i r_j / (r_k'' r_i + r_k'' r_j + r_i r_j)$$

The total contribution to the load point reliability indices is given by the following equations:

Load point failure rate $\lambda = \lambda_1 + \lambda_2 + \lambda_3$ (8.13)

Mean outage duration = $r = (\lambda_1 r_1 + \lambda_2 r_2 + \lambda_3 r_3)/\lambda$ (8.14)

c) Active failures and active failures overlapping passive failures:

Let:

λ'_{ig} = Active failure rate of component i

S_i = Switching duration of component i

λ_i = Passive failure rate of component i

r_i = Mean repair duration of component i

λ = Equivalent failure rate of the cutset

r = Equivalent mean repair duration of the cutset

i) First order cut set

Let the component in the cut set be i, then:

Load point failure rate contribution = λ_{ig} (8.15)

Load point mean outage duration = S_i (8.16)

If the component can not be switched, then:

the load point mean outage duration = r_i

ii) Second order cut set

Let the components in the cut set be i and j, where i is the actively failed component.

Load point failure rate = Active failure rate of component i .(Probability j fails passively while i is actively failed)

+

passive failure rate of component j .(Probability i fails actively while j is failed passively)

$$= \lambda_{ig}\lambda_j S_i + \lambda_j \lambda_{ig} r_j \quad (8.17)$$

If the failed component can not be switched then, the mean outage repair time is given by:

$$r = S_i r_j / (S_i + r_j) \quad (8.18)$$

If the component can be switched then the event can be terminated by the mean duration of S_i.

iii) Third order cut set

Let the components in the cutset be i, j and k and let i be the actively failed component.

Load point failure rate = Active failure rate of i(Probability j fails passively while i is actively failed) .(Probability k fails passively while i is actively failed and j is passively failed)

+

Active failure rate of i.(Probability k fails passively while i is actively failed) .(Probability j fails passively while i is actively failed and k is passively failed)

+

Passive failure rate of j.(Probability i fails actively while j is passively failed) .(Probability k fails passively while j is passively failed and i is actively failed)

+

Passive failure of j.(Probability k fails passively while j is passively failed) .(Probability i fails actively while j and k are passively failed)

+

Passive failure of k.(Probability i fails actively while k is passively failed) .(Probability j fails passively while k is passively failed and i is actively failed)

+

Passive failure rate of k.(Probability j fails passively while k is passively failed)

.(Probability i fails actively while j and k are passively failed)

Load point failure rate, $\lambda = \lambda_{ig}\lambda_j S_i \lambda_k S_i r_j/(S_i+r_j) + \lambda_{ig}\lambda_k S_i \lambda_j S_i r_k/(S_i+r_k)$

$$+ \lambda_j \lambda_{ig} r_j \lambda_k r_j S_i/(r_j+S_i) + \lambda_j \lambda_k r_j \lambda_{ig} r_j r_k/(r_j+r_k)$$

$$+ \lambda_k \lambda_{ig} r_k \lambda_j r_k S_i/(r_k+S_i) + \lambda_k \lambda_j r_k \lambda_{ig} r_k r_j/(r_k+r_j) \qquad (8.19)$$

If the event can not be terminated by switching then the mean repair duration is given by the following equations:

$$1/r = 1/S_i + 1/r_j + 1/r_k$$

$$r = S_i r_j r_k/(r_j r_k + S_i r_k + S_i r_j) \qquad (8.20)$$

Otherwise, if the event can be terminated by switching, then the mean repair time is given by the following equation:

$$r = S_i \qquad (8.21)$$

d) Active failures overlapping Maintenance Activity

i) First Order Cut Set

There can not be any contribution by maintenance outages overlapping active failures because of the assumption that if there exists an outage in the system the maintenance activity is not started.

ii). Second Order Cut Set

Let the components in the cut set be i and j, where i fails actively while j is on maintenance outage.

Load point failure rate = Maintenance outage of j.(Probability i fails actively when j is on maintenance outage)

Load point failure rate, $\lambda = \lambda_j''(\lambda_{ig} r_j'')$ (8.22)

If the event can not be terminated by switching, then the mean outage duration $= S_i r_j''/(S_i + r_j'')$ (8.23)

If the event can be terminated by switching, then the mean outage duration $= S_i$ (8.24)

iii) <u>Third Order Cut Set</u>

Let the components in the cut set be i, j and k, where i fails actively, j can be on maintenance outage and k can fail passively.

Load point failure rate = Maintenance outage rate of j.(Probability i fails actively when j is on maintenance outage).(Probability k fails passively while j is on maintenance outage and i is failed actively)

+

Maintenance outage rate of j.(Probability k fails passively when j is on maintenance outage).(Probability i fails actively while j is on maintenance outage and k is failed passively)

+

Similar terms when component k is on maintenance outage and component j fails passively.

Let the event when component i fails actively, j on maintenance outage and k fails passively be termed as event 1 and the event when component i fails actively, k on maintenance outage and j fails passively be termed as event 2. And also let the failure rate and mean repair duration contributions be called λ_1, r_1 and λ_2, r_2 respectively for event 1 and 2. Then:

$$\lambda_1 = \lambda_j''\lambda_{ig} r_j''\lambda_k\{r_j'' S_i/(r_j''+S_i) + r_j'' r_k/(r_j''+r_k)\}$$

$$\lambda = \lambda''\lambda \; + \lambda\{r''S/(r''+S) + r''r/(r''+r)\}$$

Total load point contribution = $\lambda_1 + \lambda_2$ (8.25)

If the event can not be terminated by switching, then

$$r_1 = r_j'' S_i r_k / (S_i r_k + r_j'' r_k + S_i r_j'')$$

and

$$r_2 = r_k'' S_i r_j / (S_i r_j + r_k'' r_j + r_k'' S_i)$$

The equivalent load point failure duration = $r = (\lambda_1 r_1 + \lambda_2 r_2)/(\lambda_1 + \lambda_2)$ (8.26)

If the event can be terminated by switching, then the load point failure duration, $r = S_i$ (8.27)

Active failures with stuck breakers and overlapping passive fail[illegible]

i) First Order Cut Set

Let i be the actively failed component and j be the stuck breaker present in the system, then the load point failure rate = $\lambda_{ig} Pr(j)$ (8.28)
where: Pr(j) is the probability of the stuck breaker.

If the component can not be switched, then the load point mean duration of repair = r_i (8.29)

If the component can be switched, then the load point mean duration of repair = S_i (8.30)

i) Second Order Cut Set

Let i be the actively failed component and let j be the stuck breaker.

A) If the components in the cut set are i and j, then the load point failure rate = λ Pr(j) (8.31)

B) If the components in the cut set are i and k, then

Load point failure rate = Active failure rate of i(Probability k fails while i is actively failed) (Probability j is stuck)

+

Failure rate of component k(Probability i fails actively when k is failed) (probability j is stuck

$$= \lambda_{ig}\lambda_k S_i Pr(j) + \lambda_k \lambda_{ig} r_k Pr(j)$$

$$= \lambda_k \lambda_{ig} Pr(j)[S_i + r_k] \quad (8.32)$$

Mean duration of repair

For case A

$r = r_i$, if event is terminated by repair

$r = S_i$, if event is terminated by switching (8.33)

For case B

$r = S_i r_k/(S_i+r_k)$, if event is terminated by repair

$r = S_i$, if event is terminated by switching. (8.34)

iii) <u>Third Order Cut</u>

Let i be the actively failed component and j be the stuck breaker present in the system. Following the same logic as for the second order cuts :

A) Let the components in the cut be i, j and k, then

Load point failure rate = $\lambda_{ig}\lambda_k Pr(j)[S_i+r_k]$ (8.35)

Mean duration of repair = $S_i r_k/(S_i+r_k)$, if event is terminated by repair

$= S_i$ if event terminated by switching (8.36)

B) Let the components in the cut set be i, k, l, then

$$\text{Load point failure rate} = \lambda_{ig}\lambda_k\lambda_l S_i Pr(j)[S_i r_k/(S_i+r_k) + S_i r_l/(S_i+r_l)] + \lambda_k\lambda_{ig}\lambda_l r_k Pr(j)[S_i r_k/(S_i+r_k) + r_k r_l/(r_k+r_l)] + \lambda_l\lambda_{ig}\lambda_k r_l Pr(j)[S_i r_l/(S_i+r_l) + r_k r_l/(r_k+r_l)] \quad (8.37)$$

Mean outage of repair, $r = S_i r_k r_l/(r_k r_l+S_i r_l+S_i r_k)$, if event is terminated by repair

$= S_i$, if event is terminated by switching. (8.38)

) <u>Active failures with stuck breakers overlapping Maintenance Outages</u>

The contribution to load point indices of reliability for this mode of failure can be derived by following the same logic as for the previous cases

i) <u>First order cut</u> There is no contribution to the load point indices of reliability by the first order cuts because of assumption 3.

ii) <u>Second order cutsets</u>

Let i be the actively failed component and j be the stuck breaker present in the system.

A) If the components in the cut are i and j, then the event is similar to the section d(ii), and hence there is no contribution to load point indices of reliability by this event.

B) If the components in the cut set are i and k, then:

$$\text{Load point failure rate} = \lambda''_k\lambda_{ig} r''_k Pr(j) \quad (8.39)$$

Mean duration of repair $= r''_k S_i/(r''_k+S_i)$, if the event is terminated by repair

$= S_i$, if event is terminated by switching (8.40)

iii) Third order cut set

Let i be the actively failed component and j be the stuck breaker present in the system.

A) If the components in the cut set are i, j and k, then the load point failure rate and the mean duration of repair are given by equations 8.39 and 8.40 respectively.

B) If the components in the cut set are i, k and l, then

$$\text{Load point failure rate} = \lambda''_k \lambda_{ig} r''_k \lambda_1 Pr(j)[r''_k S_i/(r''_k+S_i)+r''_k r_1/(r''_k+r_1)] + \lambda''_1 \lambda_{ig} r''_1 \lambda_k Pr(j)[r''_1 S_i/(r''_1+S_i)+r''_1 r_k/(r''_1+r_k)] \quad (8.41)$$

Mean duration of outage:

If the components in the cut set cannot be switched, then the mean duration of outage is obtained by the same logic as explained for event in section d(iii). Here event 1 is when component i is actively failed, component k is on maintenance outage, and component l is passively failed and event 2 is when component i is actively failed, component l is on maintenance outage and component k is passively failed. Then:

$$\lambda_1 = \lambda''_k \lambda_{ig} r''_k \lambda_1 Pr(j)[r''_k S_i/(r''_k+S_i) + r''_k r_1/(r''_k+r_1)]$$

$$\lambda_2 = \lambda''_1 \lambda_{ig} r''_1 \lambda_k Pr(j)[r''_1 S_i/(r''_1+S_i) + r''_1 r_k/(r''_1+r_k)]$$

$$1/r_1 = (S_i r_1 + r''_k r_1 + r''_k S_i)/(r''_1 S_i r_k)$$

$$r_1 = r''_k s_i r_1/(S_i r_1 + r''_k r_1 + r''_k S_i)$$

$$r_2 = r''_1 S_i r_k/(S_i r_k + r''_1 r_k + r''_1 S_i)$$

$$r = (\lambda_1 r_1 + \lambda_2 r_2)/(\lambda_1+\lambda_2)$$

$$= S_i, \text{ if event can be terminated by switching} \quad (8.42)$$

g) Common Cause Outages [28]

State Space Diagram for Common Cause Failures

The effect of common cause or common mode failures can be illustrated by considering a system of two components in parallel. The results can then be extended to a system having three or more components in parallel.

The model used here is similar to one proposed in references [14] and [15]. It is shown below in Figure G.1

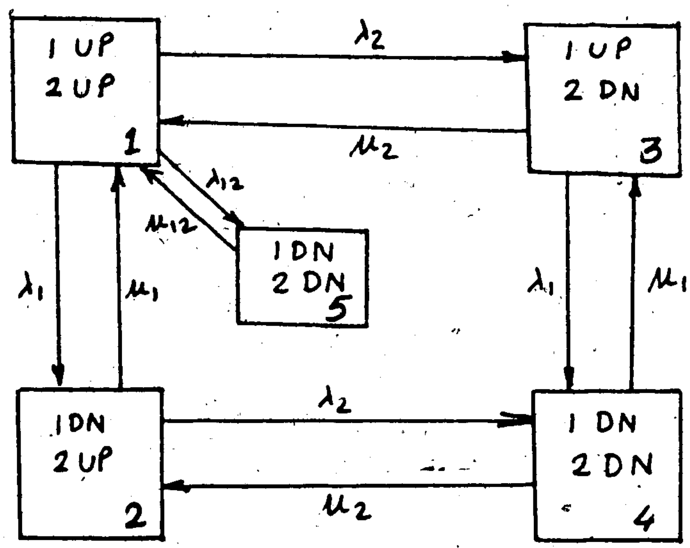

Figure G.1: Markov model of two component system including common mode outages.

The definitions of the symbols used in the Figure G.1 are listed in Table G.1

Solving a set of frequency balance equations, the following expressions for steady state probabilities P_4 and P_5 can be obtained:

$$P_4 = [(\lambda_1 \mu_2)(\lambda_2+\mu_1)\lambda_1\lambda_2\mu_{12}]/D_3 \quad (8.43)$$

$$P_5 = (\lambda_{12}\mu_1\mu_2).P_4 / \mu_{12}\lambda_1\lambda_2 \quad (8.44)$$

Table G.1: Definitions of symbols used in Figure G.1

λ_1 = Failure rate of component 1

λ_2 = Failure rate of component 2

μ_1 = Restoration rate of component 1

μ_2 = Restoration rate of component 2

λ_{12}= Common mode failure rate of components 1 and 2

μ_{12}= Common mode restoration rate of components 1 and 2

$P_1, P_2 \ldots P_5$= Probabilities of occupying states 1, 2,..5 respectively.

where:

$$D_3 = (\lambda_1+\mu_2(\lambda_2+\mu_1)(\lambda_1\lambda_2\mu_{12}+\mu_1\mu_2\lambda_{12})+\mu_{12}[\lambda_1\mu_1(\lambda_2+\mu_2)(\lambda_1+\mu_2)+\lambda_2\mu_2(\lambda_1+\mu_1)(\lambda_2+\mu_1)] \quad (8.45)$$

Assuming :

$\lambda_1\lambda_2\mu_{12} << \mu_1\mu_2\mu_{12}$

$\lambda_1+\mu_2 \simeq \mu_2$

$\lambda_2+\mu_1 \simeq \mu_1$

$\lambda_1+\mu_1 \simeq \mu_1$

$\lambda_2+\mu_2 \simeq \mu_2$

$\mu_1\mu_2+\lambda_1\mu_2+\lambda_2\mu_1 \simeq \mu_1\mu_2$

Equations for P_4 and P_5 reduce to:

$$P_4 = \lambda_1\lambda_2\mu_{12} / \mu_1\mu_2(\lambda_{12}+\mu_{12}) \quad (8.46)$$

$$P_5 = \lambda_{12}/(\lambda_{12}+\mu_{12}) \quad (8.47)$$

The probability of being in the down state is defined as:

$$P_d = P_4+P_5$$

$$= (\lambda_{12}+\lambda_1\lambda_2\mu_{12}/\mu_1\mu_2)/(\lambda_{12}+\mu_{12}) \quad (8.48)$$

Since there are no transitions between states 4 and 5, the frequency of encountering down state is:

$$f_d = f_4 + f_5$$

where: f_4 and f_5 are the frequencies of encountering states 4 and 5, respectively.

$f_d = P_4(\mu_1+\mu_2)+P_5\mu_{12}$

$= [\lambda_1\lambda_2(r_1+r_2)+\lambda_{12}]\mu_{12}/(\mu_{12}+\lambda_{12})$ (8.49)

where:

$r_1=1/\mu_1=$ Mean repair time of component 1

$r_2=1/\mu_2=$ Mean repair time of component 2

Assuming:

$\lambda_{12}\ \mu_{12} \simeq \mu_{12}$

Equations 8.48 and 8.49 reduce to:

$P_d = \lambda_{12}/\mu_{12} + \lambda_1\lambda_2/\mu_1\mu_2$ (8.50)

$f_d = \lambda_1\lambda_2(r_1+r_2)+\lambda_{12}$ (8.51)

Replacing $1/r_1$, $1/r_2$, and $1/r_{12}$ for μ_1, μ_2 and μ_{12}, respectively in equation 8.50, the resulting equation becomes:

$P_d = \lambda_{12}\ r_{12} + \lambda_1\lambda_2 r_1 r_2$ (8.52)

Failure rate = Frequency of encountering down states/Availability
Since repair rates are assumed to be very large when compared to failure rates, the availability of the system approaches unity approximately. Therefore:

Failure rate, $\lambda \simeq f_d$

$\simeq \lambda_1\lambda_2(r_1+r_2)+\lambda_{12}$ (8.53)

Mean down time $\doteq r = P_d/f_d$

$=(\lambda_{12}r_{12}+\lambda_1\lambda_2 r_1 r_2)/[\lambda_1\lambda_2(r_1+r_2)+\lambda_{12}]$ (8.54)

The average down time = U = λr

$=\lambda_{12}r_{12} + \lambda_1\lambda_2 r_1 r_2$ (8.55)

Equations 8.53, 8.54 and 8.55 represent the three main indices of load point reliability. If no common mode outages occur in the system the equations giving the three reliability indices reduce to the standard equations for two overlapping independent events, i.e.,

$\lambda = \lambda_1\lambda_2(r_1+r_2)$ (8.56)

$r = r_1 r_2/(r_1+r_2)$ (8.57)

$U = \lambda r$ (8.58)

Comparing equations 8.53 and 8.56, it can be clearly seen that the failure rate of the system including independent outages and common mode outages is given by the sum of the failure rates of the corresponding outages calculated as if they occured independently of each other. The same conclusions can be drawn by comparing equations 8.55 and 8.58 representing the average annual outage times.

Hence for Second order cut, if the components which can fail in common mode are i and j, then:

Load point failure rate contribution = λ_{ij} (8.59)

Load point mean duration of repair = r_{ij} (8.60)

Where:

λ_{ij} = Common mode failure rate of component i and j

r_{ij} = Average repair duration of components i and j failed in common mode

Third Order Cut Set

If the components in the cut set are i, j and k and if components i and j can fail in common mode, then the load point outage is possible either by the overlapping passive outage of component k or by the maintenance outage of k followed by the common mode failure of components i and j.

i) Common mode outages overlapping passive outages

For the components in parallel the load point interruptions occur when all the three components are in the outage state. This event can occur by the following order of failures

	order of failure		
i)	i	j	k
ii)	i	k	j
iii)	j	k	i
iv)	k	j	i
v)	j	i	k
vi)	k	i	j

By definition, the common mode failures can occur only in case i), iv), v) and vi)

The failure rate contribution in this mode is given by

Failure rate of load point, λ = (Common mode outage rate of component i and j)(Probability, k fails when components i and j are failed in common mode)

+

(outage of component k)(Probability of outage of components i and j in common mode while k is on outage)

$$= \lambda_{ij}(\lambda_{k} r_{ij}) + \lambda_{k}(\lambda_{ij} r_{k})$$

$$= \lambda_{ij}\lambda_{k}(r_{ij} + r_{k}) \quad (8.61)$$

Load point mean outage duration $= r = r_{ij}r_{k}/(r_{ij}+r_{k})$, if event is terminated by repair

$= S_i$, if event is terminated by switching (8.62)

ii) <u>Common mode outages overlapping maintenance</u> :-

The same logic can be extended for this mode of failure as in the above case.

Load point failure rate = Maintenance outage of component k(Probability of outage of i and j in common mode while k is on maintenance outage)

$$= \lambda''_{k}(\lambda_{ij} r''_{k}) \quad (8.63)$$

Load point outage duration $= r''_{k} r_{ij}/(r''_{k}+r_{ij})$, if event is terminated by repair

$= S_i$, if event is terminated by switching (8.64)

It may be noted that in these equations it was assumed that only two components can fail in common mode, however if more than two components can fail in common mode then similar equations can be written following the same logic described above.

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