

**RELIABILITY EVALUATION OF POWER SYSTEMS INCLUDING  
PROTECTION SYSTEM FAILURES**

**Electrical Engineering Abstract 82A218**

**A Thesis**

**Submitted to the Faculty of Graduate Studies and Research**

**in Partial Fulfilment of the Requirements**

**for the Degree of**

**Master in Science**

**in the**

**Department of Electrical Engineering**

**University of Saskatchewan**

**by**

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**Saskatoon, Saskatchewan**

**April 1982**

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To  
My Parents  
Bishan Singh Tatla  
and  
Late Chand Kaur Tatla

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## ACKNOWLEDGEMENTS

The author extends his sincere thanks and appreciations to his supervisors, Dr. R. Billinton and Dr. M. S. Sachdev, for the guidance, discussion and encouragement provided by them during the course of this work.

Special thanks are due to his wife, Surinder and daughter, Ruby, for their patience and constant encouragement to complete this work.

This work was financed by the University of Saskatchewan in the form of a Scholarship and the National Sciences and Engineering Research Council.

## UNIVERSITY OF SASKATCHEWAN

## Electrical Engineering Abstract No

**"RELIABILITY EVALUATION OF POWER SYSTEMS INCLUDING  
PROTECTION SYSTEM FAILURES"**

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M.Sc. Thesis presented to the College of Graduate Studies

April 1982

## ABSTRACT

Power transmission systems are becoming increasingly complex as the demand for electric energy increases. The protection system plays an important role in achieving high reliability by recognizing and isolating any abnormal condition in the network within minimum possible time and with a minimum effect on the healthy system. The protection system itself is, however, also a potential source of failure. This thesis describes the different failure modes within the protection system and their effect on load point reliability indices.

A number of techniques are available for reliability evaluation of power systems. Protection systems are generally assumed to be perfectly reliable in most of these techniques. Simple equations are developed in this thesis to include protection system failures in transmission system reliability evaluation. These equations can be used in conjunction with the cut set approach to evaluate the outage frequency and duration indices at different points in a transmission system.

Terminal related outages resulting in the removal of line and/or generating units can occur in a power system because of faults on the protection system i.e. ground fault on a breaker, a stuck breaker or relay condition, battery failure etc. These failures are normally of short duration but can result in multiple outages of current carrying components. The effect of such outages on the reliability indices of a composite generation and transmission system can be significant. This thesis describes and illustrates the cause and effect of terminal related outages using the configurations of two practical substations. Models suitable for including their effects in the reliability analysis of a composite generation and transmission system are also described. The results of the composite system are calculated including protection system failures using a 5-bus test system. The resulting indices are then used as starting values in the evaluation of the reliability indices of a hypothetical distribution system supplying a group of individual customer loads.

## TABLE OF CONTENTS

	Page
COPYRIGHT	ii
ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	x
1. INTRODUCTION	1
2. PROTECTION SYSTEM FAILURE MODES	6
2.1 General	6
2.2 Reliability of Protection Systems	7
2.3 Zones of Protection	8
2.4 Failure Modes of Relays and Circuit Breakers	10
2.4.1 Unrevealed failures	11
2.4.2 Revealed failures	11
2.4.3 Ground fault	11
2.5 Failure of the DC Supply	12
2.6 Estimation of Parameters	13
2.6.1 Estimation from field data	15
3. RELIABILITY EVALUATION OF TRANSMISSION AND DISTRIBUTION SYSTEMS INCLUDING PROTECTION SYSTEM FAILURE MODES	18
3.1 General	18
3.2 Failure Modes of a Component	19

	Page
3.3 Failure Modes of a Load Point	23
3.4 Duration of the Failure Modes	27
3.5 Basic Equations	29
3.5.1 Contribution to load point indices due to each failure mode	33
3.6 System Studies	56
4. PROTECTION SYSTEM RELATED MULTIPLE OUTAGES IN THE RELIABILITY ANALYSIS OF A COMPOSITE GENE- RATION AND TRANSMISSION SYSTEM	62
4.1 General	62
4.2 Classification of Outages	66
4.2.1 Independent outages	66
4.2.2 Dependent outages	67
4.2.3 Common mode outages	67
4.2.4 Terminal related outages	69
4.3 Protection System Related Outages	71
4.3.1 Regina South switching station	72
4.3.2 Squaw Rapids station	74
4.4 Models for Protection System Related Outages	76
4.5 The Evaluation of Protection System Components	83
5. COMPOSITE GENERATION AND TRANSMISSION SYSTEM RELIABILITY EVALUATION INCLUDING PROTECTION SYSTEM FAILURE MODES	87
5.1 General	87

	Page
5.2 Power System Component Models	90
5.2.1 Multistate model of a current carrying component	92
5.2.2 Multistate model of a circuit breaker	96
5.3 System Model	98
5.4 System Studies	101
5.5 Reliability Indices at Customer Load Points	117
5.5.1 Reliability indices of customers connected to Switching Station 2	119
5.5.2 Reliability indices of customers connected to Switching Station 3	120
6. CONCLUSIONS	124
REFERENCES	128
APPENDICES	133
Appendix A Definition of Outage Terms	133
Appendix B Data of the 5-Bus Test System	136



## LIST OF FIGURES

Figure		Page
2.1	Single line diagram of a hypothetical power system	9
3.1	Single line diagram of a hypothetical power system	19
3.2	Single line diagram of a section of a power system	21
3.3	State transition diagram of the system shown in Figure 3.2	21
3.4	State transition diagram of A and B shown in Figure 3.2	22
3.5	Effect of the probability of unreadiness of the protection system on reliability indices	59
3.6	Effect of the false tripping rate of the protection system on reliability indices	60
4.1	The basic simultaneous independent outage model	67
4.2	A common mode outage model - the IEEE model	68
4.3	Single line diagram of the dc supply at Regina South switching station of SPC	72
4.4	Single line diagram of Regina South switching station of SPC	72
4.5	Single line diagram of the Squaw Rapids station	75
4.6	Model 3 of Reference 23	78
4.7	Model for two lines on the same right-of-way and sharing a common breaker	79
5.1	Single line diagram of the 5-bus test system	89
5.2	Single line diagram of a section of a power system	91

Figure		Page
5.3	Markov model of component A1	91
5.4	Multistate model of component A1	93
5.5	Multistate model of breaker B1	97
5.6	Example system illustrating effect of independence assumption	99
5.7	State transition diagram of the system shown in Figure 5.6	100
5.8	Configuration at Bus 1 of the test system shown in Figure 5.1	102
5.9	Configuration at Bus 2 of the test system shown in Figure 5.1	103
5.10	Configuration at Bus 3 (4) of the test system shown in Figure 5.1	104
5.11	Configuration at Bus 5 of the test system shown in Figure 5.1	104
5.12	Radial distribution system	118

## LIST OF TABLES

Table	Page	
3.1	Component outage data	56
3.2	Reliability indices at load points A and B	57
4.1	Line originated multiple outages - Regina South	73
4.2	Line originated multiple outages - Squaw Rapids	75
4.3	Variation of two lines down and station down state probabilities with the station outage rate ( $\lambda_{ss}$ ), stuck probability of the common breaker ( $q_u$ ) and probability of battery failure ( $p_b$ )	82
5.1	State probabilities of Figure 5.6	101
5.2	Load point failure probability and frequency for the system shown in Figure 5.1	109
5.3	Annualized Load Point Indices for the system shown in Figure 5.1	110
5.4	Maximum Load Curtailed for the system shown in Figure 5.1	111
5.5	Maximum Energy Curtailed for the system shown in Figure 5.1	112
5.6	Maximum Duration of Load Curtailment for the system shown in Figure 5.1	113
5.7	Bus Indices Averages for the system shown in Figure 5.1	114
5.8	System Indices for the system shown in Figure 5.1	115
5.9	System Indices Maximums for the system shown in Figure 5.1	116
5.10	Reliability indices for customers connected to Station 2 of the 6-line system	119
5.11	Reliability indices for customers connected to Station 2 of the 8-line system	119

Table		Page
5.12	Reliability indices for customers connected to Station 3 of the 6-line system	120
5.13	Reliability indices for customers connected to Station 3 of the 8-line system	120
5.14	Reliability indices for customers connected to stations 2 and 3 of the 6-line and 8-line systems	122

## 1. INTRODUCTION

Electrical energy is an essential ingredient in the development of a modern society. In order to maintain an adequate supply of electricity to the public and industry, state and provincial bodies have enacted laws giving government and private utilities and corporations the monopoly to generate, transmit and distribute electrical energy within given geographical areas. Electric power companies have invested a substantial amount of capital in generating stations, transmission lines and distribution networks to provide an acceptable quality of electrical energy to their consumers. It is not feasible economically and technically to attempt to design a power system with one hundred percent reliability. Power system engineers have always attempted to achieve the highest possible reliability at an affordable cost. The past practices of expressing consumer load point reliability in qualitative terms are being slowly replaced by quantitative indices which are obtained through the development and use of probabilistic methods of evaluating system reliability. One objection often raised to the utilization of probability techniques is the absence of accurate component data. It should be appreciated, however, that the results obtained are simply estimates based upon the available information. As such, even in the absence of accurate data, they can be extremely valuable in consistently comparing alternate configurations and the relative benefits of configuration changes.

The research work on reliability studies of power systems basically falls into three broad categories, namely the investigation of the reliability properties of generation systems, transmission and distribution systems, and composite generation and transmission systems. A considerable amount of research has been reported in the first two system categories [1-4] but a less adequate treatment has been given to the last area due to the inherent difficulties involved in treating the composite problem.

The primary purpose of generating capacity reliability evaluation is to determine the adequacy of available and proposed generation facilities to satisfy the system load requirements. In this case the provision of an adequate transmission facility is generally assumed. Methods of evaluating the reliability of a generating system are well established [1,4] and accepted by the power industry.

Reliability evaluation of transmission and distribution systems [1,2] generally assumes the provision of sufficient generation capacity or complete availability of generating units. A considerable amount of work has been done in the establishment of consistent techniques since a 1964 publication [5] which proposed a series of practical equations for the reliability calculation of transmission systems. The results obtained by this technique were compared with results obtained by using Markov Processes [6] in Reference 7 and the original expressions were modified [7-9] to obtain a more accurate appraisal of the system. The effects of specific component failures on the remainder of the

system were included by considering a three state representation of the system, namely operating, before switching and after switching. This aspect was described in Reference 10 and subsequently used in techniques [11-15] for the reliability evaluation of Substations and Switching Stations.

The reliability evaluation of a composite generation and transmission system is concerned with the problem of determining the adequacy of the generation and transmission system in regard to providing a dependable and suitable supply at the terminal stations [4,16]. Relatively few papers [16-22] are available on the reliability evaluation of composite generation and transmission systems. Most composite generation and transmission system reliability evaluation techniques available at the present time use the representation of the system in which lines simply terminate at a bus, without extensive representation of the bus switching and circuit breaker configurations.

In most of the previously mentioned approaches used to calculate reliability indices, the protection system is considered to be one hundred percent reliable. This is obviously impossible to attain, no matter how much time, effort and money is spent. When a component of a power system fails, it is assumed that the faulted component is isolated by the associated protection system. The protection system itself is, however, a potential source of failure which is not normally considered.

This thesis describes the failure modes of protection systems and their effects on load point reliability indices. The equations developed in this thesis provide a useful extension to

those previously developed for systems in which the protection systems are assumed to be completely reliable.

The outage effects of protection system elements are normally reflected in composite system reliability calculations by simply adding a protection system factor to the failure and repair rates of lines and/or generators affected by the failure of the protection system element. This approach is accurate when only one component of the system is unavailable because of a protection system malfunction. However, when two or more components of the system are unavailable, the approach assumes an unrealistic independence between the system component outages which are actually caused by the failure of a single protection system element. The correct approach is to regard the protection system element failure rate as the simultaneous failure rate of the relevant system components.

The origin and effects of protection system related outages are described and illustrated in this thesis using the configurations of two terminal stations from the Saskatchewan Power Corporation (SPC) system. This provides an extension of the work done by Billinton and Medicherla [23]. The models for the two lines in parallel presented in Reference 23 are modified in this thesis to include the outage effects of protection system components.

This thesis also examines the effects of failures of protection system components on the individual load point reliability indices and system indices in composite system reliability evaluation. This is accomplished by representing the



terminating points at the busses in a 5-bus hypothetical power system by actual practical bus switching and circuit breaker configurations. The reliability indices at customer load points are examined by representing the distribution network from the switching station to the customer load points.

A principal concern in this thesis has been to develop relatively simple equations and techniques to include the protection system failure modes into the reliability calculations. The application of the models and techniques developed is illustrated in the thesis by considering hypothetical system examples based upon actual practical configurations. The concepts presented are quite general and can be applied to a large number of power system applications.

## 2. PROTECTION SYSTEM FAILURE MODES

### 2.1 General

Protection systems play an important role in protecting expensive equipment and also in ensuring the supply of electrical energy to consumers at high reliability. There are very large quantities of energy in a modern power system which can do very expensive damage to equipment and create danger to personnel in the case of an electrical fault, if it is not isolated promptly. In addition, these faults can disrupt electric power in healthy portions of the network.

Protective equipment are installed at appropriate places in a network to limit the damaging effects of faults and other abnormal conditions that may occur. Some of the basic equipment used in a power system network are as follows:

1. Fuses
2. Reclosers
3. Breakers and relays
4. Automatic and manual isolating switches

Protective devices are used to detect the presence of faults (short circuit and other abnormal conditions) and isolate the faulty component so that the fault will not damage the equipment or otherwise interfere with the normal operation of the rest of the power system. Circuit breakers and relays are used extensively in transmission and distribution systems. The relay after detecting the presence of an abnormal condition, closes its

electrical contacts and that energizes an auxiliary relay necessary to operate the circuit breaker to isolate the faulty component. A reliable dc supply is required for the operation of breakers in the presence of faults. It is obvious therefore that reliability is of paramount importance in a protective relay. As defined in Reference 24 "The main purpose of a protective relay is to close its contacts effectively and correctly even under adverse conditions and in the event of inadequate maintenance having been carried out". The same type of duty is expected from all components of the protection system in case of a fault. The very nature of the protection system makes this difficult, as the normal state of the protection system is passive since faults are relatively rare. The protection system is therefore expected to stand on guard and to operate only in the case of a fault in its protection zone. The system may be inactive for years and its contacts may deteriorate due to time or adverse conditions which may finally prevent the protection system from operating correctly when a fault does occur.

## 2.2 Reliability of Protection Systems

Protection system reliability can be considered from the two aspects of dependability and security [24]. Dependability is the certainty of correct operation of the protection system in response to abnormal conditions in the system, while security is the ability of the protection system to avoid operating when not actually required to operate. Unfortunately these two aspects of reliability tend to oppose one another and for relays this is

discussed in References 25-27. In general a compromise has to be made between security and dependability. Protection systems operate by sensing electrical quantities i.e. voltages, currents, phase angles etc. which enable the protection system to distinguish a fault from the normal condition on a particular component. The performance of the protection system depends upon the ability of the system to detect the electrical quantities correctly.

Protection system performance can be classified as (1) correct operation, (2) incorrect operation. Incorrect operation may be failure to operate when required and false tripping. The causes of incorrect operation are (a) poor application of the protection scheme, (b) incorrect settings, (c) personnel error, (d) equipment malfunction. Equipment that can cause incorrect operation include current transformers, voltage transformers, circuit breakers, relays, communication channels, station batteries or cables and wiring. From data collected by utilities, human error is the most contributing factor in the incorrect operation of a protection system.

### 2.3 Zones of Protection

A power system is normally divided into protection zones to minimize the effect of a component failure on the rest of the system. Figure 2.1 shows a single line diagram of a section of a power system. The square boxes represent circuit breakers,  $\overline{R}$  indicates a relay for a circuit breaker, the heavy lines represent busses and the thin lines indicate transmission lines.

The dashed lines surround the section of the system to be protected and indicate the "Primary protection zone" for relays and their respective circuit breakers on either end of the line. Since failures do occur, however, some form of back up protection is provided to trip out the adjacent breakers if the first line of protection fails. The protection in each zone is overlapped to avoid the possibility of unprotected areas.

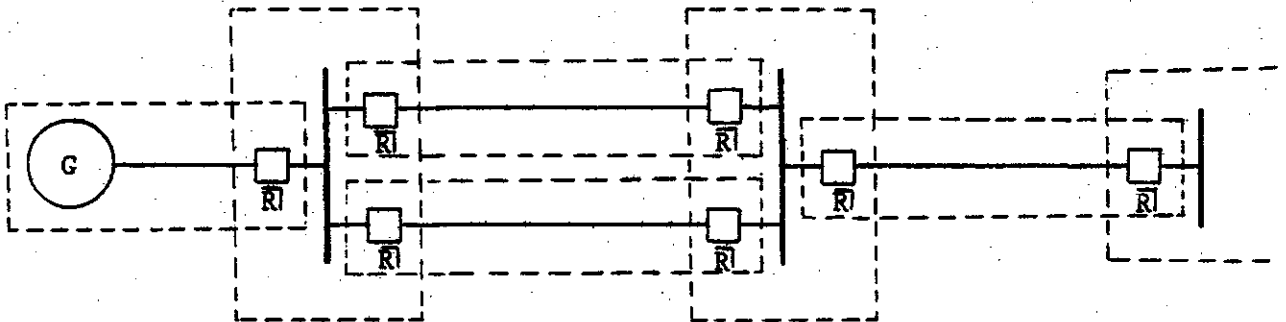


Figure 2.1 Single line diagram of a hypothetical power system.

In the case of a fault in the primary protection zone, the relay and circuit breaker protecting the primary zone should isolate the fault from the rest of the healthy system. If the primary zone protection system fails to operate, the first back up protection system should operate and isolate the faulty component together with some of the additional healthy network. If the first back up protection also fails, the second back up protection is required to isolate the fault. In this case, the portion of healthy system which is removed to isolate the fault can be relatively large.

## 2.4 Failure Modes of Relays and Circuit Breakers

The relay and the circuit breaker are two different components of the protection system. The relay detects the abnormal condition in its protection zone. Its operation is dependent on receiving a correct current or voltage signal from the appropriate current or voltage transformers and in some cases on the phase angle associated with these quantities. The operation of a circuit breaker is dependent upon the ability of its relay to operate correctly in the case of a fault and on the availability of the dc supply. The failure of associated relays, instrument transformers and other auxiliary equipment are normally assigned to the circuit breaker. A breaker as such can fail in a number of possible ways e.g. it fails to operate in the case of a fault, it fails to reclose, it gives false operation, or it itself becomes faulty etc. Two states of a component are normally considered in reliability studies i.e. the up state or operating state in which the component is performing its function and the down state or failed state when the component is unable to perform its function. In the case of a protection system there are three basic failure modes i.e. failure to operate, false tripping and failure to ground which will require other protection systems to operate.

Protection systems spend most of their life in an on guard passive state and consequently are prone to unrevealed random faults which only become apparent when the system is called upon to function, or when it is proof checked. The second type of failure is false tripping, which is detected as soon as it occurs.

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These two failure types can be described as Unrevealed failures and Revealed failures respectively. The third type of failure, i.e. failure to ground, is common to all power system components.

#### 2.4.1 Unrevealed failures

These types of failure are those which occur when the protection system is in a passive state and cause the system to fail to operate when called upon in the case of a fault. These failures are not directly revealed and remain undetected until the next proof check or until the next fault occurs within the protection zone. The protection system then fails to perform its function.

#### 2.4.2 Revealed failures

Failures of the protection system may cause false tripping of circuit breakers and these failures are directly revealed as they occur by opening circuit breakers. This could be due to a false signal from the relay to its breaker or due to the failure of the breaker itself. False tripping could be in response to external faults or spontaneous in the absence of a fault.

#### 2.4.3 Ground fault

A ground fault on the protection system can occur due to the insulation failure of the circuit breaker, current transformer or other components. These effects can be grouped and categorized as a ground fault on the circuit breaker. When a ground fault on the breaker occurs, all related breakers are normally tripped. This failure mode is basically the same as the failure mode for a



current carrying component (line or generator). In this case, the effect on the system is more severe due to the multi-outage of lines and/or generators. The duration of this event will be the switching time required to isolate the faulty component and to restore healthy components and normally is of the order of one and half hours.

## 2.5 Failure of the DC Supply

An adequate dc supply is required at substations and switching stations to energize the trip coil of the circuit breaker when the relay closes its contacts in the presence of a fault. If there is no dc supply at a substation or switching station, the protection system is idle and cannot perform its intended function. In the case of a fault on any component which requires the protection system to operate at the affected station, that substation will be isolated from the rest of the power system by the operation of the back up protection at the other connected substations. The failure of the dc supply could be due to:

- (a) Dead batteries.
- (b) Ground fault on cables.
- (c) Open circuit of cables.

There are no data available on the performance of dc batteries and it is difficult to calculate their reliability parameters without practical field data. Although it is believed by power companies and battery manufacturers that the probability of failure of dc battery sets is negligible, there is still the potential for failure due to these factors.

### 2.6 Estimation of Parameters

The failure modes of a protection system have different effects on power system performance. It is not possible to know the exact time of occurrence of unrevealed failures unless the protection system is continuously checked as in the case of computer operated relays. By proof checking the protection system at scheduled inspections, the readiness of the protection system can be improved. If the inspection reveals that one or more components of the protection system have failed, the failed components are taken out for repair and the protection system is down during the repair of the faulty components. Even with periodic inspection, there is still a chance of the protection system failing between two consecutive tests. It is not possible to do testing continuously as the protection system is not functioning during the testing period. Due to the inherent nature of these unrevealed faults, it is not possible to directly estimate the rate and mean duration of these failures. One method to estimate the unavailability or the mean fractional dead time for unrevealed faults is described in Reference 29 and the expression in short is given below.

The mean fractional dead time (D) of a single component with proof checks at time interval  $t_c$  is given by

$$D = \frac{1}{t_c} \int_0^{t_c} P_f(t) \cdot dt \tag{2.1}$$

$$\text{where } P_f(t) = \int_0^t f(t) \cdot dt \tag{2.2}$$

and  $f(t)$  is the failure density function for the occurrence of events in time domain  $t$  for the component.

The following assumptions are made in the derivation of the expression for the mean fractional dead time.

1. The testing of the protection system takes zero time.
2. Testing is 100% reliable i.e. all system faults are detected during testing and the system is back in "mint" condition.
3. If there is a fault during testing, the repair of the system is done in a very short time so that it is negligible as compared to the testing interval.
4. Failures are independent and random.
5. No compensating failures i.e. this is the assumption that two wrongs don't make a right or, that two failures cannot cancel each other out so as to present an apparent picture of the equipment working normally.

There are three main ways in which failure rate data for the protection system can be obtained in order to calculate the mean fractional dead time of the system by the above formula.

- a) Field experience
- b) Sample testing
- c) Prediction

The data needed to obtain the failure density function  $f(t)$  is not usually available for protection system components. One other method to estimate this failure mode is discussed in Reference 30 by estimating the unreadiness probability which is stated as "the limiting ratio of the number of failures to isolate the faults to the number of times it is called upon to isolate the fault". The data required for evaluation by this method is also

quite complex and hard to obtain. The concepts of unreadiness probability is used in References 28,31,32 et. al. but other names are used to describe it. Rai et. al. [35] presented a relatively simple approach to evaluate the three failure modes of a protection system from the reliability performance data of the system components. It is not normally possible to evaluate the parameters by this approach due to the lack of relevant data.

#### 2.6.1 Estimation from field data

An alternative approach for evaluation of the reliability parameters of a protection system is from field data.

The probability of unreadiness of the protection system can be estimated from the stuck probabilities of the breaker and its relay. The probability of a stuck breaker and the probability of its relay not detecting a fault in its protection zone when required to do so can be considered two independent events.

If  $P_{bi}$  = Stuck probability of breaker  $i$  and its tripping coil.

$P_{rei}$  = The probability that the relay of breaker  $i$  fails to detect the fault when required to do so.

$P_i$  = The probability of the protection system not operating when required in the case of a fault in its primary protection zone.

By taking  $P_{bi}$  and  $P_{rei}$  as two stochastic independent events,  $P_i$  can be written in terms of  $P_{bi}$  and  $P_{rei}$  as shown

$$P_i = P_{bi} + P_{rei} - P_{bi} \cdot P_{rei} \quad (2.3)$$

$P_{bi}$  and  $P_{rei}$  can be estimated as the limiting values of the respective relations.

$$P_{rei} = \frac{\text{Number of times the relay } i \text{ fails to detect a fault in its protection zone when required to do so}}{\text{Total number of faults in the primary protection zone of relay } i}$$

$$P_{bi} = \frac{\text{Number of times breaker } i \text{ fails to respond when required}}{\text{Total number of trip commands given by relay } i}$$

Total number of trip commands given to breaker  $i$  by relay  $i$  is not equal to the total number of faults in the protection zone of breaker  $i$ , however, as the reliability of relays in a power system is relatively high, these two values will be very close.

False tripping or revealed faults become immediately known by the opening of the relevant circuit breakers. The rate and mean duration can be directly estimated from the past performance of the protection system.

$$\text{False tripping rate} = \frac{\text{Total number of false trippings}}{\text{In service time in time units}}$$

Mean duration = Average repair time to put the protection system back in service.

A ground fault on the protection system also becomes immediately known as it creates an abnormal condition in the power system. The rate and mean duration can be calculated in a manner similar to that used for revealed faults.

The different basic failure modes of a protection system have been discussed in this chapter. These systems have two failure modes i.e. failure to trip and false tripping in addition to the

basic one involving ground faults. Consistent data to estimate reliability parameters of the failure to trip and false tripping failure modes are not normally available for protection system components. The best approach is to estimate these parameters from field data. These parameters are used in the power system reliability calculations detailed in the following chapters.

### 3. RELIABILITY EVALUATION OF TRANSMISSION AND DISTRIBUTION SYSTEMS INCLUDING PROTECTION SYSTEM FAILURE MODES.

#### 3.1 General

During the last two decades, considerable research work has been reported on reliability studies of transmission and distribution schemes [1-3]. One of the main concerns has been the development of accurate and consistent models to represent component and system behaviour. A two state weather model was developed to include environmental effects in the reliability predictions of overhead transmission and distribution systems [5]. In regard to the inclusion of circuit breakers and protective elements in the transmission and distribution system analysis, a three state component model was described [10,11] which gives a more realistic representation for certain applications than that given by the previous two state component model. According to this model, when a component fails, the system protection may isolate a number of unfaulted components. Following which, through appropriate switching operations, all but the minimum number of components that must be kept out of service for the isolation of the failed component are restored to service as soon as possible. Thus a system component has three possible states namely, operating, before switching and after switching. The three state component model was then used in studies [12-15] together with a multi-state circuit breaker model [36,37] for reliability evaluation of substations and switching stations. All these computer techniques used the minimal cut set approach based

on the method of Nelson et. al. [38].

In this chapter, reliability indices at the load points of the hypothetical power system shown in Figure 3.1 are evaluated.

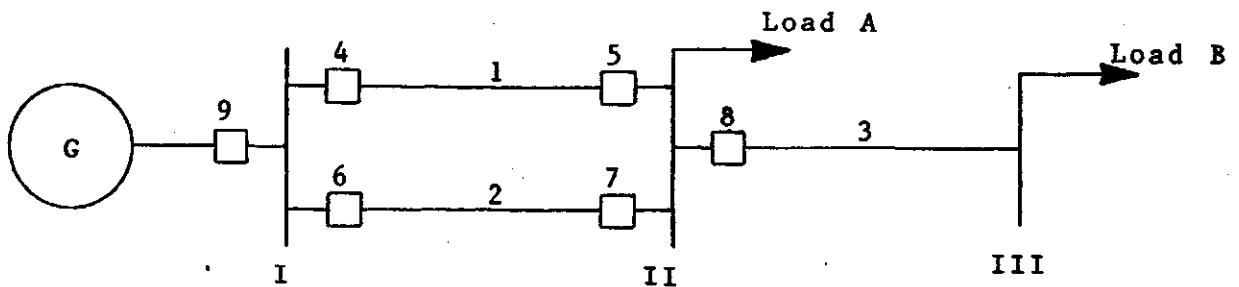


Figure 3.1 Single line diagram of a hypothetical power system

The simple equations shown in References 8 and 9 are used and the consideration of the protection system failure modes is included. One assumption made is that the times to failure and the times to repair for all components are exponentially distributed. This is quite commonly used in many power system reliability studies. Results are presented in order to obtain a physical feeling for the manner in which protection system failures affect the reliability indices. The cut set technique together with the derived equations can be used to calculate the reliability indices for a system having a large number of components.

### 3.2 Failure Modes of a Component

Power system components can be classified into two categories according to their intended function. The first category includes current carrying components such as transmission lines,



transformers, generators, reactors, buses ect.. These components can be in any of the following states:

- (i) Operating
- (ii) Permanent outage
- (iii) Temporary outage
- (iv) Out for repair or preventive maintenance
- (v) Overload outage.

Definitions of various failure modes are given in Appendix A.

The second category includes components of the protection system such, as circuit breakers, relays, reclosers, disconnect switches, carrier equipment, station batteries ect.. Due to the failure of these components, the protection system can be in any one of following states:

- (i) Operating
- (ii) Faulted
- (iii) Stuck when called upon to operate or not closing when called upon to do so
- (iv) False tripping

In Figure 3.2, X is the current carrying component(line) with the associated primary protection Y at one of its ends. If only the permanent outage of X is considered and its protection system is 100% reliable, X can be represented by a Markov model as shown in Figure 3.3 i.e. X up (operating) or X down (out for corrective maintenance). The protection system has many failure modes as described in Chapter 2. Figure 3.4 represents the state space transition diagram of X and its primary protection Y by considering only the permanent outage of X and the three basic

failure modes of Y. Instead of two states in Figure 3.3, there are eight states in Figure 3.4. There are actually even more states due to the many failure modes of X and Y which are neglected in Figure 3.4.

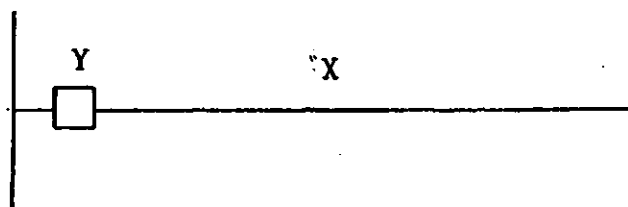
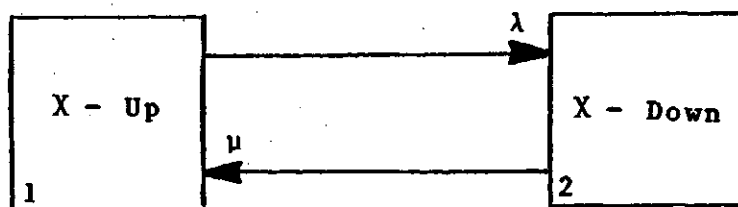


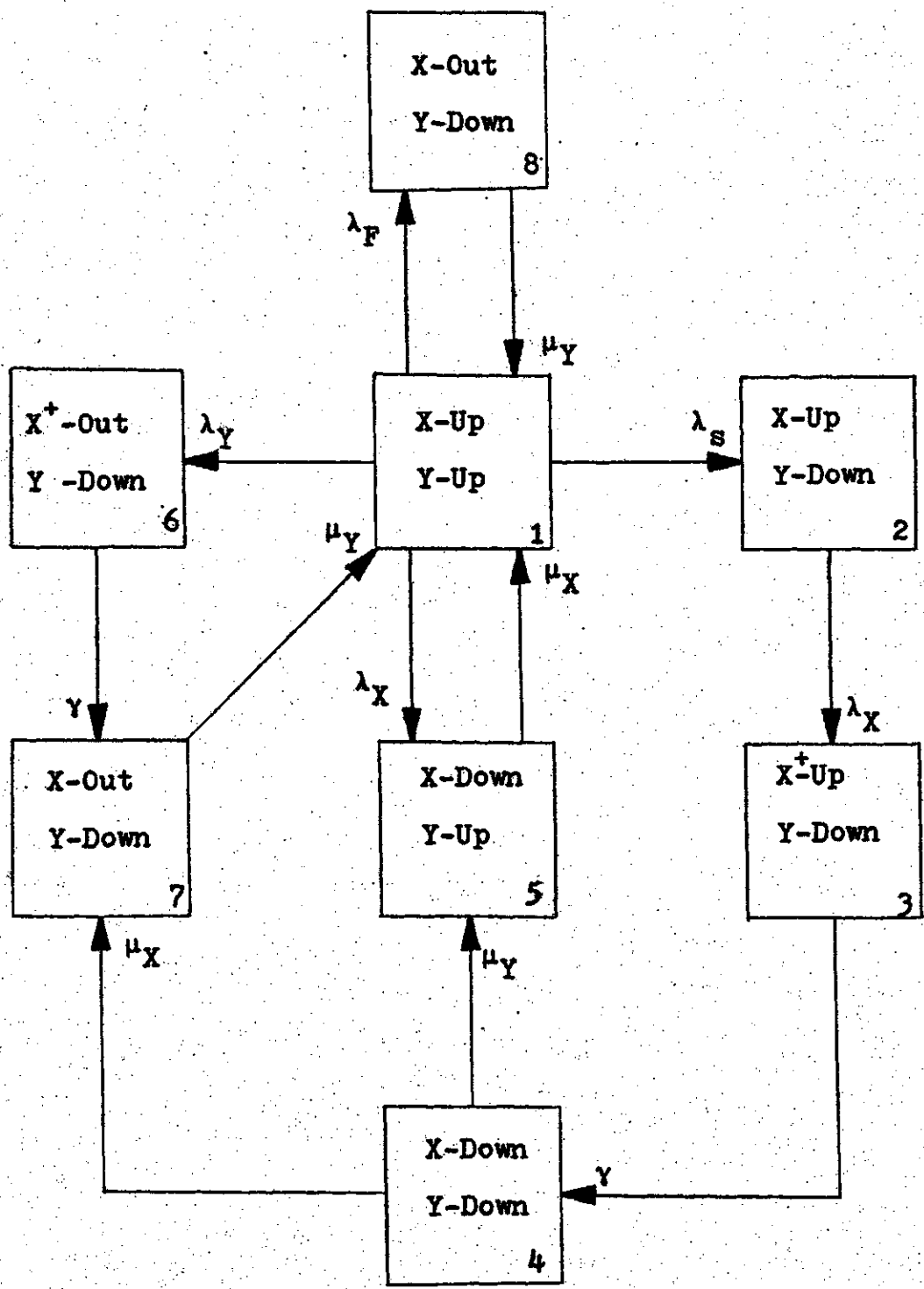
Figure 3.2 Single line diagram of a section of a power system



$\lambda$  = failure rate of X in failures/year

$\mu$  = repair rate of X in repairs/year

Figure 3.3 State transition diagram of the system shown in Figure 3.2



- $\lambda_X$  = Failure rate of X in failures per year
- $\mu_X$  = Repair rate of X in repairs per year
- $\lambda_Y$  = Ground fault rate of Y in failures per year
- $\lambda_S$  = Rate of breaker stuck condition per year
- $\gamma$  = Switching rate per year
- $\lambda_F$  = False tripping rate of Y in failures per year
- $\mu_Y$  = Repair rate of Y in repairs per year
- $X^+$  = X and some other components are out of service

Figure 3.4 State transition diagram of X and Y shown in Figure 3.2

### 3.3 Failure Modes of a Load Point

Component outages may or may not lead to a load point outage depending upon the system configuration and the number of contingencies considered. The various basic events, which lead to load point failure by taking into consideration the different outage modes of components and the protection system failure modes, are evaluated in this section for the system in Figure 3.1. It is assumed that each line is capable of carrying the total load requirement.

#### Load point failure modes

- 1.(i) Permanent outage of line 1 and the outage not isolated by the primary protection of line 1 (Breaker 4 or 5 or their relays) causing an interruption of supply at load points A and B.
- (ii) Temporary outage of line 1 and the outage not isolated by the primary protection of line 1 causing an interruption of supply at load points A and B.
- 2.(i) Permanent outage of line 2 and the outage not isolated by the primary protection of line 2 (Breaker 6 or 7 or their relays) causing an interruption of supply at load points A and B.
- (ii) Temporary outage of line 2 and the outage not isolated by the primary protection of line 2 causing an interruption of supply at load points A and B.
3. Permanent outage of line 1 overlapping the permanent outage of line 2 or vice versa causing an interruption of supply at load points A and B.

4. Permanent outage of line 1 overlapping the false tripping of breaker 6 or 7 or false tripping of breaker 6 or 7 overlapping the permanent outage of line 1 causing interruption of supply at load points A and B.
5. Same as (4) but for line 2 and breaker 4 or 5.
6. Permanent or temporary outage of line 3 causing an interruption at load point B.
7. False tripping of breaker 8 causing an interruption of supply at load point B.
8. The permanent or temporary outage of line 3 and the outage not isolated by the primary protection of line 3 (breaker 8 and its relay) causing an interruption of supply to load point A. (For load point B it is already considered in failure mode 6).
9. The permanent outage of line 1 is overlapped by a temporary outage of line 2 or the permanent outage of line 2 is overlapped by a temporary outage of line 1 causing an interruption of supply at load points A and B.
10. False tripping of breaker 4 or 5 is overlapped by a temporary outage of line 2 or false tripping of breaker 6 or 7 is overlapped by a temporary outage of line 1 causing an interruption of supply at load points A and B.
11. The maintenance outage period of line 1 (including maintenance of its protection system) is overlapped by a permanent or temporary outage of line 2 or the maintenance outage period of line 2 (including maintenance of its primary protection system) is overlapped by a permanent or a

- temporary outage of line 1 resulting in the interruption of supply at the load points A and B.
12. The maintenance outage period of line 1 (including maintenance of its primary protection) is overlapped by a false tripping of breaker 6 or 7 or the maintenance outage period of line 2 (including maintenance of its primary protection system) is overlapped by a false tripping of breaker 4 or 5 resulting in the interruption of supply at the load points A and B.
  13. Ground fault on breaker 4 or 5 or 6 or 7 or 8 causing an interruption of supply at load points A and B.
  14. Repair period of breaker 4 or 5 due to a ground fault (after switching action) is overlapped by a permanent outage of line 2 or the repair period of line 2 due to a permanent outage is overlapped by the repair period of breaker 4 or 5 due to a ground fault causing an interruption of supply at load points A and B.
  15. Same as (14) but for breaker 6 or 7 and line 1.
  16. Repair period of breaker 4 or 5 due to a ground fault (after switching action) is overlapped by a temporary outage of line 2 causing an interruption of supply at load points A and B.
  17. Same as (16) but for breaker 6 or 7 and line 1.
  - 18.(1) Repair period of breaker 4 or 5 due to a ground fault (after switching action) is overlapped by a false tripping of breaker 6 or 7 causing an interruption of supply at the load points A and B.

(ii) Repair period of breaker 6 or 7 due to a false tripping is overlapped by a ground fault on breaker 4 or 5 causing an interruption of supply at the load point A and B.

A ground fault on breaker 4 or 5 itself causes an interruption of supply at load points A and B as considered in failure mode (13). The duration of an interruption in case of (13) is the switching time required to isolate faulty breaker and restoring supply to the healthy line, however, the duration of an interruption in case of 18(ii) is the overlapping of repair periods of breakers. Same is true for failure modes (14) and (15) when permanent outage of a line is overlapped by repair period of breakers due to ground faults.

19. Same as failure mode (18) but in this case breakers 4 and 5 are interchanged with breakers 6 and 7.
20. Repair period of breaker 4 or 5 due to a false tripping is overlapped by a false tripping of breaker 6 or 7 or vice versa causing an interruption of supply at load points A and B.
21. Maintenance period of line section i is overlapped by a ground fault on breaker j of the parallel line causing an interruption of supply at load points A and B. The outage duration as explained in 18(ii).

The failure modes (3),(6),(9),(11) and (13) considered in this chapter are the same as those considered in References 8 and 9. All the other failure modes are due to protection system failures. The probability of an event in which line temporary outages

overlap is very small as the duration of a temporary outage is small (less than 5 minutes) and, therefore, such an event is neglected. The probability of component overload during the outage of another parallel line component is also neglected as each line is considered to be capable of carrying the total load requirement. The temporary outages of breakers are also neglected.

In addition to the load point failure modes described above, there are some other modes of system operation which can be considered as failures to meet the acceptable standards. The violation may be due to frequency, voltage level, transient stability etc.. These criteria can be considered if required.

#### 3.4 Duration of the Failure Modes

The outage duration due to each failure mode will be different depending upon the components involved in the failure mode. The duration of an outage due to overlapping of component temporary outages is disregarded as the only concern in this case is the frequency of this temporary outage and not its duration.

Duration of a permanent outage of a line is affected by its primary protection system. If the primary protection of a line recognizes the fault and isolates it from the rest of the healthy system, the duration of the outage is only the time taken to repair the line. If, however, the primary protection system does not recognize the fault on the line and the fault is cleared by the second zone of protection, the duration of the outage is the



time taken to repair the line and the faulty primary protection system.

If  $r_{li}$  = Average time to repair line i

$r_{lpi}$  = Average time to repair line i and its faulty primary protection system.

$p_i$  = The probability that the primary protection system detect the fault and clear it.

$q_i$  = The probability that the primary protection system does not clear the fault on the line i.

Depending upon the protection system, the expected time to restore the line to service is given by the following expression

$$r_i = r_{li} \cdot p_i + r_{lpi} \cdot q_i \quad (3.1)$$

where  $r_i$  = Average outage time of line i by considering the protection system failure to recognize a fault in its protection zone.

For line 1 and breakers 4 and 5, the average repair time is as given below

$$r_1 = r_{1l} \cdot p_1 + r_{1lp1} \cdot q_1 \quad (3.2)$$

If  $P_4$  and  $P_5$  are the probabilities of breakers 4 and 5 (including their relays) respectively, of not clearing a fault in their primary protection zone,  $p_1$  and  $q_1$  can be written as follows

$$p_1 = 1 - P_4 - P_5 + P_4 \cdot P_5 \quad (3.3)$$

$$q_1 = P_4 + P_5 - P_4 \cdot P_5 \quad (3.4)$$

It is possible to derive expressions for other similar failure modes.

### 3.5 Basic Equations

#### List of Symbols :

(The subscripts are arranged in alphabetical order for ease of reference)

- $\lambda_{FF}$  = Overlapping outage rate of false tripping of breakers.
- $\lambda_{FFi-j}$  = Overlapping outage rate of false tripping of breaker i by false tripping of breaker j of a parallel line.
- $\lambda_{FGB}$  = Contribution to load point outage rate due to overlapping of false tripping of breakers by a ground fault on breakers of a parallel line.
- $\lambda_{FGBi-j}$  = Overlapping outage rate of false tripping of breaker i by a ground fault on breaker j.
- $\lambda_{Fi}$  = False tripping rate of all breakers of line section i.
- $\lambda_{FL}$  = Contribution to the load point outage rate due to false tripping of breakers or overlapping false tripping of breakers.
- $\lambda_{FLi-j}$  = Overlapping outage rate of false trippings of breakers i and j.
- $\lambda_{GB}$  = Outage rate at the load point due to a ground fault on breakers.
- $\lambda_{GBF}$  = Contribution to load point outage rate due to overlapping of ground faults on breakers by false tripping of breakers of a parallel line.
- $\lambda_{GBFi-j}$  = Overlapping outage rate of ground faults on breaker i by false tripping of breaker j.
- $\lambda_{GBL}$  = Contribution to load point outage rate due to a ground fault on breakers or overlapping of a ground fault by other outages and vice versa.
- $r_{GBL}$  = Average outage duration at load point due to a ground fault on breakers or overlapping of a ground fault by other outages and vice versa.
- $\lambda_{GBP}$  = Contribution to the load point outage rate due to overlapping of ground fault outages of breakers by permanent outages of lines.
- $\lambda_{GBPi-j}$  = Overlapping outage rate of a repair period of breaker i due to a ground fault by a permanent outage of line j.

- $\lambda_{GBT}$  = Contribution to load point outage rate due to overlapping of ground fault outages on breakers by temporary outages of lines.
- $\lambda_{GBTi-j}$  = Overlapping outage rate of a repair period of breaker  $i$  due to ground faults by a temporary outage of line  $j$ .
- $\lambda_{GLi}$  = Outage rate of breaker  $i$  due to a ground fault which is not overlapping any other outage of a parallel line and the outage time of this failure is switching time.
- $\lambda_i$  = Permanent outage rate of line  $i$  or ground fault rate of breaker  $i$ .
- $r_i$  = Expected repair time of component  $i$ .
- $\lambda_i$  = Maintenance outage rate of line  $i$  including its primary protection system.
- $P_i$  = Probability of breaker  $i$  and its relay not isolating a faulty component in the primary protection zone.
- $\lambda_{i-j}$  = Overlapping outage rate of components  $i$  and  $j$  due to permanent outage.
- $r_{i-j}$  = Overlapping outage duration of components  $i$  and  $j$  due to permanent outages.
- $\lambda_{iT}$  = Temporary outage rate of line  $i$ .
- $\lambda_{MFi-j}$  = Overlapping outage rate of a maintenance period of line  $i$  and false tripping of breaker  $j$ .
- $\lambda_{MFL}$  = Contribution to load point outage rate due to a maintenance period of a line section overlapped by false tripping of the breakers on a parallel line.
- $\lambda_{MGB}$  = Contribution to load point outage rate due to overlapping of maintenance period of lines by a ground fault on breakers of a parallel line.
- $\lambda_{MGBi-j}$  = Overlapping outage rate of a maintenance period of line  $i$  by a ground fault on breaker  $j$ .
- $\lambda_{ML}$  = Contribution to the load point outage rate due to line permanent outages overlapping line section maintenance outages.
- $r_{ML}$  = Load point average outage duration due to line permanent outages overlapping parallel line section maintenance outages.
- $\lambda_{MLi-j}$  = Overlapping outage rate of a maintenance period of line  $i$  by a permanent outage of line  $j$ .

- $\lambda_{MTL}$  = Contribution to the load point outage rate due to overlapping of a maintenance period of a line by a temporary outage of a healthy line.
- $\lambda_{MTLi-j}$  = Overlapping outage rate of a maintenance period of line  $i$  by a temporary outage of line  $j$ .
- $\lambda_{Obi}$  = False tripping rate of breaker  $i$ .
- $\lambda_{OGi}$  = Overlapping outage rate of other outages of parallel components by a ground fault on breaker  $i$  of a parallel line.
- $\lambda_{PFi}$  = Contribution to the load point outage rate due to protection system false tripping overlapping a line permanent outage or vice versa in failure mode  $i$ .
- $\lambda_{PFi-j}$  = Overlapping outage rate of permanent outage of line  $i$  and false tripping of breaker  $j$  and vice versa.
- $\lambda_{PFL}$  = Contribution to the load point outage rate due to permanent outage of lines overlapping false tripping of breakers and vice versa.
- $r_{PFL}$  = Load point average outage duration due to permanent outage of lines overlapping breakers false tripping and vice versa.
- $\lambda_{PGB}$  = Contribution to load point outage rate due to overlapping of permanent outages of lines by a ground fault on the breakers of a parallel line.
- $\lambda_{PGBi-j}$  = Overlapping outage rate of a permanent outage of line  $i$  by a ground fault on breaker  $j$ .
- $\lambda_{PL}$  = Contribution to the load point outage rate due to line permanent outages.
- $r_{PL}$  = Load point average outage duration due to line permanent or overlapping permanent outages.
- $\lambda_{PLi}$  = Contribution to the load point outage rate due to permanent outages or overlapping permanent outages in failure mode  $i$ .
- $\lambda_{PSFL}$  = Contribution to the load point outage rate due to all failure modes associated with protection system failures.
- $r_{PSFL}$  = Load point average outage duration due to all failure modes associated with protection system failures.
- $\lambda_{PT}$  = Contribution to the load point outage rate due to overlapping of a permanent outage of a line by a temporary outage of a parallel line.

- $\lambda_{PTi-j}$  = Contribution to the load point outage rate due to overlapping of a permanent outage of line  $i$  by a temporary outage of line  $j$ .
- $T_{si}$  = Switching time of component  $i$ .
- $\lambda_{TFi-j}$  = Overlapping outage rate of false tripping of breaker  $j$  and temporary outage of line  $i$ .
- $\lambda_{TFL}$  = Contribution to the load point outage rate due to overlapping of false tripping of breakers by temporary outages of lines.
- $\lambda_{TL}$  = Contribution to the load point outage rate due to line temporary outages overlapping component maintenance or permanent outages.
- $\lambda_{UL}$  = Total contribution to the load point outage rate due to permanent and temporary outages of lines and the lines not isolated by the primary protection system.
- $\lambda_{ULi}$  = Contribution to the load point outage rate due to permanent and temporary outages of line  $i$  and the outage not isolated by its primary protection system.
- $\lambda_{UPLi}$  = Contribution to the load point outage rate due to permanent outage of line  $i$  and the outage not isolated by its primary protection system.
- $\lambda_{UTLi}$  = Contribution to the load point outage rate due to temporary outage of line  $i$  and the outage not isolated by its primary protection system.

$r$  and  $U$  denote average outage duration and average annual outage time. The suffixes are those which correspond to the respective outage rate.

It is assumed that the average repair time for a breaker is the same for all the different failure modes.

The most common reliability indices considered at the load point are frequency of an outage, average duration of an outage and average annual outage time.

A system of two components in series with outage rates  $\lambda_1$  and  $\lambda_2$  and repair durations  $r_1$  and  $r_2$  respectively has the following reliability indices:

$$\text{System outage rate} = \lambda_s = \lambda_1 + \lambda_2 \quad (3.5)$$

$$\text{System average outage duration} = r_s = \frac{\lambda_1 \cdot r_1 + \lambda_2 \cdot r_2}{\lambda_s} \quad (3.6)$$

$$\text{System total average outage time} = U_s = \frac{\lambda_s \cdot r_s}{1 + \lambda_s \cdot r_s} \quad (3.7)$$

If the above components are connected to form a two component parallel system, the corresponding reliability indices are as follows:

$$\text{System outage rate} = \lambda_p = \lambda_1 \cdot \lambda_2 \cdot (r_1 + r_2) \quad (3.8)$$

$$\text{System average outage duration} = r_p = \frac{r_1 \cdot r_2}{(r_1 + r_2)} \quad (3.9)$$

$$\text{System total average outage time} = U_p = \frac{\lambda_p \cdot r_p}{1 + \lambda_p \cdot r_p} \quad (3.10)$$

If  $\lambda r \ll 1$  the system average annual outage time is approximated as

$$U = \lambda r \text{ i.e. } U_s = \lambda_s \cdot r_s \quad \text{and} \quad U_p = \lambda_p \cdot r_p \quad (3.11)$$

These formulas can be extended for the consideration of a large number of series or parallel components. These expressions are used in the formulation of load point reliability indices. The adverse weather effect is not considered in this thesis but can be easily included if desired.

### 3.5.1 Contribution to load point indices due to each failure mode

In this section, basic equations are formed for each failure mode in order to evaluate average failure rate, average outage duration and average annual outage time at each load point. The total annual reliability indices are then evaluated by combining all the failure mode values. The indices due to each failure mode

are as follows:

Failure mode 1

Load point A

$$(i) \quad \lambda_{UPL1} = P_4 \cdot \lambda_1 + P_5 \cdot \lambda_1 - P_4 \cdot P_5 \cdot \lambda_1 \quad (3.12)$$

$$r_{UPL1} = T_{s1}$$

$$(ii) \quad \lambda_{UTL1} = (P_4 + P_5 - P_4 \cdot P_5) \lambda_{1T} \quad (3.13)$$

$$r_{UTL1} = 0$$

The total contribution to the outage rate due to Permanent and temporary failures of line 1 not cleared by its primary protection system is

$$\begin{aligned} \lambda_{UL1} &= \lambda_{UPL1} + \lambda_{UTL1} \\ &= (P_4 + P_5 - P_4 \cdot P_5)(\lambda_1 + \lambda_{1T}) \end{aligned} \quad (3.14)$$

$$U_{UL1} = U_{UPL1} = (P_4 + P_5 - P_4 \cdot P_5) \cdot T_{s1} \cdot \lambda_1 \quad (3.15)$$

$$r_{UL1} = \frac{U_{UL1}}{\lambda_{UL1}} = \frac{\lambda_1}{\lambda_1 + \lambda_{1T}} \cdot T_{s1} \quad (3.16)$$

Load point B

Same as for the load point A

Failure mode 2

Similar to failure mode 1, the expressions are as shown below

$$\lambda_{UL2} = (P_6 + P_7 - P_6 \cdot P_7)(\lambda_2 + \lambda_{2T}) \quad (3.17)$$

$$U_{UL2} = (P_6 + P_7 - P_6 \cdot P_7) \cdot \lambda_2 \cdot T_{s2} \quad (3.18)$$

$$r_{UL2} = \frac{\lambda_2}{\lambda_2 + \lambda_{2T}} \cdot T_{s2} \quad (3.19)$$

For load points A and B, the expressions are the same

Failure mode 3

$$(i) \quad \lambda_{12} = \lambda_1 \cdot \lambda_2 r_1 \cdot (1 - P_6 - P_7 + P_6 \cdot P_7) \quad (3.20)$$

where  $(1-P_6-P_7+P_6 \cdot P_7)$  is the weighting factor that the fault on line 2 is cleared by its primary protection system.

$$r_{12} = \frac{r_1 \cdot r_2}{r_1 + r_2}$$

where  $r_{12}$  is calculated as for a two component parallel system.

$$(ii) \quad \lambda_{21} = \lambda_2 \cdot \lambda_1 r_2 \cdot (1-P_4-P_5+P_4 \cdot P_5) \quad (3.21)$$

where  $(1-P_4-P_5+P_4 \cdot P_5)$  is the weighting factor that the fault on line 1 is isolated by its primary protection system.

$$r_{21} = \frac{r_1 \cdot r_2}{r_1 + r_2}$$

The following expressions are obtained by combining the expressions of (i) and (ii)

$$\begin{aligned} \lambda_{PL3} &= \lambda_{12} + \lambda_{21} \\ &= \lambda_1 \cdot \lambda_2 \cdot (r_1 \cdot (1-P_6-P_7+P_6 \cdot P_7) + r_2 \cdot (1-P_4-P_5+P_4 \cdot P_5)) \end{aligned} \quad (3.22)$$

$$r_{PL3} = \frac{r_1 \cdot r_2}{r_1 + r_2}$$

$$U_{PL3} = \lambda_{PL3} \cdot r_{PL3} \quad (3.23)$$

The contribution of this failure mode to the indices at load points A and B is the same.

#### Failure mode 4

(i) line 1 - breaker 6

(a) Line 1 permanent outage is overlapped by breaker 6 false tripping:

$$\lambda_{PF1-6} = \lambda_1 \cdot \lambda_{ob6} \cdot r_1 \quad (3.24)$$

$$r_{PF1-6} = \frac{r_1 \cdot r_6}{r_1 + r_6} \quad (3.25)$$

(b) Breaker 6 false tripping is overlapped by line 1 permanent outage:

$$\lambda_{PF6-1} = \lambda_{ob6} \cdot \lambda_1 \cdot r_6 \cdot (1-P_4-P_5+P_4 \cdot P_5) \quad (3.26)$$

$$r_{PF6-1} = r_{PF1-6}$$



$$U_{PF1-6} = \lambda_1 \cdot \lambda_{ob6} \cdot (r_1 + r_6 \cdot (1 - P_4 - P_5 + P_4 \cdot P_5)) \cdot \frac{r_1 \cdot r_6}{r_1 + r_6} \quad (3.27)$$

(ii) line 1-breaker 7

(a) Line 1 permanent outage overlapped by breaker 7 false

tripping:

$$\lambda_{PF1-7} = \lambda_1 \cdot \lambda_{ob7} \cdot r_1 \quad (3.28)$$

$$r_{PF1-7} = \frac{r_1 \cdot r_7}{r_1 + r_7} \quad (3.29)$$

(b) Breaker 7 false tripping overlapped by line 1 permanent

outage:

$$\lambda_{PF7-1} = \lambda_{ob7} \cdot \lambda_1 \cdot r_7 \cdot (1 - P_4 - P_5 + P_4 \cdot P_5) \quad (3.30)$$

$$r_{PF7-1} = r_{PF7-1}$$

$$U_{PF1-7} = \lambda_{ob7} \cdot \lambda_1 \cdot (r_1 + r_7 \cdot (1 - P_4 - P_5 + P_4 \cdot P_5)) \cdot \frac{r_1 \cdot r_7}{r_1 + r_7} \quad (3.31)$$

The following expressions are obtained by combining the expressions of (i) and (ii)

$$\lambda_{PF4} = \lambda_1 \cdot r_1 \cdot (\lambda_{ob6} + \lambda_{ob7}) + \lambda_1 \cdot (1 - P_4 - P_5 + P_4 \cdot P_5) \cdot (\lambda_{ob6} \cdot r_6 + \lambda_{ob7} \cdot r_7) \quad (3.32)$$

$$U_{PF4} = U_{PF1-6} + U_{PF1-7} \quad (3.33)$$

$$r_{PF4} = \frac{U_{PF4}}{\lambda_{PF4}} \quad (3.34)$$

The contribution to the indices at load points A and B is the same for this failure mode.

#### Failure mode 5

These expressions are similar to the expressions obtained for failure mode 4 and are as follows

$$(i) \quad \lambda_{PF2-4} = \lambda_2 \cdot \lambda_{ob4} \cdot r_2 \quad (3.35)$$

$$r_{PF2-4} = \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.36)$$

$$\lambda_{PF4-2} = \lambda_{ob4} \cdot \lambda_2 \cdot r_4 \cdot (1 - P_6 - P_7 + P_6 \cdot P_7) \quad (3.37)$$

$$r_{PF4-2} = r_{PF2-4}$$

$$U_{PF2-4} = \lambda_2 \cdot \lambda_{ob4} \cdot (r_2 + r_4 \cdot (1 - P_6 - P_7 + P_6 \cdot P_7)) \cdot \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.38)$$

$$(ii) \lambda_{PF2-5} = \lambda_2 \cdot \lambda_{ob5} \cdot r_2 \quad (3.39)$$

$$r_{PF2-5} = \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.40)$$

$$\lambda_{PF5-2} = \lambda_{ob5} \cdot \lambda_2 \cdot r_5 \cdot (1 - P_6 - P_7 + P_6 \cdot P_7) \quad (3.41)$$

$$r_{PF5-2} = r_{PF2-5}$$

$$U_{PF2-5} = \lambda_2 \cdot \lambda_{ob5} \cdot (r_2 + r_5 (1 - P_6 - P_7 + P_6 \cdot P_7)) \cdot \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.42)$$

The following expressions are obtained by combining the expressions (i) and (ii)

$$\lambda_{PF5} = \lambda_2 r_2 (\lambda_{ob4} + \lambda_{ob5}) + \lambda_2 (1 - P_6 - P_7 + P_6 \cdot P_7) (\lambda_{ob4} r_4 + \lambda_{ob5} r_5) \quad (3.43)$$

$$U_{PF5} = U_{PF2-4} + U_{PF2-5} \quad (3.44)$$

$$r_{PF5} = \frac{U_{PF5}}{\lambda_{PF5}} \quad (3.45)$$

The total contribution to the reliability indices due to overlapping permanent outage of line i and the false tripping of breaker j is as follows.

$$\lambda_{PFL} = \lambda_{PF4} + \lambda_{PF5} \quad (3.46)$$

$$U_{PFL} = U_{PF4} + U_{PF5} \quad (3.47)$$

$$r_{PFL} = \frac{U_{PFL}}{\lambda_{PFL}} \quad (3.48)$$

The contribution to the indices at the load points A and B is the same.

#### Failure mode 6

This failure mode contributes to the indices at load point B only.

$$(i) \lambda_{PL6} = \lambda_3 \quad , \quad r_{PL6} = r_3 \quad (3.49)$$

$$(ii) \lambda_{TL6} = \lambda_{3T} \quad , \quad r_{TL6} = 0 \quad (3.50)$$

Failure mode 7

This failure mode does not affect the indices at load point A.

$$\lambda_{F3} = \lambda_{ob8} \quad ; \quad r_{F3} = r_8 \quad (3.51)$$

Failure mode 8

This failure mode contributes to the indices at load point A only, as for the load point B it is already considered in failure mode 6.

(i) Permanent outage of line 3

$$\lambda_{UPL3} = P_8 \cdot \lambda_3 \quad (3.52)$$

$r_{UPL3} = T_{s3}$ , i.e. switching time required to isolate line 3 and reclose breakers 4 and 6.

(ii) Temporary outage of line 3

$$\lambda_{UTL3} = P_8 \cdot \lambda_{3T} \quad (3.53)$$

Average outage duration in this case is the duration of a temporary outage which is only a few minutes and is neglected as the only term of concern in the temporary outage is its frequency not its duration.

The following expressions are obtained by combining the expressions (i) and (ii)

$$\lambda_{UL3} = P_8 \cdot (\lambda_3 + \lambda_{3T}) \quad (3.54)$$

$$U_{UL3} = P_8 \cdot \lambda_3 \cdot T_{s3} \quad (3.55)$$

Failure mode 9

(i) Line 1 permanent outage - Line 2 temporary outage

$$\lambda_{PT12} = \lambda_1 \cdot \lambda_{2T} \cdot r_1 \cdot (1 - P_6 - P_7 + P_6 \cdot P_7) \quad (3.56)$$

The outage duration is neglected.

(ii) Line 2 permanent outage - Line 1 temporary outage

$$\lambda_{PT2-1} = \lambda_2 \cdot \lambda_{1T} \cdot r_2 \cdot (1 - P_4 - P_5 + P_4 \cdot P_5) \quad (3.57)$$

The contribution to the indices at load points A and B is the same for this failure mode and is as follows.

$$\lambda_{PT} = \lambda_1 \lambda_{2T} r_1 (1 - P_6 - P_7 + P_6 P_7) + \lambda_2 \lambda_{1T} r_2 (1 - P_4 - P_5 + P_4 P_5) \quad (3.58)$$

#### Failure mode 10

(i) False tripping of breaker 4 or 5 is overlapped by a temporary outage of line 2.

$$\lambda_{TF2-4} = \lambda_{ob4} \cdot \lambda_{2T} \cdot r_4 (1 - P_6 - P_7 + P_6 P_7) \quad (3.59)$$

$$\lambda_{TF2-5} = \lambda_{ob5} \cdot \lambda_{2T} \cdot r_5 (1 - P_6 - P_7 + P_6 P_7) \quad (3.60)$$

(ii) False tripping of breaker 6 or 7 is overlapped by a temporary outage of line 1.

$$\lambda_{TF1-6} = \lambda_{ob6} \cdot \lambda_{1T} \cdot r_6 (1 - P_4 - P_5 + P_4 P_5) \quad (3.61)$$

$$\lambda_{TF1-7} = \lambda_{ob7} \cdot \lambda_{1T} \cdot r_7 (1 - P_4 - P_5 + P_4 P_5) \quad (3.62)$$

The outage duration is neglected. The contribution to the failure rates at load points A and B is the same. This can be obtained from (i) and (ii) and is as follows.

$$\lambda_{TFL} = \lambda_{2T} (1 - P_6 - P_7 + P_6 P_7) (\lambda_{ob4} \cdot r_4 + \lambda_{ob5} \cdot r_5) + \lambda_{1T} (1 - P_4 - P_5 + P_4 P_5) (\lambda_{ob6} \cdot r_6 + \lambda_{ob7} \cdot r_7) \quad (3.63)$$

#### Failure mode 11

(i) Maintenance outage period of line i overlapped by a permanent outage of line j.

$$(a) \quad \lambda_{ML1-2} = \lambda_1 \cdot \lambda_2 \cdot r_1 \cdot (1 - P_6 - P_7 + P_6 P_7) \quad (3.64)$$

$$r_{ML1-2} = \frac{r_1 \cdot r_2}{r_1 + r_2} \quad (3.65)$$

$$(b) \quad \lambda_{ML2-1} = \lambda_2 \cdot \lambda_1 \cdot r_2 \cdot (1 - P_4 - P_5 + P_4 P_5) \quad (3.66)$$

$$r_{ML2-1} = \frac{r_2 \cdot r_1}{r_2 + r_1} \quad (3.67)$$

The following expressions are obtained by combining the expressions (a) and (b).

$$\lambda_{ML} = \lambda_1'' \lambda_2'' r_1'' (1 - P_6 - P_7 + P_6 P_7) + \lambda_2'' \lambda_1'' r_2'' (1 - P_4 - P_5 + P_4 P_5) \quad (3.68)$$

$$U_{ML} = \lambda_1'' \lambda_2'' r_1'' (1 - P_6 - P_7 + P_6 P_7) \cdot \frac{r_1'' \cdot r_2''}{r_1'' + r_2''} + \lambda_2'' \lambda_1'' r_2'' \cdot (1 - P_4 - P_5 + P_4 P_5) \cdot \frac{r_2'' \cdot r_1''}{r_2'' + r_1''} \quad (3.69)$$

(ii) Maintenance outage period of line i overlapped by a temporary outage of line j. The outage duration is neglected in this case.

$$(a) \quad \lambda_{MTL1-2} = \lambda_1'' \cdot \lambda_{2T}'' \cdot r_2'' \cdot (1 - P_6 - P_7 + P_6 P_7) \quad (3.70)$$

$$(b) \quad \lambda_{MTL2-1} = \lambda_2'' \cdot \lambda_{1T}'' \cdot r_1'' \cdot (1 - P_4 - P_5 + P_4 P_5) \quad (3.71)$$

The following expressions are obtained by combining the expressions (a) and (b)

$$\lambda_{MTL} = \lambda_1'' \lambda_{2T}'' r_1'' (1 - P_6 - P_7 + P_6 P_7) + \lambda_2'' \lambda_{1T}'' r_2'' (1 - P_4 - P_5 + P_4 P_5) \quad (3.72)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

#### Failure mode 12

(i) Line section 1 on maintenance overlapped by a false tripping of breaker 6 or 7.

$$(a) \quad \lambda_{MF1-6} = \lambda_1'' \cdot \lambda_{ob6}'' \cdot r_1'' \quad (3.73)$$

$$r_{MF1-6} = \frac{r_1'' \cdot r_6''}{r_1'' + r_6''} \quad (3.74)$$

$$(b) \quad \lambda_{MF1-7} = \lambda_1'' \cdot \lambda_{ob7}'' \cdot r_1'' \quad (3.75)$$

$$r_{MF1-7} = \frac{r_1'' \cdot r_7''}{r_1'' + r_7''} \quad (3.76)$$

(ii) Line section 2 on maintenance overlapped by a false tripping of breaker 4 or 5 .

$$(a) \lambda_{MF2-4} = \lambda_2 \cdot \lambda_{ob4} \cdot r_2 \quad (3.77)$$

$$r_{MF2-4} = \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.78)$$

$$(b) \lambda_{MF2-5} = \lambda_2 \cdot \lambda_{ob5} \cdot r_2 \quad (3.79)$$

$$r_{MF2-5} = \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.80)$$

The following expressions are obtained by combining expressions (i) and (ii)

$$\lambda_{MFL} = \lambda_1 \cdot r_1 (\lambda_{ob6} + \lambda_{ob7}) + \lambda_2 \cdot r_2 (\lambda_{ob4} + \lambda_{ob5}) \quad (3.81)$$

$$U_{MFL} = \lambda_{MF1-6} \cdot r_{MF1-6} + \lambda_{MF1-7} \cdot r_{MF1-7} + \lambda_{MF2-4} \cdot r_{MF2-4} + \lambda_{MF2-5} \cdot r_{MF2-5} \quad (3.82)$$

$$r_{MFL} = \frac{U_{MFL}}{\lambda_{MFL}} \quad (3.83)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

### Failure mode 13

#### Load point A

$$\lambda_{GB} = \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8 \quad (3.84)$$

If there is no overlapping of other failure modes of a line section by ground faults on the breakers of a parallel line, then the average outage duration is the switching time required to isolate the faulty breaker and to restore supply to the healthy breakers. Expressions for overlapping outages are given in the next series of failure modes.

The different possible overlapping outages are as follows.

(i) Overlapping of a permanent outage of line 1 by an earth fault on breaker 6 or 7.

(ii) Overlapping of a maintenance outage of line 1 by an earth fault on breaker 6 or 7.

(iii) Overlapping of a permanent outage of line 2 by an earth fault on breaker 4 or 5.

(iv) Overlapping of a maintenance outage of line 2 by an earth fault on breaker 4 or 5.

(v) Overlapping of the false tripping of breaker 4 or 5 by an earth fault on breaker 6 or 7.

(vi) Overlapping of the false tripping of breaker 6 or 7 by an earth fault on breaker 4 or 5.

Overlapping of an earth fault on two breakers is neglected. The overlapping outage rate for each breaker is as follows.

$$\begin{aligned}\lambda_{OG4} &= \lambda_2 \cdot \lambda_4 r_2 + \lambda_2 \cdot \lambda_4 r_2 + \lambda_{ob6} \cdot \lambda_4 \cdot r_6 + \lambda_{ob7} \cdot \lambda_4 \cdot r_7 \\ &= \lambda_4 (\lambda_2 r_2 + \lambda_2 r_2 + \lambda_{ob6} r_6 + \lambda_{ob7} r_7)\end{aligned}\quad (3.85)$$

$$\lambda_{OG5} = \lambda_5 (\lambda_2 r_2 + \lambda_2 r_2 + \lambda_{ob6} r_6 + \lambda_{ob7} r_7) \quad (3.86)$$

$$\lambda_{OG6} = \lambda_6 (\lambda_1 r_1 + \lambda_1 r_1 + \lambda_{ob4} r_4 + \lambda_{ob5} r_5) \quad (3.87)$$

$$\lambda_{OG7} = \lambda_7 (\lambda_1 r_1 + \lambda_1 r_1 + \lambda_{ob4} r_4 + \lambda_{ob5} r_5) \quad (3.88)$$

Outage rate at load point A due to a ground fault on breaker  $i$  of average duration  $T_{si}$  is as follows.

$$\lambda_{GL4} = \lambda_4^{-\lambda_{OG4}} \quad (3.89)$$

$$\lambda_{GL5} = \lambda_5^{-\lambda_{OG5}} \quad (3.90)$$

$$\lambda_{GL6} = \lambda_6^{-\lambda_{OG6}} \quad (3.91)$$

$$\lambda_{GL7} = \lambda_7^{-\lambda_{OG7}} \quad (3.92)$$

Overlapping outage rates are taken into consideration in failure modes 14, 15, 18, 19 and 21.

#### Load point B

The outage rate and average outage duration indices at load point A are also contributions to the indices at load point B. The

outage duration for breaker 8 is its repair time in this case.

#### Failure mode 14

(i) Repair period of breaker 4 or 5 due to a ground fault overlapped by a permanent outage of line 2.

$$\lambda_{GBP4-2} = \lambda_4 \cdot \lambda_2 r_4 (1 - P_6 - P_7 + P_6 P_7) \quad (3.93)$$

$$r_{GBP4-2} = \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.94)$$

$$\lambda_{GBP5-2} = \lambda_5 \cdot \lambda_2 r_5 (1 - P_6 - P_7 + P_6 P_7) \quad (3.95)$$

$$r_{GBP5-2} = \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.96)$$

(ii) Permanent outage of line 2 is overlapped by a ground fault on breaker 4 or 5.

$$\lambda_{PGB2-4} = \lambda_2 \cdot \lambda_4 r_2 \quad (3.97)$$

$$r_{PGB2-4} = \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.98)$$

$$\lambda_{PGB2-5} = \lambda_2 \cdot \lambda_5 r_2 \quad (3.99)$$

$$r_{PGB2-5} = \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.100)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

#### Failure mode 15

(i) Repair period of breaker 6 or 7 due to a ground fault overlapped by a permanent outage of line 1.

$$\lambda_{GBP6-1} = \lambda_6 \cdot \lambda_1 r_6 (1 - P_4 - P_5 + P_4 P_5) \quad (3.101)$$

$$\lambda_{GBP7-1} = \lambda_7 \cdot \lambda_1 r_7 (1 - P_4 - P_5 + P_4 P_5) \quad (3.102)$$

$$r_{GBP6-1} = \frac{r_1 \cdot r_6}{r_1 + r_6} \quad (3.103)$$

$$r_{GBP7-1} = \frac{r_1 \cdot r_7}{r_1 + r_7} \quad (3.104)$$

(ii) Permanent outage of line 1 is overlapped by a ground



fault on breaker 6 or 7.

$$\lambda_{PGB1-6} = \lambda_1 \cdot \lambda_6 r_1 \quad (3.105)$$

$$r_{PGB1-6} = r_{GBP6-1}$$

$$\lambda_{PGB1-7} = \lambda_1 \cdot \lambda_7 r_1 \quad (3.106)$$

$$r_{PGB1-7} = r_{GBP7-1}$$

The following expressions are obtained from the expressions of failure modes 14 and 15.

$$\lambda_{GBP} = \lambda_2(1-P_6-P_7+P_6P_7)(\lambda_4r_4+\lambda_5r_5)+\lambda_1(1-P_4-P_5+P_4P_5)(\lambda_6r_6+\lambda_7r_7) \quad (3.107)$$

$$U_{GBP} = \lambda_{GBP4-2} \cdot r_{GBP4-2} + \lambda_{GBP5-2} \cdot r_{GBP5-2} + \lambda_{GBP6-1} \cdot r_{GBP6-1} + \lambda_{GBP7-1} \cdot r_{GBP7-1} \quad (3.108)$$

$$r_{GBP} = \frac{U_{GBP}}{\lambda_{GBP}}$$

$$\lambda_{PGB} = \lambda_2 r_2 (\lambda_4 + \lambda_5) + \lambda_1 r_1 (\lambda_6 + \lambda_7) \quad (3.109)$$

$$U_{PGB} = \lambda_{PGB2-4} \cdot r_{PGB2-4} + \lambda_{PGB2-5} \cdot r_{PGB2-5} + \lambda_{PGB1-6} \cdot r_{PGB1-6} + \lambda_{PGB1-7} \cdot r_{PGB1-7} \quad (3.110)$$

$$r_{PGB} = \frac{U_{PGB}}{\lambda_{PGB}}$$

It is to be noted that the contribution to the indices at load points A and B due to failure mode 15 is the same.

#### Failure mode 16

(i) Repair period of breaker 4 due to a ground fault overlapped by a temporary outage of line 2.

$$\lambda_{GBT4-2} = \lambda_4 \cdot \lambda_2 T r_4 (1-P_6-P_7+P_6P_7) \quad (3.111)$$

(ii) Repair period of breaker 5 due to a ground fault overlapped by a temporary outage of line 2.

$$\lambda_{GBT5-2} = \lambda_5 \cdot \lambda_2 T r_5 (1-P_6-P_7+P_6P_7) \quad (3.112)$$

The contribution to the indices at load points A and B due to this failure mode is the same. The average outage

duration is neglected in this case.

### Failure mode 17

The repair period of breaker 6 or 7 due to a ground fault overlapped by a temporary outage of line 1.

$$\lambda_{GBT6-1} = \lambda_6 \cdot \lambda_{1T} r_6 (1 - P_4 - P_5 + P_4 P_5) \quad (3.113)$$

$$\lambda_{GBT7-1} = \lambda_7 \cdot \lambda_{1T} r_7 (1 - P_4 - P_5 + P_4 P_5) \quad (3.114)$$

The contribution to the indices at load points A and B is the same. The average outage duration is neglected.

The following expressions are obtained from the expressions of failure modes 16 and 17.

$$\lambda_{GBT} = \lambda_{2T} (\lambda_4 r_4 + \lambda_5 r_5) (1 - P_6 - P_7 + P_6 P_7) + \lambda_{1T} (\lambda_6 r_6 + \lambda_7 r_7) \cdot (1 - P_4 - P_5 + P_4 P_5) \quad (3.115)$$

### Failure mode 18

(i) Overlapping of a ground fault by a false tripping

(a) Repair period of breaker 4 due to a ground fault overlapped by a false tripping of breaker 6 or 7.

$$\lambda_{GBF4-6} = \lambda_4 \cdot \lambda_{ob6} \cdot r_4 \quad (3.116)$$

$$\lambda_{GBF4-7} = \lambda_4 \cdot \lambda_{ob7} \cdot r_4 \quad (3.117)$$

$$r_{GBF4-6} = \frac{r_6 \cdot r_4}{r_6 + r_4} \quad (3.118)$$

$$r_{GBF4-7} = \frac{r_7 \cdot r_4}{r_7 + r_4} \quad (3.119)$$

(b) Repair period of breaker 5 due to a ground fault overlapped by a false tripping of breaker 6 or 7.

$$\lambda_{BGF5-6} = \lambda_5 \cdot \lambda_{ob6} \cdot r_5 \quad (3.120)$$

$$\lambda_{BGF5-7} = \lambda_5 \cdot \lambda_{ob7} r_5 \quad (3.121)$$

$$r_{BGF5-6} = \frac{r_5 \cdot r_6}{r_5 + r_6} \quad (3.122)$$

$$r_{BGF5-7} = \frac{r_5 \cdot r_7}{r_5 + r_7} \quad (3.123)$$

(ii) Overlapping of a false tripping by a ground fault

(a) Repair period of breaker 6 due to a false tripping overlapped by a ground fault on breaker 4 or 5.

$$\lambda_{\text{FGB6-4}} = \lambda_{\text{ob6}} \cdot \lambda_4 \cdot r_6 \quad (3.124)$$

$$\lambda_{\text{FGB6-5}} = \lambda_{\text{ob6}} \cdot \lambda_5 \cdot r_6 \quad (3.125)$$

$$r_{\text{FGB6-4}} = \frac{r_6 \cdot r_4}{r_6 + r_4} \quad (3.126)$$

$$r_{\text{FGB6-5}} = \frac{r_6 \cdot r_5}{r_6 + r_5} \quad (3.127)$$

(b) Repair period of breaker 7 due to a false tripping overlapped by a ground fault on breaker 4 or 5.

$$\lambda_{\text{FGB7-4}} = \lambda_{\text{ob7}} \cdot \lambda_4 \cdot r_7 \quad (3.128)$$

$$\lambda_{\text{FGB7-5}} = \lambda_{\text{ob7}} \cdot \lambda_5 \cdot r_7 \quad (3.129)$$

$$r_{\text{FGB7-4}} = \frac{r_7 \cdot r_4}{r_7 + r_4} \quad (3.130)$$

$$r_{\text{FGB7-5}} = \frac{r_7 \cdot r_5}{r_7 + r_5} \quad (3.131)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

#### Failure mode 19

(i) Overlapping of a ground fault by a false tripping

(a) Repair period of breaker 6 due to a ground fault overlapped by a false tripping of breaker 4 or 5.

$$\lambda_{\text{GBF6-4}} = \lambda_6 \cdot \lambda_{\text{ob4}} \cdot r_6 \quad (3.132)$$

$$\lambda_{\text{GBF6-5}} = \lambda_6 \cdot \lambda_{\text{ob5}} \cdot r_6 \quad (3.133)$$

$$r_{\text{GBF6-4}} = \frac{r_6 \cdot r_4}{r_6 + r_4} \quad (3.134)$$

$$r_{\text{GBF6-5}} = \frac{r_6 \cdot r_5}{r_6 + r_5} \quad (3.135)$$

(b) Repair period of breaker 7 due to a ground fault overlapped by a false tripping of breaker 4 or 5.

$$\lambda_{\text{GBF7-4}} = \lambda_7 \cdot \lambda_{\text{ob4}} \cdot r_7 \quad (3.136)$$

$$\lambda_{GBF7-5} = \lambda_7 \cdot \lambda_{ob5} r_7 \quad (3.137)$$

$$r_{GBF7-4} = \frac{r_7 \cdot r_4}{r_7 + r_4} \quad (3.138)$$

$$r_{GBF7-5} = \frac{r_7 \cdot r_5}{r_7 + r_5} \quad (3.139)$$

(ii) Overlapping of a false tripping by a ground fault

(a) Repair period of breaker 4 due to the false tripping overlapped by a ground fault on breaker 6 or 7.

$$\lambda_{FGB4-6} = \lambda_{ob4} \cdot \lambda_6 r_4 \quad (3.140)$$

$$\lambda_{FGB4-7} = \lambda_{ob4} \cdot \lambda_7 r_4 \quad (3.141)$$

$$r_{FGB4-6} = \frac{r_4 \cdot r_6}{r_4 + r_6} \quad (3.142)$$

$$r_{FGB4-7} = \frac{r_4 \cdot r_7}{r_4 + r_7} \quad (3.143)$$

(b) Repair period of breaker 5 due to the false tripping overlapped by a ground fault on breaker 6 or 7.

$$\lambda_{FGB5-6} = \lambda_{ob5} \cdot \lambda_6 r_5 \quad (3.144)$$

$$\lambda_{FGB5-7} = \lambda_{ob5} \cdot \lambda_7 r_5 \quad (3.145)$$

$$r_{FGB5-6} = \frac{r_5 \cdot r_6}{r_5 + r_6} \quad (3.146)$$

$$r_{FGB5-7} = \frac{r_5 \cdot r_7}{r_5 + r_7} \quad (3.147)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

The following expressions are obtained from the expressions of failure modes 18(i) and 19(i).

$$\lambda_{GBF} = (\lambda_{ob6} + \lambda_{ob7})(\lambda_4 r_4 + \lambda_5 r_5) + (\lambda_{ob4} + \lambda_{ob5})(\lambda_6 r_6 + \lambda_7 r_7) \quad (3.148)$$

$$U_{GBF} = (\lambda_{GBF4-6} + \lambda_{GBF6-4}) \cdot r_{GBF4-6} + (\lambda_{GBF4-7} + \lambda_{GBF7-4}) \cdot r_{GBF4-7} \\ + (\lambda_{GBF5-6} + \lambda_{GBF6-5}) \cdot r_{GBF5-6} + (\lambda_{GBF5-7} + \lambda_{GBF7-5}) \cdot r_{GBF5-7} \quad (3.149)$$

$$r_{GBF} = \frac{U_{GBF}}{\lambda_{GBF}} \quad (3.150)$$

The following expressions are obtained from the expressions of failure modes 18(ii) and 19(ii).

$$\lambda_{FGB} = (\lambda_4 + \lambda_5)(\lambda_{ob6}r_6 + \lambda_{ob7}r_7) + (\lambda_6 + \lambda_7)(\lambda_{ob4}r_4 + \lambda_{ob5}r_5) \quad (3.151)$$

$$U_{FGB} = (\lambda_{FGB6-4} + \lambda_{FGB4-6})r_{FGB4-6} + (\lambda_{FGB7-4} + \lambda_{FGB4-7})r_{FGB4-7} \\ + (\lambda_{FGB6-5} + \lambda_{FGB5-6})r_{FGB5-6} + (\lambda_{FGB7-5} + \lambda_{FGB5-7})r_{FGB5-7} \quad (3.152)$$

$$r_{FGB} = \frac{U_{FGB}}{\lambda_{FGB}} \quad (3.153)$$

#### Failure mode 20

(i) Repair period of breaker 4 due to a false tripping is overlapped by a false tripping of breaker 6 or 7.

$$\lambda_{FF4-6} = \lambda_{ob4} \cdot \lambda_{ob6} r_4 \quad (3.154)$$

$$\lambda_{FF4-7} = \lambda_{ob4} \cdot \lambda_{ob7} r_4 \quad (3.155)$$

$$r_{FF4-6} = \frac{r_4 \cdot r_6}{r_4 + r_6} \quad (3.156)$$

$$r_{FF4-7} = \frac{r_4 \cdot r_7}{r_4 + r_7} \quad (3.157)$$

(ii) Repair period of breaker 5 due to a false tripping is overlapped by a false tripping of breaker 6 or 7.

$$\lambda_{FF5-6} = \lambda_{ob5} \cdot \lambda_{ob6} r_5 \quad (3.158)$$

$$\lambda_{FF5-7} = \lambda_{ob5} \cdot \lambda_{ob7} r_5 \quad (3.159)$$

$$r_{FF5-6} = \frac{r_5 \cdot r_6}{r_5 + r_6} \quad (3.160)$$

$$r_{FF5-7} = \frac{r_5 \cdot r_7}{r_5 + r_7} \quad (3.161)$$

(iii) Repair period of breaker 6 due to a false tripping is overlapped by a false tripping of breaker 4 or 5.

$$\lambda_{FF6-4} = \lambda_{ob6} \cdot \lambda_{ob4} r_6 \quad (3.162)$$

$$\lambda_{FF6-5} = \lambda_{ob6} \cdot \lambda_{ob5} r_6 \quad (3.163)$$

$$r_{FF6-4} = r_{FF4-6}$$

$$r_{FF6-5} = r_{FF5-6}$$

(iv) Repair period of breaker 7 due to a false tripping is overlapped by a false tripping of breaker 4 or 5.

$$\lambda_{FF7-4} = \lambda_{ob7} \cdot \lambda_{ob4} r_7 \quad (3.164)$$

$$\lambda_{FF7-5} = \lambda_{ob7} \cdot \lambda_{ob5} r_7 \quad (3.165)$$

$$r_{FF7-4} = r_{FF4-7}$$

$$r_{FF7-5} = r_{FF5-7}$$

The following expressions are obtained for this failure mode from (i), (ii), (iii) and (iv).

$$\lambda_{FF} = \lambda_{ob4} (\lambda_{ob6} (r_4 + r_6) + \lambda_{ob7} (r_4 + r_7)) + \lambda_{ob5} (\lambda_{ob6} (r_5 + r_6) + \lambda_{ob7} (r_5 + r_7)) \quad (3.166)$$

$$U_{FF} = \lambda_{ob4} r_4 (\lambda_{ob6} r_6 + \lambda_{ob7} r_7) + \lambda_{ob5} r_5 (\lambda_{ob6} r_6 + \lambda_{ob7} r_7) \quad (3.167)$$

$$r_{FF} = \frac{U_{FF}}{\lambda_{FF}} \quad (3.168)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

### Failure mode 21

(i) Maintenance period of line section 1 is overlapped by a ground fault on breaker 6 or 7.

$$\lambda_{MGB1-6} = \lambda_1 \lambda_6 r_1 \quad (3.169)$$

$$\lambda_{MGB1-7} = \lambda_1 \lambda_7 r_1 \quad (3.170)$$

$$r_{MGB1-6} = \frac{r_1 \cdot r_6}{r_1 + r_6} \quad (3.171)$$

$$r_{MGB1-7} = \frac{r_1 \cdot r_7}{r_1 + r_7} \quad (3.172)$$

(ii) Maintenance period of line section 2 is overlapped by a ground fault on breaker 4 or 5.

$$\lambda_{MGB2-4} = \lambda_2 \cdot \lambda_4 r_2 \quad (3.173)$$

$$\lambda_{MGB2-5} = \lambda_2 \cdot \lambda_5 r_2 \quad (3.174)$$

$$r_{MGB2-4} = \frac{r_2 \cdot r_4}{r_2 + r_4} \quad (3.175)$$

$$r_{MGB2-5} = \frac{r_2 \cdot r_5}{r_2 + r_5} \quad (3.176)$$

The following expressions are obtained from the expressions (i) and (ii)

$$\lambda_{MGB} = \lambda_1 r_1 (\lambda_6 + \lambda_7) + \lambda_2 r_2 (\lambda_4 + \lambda_5) \quad (3.177)$$

$$U_{MGB} = \lambda_{MGB1-6} \cdot r_{MGB1-6} + \lambda_{MGB1-7} \cdot r_{MGB1-7} + \lambda_{MGB2-4} \cdot r_{MGB2-4} + \lambda_{MGB2-5} \cdot r_{MGB2-5} \quad (3.178)$$

$$r_{MGB} = \frac{U_{MGB}}{\lambda_{MGB}} \quad (3.179)$$

The contribution to the indices at load points A and B due to this failure mode is the same.

The contributions due to the indices at the load points due to the different outage conditions can be obtained from the expressions derived for each considered failure mode. These are as follows:

#### Load point A

Contribution due to

(A) Permanent outages or overlapping permanent outages

$$\lambda_{PLA} = \lambda_1 \lambda_2 (r_1 (1 - P_6 - P_7 + P_6 P_7) + r_2 (1 - P_4 - P_5 + P_4 P_5)) \quad (3.180)$$

$$r_{PLA} = \frac{r_1 \cdot r_2}{r_1 + r_2} \quad (3.181)$$

$$U_{PLA} = \lambda_{PLA} \cdot r_{PLA} \quad (3.182)$$

(B) Line temporary outages overlapping line maintenance or permanent outages.

The following expressions are obtained by considering failure

modes 9 and 11(ii) as series subsystems.

$$\lambda_{TLA} = \lambda_{2T}(1-P_6-P_7+P_6P_7)(\lambda_1''r_1''+\lambda_1r_1)+(1-P_4-P_5+P_4P_5)(\lambda_2''r_2''+\lambda_2r_2)\lambda_{1T} \quad (3.183)$$

Average duration is neglected in this case.

(C) Line permanent outage overlapping a line section maintenance outage period.

Failure mode 11(ii) contributes to this outage condition.

$$\lambda_{MLA} = \lambda_1''\lambda_2r_1''(1-P_6-P_7+P_6P_7)+\lambda_1\lambda_2''r_2''(1-P_4-P_5+P_4P_5) \quad (3.184)$$

$$U_{MLA} = \lambda_1''\lambda_2r_1''(1-P_6-P_7+P_6P_7) \cdot \frac{r_1'' \cdot r_2}{r_1''+r_2} + \lambda_1\lambda_2''r_2''(1-P_4-P_5+P_4P_5) \cdot \frac{r_2''r_1}{r_2''+r_1} \quad (3.185)$$

$$r_{MLA} = \frac{U_{MLA}}{\lambda_{MLA}} \quad (3.186)$$

(D) Failure to clear a fault by the primary protection system of a line.

Failure modes 1, 2 and 8 contribute to this outage condition.

$$\lambda_{ULA} = (P_4+P_5-P_4P_5)(\lambda_1+\lambda_{1T})+(P_6+P_7-P_6P_7)(\lambda_2+\lambda_{2T})+P_8(\lambda_3+\lambda_{3T}) \quad (3.187)$$

$$U_{ULA} = \lambda_1T_{s1}(P_4+P_5-P_4P_5)+\lambda_2T_{s2}(P_6+P_7-P_6P_7)+P_8\lambda_3T_{s3} \quad (3.188)$$

$$r_{ULA} = \frac{U_{ULA}}{\lambda_{ULA}} \quad (3.189)$$

(E) False tripping of breakers overlapping the false tripping of breakers or overlapping of the false tripping of breakers by other outages or overlapping of other outages by the false tripping of breakers (other outages are maintenance, permanent and temporary outages and a ground fault on breakers).

Failure modes 4, 5, 10, 12, 18(i), 19(i) and 20 contribute to this outage condition.



$$\lambda_{FLA} = \lambda_{PFL} + \lambda_{TFL} + \lambda_{MFL} + \lambda_{GBF} + \lambda_{FF} \quad (3.190)$$

$$U_{FLA} = U_{PFL} + U_{MFL} + U_{GBF} + U_{FF} \quad (3.191)$$

$$r_{FLA} = \frac{U_{FLA}}{\lambda_{FLA}} \quad (3.192)$$

(F) Ground fault on breakers or overlapping of a ground fault on breakers by other outages or overlapping of other outages by a ground fault on breakers (other outages in this case are permanent, temporary and maintenance outages of lines and false tripping of breakers).

Failure modes 13, 14, 15, 16, 17, 18(ii), 19(ii) and 21 contribute to this condition.

$$\lambda_{GBLA} = \sum_{i=4}^8 \lambda_{GLi} + \lambda_{GBP} + \lambda_{PGB} + \lambda_{GBT} + \lambda_{FGB} + \lambda_{MGB} \quad (3.193)$$

$$U_{GBLA} = \sum_{i=4}^8 (\lambda_{GLi} \cdot T_{si}) + U_{GBP} + U_{PGB} + U_{FGB} + U_{MGB} \quad (3.194)$$

$$r_{GBLA} = \frac{U_{GBLA}}{\lambda_{GBLA}} \quad (3.195)$$

It should be appreciated that the indices obtained for conditions (D) and (E) are due to the protection system failure modes. From (D) and (E), the following expressions are obtained for the indices at load point A due to protection system failures.

$$\lambda_{PSFLA} = \lambda_{ULA} + \lambda_{FLA} \quad (3.196)$$

$$U_{PSFLA} = U_{ULA} + U_{FLA} \quad (3.197)$$

$$r_{PSFLA} = \frac{U_{PSFLA}}{\lambda_{PSFLA}} \quad (3.198)$$

Expressions for the reliability indices at load point A are obtained by adding the indices of conditions (A), (B), (C), (D), (E) and (F) as in a series system. Each condition is taken as a subsystem of a series system.

$$\lambda_{LA} = \lambda_{PLA} + \lambda_{TLA} + \lambda_{MLA} + \lambda_{ULA} + \lambda_{FLA} + \lambda_{GBLA} \quad (3.199)$$

$$U_{LA} = U_{PLA} + U_{TLA} + U_{MLA} + U_{ULA} + U_{FLA} + U_{GBLA} \quad (3.200)$$

$$r_{LA} = \frac{U_{LA}}{\lambda_{LA}} \quad (3.201)$$

### Load point B

All the failure modes of load point A are also the failure modes of load point B except failure mode 8. In addition, failure modes 6 and 7 are also failure modes of load point B.

The conditions (A) to (F) are included as in the analysis of load point A.

(A) Failure modes 3 and 6(i) contribute to this case.

$$\lambda_{PLB} = \lambda_1 \lambda_2 (r_1 (1 - P_6 - P_7 + P_6 P_7) + r_2 (1 - P_4 - P_5 + P_4 P_5)) + \lambda_3 \quad (3.202)$$

$$\begin{aligned} U_{PLB} &= \lambda_{PL3} \cdot r_{PL3} + \lambda_3 \cdot r_3 \\ &= \lambda_1 \lambda_2 (r_1 (1 - P_6 - P_7 + P_6 P_7) + r_2 (1 - P_4 - P_5 + P_4 P_5)) \cdot \frac{r_1 \cdot r_2}{r_1 + r_2} + \lambda_3 r_3 \end{aligned} \quad (3.203)$$

$$r_{PLB} = \frac{U_{PLB}}{\lambda_{PLB}} \quad (3.204)$$

(B) Failure mode 6(ii), 9 and 11(i) contribute in this case.

$$\begin{aligned} \lambda_{TLB} &= \lambda_{PT} + \lambda_{MTL} + \lambda_{3T} \\ &= (1 - P_6 - P_7 + P_6 P_7) (\lambda_1'' r_1'' + \lambda_1 r_1) \lambda_{2T} + (1 - P_4 - P_5 + P_4 P_5) (\lambda_2'' r_2'' \\ &\quad + \lambda_2 r_2) \lambda_{1T} + \lambda_{3T} \end{aligned} \quad (3.205)$$

Average outage duration is neglected in this case.

(C) Same as for the indices at load point A.

(D) Failure mode 8 is not contributing to the indices at load point B.

$$\lambda_{ULB} = (P_4 + P_5 - P_4 P_5)(\lambda_1 + \lambda_{1T}) + (P_6 + P_7 - P_6 P_7)(\lambda_2 + \lambda_{2T}) \quad (3.206)$$

$$U_{ULB} = \lambda_1 T_{s1}(P_4 + P_5 - P_4 P_5) + \lambda_2 T_{s2}(P_6 + P_7 - P_6 P_7) \quad (3.207)$$

$$r_{ULB} = \frac{U_{ULB}}{\lambda_{ULB}} \quad (3.208)$$

(E) In addition to all the failure modes which contribute to the indices at load point A, failure mode 7 also contributes to the indices at load point B.

$$\lambda_{FLB} = \lambda_{PFL} + \lambda_{F3} + \lambda_{TFL} + \lambda_{MFL} + \lambda_{GBF} + \lambda_{FF} \quad (3.209)$$

$$U_{FLB} = U_{PFL} + \lambda_{F3} \cdot r_{F3} + U_{MFL} + U_{GBF} + U_{FF} \quad (3.210)$$

$$r_{FLB} = \frac{U_{FLB}}{\lambda_{FLB}} \quad (3.211)$$

(F) All the failure modes which contribute to the indices at load point A also contribute to the indices at load point B.

Failure mode 13 is to be reconsidered in this case.

$$\lambda_{GBLB} = \sum_{i=4}^8 \lambda_{GLi} + \lambda_{GBP} + \lambda_{PGB} + \lambda_{GBT} + \lambda_{FGB} + \lambda_{MGB} \quad (2.212)$$

$$U_{GBLB} = \sum_{i=4}^8 (\lambda_{GLi} \cdot T_{si}) + \lambda_8 r_8 + U_{GBP} + U_{PGB} + U_{FGB} + U_{MGB} \quad (2.213)$$

$$r_{GBLB} = \frac{U_{GBLB}}{\lambda_{GBLB}} \quad (2.214)$$

The indices due to protection system failures are as follows.

$$\lambda_{PSFL_B} = \lambda_{UL_B} + \lambda_{FL_B} \quad (3.215)$$

$$U_{PSFL_B} = U_{UL_B} + U_{FL_B} \quad (3.216)$$

$$r_{PSFL_B} = \frac{U_{PSFL_B}}{\lambda_{PSFL_B}} \quad (3.217)$$

As for load point A, all the indices at load point B are obtained in the same way as follows.

$$\lambda_{L_B} = \lambda_{PL_B} + \lambda_{TL_B} + \lambda_{ML_B} + \lambda_{UL_B} + \lambda_{FL_B} + \lambda_{GBL_B} \quad (3.218)$$

$$U_{L_B} = U_{PL_B} + U_{ML_B} + U_{UL_B} + U_{FL_B} + U_{GBL_B} \quad (3.219)$$

$$r_{L_B} = \frac{U_{L_B}}{\lambda_{L_B}} \quad (3.220)$$

Reliability indices at load points A and B have the following relationship between them.

$$\lambda_{L_B} = \lambda_{L_A} + (1 - P_8)(\lambda_3 + \lambda_{3T}) + \lambda_{ob8} \quad (3.221)$$

$$U_{L_B} = U_{L_A} + \lambda_8 r_8 - \lambda_3 r_3 - P_8 \lambda_3 T_{s3} + \lambda_{F3} r_{F3} \quad (3.222)$$

Equations 3.12 to 3.222 can be used to provide a detailed examination of the relative contributions to the reliability indices at load points A and B. Numerical reliability indices at load points A and B are calculated in the next section using these equations.

### 3.6 System Studies

The expressions derived in the previous section are used in this section to evaluate the reliability indices for the system shown in Figure 3.1. The assumed outage data for the system components are given in Table 3.1.

Table 3.1 Component outage data

	Permanent failure	Temporary failure	Maintenance outage (only for lines 1 & 2)
Outage rate of lines	0.5 f/yr	1.0 f/yr	3.0 f/yr
Average outage duration	7.5 hours	---	8.0 hours
Ground fault rate for breakers (including c.t. of its relay)			= 0.005 f/yr
Average repair time for protection system outage			= 24 hours
Switching time for each component			= 1.5 hours

#### Assumptions

- i) Lines 1, 2 and 3 are identical and have the same reliability data.
- ii) Only lines 1, 2 and 3 have temporary failures.
- iii) All the breakers and their relays are identical having the same data.
- iv) Switching time for all components is equal.

The reliability indices have been calculated using the above assumptions, for different values of unreadiness probability and

false tripping rate. Some of the calculated results are tabulated in Table 3.2. Figures 3.5 and 3.6 utilize a range of results to show the effect of variation of the unreadiness probability and false tripping rate on the failure rate and annual outage time of load points A and B.

Table 3.2 Reliability indices at load points A and B

Set no.	Type Of indices	Stuck Proba- bility	False tripping rate (f/yr)	Load point A			Load point B		
				Average failure rate (f/yr)	Average outage durat. (hours)	Annual outage time (hrs/yr)	Average failure rate (f/yr)	Average outage durat. (hours)	Annual outage time (hrs/yr)
1		0.00	0.00						
	A			0.000428	3.750000	0.001605	0.500428	7.496792	3.751605
	B			0.002683			1.002683		
	C			0.000913	3.870968	0.003535	0.000913	3.870968	0.003535
	D			0.025082	1.506042	0.037775	0.030082	8.984546	0.270275
	E			0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	F			0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	E+F			0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Total			0.029106	1.474439	0.042915	1.534106	2.623948	4.025415
2		0.001	0.001						
	A			0.000427	3.750000	0.001602	0.500427	7.496799	3.751602
	B			0.002677			1.002677		
	C			0.000911	3.870968	0.003528	0.000911	3.870968	0.003528
	D			0.025082	1.506078	0.037776	0.030082	8.984590	0.270276
	E			0.007497	0.500000	0.003749	0.005997	0.500000	0.002999
	F			0.000022	2.946229	0.000065	0.002022	23.771935	0.048065
	E+F			0.007519	0.507126	0.003813	0.008019	6.367833	0.051063
	Total			0.036617	1.275880	0.046719	1.542117	2.643424	4.076469
3		0.005	0.001						
	A			0.000424	3.750000	0.001589	0.000427	3.750000	3.751589
	B			0.002656			1.002656		
	C			0.000904	3.870968	0.003500	0.000904	3.870968	0.003500
	D			0.025082	1.506042	0.037774	0.030082	8.984614	0.270274
	E			0.037425	0.500000	0.018713	0.029925	0.500000	0.014963
	F			0.000022	2.952501	0.000064	0.002022	23.773353	0.048064
	E+F			0.037447	0.501426	0.018777	0.031947	1.972869	0.063027
	Total			0.066513	0.926748	0.061640	1.566013	2.610701	4.088390
4		0.01	0.001						
	A			0.000420	3.750000	0.001573	0.500420	7.496824	3.751589
	B			0.002629			1.002629		
	C			0.000895	3.870968	0.003465	0.000895	3.870986	0.003500
	D			0.025082	1.505996	0.037773	0.030082	8.984643	0.270274
	E			0.074700	0.500000	0.037350	0.059700	0.500000	0.014963
	F			0.000022	2.960412	0.000064	0.002022	23.775118	0.048064
	E+F			0.074722	0.500712	0.037414	0.061722	1.262345	0.063027
	Total			0.103747	0.773274	0.080225	1.595747	2.610701	4.088390

Table 3.2 continues on the next page

Table 3.2 continued from the previous page

Set no.	Type Of indices	Stuck Probabi- lity rate (f/yr)	False tripping rate (f/yr)	Load point A			Load point B		
				Average failure rate (f/yr)	Average outage durat. (hours)	Annual outage time (hrs/yr)	Average failure rate (f/yr)	Average outage durat. (hours)	Annual outage time (hrs/yr)
5		0.05	0.001						
	A			0.000386	3.750000	0.001449	0.500386	7.497105	3.751449
	B			0.002421			0.002421		
	C			0.000824	3.870968	0.003190	0.000824	3.870968	0.003190
	D			0.025080	1.505639	0.037761	0.030080	8.984643	0.270261
	E			0.367500	0.500000	0.183750	0.292500	0.500000	0.146250
	F			0.000020	3.026641	0.000062	0.002020	23.788926	0.048062
	E+F			0.367520	0.500140	0.183812	0.294520	0.659756	0.194312
	Total			0.396231	0.570907	0.226211	1.828231	2.307810	4.219211
6		0.001	0.005						
	A			0.000427	3.750000	0.001602	0.500427	7.496799	3.751602
	B			0.002677			1.002677		
	C			0.000911	3.870968	0.003528	0.000911	3.870968	0.003528
	D			0.025082	1.506262	0.037780	0.030082	8.984743	0.270280
	E			0.007497	0.500000	0.003749	0.005997	0.500000	0.002999
	F			0.000110	2.982325	0.000328	0.010110	23.771424	0.240328
	E+F			0.007607	0.535879	0.004076	0.016107	15.106920	0.243326
	Total			0.036705	1.280120	0.046987	1.550205	2.753660	4.268737
7		0.001	0.01						
	A			0.000427	3.750000	0.001602	0.500427	7.496799	3.751602
	B			0.002677			1.002677		
	C			0.000911	3.870968	0.003528	0.000911	3.870968	0.003528
	D			0.025082	1.506491	0.037786	0.030082	8.984934	0.270332
	E			0.007497	0.500000	0.003749	0.005997	0.500000	0.002999
	F			0.000221	3.027043	0.000669	0.020221	23.770786	0.480669
	E+F			0.007718	0.572359	0.004417	0.026218	18.447919	0.483667
	Total			0.036816	1.285679	0.047334	1.560316	2.889853	4.509084
8		0.001	0.05						
	A			0.000427	3.750000	0.001602	0.500427	7.496799	3.751602
	B			0.002677			1.002677		
	C			0.000911	3.870968	0.003528	0.000911	3.870968	0.003528
	D			0.025082	1.508326	0.037832	0.030082	8.984664	0.270332
	E			0.007497	0.500000	0.003749	0.005997	0.500000	0.002999
	F			0.001149	3.369426	0.003871	0.020221	23.765685	2.403871
	E+F			0.008646	0.881275	0.007619	0.026218	22.463494	2.406869
	Total			0.037744	1.340126	0.050582	1.560316	2.889853	6.432332

## Type of indices

## Description

A	Permanent failure indices
B	Temporary failure indices
C	Maintenance outage indices
D	Breaker ground fault indices
E	Failure of primary protection system to clear fault
F	False tripping of breakers

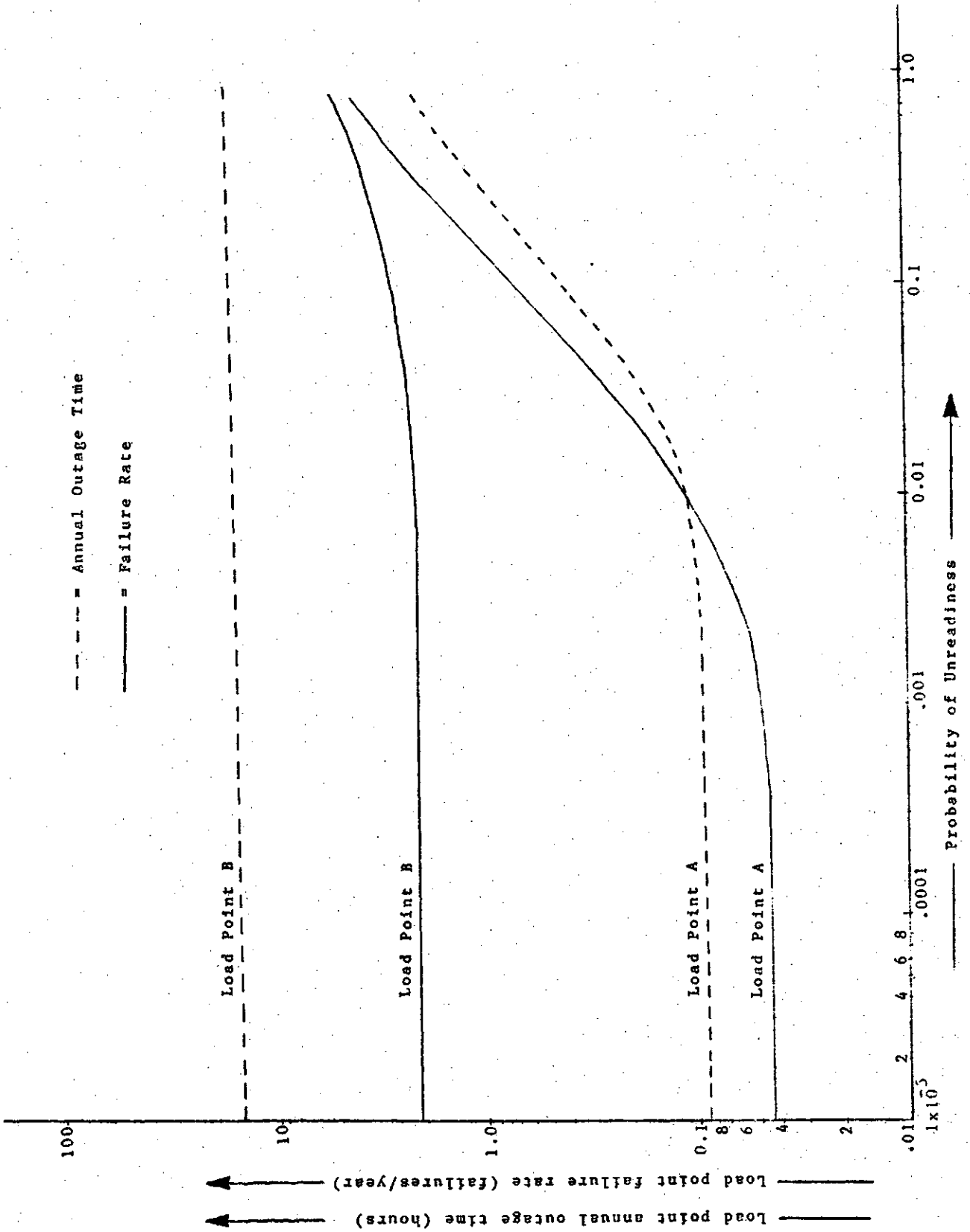


Figure 3.5 Effect of the probability of unreadiness of the protection system on reliability indices



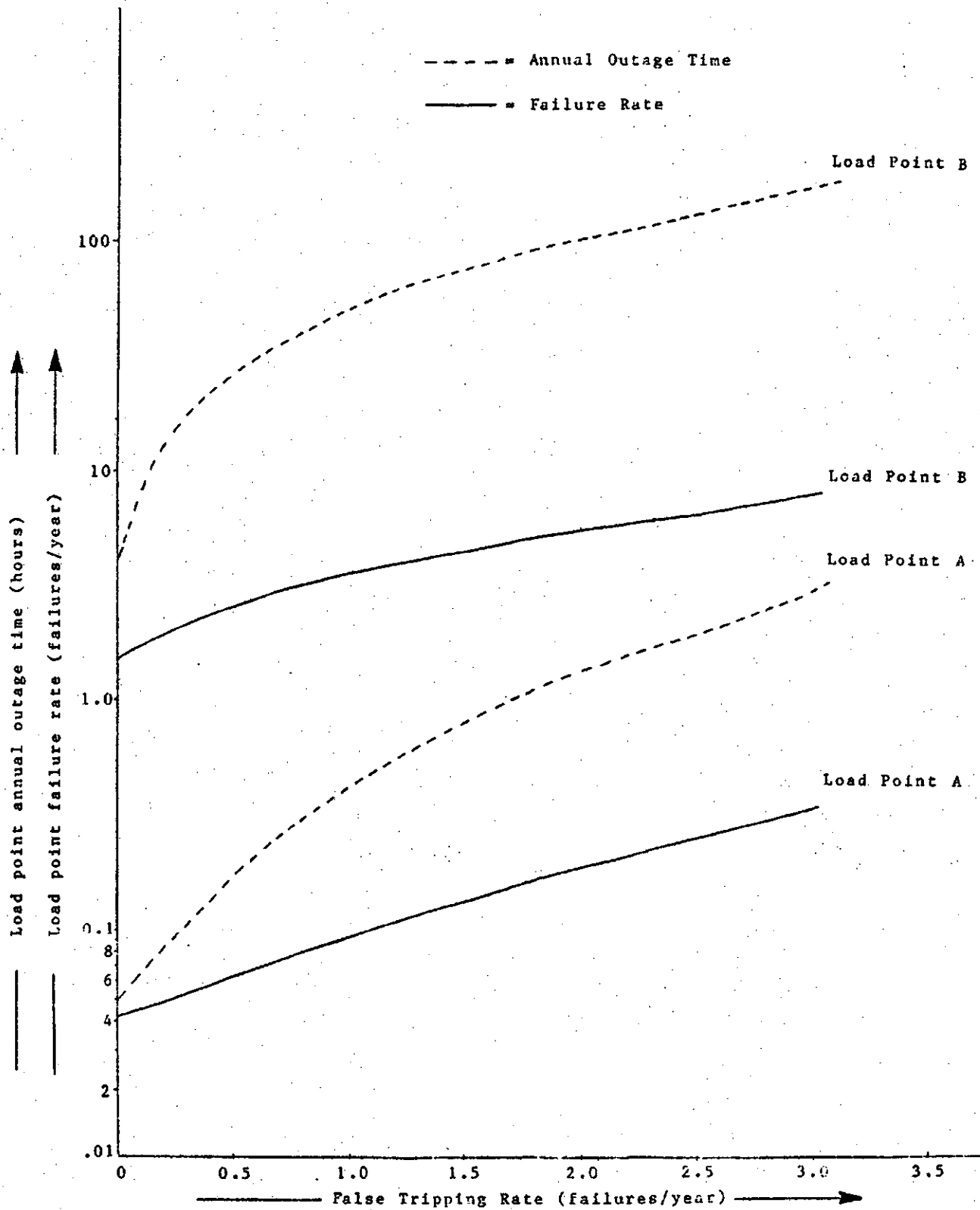


Figure 3.6 Effect of the false tripping rate of the protection system on reliability indices

It is difficult to intuitively state the relationship between the reliability indices and the probability of unreadiness and false tripping rate. It is, however, clear from the results tabulated and the curves plotted that the reliability indices do change with a change in the unreadiness probability and the false tripping rate of the protection system. If the probability of unreadiness is less than 0.001 then the indices are not significantly affected. The indices, however, are very dependent upon the false tripping rate over the entire practical range. Table 3.2 shows the numerical indices obtained and the relative contributions from the various failure conditions.

In this chapter, a series of equations have been developed for evaluating the load point reliability indices by considering the different failure modes of lines and the protection system. Reliability predictions obtained without consideration of protection system failure modes can be considerably in error. The failure mode and effect analysis technique used in this chapter is a very powerful method for determining system reliability indices. The equations provide an extension to previously developed expressions which are valid for components within which the protection system is assumed to be perfectly reliable. The equations given in this chapter apply not only to the system in Figure 3.1 but to systems with any number of components. The primary consideration is the effect of the failure of a component or components on the load point considered.

#### 4. PROTECTION SYSTEM RELATED MULTIPLE OUTAGES IN THE RELIABILITY ANALYSIS OF A COMPOSITE GENERATION AND TRANSMISSION SYSTEM

##### 4.1 GENERAL

As noted earlier, the protection system plays a vital role in providing electrical energy at acceptable quality to consumers by recognizing and isolating any abnormal condition in the network with minimum possible effect on the power system. Substations and switching stations are the points of energy transfer between generating stations and different transmission and distribution circuits. Different bus and circuit breaker arrangements are used to reduce the severity of component outages on the rest of the healthy network.

Considerable attention has been devoted by power utilities in recent years to the evaluation of the effectiveness of their systems from a reliability viewpoint. This is evident from the published research work done in the last two decades[1-3].

The reliability evaluation of a composite system is concerned with the problem of assessing the adequacy of the combined generation and transmission system with respect to the terminal stations [4,16]. Such an evaluation involves the simulation and load flow analysis of each "credible" outage condition in the system in order to determine the capability of the system to supply individual bus loads without voltage violations, line and generator overloads etc. and to quantitatively express the deficiencies, if any, in terms of reliability indices.

A composite generation and transmission system reliability evaluation technique [17-20], which includes a system representation of the form used in an ac load flow analysis, has been developed at the University of Saskatchewan. An important aspect of this technique is the calculation of individual load point reliability indices and overall system indices. The program considers all possible first and second order independent simultaneous outage combinations of generating units, transmission lines and transformers. The contingency level to be considered will be dependent upon the system size and the system characteristics. Even for a moderately sized power system, the computational cost to examine third, fourth and higher order contingencies is prohibitive. Dandeno et. al. [23] have reported a program for bulk power electric system adequacy assessment which examines up to five independent simultaneous outages. This method uses a fast and approximate DC load flow technique to analyze each selected system contingency. Such an analysis calculates the MW flow over the lines but provides no information about bus voltages. Reference 22 describes the basis of a digital computer program for evaluating both the system and load point reliability indices using an ac load flow.

The papers referenced earlier basically assume that the outages of power system components are independent of each other i.e. when one component fails it does not put any other healthy component out of service. It was also assumed that simultaneous or overlapping outages constituting a contingency situation are independent. This assumption is not true for all outage

situations. An additional set of outages has been defined and designated as common-cause or common mode [39]. Their effect on the down state of two or more lines and on bus and system indices of a composite generation and transmission system has been examined in References 40 and 20 respectively. The outage of two or more current carrying components (lines and/or generators) can also occur due to protection system related single or double contingency outage situations.

The probability of occurrence of an event consisting of a set of simultaneous independent outages is the product of the individual outage probabilities. Even if the probabilities of individual outages are high, the product can become quite small. The probability of a protection system related outage resulting in a similar event can, however, be many times larger. The effect of such outages on reliability indices can be significant as compared with second and higher order simultaneous independent outages. It is therefore necessary to consider first and second order protection system related outages before considering higher order simultaneous independent outages.

Multiple outages of current carrying components which result from causes such as a ground fault on a breaker, a stuck breaker or relay condition, battery supply failure etc. are referred to in this chapter as protection system related outages. Some of these outages were described in Reference 23 as station originated outages and some models were described for representing such failures in composite reliability analysis. The outages examined in this chapter are all protection system related and the models

described in Reference 23 are modified to include these outages. The configurations of two terminal stations from an actual system are used to examine these outages.

#### Notation

AF	active failure
$\lambda_i$	independent failure rate in failures per year of component i
$\mu_i$	independent repair rate in repairs per year of component i
$\lambda_C$	common-cause failure rate in failures per year
$\mu_C$	common-cause repair rate in repairs per year
$\lambda_S$	station originated failure rate in failures per year
$\mu_S$	station originated repair rate in repairs per year
$P_b$	probability of failure of the dc supply at a switching station in the case of a fault
$\lambda_{SS}$	isolation rate of a switching station due to a stuck breaker condition or the failure of a relay scheme in the case of a fault
$\mu_{SS}$	switching rate to reconnect the switching station to the rest of the healthy network
n	total number of components at a switching station.
$\lambda_{SW}$	outage rate of a switching station per year from the rest of the network due to the failure of a component and the dc supply at the same time.
$r_{SW}$	average duration of an outage of the switching station in hours.
L	total load connected to the switching station and assume this load is constant in the year or any duration of a period considered.
S	loss in dollars per MWh loss of energy.
$q_u$	probability of unreadiness of circuit breaker and its relay scheme.

## 4.2 Classification of Outages

A power system normally contains a number of generating units, transmission lines and transformers. These components are referred to in this chapter as current carrying components of the power system. Most of the failures of these components can be grouped into the following four categories :

1. Independent outages
2. Dependent outages
3. Common Mode outages
4. Terminal related outages

### 4.2.1 Independent outages

Independent outages of two or more components are referred to as overlapping or simultaneous independent outages. The outage of each component is caused by an independent event. The probability of such an outage is the product of the failure probabilities for each of the components. The component model normally used is the simple two state representation in which the component is either up or down. The state space diagram of Figure 4.1 shows all possible states for a two component configuration considering independent outages.

Most of the presently available techniques for composite system reliability evaluation assume that the outages constituting a contingency situation are independent.

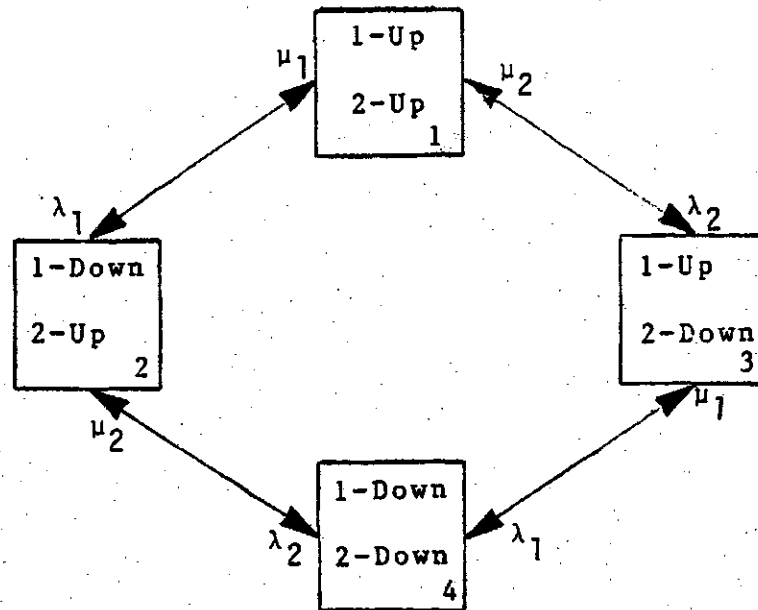


Figure 4.1 The basic simultaneous independent outage model

#### 4.2.2 Dependent outages

As the name implies, these outages are dependent upon the occurrence of one or more other outages. An example is the removal from service of the second line of a double circuit line due to overload which resulted from an independent outage of the first line of the double circuit configuration. These outages are not normally included in the reliability evaluation of composite systems.

#### 4.2.3 Common mode outages

As stated earlier, the probability of occurrence of an event consisting of two or more simultaneous independent outages is the product of the individual outage probabilities. If the probabilities of individual outages are low, the product can become quite small. The probability of a common mode outage resulting in a similar event can, however, be many times larger.



The effect of common-cause outages on reliability indices can be significant as compared with the effect of second and higher order outages. A common mode outage is an event having an external cause with multiple failure effects where the effects are not consequences of each other.

The Task Force on Common Mode Outages of Bulk Power Supply Facilities of the IEEE Subcommittee on the Application of Probability Methods in the Power Engineering Society suggested a common mode outage model for two transmission lines on the same right-of-way or on the same transmission tower. This model is shown in Figure 4.2. It is similar to the model of Figure 4.1 except for the direct transition rate of  $\lambda_c$  from state 1 to state 4.

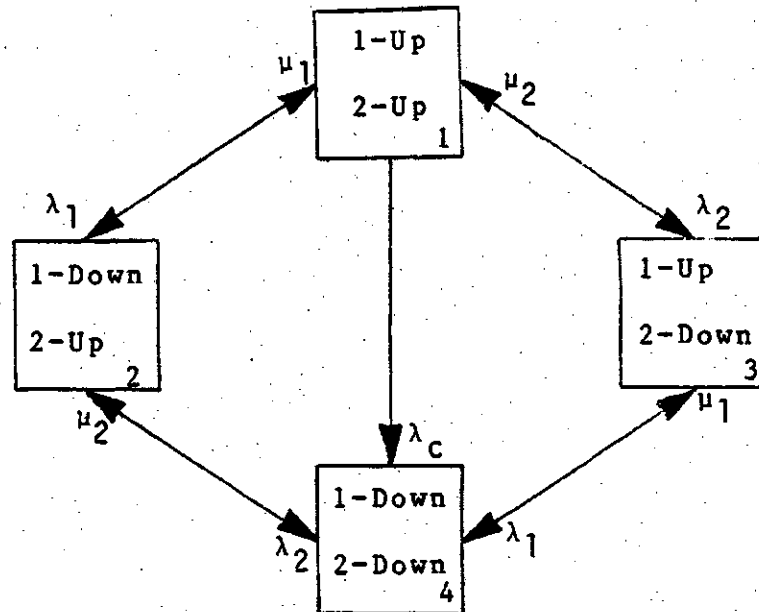


Figure 4.2 A common mode outage model - The IEEE model

This model assumes basically the same restoration process for all failures including common mode failures. Various other possible common mode outage models are described in Reference 20 which also

examined the effect of common mode outages on reliability indices of a practical system.

#### 4.2.4 Terminal related outages

The outage of two or more current carrying components can arise due to terminal related causes. These outages can be categorized into two parts :

- i) station originated
- ii) line originated

The outage of two or more transmission lines (not necessarily on the same right-of-way) and/or generating units can arise due to station originated causes. The cause of these outages could be a ground fault on a breaker, a bus fault, a stuck breaker condition etc. or a combination of these events. The outage effects of terminal station components are normally reflected in reliability calculations by combining these outages with independent outage rates of lines and/or generators affected by the failure of the station component. This approach is accurate only when one component of the system is out because of the failure of a terminal component. Such an approach assumes unrealistic independence between those system component outages which are actually caused by a single or double contingency in the terminal station. The correct approach is to regard these outages as separate events. The effect of these outages on composite system reliability have not been extensively analysed and can have an appreciable effect on the load point reliability indices.

Line originated multiple outages can occur due to a fault on a line when the primary protection of the faulty line fails to

isolate it from the rest of the healthy system. In such a situation, the back up protection operates which results in a multiple outage of current carrying components. The outage effects of such incidents are not normally included in composite system reliability analysis. These outages should be considered in combination with the independent failure events by weighting the independent failure rates of the line with the probability of successful operation of the associated primary protection to isolate that line.

It is important to realize that common mode transmission outages normally involve transmission lines on the same right-of-way, whereas, the terminal related outages can involve system components (which need not be on the same right-of-way) such as generating units and transmission lines. The effect of certain terminal related outages can, therefore, be more pronounced than common cause outages. The average duration of terminal related outages will, however, be considerably less than common cause outages.

Station originated outages have been discussed in a recent paper [23] and some of these outages i.e. a ground fault on breakers and the stuck breaker condition are termed in this chapter as protection system related outages because these outages occur due to the failure of protection system components. Line originated multiple outages are all protection system related.

Four fundamentally different types of outages which can occur in a power system have been described in this section. Protection system related outages are considered in detail in the next section.

### 4.3 Protection System Related Outages

All multiple outages which occur due to the failure of protection system components i.e. a ground fault on a breaker, a stuck breaker condition, the failure of a relay scheme to detect a fault, the failure of the dc supply etc. are termed as protection system related outages.

The origin and effects of station originated outages which occur because of a ground fault on a breaker and the stuck breaker condition, have been described and illustrated in Reference 23. Practical system configurations and selected models were presented to investigate the combined effects of independent, common-cause and station originated outages on a two component system. The models and discussion presented in Reference 23 did not include the line originated outages and the effects of these outages are described in this section using the configurations of two terminal stations from the Saskatchewan Power Corporation (SPC) system.

The switching station configurations analyzed are those of the Regina South station and the Squaw Rapids station. The Regina South switching station has a  $1\frac{1}{2}$  breaker configuration and that of Squaw Rapids is a ring bus configuration. At both stations, there is only one dc battery set which supplies the dc requirement of the station. The single line diagram of the dc supply at the switching stations is as in Figure 4.3. In these studies, active failures on lines in combination with a stuck breaker or stuck relay scheme, and active failure on all system components in combination with failure of the dc supply are considered. It is assumed that breakers protecting the same line at a station have a

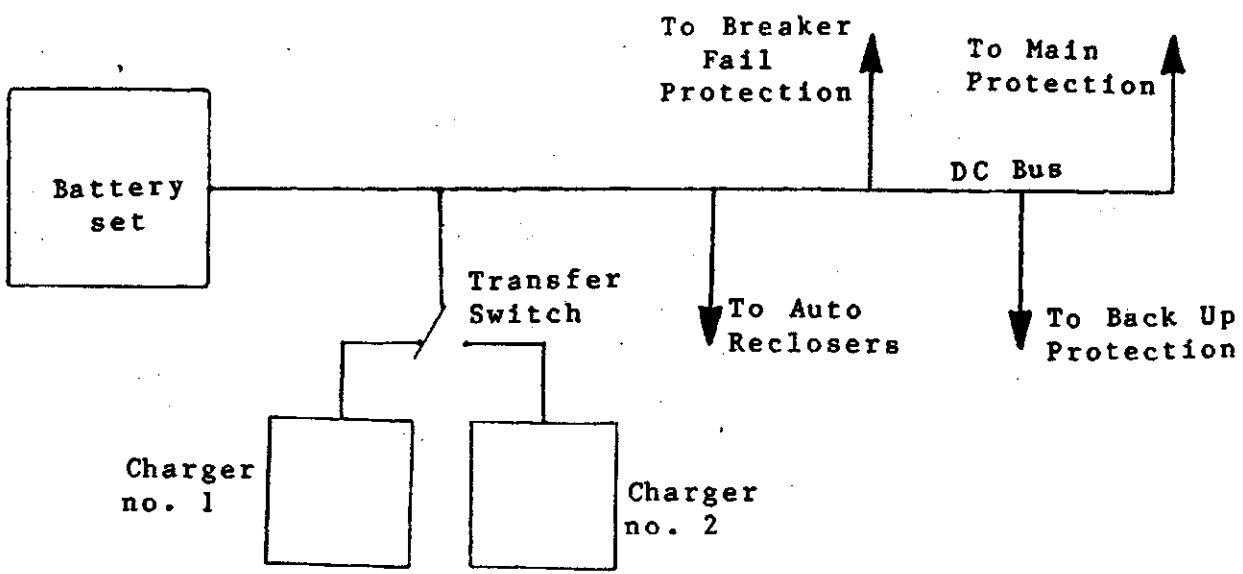


Figure 4.3 Single line diagram of dc supply at Regina South switching station of SPC

common relay scheme for their operation in the case of a fault on that line.

4.3.1 Regina South switching station

The single line diagram of the Regina South switching station (RSS) is given in Figure 4.4. RSS supplies power to the city of

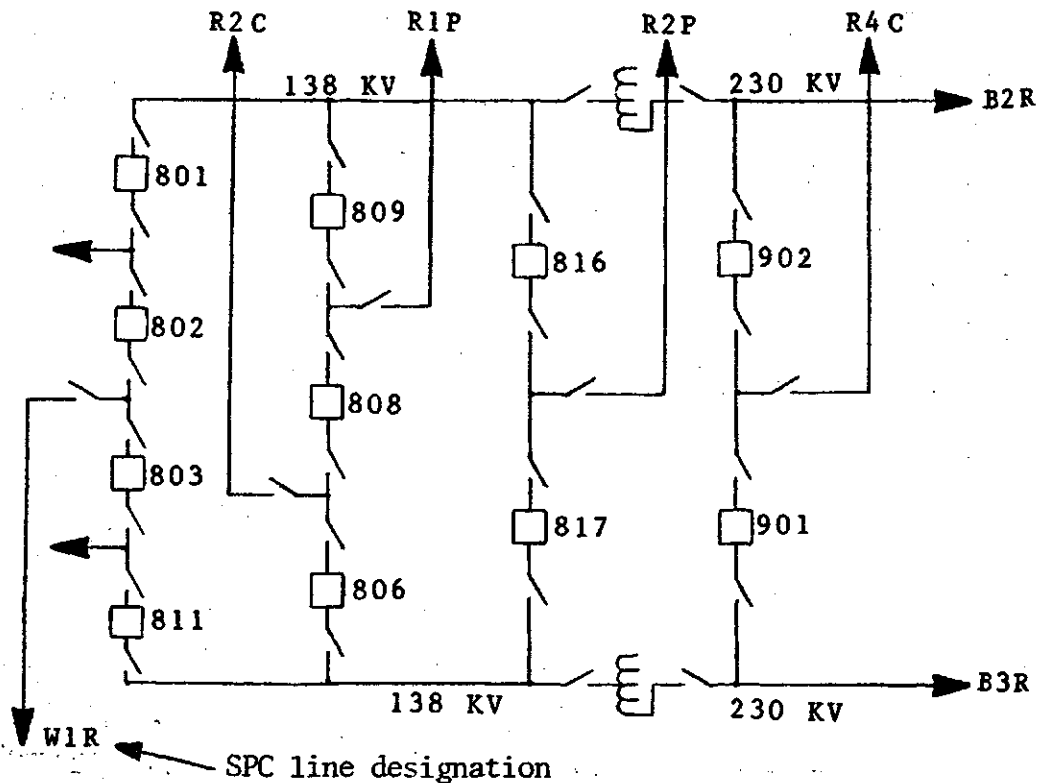


Figure 4.4 Single line diagram of Regina South switching station of SPC

Regina and the adjacent area and is a vital transmission junction between the Boundary Dam generating plant and the rest of the SPC network. About 40% of the power requirement of the SPC system is generated at Boundary Dam and fault free operation of RSS is essential to supply power to Regina and adjacent area with high reliability. Table 4.1 lists the line originated events which result in an outage of two or more than two transmission lines.

Table 4.1 Line originated multiple outages - Regina South

Case Description	Effect
AF on R4C or B3R & 901 stuck	R4C and B3R out
AF on R4C or B2R & 902 stuck	R4C and B2R out
AF on R4C & relay scheme of 901 and 902 fails	R4C, B2R, B3R, R2P, R1P & R2C out
AF on R2P or B2R & 816 stuck	R2P and B2R out
AF on R2P or B3R & 817 stuck	R2P and B3R out
AF on R2P & relay scheme of 816 and 817 fails	R4C, B2R, B3R, R2P, R1P & R2C out
AF on R1P or R2C & 808 stuck	R1P and R2C out
AF on R1P or B2R & 809 stuck	R1P and B2R out
AF on R1P & relay scheme of 808 and 809 fails	R1P, R2C and B2R out
AF on R2C or B3R & 806 stuck	R2C and B3R out
AF on R2C & relay scheme of 806 and 808 fails	R1P, R2C and B3R out

Failure of the dc supply is not considered in Table 4.1. Failure of the dc supply could remove all the protection system at RSS. In such a situation, an active failure (AF) on any line connected to RSS or AF on any of the breakers at RSS, which

require the protection system at RSS to operate to isolate the faulty condition, could isolate RSS from the rest of the SPC network by the operation of back up protection at the switching stations connected to RSS.

Table 4.1 shows a large number of line originated events which cause an outage of two or more than two lines of the system. The probability associated with these events may be small but their total effect on bus and system reliability can be significant. The duration of these multi-outages will be equal to the switching time required to isolate the faulted line and protection system components and to put the healthy lines back into service. These durations will be dependent upon the operating practices of the individual stations and whether the switching is completed manually or automatically.

#### 4.3.2 Squaw Rapids station

The single line diagram of the Squaw Rapids station is given in Figure 4.5. This station has a ring bus configuration and feeds the SPC system through two transmission lines S1B and S2B. There are six 33.5 MW generating units and two 39.0 MW generating units at the station. Two generating units are connected to one step up transformer which is connected to the ring bus. Table 4.2 lists the line originated events which result in an outage of two or more than two transmission lines, and/or generating units. All the events listed in Table 2 [23] and Table 4.2 are protection system related. An examination of these tables shows that there are a large number of single and double contingency events which

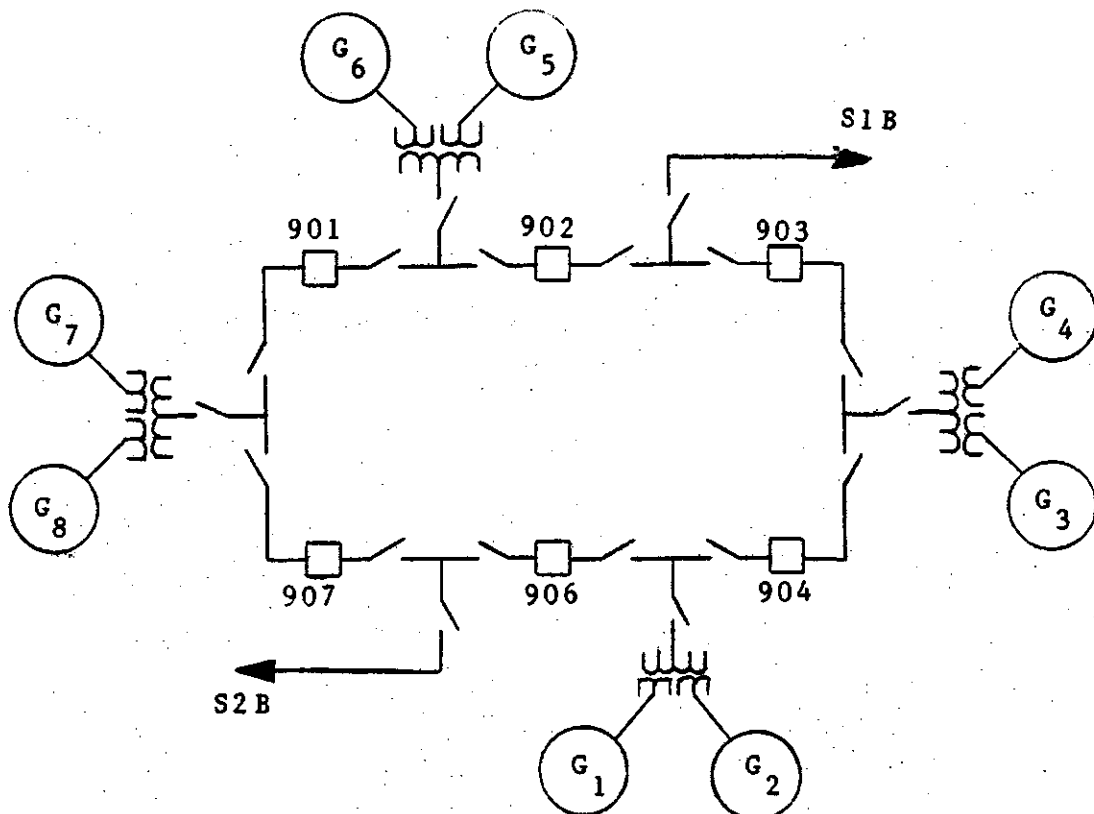


Figure 4.5 Single line diagram of the Squaw Rapids station.

cause outage of more than two current carrying components and could have a significant effect on load point and system reliability indices.

Table 4.2 Line originated multiple outages - Squaw Rapids

Case Description	Effect
AF on S1B & 902 stuck	S1B, G5 and G6 out
AF on S1B & 903 stuck	S1B, G3 and G4 out
AF on S1B & relay scheme of 902 and 903 fails	S1B, G3, G4, G5 and G6 out
AF on S2B & 906 stuck	S2B, G1 and G2 out
AF on S2B & 907 stuck	S2B, G7 and G8 out
AF on S2B & relay scheme of 906 and 907 fails	S2B, G1, G2, G7 and G8 out

Failure of the dc battery set at Squaw Rapids could have similar effects as in the case of RSS.



Multiple outages due to protection system components are described and illustrated in this section with reference to two terminal station configurations in a practical system. The numerical evaluation of each of these events can be accomplished using the equations described in Chapter 3. These equations cannot be used as such in the reliability evaluation of a composite system. A suitable model is needed to take into consideration the outages due to protection system components in the evaluation of the load point and system reliability indices of a composite system. A series of models were proposed in Reference 23 to include independent, common-cause and station originated outages for two current carrying components. In Reference 23, different reduced models were suggested to combine the event data resulting from the failure modes and effect analysis detailed in Tables 1 and 2 [23]. Model 3[23] is modified in the next section to include line originated events and those events which cause the isolation of the switching station. It is important to realize that the development of a single model suitable for all practical situations is not possible and models in Reference 23 and in this chapter can be modified or new models can be created to suit the given data.

#### 4.4 Models for Protection System Related Outages

In the previous section, the origin and possible cases of protection system related contingencies resulting in multiple outages have been described with reference to the Regina South switching station and the Squaw Rapids station. The inclusion of

these outages in the reliability evaluation of a composite generation and transmission system requires the development of one or more suitable models. As noted earlier, selected possible models were presented and analyzed in Reference 23. In this section, one possible model is described for studying the effects of protection system related outages but a more general approach, to include protection system failure modes in composite system reliability analysis, will be described in the next chapter.

Model 3[23] in Figure 4.6 is modified as in Figure 4.7. This model can be used to include the outages affecting two lines on the same right-of-way and sharing a common breaker at the terminating station. It can be extended to more than two current carrying components. In this model, two additional states are created. State 7 represents the situation when both lines are down due to the failure of the common breaker to isolate the faulty line and state 8 represents the event when the switching station is isolated from the rest of the healthy network. This model has been used in this chapter for system studies to show the impact of protection system related outages upon the down state of two lines and of switching station isolation. Other models can be created to suit the data and needs of a particular situation.

The model shown in Figure 4.7 has been solved for the steady state probability  $P_i$  of each state by applying the frequency balance approach. States 2 and 3 are merged as the assumption has been made that lines 1 and 2 have identical failure and repair rates. The state equations are listed on the next page.

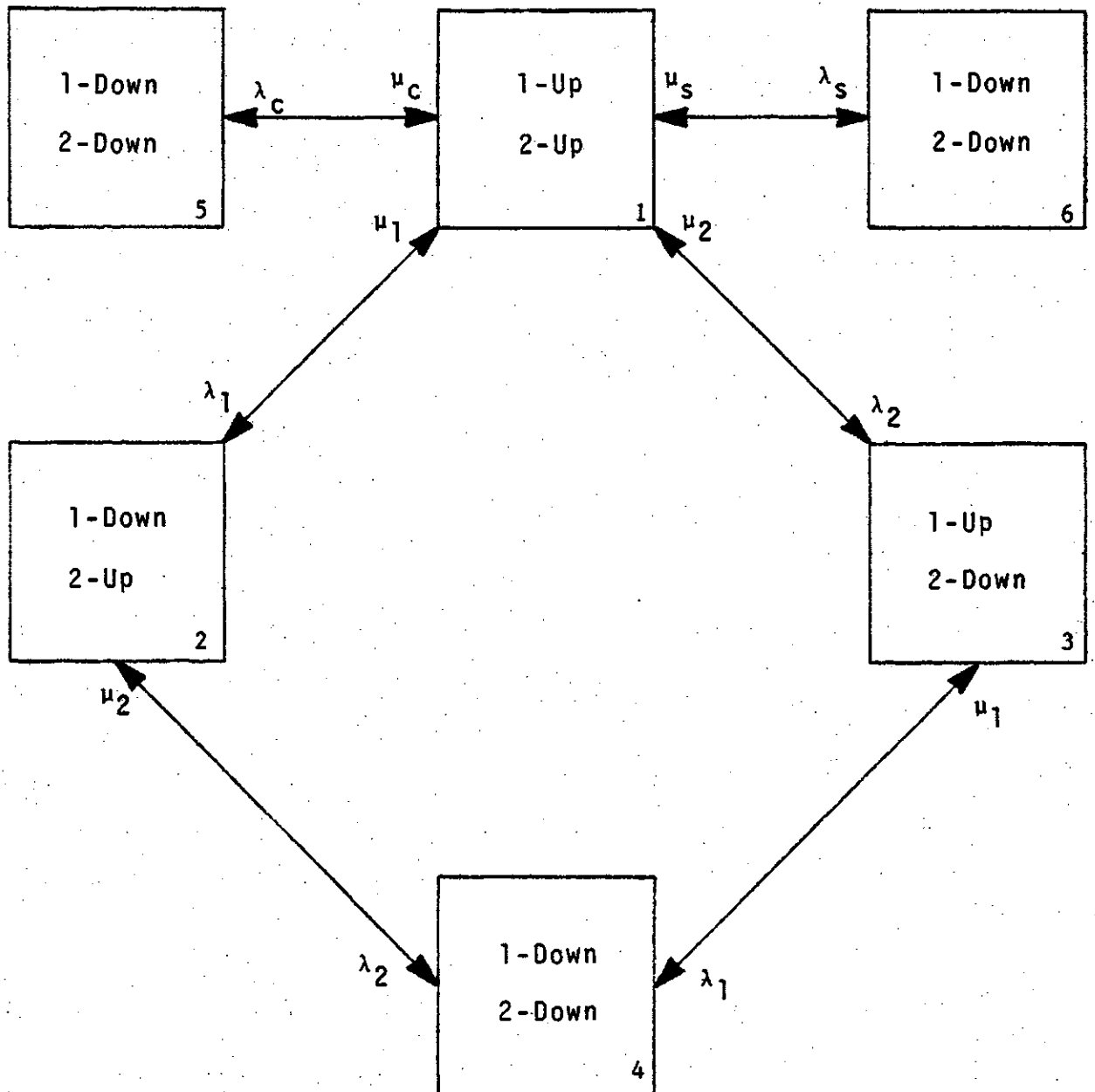


Figure 4.6 Model 3 of Reference 23

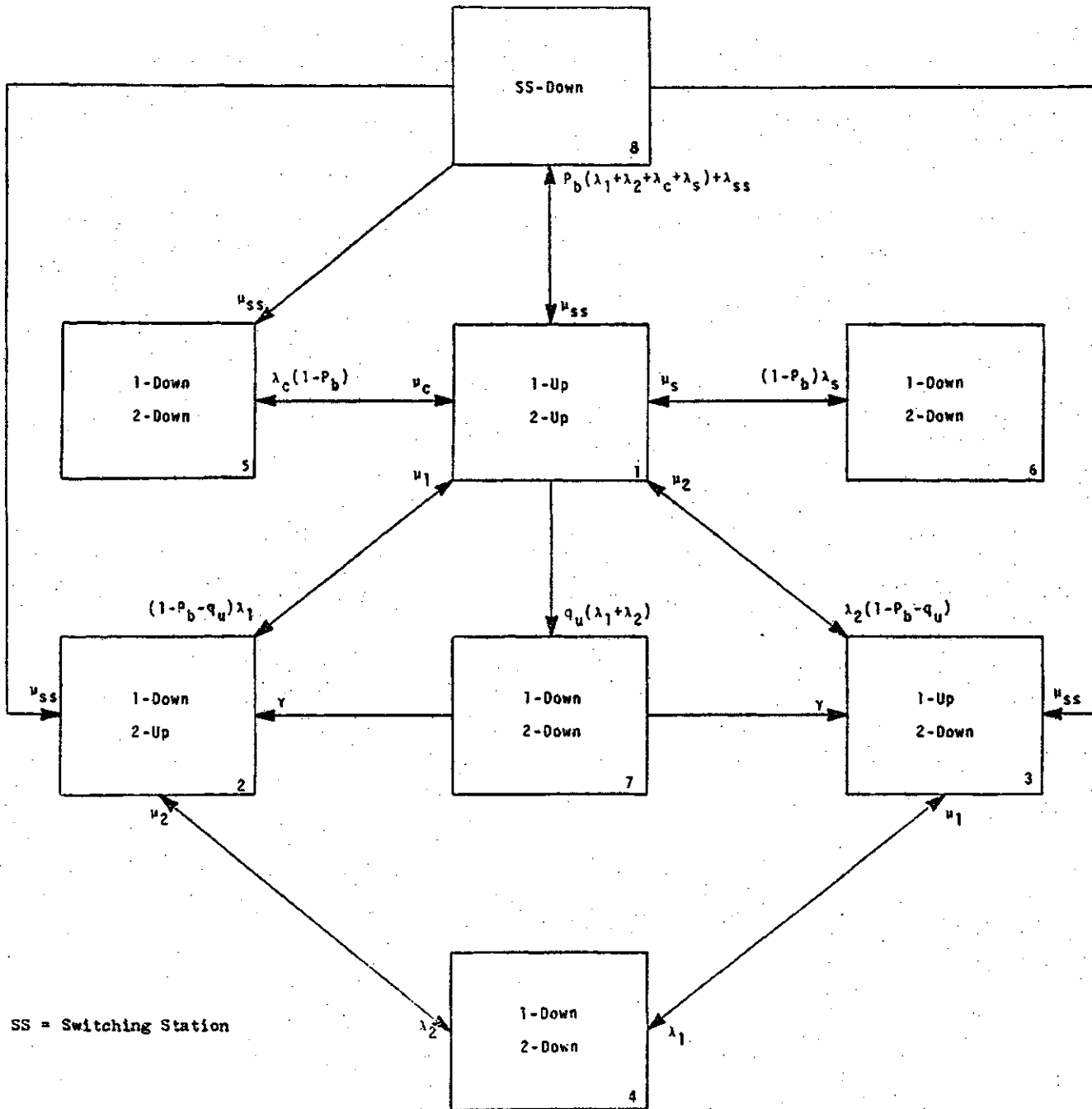


Figure 4.7 Model for two lines on the same right-of-way and sharing a common breaker

$$\text{State 1} \quad (2\lambda + \lambda_c + \lambda_s + \lambda_{ss})P_1 - \mu P_2 - \mu_s P_6 - \mu_c P_5 - \mu_{ss} P_8 = 0 \quad (4.1)$$

$$\text{State 2} \quad 2\lambda(1 - q_u - p_b)P_1 - (\lambda + \mu)P_2 + 2\mu P_4 + \gamma P_7 + \mu_{ss} P_8 = 0 \quad (4.2)$$

$$\text{State 4} \quad \lambda P_2 - 2\mu P_4 = 0 \quad (4.3)$$

$$\text{State 5} \quad \lambda_c(1 - p_b)P_1 - \mu_c P_5 + \mu_{ss} P_8 = 0 \quad (4.4)$$

$$\text{State 6} \quad \lambda_s(1 - p_b)P_1 - \mu_s P_6 = 0 \quad (4.5)$$

$$\text{State 7} \quad 2q_u \lambda P_1 - \gamma P_7 = 0 \quad (4.6)$$

$$\text{State 8} \quad (P_b(2\lambda + \lambda_c + \lambda_s) + \lambda_{ss})P_1 - 3\mu_{ss} P_8 = 0 \quad (4.7)$$

In addition to equations 4.1 to 4.7

$$P_1 + P_2 + P_4 + P_5 + P_6 + P_7 + P_8 = 1 \quad (4.8)$$

$$\text{From (4.5)} \quad P_6 = \frac{\lambda_s(1 - p_b)}{\mu_s} P_1 \quad (4.9)$$

$$\text{From (4.6)} \quad P_7 = \frac{2q_u \lambda}{\gamma} P_1 \quad (4.10)$$

$$\text{From (4.7)} \quad P_8 = \frac{P_b(2\lambda + \lambda_c + \lambda_s) + \lambda_{ss}}{3\mu_{ss}} P_1 \quad (4.11)$$

From (4.4) and (4.11)

$$P_5 = \frac{3\lambda_c + \lambda_{ss} + P_b(2\lambda - 2\lambda_c + \lambda_s)}{3\mu_c} P_1 \quad (4.12)$$

From (4.2), (4.3), (4.10) and (4.11)

$$P_2 = \frac{6\lambda + P_b(\lambda_c + \lambda_s + 4\lambda) + \lambda_{ss}}{3\mu} P_1 \quad (4.13)$$

$$P_4 = \frac{6\lambda^2 + \lambda P_b(\lambda_c + \lambda_s - 4\lambda) + \lambda_{ss} \lambda}{6\mu^2} P_1 \quad (4.14)$$

The following expressions are obtained for state probabilities from the equations 4.8 to 4.14

$$P_1 = \frac{1}{D} \quad (4.15)$$

$$P_2 = \frac{A_{12}}{D} \quad (4.16)$$

$$P_4 = \frac{A_{14}}{D} \quad (4.17)$$

$$P_5 = \frac{A_{15}}{D} \quad (4.18)$$

$$P_6 = \frac{A_{16}}{D} \quad (4.19)$$

$$P_7 = \frac{A_{17}}{D} \quad (4.20)$$

$$P_8 = \frac{A_{18}}{D} \quad (4.21)$$

where

$$D = 1 + A_{12} + A_{14} + A_{15} + A_{16} + A_{17} + A_{18} \quad (4.21)$$

$$A_{12} = \frac{6\lambda + P_b(\lambda_c + \lambda_s - 4\lambda) + \lambda_{ss}}{3\mu} \quad (4.22)$$

$$A_{14} = \frac{6\lambda^2 + \lambda P_b(\lambda_c + \lambda_s - 4\lambda) + \lambda\lambda_{ss}}{6\mu^2} \quad (4.23)$$

$$A_{15} = \frac{3\lambda_c + \lambda_{ss} + P_b(2\lambda - 2\lambda_c + \lambda_s)}{3\mu_c} \quad (4.24)$$

$$A_{16} = \frac{\lambda_s(1 - P_b)}{\mu_s} \quad (4.25)$$

$$A_{17} = \frac{2q_u \lambda}{\gamma} \quad (4.26)$$

$$A_{18} = \frac{P_b(2\lambda + \lambda_c + \lambda_s) + \lambda_{ss}}{3\mu_{ss}} \quad (4.27)$$

$$\begin{aligned} \text{Probability of both lines down} &= P_4 + P_5 + P_6 + P_7 \\ &= \frac{1}{D} \cdot (A_{14} + A_{15} + A_{16} + A_{17}) \end{aligned} \quad (4.28)$$

$$\text{Probability of switching station down} = P_8 = \frac{A_{18}}{D} \quad (4.29)$$

The probability of both lines or the switching station being out of service is a complex function of all the rates in the state space diagram. The probabilities of both lines or the station being out of service calculated for the model of Figure 4.7 are listed in Table 4.3. The probabilities have been calculated by varying the station outage rate ( $\lambda_{ss}$ ), stuck probability of the common breaker ( $q_u$ ) and probability of battery failure ( $P_b$ ). This table indicates that there is a significant increase in the probabilities with the increase in the considered parameters. The following data have been used to calculate the probabilities.

Failure rate ( $\lambda$ ) = 2.57 f/yr, Repair time = 8.0 hours  
 Switching time = 1.5 hours, Common mode repair time = 12.0 hours  
 Switching time to put isolated station into service = 2.5 hours

Table 4.3 Variation of two lines down and station down state probabilities with the station outage rate ( $\lambda_{ss}$ ), stuck probability of the common breaker ( $q_u$ ) and probability of battery failure ( $P_b$ )

$\lambda_c/\lambda$	$\lambda_s/\lambda$	$\lambda_{ss}$	$q_u$	$P_b$	Probability of both lines down	Probability of station being down
0.00	0.00	0.00	0.00	0.00	0.00000548	0.00
0.0000	0.1000	0.0010	0.0100	0.0010	0.00005799	0.000000661
0.0000	0.1500	0.0010	0.0100	0.0010	0.00007987	0.00000062
0.0000	0.1000	0.0050	0.0100	0.0010	0.00005800	0.00000098
0.0000	0.1000	0.0010	0.0500	0.0010	0.00009303	0.00000061
0.0000	0.1000	0.0010	0.0750	0.0010	0.00011493	0.00000061
0.0000	0.1000	0.0010	0.0100	0.0500	0.00005568	0.00002565
0.0000	0.1000	0.0010	0.0100	0.1000	0.00005332	0.00005121
0.0000	0.1000	0.0010	0.1000	0.0010	0.00013682	0.00000061
0.0000	0.1000	0.0100	0.0100	0.0010	0.00005800	0.00000146
0.1500	0.1000	0.0010	0.0100	0.0010	0.00058583	0.00000064
0.1500	0.1000	0.0050	0.0100	0.0010	0.00058764	0.00000102
0.1500	0.1000	0.0075	0.0100	0.0010	0.00058878	0.00000126
0.1500	0.1000	0.0100	0.0100	0.0010	0.00058991	0.00000149
0.1500	0.1000	0.0200	0.0100	0.0010	0.00059445	0.00000244
0.1500	0.1000	0.0500	0.0100	0.0010	0.00060808	0.00000528
0.1500	0.1000	0.0750	0.0100	0.0010	0.00061943	0.00000764
0.1500	0.1000	0.0010	0.0200	0.0010	0.00059458	0.00000064
0.1500	0.1000	0.0010	0.0300	0.0010	0.00060333	0.00000064
0.1500	0.1000	0.0010	0.0400	0.0010	0.00061208	0.00000064
0.1500	0.1000	0.0010	0.0500	0.0010	0.00062083	0.00000064
0.1500	0.1000	0.0010	0.0600	0.0010	0.00062958	0.00000064
0.1500	0.1000	0.0010	0.0750	0.0010	0.00064270	0.00000064
0.1500	0.1000	0.0010	0.0900	0.0010	0.00065582	0.00000064
0.1500	0.1000	0.0010	0.1000	0.0010	0.00066457	0.00000064
0.1500	0.1000	0.0010	0.2000	0.0010	0.00075205	0.00000064
0.1500	0.1000	0.0010	0.5000	0.0010	0.00101439	0.00000064
0.1500	0.1000	0.0010	0.0100	0.0020	0.00058788	0.00000119
0.1500	0.1000	0.0010	0.0100	0.0040	0.00059199	0.00000228
0.1500	0.1000	0.0010	0.0100	0.0060	0.00059610	0.00000338
0.1500	0.1000	0.0010	0.0100	0.0080	0.00060021	0.00000447
0.1500	0.1000	0.0010	0.0100	0.0100	0.00060432	0.00000557
0.1500	0.1000	0.0010	0.0100	0.0200	0.00062486	0.00001104
0.1500	0.1000	0.0010	0.0100	0.0400	0.00066594	0.00002198
0.1500	0.1000	0.0010	0.0100	0.0600	0.00070703	0.00003293
0.1500	0.1000	0.0010	0.0100	0.0800	0.00074811	0.00004397
0.1500	0.1000	0.0010	0.0100	0.1000	0.00078920	0.00005482

$$\text{Expected loss of energy} = L \cdot U_{sw} = L \cdot (P_b \cdot \sum_{i=1}^n \lambda_i) \cdot r_{sw} \text{ MWH/yr} \quad (4.33)$$

$$\text{Expected loss in dollars} = X = L \cdot (P_b \cdot \sum_{i=1}^n \lambda_i) \cdot r_{sw} \cdot S \text{ dollars/yr} \quad (4.34)$$

If Y dollars is the cost to provide an extra dc battery set or any other alternate source of dc supply, the selection between different alternatives should be based on the comparison of X and Y. In this way, it is possible to evaluate different schemes and to make decisions not only on the basis of lowest cost but also on an evaluation of worth.

If after conducting a reliability cost-reliability worth analysis, it is decided that an extra battery set is needed, the probability of loss of both battery sets at the same time will be  $P_b^2$ . This assumes independent failures of the dc supply. Care should be taken to insure that the probability of a common mode failure is virtually negligible. The probability of failure of one battery set is relatively low, and therefore the chance associated with both battery sets failing at the same time will be very small and therefore the expected loss of energy will be negligible.

In this chapter, the cause and effect of protection system related outages have been described and illustrated using the configurations of two practical switching stations. A possible model is examined for considering these outages in the reliability evaluation of composite generation and transmission systems and a more general approach will be discussed in the next chapter. The selection of the right model in any particular case is dependent



entirely on the data for the situation. A simple method to compare the different protection system configurations suitable for a particular situation is also described.

The studies presented in this chapter do not provide any general conclusions. They do, however, illustrate the importance of recognizing the effect of protection system failures, and suggest a need to include protection system related outages in the reliability evaluation of composite generation and transmission systems. The effect of protection system related outages is, therefore, examined in the next chapter using 5-bus test system.

## 5 COMPOSITE GENERATION AND TRANSMISSION SYSTEM RELIABILITY EVALUATION INCLUDING PROTECTION SYSTEM FAILURE MODES

### 5.1 General

A primary question arising in the reliability analysis of a composite generation and transmission system is the contingency level which must be considered for an adequate assessment of load point reliability. Selection of an appropriate contingency level will be dictated by the probabilities of element outage situations, the severity associated with specific outages and the criteria used for system success or failure. The approaches used at present are based on fixed criteria such as single and/or double contingencies and variable criteria such as those contingencies which have a reasonable probability of occurrence or be of a certain system severity. In general, the selection of a contingency level based on system element outage statistics appears to be an acceptable approach.

Composite system reliability evaluation techniques at the present time use a representation of the system in which lines simply terminate at a bus without extensive representation of the bus switching and breaker configuration. As discussed in Chapter 4, these techniques consider independent overlapping outages, and common-cause outages. The outages relating to terminal station components are normally included by increasing the failure rate of the transmission lines by some fixed amount. This is a valid addition for those terminal related failures which impact only on

the transmission element concerned. Such a treatment, however, does not recognize the multiple outage events described in Chapter 4 and does not simulate such a situation.

Data collected by Commonwealth Edison Company [41] on their system performance have demonstrated that almost 40% of their outages were terminal related. The studies in Chapter 4 and Reference 23 have shown a large number of possible single and double contingencies relating to protection systems which cause outage of two or more than two lines and/or generators. The effect of such outages can be significant on the reliability indices of a composite system. This situation is examined in this chapter using the 5-bus Test System shown in Figure 5.1. The terminating points at each bus are represented as in a practical system with bus switching and circuit breaker configurations.

The selection of a particular protection system related outage model is entirely dependent upon the configuration and data of the system under consideration. The computer model selected must behave in the same way as the actual system or the results will not be appropriate. Models described in Reference 23 and Chapter 4 require the combination of the event data resulting from the failure mode and effect analysis into reduced models. This involves extensive manipulation and data collection which is not available at this time. The models used in this chapter are based upon the approach described in Reference 42 and are discussed in the next section. The digital computer program described in Reference 43 has been modified to accept an additional level of element outage data relating to protection system components.

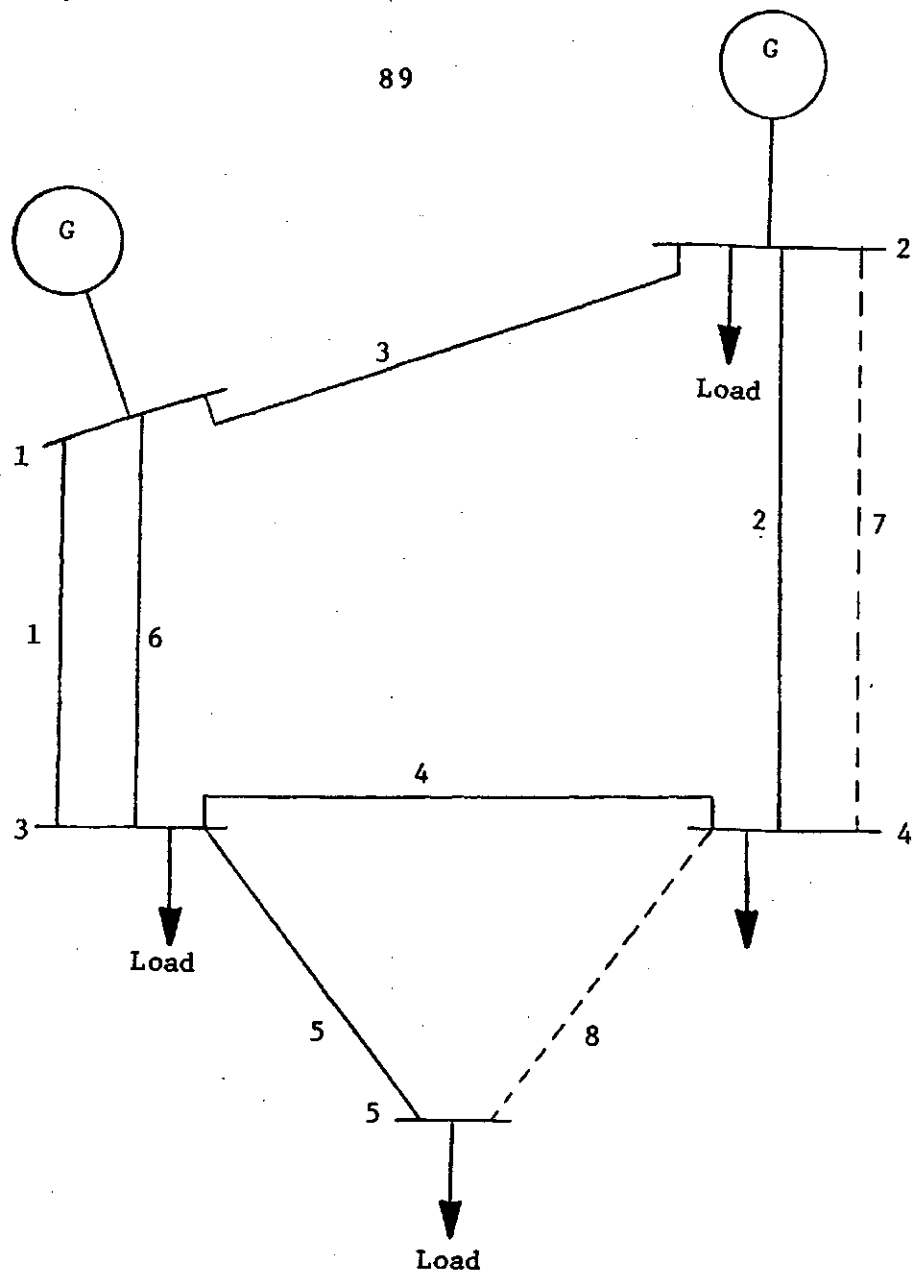


Figure 5.1 Single line diagram of the 5-bus test system

The failure mode and effect analysis technique is used to include the effect of stuck probabilities and ground faults in the protection system. Battery failures are not considered but can be easily included if the relevant data is available.

Reliability assessment in distribution systems is concerned with system performance at the customer end i.e. at the load points. In this chapter, the reliability indices at the customer load point are also evaluated by representing the distribution

network from the switching station to the customer load point and considering the load point reliability indices calculated for the composite generation and transmission system as the indices of the power supply at the supply point of the primary main feeder. The relative contribution of the indices at the load points due to the main component segments can therefore be seen.

## 5.2 Power System Component Models

The failure modes of current carrying components and protection system components have been discussed in the previous chapters. A general approach for modelling a power system for reliability studies including protection system failure modes was described in a recent paper [42]. The concept used is quite general and can be modified according to the study desired and data available. Some assumptions have to be made, however, in each case.

### Notation

- $\lambda$  failure rate of the component
- $P_i$  probability of breaker  $i$  failing to open in response to a fault in its primary protection zone. The cause may be a stuck breaker or a failure of its relay scheme to detect a fault.
- $\gamma$  switching rate. This is assumed to be the same in all cases where a switching procedure is required.
- $\mu$  repair rate of the component when the protection system performs its function.
- $\mu_i$  repair rate from the after switching state when breaker  $i$  fails to trip.
- $P_i$  probability of state  $i$
- $A_i$  current carrying component  $i$
- $B_i$  circuit breaker  $i$

Figure 5.2 is the single line diagram of a section of a power system. In Figure 5.2,  $A_1$  is the current carrying component (transmission line) and  $B_1$  and  $B_2$  represent its primary protection at its both ends. I and II are the terminal stations of  $A_1$  where other components are connected with proper bus switching and circuit breaker arrangement.

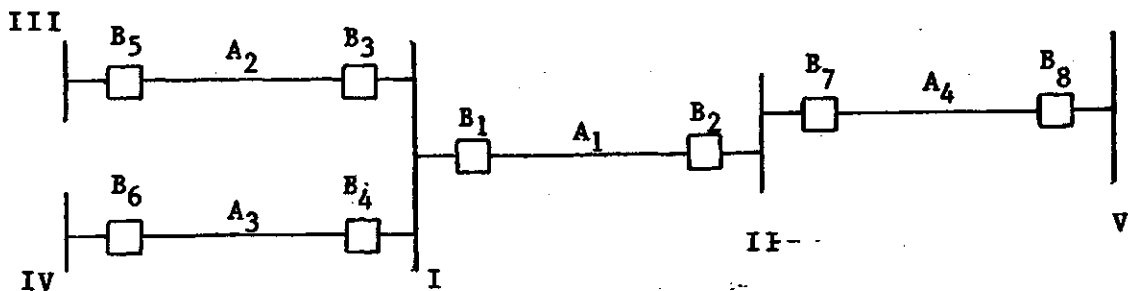


Figure 5.2 Single line diagram of a section of a power system

If  $B_1$  and  $B_2$  are 100% reliable,  $A_1$  can be represented by a Markov Model as in Figure 5.3 i.e.  $A_1$  up (in service) or  $A_1$  down (out for corrective maintenance). If  $B_1$  and  $B_2$  are not 100% reliable,  $A_1$  cannot be represented as in Figure 5.3.

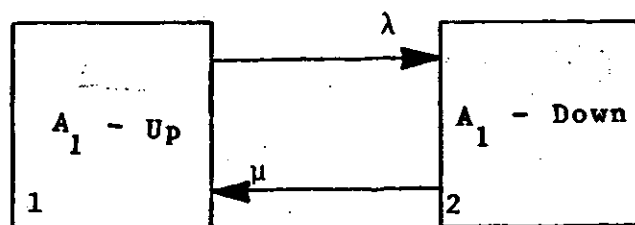


Figure 5.3 Markov Model of component  $A_1$

$B_1$  and  $B_2$  can fail in a number of possible ways as discussed earlier i.e. (i) they can fail to ground (ii) they can fail to trip (iii) they can false trip. A modelling approach was discussed in Reference 42 in order to include the failure modes of  $A_1$ ,  $B_1$  and  $B_2$ . As the detailed data required in the models in Reference 42

are not available at this time, therefore, some assumptions must be made. The modified models can then be used in a composite generation and transmission system reliability evaluation for the power system of Figure 5.1.

#### Assumptions Made

(a) All breakers and relays in the protection zone of a component are identical.

(b) Failure to trip of two and more breakers of the protection zone at the same time is negligible.

(c) No switching is required when a protection system works properly in the case of a fault in the primary protection zone (in case of lines and generators only).

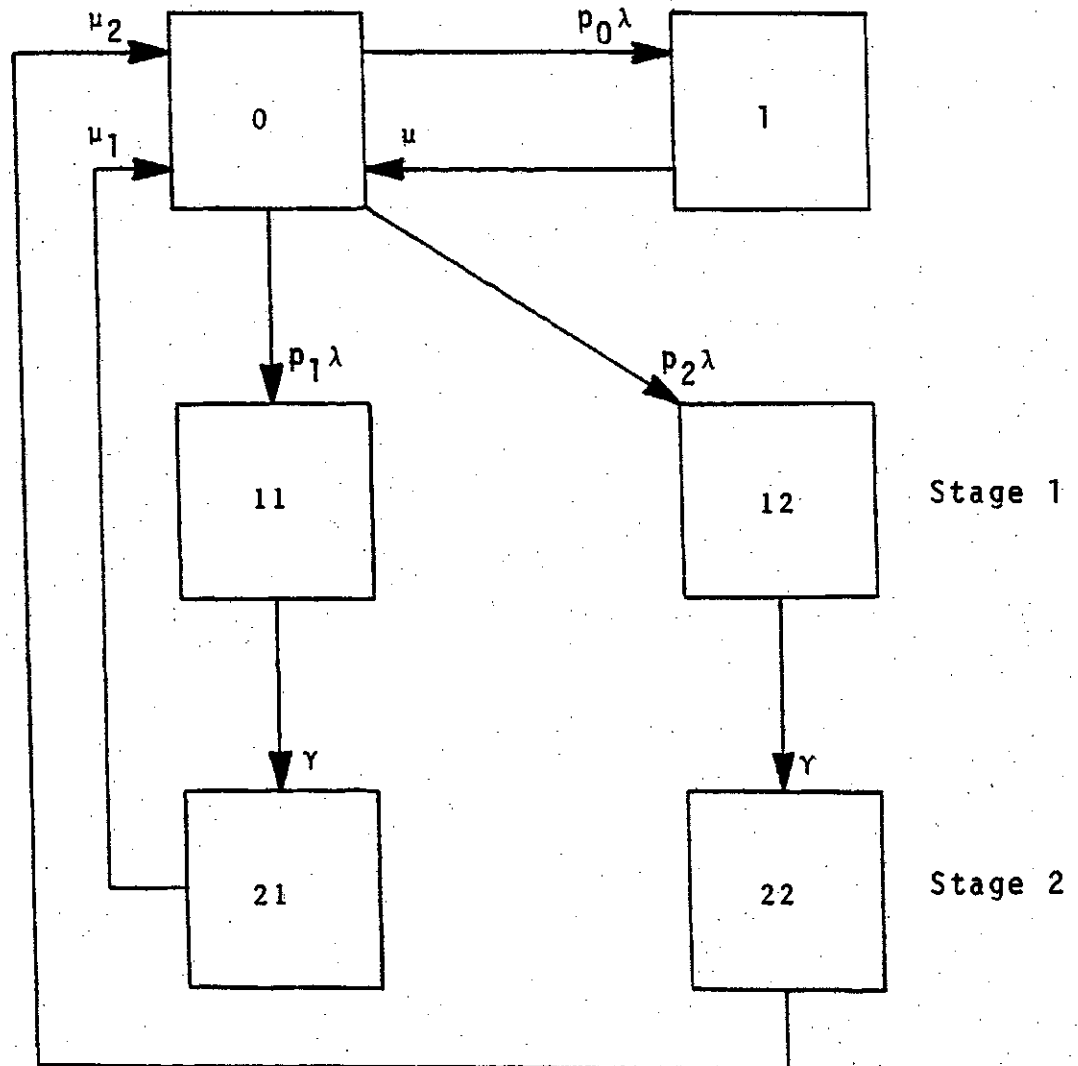
(d) DC supply at a switching station is 100% reliable.

(e) The protection zone of a component is assumed to extend to all the nearest breakers around the component.

By considering the above assumptions, models in Reference 42 can be simplified and used in practical applications.

#### 5.2.1 Multistate model of a current carrying component

Figure 5.4 shows a state transition diagram for a current carrying component  $A_1$  in Figure 5.2. In this diagram, the probability of successful operation of the protection system ( $B_1$  and  $B_2$ ) is taken into consideration. States 0 and 1 are similar to the two state component model of  $A_1$ . The remaining states are due to the failure of the breakers of the protection zone to trip in the case of a fault on  $A_1$ . These states are categorized into two stages. Stage 1 represents the states of the system before switching (after the back up protection clears the fault). Stage 2 represents the states of the system in which



- States 0,1 Basic two state component model including the probability of successful operation of the primary protection zone breakers.
- State 11 Breaker  $B_1$  fails to open when  $A_1$  fails to ground. Components out of service are  $A_1$ ,  $A_2$  and  $A_3$ .
- State 12 Breaker  $B_2$  fails to open when  $A_1$  fails to ground. Components out of service are  $A_1$  and  $A_4$ .
- State 21  $A_1$  and  $B_1$  under repair after the switching operation during which  $A_2$  and  $A_3$  are restored to service.
- State 22  $A_1$  and  $B_2$  under repair after the switching operation during which  $A_4$  is restored to service.

Figure 5.4 Multi-state model of component  $A_1$



faulty components are under repair (after the healthy components are restored to service). States of stage 1, represent the components that are isolated if breaker  $i$  fails to trip i.e. for the system shown in Figure 5.2, if  $B_1$  fails to trip in the case of an active fault on  $A_1$ , the current carrying components which will be isolated are  $A_1$ ,  $A_2$  and  $A_3$ . The states of stages 1 and 2 are represented by two numbers, the first indicates the stage and the second the state number. State  $i$  in stage 1 or 2 indicate that breaker  $i$  failed to trip.

Using the frequency balance approach, the probability of each state is calculated as follows:

$$P_0 \cdot p_i \lambda = P_{1i} \cdot \gamma \quad (5.1)$$

$$P_0 \cdot p_0 \lambda = P_1 \cdot \mu \quad (5.2)$$

$$P_{1i} \cdot \gamma = P_{2i} \cdot \mu_i \quad (5.3)$$

$$P_{1i} = \frac{\lambda p_i}{\gamma} P_0 \quad (5.4)$$

$$P_{2i} = \frac{\lambda p_i}{\mu_i} P_0 \quad (5.5)$$

$$P_0 + P_1 + \sum_i^n (P_{1i} + P_{2i}) = 1 \quad (5.6)$$

$$P_0 = \frac{1}{G} \quad (5.7)$$

$$\text{where } G = 1 + \frac{p_0 \lambda}{\mu} + \lambda \cdot \sum_i^n \left( \frac{p_i}{\gamma} + \frac{p_i}{\mu_i} \right) \quad (5.8)$$

As it is assumed that all breakers and relays of a protection zone are identical, therefore, all  $p_i$  and  $\mu_i$  are equal.

$$P_0 = 1 - \sum_i^n p_i \quad (5.9)$$

$$G = 1 + n \lambda p_i \left( \frac{1}{\gamma} + \frac{1}{\mu_i} - \frac{1}{\mu} \right) + \frac{\lambda}{\mu} \quad (5.10)$$

where  $n$  is the number of breakers associated with the protection zone.

$$\text{If } \mu_i = \mu,$$

$$\begin{aligned} G &= 1 + \frac{\lambda}{\mu} + \frac{n\lambda p_1}{\gamma} \\ &= \frac{\mu\gamma + \gamma\lambda + np_1\lambda\mu}{\mu\gamma} \end{aligned} \quad (5.11)$$

$$P_0 = \frac{\mu\gamma}{\mu\gamma + \lambda\gamma + np_1\lambda\mu} \quad (5.12)$$

$$P_1 = \frac{p_0\lambda}{\mu} P_0 \quad (5.13)$$

As the repair time is assumed to be the same in all the failure cases, state 1 and all the states of stage 2 are the down states of the component where only the faulted component is out for corrective maintenance.

$$\begin{aligned} \text{Probability of down state} &= P_1 + \sum_i^n P_{2i} \\ &= \frac{p_0\lambda}{\mu} P_0 + \lambda P_0 \sum_i^n \left( \frac{p_i}{\mu_i} \right) \\ &= \frac{\lambda}{\mu} P_0 \end{aligned} \quad (5.14)$$

$$\text{Probability of state } i \text{ of stage } 1 = \frac{\lambda p_i}{\gamma} P_0 \quad (5.15)$$

Similarly models for other current carrying components can be derived and solved to obtain the state probabilities.

### 5.2.2 Multistate model of a circuit breaker

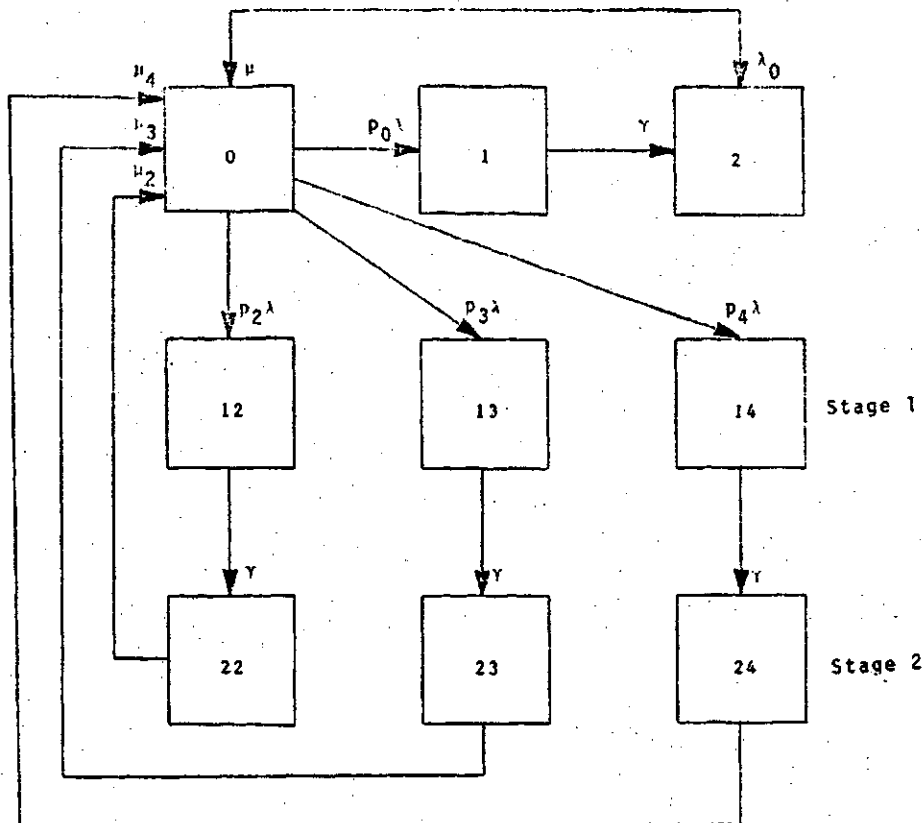
Figure 5.5 is the state transition diagram for the circuit breaker  $B_1$  (in Figure 5.2). In this diagram, the probability of successful operation of the breakers of the protection zone is considered together with a ground fault and a false tripping of  $B_1$ . States 0, 1 and 2 are the same as in the three state model of a breaker [36]. The remaining states are categorized into two stages. These states are due to the failure of the breakers of the protection zone to trip in the case of an active fault on  $B_1$ . Stage 1 represents the states of the system before switching operation when breaker 1 fails to trip in the case of a ground fault on  $B_1$  (after the back up protection clears the fault). Stage 2 represents the states of the system in which faulty breakers are under repair (after the healthy breakers are reclosed). Each state in Figure 5.5, represents the current carrying components that are isolated due to the failed breakers except state 0 which is the up state of the breaker  $B_1$ . The detailed description of the states is given in the diagram. In Figure 5.5, it is assumed that the time to repair a breaker is the same for all failure modes.

The state probabilities can be obtained by solving the model in Figure 5.5 using the frequency balance approach.

$$\text{Probability of the up state} = P_0 = \frac{\gamma\mu}{\mu\gamma + \lambda\mu + (\lambda + \lambda_0)\gamma} \quad (5.16)$$

$$P_2 = \frac{\gamma(\lambda_0 + p_0\lambda)}{\mu\gamma + \lambda\mu + (\lambda + \lambda_0)\gamma} \quad (5.17)$$

$$P_1 = \frac{p_0\lambda}{\gamma} P_0 \quad (5.18)$$



- States 0,1,2 Basic three state model of the circuit breaker.  
 0 - Normal state of the breaker  $B_1$ .  
 1 - Breaker  $B_1$  fails to ground and in this case the probability of the successful operation of all the breakers of the protection zone is taken into consideration.  
 Components down are  $A_1$ ,  $A_2$  and  $A_3$ .  
 2 - Breaker  $B_1$  under repair due to a ground fault (after switching) or due to a false tripping.  
 Component down is only  $A_1$ .
- State 12 Breaker  $B_2$  fails to trip when  $B_1$  fails to ground. Back up protection operates and isolates  $A_4$  in addition to  $A_1$ ,  $A_2$  and  $A_3$ .
- State 13 Breaker  $B_3$  fails to trip when  $B_1$  fails to ground. Components isolated in this case will be  $A_1$ ,  $A_2$ ,  $A_3$  and possibly others depending upon the system configuration.
- State 14 Breaker  $B_4$  fails to trip when  $B_1$  fails to ground. Other components may be isolated in addition to  $A_1$ ,  $A_2$  and  $A_3$ .
- State 22 Breakers  $B_1$  and  $B_2$  are under repair. Component down is only  $A_1$ .
- State 23 Breakers  $B_1$  and  $B_3$  are under repair. Components down are  $A_1$  and  $A_2$ .
- State 24 Breakers  $B_1$  and  $B_4$  are under repair. Components down are  $A_1$  and  $A_3$ .

Figure 5.5 Multistate model of breaker  $B_1$

$$\text{Probability of state 1 of stage 1} = \frac{p_1 \lambda \mu}{\mu \gamma + \lambda \mu + (\lambda + \lambda_0) \gamma} \quad (5.19)$$

$$\text{Probability of state 1 of stage 2} = \frac{p_1 \lambda \gamma}{\mu \lambda + \mu \gamma + (\lambda + \lambda_0) \gamma} \quad (5.20)$$

$$\text{where } p_0 = 1 - \sum_i^n p_i \quad (5.21)$$

$n$  = number of breakers of the protection zone

$\lambda_0$  = false tripping rate of a breaker

Similar models for other circuit breakers can be solved to obtain the required state probabilities.

### 5.3 System Model

The individual current carrying component models and circuit breaker models can be combined to obtain a system model. A practical system has a large number of components, therefore, to solve the complete Markov model for the state probabilities will be computationally expensive. This problem can be solved by assuming independent component failures. The probability of any system state can then be derived from the appropriate component state probabilities by simple multiplication. There will be, however, some approximations and impossible states which actually cannot occur as discussed in Reference 42. The results obtained by solving the Markov model and assuming component independence were compared for a specific case. The results were found to be very close.

The results are compared in this chapter for the system shown in Figure 5.6. There are three lines and two circuit breakers in this configuration. The power flow is in the directions shown.

Figure 5.7 is the state space transition diagram for the system shown in Figure 5.6.

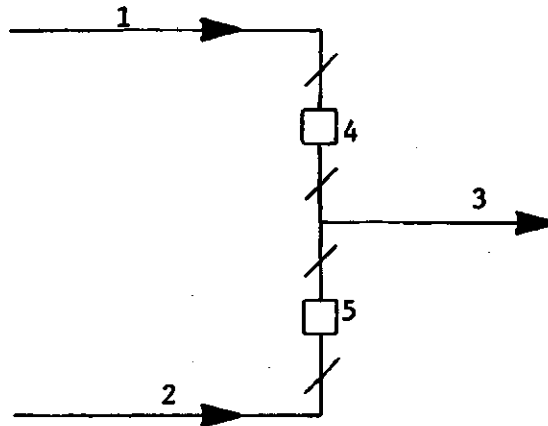


Figure 5.6 Example system illustrating effect of independence assumption

In Figure 5.7, a bar under a component number indicates a before switching state and a bar above a component number indicates an after switching state of the component. State probabilities obtained from the transition diagram compared with those obtained assuming component independence have been found to be very close. One set of these results is shown in Table 5.1 and indicates a close agreement.

In Figure 5.7, only the line faults and ground faults on breakers are considered. False tripping and the probability of the protection system not operating when required are not considered, however, they can be easily included. The Markov model shown in Figure 5.7 considers only upto two contingencies. The following data were utilized to calculate the results shown in Table 5.1

$$\lambda_1 = \lambda_2 = \lambda_3 = 2.0 \text{ failures/year, } r_1 = r_2 = r_3 = 12 \text{ Hours}$$

$$\lambda_4 = \lambda_5 = 0.01 \text{ failures/year, } r_4 = r_5 = 20 \text{ Hours}$$

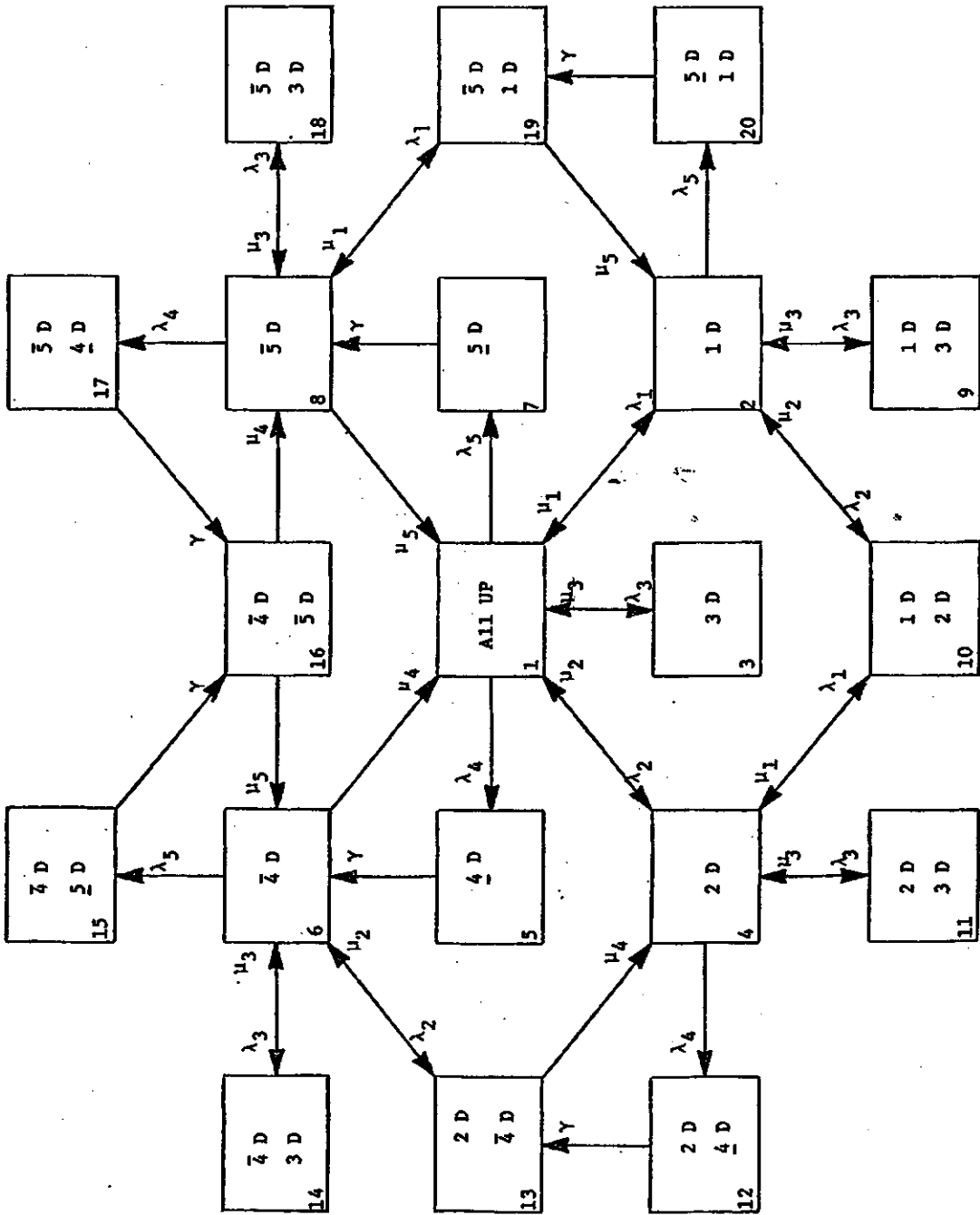


Figure 5.7 State transition diagram of the system shown in Figure 5.6

Switching time = 1.5 Hours

$$\mu_i = \frac{1}{r_i}, \quad \gamma = \frac{1}{\text{Switching time}}$$

Table 5.1 State probabilities of Figure 5.6

State No.	Markov Model	Independence Assumption
1	0.99177713D+00	0.99177686D+00
2	0.27171976D-02	0.27171968D-02
3	0.27171976D-02	0.27171968D-02
4	0.27171976D-02	0.27171968D-02
5	0.16982485D-05	0.16982481D-05
6	0.22643313D-04	0.22643307D-04
7	0.16982485D-05	0.16982481D-05
8	0.22643313D-04	0.22643307D-04
9	0.74443770D-05	0.74443743D-05
10	0.74443770D-05	0.74443743D-05
11	0.74443770D-05	0.74443743D-05
12	0.46527355D-08	0.46527343D-08
13	0.62036473D-07	0.62036453D-07
14	0.62036473D-07	0.62036453D-07
15	0.38772795D-10	0.38772786D-10
16	0.51697059D-09	0.51697045D-09
17	0.38772795D-10	0.38772786D-10
18	0.62036473D-07	0.62036453D-07
19	0.62036473D-07	0.62036453D-07
20	0.46527355D-08	0.46527343D-08

#### 5.4 System Study

Composite generation and transmission system reliability evaluation including protection system failure modes is illustrated in this section for the test system shown in Figure 5.1.

Figure 5.1 is the single line representation of the power system as used in a basic ac load flow analysis. The dotted lines indicate new additions to the system. In order to include the effects of the protection system failure modes, bus switching and circuit breaker configurations at each terminating station have been included. Single line diagrams of the switching stations are as shown in Figures 5.8 to 5.11 and are based on the configurations of a practical system.



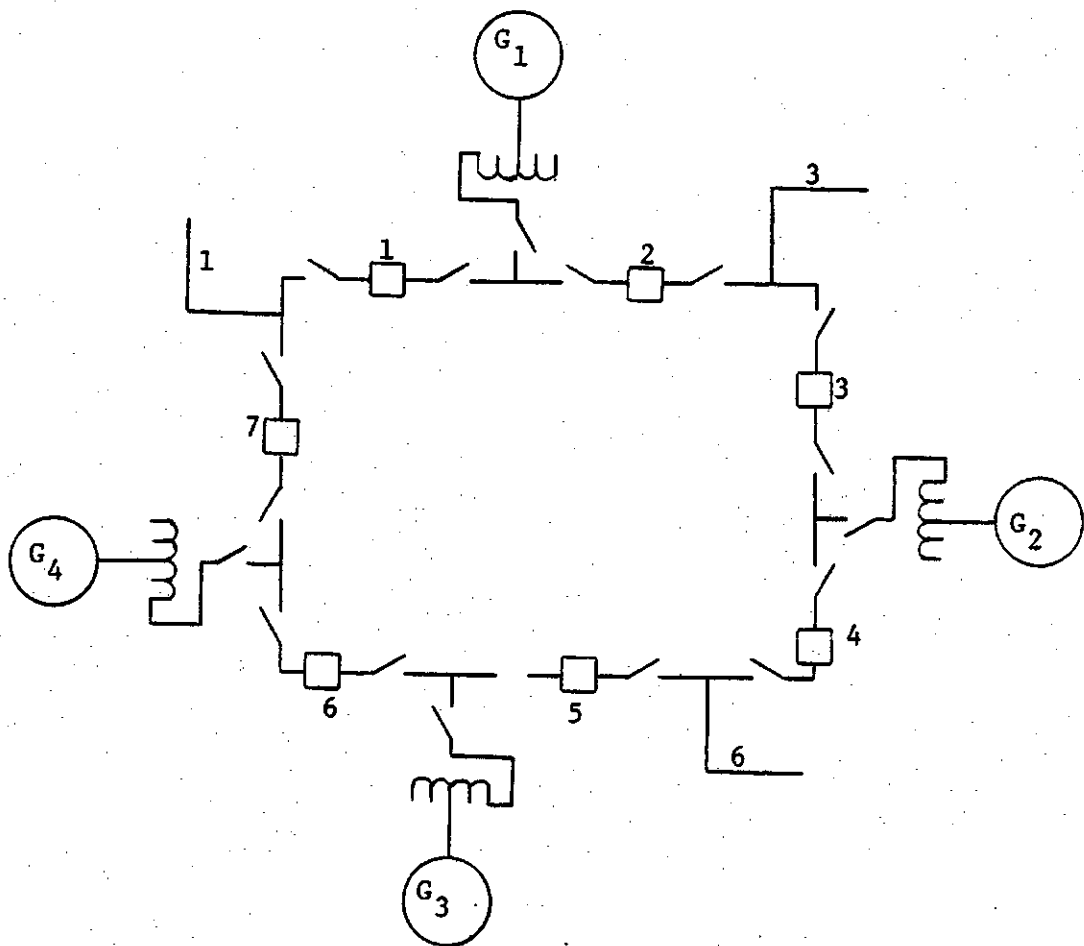


Figure 5.8 Configuration at Bus 1 of the test system shown in Figure 5.1



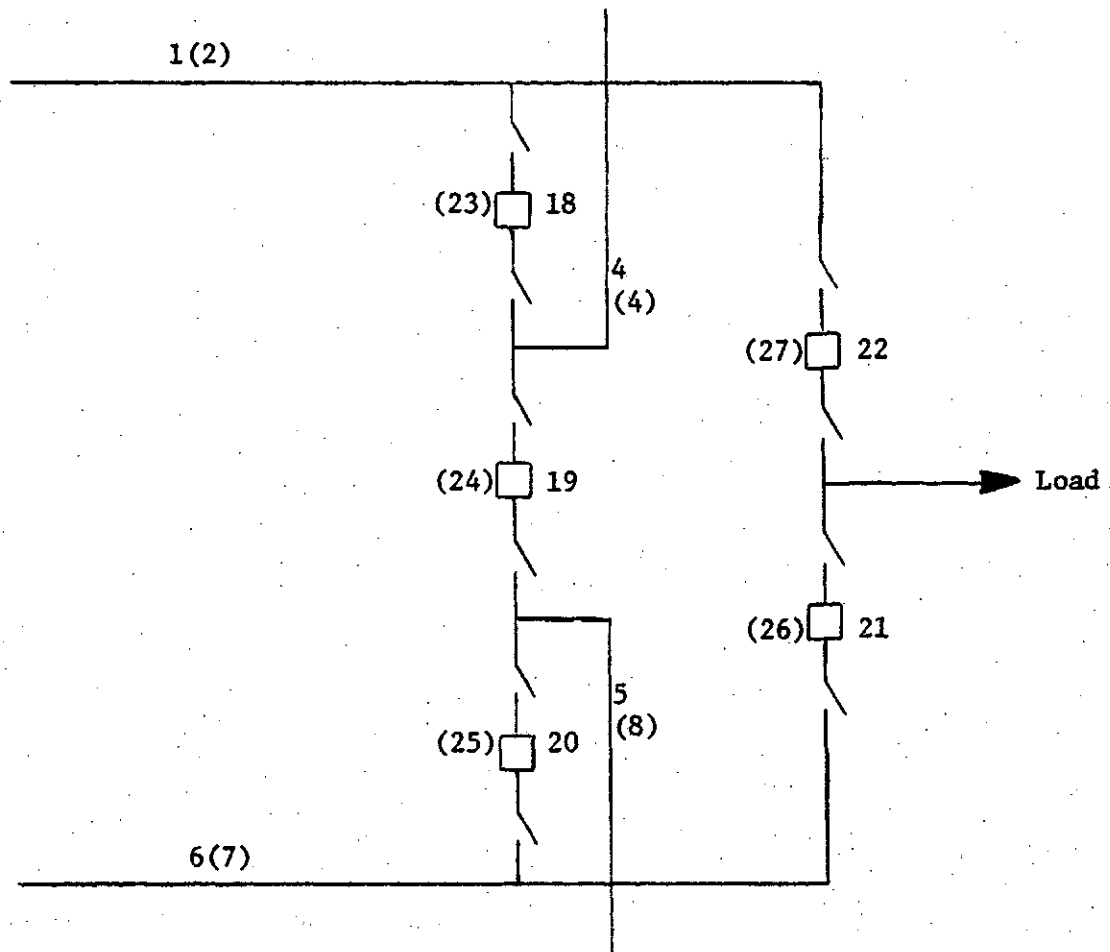


Figure 5.10 Configuration at Bus 3 (4) of the test system shown in Figure 5.1

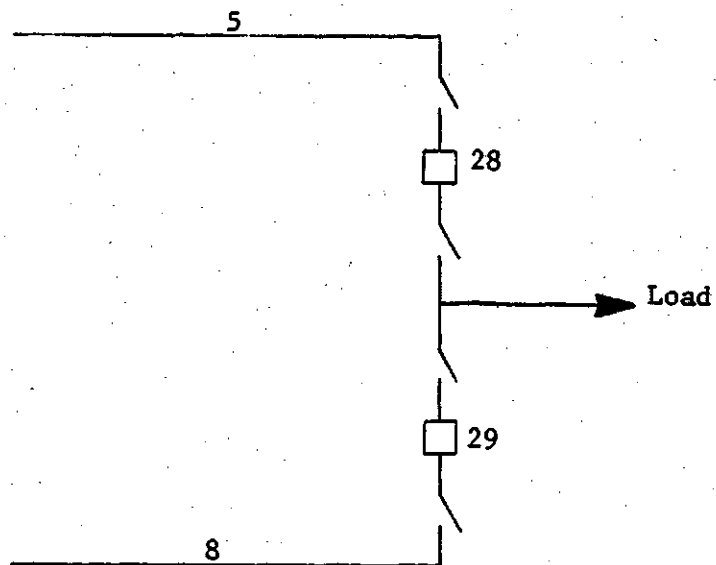


Figure 5.11 Configuration at Bus 5 of the test system shown in Figure 5.1

The line data, generator data, load data and outage data are available in Reference 17 and are also given in Appendix B together with the circuit breaker data.

The models described in the previous sections have been utilized in the digital computer program illustrated in References 43 and 44. In order to include the effects of the protection system, the computer program has been modified to accept an additional level of component outage data relating to the protection system. The failure mode and effect analysis technique has been utilized for each protection system related outage situation to determine which current carrying components were out of service in that particular system state. This has then been utilized as input data to the program.

A set of annualized bus and system indices is defined in Reference 19. This set of indices has been evaluated for the 6-line and 8-line systems shown in Figure 5.1 and are given in Tables 5.2 to 5.9. The reliability indices calculated with and without considering protection system failures are included in these tables for comparison purposes.

The annualized bus indices are listed in Tables 5.2 and 5.3. Table 5.2 shows the effect of protection system failures on the bus failure probabilities and frequencies. For the 6-line system, single independent outages do not have any effect at bus 2, however, there is a significant contribution to the indices when single outages of protection systems (ground faults) are included.

The contribution to the indices at bus 2 remains the same due to protection system failures even when double contingency situations are considered. This is because the major contribution in this case is from the load point breakers (15 and 16, Figure 5.9). The indices at buses 3, 4 and 5 are dominated by single outages, however, the indices do change significantly in all the cases when protection system failures are included in the analysis. The effect on the failure frequency is more noticeable in all the cases listed in Table 5.2.

For the 8-line system, the single independent outages of current carrying components do not have any impact on the system performance. When protection system related single or double contingency levels are included, the indices at all the buses increase. The contribution to the failure probabilities at buses 3, 4 and 5 due to protection system failures is more significant in this case and is 12%, 37% and 16% respectively. When a double contingency level is considered together with the failures of protection systems, the failure frequencies at buses 3, 4 and 5 are 1.33, 3 and 1.6 times the indices when protection system failures are not included.

An examination of Table 5.3 shows that the annualized number of load curtailments increase at all the buses due to protection system failures. The indices at buses 3 and 5 are dominated by single outages in the case of the 6-line system and those at buses

2 and 4 are dominated by protection system failures. For the 8-line system, the major contribution is due to the outages relating to protection systems. The annualized load curtailment, energy curtailed and duration of curtailment indices increase significantly at all buses for the 6-line system, however, for the 8-line system the indices at all buses are dominated by protection system failures. The annualized number of voltage violations increases moderately at all buses in the case of the 6-line system and there is a significant increase in the case of the 8-line system.

The maximum bus indices i.e. maximum load curtailed, maximum energy curtailed and maximum duration of load curtailment are listed in Tables 5.4, 5.5 and 5.6 respectively. In the case of the 6-line system, the maximum indices at buses 2 and 4 are dominated by the protection system failures. At buses 3 and 5, the major effect is due to single outages and independent overlapping outages, however, the maximum load curtailed at bus 3 due to single outage situations changes with protection system failures. For the 8-line system, the maximum load curtailed and energy curtailed change significantly in the case of buses 2 and 3 with the consideration of protection system failures. The same indices at buses 4 and 5 change in the single outage situation. The maximum duration of load curtailment changes for single contingency cases for the 8-line system and the contribution is due to the load point breakers.

The annualized bus averages obtained with and without protection system failures are compared in Table 5.7. The duration of the multiple outage relating to protection system failures is of the order of one and one half hours, therefore, the average energy not supplied and duration of curtailment increases in some cases and decreases in others with the inclusion of protection system failures. The average load curtailed increases at all the buses.

The general increase in all bus indices by considering protection system failures can be seen in both the 6-line and 8-line systems. The increase is most significant in the case of the 8-line system as the single line outages having relatively high probability do not have any effect on the system performance. The annualized system indices obtained with and without protection system failures are compared in Tables 5.8 and 5.9. These tables show a significant increase in most of the system indices with the inclusion of protection system failures.

Table 5.2 Load Point Failure Probability and Frequency for the system shown in Figure 5.1

Case	Description 6-line System	Bus 2		Bus 3		Bus 4		Bus 5	
		Probability	Frequency	Probability	Frequency	Probability	Frequency	Probability	Frequency
1	Single Outages	0.00000000	0.00000000	0.00796343	7.15040588	0.00497714	4.46247101	0.00597257	5.35334723
2	Sgl out with GF	0.00000298	0.01750194	0.007977584	7.25271797	0.00498117	4.50454330	0.00597592	5.40068007
3	Sgl out with PF	0.00000302	0.01770118	0.00802567	7.54275608	0.00500388	4.63631058	0.00599639	5.51914549
4	Double Outages	0.00000255	0.00453407	0.00898056	8.19758320	0.00562033	5.12946749	0.00671280	6.10382032
5	Db1 out with PF	0.00000557	0.02223290	0.00904215	8.58948517	0.00564665	5.30302286	0.00673614	6.26370573
8-line System									
1	Single Outages	0.00000000	0.00000000	0.00000000	0.00000000	0.00000000	0.00000000	0.00000000	0.00000000
2	Sgl out with GF	0.00000296	0.01740032	0.00000296	0.01740032	0.00000296	0.01740032	0.00000296	0.01740032
3	Sgl out with PF	0.00000300	0.01759548	0.00000772	0.04528866	0.00001789	0.10497621	0.00000602	0.03536223
4	Double Outages	0.00000000	0.00000000	0.00006452	0.11465392	0.00003071	0.05452624	0.00003184	0.05653557
5	Db1 out with PF	0.00000300	0.01759548	0.00007219	0.15986431	0.00004858	0.15946524	0.00003784	0.09185916

Sgl. out = Single outage

Db1. out = Double outage

GF = Ground fault on circuit breakers

PF = Protection System failure modes



Table 5.3 Annualized Load Point Indices for the system shown in Figure 5.1

Case no.	No. of Curtailments					Load Curtailed (MWh)					Energy Curtailed (MWh)					Duration of Curtailment (Hrs.)					Voltage Violations				
	2	3	4	5		2	3	4	5		2	3	4	5		2	3	4	5		2	3	4	5	
<b>6-line System</b>																									
1	0.00	2.69	0.00	0.00	0.90	0.00	38.76	0.00	8.96	0.00	377.21	0.00	87.20	0.00	26.16	0.00	8.72	0.00	4.46	4.46	0.00	4.46	4.46	5.36	
2	0.02	2.77	0.03	0.92	0.35	41.15	1.05	9.22	0.52	380.54	1.57	87.53	0.04	8.75	0.02	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	5.40	
3	0.02	2.98	0.07	0.95	0.35	45.50	2.81	9.54	0.53	387.06	4.20	88.00	0.11	8.80	0.02	4.61	4.61	4.61	4.61	4.61	4.61	4.61	4.61	5.52	
4	0.00	3.14	0.04	1.05	0.01	49.13	0.60	10.43	0.07	448.61	2.95	99.08	0.22	9.96	0.00	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07	6.10	
5	0.02	3.43	0.12	1.11	0.37	55.87	3.41	11.00	0.60	458.41	7.15	99.87	0.33	10.04	0.02	5.21	5.21	5.21	5.21	5.21	5.21	5.21	5.21	6.26	
<b>6-line System</b>																									
1	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.02	0.02	0.02	0.02	0.35	1.48	0.70	0.17	0.52	2.21	1.04	0.26	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	
3	0.02	0.05	0.10	0.04	0.35	3.76	4.20	0.35	0.53	5.61	6.27	0.53	0.03	0.07	0.16	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	
4	0.03	0.06	0.00	0.00	0.00	0.82	0.12	0.02	0.00	4.06	0.58	0.10	0.00	0.32	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.06	
5	0.02	0.11	0.11	0.04	0.35	4.58	4.32	0.37	0.53	9.67	6.85	0.63	0.33	0.39	0.18	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.09	

Case no.	Description
1	Single Outages
2	Single Outages with ground fault on Protection System
3	Single Outages with Protection System failure modes
4	Double Outages
5	Double Outages with Protection System failure modes

Table 5.4 Maximum Load Curtailed for the system shown in Figure 5.1

Case no.	MLC MW	Bus no. 2 Outage Condition	Probability	MLC MW	Bus no. 3 Outage Condition	Probability	MLC MW	Bus no. 4 Outage Condition	Probability	MLC MW	Bus no. 5 Outage Condition	Probability
<b>6-line System</b>												
1	0.000	-	0.000	14.4193	L1 Out	0.0014931	0.000	-	0.000	10.00	L5 Out	0.0009954
2	20.000	B15 CF	0.0000015	85.000	B21 GF	0.0000015	40.00	B27 CF	0.0000015	10.00	L5 Out	0.0009947
3	20.000	B15 CF	0.0000015	85.000	L1 Out & B22 Stuck	0.0000022	40.00	L2 Out & B26 Stuck	0.0000075	10.00	L5 Out	0.0009948
4	3.2258	L1, L6 Out	0.0000026	85.000	L1, L2 Out	0.0000085	40.00	L2, L4 Out	0.0000057	10.00	L5 Out	0.0011152
5	20.000	B15 CF	0.0000015	85.000	L1, L2 Out	0.0000085	40.00	L2 Out & B26 Stuck	0.0000075	10.00	L5 Out	0.0011154
<b>8-line System</b>												
1	0.000	-	0.000	0.000	-	0.000	0.00	-	0.00	0.00	-	0.000
2	20.000	B15 CF	0.0000015	85.000	B21 GF	0.0000015	40.00	B26 GF	0.0000015	10.00	B28 GF	0.0000015
3	20.000	B15 CF	0.0000015	85.000	L2 Out & B22 Stuck	0.0000022	40.00	L2 Out & B26 Stuck	0.0000074	10.00	L8 Out & B29 Stuck	0.0000015
4	0.000	-	0.000	13.5284	L1, L2 Out	0.0000085	25.9279	L1, L6 Out	0.0000025	10.00	L5, L8 Out	0.0000011
5	20.000	B15 CF	0.0000015	85.000	L1 Out & B22 Stuck	0.0000022	40.000	L2 Out & B26 Stuck	0.0000074	10.00	L8 Out & B29 Stuck	0.0000015

Case no. Description

- 1 Single Outages
- 2 Single Outages with ground fault on Protection System
- 3 Single Outages with Protection System failure modes
- 4 Double Outages
- 5 Double Outages with Protection System failure modes

CF Ground Fault on Protection System  
 B Breaker  
 L Line

Table 5.5 Maximum Energy Outrtailed for the system shown in Figure 5.1

Case no.	NEC MWH	Bus no. 2 Outage Condition	Probability	MEC MWH	Outage Condition	Bus no. 3 Probability	MEC MWH	Outage Condition	Bus no. 4 Probability	MEC MWH	Outage Condition	Bus no. 5 Probability
<b>6-line System</b>												
1	0.000	-	0.000	140.3335	L1 Out	0.0014931	0.000	-	0.000	97.2692	L5 Out	0.0009954
2	29.8738	B15 GF	0.0000015	140.3335	L1 Out	0.0014931	59.7476	B27 GF	0.0000015	97.2390	L5 Out	0.0009947
3	29.8741	B15 GF	0.0000015	140.2976	L1 Out	0.0014922	59.7990	L2 Out & B26 Stuck	0.0000075	97.2444	L5 Out	0.0009948
4	15.9130	L1,L6 Out	0.0000026	420.1354	L1,L2 Out	0.0000085	197.6550	L2,L4 Out	0.0000037	97.2859	L5 Out	0.0011152
5	29.8741	B15 GF	0.0000015	420.0808	L1,L2 Out	0.0000085	197.6294	L2,L4 Out	0.0000037	97.2616	L5 Out	0.0011144
<b>8-line System</b>												
1	0.000	-	0.000	0.000	-	0.000	0.000	-	0.000	0.000	-	0.000
2	29.8432	B15 GF	0.0000015	126.8337	B21 GF	0.0000015	59.6864	B26 GF	0.0000015	14.9216	B28 GF	0.0000015
3	29.8432	B15 GF	0.0000015	126.8659	L1 Out & B22 Stuck	0.0000022	59.7372	L2 Out & B26 Stuck	0.0000074	14.9241	L8 Out & B29 Stuck	0.0000015
4	0.000	-	0.000	66.6420	L1,L2 Out	0.0000085	127.4724	L1,L6 Out	0.0000025	49.1366	L5,L8 Out	0.0000011
5	29.8432	B15 GF	0.0000015	126.8659	L1 Out & B22 Stuck	0.0000022	127.4516	L1,L6 Out	0.0000025	49.1286	L5,L8 Out	0.0000011

Case no. Description

- 1 Single Outages
- 2 Single Outages with ground fault on Protection System
- 3 Single Outages with Protection System failure modes
- 4 Double Outages
- 5 Double Outages with Protection System failure modes

GF - Ground Fault on Protection System  
 B Breaker  
 L Line

Table 5.6 Maximum Duration of Load Curtailment for the system shown in Figure 5.1

Case no.	Bus no. 2		Bus no. 3		Bus no. 4		Bus no. 5	
	MDLC Hours	Outage Condition	MDLC Hours	Outage Condition	MDLC Hours	Outage Condition	MDLC Hours	Outage Condition
<b>e-line System</b>								
1	0.000	-	9.732	L1 Out	0.000	-	9.727	L5 Out
2	1.494	E15 CF	9.729	L1 Out	0.0014921	1.494 B27 CF	9.724	L5 Out
3	1.494	E15 CF	9.730	L1 Out	0.0014922	1.492 L2 Out & B26 Stuck	9.724	L5 Out
4	4.933	L1, L6 Out	9.634	L1 Out	0.0016727	4.943 L1 L2 Out	9.629	L5 Out
5	4.932	L1, L6 Out	9.631	L1 Out	0.0016717	4.942 L1, L2 Out	9.626	L5 Out
<b>8-line System</b>								
1	0.000	-	0.000	-	0.000	-	0.000	-
2	1.492	B15 CF	1.492	B21 CF	0.0000015	1.492 B26 GF	1.492	B28 GF
3	1.492	B15 CF	1.493	L1 Out & B22 Stuck	0.0000022	1.293 L2 Out & B26 Stuck	1.492	L8 Out & B29 Stuck
4	0.000	-	4.926	L1, L2 Out	0.0000085	4.916 L1, L6 Out	4.914	L5, L8 Out
5	1.492	B15 CF	4.925	L1, L2 Out	0.0000084	4.916 L1, L6 Out	4.913	L5, L8 Out

Case no.	Description
1	Single Outages
2	Single Outages with ground fault on Protection System
3	Single Outages with Protection System failure modes
4	Double Outages
5	Double Outages with Protection System failure modes
GF	Ground Fault on Protection System
B	Breaker
L	Line

Table 5.7 Bus Indices Averages for the system shown in Figure 5.1

Case no.	Bus no. 2				Bus no. 3				Bus no. 4				Bus no. 5			
	Load Curtailed MW	Energy not Supplied MWH	Duration of Curtailment Hours	Load Curtailed MW	Energy not Supplied MWH	Duration of Curtailment Hours	Load Curtailed MW	Energy not Supplied MWH	Duration of Curtailment Hours	Load Curtailed MW	Energy not Supplied MWH	Duration of Curtailment Hours	Load Curtailed MW	Energy not Supplied MWH	Duration of Curtailment Hours	
<b>6-line System</b>																
1	0.000	0.000	0.000	14.419	140.333	9.732	0.000	0.000	0.000	0.000	0.000	10.000	97.259	9.727		
2	20.000	29.874	1.494	14.831	137.160	9.248	40.000	59.748	1.494	10.000	94.897	9.490	10.000	94.897		
3	20.000	29.874	1.494	15.284	130.015	8.507	40.000	59.781	1.495	10.000	92.291	9.229	10.000	92.291		
4	3.226	15.913	4.933	15.660	143.004	9.132	13.324	65.837	4.941	9.900	94.064	9.502	9.900	94.064		
5	16.581	27.028	1.630	16.307	133.607	8.206	29.628	62.132	2.097	9.905	89.952	9.082	9.905	89.952		
<b>8-line System</b>																
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
2	20.000	29.843	1.492	85.000	126.834	1.492	40.000	59.686	1.492	10.000	14.922	1.492	10.000	14.922		
3	20.000	29.843	1.492	83.025	123.906	1.492	40.000	59.729	1.493	10.000	14.923	1.492	10.000	14.923		
4	0.000	0.000	0.000	12.752	62.823	4.926	25.928	127.472	4.916	10.000	49.137	4.914	10.000	49.137		
5	20.000	29.843	1.492	41.714	87.990	2.109	39.420	62.521	1.586	10.000	16.761	1.676	10.000	16.761		

Case no. Description:

- 1 Single Outages
- 2 Single Outages with ground fault on Protection System
- 3 Single Outages with Protection System failure modes
- 4 Double Outages
- 5 Double Outages with Protection System failure modes

Table 5.8 System Indices for the system shown in Figure 5.1

Case number as described under the table

Indices	1	2	3	4	5	1	2	3	4	5
Bulk Power Supply Disturbances	3.58441	3.73182	3.98695	4.18177	4.58405	0.000	0.06960	0.20305	0.06660	0.066956
<u>IEEE Indices</u>										
(i) Bulk Power Interruption Index (MW/Year)	0.30789	0.33402	0.37551	0.38816	0.45575	0.000	0.01740	0.05590	0.00620	0.06210
(ii) Bulk Power Energy Curtailment Index (MWh/Year)	2.99617	3.03331	3.09544	3.55294	3.65185	0.000	0.02596	0.08345	0.03955	0.11336
(iii) Bulk Power Supply Average MVA Curtailment Index (MVA/Disturbance)	13.31402	13.87323	14.59862	14.90757	15.41042	0.000	38.75000	42.67300	14.42507	25.65656
(iv) Modified Bulk Power Energy Curtailment Index	0.00034203	0.00034627	0.00035336	0.00040559	0.00041688	0.000	0.00000296	0.00000953	0.00000349	0.00001351
(v) Severity Index (System-Minutes)	179.770	181.998	185.727	213.176	219.111	0.000	1.558	5.007	1.833	6.825
<u>System Indices Average</u>										
(i) Average # of Load Curtailments/Load Point/Year	0.89610	0.93514	1.00464	1.16838	1.16838	0.000	0.01740	0.05081	0.01779	0.06633
(ii) Average # of Voltage Violations/Load Point/Year	3.57097	3.60463	3.69580	4.06504	4.18966	0.000	0.01740	0.05050	0.04140	0.07167
(iii) Average # of Hours of Load Curtailments/Load Point/yr. (hours)	8.71995	8.77277	8.87701	9.99454	10.15118	0.000	0.02596	0.07504	0.02762	0.16539
(iv) Average Load Curtailment/Local Point/Year (MW)	11.93073	12.94310	14.55099	15.04138	17.66018	0.000	0.67426	2.16617	0.24083	2.40343
(v) Average Energy Curtailment/Local Point/Year (MWh)	116.10169	117.54060	119.94843	137.67625	141.50903	0.000	1.00611	3.23360	1.12399	4.41633

Case #	Description
1	Single outage
2	Single outage with ground fault on Protection System
3	Single outage with Protection System failures
4	Double outage
5	Double outage with Protection System failures

Table 5.9 System Indices Maximums for the system shown in Figure 5.1

Case no.	Maximum Load Curtailed (MLC)		Maximum Energy Curtailed (MEC)		Probability	Outage Condition	Probability
	MLC (MW)	Outage Condition	MEC (MWH)	Outage Condition			
<b>6-line System</b>							
1	14.42	L1 Out	0.00149314	140.33	L1 Out	0.00149314	0.00149314
2	85.00	B21 GF	0.00000149	140.29	L1 Out	0.00149211	0.00149211
3	95.00	B21 GF & B20 Stuck	0.00000001	141.90	B21 GF & B20 Stuck	0.00000001	0.00000001
4	90.47	L1 & L2 Out	0.00000851	447.15	L1 & L2 Out	0.00000851	0.00000851
5	95.00	B21 GF & B20 Stuck	0.00000001	447.09	L1 & L2 Out	0.00000851	0.00000851
<b>8-line System</b>							
1	0.00	-	0.000	0.00		0.000	0.000
2	85.00	B21 GF	0.00000148	126.83	B21 GF	0.00000148	0.00000148
3	85.00	L1 Out & B22 Stuck	0.00000223	126.87	L1 Out & B22 Stuck	0.00000223	0.00000223
4	29.16	L1 & L6 Out	0.00000254	143.38	L1 & L6 Out	0.00000254	0.00000254
5	85.00	L1 Out & B22 Stuck	0.00000223	143.35	L1 & L6 Out	0.00000253	0.00000253

Case no.	Description
1	Single Outages
2	Single Outages with ground fault on breakers
3	Single Outages with Protection System failure modes
4	Double Outages
5	Double Outages with Protection System failure modes
GF	Ground Fault on Protection System
B	Breaker
L	Line

### 5.5 Reliability Indices at Customer Load Points

The basic indices normally used to predict the reliability at the customer load point are : Load Point Failure Rate, Average Load Point Outage Duration and Annual Load Point Outage Time. Utilities also calculate service performance indices and the most common performance indices are : System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI) and Average Service Availability Index (ASAI). A recent paper [45] reviewed some of the basic techniques for the evaluation of load point reliability indices and performance indices and provided example calculations on a radial distribution system.

It was assumed in Reference 45 that power supply up to the feeder breaker was 100% reliable, however, this is not the case as illustrated in the previous section. In this section, customer load point reliability indices are calculated including the bulk supply effects. This is accomplished by taking into consideration the probability and frequency of failure at the feeder point (load point of a composite system) of switching stations 2 and 3 of Figure 5.1 and representing the distribution system as shown in Figure 5.12. Identical radial circuits are used to represent the distribution configurations connected to the switching stations 2 and 3. In a practical network, the distribution facilities may be much more complex than those shown in Figure 5.12. The configurations utilized does permit, however, a relative comparison of the contributions to the customer indices from the composite system and the distribution network.





### 5.5.1 Reliability indices of customers connected to Switching Station 2

#### (i) 6-line system

Failure rate and average outage duration of power supply to the distribution feeders are as follows:

Failure rate (Table 5.3, # of curtailments) = 0.02 f/yr  
 Average outage time (Table 5.7, Duration of curtailment) = 1.63 hrs

Table 5.10 Reliability indices for customers connected to Station 2 of the 6-line system

Component	Load Point A			Load Point B			Load Point C		
	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr
Feeder power supply	0.02	1.63	0.034	0.02	1.63	0.034	0.02	1.63	0.034
Primary main									
2 m section	0.20	3.0	0.60	0.20	3.00	0.60	0.20	3.0	0.60
3 m section	0.30	0.50	0.15	0.30	3.0	0.90	0.30	3.0	0.90
1 m section	0.10	0.50	0.05	0.10	0.50	0.05	0.10	3.0	0.30
Primary lateral									
3 m section	0.75	1.0	0.75	0.075	0.50	0.038	0.075	0.05	0.038
2 m section	0.05	0.50	0.025	0.50	1.0	0.50	0.05	0.50	0.025
1 m section	0.025	0.50	0.013	0.025	0.50	0.013	0.25	1.0	0.25
Total	1.445	1.12	1.622	1.22	1.75	2.135	0.995	2.16	2.147

#### (ii) 8-line system

Failure rate (Table 5.3, # of curtailments) = 0.02 f/yr  
 Average outage time (Table 5.7, Duration of curtailment) = 1.49 hrs

Table 5.11 Reliability indices for customers connected to Station 2 of the 8-line system

Component	Load Point A			Load Point B			Load Point C		
	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr
Feeder power supply	0.02	1.49	0.03	0.02	1.49	0.03	0.02	1.49	0.03
Primary main	0.60	1.33	0.80	0.60	2.58	1.55	0.60	3.0	1.80
Primary Laterals	0.825	0.96	0.788	0.60	0.92	0.551	0.375	0.83	0.313
Total	1.445	1.12	1.618	1.22	1.75	2.131	0.995	2.15	2.143

### 5.5.2 Reliability indices of customers connected to Switching Station 3

#### (i) 6-line system

Failure rate and average outage duration of power supply to the distribution feeders are as follows:

Failure rate (Table 5.3, # of curtailments) = 3.43 f/yr  
 Average outage time (Table 5.7, Duration of curtailment) = 8.206 hrs.

Table 5.12 Reliability indices for customers connected to Station 3 of the 6-line system

Component	Load Point A			Load Point B			Load Point C		
	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr
Feeder power supply	3.43	8.21	28.15	3.43	8.21	28.15	3.43	8.21	28.15
Primary main	0.60	1.33	0.80	0.60	2.58	1.55	0.60	3.0	1.80
Primary laterals	0.825	0.96	0.788	0.60	0.92	0.55	0.375	0.83	0.313
Total	4.855	6.12	29.73	4.63	6.53	30.25	4.405	6.87	30.26

#### (ii) 8-line system

Failure rate and average outage duration of power supply to the distribution feeders are as follows:

Failure rate (Table 5.3, # of curtailments) = 0.11 f/yr  
 Average outage time (Table 5.7, Duration of curtailment) = 2.11 hrs

Table 5.13 Reliability indices for customers connected to Station 3 of the 8-line system

Component	Load Point A			Load Point B			Load Point C		
	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr	$\lambda$ f/yr	r hrs	$\lambda r$ hrs/yr
Feeder power supply	0.11	2.11	0.232	0.11	2.11	0.232	0.11	2.11	0.232
Primary main	0.60	1.33	0.80	0.60	2.58	1.55	0.60	3.0	1.80
Primary laterals	0.825	0.95	0.788	0.60	0.92	0.55	0.375	0.83	0.313
Total	1.535	1.19	1.82	1.31	1.78	2.332	1.085	2.16	2.345

The relative contributions to the reliability indices for customers connected to Station 2 in the 6-line and 8-line systems are shown in Tables 5.10 and 5.11 respectively. These tables show that the contribution due to bulk power supply is relatively very small in comparison to the contribution by the distribution network. This is because the distribution feeder is directly connected to the generating station and the transmission system does not have much effect in this case. The reliability indices of customers connected to Station 3 are listed in Tables 5.12 and 5.13 for the 6-line and 8-line systems respectively. Table 5.12 shows that the contribution due to bulk power supply for customers at load point A is 68% of the total indices calculated where as it is only 7% in the case of the 8-line system (Table 5.13). This abrupt change in the contribution is due to the inadequate transmission facilities in the case of the 6-line system. Similar effects are for customers at load point B and C. With the increase in transmission facilities i.e. by installing lines 7 and 8 in the system of Figure 5.1, the contribution due to the composite system decreases significantly. The results shown in Table 5.14 are for comparison purposes. The indices for the customers connected to Station 2 are the same in both the 6-line and 8-line systems. In the case of Station 3, there is a big change in the indices from the 6-line system to the 8-line system cases for the reasons described earlier.

A summary of the results is shown in Table 5.14.

Table 5.14 Reliability indices for customers connected to stations 2 and 3 of the 6-line and 8-line systems

Case description	Load Point A			Load Point B			Load Point C		
	Fail. rate	Ave. out. dur.	Annual outage time	Fail. rate	Ave. out. dur.	Annual outage time	Fail. rate	Ave. out. dur.	Annual outage time
	$\lambda$ f/yr	r hrs	U hrs/yr	$\lambda$ f/yr	r hrs	U hrs/yr	$\lambda$ f/yr	r hrs	U hrs/yr
6-Line System									
Station 2	1.445	1.12	1.620	1.22	1.75	2.1326	0.995	2.16	2.145
Station 3	4.855	6.12	29.73	4.63	6.53	30.25	4.405	6.87	30.26
8-Line System									
Station 2	1.445	1.12	1.617	1.22	1.746	2.131	0.995	2.15	2.143
Station 3	1.535	1.19	1.82	1.31	1.78	2.332	1.085	2.16	2.345

The effect of protection system related outages on bus and system indices has been illustrated in this chapter using a 5-bus hypothetical test system. The reliability indices of a 6-line system are dominated by independent overlapping outages, however, the results show that the protection system failure modes have a significant impact on all the indices and on the maximum bus indices in particular. For the 8-line system, the main contribution to the reliability indices is due to protection system related outages as single line outages do not have any effect on the system performance. The results demonstrate that before considering second and higher order independent events,

multiple outages due to protection system failures should be taken into consideration in order to provide a realistic appraisal.

The analysis of customer load point reliability indices illustrates the effect of composite generation and transmission system reliability indices on customer load point predictions. It also illustrates that the contribution to the customer indices due to the composite system decreases significantly with an improvement in the transmission facilities of the bulk power supply. The reliability indices for customers connected to switching stations, where there is no generation, have higher values than those customers connected directly to a generating source. This is due to the impact of transmission system outages, however, this effect diminishes with an increase in the transmission facilities. The results calculated by considering generation, transmission and distribution systems together give a more practical appraisal of the system than considering either composite or distribution facilities singly.

The approach described in this chapter is quite general and can be extended to a wide range of practical systems depending upon the data available.

## 6. CONCLUSIONS

This thesis has illustrated the different failure modes which exist within a protection system and has considered their effects on load point reliability indices. In most of the presently available techniques for composite system reliability evaluation, protection systems are assumed to be perfectly reliable. Some aspects of the problem particularly in the composite system analysis, are so complex that an accurate model may sometimes become computationally expensive. Realistic models should therefore adequately represent the true system performance under all system conditions and at the same time be computationally manageable. This may require making some simplifying but reasonable assumptions. The selection of the best possible model to describe a practical situation is possible only with comprehensive data collection.

A protection system has many failure modes i.e. a stuck breaker or relay condition, a false tripping, failure of the dc supply etc. in addition to ground faults. Each failure mode has a different impact on the system. To estimate the parameters of the protection system failure modes, reliability performance data is required for each component of the system. Unfortunately, detailed data on protection system components are not generally available at this time. A consistent effort in this area is required from the utility companies. The models developed in this thesis and their utilization in composite system reliability

evaluation should prove useful in deciding which data should be collected and in justifying the cost associated with collecting these data.

The failure modes and effect analysis method is a very powerful reliability technique and has been applied to determine the various load point failure modes within the transmission system. This requires a detailed knowledge of the behaviour of the system and all the inherent system processes that lead to a load point failure. The contribution to the load point reliability indices due to various failure modes can be evaluated using the equations described in this thesis.

In this thesis, transmission and distribution systems reliability performance has been measured in terms of frequency of failure, average outage duration and total annual outage time. All three indices are important in order to make a meaningful comparison of various system configurations. The reliability indices have been obtained at different load points of the system. This approach is very useful because a general level of system reliability does not indicate how the different continuity requirements of the customers are being satisfied.

Composite generation and transmission system reliability evaluation techniques at the present time consider only independent overlapping outages, and common-cause outages as defined in Reference 39. The outages relating to terminal stations and protection systems have in some cases been accounted for by increasing the failure rate of the associated transmission lines and generators by some fixed amount. This treatment is



valid only if one component is out due to a terminal related failure. This approach, however, does not recognize that multiple outages of current carrying components can occur due to a protection system related cause and does not simulate such a situation.

This thesis has described and illustrated the cause and effect of terminal related outages using the configurations of two practical substations. The basic approach to consider these outages in reliability evaluation of a composite generation and transmission system has been described based on the approach utilized in Reference 43. The load point and bus indices have been calculated for a 5-bus test system including protection system failures. The reliability indices of the 6-line system are dominated by single line outages, however, the results show a significant increase with the inclusion of protection system related events. For the 8-line system, protection system related outages have a larger contribution to the load point and system indices than independent overlapping outages. It is suggested therefore that protection system related outages which involve two or more current carrying components should be considered in the reliability analysis of a composite generation and transmission system.

It appears obvious that composite system reliability evaluation leading to individual load point and global system indices involves much more than the creation and examination of a large number of system outage conditions generated by independent removal of generation and transmission elements. The desire to

examine high order independent events has dictated the need for approximate solution techniques for the network and for the selection of system and load point failure criteria. Recognition and classification of dependent events such as common mode failures and terminal related outages may, however, obviate the need to examine high order independent outage events and also lead to a more realistic appraisal of practical systems. These events, however, require detailed analysis and data before they can be consigned as input to a system appraisal program. They cannot be included by simple addition to the independent failure rates of the current carrying components but should be included as an additional level of component outage data.

Customer reliability indices calculated considering only outages in the distribution system will give optimistic results because outage effects of the composite generation and transmission system are not reflected in that evaluation. In this thesis, customer reliability indices have been calculated considering the resulting indices of the composite system as starting values and these indices give a more practical appraisal of the power system as a whole.

It must be noted that the application of the techniques described in this thesis depend upon having collected sufficient information regarding component failure rates, the associated expected outage durations and the criteria of load point failure. The importance of data collection with the objective of reliability evaluation of various design alternatives should be realized by utility personnel and effort expended to consistently collect the required data.

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## APPENDICES

## Appendix A

## Definitions of Outage Terms

## A.1 Outage Definitions [53]

## 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 component.

## Outage Categories

## 1. Forced Outage

A forced outage is an outage that results from emergency conditions directly associated with a component requiring that it be taken out of service immediately, either automatically or as soon as switching operation can be performed, or an outage caused by improper operation of equipment or human error.

## 2. Scheduled Outage

A scheduled outage is an outage that results when a component is deliberately taken out of service at a selected time, usually for the purpose of construction, preventive maintenance or repair.

## Forced Outage Categories

## 1. Transient Forced Outage

A transient or temporary forced outage is an outage whose cause is self-clearing so that the affected component can be restored to service either automatically or as soon as a switch or



circuit breaker can be reclosed or a fuse replaced. An example of a temporary forced outage is a lighting flashover which does not permanently disable the flashed component.

## 2. Permanent Forced Outage

A permanent or sustained forced outage is an outage whose cause is not self-clearing, but must be corrected by eliminating the hazard or by repairing or replacing the component before it can be returned to service. An example of a sustained forced outage is a wire burndown.

### Exposure Time:

Exposure time is the time during which a component is performing its intended function and is subject to outage.

### Switching Time:

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

## A.2 Definitions of Customer and System Oriented Reliability indices [54]

### 1. System Average Interruption Frequency Index

This index is defined as the average number of interruptions per customer served per time unit. It is determined by dividing the number of customer interruptions in a year by the number of

customer served. This index may be applied to sustained and/or temporary interruptions, and this should be designated in the index.

## 2. System Average Interruption Duration Index

This index is defined as the average interruption duration for customers served during a specified time period. It is determined by dividing the sum of all customer interruption durations during the specified period by the number of customers served during that period.

## 3. Customer Average Interruption Frequency Index

This index is defined as the average number of interruptions per customer interrupted per time unit. It is determined by dividing the number of customer interruptions observed in a year by the number of customers affected. Count customers affected only once regardless of number of interruptions that may be experienced.

## 4. Customer Average Interruption Duration Index

This index is defined as the average interruption duration for customers interrupted during a specified time period. It is determined by dividing the sum of all customer interruption durations during the specified period by the number of sustained customer interruptions during that period.

## Appendix B

## Data of the 5-Bus Test System

Table B1. Transmission line data

## Line Data

Lines are assumed to be 795 ACSR 54/7.

Current carrying capability = 374amps. = 0.71 p.u.  
 Failure rate = 0.05 failures/year/mile  
 Expected repair duration = 10 hours

Line	Length miles	Impedance P.U.	Susceptance (b/2)	Failure rate	Probability of failure
1,6	30	0.0342+j0.1800	0.0106	1.5	0.001713
2,7	100	0.1140+j0.6000	0.0352	5.0	0.005710
3	80	0.0912+j0.4800	0.0282	4.0	0.004568
4,5,8	20	0.0228+j0.1200	0.0071	1.0	0.001142

Table B2. Generation and load data

Base MVA =100,

Base KV =110

Bus No. no. Of units	Capacity Of each unit MW	Total bus capacity MW	Type of units	Failure rate p. unit f/yr	Repair rate p. unit r/yr	Probability of outage	
1	4	20	80	Thermal	1.1	73	0.015
2	7	5	130	Hydro	0.5	100	0.005
	1	15		Hydro	0.5	100	0.005
	4	20		Hydro	0.5	100	0.005

Swing Bus : 1

(If bus 1 is isolated from the network due to an outage condition, Bus 2 is selected as the swing bus.)

Peak load is considered constant through out the year.

Bus	Peak load	Power factor	Generation allotted under Peak Load	VAR Limits	Voltage Limits	
	MW		MW	MVAR	Maximum	Minimum
					P.U.	
1	0		Swing Bus	-20 to +20	1.05	0.97
2	20	1.0	110	-30 to +40	1.05	0.97
3	85	1.0	---	-----	1.05	0.97
4	40	1.0	---	-----	1.05	0.97
5	10	1.0	---	-----	1.05	0.97
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	155					
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Table B3. Circuit Breaker Data

Ground fault rate per unit = 0.01 failure/year  
 Unreadiness probability = 0.01  
 Average repair time = 20 hours  
 Average switching time = 1.5 hours  
 False tripping rate is neglected