

RELIABILITY EVALUATION OF SUBTRANSMISSION CONFIGURATIONS IN ELECTRIC POWER SYSTEMS

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by

RAJNISH GUPTA

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Head of the Department of Electrical Engineering,
University of Saskatchewan,
Saskatoon, Canada S7N 0W0.

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UNIVERSITY OF SASKATCHEWAN

Electrical Engineering Abstract 91A345

**RELIABILITY EVALUATION OF SUBTRANSMISSION
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Student: RAJNISH GUPTA

Supervisors: Dr. R. BILLINTON and Dr. N.A. CHOWDHURY

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ABSTRACT

An electric power system as a whole is an enormous entity. It is very difficult to evaluate the reliability of a complete power system on this basis. It has been, therefore, divided into the three functional zones of generation, transmission and distribution. The distribution functional zone can be further subdivided into subtransmission and radial parts. This thesis pertains to the analysis of an electric subtransmission system. An analysis of a subtransmission system involves the identification of the individual component failure modes based on which load point failure events and restoration modes are assessed. Component permanent, maintenance and temporary failure modes are considered in the reliability predictions. In addition active failures and adverse weather effects have also been considered.

A digital computer program 'SUBTREL' which takes into consideration most of the factors affecting the adequacy of a subtransmission system and which is highly user friendly is presented in this thesis. The RBTS subtransmission system, which is sufficiently large that practical factors can be realistically modelled and assessed yet sufficiently small that the effect of sensitivity studies can be easily identified, is utilized as the test system for studies described in this thesis. The radial part of the RBTS distribution system is described briefly and analysis of the radial distribution segment is done by making use of the computer program 'DISREL'. Some sensitivity studies are also performed on the RBTS distribution system by making use of the above mentioned computer programs. Finally a comparison of the subtransmission system and the radial distribution system, with regard to their reliability indices, is made.

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LIST OF ABBREVIATIONS

HL-I	Hierarchical level I
HL-II	Hierarchical level II
HL-III	Hierarchical level III
LOLE	Loss of load expectation
LOEE	Loss of energy expectation
F&D	Frequency and duration
EUE	Expected unsupplied energy
CRM	Capacity reserve margin
SAIFI	System average interruption frequency index
SAIDI	System average interruption duration index
CAIFI	Customer average interruption frequency index
CAIDI	Customer average interruption duration index
ASAI	Average service availability index
ASUI	Average service unavailability index
ASCI	Average system curtailment index
ACCI	Average customer curtailment index
SUBTREL	Subtransmission system reliability
TLOC	Total loss of continuity
RBTS	Roy Billinton Test System
RTS	Reliability Test System
IEEE	Institute of Electrical and Electronics Engineers
SP1	Supply point 1
SP2	Supply point 2
SP3	Supply point 3
DISRTEL	Distribution system reliability
UPM	Units per million
SM	System minutes

Cust.	Customer
Inter.	Interruption
Resdl.	Residential
Sm.Ind.	Small industrial
G&I	Government and institutional
Comml.	Commercial

1. POWER SYSTEM RELIABILITY

1.1. Introduction

The primary function of an electric power system is to supply electrical energy to all its customers as economically as possible and with an acceptable degree of quality and continuity. While satisfying this function, the power system must remain within a set of operational constraints some of which relate directly to the quality of supply such as bus-bar voltage violations and frequency variations. Other constraints which are not directly seen by consumers are equally important in an operating sense and include equipment ratings, system stability limits and fault levels.

In order to achieve the required degree of reliability, power system managers, designers, planners and operators have utilized a wide range of criteria in their respective area of activity. Initially all of these criteria [1] were deterministically based and many of these criteria and associated techniques are still in use today. The basic weakness of deterministic criteria is that they do not respond to, nor do they reflect the probabilistic or stochastic nature of system behaviour, of customers demands, or of component failures. These factors can be incorporated in a probabilistic approach to electric power system reliability assessment. Power system reliability assessment, both deterministic and probabilistic, can be divided into two basic aspects: system adequacy and system security [1, 2, 3, 4, 5]. This categorisation is shown in Figure 1.1.

Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. Adequacy is therefore associated with static conditions which do not include system disturbances.

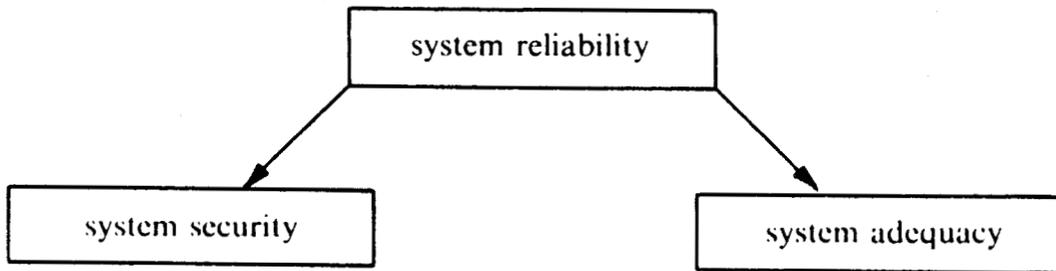


Figure 1.1: Subdivision of system reliability.

Security relates to the ability of the system to respond to disturbances arising within that system. Security is therefore associated with the response of the system to whatever perturbations it is subjected to. These include the conditions associated with both local and widespread disturbances and the loss of major generation and transmission facilities.

Most of the probabilistic techniques presently available for reliability evaluation are in the domain of adequacy assessment. Many probabilistic techniques are now in use [1, 2, 3] which are based on the fact that power systems behave stochastically and all input and output states and event parameters are probabilistic variables.

1.2. Reliability Evaluation at Hierarchical Levels

A power system as a whole is a very complex entity. It can be broadly classified into the three basic functional zones [2, 3, 6] of generation, where the electrical energy is generated, transmission, which is responsible for transmitting the generated energy to the major load points and distribution, which connects the individual customer load points to the transmission zone. Each functional zone can be considered as a separate entity which operates in conjunction with the others. For the sake of simplicity and convenience, functional zones can be combined to form the three hierarchical levels (HL's) shown in Figure 1.2 [1, 2, 3, 4]. Reliability analysis is normally done independently within each functional zone and also at HL-I and HL-II. The reliability of a complete system at HL-

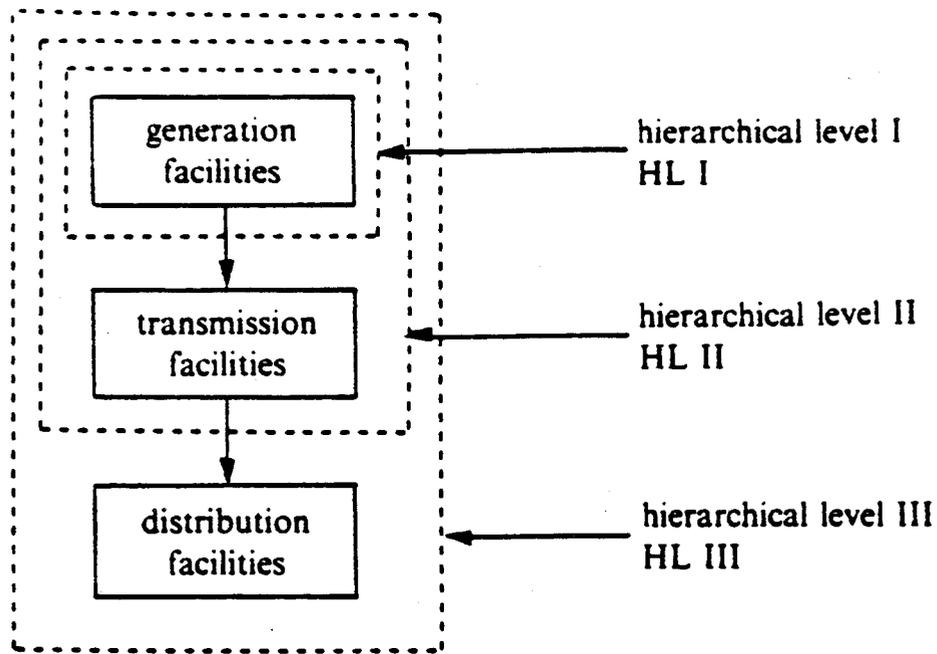


Figure 1.2: Hierarchical levels.

III can be evaluated by suitably combining the analysis of the distribution functional zone with the results at HL-II.

Only the generation of electrical energy is considered at HL-I. The reliability of the transmission system and its ability to move the generated energy to the customer load points is not considered. The concern is to estimate the generating capacity required to satisfy the system demand and to have sufficient capacity to perform corrective and preventive maintenance on the generating facilities. In the past, deterministic criteria [1] such as the percentage reserve method, a reserve equal to one or more of the largest units, etc. were used. These criteria have been largely replaced by probabilistic methods which take into consideration the actual factors that influence the reliability of the system. Basic probabilistic criteria [2, 3, 7] which are presently used at HL-I are loss of load expectation (LOLE), loss of energy expectation (LOEE) and frequency and duration (F&D). The LOLE is the expected number of days in which the daily peak load is expected to exceed the available generating capacity. It, therefore, indicates the expected number of days in which a load loss or deficiency will occur. It does not indicate the

severity of the deficiency nor the frequency and the duration of loss of load. The LOEE is the expected energy that will not be supplied by the generating system due to those occasions when the load demand exceeds the available generating capacity. It measures the severity of deficiencies rather than just the existence of deficiencies. The F&D parameters extend the LOLE calculations by identifying the expected frequency of encountering a deficiency and the expected duration of the deficiency. They, therefore, contain physical characteristics which make them sensitive to additional parameters of the generating system, and provide more information to power system planners. Table 1.1 shows a summary of the techniques and indices presently used by Canadian utilities [3].

Table 1.1: Basic HL-I criteria and indices used in Canada.[3]

<i>System</i>	<i>Type of Criterion</i>	<i>Index</i>
British Columbia Hydro & Power Authority	LOLE	1 day/10 year
Alberta Interconnected System	LOLE	0.2 days/year
Saskatchewan Power Corporation	EUE	200 Units per million (UPM)
Manitoba Hydro	LOLE	0.003 days/year (with connections) 0.1 days/year (without connections)
Ontario Hydro	EUE	25 system minutes (SM)
Hydro Quebec	LOLE	2.4 h/year
New Brunswick Electric Power Commission	CRM ^a	Largest unit or 20% of the system peak (whichever is larger)
Nova Scotia Power Corporation	LOLE ^b	0.1 days/year (under review)
Newfoundland and Labrador Hydro	LOLE	0.2 days/year
LOLE (Loss of load expectation) EUE (Expected unsupplied energy) CRM (Capacity reserve margin)		

^a With supplementary checks for LOLE.

^b With supplementary checks for CRM.

Bulk transmission is considered in conjunction with the generation facilities in the case of HL-II evaluation. An HL-II configuration is usually termed as a composite system or bulk transmission system [1]. Reliability evaluation at this level extends the HL-I indices

by including the ability to move the generated energy through the bulk transmission system. HL-II studies can be used to assess the adequacy of a system including the impact of various reinforcement alternatives at both the generation and transmission levels. These effects can be assessed by evaluating two sets of indices: individual bus (load point) indices and overall system indices. The load point indices show the effect on individual busbars and provide input values to the next hierarchical level and the system indices give an assessment of overall system adequacy. The indices are expected values and are highly dependent on the modelling assumptions used in the computer simulation. Adequacy assessment at HL-II is still very much in the development phase. There is no consensus on techniques, criteria or indices and there are many power utilities and related organisations doing interesting and innovative work in this area. Many computer programs have been and are being developed [8] to evaluate composite system adequacy. Some of the better known programs are:

COMREL	University of Saskatchewan, Canada
GATOR	Florida Power Corporation, USA
PROCOSE	Ontario Hydro, Canada
RELACS	University of Manchester Institute of Science and Technology, UK
SYREL	Electric Power Research Institute/Power Technologies, Inc. USA
SYREL	Shawinigan Lavalin, Canada
TPLAN	Power Technologies Inc., USA.

The above programs are based on contingency enumeration methodologies which involve selection and evaluation of contingencies to determine specified system failure conditions and adequacy indices.

HL-III includes all the three functional zones starting with the generation facilities and terminating at the individual customer load points. The overall problem of HL-III evaluation can become very complex in most practical systems. For this reason, the distribution functional zone is usually considered as a separate entity. The HL-III indices can be evaluated, however, by using the HL-II load point indices as the input values to the distribution functional zone being analyzed. The objective of an HL-III study is to obtain suitable adequacy indices at the actual customer load points. The primary indices are the expected frequency of failure, the average duration of failure and the annual un-

availability of the load points. Additional indices, such as expected load disconnected or energy not supplied, can also be obtained. The conventional analytical methods [1] for evaluating these indices utilize techniques which are based on the minimal cutset technique [9, 10, 11] or failure modes analysis [1, 9] in conjunction with sets of analytical equations which can account for all realistic failure and restoration processes.

1.3. Electric Distribution System

The electric distribution system is that part of an electric power system which links the bulk power source or sources to the customer's facilities. Subtransmission circuits, distribution substations, distribution or primary feeders, distribution transformers, secondary circuits and customer service connections form different parts of a distribution system. Reliability assessment in a distribution system, therefore, indicates how adequately the different parts of the system are able to perform their intended function. The distribution system is an important part of the total electric system as it provides the final link between the bulk system and the customer.

A distribution system can be broadly classified into two basic areas. One which connects the bulk transmission system to the distribution substation and the other which connects the distribution substation to the customer load. The first area [6] which is often designated as the subtransmission system is usually the network type of distribution and is used most often to supply bulk loads, such as industrial plants and large commercial buildings, where continuity of service is of considerable importance. Ring arrangements are often used for subtransmission circuits. A ring is a circuit or circuits which start from a power supply point or bus and tie together a number of power supply points or buses. The second area, which connects the customer load to the distribution substation, is usually radially connected [10]. The radial distribution system normally uses primary or main feeders and lateral distributors. A main feeder originates from the substation and passes through the major load centres. The individual load points are connected to the main feeder by lateral distributors with distribution transformers at their ends. A main feeder is constructed using single, parallel or meshed circuits. Many distribution systems used in practice have a single circuit main feeder and are operated as radial systems using normally open switches in the meshed circuit. The main feeder, in some cases, may have branches to reach widely distributed areas.

The basic reliability indices [1] normally used at the customer level are load point failure rate, load point outage duration and annual unavailability. The load point failure rate λ_l (f/yr) is the expected number of interruptions of load point 'l' in a year and is given by

$$\lambda_l = \sum_i \lambda_i \quad (1.1)$$

Here λ_i denotes the component failure rate (f/yr) and the summation index 'i' includes all these components for which the failure of any one will result in an interruption at load point 'l'. The load point outage duration r_l (hr/repair) is the average time for which the load point 'l' is on outage whenever an interruption occurs and is given by

$$r_l = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} \quad (1.2)$$

The annual load point unavailability U_l (hr/yr) is the expected total time in a year that the load point will be on outage. It is given by

$$U_l = \sum_i \lambda_i r_i \quad (1.3)$$

The product of λ_i and r_i is the contribution of component 'i' to the annual unavailability of the load point 'l'.

The basic indices are important with respect to a particular load point, but they do not give an overall appreciation of the area or system performance. Additional indices can be calculated using the three basic indices and the number of customers/load connected at each load point in the system. The most common additional or system indices [1, 12] are as follows:

1. System average interruption frequency index, SAIFI
2. Customer average interruption frequency index, CAIFI
3. System average interruption duration index, SAIDI
4. Customer average interruption duration index, CAIDI

5. Average service availability (unavailability) index, ASAI (ASUI)
6. Energy not supplied index, ENS
7. Average system curtailment index, ASCI
8. Average customer curtailment index, ACCI

All these indices are defined in Appendix A.

The two sets of indices, individual load point and aggregate system values, constitute a complete set which describes the reliability of a given distribution system. In most systems, the bulk of the inadequacy of the individual load points comes from the distribution system [1]. The HL-I and HL-II indices are very important, however, because failures in these parts of the system affect large sections of the system and therefore can have widespread and perhaps catastrophic consequences for both society and its environment. Failures in the distribution system, although much more frequent, have much more localized effects.

1.4. Objective and Scope of Thesis

A distribution system, as discussed in the last section, can be divided into two basic segments. The work reported in this thesis has been concentrated in the subtransmission segment of the distribution system. Some studies in the radial part of the distribution system have also been performed. The basic objective of this research work was to assess the different kinds of load point failure events and restoration modes resulting from the component failure modes which affect the subtransmission reliability.

The effects of overlapping outages of three or more components are not usually considered in the reliability evaluation of a system due to the belief that such outages do not contribute significantly to the reliability indices. This research work examines the effects due to higher order outage events on system reliability indices and their contributions to the final reliability indices.

In the past, reliability indices were evaluated using hand calculations and therefore it was cumbersome to include the effects of third order outages and adverse weather con-

tributions to the final indices. The results obtained were, therefore, optimistic. A main objective of this research work was to develop a digital computer program which can consider the effect of third order outages, adverse weather effect and some of the other factors which affect the reliability of a subtransmission system.

In order to increase the reliability of a subtransmission system, the major concern is the location of additional facilities, i.e. in which part of the system should money be invested, in order to obtain enhanced system performance. An attempt has been made, by performing sensitivity studies, to determine the part(s)/component(s) of the system which contribute most to the system unreliability indices. Studies of this type will enable a power system engineer to create flexible decision strategies which involve adding the right equipment, at the right time and in the right location, so as to obtain maximum economic benefits at acceptable reliability levels.

References 1 and 7 show that more than 80% of the customer unavailability originates from outages in the distribution system and that a very high percentage of these occur in the radial segment. A comparison is made in this thesis between the subtransmission system and the radial system in order to see how significant are the subtransmission system effects on the total distribution system reliability indices.

1.5. Thesis Outline

The thesis is structured as follows. Chapter 2 gives an overview of subtransmission system outages. It describes different types of failure and restoration modes which affect the reliability of a system. Equations for up to second order overlapping outages are also given in this chapter. Chapter 3 briefly explains the computer program developed to obtain the reliability indices of a subtransmission system. The results of studies on a small system are presented in order to illustrate the working ability of the program. The behaviour of the reliability indices as the input parameters are varied is also explained. Chapter 4 describes the test system used for the reliability evaluation. The results of studies on the test system using the developed computer program are presented. In Chapter 5, the behaviour of the reliability indices for the test system, as the input parameters are varied, is explained in detail. Chapter 6 explains briefly, the computer program

developed to obtain the mean values of the radial distribution system reliability indices. The results of studies on the test system are presented. The behaviour of the reliability indices as the input parameters are varied is examined. The results obtained for the sub-transmission system are compared with those obtained for the radial distribution system. The last chapter concludes and summarizes the work described in the thesis.

2. CLASSIFICATION OF SUBTRANSMISSION SYSTEM OUTAGES

2.1. Introduction

A subtransmission system is that portion of an electric power system which links the bulk transmission system with the radial part of the distribution system. Considerable attention has been devoted within the past few years to the reliability evaluation of this portion of the power system and a large number of papers have been published [13] and accurate and consistent techniques [1] have been developed. A theoretically accurate Markov approach [9] can be utilized but is limited in application because of computer storage and the rounding errors which occur in the solution of relatively large systems. Monte Carlo simulation techniques [14] can be utilized which require a minimum of assumptions but do require a large amount of computer time and cannot be efficiently applied in relatively large practical systems. The most practical technique is one which utilises failure modes and effect analysis [1, 15, 16]. This procedure requires the identification of the different component failure modes and the effect of these events on load point and system success. The failure modes are directly related to the minimal cutsets [1, 9, 17, 18] of the system and therefore the latter are used to identify the failure modes. A cutset can be defined as a set of system components which, when failed, causes failure of the system. The minimum subset of any given set of components which causes system failure is known as a minimal cutset. The assumptions and the algorithm developed to deduce the minimal paths and cutsets from a simple description of the topology of the network are given in References 9, 18 and 19. The failure modes that are identified in this way represent component outages that must overlap to cause a system outage. The events are therefore defined [1] as overlapping outages and the associated outage time is defined as the overlapping outage time. Each overlapping event is effectively a set of parallel elements and its effect can be evaluated using the equations developed for paral-

lel components [2]. Since each of these overlapping outages will cause system failure, all the overlapping outages are effectively in series from a reliability point of view. The system indices can therefore be evaluated by applying the equations developed for series components [1] in order to combine all the overlapping outages. The developed equations [1] give results which compare very closely with those predicted by a theoretically accurate Markov approach.

The load point failure modes considered in this thesis are those which arise due to component permanent, temporary and maintenance outages. The three types of failure modes are discussed in detail in this chapter. It is found from experience that the failure rates of most components are a function of the weather to which they are exposed. In adverse weather conditions, the failure rate of a component can be many times greater than that found in normal weather conditions. For these reasons, the effect of adverse weather on power system reliability has been considered for many years and techniques [1, 6, 20] have been developed that permit these effects to be included in the analysis. A two state weather model [1] is considered in this chapter to illustrate the effect of severe weather periods on system reliability performance.

2.2. Component Failure Modes

Permanent, maintenance and temporary failures are the component failure modes considered in this thesis in the reliability evaluation of subtransmission systems. The permanent outage of a component requires that it be taken out of service for a period of time during which it is repaired. The actual outage time may be the replacement time for a spare component. The data required for the evaluation of permanent forced outages [1, 17] are as follows:

1. Permanent failure rate is the total number of component permanent failures per year that requires the removal of the component from service for repair/replacement due to permanent failure mode. It is denoted by λ .
2. Repair time is the time taken to repair a component permanent failure mode and is denoted by r .
3. Replacement time is the time taken to replace a faulty component. It is denoted by r_p .

When there is a component failure in the system it is important that the component should be repaired or replaced as quickly as possible in order to make it available for use again in the shortest possible time. The ability to restore a component to service is sometimes designated as maintainability and is defined as a measure of the speed with which loss of performance is detected, the fault located, repair completed, and a check made that the equipment is functioning normally again. A maintenance outage is basically different from a component forced outage. Power system components must be taken out of service for periodic inspection and maintenance. Such an action is desirable to forestall, by preventive methods, the occurrence of a future failure or malfunction and therefore maintenance is a dependent activity. The actual removal of a component is dependent upon the load level in the system and whether or not an outage already exists. Scheduled maintenance is simulated only on overlapping events associated with parallel and meshed networks. It has been established from operating experience that a major cause of double contingency outages is the occurrence of an outage at a time when another device has been taken out for maintenance. The following parameters [1, 17] are required to consider the effects of scheduled maintenance in the reliability evaluation of electric power systems.

1. Maintenance outage rate is the average number of occasions per year that a component is taken out for service for preventive or scheduled maintenance. It is denoted by λ .
2. Average maintenance time is the average duration of all preventive maintenance outages and is denoted by r .

Many of the outages in subtransmission schemes are of a temporary nature. If a component fault is cleared by a reclosing operation of a circuit breaker or by an automatic switching operation, a temporary outage is said to have occurred, e.g. opening and reclosing of a breaker following a flashover due to lightning surges. The durations associated with such outages are generally of the order of a few minutes. The consideration of temporary outages in subtransmission systems is very important because temporary interruptions can cause considerable irritation to the customers. In many industries involving continuous processes, a momentary outage can cause complete wastage of the product in process resulting in a heavy economic loss. In many overhead distribution

schemes, the intensity of component temporary outages is governed by the environment. The following parameters are required [1, 21] in considering the effects of temporary failures in the reliability evaluation of a subtransmission system.

1. Temporary failure rate is the number of temporary component outages per year and is denoted by λ_t .
2. Reclosure time is the time during which the component is not available due to a temporary outage. It is denoted by r_c .

The component failure modes can further be classified into passively failed or actively failed events [1, 17, 22]. Each mode can have a distinctly different impact on the behaviour of the system. These events can be defined as :

1. A passive event is a component failure mode which does not cause operation of the protection breakers, e.g. open circuits, inadvertent opening of breakers. Such an event do not therefore have an impact on the remaining healthy components.
2. An active event is a component failure mode which causes the operation of the entire primary protection zone around the failed component and can therefore result in the removal of other healthy components and branches from service.

A passive event can be combined with its corresponding active event to produce a total failure event in which the separate identities of the passive and active events are lost. The component reliability data normally specified are therefore the active failure rate ' λ_a ', total failure rate ' λ ', switching or isolation time ' s ' and repair time ' r '.

2.3. Load Point Failure Modes

The essential requirement of a reliability assessment is to identify whether the failure of a component or a combination of components causes the failure of the load point of interest. If it does, the event must be counted as a load point failure event. If it does not, the event can be disregarded at least as far as the load point of interest is concerned. Depending upon the configuration of the system, component failures may or may not result in load point interruption. As discussed previously, the failure events of any load point can be identified using the minimal cutsets associated with the minimal paths

to that load point. The number of components defining a failure event is the order of its associated minimal cut. These minimal cuts can be evaluated using the techniques discussed in References 1, 9, 17, 18. The following [21] procedure is adopted in the program developed in this research project to evaluate the reliability indices of the failure events.

1. Identify the components in the minimal cutset.
2. Identify the possible outage modes (i.e. permanently failed, maintenance, actively failed, temporarily failed) of each component in the minimal cutset.
3. Identify the corresponding restoration modes (i.e. repair, replacement, switching or reclosure).
4. Apply the appropriate equations for the modes of failure and restoration and the order of cutset.
5. Repeat steps (2-4) as many times as there are combinations of component outage modes for the particular cutset being considered.
6. Repeat steps (1-5) as many times as there are cutsets associated with each load point.
7. Repeat steps (1-6) as many times as there are load points in the system being considered.

The various basic events, based on the above procedure, which lead to load point failure are listed below using the system of Figure 2.1.

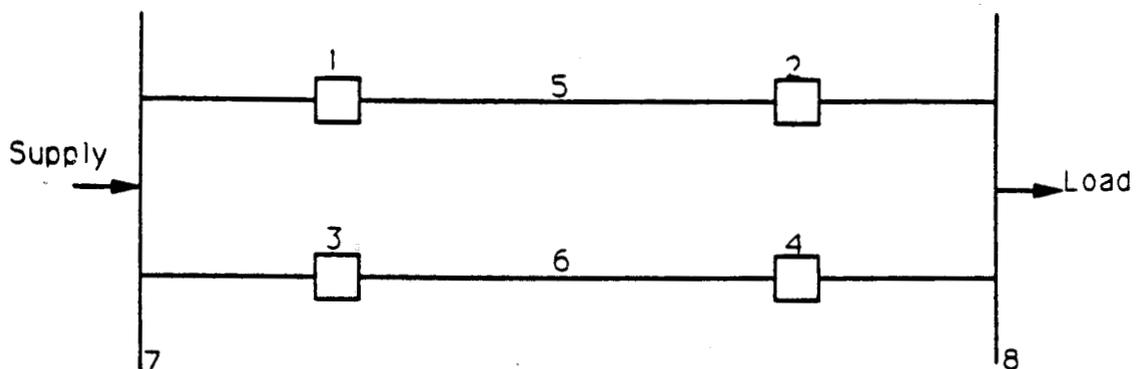


Figure 2.1: Two line configuration.

1. The active failures of breakers 1 or 2 or 3 or 4.
2. The permanent or temporary outage of busbars 7 or 8.
3. The permanent outage of breakers 1 or 2 or line 5 overlapping the permanent outage of breakers 3 or 4 or line 6 or vice-versa.

Equations representing the reliability indices, when the permanent outage of breaker 1 overlaps the permanent outage of breaker 3 and vice-versa, are as follows. Similar equations are created for other events.

$$\lambda_{pp} = \lambda_1 \lambda_3 (r_1 + r_3) \quad (2.1)$$

$$r_{pp} = \frac{r_1 r_3}{r_1 + r_3} \quad (2.2)$$

$$U_{pp} = \lambda_1 \lambda_3 r_1 r_3 \quad (2.3)$$

4. The maintenance outage of breakers 1 or 2 or line 5 overlapped by a permanent or a temporary outage of breakers 3 or 4 or line 6 or vice-versa.

Equations representing the reliability indices, when the permanent outage of breaker 3 overlaps the maintenance outage of breaker 1 and vice-versa, are as follows.

Similar equations are created for other events.

$$\lambda_{pm} = \lambda_1'' (\lambda_3 r_1'') + \lambda_3'' (\lambda_1 r_3'') \quad (2.4)$$

$$U_{pm} = \lambda_1'' (\lambda_3 r_1'') \frac{r_1' r_3''}{r_1'' + r_3} + \lambda_3'' (\lambda_1 r_3'') \frac{r_1 r_3''}{r_1 + r_3''} \quad (2.5)$$

$$r_{pm} = \frac{U_{pm}}{\lambda_{pm}} \quad (2.6)$$

Similar equations representing the reliability indices, when the temporary outage of breaker 3 overlaps the maintenance outage of breaker 1 and vice-versa, are as follows.

$$\lambda_{tm} = \lambda_1(\lambda_{t3}r_1) + \lambda_3(\lambda_{t1}r_3) \quad (2.7)$$

$$U_{tm} = \lambda_1(\lambda_{t3}r_1) \frac{r_1r_{c3}}{r_1 + r_{c3}} + \lambda_3(\lambda_{t1}r_3) \frac{r_{c1}r_3}{r_{c1} + r_3} \quad (2.8)$$

$$r_{tm} = \frac{U_{tm}}{\lambda_{tm}} \quad (2.9)$$

5. The permanent outage of breakers 1 or 2 or line 5 overlapped by a temporary outage of breakers 3 or 4 or line 6 or vice-versa. Equations representing the reliability indices, when the temporary outage of breaker 3 overlaps the permanent outage of breaker 1 and vice-versa, are as follows. Similar equations are created for other events.

$$\lambda_{pt} = \lambda_{t1}\lambda_3(r_{c1} + r_3) + \lambda_1\lambda_{t3}(r_1 + r_{c3}) \quad (2.10)$$

$$U_{pt} = \lambda_{t1}\lambda_3(r_{c1} + r_3) \frac{r_{c1}r_3}{r_{c1} + r_3} + \lambda_1\lambda_{t3}(r_1 + r_{c3}) \frac{r_1r_{c3}}{r_1 + r_{c3}} \quad (2.11)$$

$$r_{pt} = \frac{U_{pt}}{\lambda_{pt}} \quad (2.12)$$

The probability of an event in which two independent component temporary outages overlap is very small and therefore such an event is not included.

2.4. Weather Effect on Load Point Failure Modes

A subtransmission system can be composed of either overhead or underground facilities or both. Overhead schemes operate in a fluctuating weather environment. Components tend to fail more frequently under severe weather conditions than they do in normal weather situations. Weather conditions that create high component failure rates are generally rare and of short duration. Component failure rates, however, increase sharply, during these periods, and the probability of overlapping failures is far greater than that in normal weather. This results in a situation in which component failures are not randomly distributed throughout the year but are more probable in constrained short periods in the year. This phenomenon is called the adverse weather bunching effect [1]. If this fact is neglected, the reliability indices evaluated for a load point can be over-optimistic and

consequently very misleading. Techniques [1] used to account for failure bunching do not imply that there is dependence between the failures of components. Although the components may reside within a common environment which affects their failure rates, the actual failure process of overlapping outages still assumes the component failures to be independent. There is a large range of possible weather conditions but because of the difficulty of collecting suitable and acceptable data, this range is classified into the two states of normal and adverse. The criterion for deciding to which category a given weather event should be assigned is dependent on the impact of the weather on the failure rate of a component. Those weather conditions having little or no effect on the failure rate should be classified as normal and those having a large effect should be classed as adverse. In order to incorporate the two state weather model, the average durations of normal and adverse weather periods must be known. In addition, permanent failure, active failure and temporary failure rates must be subdivided into the respective rates experienced during normal and adverse weather. These failure rates must be expressed as the number of failures per year of that particular weather condition and not as the number of failures in the calendar year. As an example, consider the average total failure rate λ_{av} of a component and its two subdivided rates λ and λ' . These outage rates are related as follows;

$$\lambda_{av} = \frac{N}{(N+S)}\lambda + \frac{S}{(N+S)}\lambda'$$

where,

λ = failure rate during normal weather expressed in failures/year of normal weather,

λ' = failure rate during adverse weather expressed in failures/year of adverse weather,

N = Average duration of normal weather,

S = Average duration of adverse weather.

The first contribution [6, 20] to the evaluation of a two-state weather model proposed a set of approximate equations for use with a network reduction method. These, although a major step forward, contained certain weaknesses which were identified from a Markov analysis [23] of the same problem. Subsequently a modified set of equations were proposed [20] which now form the basis of most evaluation methods. The modified set of equations are provided in References 1 and 20.

2.5. Summary

This chapter presents some simple equations to evaluate the reliability indices of subtransmission systems in terms of the outage frequency and duration at various system load points. These equations can be used in conjunction with a standard failure modes and effects approach to analyse a relatively complex configuration in a sequential manner. The failure modes recognized in this chapter are permanent, temporary and maintenance outages. The separation of various modes of component failures can pinpoint the components and their parameters which make a significant contribution to system failure. The two state weather model is also discussed briefly. Although the model is discussed in this chapter in relation to weather, the technique may clearly be related to any two state environmental stress model provided the appropriate failure rates and the average duration of the two environmental stresses are known.

The concepts presented in this chapter were utilized in the development of a computer program for evaluating the reliability indices of subtransmission systems. The program and its application are discussed in Chapter 3.

3. SUBTRANSMISSION SYSTEMS RELIABILITY EVALUATION

3.1. Introduction

The manual solution of reliability models for subtransmission systems, involving components having different modes of failure, is extremely laborious and becomes quite unmanageable as the number of components increases. The inclusion of weather dependent failures and different repair and switching procedures requires the utilization and solution of many complicated equations. The representation of up to second order overlapping outages in numerical form is relatively straight forward and their evaluation is simple. It is difficult, however, to evaluate the equations for third order outages which may have an appreciable contribution to the total system reliability indices. It was therefore decided to develop a digital computer program for the evaluation of subtransmission system reliability indices. This chapter briefly describes the computer program developed for the evaluation of reliability performance in subtransmission systems. The program is designated as 'SUBTREL'. It is quite general and can be used for reliability evaluation of any type of subtransmission system. The equations described in Reference 1 and in Appendix B of this thesis were utilized in the development of the program. The program is structured in such a way that a knowledge of reliability techniques is not required in order to use the program. The analysis can be done by knowing the system configuration and developing familiarity with its operation. Sensitivity analysis with respect to the input parameters can be performed using the program. A small subtransmission system is also presented in this chapter to illustrate the use of the program.

3.2. User Friendly Program

The program 'SUBTREL' calculates basic reliability indices and also system performance indices of subtransmission systems taking into consideration some of the factors affecting the reliability performance of the system. It is written in FORTRAN-77. The algorithms are programmed to select the various possible combinations of occurrences within the system which can cause interruption to the designated load point. In order to debug the program and for simplicity in use, it has been divided into fifteen modules or subroutines. These subroutines are based on the different conditions which are imposed on the system and basic reliability indices are calculated in each of the modules selected by the user. The program requires two input data files and generates three output data files. A simplified flowchart for the computer program is shown in Figure 3.1. The basic steps involved in performing the failure analysis and the computation of the reliability indices are explained in Figure 3.1.

The first step consists of reading the input data from data file 1, which requires information on the number of components in the system, the number of load points in the system, the number of customers and load connected in each load point, each element number which undergoes an active failure with the element numbers which are affected by the failure of that particular element and elements in a path from the supply to the load point for each load point. The program then reads the input data from data file 2 which requires information on the component reliability parameters of all components of the system. The average durations of normal and adverse weather periods are also specified in data file 2.

The program execution then starts with the determination of the minimal cutsets for the load point under consideration. The algorithm used in determining the minimal cutsets is described in References 18 and 19. The components undergoing active failures with respect to a particular load point are evaluated next. Only first order active failure events are considered. If any element on active failure has already been evaluated as a first order minimal cut it is not necessary to consider the active failure of that element any further. When all the minimal cutsets and active failure events have been deter-

mined, the computations are made for the contribution of each cutset to the basic reliability indices of the subtransmission system. The indices are computed using the appropriate equations described in Reference 1 and also in Appendix B. These equations are stored in the computer as subroutines. When these computations have been made for all the cutsets, the total contribution to the load point reliability indices due to active failures is evaluated. When all the above computations are completed, the overall reliability indices are determined by combining the outages of all active, permanent, temporary and maintenance modes for a particular load point. At the same time it also considers the effect of adverse weather conditions on permanent and temporary outages. Indices evaluated include load point failure rate, λ (f/yr), outage duration, r (hr) and annual unavailability, U (hr/yr). The system performance indices, SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS are then evaluated using the basic reliability indices and the customer data at each load point. These indices are defined in Appendix A.

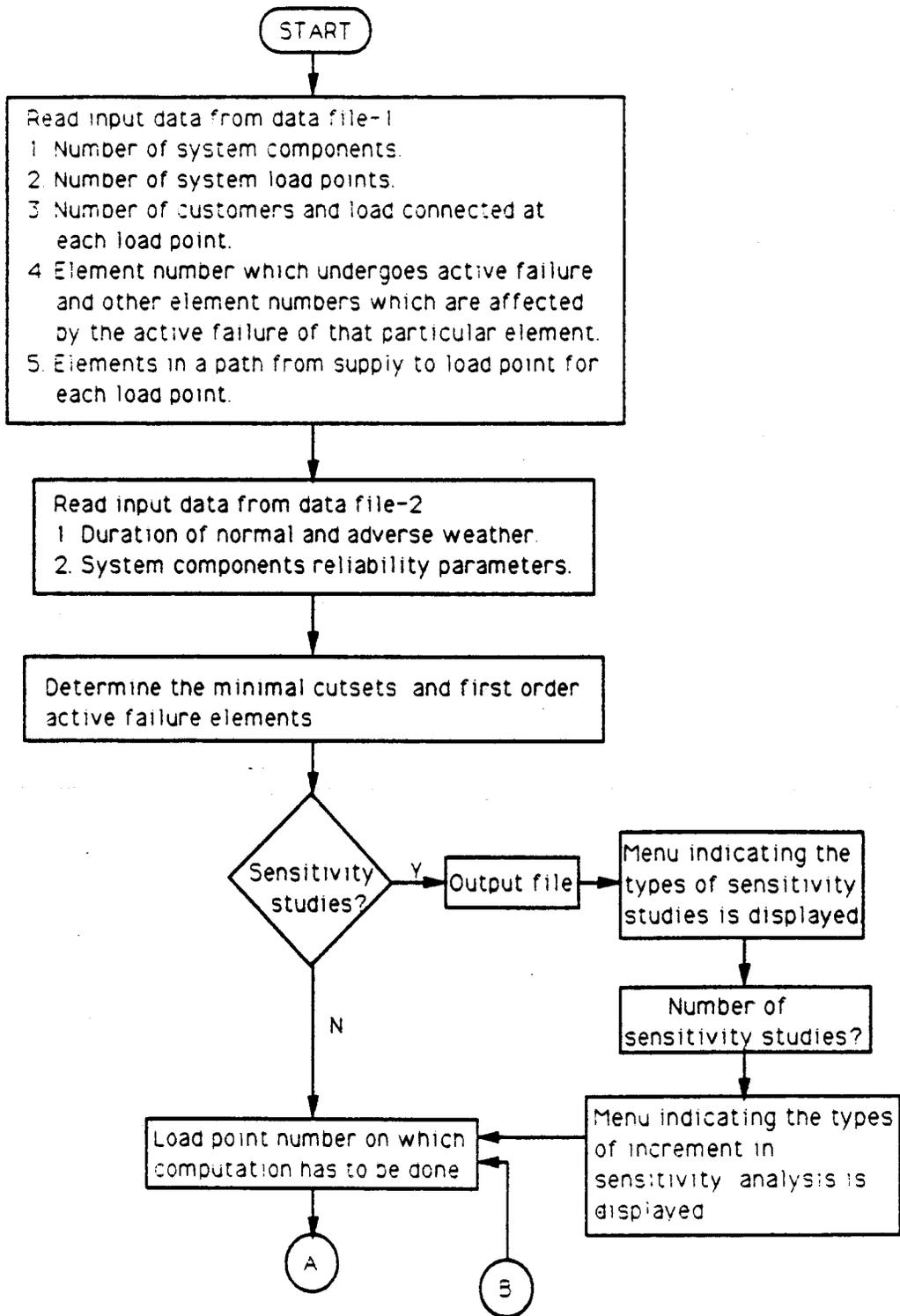
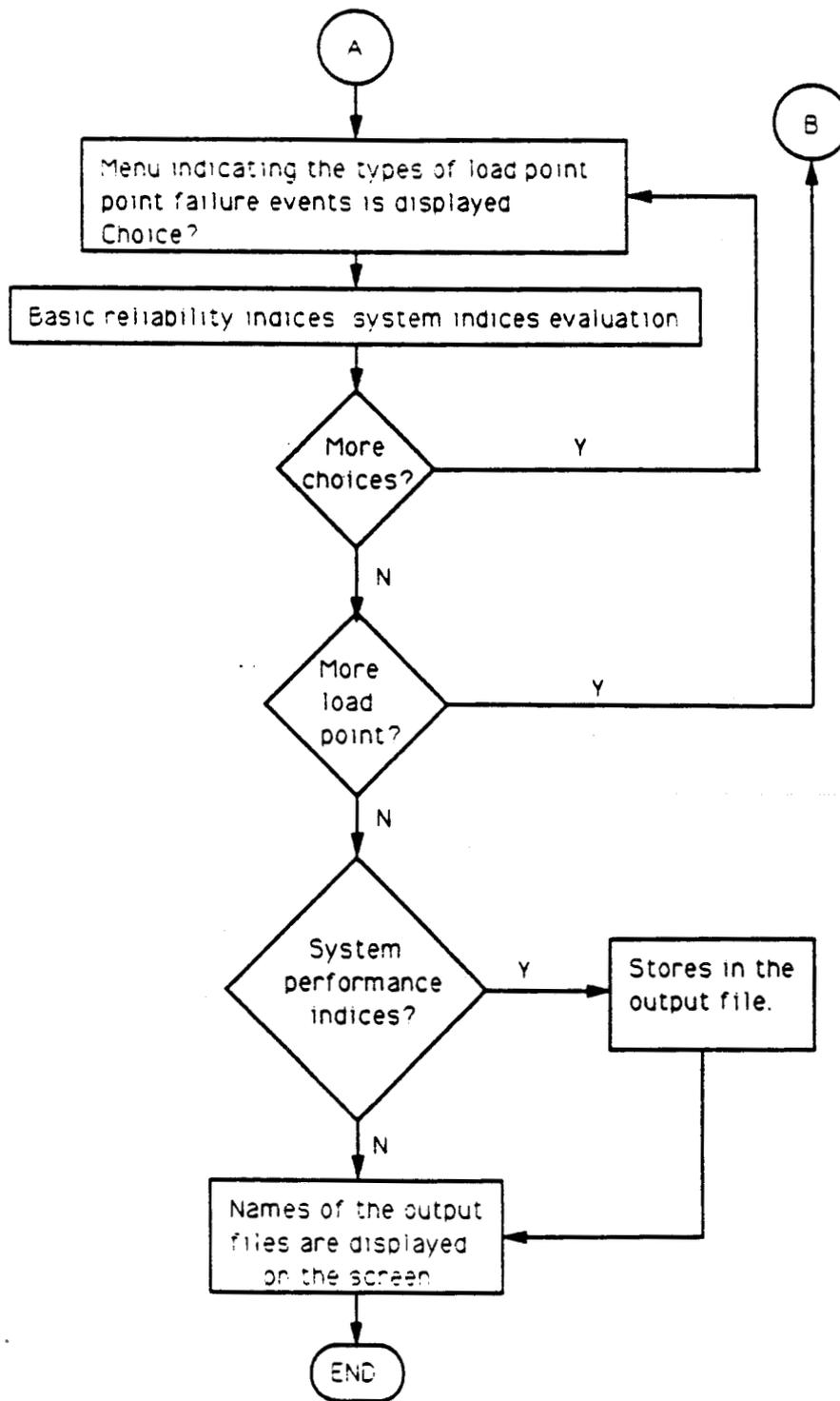


Figure 3.1: Flowchart of the computer program.

Figure 3.1, continued



Sensitivity analysis can also be performed, if desired, using the program. In order to perform these studies, an output file name has to be provided by the user. The type of sensitivity studies performed must be selected from the options that appear on the screen during the execution of the program. Once an option has been selected, the program evaluates the reliability indices for the number of times, as desired by the user, for a particular load point.

The dimensions of the arrays in the program can be increased, if the computer size can accommodate a larger number of components. It should be noted that the limit to the number of components which can be handled by the program is determined only by the size of the computer available. Detailed structure of input data files, interactive features and subroutines of the program are provided in Appendix C.

3.3. System Studies

The computer program described in the previous section has been used in a number of system studies. An example is presented here to illustrate the ability of the program. The single line diagram of the subtransmission system considered is shown in Figure 3.2. The system has one load point and two supply points. The voltage at one of the supply points is 120kV and at the other is 66kV. The supply points are connected to the load point by overhead transmission lines. These lines are equipped with 120kV and 66kV breakers. The 120kV supply to one of the lines is stepped down to 66kV by a transformer. The elements are numbered as follows:

Transformer(120/66kV)-	6
66kV Bus	- 8
66kV Breaker	- 1,3,7
66kV Line	- 2
120kV Breaker	- 4
120kV Line	- 5

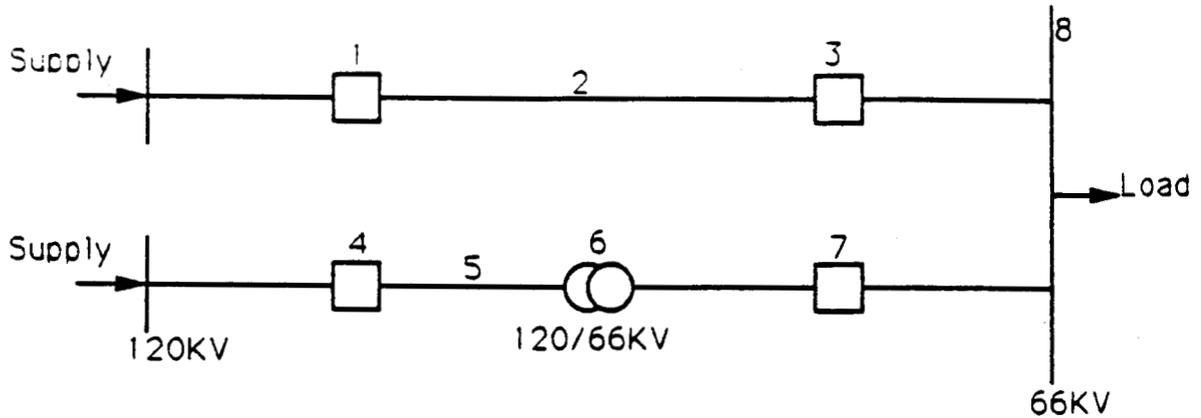


Figure 3.2: Single line diagram of the test system.

The criterion used for the evaluation of the reliability indices is 'total loss of continuity', i.e. a load point fails only when all the connections between the load point and the supply are broken. The reliability data for the system components are given in Table 3.1. The table includes sufficient data to perform basic reliability analysis of the system. It has been assumed that no temporary outages can occur on the breakers. Busbars are not taken out for maintenance and only transmission lines are exposed to the environment. The average load seen by the load point due to diversity between customers and normal load variations through the day and through the year is assumed to be 8 MW. The number of customers at the load point is 500.

3.4. Test System Results

A range of reliability indices was calculated for a number of studies. In the system shown in Figure 3.2, there are two active failure (first order) events. In addition, the system has 1 first order, 12 second order and 0 third order minimal cuts. Table 3.2 shows the basic reliability indices for the different conditions imposed on the system.

Table 3.2 shows the contribution from all mincuts up to the third order. The third order contributions are zero, as there are no third order minimal cuts in this system. In the case of adverse weather, only overlapping permanent outages due to adverse weather were considered as only permanent failure rates of transmission lines are given in Table

Table 3.1: Reliability data for the test system.

Components	λ	λ_a	λ_t	λ''	r	r''	r _c	s
Transformer								
120/66	0.0150	0.0100	0.0050	2.0	336	2.00	1.000	1.0
Breakers								
66	0.0200	0.0010	0.0000	1.5	48	6.00	0.000	1.0
120	0.0150	0.0010	0.0000	1.0	48	4.00	0.000	1.0
Busbar								
66	0.0113	0.0010	0.0156	0.0	4	0.00	0.083	1.0
Lines (One weather state)								
66	0.5000	0.0500	3.0000	2.0	6	8.2	0.083	1.0
120	0.7000	0.0500	1.7000	1.0	8	6.0	0.1667	1.0
Lines (Two weather state)								
66(nor)	0.20075	0.000	0.0000	0.0	6	0.0	0.0000	0.0
(adv)	80.3000	0.000	0.0000	0.0	0	0.0	0.0000	0.0
120(nor)	0.28105	0.000	0.0000	0.0	8	0.0	0.0000	0.0
(adv)	112.420	0.000	0.0000	0.0	0	0.0	0.0000	0.0

weather data:

average duration of normal weather = 200 hr

average duration of adverse weather = 2 hr

where,

λ = permanent (total) failure rate (f/yr) [for lines (f/yr)]

λ_a = active failure rate (f/yr) [for lines (f/yr)]

λ_t = temporary failure rate (f/yr) [for lines (f/yr)]

λ'' = maintenance outage rate (o/yr)

r = repair time (hr)

r'' = maintenance outage time (hr)

r_c = reclosure time (hr)

s = switching time (hr)

single weather state- rates are annual averages

two weather state - rates are per year of appropriate weather condition

Table 3.2: Basic reliability indices at the test system.

No.	Condition	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	ACTIVE	.20000E-02	1.000	.20000E-01
2	P+PP+PPP	.12481E-01	4.176	.52119E-01
3	MP	.43630E-03	3.533	.15414E-01
4	T+PT	.20816E-01	0.086	.18070E-02
5	MT	.14572E-01	0.119	.17448E-02
6	P(W)P(W)	.41616E-01	5.407	.22502E+00
7	MP(W)	.00000E+00	0.000	.00000E+00
8	P(W)T(W)	.00000E+00	0.000	.00000E+00
9	MT(W)	.00000E+00	0.000	.00000E+00
10	MPP	.00000E+00	0.000	.00000E+00
11	PPT	.00000E+00	0.000	.00000E+00
12	MPT	.00000E+00	0.000	.00000E+00
13	P(W)P(W)P(W)	.00000E+00	0.000	.00000E+00
14	MP(W)P(W)	.00000E+00	0.000	.00000E+00
15	P(W)P(W)T(W)	.00000E+00	0.000	.00000E+00
16	MP(W)T(W)	.00000E+00	0.000	.00000E+00
	TOTAL	.95848E-01	3.110	.29811E+00

where,

P = Permanent outage,

P(W) = Permanent outage in adverse weather conditions,

T = Temporary outage,

T(W) = Temporary outage in adverse weather conditions,

M = Maintenance outage,

PP = Overlapping permanent outages,

MPT = Maintenance outage overlapped by permanent and temporary outages.

Other terms can be similarly defined.

3.1 . All other adverse weather values were assumed to be zero. Overlapping temporary failures are quite frequent because the temporary failure rate is very high in comparison with other failure rates. Since there is only one first order and no third order minimal cuts, the percentage contribution due to second order events with 12 mincuts is greater than that of first and third order events, as shown in Table 3.3. The evaluated system indices are shown in Table 3.4.

Table 3.3: Percentage contribution of outages for test system.

No.	Condition	Percentage Contribution	
		Failure Rate	Annual Unavailability
1	1st order	30.152	16.268
2	2nd order	69.848	83.732
3	3rd order	0.000	0.000

Table 3.4: System indices.

SAIFI = 0.09585 interruptions/customer-yr

SAIDI = 0.29811 hr/customer-yr

CAIDI = 3.11022 hr/customer interruption

ASAI = 0.9999999319

ASUI = 0.0000000680

ENS = 2384.8637 kWhr/yr

AENS = 4.76972 kWhr/customer yr

The effects of varying the input parameters on the reliability indices are discussed in the following sections.

3.4.1. Component effect

Figure 3.3 shows the variation in the load point failure rate due to increase in the component permanent failure rates. Figure 3.3 provides an indication of the degree to which each component contributes to the load point failure rate. In this system, the major portion of the load point failure rate comes from busbar permanent failure events as the busbar forms the only first order minimal cut. The transmission line failure rate is higher than that of the transformer and the breaker failure rates hence the load point failure rate characteristic due to the variation in transmission line failure rate has a greater slope than that due to the variation in transformer or breaker failure rates. As the individual component failure rate increments increase, the transmission line failure events increase to the point at which they exceed the effect on the load point failure rate of the busbar failure events, as shown in Figure 3.3.

3.4.2. Weather effect

Figure 3.4 shows the effect of normal and adverse weather durations on the load point unavailability of the system. The load point unavailability increases with an increase in the adverse weather duration and decreases with an increase in the normal weather duration. It has been assumed in all the equations used in the program, that repair/restoration cannot be performed during adverse weather. If the normal weather duration is increased, the probability of a repair being completed before the weather changes from normal to adverse is increased and therefore the unavailability of the system decreases with the increase in normal weather duration. When the adverse weather duration is increased, the probability of a repair being completed decreases and hence the unavailability of the system increases, as shown in Figure 3.4.

3.4.3. Variation in system indices

The influence on the system performance indices of the variation in component repair times is shown in Figure 3.5. SAIFI is defined as the average number of customer interruptions per customer in the system and is given by Equation 3.1.

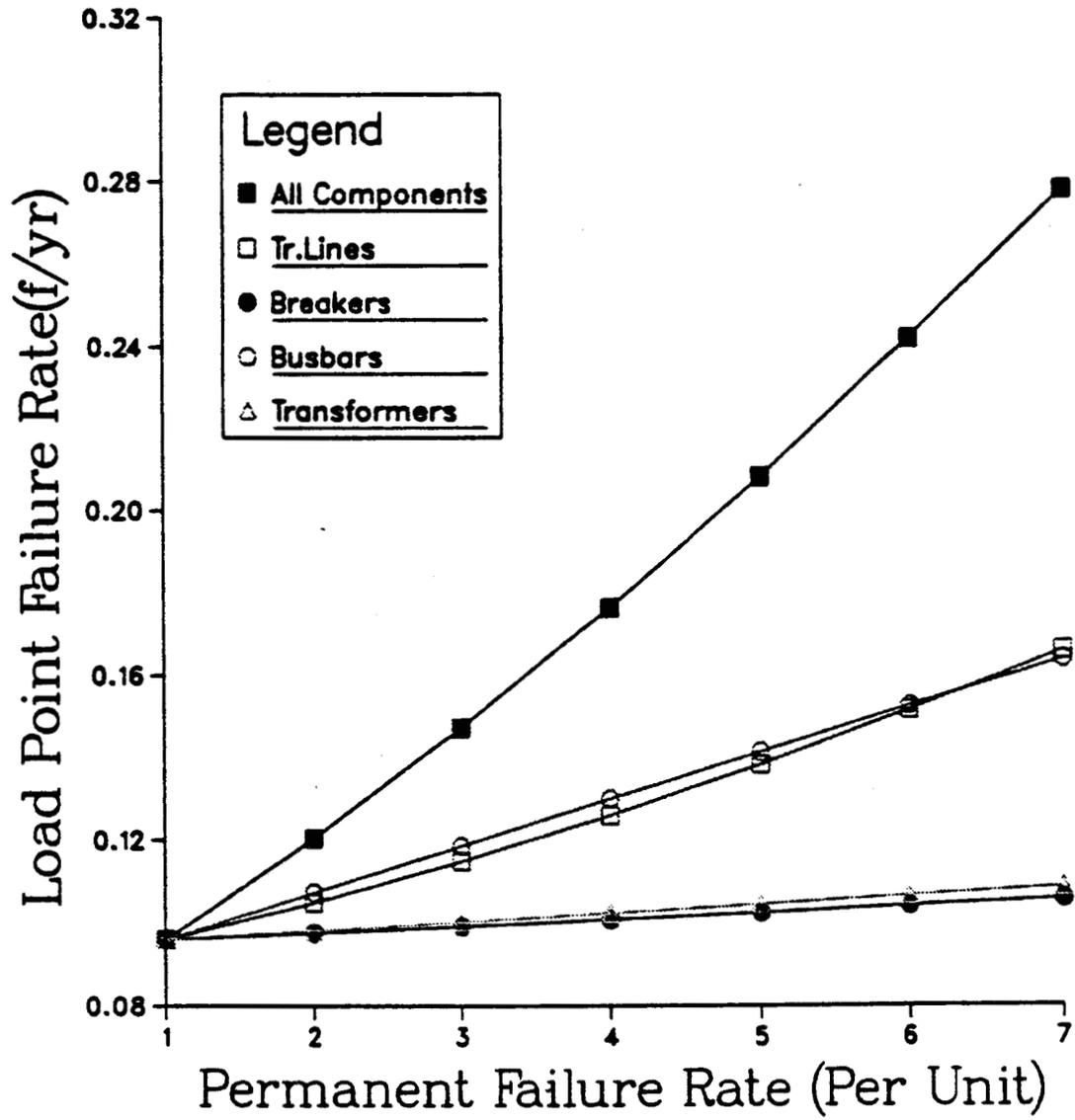


Figure 3.3: Load point failure rate variation.

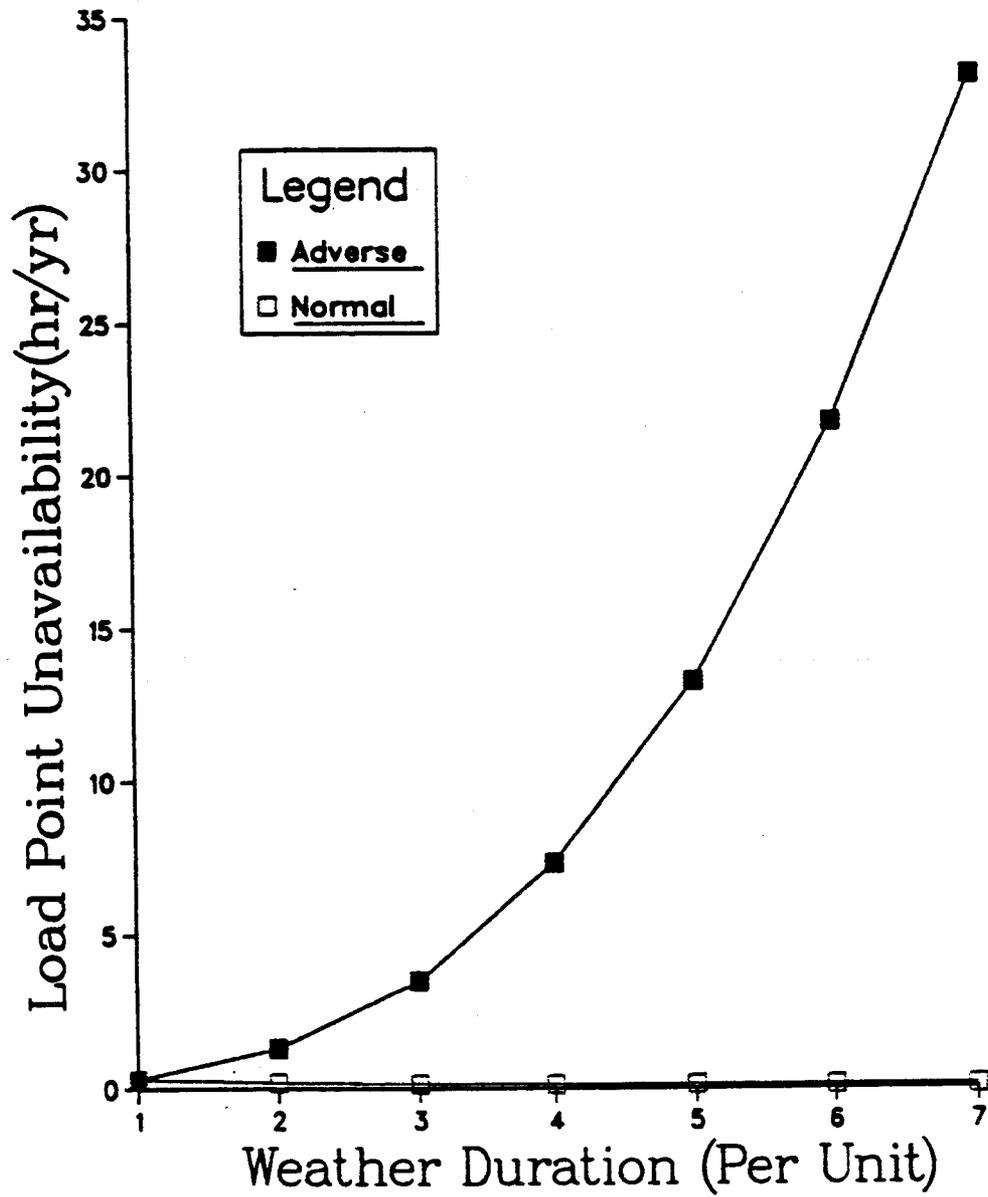


Figure 3.4: Load point unavailability variation.

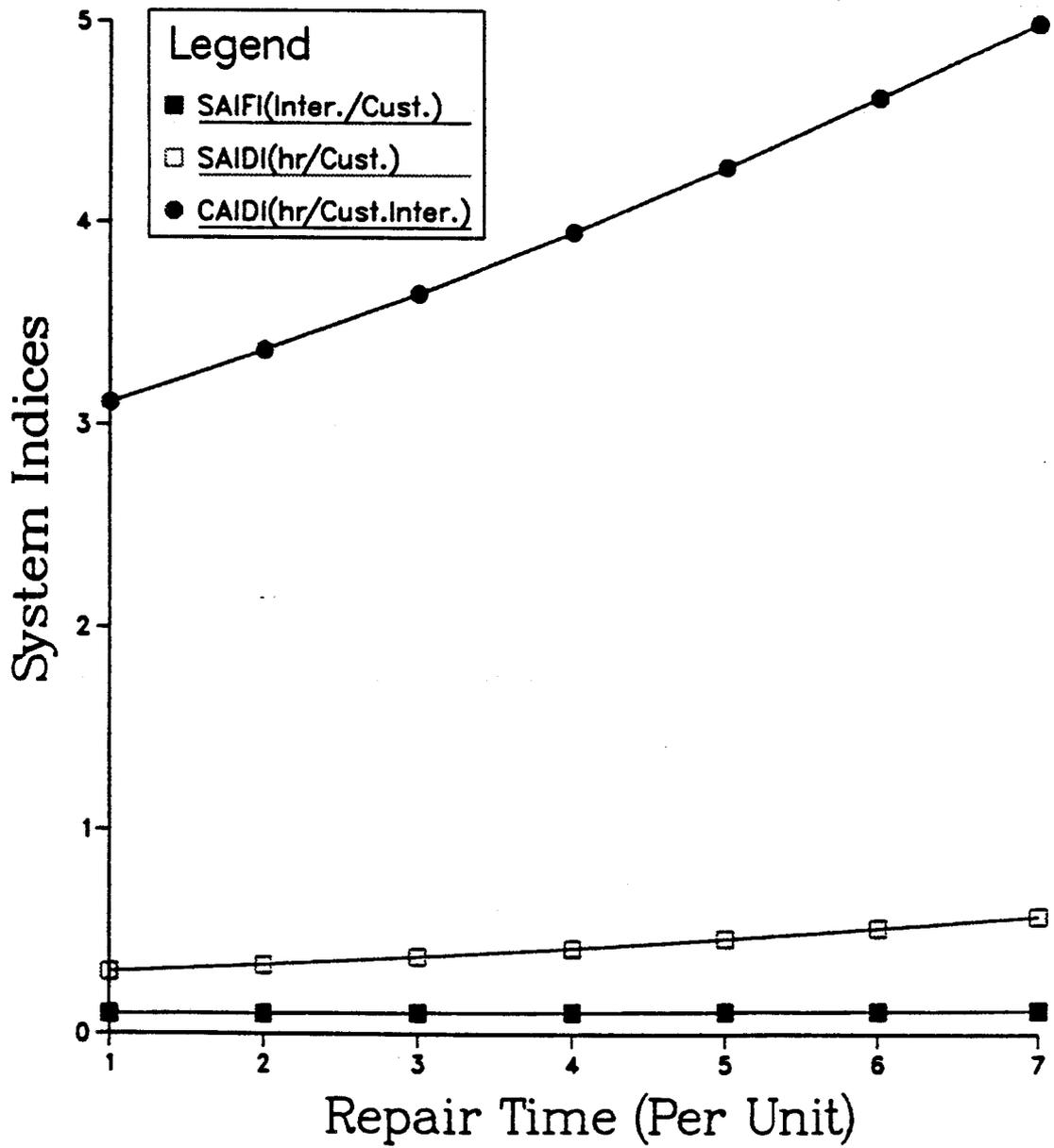


Figure 3.5: System indices variation.

$$SAIFI = \frac{\sum_{i=1}^l \lambda_i N_i}{\sum_{i=1}^l N_i} \quad (3.1)$$

λ denotes the failure rate and N the number of customers at load point 'i' in the system. It can be observed from Equation 3.1 that the component repair time is not present in the equation for SAIFI. SAIFI in Figure 3.5 increases slightly, however, with increases in the component repair times. This is due to the fact that SAIFI includes all load point failure events, which in the case of overlapping outages depend upon the repair times of the individual components.

SAIDI is defined as the average customer outage duration per customer in the system and is given by Equation 3.2.

$$SAIDI = \frac{\sum_l U_l N_l}{\sum_l N_l} \quad (3.2)$$

U denotes the annual load point unavailability at the load point 'l'. Increasing the component repair times leads to a higher value of SAIDI as shown in Figure 3.5.

CAIDI is the average customer interruption duration per customer interruption and is given by Equation 3.3.

$$CAIDI = \frac{\sum_l U_l N_l}{\sum_l \lambda_l N_l} \quad (3.3)$$

Increasing the component repair times results in an increase in CAIDI as the load point outages are of comparatively longer duration.

3.5. Summary

This chapter describes a computer program developed to evaluate the reliability performance of subtransmission systems. The program is quite general and can be used for reliability evaluation of any type of subtransmission system. The program is capable of handling the basic component failure modes encountered in subtransmission systems and in addition also considers weather dependent failures. The output of the program provides concise sequential results of all load point failure events as selected by the user during the execution of the program. The program has been successfully applied to many system configurations and a simple example is presented in this chapter to illustrate the basic procedure. The effects of varying the input parameters of the system on the basic reliability indices are also illustrated.

The next chapter presents the inherent features of a typical subtransmission system and the evaluation of this system using the program described in this chapter.

4. SUBTRANSMISSION SYSTEM STUDIES

4.1. Introduction

The computer program 'SUBTREL' described in Chapter 3 has been utilized in a number of system studies. In this chapter, two examples are presented to illustrate the capabilities of the program. The studies mentioned in this chapter are conducted using a reliability test system designated as the Roy Billinton Test System and abbreviated as the RBTS [24]. The RBTS is a basic reliability test system which evolved in 1988 from the reliability education and research programs conducted by the Power Systems Research Group at the University of Saskatchewan. This test system provides a consistent and generally acceptable set of data that can be utilized in generation capacity, composite system reliability and distribution system reliability evaluation. It also provides a consistent basis for comparison of results obtained by using different methods. Prior to its development, the IEEE reliability test system (IEEE-RTS) [21] developed by the Application of Probability Method Subcommittee was the only test system widely utilized. The IEEE-RTS is used to compare and test a wide range of generating capacity and composite system evaluation techniques and subsequent computer programs. The IEEE-RTS has a reasonably large power network which requires the use of computer programs to obtain system indices. It is, therefore, only partially suited to the development of basic concepts and an appreciation of the assumptions associated with conducting practical system reliability studies. The main objective in designing the RBTS is to make it sufficiently small to permit the conduct of a large number of reliability studies with reasonable solution time and at the same time sufficiently detailed to reflect the actual complexities involved in a practical reliability analysis. Reference 24 provides the basic generation and transmission data for the RBTS for a range of generating and composite system adequacy studies. An extension of the RBTS [26], which includes distribution systems, was published in 1990. The distribution systems of the RBTS contain the essen-

tial elements found in a practical system. These systems are sufficiently small and can be analysed using hand calculations with little difficulty.

A brief description of the subtransmission portion of the distribution systems of the RBTS and the data needed to perform basic reliability analysis of the subtransmission system are presented in this chapter. The analyses of the results for a range of studies on the RBTS utilizing the computer program 'SUBTREL' are also presented.

4.2. System Description

The RBTS has five load busbars (Bus-2 to Bus-5) of which only two busbars (Bus-2 & Bus-4) are selected for further studies. Subtransmission networks are designed for the two selected busbars. General utility principles and practices regarding topology, ratings and loading levels have been followed in designing these subtransmission networks. The single line diagrams are shown in Figures 4.1 and 4.2 for Bus-2 and Bus-4 respectively.

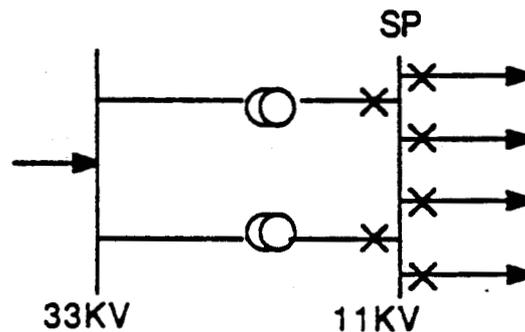


Figure 4.1: Single line diagram for RBTS Bus-2.

The following comments relate to these designs.

1. The load level of Bus-4 (40MW) is sufficient to justify higher reliability provided by a 33 kV ring linking three supply points (SP1, SP2 and SP3). The load level of Bus-2 (20MW) justifies a single supply point.
2. All 33kV lines are overhead transmission lines.

The number of customers and individual loads connected at each supply point is

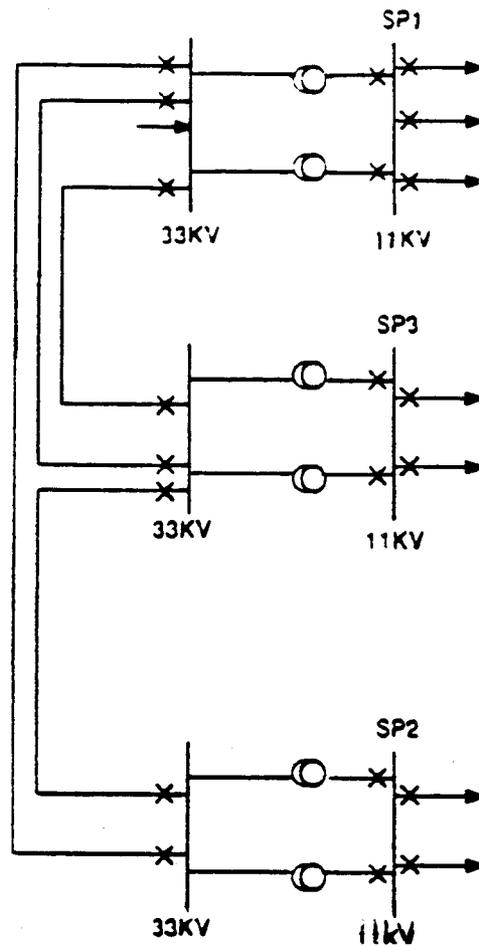


Figure 4.2: Single line diagram for RBTS Bus-4.

shown in Table 4.1. It is assumed that the defined average load is the average value seen by a supply point. The reliability data for system components in Bus-2 & Bus-4 of the RBTS are given in Table 4.2. The data to conduct reliability analysis including weather effects on the 33kV overhead line system, permanent failures, temporary failures, maintenance outages and active failures are shown in Table 4.2. The table also includes 33kV circuit lengths and transformer ratings.

Table 4.1: Customer and loading data for Bus-2 and Bus-4 of the RBTS.

No.	Supply Point	Average Load(MW)	Peak Load(MW)	No. of Customers
Bus-2				
1	SP	12.291	20.000	1908
Bus-4				
1	SP1	10.475	17.040	2183
2	SP2	7.010	11.408	1303
3	SP3	7.095	11.552	1293
	TOTAL	24.580	40.000	4779

4.3. System Studies

A range of reliability indices are calculated for a number of studies. The methods for evaluating these indices are already discussed in previous chapters. The indices are :

a) Load point indices

1. Failure rate
2. Outage time
3. Annual unavailability

b) System performance indices

1. SAIFI
2. SAIDI
3. CAIDI
4. ASAI
5. ASUI
6. ENS
7. AENS

The load point indices are calculated at each specified load and system performance indices are calculated for the overall system.

Table 4.2: Reliability data for Bus-4.

Comp.	Perm. failure rate (f/yr)	Active failure rate (f/yr)	Temp. failure rate (f/yr)	Maint. outage rate (o/yr)	Rep. time (hr)	Maint. time (hr)	Reclosure time (hr)	Switching time (hr)
Transformer 33/11	0.0150	0.0150	0.050	1.0	15	120	0.083	1.0
Breakers 33	0.0020	0.0015	0.020	0.5	4	96	0.083	1.0
11	0.0060	0.0040	0.060	1.0	4	72	0.083	1.0
Busbars 33	0.0010	0.0010	0.010	0.5	2	8	0.083	1.0
11	0.0010	0.0010	0.010	1.0	2	8	0.083	1.0
Line (One weather state) 33	0.0460	0.0460	0.060	0.5	8	8	0.083	2.0
Line (Two weather state) 33(nor)	0.0139	0.0139	0.018	0.5	8	8	0.083	2.0
(adv)	5.8600	5.8600	7.600					

weather data:

average duration of normal weather = 724 hr

average duration of adverse weather = 4 hr

line failure occurring in adverse

weather = 70% of total

33kV line length:

SP1-SP2 = 10km

SP2-SP3 = 10km

SP1-SP3 = 15km

transformer ratings:

SP1 = 16MVA each

SP2 = 10MVA each

SP3 = 10MVA each

Perm. = Permanent

Temp. = Temporary

Maint. = Maintenance

Rep. = Repair (Replacement for transformer)

Reliability indices are evaluated between the 33kV busbar and the 11kV supply point busbar. Any failure on the incoming 33kV supply circuits is ignored. The effect of passive and active failures on all components from the 33kV busbar down to the 11kV supply point busbar together with active failures on the outgoing 11kV feeder breakers are considered in the studies. The system is considered to be failed if there is no continuous path from the source bus to the load bus. Overlapping outages beyond the third order are neglected in the studies. The first set of studies pertain to the reliability evaluation of the subtransmission system of RBTS Bus-2. Bus-2 in the RBTS has only one supply point as shown in Figure 4.1. The second study system is the RBTS Bus-4 which has three supply points as shown in Figure 4.2.

4.3.1. RBTS Bus-2 studies

There are 8 active failure (first order) events. In addition, there are two 1st order, four 2nd order and zero 3rd order minimal cuts. Table 4.3 shows the reliability indices for different outage combinations.

It is observed from Table 4.3 that during adverse weather, reliability indices due to second order minimal cuts are zero as there are no transmission lines considered in this system. The indices due to transmission line outages are the only ones which are affected by adverse weather. The third order contribution is zero as there are no third order minimal cuts in the system.

Table 4.4 shows that the contribution of the first order minimal cuts is very high as compared to that of the second order minimal cuts. This accounts for the fact that the lower order outages are more important than the higher order outages as far as the evaluation of reliability indices is concerned. All first order outages, therefore, have to be considered in order to achieve more realistic results.

Performance indices evaluated for RBTS Bus-2 are shown in Table 4.5.

Table 4.3: Basic reliability indices at Bus-2.

No.	Condition	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	ACTIVE	.54000E-01	1.000	.54000E-01
2	P+PP+PPP	.20012E-02	2.002	.40071E-02
3	MP	.92055E-03	10.37	.95505E-02
4	T+PT	.20006E-01	.0830	.16605E-02
5	MT	.48219E-02	.0829	.39987E-03
6	P(W)P(W)	.00000E+00	0.000	.00000E+00
7	MP(W)	.00000E+00	0.000	.00000E+00
8	P(W)T(W)	.00000E+00	0.000	.00000E+00
9	MT(W)	.00000E+00	0.000	.00000E+00
10	MPP	.00000E+00	0.000	.00000E+00
11	PPT	.00000E+00	0.000	.00000E+00
12	MPT	.00000E+00	0.000	.00000E+00
13	P(W)P(W)P(W)	.00000E+00	0.000	.00000E+00
14	MP(W)P(W)	.00000E+00	0.000	.00000E+00
15	P(W)P(W)T(W)	.00000E+00	0.000	.00000E+00
16	MP(W)T(W)	.00000E+00	0.000	.00000E+00
	TOTAL	.81750E-01	0.8516	.69618E-01

where,

P = Permanent outage,

P(W) = Permanent outage in adverse weather conditions,

T = Temporary outage,

T(W) = Temporary outage in adverse weather conditions,

M = Maintenance outage,

PP = Overlapping permanent outages,

MPT = Maintenance outage overlapped by permanent and temporary outages.

Other terms can be similarly defined

Table 4.4: Percentage contribution of outages for Bus-2.

Sl. No.	Condition	Percentage Contribution	
		Failure Rate	Annual Unavailability
1	1st order	92.966	85.696
2	2nd order	7.034	14.304
3	3rd order	0.000	0.000

Table 4.5: System indices of Bus-2.

SAIFI = 0.08175 interruptions/customer-yr

SAIDI = 0.06962 hr/customer-yr

CAIDI = 0.85160 hr/customer interruption

ASAI = 0.9999999958

ASUI = 0.0000000042

ENS = 855.67413 kWhr/yr

AENS = 0.44847 kWhr/customer yr

4.3.2. RBTS Bus-4 studies

There are three supply points in RBTS Bus-4, namely supply point-1 (SP1), supply point-2 (SP2) and supply point-3 (SP3). The reliability indices for these supply points obtained under different conditions imposed on the system are shown in Tables 4.6, 4.7 and 4.8 respectively. The indices are evaluated by utilizing the computer program 'SUB-TREL'. Hand calculations up to the second order outages are provided in Appendix C. The computer and hand calculated indices for the outages up to the second order are exactly the same. This demonstrates the effectiveness of the computer program.

The absence of transmission lines in the SP1 circuit results in the adverse weather second order contribution being zero. All the third order contributions are zero as there are no third order minimal cuts in SP1. This is shown in Table 4.6. Table 4.9 shows that the contribution of the first order minimal cuts is very high as compared to the second order minimal cuts

Table 4.6: Basic reliability indices at Bus-4 (for supply point 1).

No.	Condition	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	ACTIVE	.54500E-01	1.000	.54500E-01
2	P+PP+PPP	.20012E-02	2.001	.40071E-02
3	MP	.92055E-03	10.370	.95505E-02
4	T+PT	.20006E-01	0.083	.16605E-02
5	MT	.48219E-02	0.082	.39987E-03
6	P(W)P(W)	.00000E+00	0.000	.00000E+00
7	MP(W)	.00000E+00	0.000	.00000E+00
8	P(W)T(W)	.00000E+00	0.000	.00000E+00
9	MT(W)	.00000E+00	0.000	.00000E+00
10	MPP	.00000E+00	0.000	.00000E+00
11	PPT	.00000E+00	0.000	.00000E+00
12	MPT	.00000E+00	0.000	.00000E+00
13	P(W)P(W)P(W)	.00000E+00	0.000	.00000E+00
14	MP(W)P(W)	.00000E+00	0.000	.00000E+00
15	P(W)P(W)T(W)	.00000E+00	0.000	.00000E+00
16	MP(W)T(W)	.00000E+00	0.000	.00000E+00
	TOTAL	.82250E-01	0.852	.70118E-01

In the third order adverse weather (W) outage conditions, and particularly during the condition of a temporary failure overlapping two permanent outages (P(W)P(W)T(W)), the indices at SP2 are comparable to those due to second order outages as shown in Table 4.7. This is due to the fact that the transmission lines have higher failure rates under adverse weather conditions compared to those under normal weather conditions. At SP2, the contribution of the failure rate due to the second order minimal cuts is comparable to that of the first order minimal cuts due to a larger number of second order minimal cuts

Table 4.7: Basic reliability indices at Bus-4 (for supply point 2).

No.	Condition	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	ACTIVE	.91500E-01	1.000	.91500E-01
2	P+PP+PPP	.33938E-02	2.230	.75688E-02
3	MP	.11737E-01	7.403	.86898E-01
4	T+PT	.30556E-01	0.082	.25357E-02
5	MT	.19840E-01	0.082	.16446E-02
6	P(W)P(W)	.17438E-01	7.971	.13901E+00
7	MP(W)	.10781E-01	9.981	.10760E+00
8	P(W)T(W)	.45025E-01	4.065	.18303E+00
9	MT(W)	.14011E-01	2.874	.40275E-01
10	MPP	.21201E-04	3.801	.80601E-04
11	PPT	.77260E-06	0.081	.62821E-07
12	MPT	.14842E-04	0.082	.12178E-05
13	P(W)P(W)P(W)	.31350E-02	6.656	.20871E-01
14	MP(W)P(W)	.10496E-02	7.768	.81531E-02
15	P(W)P(W)T(W)	.12182E-01	4.077	.49673E-01
16	MP(W)T(W)	.27272E-02	0.082	.22376E-03
	TOTAL	.26341E+00	2.805	.73907E+00

and outage combinations. The percentage unavailability due to the second order minimal cuts is higher than that due to the first order minimal cuts as shown in Table 4.10. This is due to the fact that maintenance requires more time compared to other corrective actions and may cause overlapping outages resulting in a load point failure. Outages due to third order minimal cuts have a small contribution to the resulting indices.

No two transmission lines form a second order minimal cut at SP3. As a result of which second order reliability indices under adverse weather conditions do not contribute significantly to the final indices as observed from Table 4.8. Active failures have a considerable contribution to the final indices for all the supply points. Table 4.11 shows that the contribution from the first order failures is the highest at SP3. The third order contribution is higher than that of the second order as the number of third order minimal cuts is higher than that of second order minimal cuts.

Table 4.8: Basic reliability indices at Bus-4 (for supply point 3).

No.	Condition	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	ACTIVE	.93000E-01	1.000	.93000E-01
2	P+PP+PPP	.30023E-02	2.001	.60100E-02
3	MP	.92055E-03	10.375	.95505E-02
4	T+PT	.30006E-01	0.083	.24905E-02
5	MT	.48219E-02	0.082	.39987E-03
6	P(W)P(W)	.00000E+00	0.000	.00000E+00
7	MP(W)	.00000E+00	0.000	.00000E+00
8	P(W)T(W)	.00000E+00	0.000	.00000E+00
9	MT(W)	.00000E+00	0.000	.00000E+00
10	MPP	.42619E-04	3.795	.16176E-03
11	PPT	.15496E-05	0.081	.12600E-06
12	MPT	.33854E-04	0.082	.27777E-05
13	P(W)P(W)P(W)	.62708E-02	6.656	.41743E-01
14	MP(W)P(W)	.21344E-02	8.189	.17480E-01
15	P(W)P(W)T(W)	.24366E-01	4.077	.99357E-01
16	MP(W)T(W)	.55409E-02	0.082	.45454E-03
	TOTAL	.17014E+00	1.590	.27065E+00

Table 4.9: Percentage contribution of outages for supply point 1.

Sl. No.	Condition	Percentage Contribution	
		Failure Rate	Annual Unavailability
1	1st order	93.009	85.789
2	2nd order	6.991	14.202
3	3rd order	0.000	0.000

The system indices for Bus-4 are shown in Table 4.12. Bus-4 has three load points and Bus-2 has only one load point. The SAIFI, SAIDI, CAIDI and ASAI values for Bus-4 are, therefore, higher than that for Bus-2. ENS depends upon the average load

Table 4.10: Percentage contribution of outages for supply point 2.

Sl. No.	Condition	Percentage Contribution	
		Failure Rate	Annual Unavailability
1	1st order	47.264	13.529
2	2nd order	45.473	75.781
3	3rd order	7.263	10.690

Table 4.11: Percentage contribution of outages for supply point 3.

Sl. No.	Condition	Percentage Contribution	
		Failure Rate	Annual Unavailability
1	1st order	74.056	37.499
2	2nd order	3.380	3.679
3	3rd order	22.565	58.822

connected to the load point and the unavailability of each load point. Since both of these values in the case of Bus-4 are higher compared to those of Bus-2, the ENS of Bus-4 is higher than that of Bus-2.

4.4. Summary

The computer program 'SUBTREL', for the reliability evaluation of subtransmission systems, is suitable for analysing a wide range of networks of sizes normally encountered in actual systems. In this chapter, two system examples are presented to expose the salient features of the program. These two systems, forming two parts of the RBTS, serve as useful examples in order to demonstrate the evaluation technique. The merits of these systems are:

1. Their simplicity which makes them suitable not only for computer programming but also for hand calculations and

2. Their efficiency in recognising real operational features of a system.

In the next chapter, results of a large number of sensitivity studies performed on these two subtransmission systems by making use of the computer program 'SUBTREL' are presented. This will illustrate the additional capability of the program.

Table 4.12: System indices for Bus-4.

SAIFI = 0.15542 interruptions/customer-yr

SAIDI = 0.30676 hr/customer-yr

CAIDI = 1.97372 hr/customer interruption

ASAI = 0.9999999927

ASUI = 0.0000000073

ENS = 3172.83496 kWhr/yr

AENS = 0.66391 kWhr/customer yr

5. SUBTRANSMISSION SYSTEM SENSITIVITY STUDIES

5.1. Introduction

In order to increase the reliability of subtransmission systems, suitable locations to install additional facilities have to be determined. The problem is then to find the parts of the system where money should be invested in order to enhance system performance. By performing sensitivity studies, one can determine the part(s)/component(s) of a system which contribute most to the system unreliability indices. These studies will enable power system engineers to have flexible decision strategies which involve adding the right equipment, at the right time and in the right location in order to obtain optimum economic benefit at an increased reliability level. A comparison of different kinds of customers can be made with regard to the reliability indices and the effect of geographical factors on different types of customers can also be assessed by performing sensitivity studies. It has been observed from the sensitivity studies that the customer reliability is influenced by the amount of equipment exposed to adverse weather conditions. The variation in the customer reliability can be assessed by sensitivity studies. In component installation planning, full attention must be given to the environmental conditions in which the component will operate.

The results of some of the system studies obtained by utilizing the program 'SUB-TREL' have been presented in Chapter 4. The program is not only capable of evaluating the reliability indices but also is capable of performing sensitivity studies. The effects of varying the input parameters on the reliability indices are discussed in this chapter. The input parameters which have been utilized for the base case analysis, for RBTS Bus-2 and Bus-4, are shown in Tables 4.1 and 4.2 in Chapter 4. Sensitivity analysis consisting of a given number of cycles with respect to each of the base case parameters have been performed. In each cycle, a parameter is incremented by a fixed number or incremented

as an integer multiple of the base case value as provided by the user during the execution of the program. Other parameters are held fixed at their base levels. The results of the analysis have been plotted and are discussed in the next two sections.

5.2. RBTS Bus-2 Sensitivity Studies

5.2.1. Effect of change in component failure rates on supply point failure rate

Figure 5.1 shows the variation in supply point failure rate for corresponding variations in component failure rates for different types of failure modes. The maximum contribution in the supply point failure rate of the system comes from the component active failure rates due to the fact that the active failure events form the maximum number of first order outages. Reliability indices due to transmission line outages are the only ones which are affected by adverse weather conditions. Due to the absence of transmission lines in the circuit, there is no variation in the supply point failure rate with increments of component failure rates in adverse weather conditions. This fact is shown in Figure 5.1. In spite of the fact that component temporary outages have lower values than that of component maintenance outages, the slope of the supply point failure rate due to variations in component temporary outages is more than that due to variations in component maintenance outages. This is due to the fact that temporary outages form a larger number of failure events compared to that formed by maintenance outages. A maintenance outage cannot form a first order outage event and no maintenance is carried out if there is any outage already existing in a related portion of the system. This is one of the assumptions [28] made in order to evaluate the interruptions due to component maintenance outage.

5.2.2. Effect of variation in duration on unavailability

The annual unavailability is the expected total time in a year that a load point will be on outage. It is thus directly related to the load point restoration duration. Figure 5.2 shows the variation of supply point unavailabilities with the variation of different types of restoration modes. RBTS Bus-2 has two 1st order, four 2nd order and no 3rd order total failure events. In addition, it has eight 1st order active failure events. Due to the large number of active failure events in Bus-2, the supply point unavailability due to a varia-

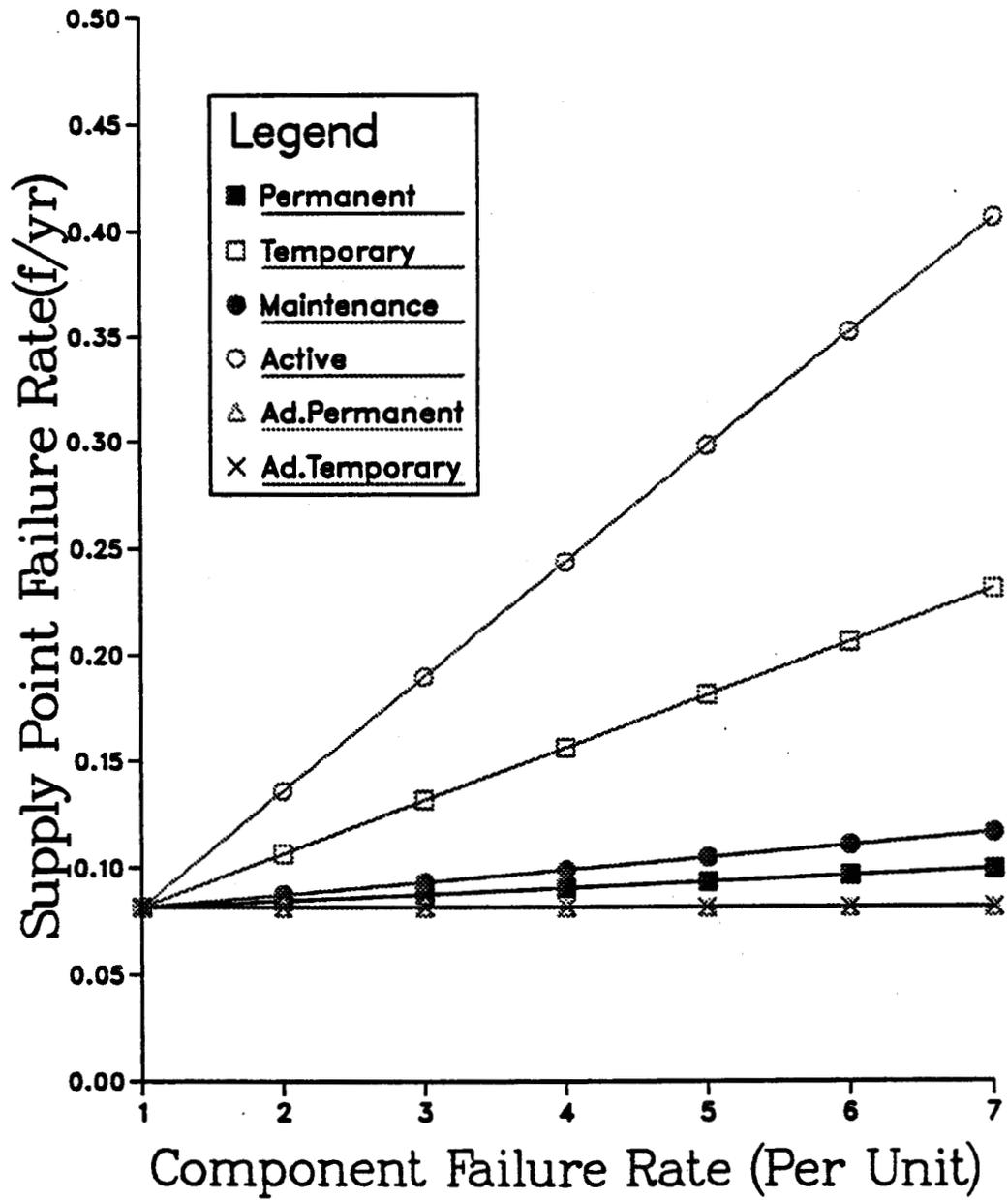


Figure 5.1: Variation in supply point failure rates with component failure rates increment.

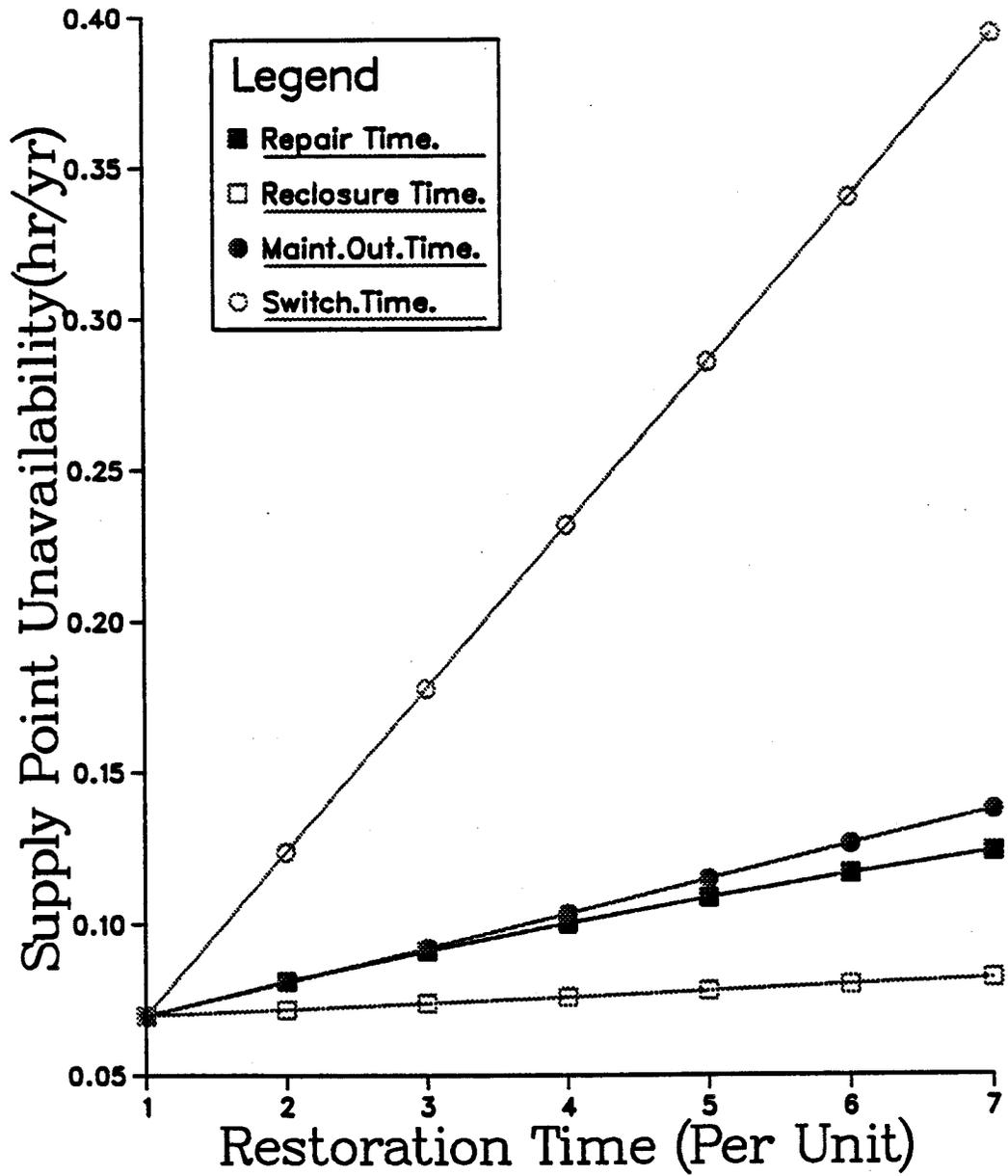


Figure 5.2: Variation of unavailability of supply point with increments of component restoration time.

tion in component switching time is maximum as shown in Figure 5.2. The slopes of the supply point unavailability due to other restoration times, i.e. maintenance outage time, repair time and restoration time, are directly proportional to their respective circuit component restoration time.

5.2.3. Effect of variation in component permanent failure rate on different outages

Figure 5.3 shows the contribution of 1st, 2nd and 3rd order outages to the supply point failure rate when component permanent failure rates are increased.

With an increase in the component permanent failure rates, the 1st order outages, though maximum, decrease and the value of 2nd order outages increases. This is due to the fact that there are a larger number of 2nd order outages than 1st order outages. Figure 5.3 shows that at higher values of permanent failure rate the effect of 2nd order outages dominates the effect of 1st order outages. Since there is no 3rd order outage, its contribution is zero.

5.2.4. Contribution of component failure rates on supply point failure rate

Figure 5.4 shows the contribution of the failure rate of each component to the supply point failure rate of the system. The curves are drawn by increasing the failure rate of a particular component keeping the other component failure rates constant. In this system, busbars form the maximum number of 1st order total failure events. The supply point failure rate characteristic due to variations in busbar permanent failure rates, thus, has the greatest slope.

Other components contribute to the supply point failure rate in accordance with their respective values.

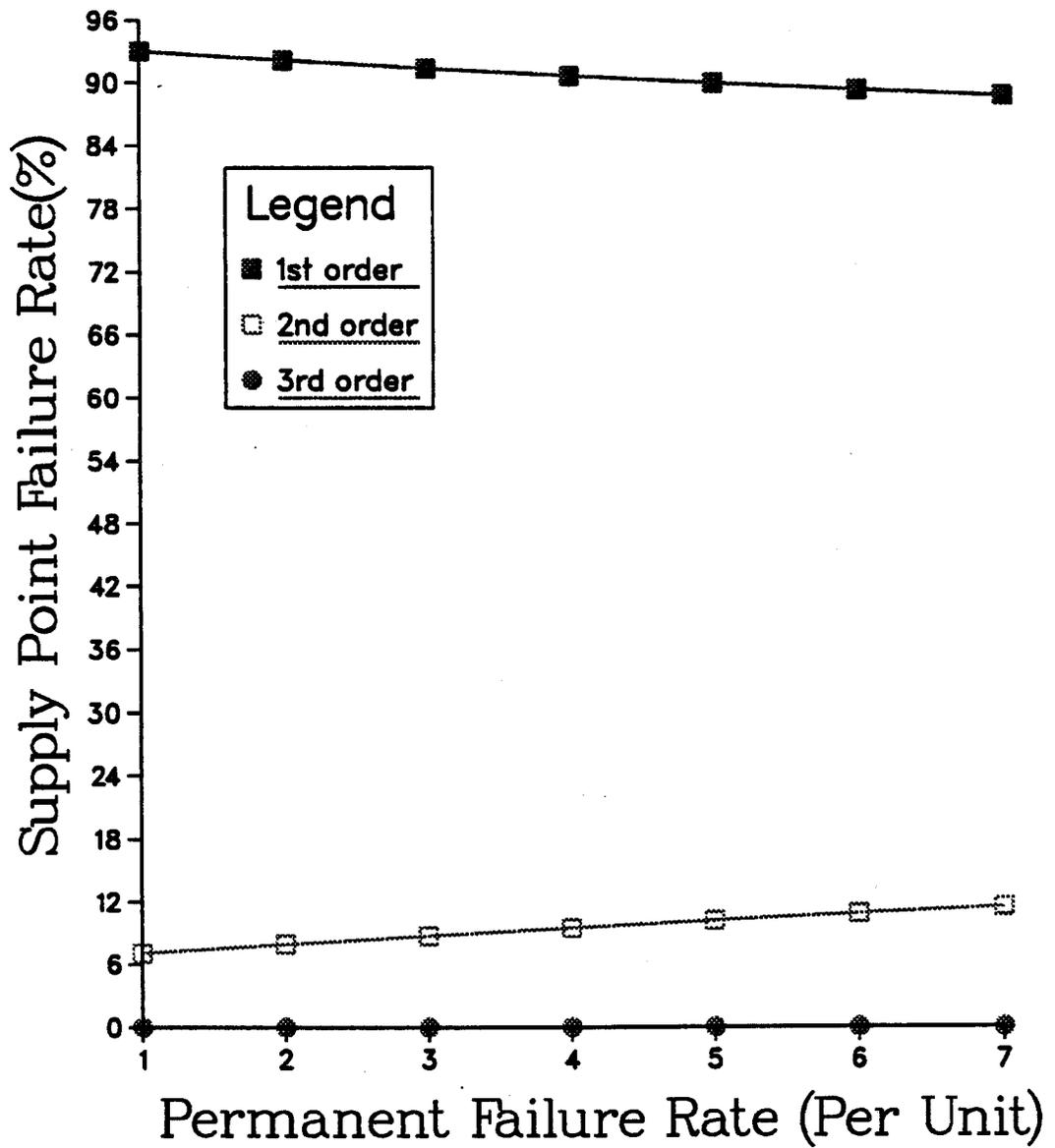


Figure 5.3: Supply point failure rate variation with component permanent failure rates increment.

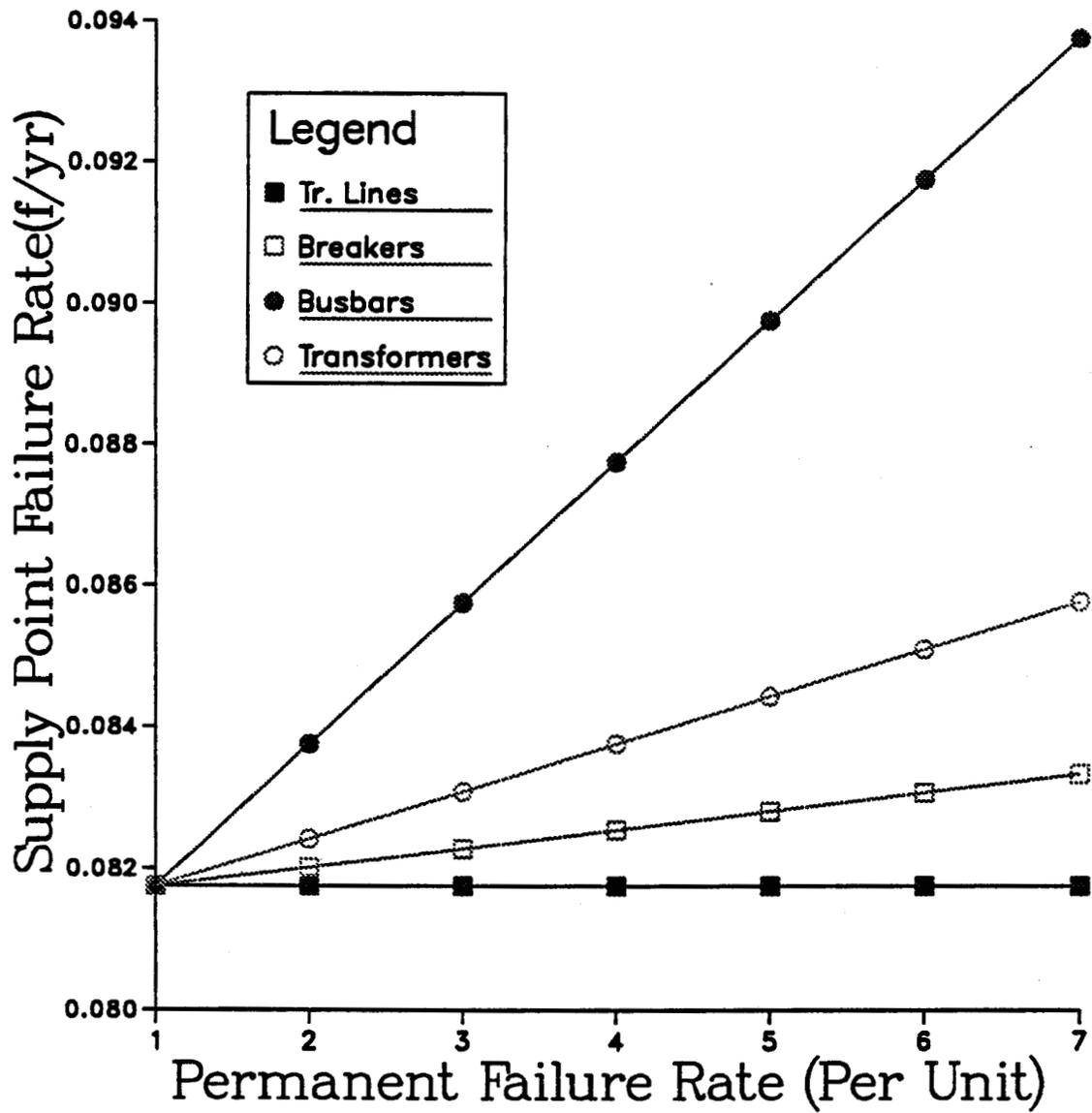


Figure 5.4: Percentage supply point failure rate variation with component permanent failure rates increment.

5.2.5. Effect of component repair time on performance indices

Figure 5.5 shows the variation in system performance indices with corresponding variations in component repair times. In this system, SAIFI is the weighted average of the supply point failure rates. It is not affected by a variation in component repair times as shown in Figure 5.5. SAIDI is the weighted average of annual unavailability of supply point in this system. It increases with corresponding increases in component repair times. CAIDI is the ratio of SAIDI to SAIFI. It also increases with a corresponding increase in the component repair times as shown in Figure 5.5.

5.3. RBTS Bus-4 Sensitivity Studies

5.3.1. Effect of change in component failure rates

Figures 5.6, 5.7 and 5.8 show the variation in the failure rates at the supply points SP1, SP2 and SP3 respectively with increments in component failure rates for different types of failure modes.

Due to the absence of transmission lines in the SP1 circuit, there is no variation in the supply point failure rate with increments in component failure rates in adverse weather conditions as shown in Figure 5.6. Active failure events constitute the maximum number of first order outages. The slope of supply point failure rates due to variation in component active failure rates is, therefore, maximum.

In the SP2 circuit, the supply point failure rate characteristic due to the variations in adverse weather permanent failure rates has a greater slope than that due to variations in adverse weather temporary failure rates. This is shown in Figure 5.7. This is due to the fact that second and higher order overlapping outages of temporary failures are usually neglected as their reclosure time is negligible. Other outages in association with permanent failures, however, cannot be neglected due to the fact that they are frequent and their repair times are significant. The slope of the supply point failure rate due to variations in component temporary failure rates is higher than that due to variations in component permanent failure rates since component failure rates in the single weather state

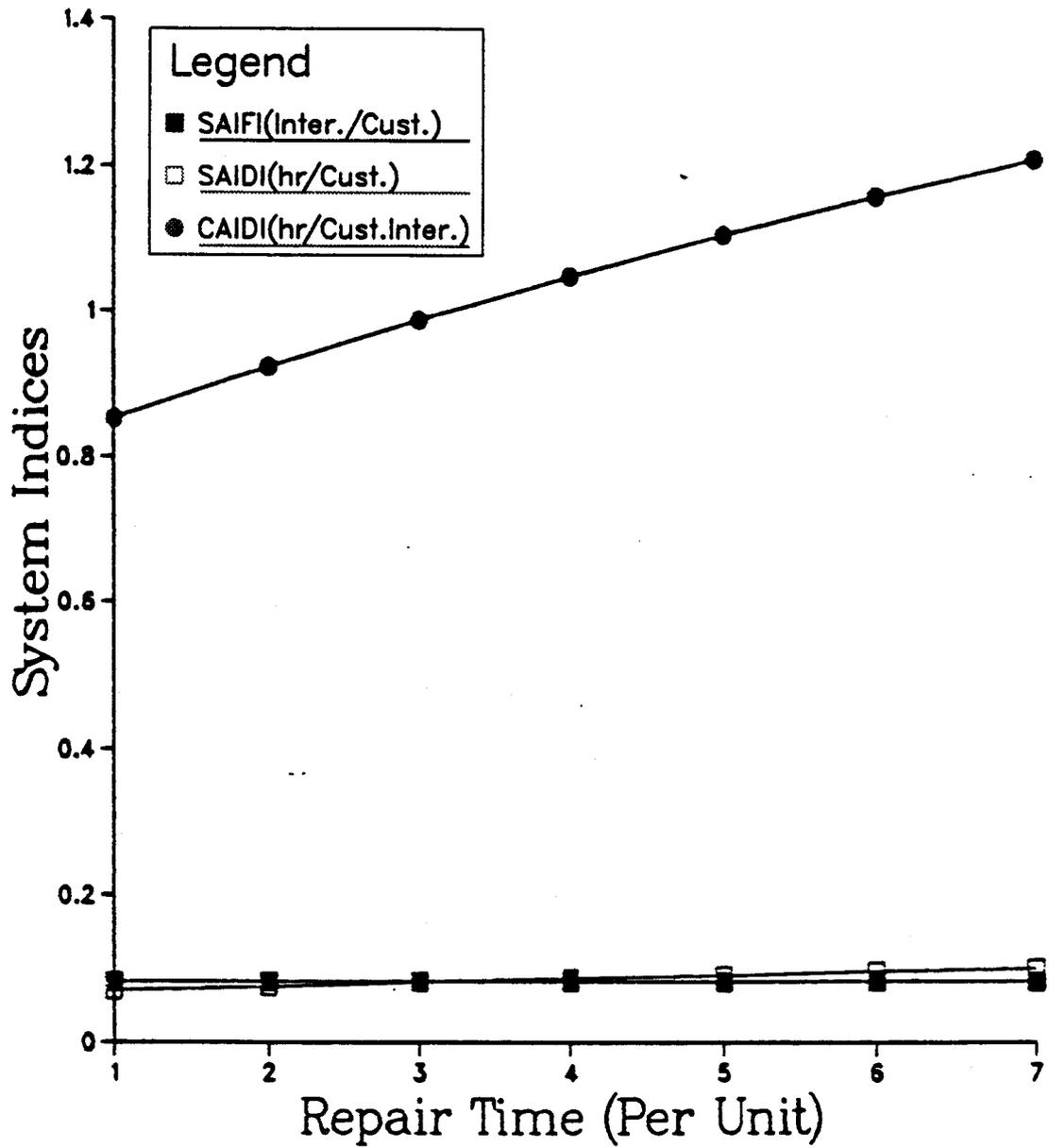


Figure 5.5: Effect of variation in component repair time on performance indices.

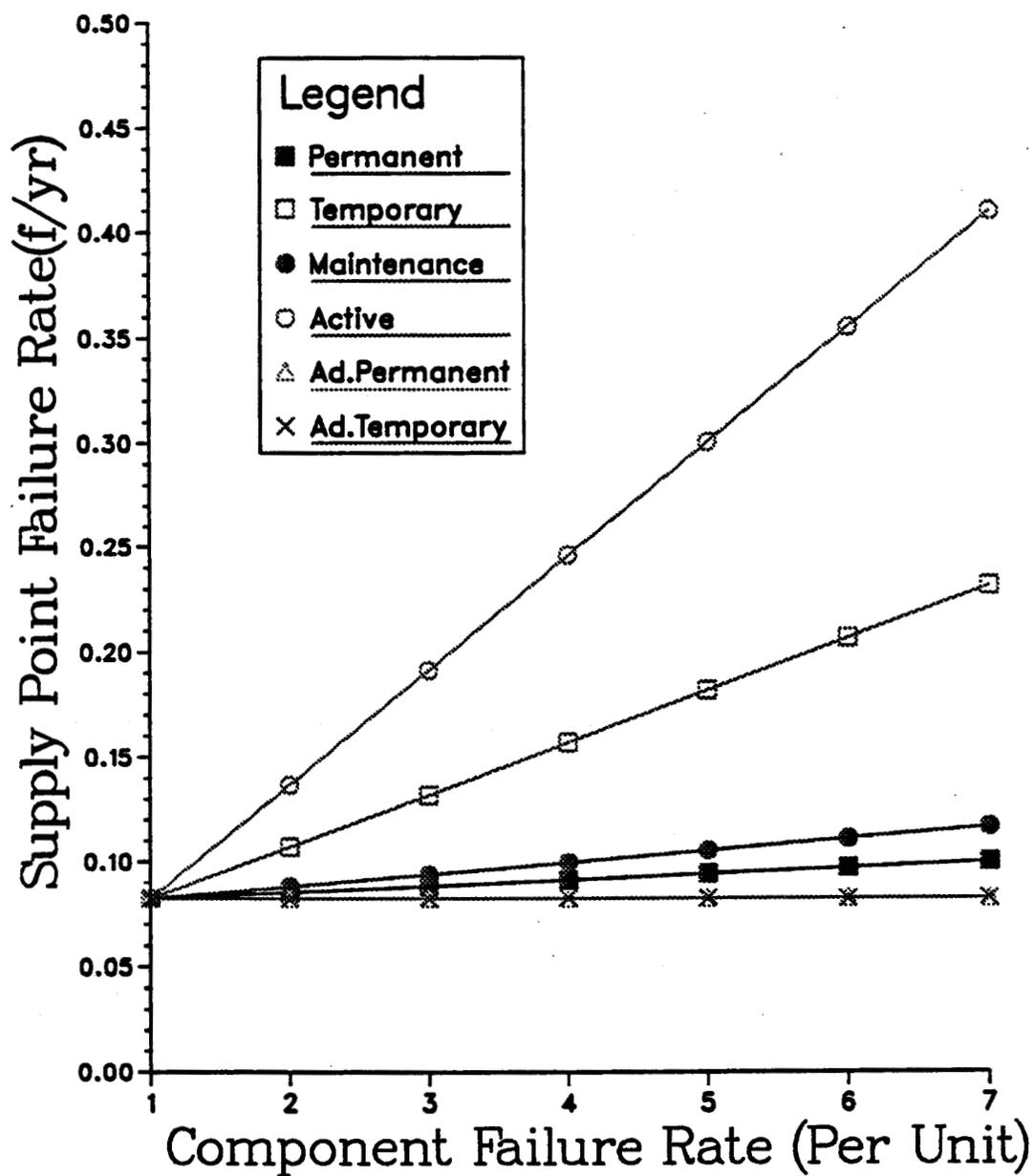


Figure 5.6: Variation in failure rates of SP1 with increments in component failure rates.

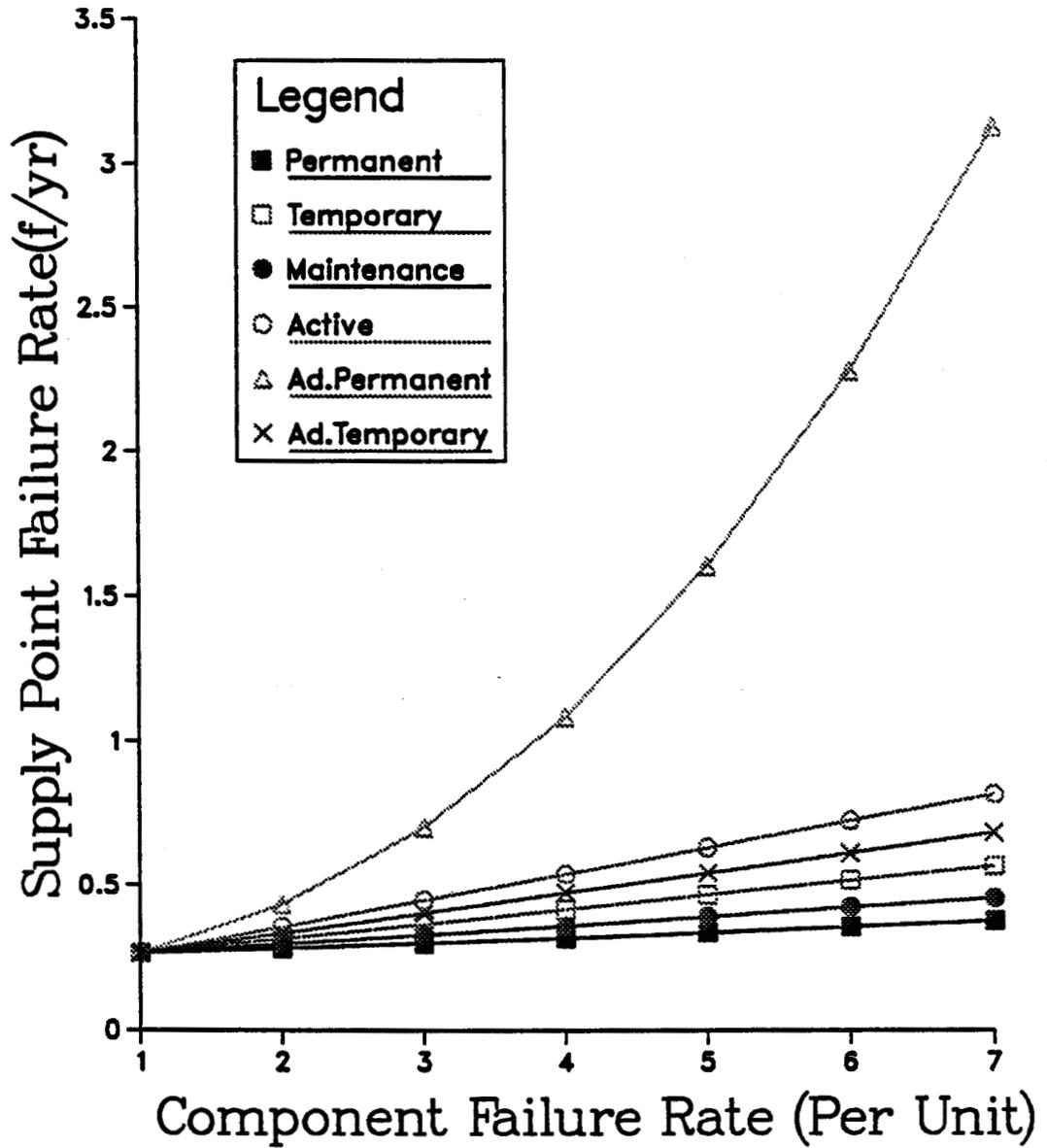


Figure 5.7: Variation in failure rates of SP2 with increments in component failure rates.

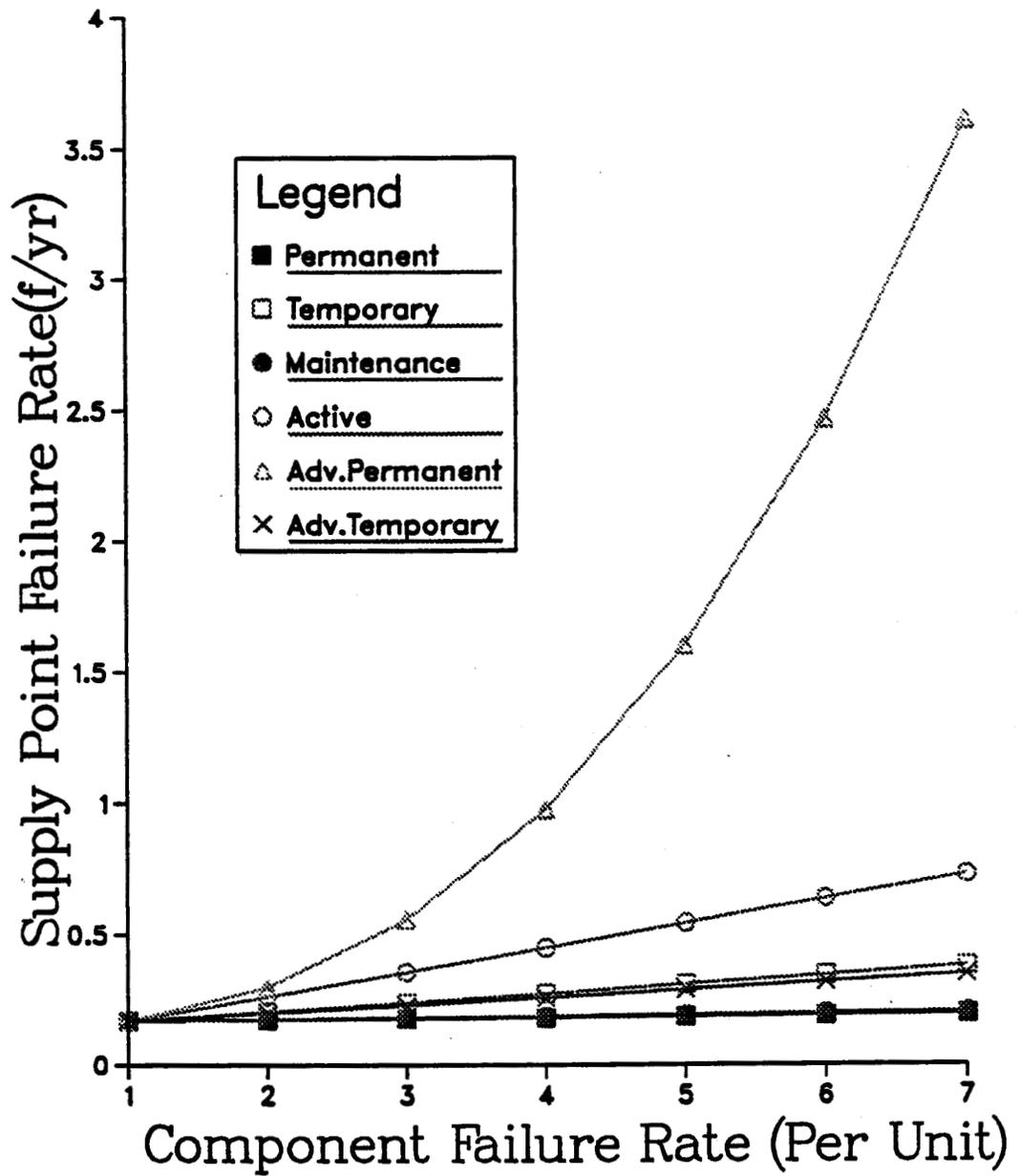


Figure 5.8: Variation in failure rates of SP3 with increments in component failure rates.

of the former are larger than those of the latter. There are no first order temporary outages under adverse weather conditions in the SP2 circuit. The effect of a variation in the first order active failure rates is more pronounced than that due to a variation in the temporary failure rates in adverse weather.

In the SP3 circuit, there are only four 2nd order minimal cuts. These cuts do not include any transmission lines. Consequently, the contribution of adverse weather to the supply point indices is only due to the third order outages. The contribution of the second order temporary failures is more than that of the third order adverse weather temporary failures. The slope of the curve shown in Figure 5.8 due to variations in temporary failure rates is, therefore, greater than that due to variations in adverse weather temporary failure rates.

5.3.2. Contribution of component failure rates

Figures 5.9 to 5.11 show the contribution of the 1st, 2nd and 3rd order outages to the supply point failure rate.

It is observed from Figures 5.9, 5.10 and 5.11 that the percentile contribution of the 2nd order outages increases with increases in components failure rate. Failure rates of the supply points due to 1st and 3rd order outages are either constant or decrease with increase in component permanent failure rates.

Figures 5.12, 5.13 and 5.14 show the contribution of the 2nd order overlapping outages to the supply point failure rates due to variations in component permanent failure rates.

It is observed from Figures 5.12 and 5.14 that the characteristic due to the 2nd order outages of SP1 and SP3 have the greatest slopes when the transformers contribute to the failure events. Since there are no transmission lines contributing to the second order failure events, their contribution to the supply point failure rate is zero. From Figure 5.13 it is observed that the contribution of the 2nd order outages supply point failure rate of SP2 have the greatest slope when transmission lines contribute to the failure events.

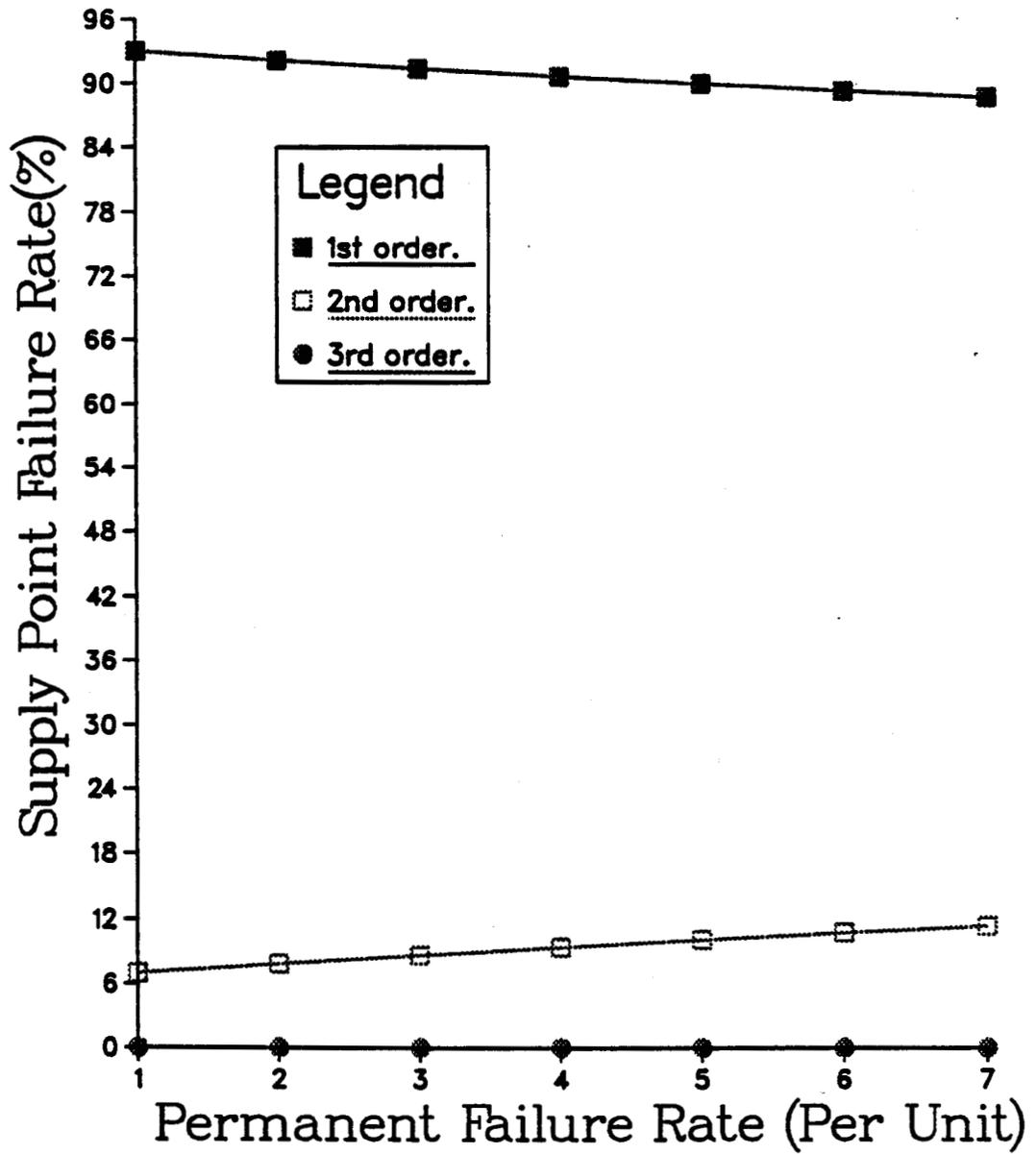


Figure 5.9: Variation in failure rate of SP1 with variation in component permanent failure rate.

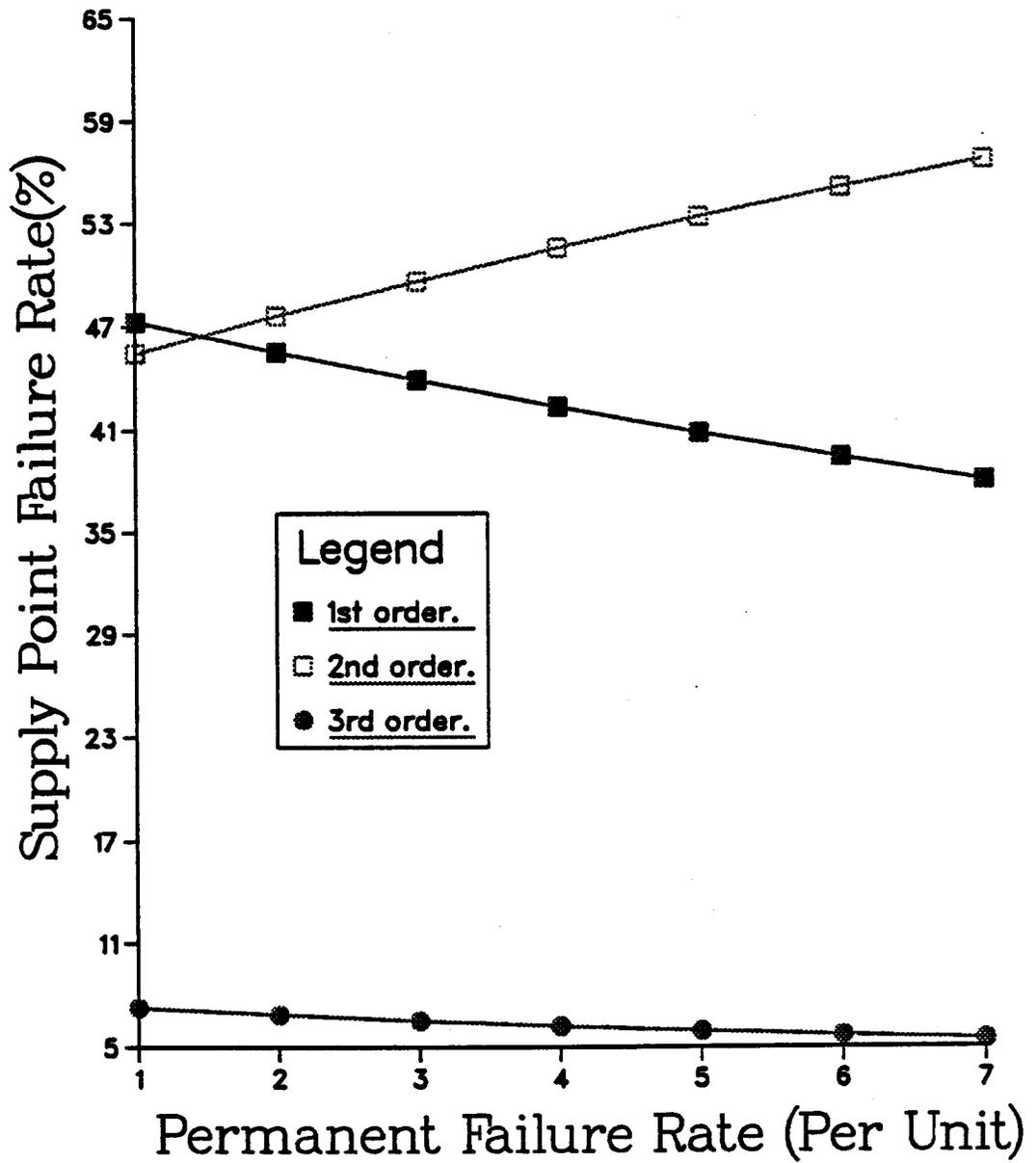


Figure 5.10: Variation in failure rate of SP2 with variation in component permanent failure rate.

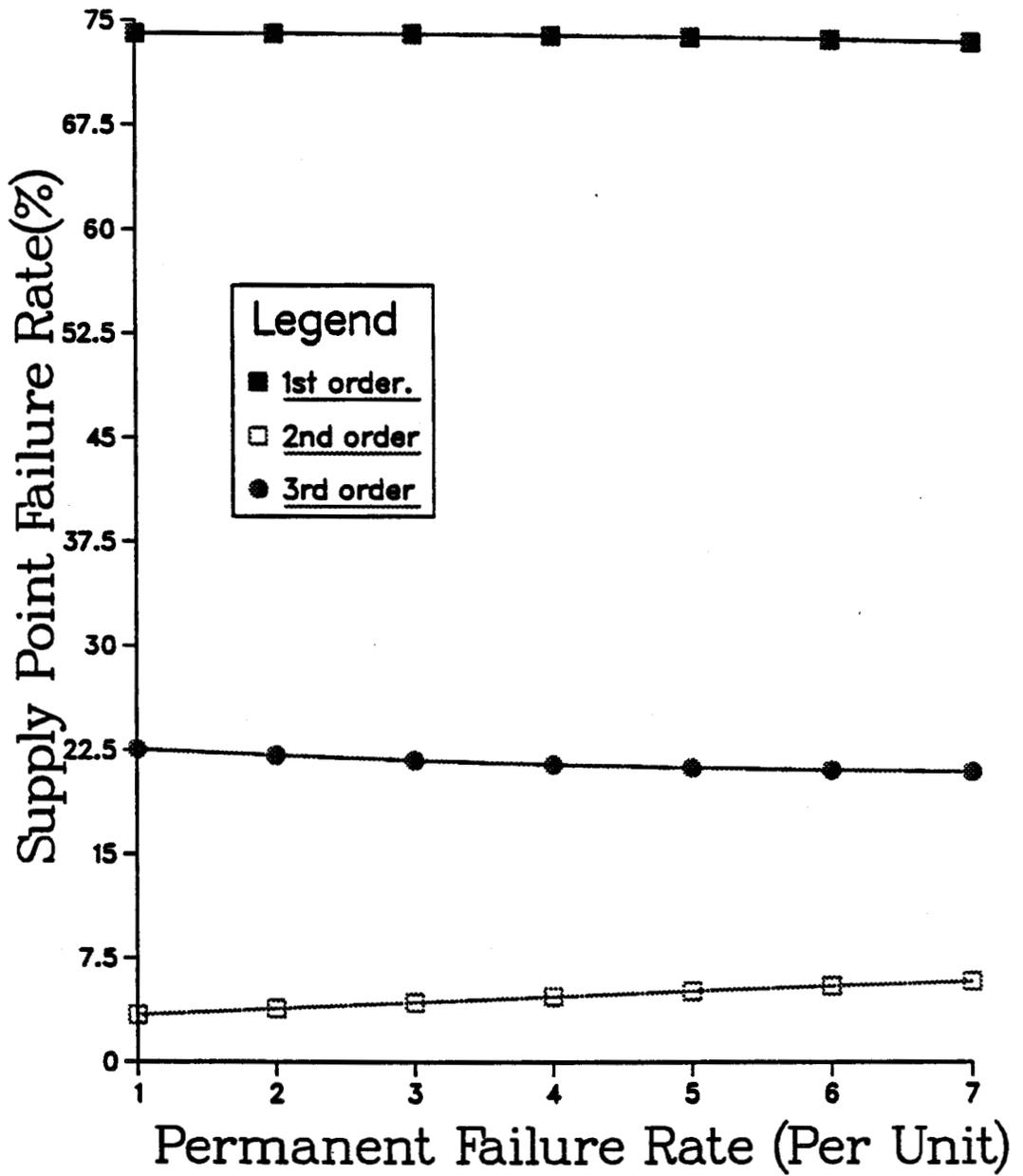


Figure 5.11: Variation in failure rate of SP3 with variation in component permanent failure rate.

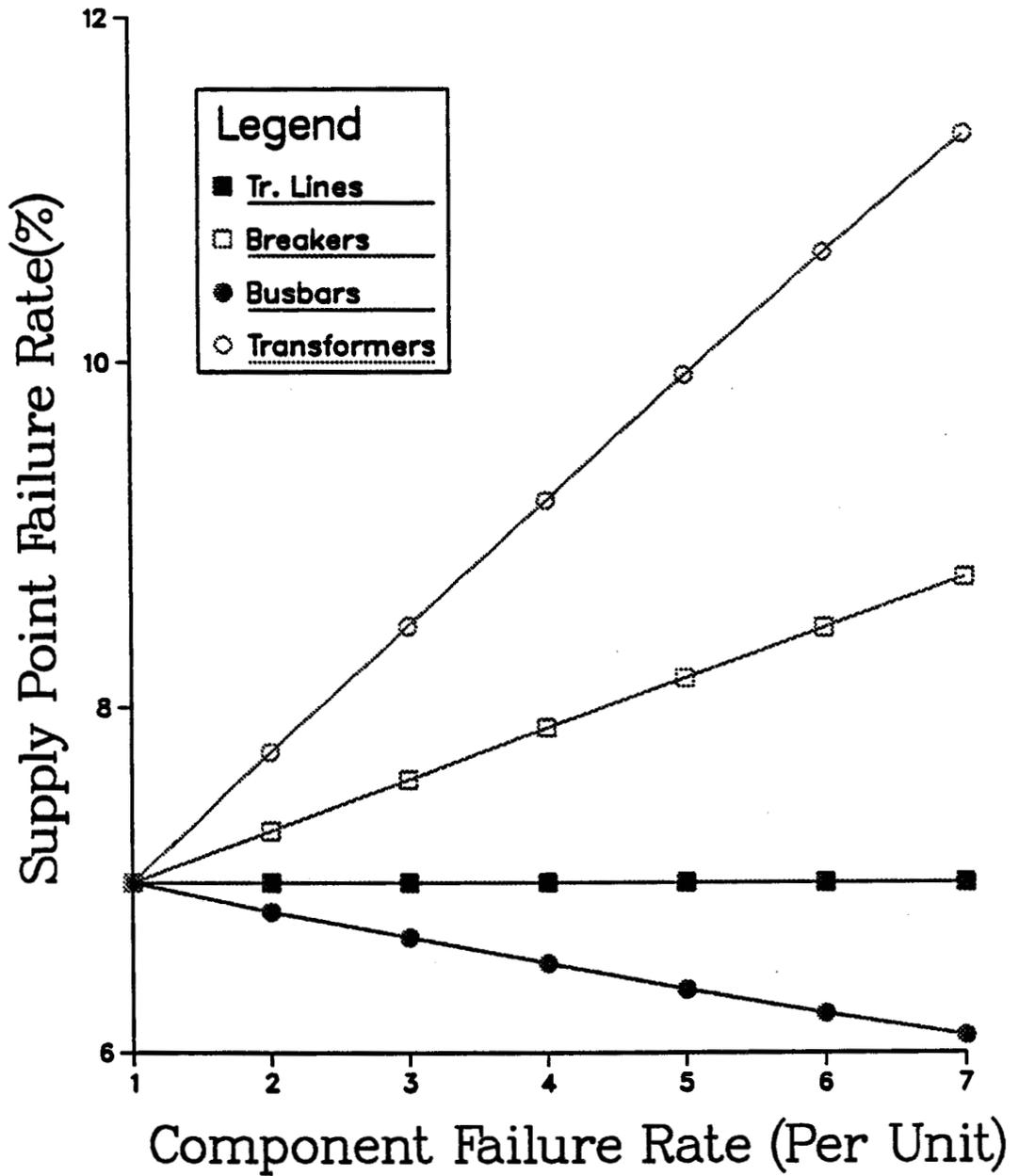


Figure 5.12: Variation in 2nd order outage failure rate of SP1 with a variation in component failure rate.

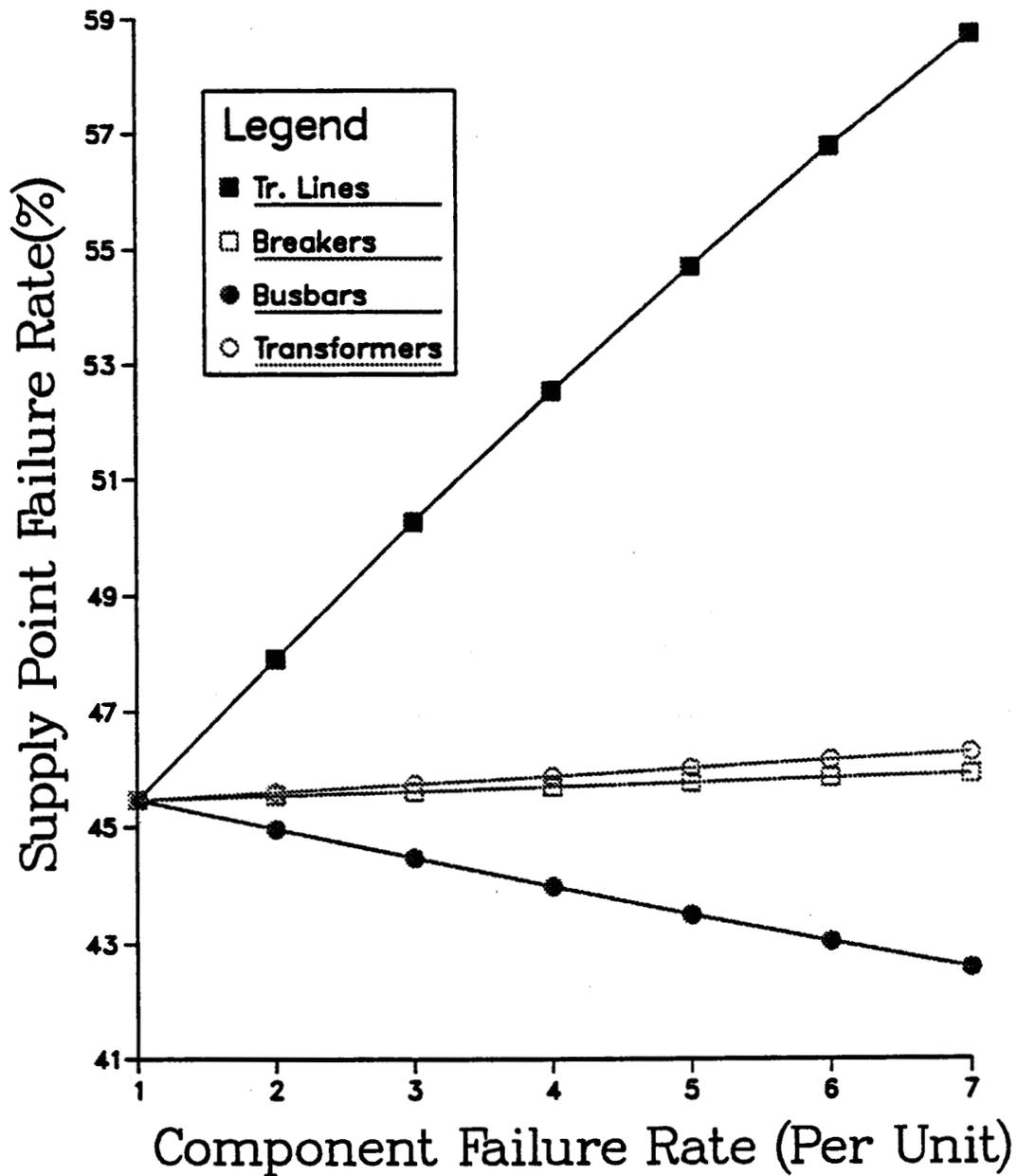


Figure 5.13: Variation in 2nd order outage failure rate of SP2 with a variation in component failure rate.

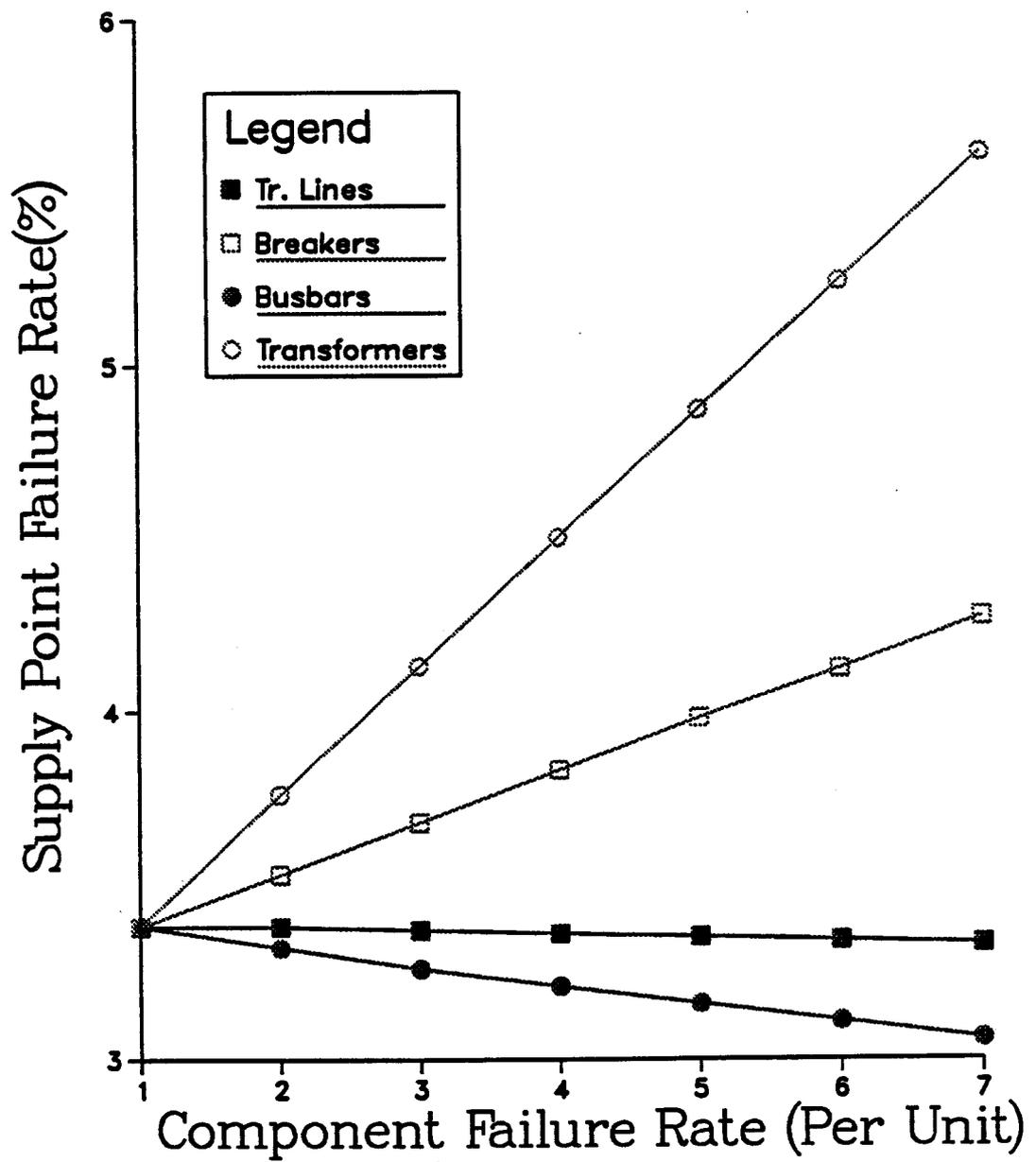


Figure 5.14: Variation in 2nd order outage failure rate of SP3 with a variation in component failure rate.

5.3.3. Comparison between normal and adverse weather failure rates

Figure 5.15 shows percentile variations in the supply point failure rates during adverse and normal weather with corresponding changes in the component permanent failure rates in normal weather. It should be noticed in Figures 5.15 and 5.16 that the sum of percentile contributions from normal and adverse weather at any particular set of permanent failure is 100 percent. Figure 5.15 shows that the percentile contribution of the normal weather failure rates on the failure rate of supply points 2 & 3 increases slightly as the component permanent failure rates are increased. Since adverse weather conditions do not affect SP1, a variation in adverse weather failure rate does not contribute to the supply point failure rate of SP1.

Figure 5.16 shows the percentile contribution of the adverse weather failure rate on the failure rate of supply points. The supply point failure rate of SP2 and SP3 increases exponentially as the component permanent failure rates in adverse weather condition are increased. A significant portion of the supply point failure rate is due to the adverse weather failure rate.

It is important to consider weather effects in the reliability evaluation of sub-transmission systems. The reliability indices evaluated for a subtransmission system supply point can be over-optimistic and, therefore, quite misleading, if the weather effects are not considered.

5.3.4. Effect of weather duration

The duration of normal weather is varied while keeping the ratio $N/(N+S)$ constant. Figure 5.17 shows the variation in the supply point failure rates of the three supply points with a corresponding increase in the duration of normal weather. Since the ratio $N/(N+S)$ is kept constant, adverse weather duration increases with an increase in the normal weather duration. Figure 5.18 shows variations in the supply point unavailability of the three supply points with corresponding increases in the duration of normal weather.

Supply point 1 does not contain any transmission lines. There is, therefore, no effect

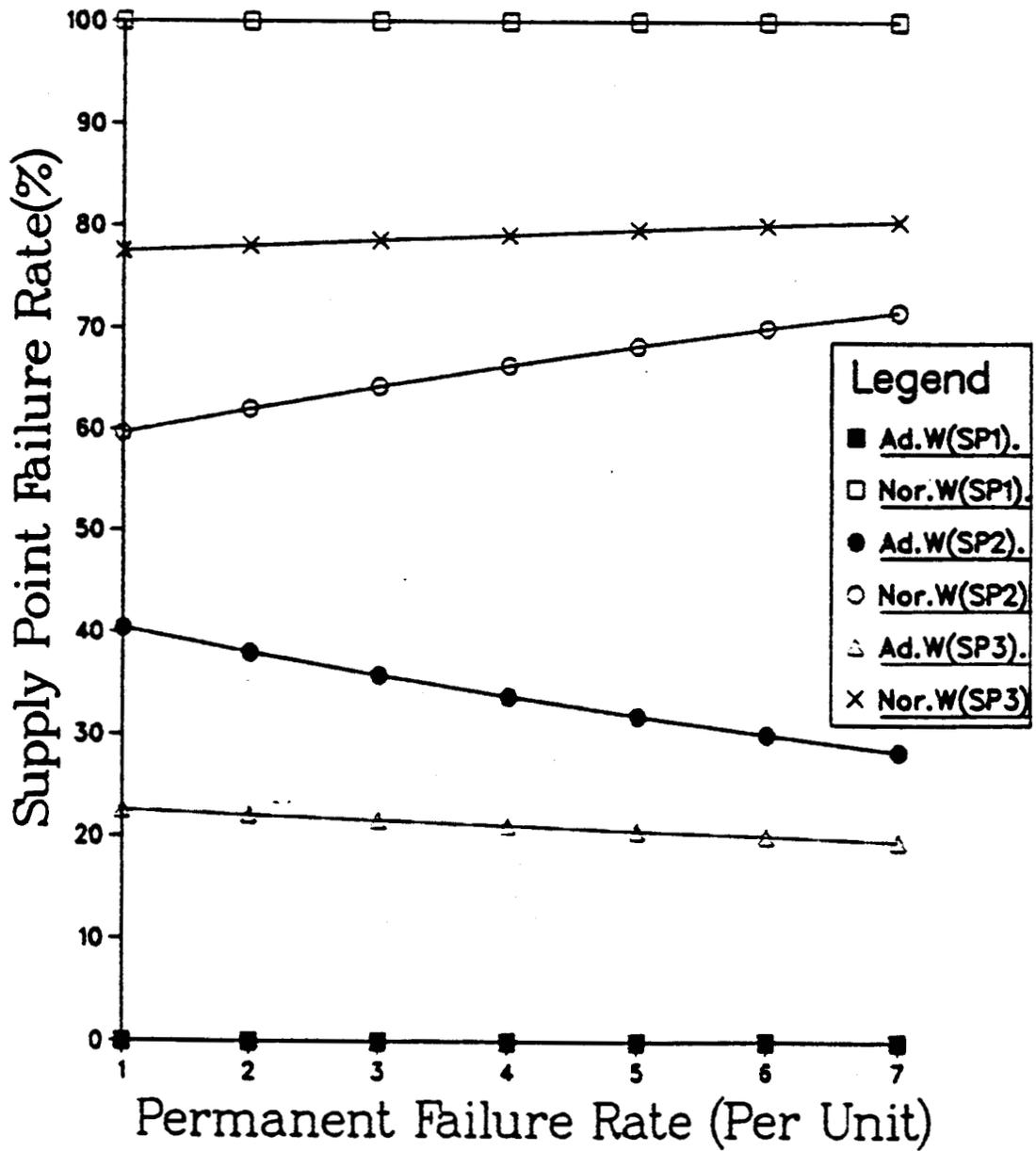


Figure 5.15: Comparison of normal and adverse weather percentage supply point failure rates with variations in the component permanent failure rate.

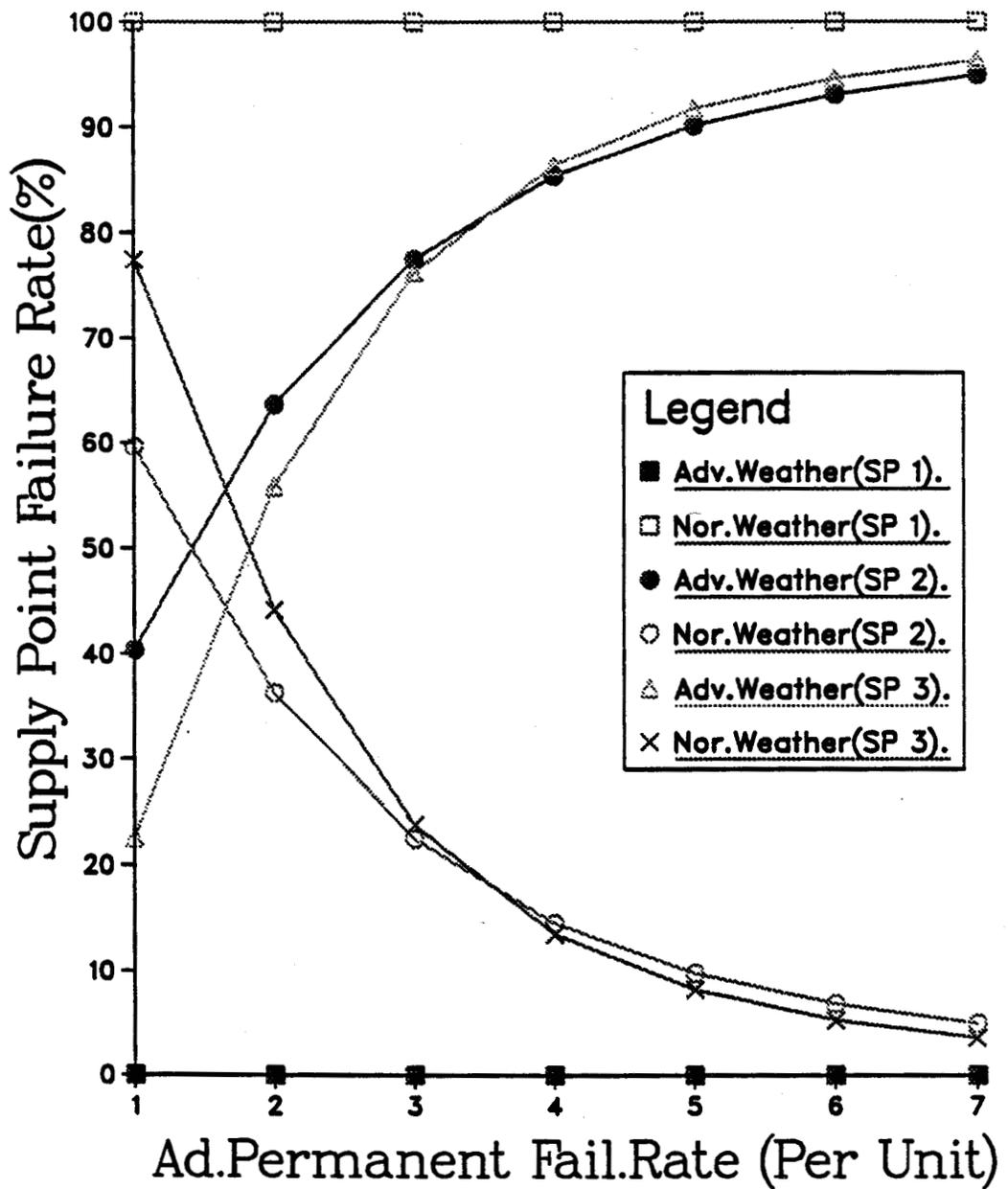


Figure 5.16: Comparison of normal and adverse weather percentage supply point failure rates with variations in the component adverse permanent failure rate.

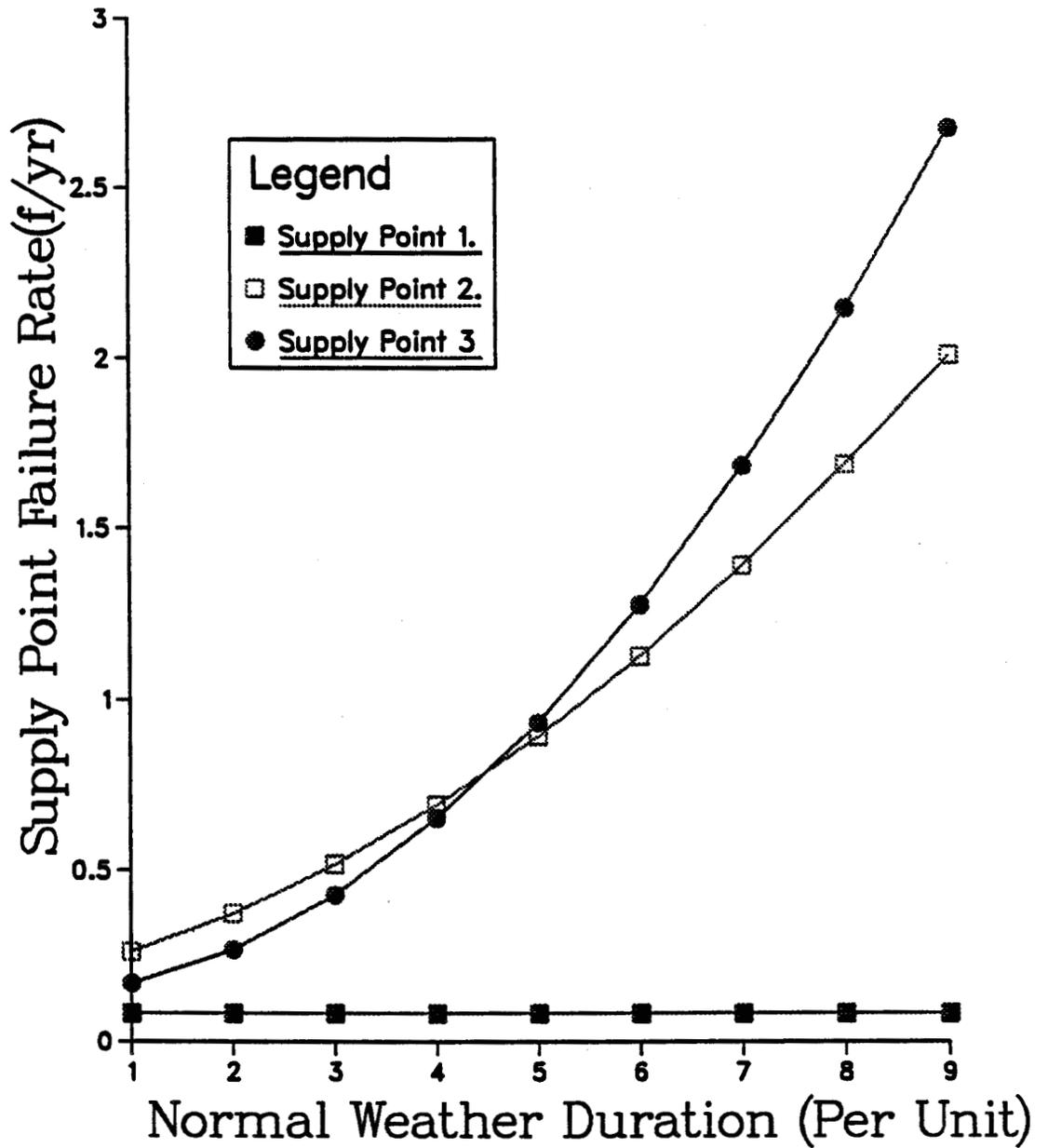


Figure 5.17: Variation in supply point failure rate with increments in weather duration keeping $N/(N+S)$ constant.

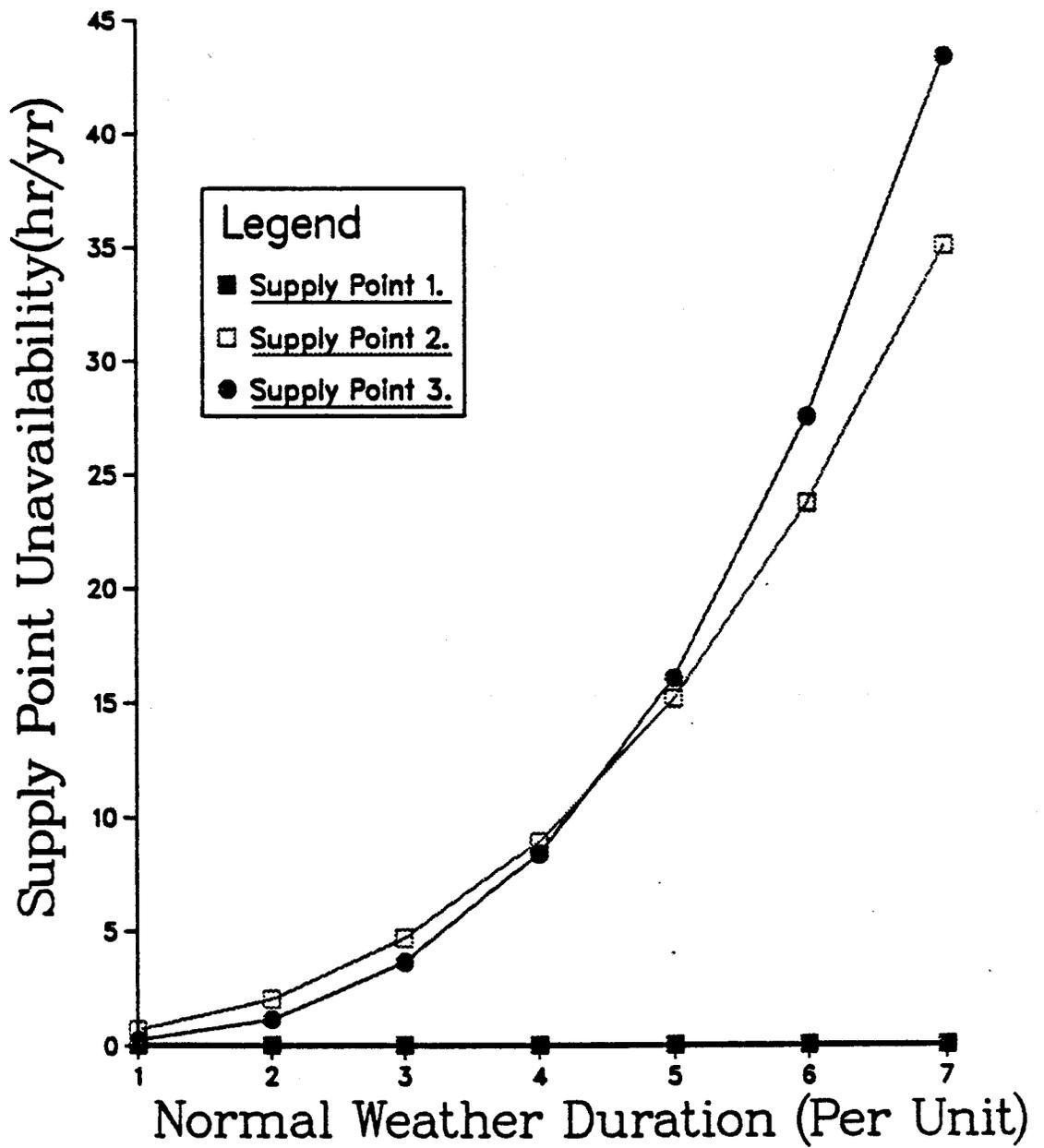


Figure 5.18: Variation in supply point unavailability with increments in weather duration keeping $N/(N+S)$ constant.

of adverse weather conditions on its reliability indices. Reliability indices of the SP2 have higher values than that of the SP3 at a normal weather duration lower than approximately 4.5 times of its base value. This is due to the fact that the SP2 has a larger number of 2nd order outages compared to that of the SP3. As shown in Figures 5.17, at a higher value of weather duration than 4.5 times its base value and 5.18, the reliability indices of the SP3 are greater than those of the SP2. This is due to the fact that the SP3 has a larger number of 3rd order outages compared to that of the SP2. 3rd order outages, therefore, cannot be neglected during the evaluation of reliability indices.

Figures 5.19, 5.20 and 5.21 show variations in the reliability indices of the three respective supply points with corresponding increases in the normal weather duration keeping the ratio $N/(N+S)$ constant.

SP1 indices are not affected by the adverse weather condition. In the SP2 and the SP3, unavailability increases sharply, as shown in Figures 5.20 and 5.21 with an increase in adverse weather duration. Failure rates of both the supply points, though small, also increase. This is due to the fact that the failure rate of a supply point depends upon the weather duration in the case of overlapping outages.

5.3.5. Error factor

It is observed that the system failure rate increases very sharply as the number of failures occurring in adverse weather increase. The error factor is defined as the ratio of the system failure rate when failures occur in adverse weather to the system failure rate when failures occur in normal weather. Figure 5.22 shows variation in error factor as a function of the percentage of failures that occur in adverse weather. The error increases rapidly as the percentage of adverse weather failure increases. This indicates that the results will be highly optimistic if weather effects are ignored.

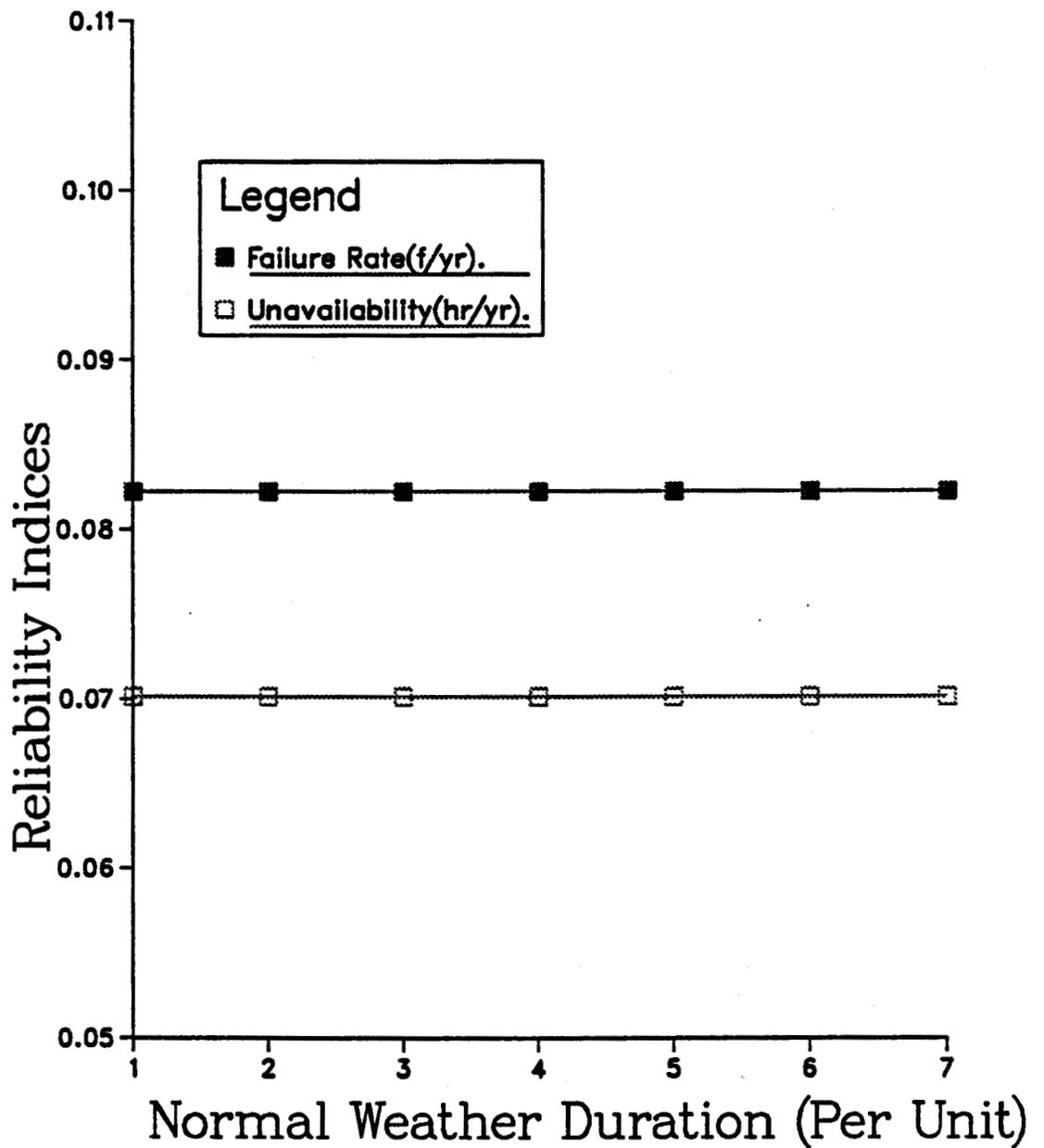


Figure 5.19: Variation in reliability indices of SP1 with increments in weather duration keeping $N/(N+S)$ constant.

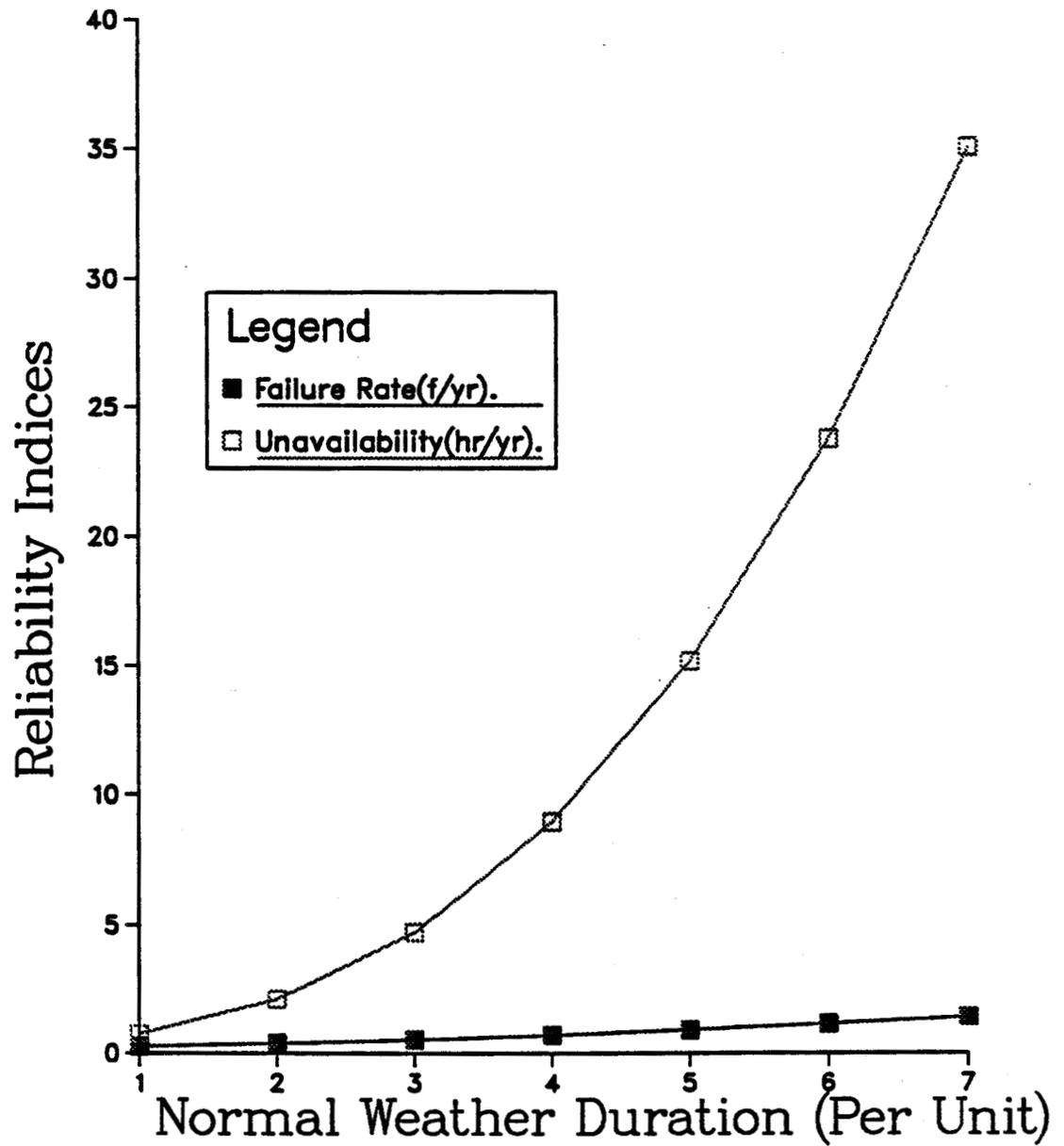


Figure 5.20: Variation in reliability indices of SP2 with increments in weather duration keeping $N/(N+S)$ constant.

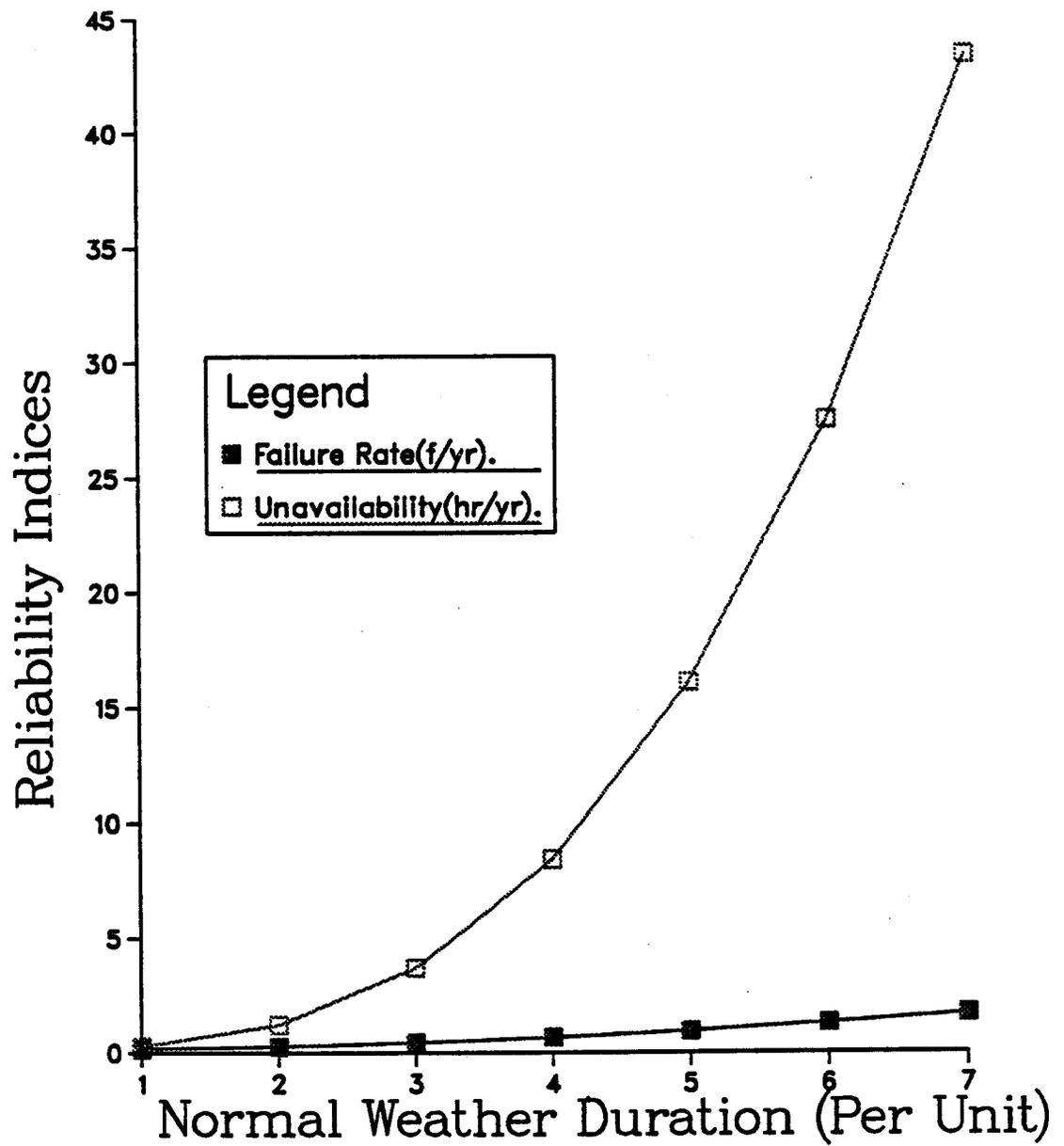


Figure 5.21: Variation in reliability indices of SP3 with increments in weather duration keeping $N/(N+S)$ constant.

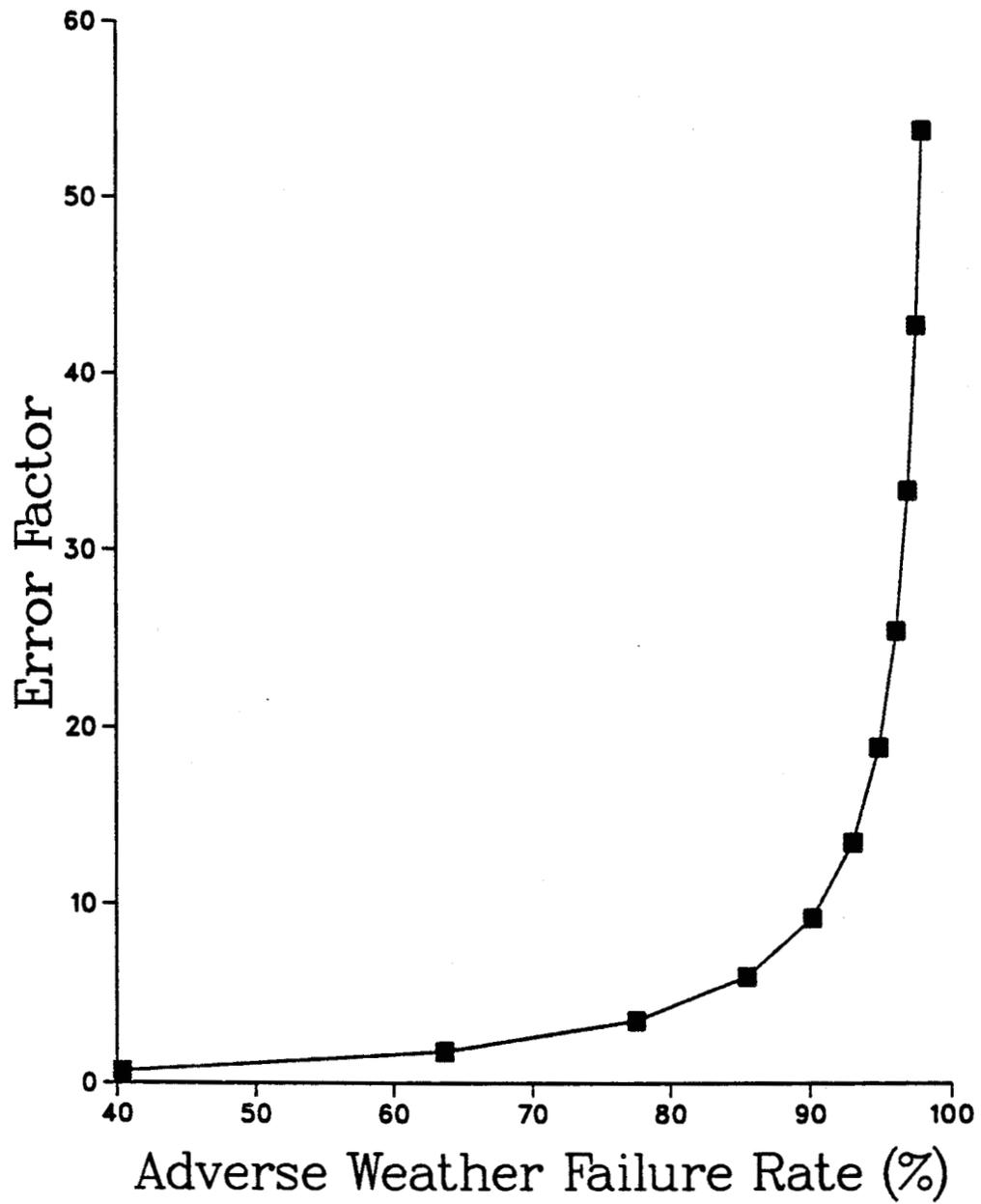


Figure 5.22: Variation of error factor.

5.3.6. Performance indices

With a variation in an input parameter, SAIFI changes in the same way as the load point failure rate changes. This is because SAIFI is the weighted average of the load point failure rates. SAIFI as a function of the component permanent failure rates is shown in Figure 5.23. SAIFI increases with an increase in the component permanent failure rates. The system has a different number of customers at each supply point and, therefore, the failure rate of each of the supply points will have different weight during the evaluation of SAIFI.

SAIDI has been evaluated as the weighted average of the annual unavailability at the relevant supply points in the system. The variation in SAIDI with the variation in input parameters is, therefore, identical to the annual supply point unavailabilities. These characteristics are shown in Figures 5.24 and 5.25.

In Figure 5.24, it is observed that an increase in the value of the component failure rates increases the value of supply point SAIDI and consequently system SAIDI. It is also noticed that the system SAIDI lies in between the supply point SAIDI indicating that the system SAIDI is a weighted average of supply point SAIDI. SAIDI increases with an increase in component repair times as can be seen from Figure 5.25. It is noticed from Figures 5.24 and 5.25 that the increase in system SAIDI is relatively more with the variation in component failure rates than with the variation in component restoration times. This observation is valid for the RBTS Bus-4.

CAIDI is the average customer interruption duration per customer interruption. An increase in the component failure rate leads to a higher number of interruptions in the system. By increasing the component restoration times, higher values of CAIDI are obtained. The variations in CAIDI are shown in Figures 5.26 and 5.27.

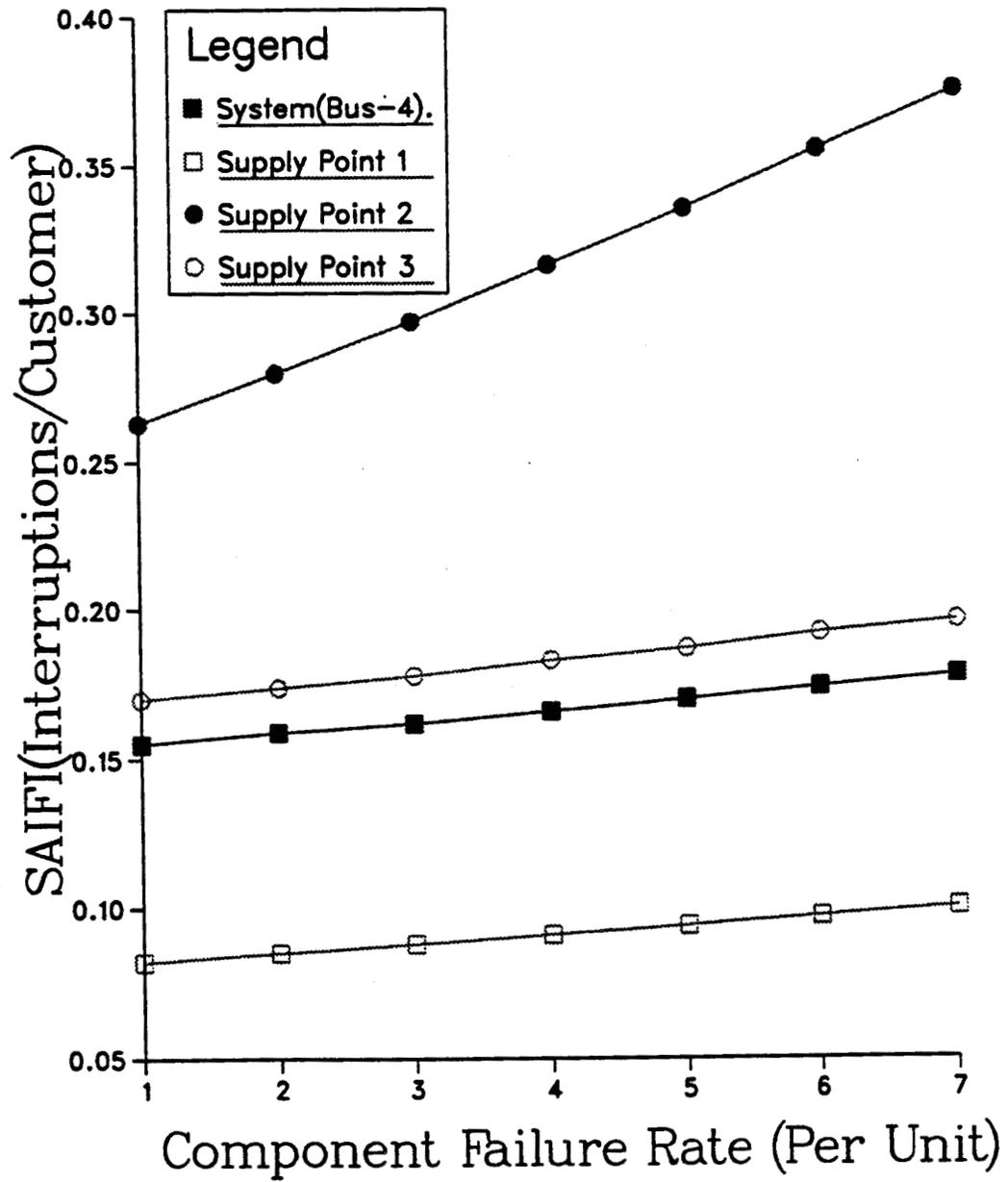


Figure 5.23: Variation of SAIFI with increments of component failure rate.

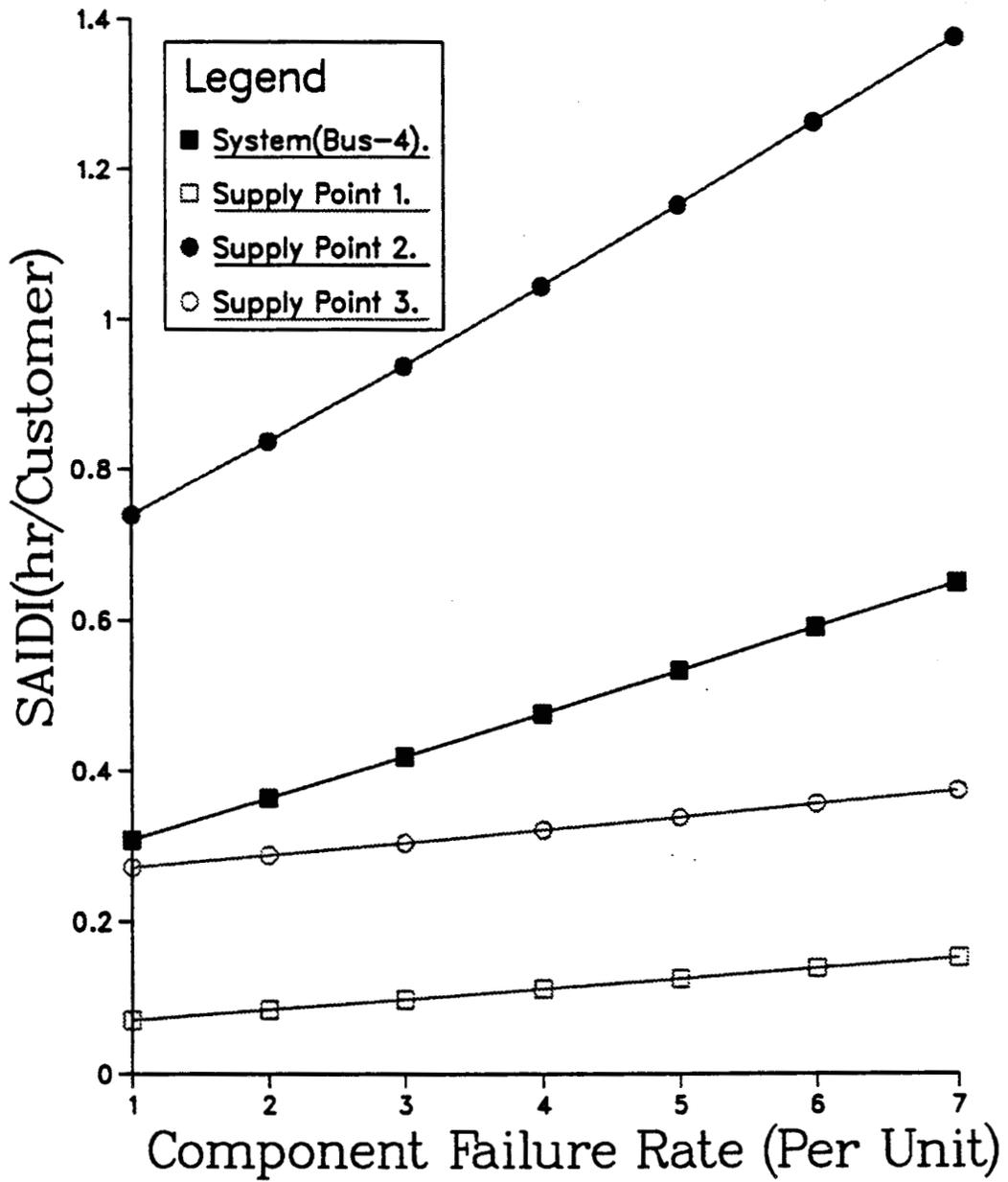


Figure 5.24: Variation in SAIDI with increments in component failure rate.

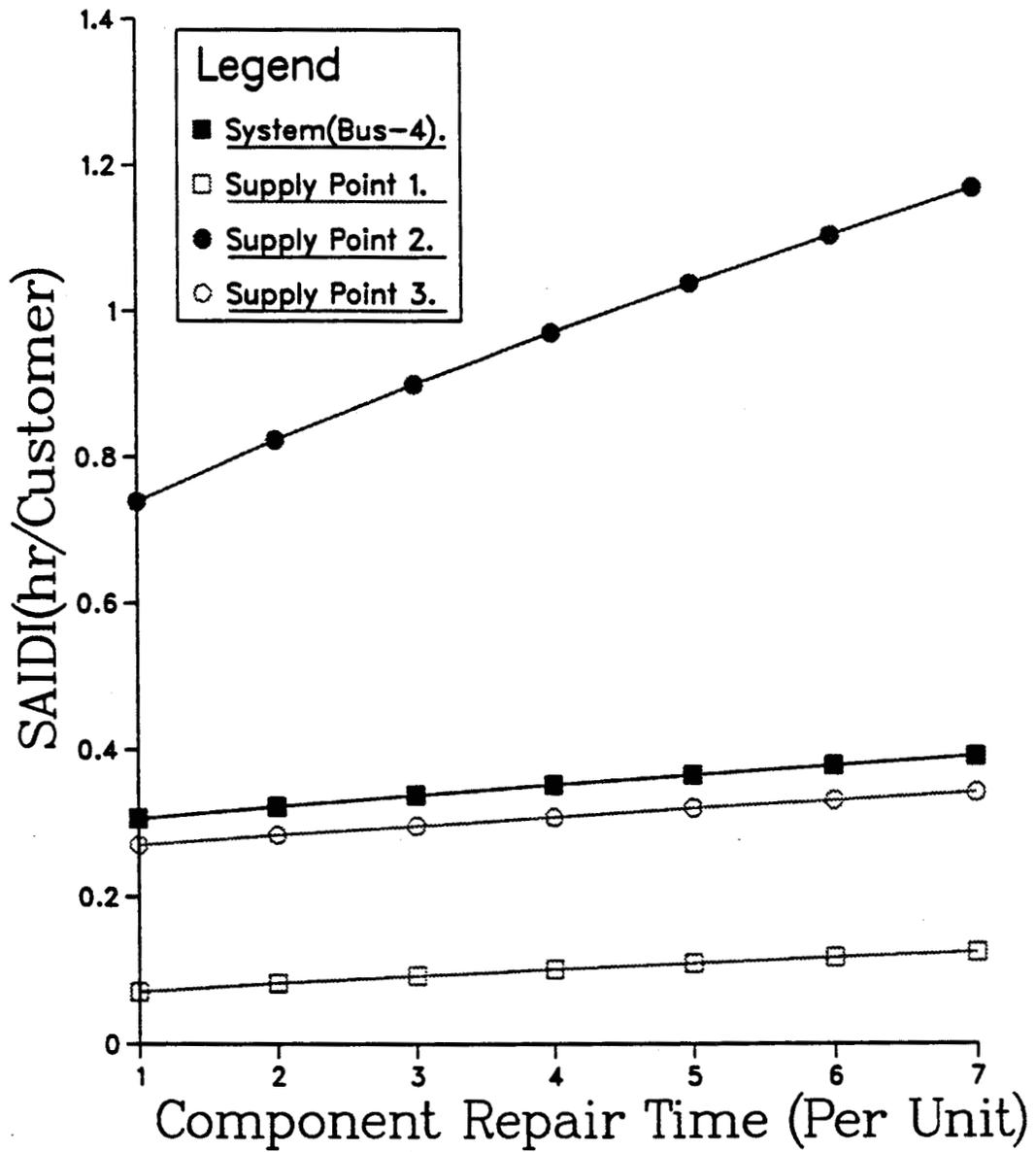


Figure 5.25: Variation in SAIDI with increments in component repair time.

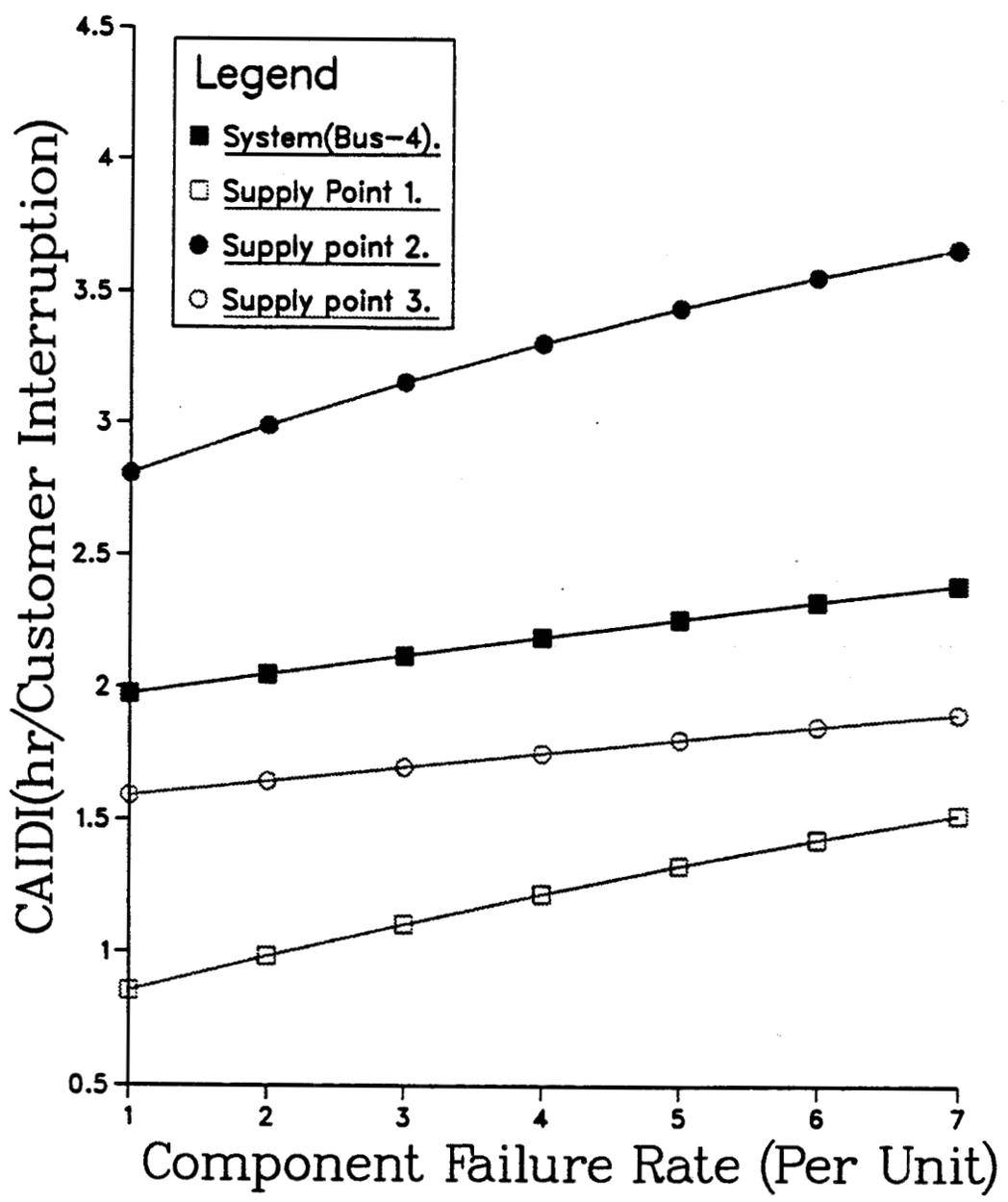


Figure 5.26: Variation in CAIDI with increments in component failure rate.

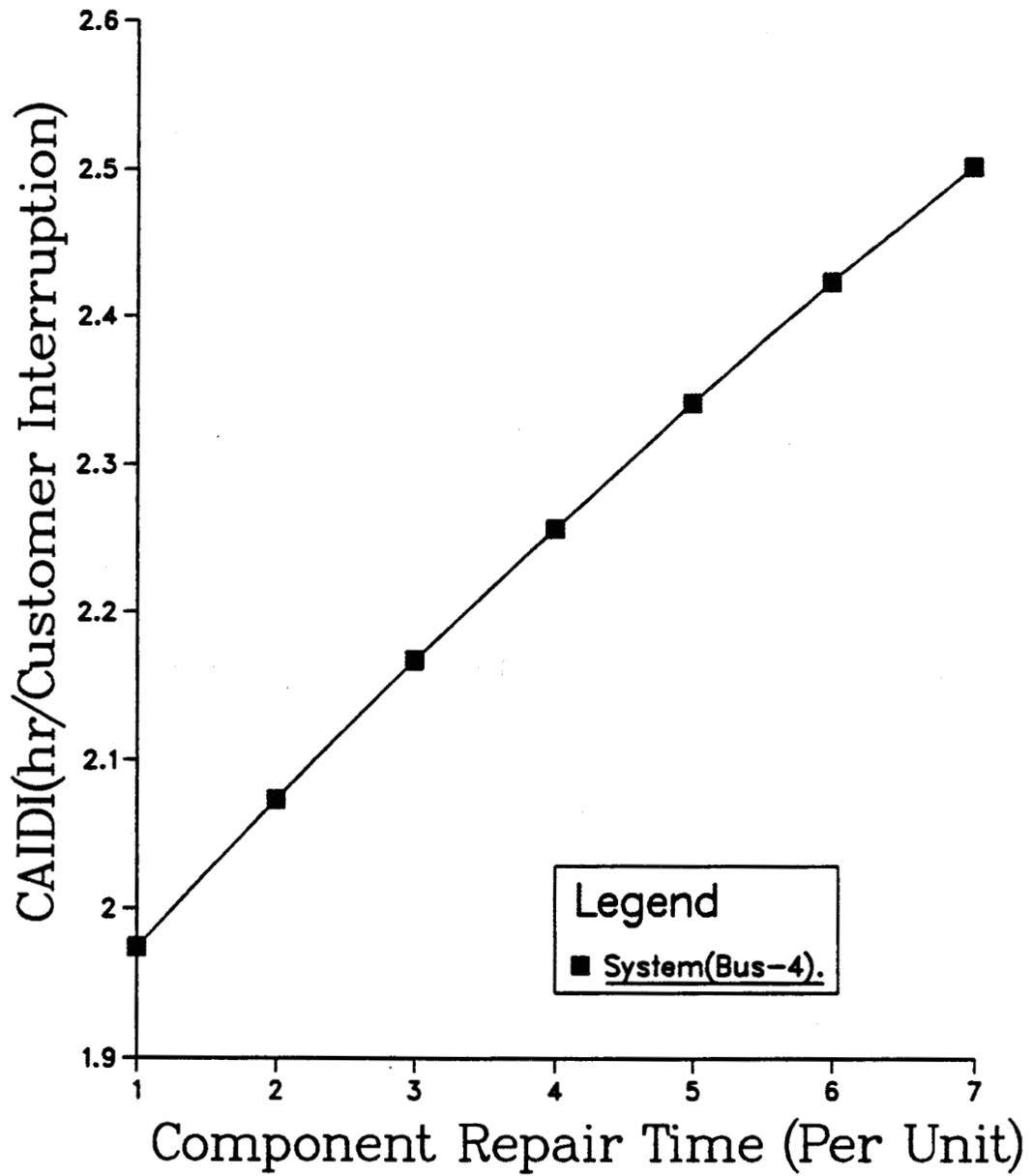


Figure 5.27: Variation in CAIDI with increments in component repair time.

5.4. Summary

The results shown in this chapter indicate that a large number of sensitivity studies can be performed in the network subtransmission system providing a huge amount of information about the system. A system can be designed to be more reliable by conducting and utilizing the results of a suitable set of sensitivity studies.

References 1 and 7 show that more than 80% of the customer unavailability originates from outages in distribution systems. A very high percentage of these outages occur in the last segment of distribution system which is usually radially connected. A major objective of this research activity is to investigate the percentile contribution of the subtransmission systems on customer reliability. In the next chapter, the last segment of the distribution system is briefly discussed and sensitivity studies are performed on this segment by utilizing a computer program. These studies are then compared with those of the network subtransmission system.

6. SENSITIVITY STUDIES IN THE RADIAL DISTRIBUTION SYSTEM

6.1. Introduction

The simplest and the most common configuration in a distribution system is the radial circuit configuration. The circuit is usually connected to a single supply source. Primary or main feeders and lateral distributors fan out in an area to connect individual customers. A primary feeder radiates from a substation and branches into subfeeders connecting the major load centres. It is the function of lateral distributors to connect individual load points to primary feeders. At various points along these lateral distributors, distribution transformers transform the primary voltage to secondary voltage. Usually primary feeders and lateral distributors are not looped. They may, however, be connected to adjacent circuits. There are also many systems although constructed utilizing meshed circuits, are operated as radial systems using normally open switches. It is stated in References 1, 7 and 29 that a radial system has all its components connected in series and failure in any of its components results in the system failure. This statement is valid if there is no protective device in the circuit that recognizes and isolates abnormal primary or lateral conditions. The introduction of protective equipment in the circuit will, however, limit the effects of an outage to those customers whose supply directly depends on the faulty component. Protective equipment is usually installed at the beginning of a link [30] or a branch in order to protect preceding equipment from faults within that link or branch. A link, as mentioned in Reference 30, is a homogeneous connection between any two nodes or buses. It may be a piece of electrical equipment connecting two points such as a transformer, or a length of line or cable composed of the same material over its entire length. Some of the basic protective equipments used in distribution systems are:

1. Fuses
2. Reclosers
3. Breakers

4. Automatic and manual isolating or disconnecting switches

Distribution circuits are ever changing due to unforeseen growth of existing loads and due to alteration of circuit configurations in order to serve new loads or to meet increasing demands of the existing loads. These changes result in many uncertain circuit operating conditions. The major problems associated with circuit dynamics encountered by utilities are in designing, monitoring and altering circuit configurations to accommodate these uncertain circuit conditions and still operate within predetermined limits of the various interacting performance characteristics associated with distribution circuits. Primary circuit characteristics operating outside their normal limits can result in severe economic losses to the public and the utility. The necessity of periodic evaluation of the circuit performance characteristics is complicated by the massive size of distribution systems. Hand calculation of reliability indices becomes impractical and, therefore, digital computer programs can be used. Some computer programs have been developed for the reliability evaluation of radial distribution systems which includes a microcomputer based database management system [31] and the 'DISREL' [10]. The computer program 'DISREL' has been developed at the University of Saskatchewan.

The digital computer program 'DISREL' is briefly described in this chapter. This chapter also presents the analysis and sensitivity studies performed on the RBTS Bus-4 radial distribution system by utilizing the computer program. Finally, these results are compared with those obtained from the RBTS Bus-4 subtransmission system illustrated in Chapters IV and V.

6.2. The RBTS Distribution System

The RBTS distribution system is developed as a part of the RBTS (Roy Billinton Test System). It has most of the significant elements found in a practical system. The RBTS has 5 load busbars (Bus-2 to Bus-6). Distribution networks have been designed for Bus-2 and Bus-4 [26]. All parts of the system at or below 11kV are supplied by radial systems or loop systems that operate as radial systems under normal operating conditions. The single line diagrams for the distribution systems at the RBTS Buses 2 and 4 are shown in Figures 6.1 and 6.2 respectively. The peak load levels of Bus-2 and Bus-4 are

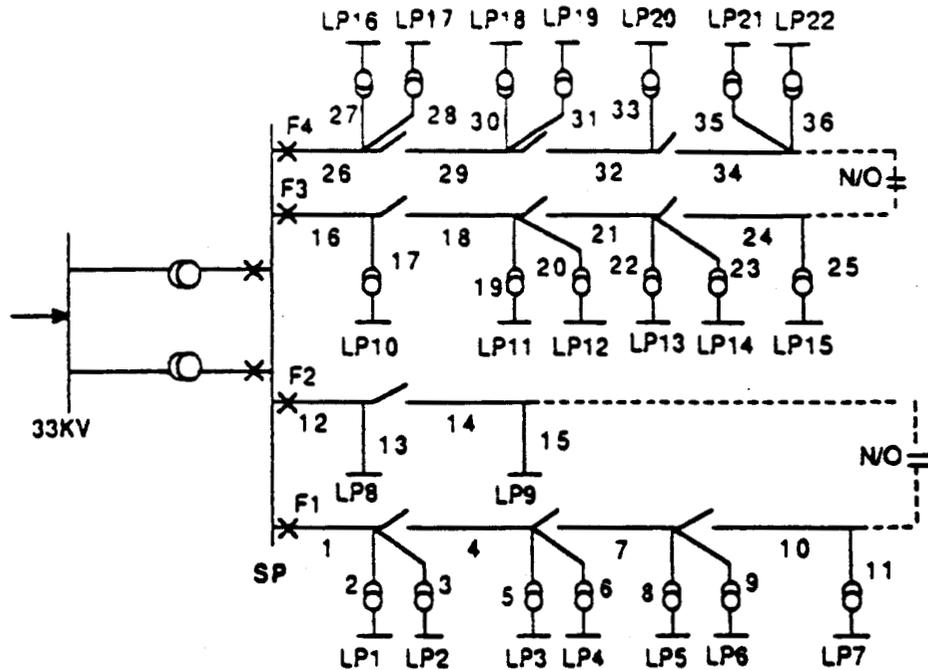


Figure 6.1: Single line diagram for the RBTS Bus-2 distribution system.

20 and 40 MW respectively. The 11 kV feeders are operated as radial feeders, although they are connected as a mesh through normally open switches. The fusegears and disconnects in the radial feeders are assumed to be 100% reliable. The alternate supply is assumed to be 100% available.

The customer data, feeder type and length data and component reliability data are shown in Tables 6.1, 6.2 and 6.3 respectively [32]. The RBTS Bus-4 supplies power to residential (Resdl.), small industrial (Sm.Ind.) and commercial (Comm.) users, whereas Bus-2, in addition to supplying power to these three sectors, also serves government and institutional (G&I) loads.

The studies performed in this thesis assume that the main and lateral sections of the radial feeders are composed of overhead lines and the low voltage transformer connecting the feeder to the customer premises is replaced rather than repaired.

In this chapter, analysis of the RBTS Bus-4 radial distribution system is performed

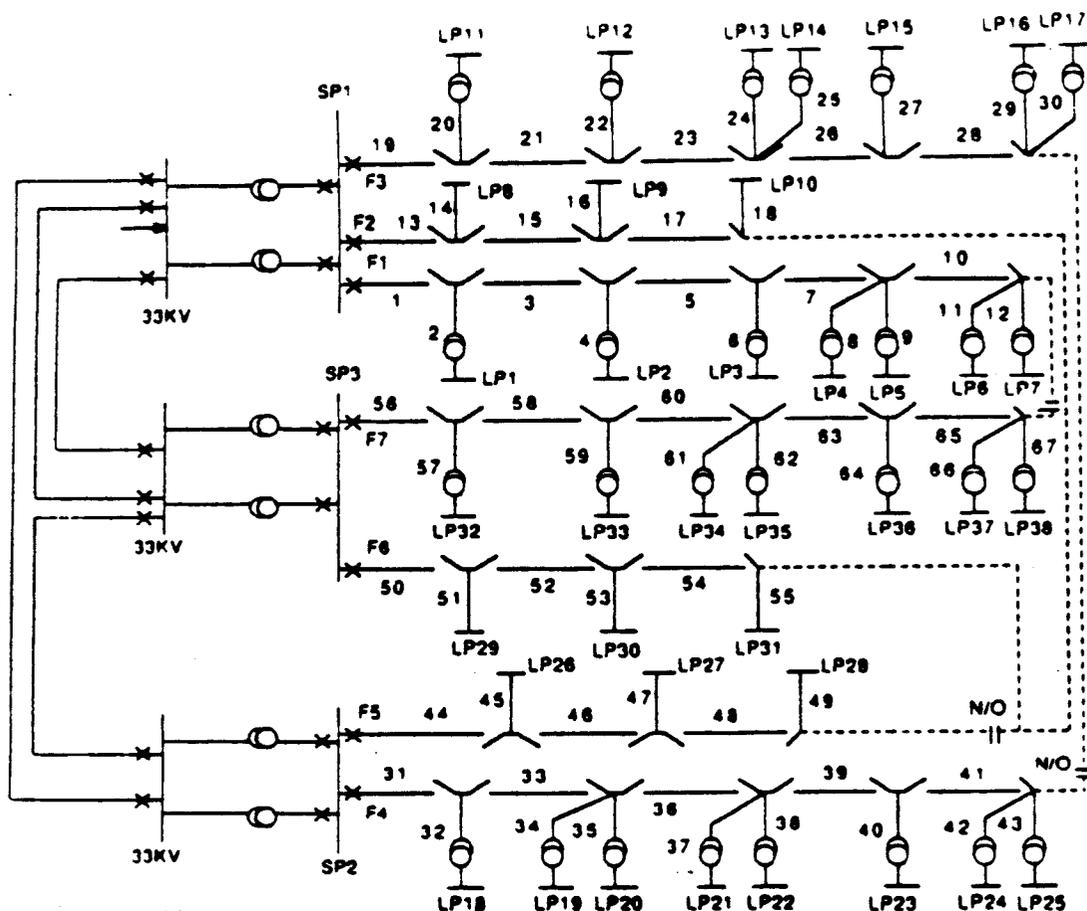


Figure 6.2: Single line diagram for the RBTS Bus-4 distribution system.

utilizing the software 'DISREL'. The RBTS Bus-4 has 7 feeders and 38 load points distributed on these feeders. In this system, seven circuit breakers are used to connect the radial primary feeder to the 11 kV busbar. When a fault occurs on a feeder its associated circuit breaker opens and interrupts the service to all customers supplied by the feeder. Isolators are installed at the junctions between the feeders and the lateral distributors. After locating a fault on a lateral distributor, the faulty section can be isolated by opening the proper switches and service can be restored to the remainder of the feeder before repair is done. The purpose of the fuses in the lateral distributor is to open the circuit in the case of a fault in a transformer or on its associated secondary line and consequently to prevent a possible shutdown of a considerable portion of the feeder or the entire feeder. There is also a provision for alternate supply in the case of a failure in the system. This alternate source is used to supply that section of the main feeder which becomes discon-

Table 6.1: Customer types, number and load data.

Load pts.	Customer type	Average Load per load pt. (MW)	No. of Customers per load pt.
Bus-2:			
1-3,10,11	Resdl.	0.535	210
12,17-19	Resdl.	0.450	200
8	Sm.Ind.	1.000	1
9	Sm.Ind.	1.150	1
4,5,13,14	G&I	0.566	1
20,21	G&I	0.566	1
6,7,15	Comml.	0.454	10
16,22	Comml.	0.454	10
Total:		12.291	1908
Bus-4:			
1-4,11-13	Resdl.	0.545	220
18-21	Resdl.	0.545	220
32-35	Resdl.	0.545	220
5,14,15,22	Resdl.	0.500	200
23,36,37	Resdl.	0.500	200
8,10,26-30	Sm.Ind.	1.000	1
9,31	Sm.Ind.	1.500	1
6,7,16,17	Comml.	0.415	10
24,25,38	Comml.	0.415	10
Total:		24.580	4779

Table 6.2: Feeder data for the RBTS distribution systems.

Sl. No.	Length (km)	Feeder Section Numbers
Bus-2:		
1	0.60	2,6,10,14,17,21,25,28,30,34
2	0.75	1,4,7,9,12,16,19,22,24,27,29,32,35
3	0.80	3,5,8,11,13,15,18,20,23,26,31,33,36
Bus-4:		
1	0.60	2,6,10,14,17,21,25,28,30,34,38,41,43,46,49,51,55,58,61,64,67
2	0.75	1,4,7,9,12,16,19,22,24,27,29,32,35,37,40,42,45,48,50,53,56,60,63,65
3	0.80	3,5,8,11,13,15,18,20,23,26,31,33,36,39,44,47,52,54,57,59,62,66

Table 6.3: Component reliability data for the RBTS distribution systems.

Comp. type	Total fail. rate (f/yr)	Active fail. rate (f/yr)	Repair time (hr)	Repl. time (hr)	Swit. time (hr)
Transformers					
LT	0.015	0.015	200.0	10.0	1.0
Breakers					
11kV	0.006	0.0040	4.0	---	1.0
Busbars					
11kV	0.001	0.001	2.0	---	1.0
Lines					
11kV	0.065	0.065	5.0	---	1.0

Note: Lines failure rates are in f/yr-km.

nected from the main supply after the faulty section has been isolated. The feeders alternately connected in the RBTS Bus-4 are:

1. F1 with F7
2. F2 with F5
3. F2 with F6
4. F3 with F4
5. F5 with F6

Feeders F1 and F7 are connected to each other through a normally open switch. In the event of a failure in feeder F1 the faulty section is isolated and supply is restored to the healthy section of F1 from its main supply. A section of feeder F1 which becomes disconnected from its main supply due to the isolation of the faulty section can be put to service by connecting it to feeder F7. In the same way, F1 becomes the alternate supply path to the disconnected portion of feeder F7 in the event of a failure in F7. Other feeder combinations can similarly be explained.

6.3. General Description of the Program 'DISREL'

The RBTS radial distribution system discussed in the previous section can be analysed by utilizing the computer program 'DISREL' (Distribution reliability) [10]. In order to enhance the understanding of the analysis of a radial distribution system a brief description of the 'DISREL' program is presented.

The program 'DISREL' is used to assess reliability indices of radial systems of the size and complexities of an actual system. It can analyse a wide range of radial distribution systems differing in configuration, operating procedures, protection schemes and mode of restoration. The program can handle systems with up to 300 components and 100 load points. Systems with a branched primary feeder and/or a provision of alternate supply can also be analyzed. The program computes the basic load point indices, i.e. failure rate, average outage duration and annual unavailability. In addition, the program computes the system indices namely SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS. In order to perform reliability analysis of a system, this program recognizes service continuity as the prime performance criterion. The program also has an access to sensitivity studies. Sensitivity analysis can be performed with respect to the component

failure rates and repair times, restoration times and the probabilities associated with the fuse and the alternate supply. The program is structured in such a way that a knowledge of reliability technique is not required in order to use the program. The analysis can be performed by knowing the configuration and operating practices of a system. This program is primarily written for the analysis of radial distribution systems and therefore it considers only first order component failures. Systems using parallel or meshed circuits can, however, be analyzed if the effects of overlapping failures are not required in the analysis.

A detailed description of the program is presented in Reference 10.

6.4. Sensitivity Studies

The base case in these sensitivity studies considers all fuses and alternate supplies to be 100% reliable. The effect of varying the input parameters on the reliability indices are illustrated in the following sections. The input parameters for the base case are shown in Table 6.3. In each sensitivity study, a parameter is increased by 0.4 times its base value keeping the other parameters fixed at their base values.

6.4.1. Variation in SAIFI with a variation in failure rate

Figure 6.3 shows the variation in SAIFI with increments in the values of transmission line failure rates. SAIFI is the average number of customer interruptions per customer in the system. It is directly proportional to the failure rate. The failure rate of a load point is the summation of the failure rates of all the components present in between the supply and that particular load point. From Figure 6.3 it can be observed that the values of SAIFI in the cases of feeders F1, F3, F4 and F7 are higher than those of feeders F2, F5 and F6. This is due to the fact that feeders F1, F3, F4 and F7 have a transformer as an extra element in them. Due to the presence of an extra element, the system failure rate is increased resulting in an increase in the value of SAIFI. In addition, feeders F1, F3, F4 and F7 are longer than feeders F2, F5 and F6. The high failure rates, i.e., SAIFI values, are due to a larger exposure to failure. Feeder F4 has the highest value of SAIFI as it has the highest-number of load points in it.

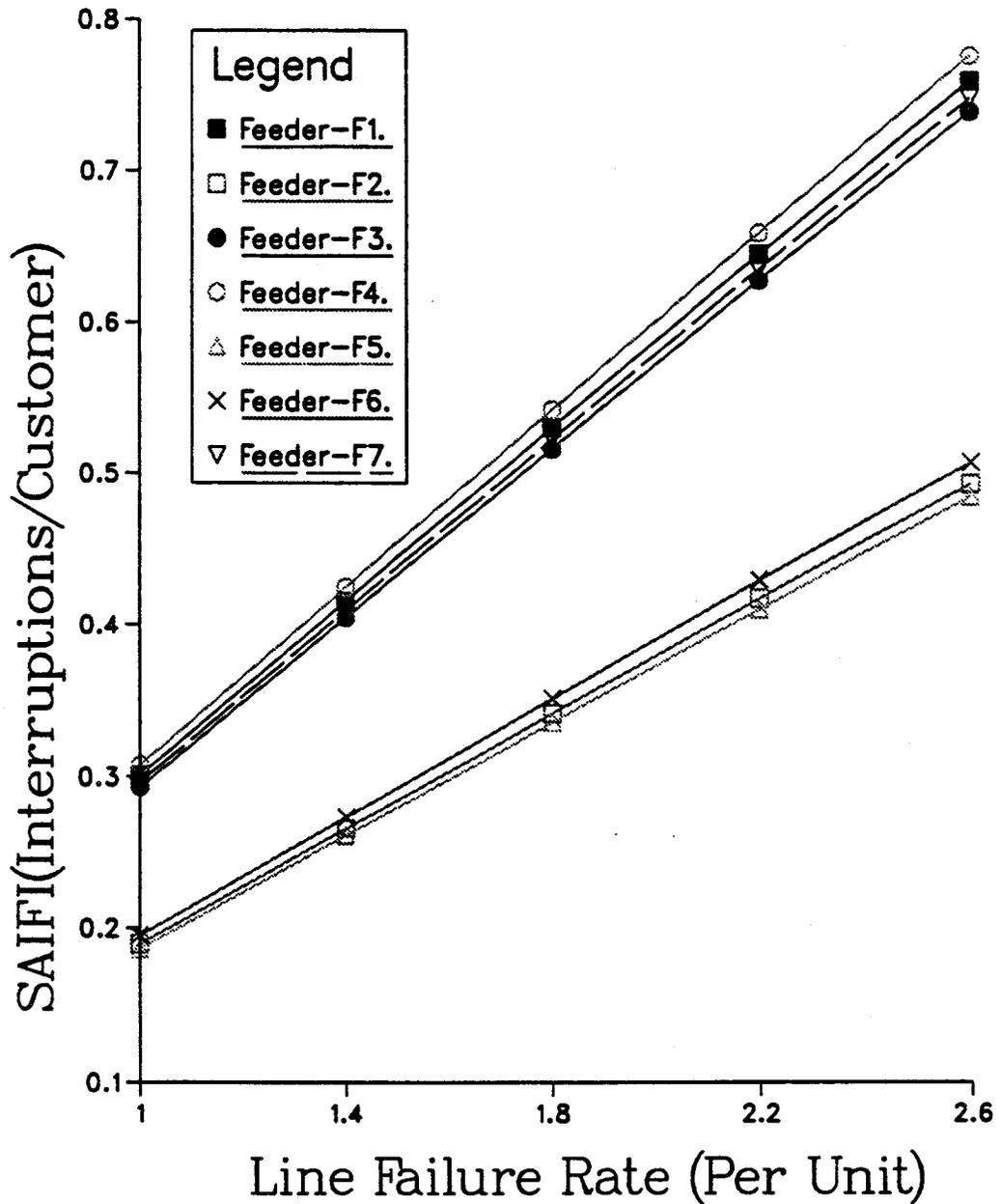


Figure 6.3: Variation in SAIFI with variation in failure rates of transmission lines.

6.4.2. Variation in SAIDI with a variation in repair time

SAIDI is the average customer interruption duration per customer in the system. The behaviour of SAIDI due to variations in the input parameters is similar to that of the annual load point unavailability. An increase in the value of the line restoration time leads to a higher value of SAIDI. The reduced outage times, hence SAIDI values, of feeders F1, F3, F4 and F7 are due to the exclusion of load point transformers serving the small industrial users on these feeders. This fact is shown in Figure 6.4.

6.4.3. Variation in CAIDI with a variation in failure rate

Figure 6.5 shows the variation in CAIDI with a variation in failure rate. CAIDI is the ratio of SAIDI to SAIFI. As failure rates increase, the value of CAIDI decreases as seen in Figure 6.5. In the case of feeders F2, F5 and F6 the ratio of SAIDI to SAIFI remains constant for all increments in failure rate. The CAIDIs of feeders F2, F5 and F6 in Figure 6.5, therefore, exhibit straight line characteristics with zero slope.

6.4.4. Variation in SAIDI with increments in the restoration rates of transformers

Figures 6.6, 6.7, 6.8 and 6.9 show the effect of repair and replacement times of a transformer on the value of SAIDI.

It can be observed that a variation in repair time has a greater effect on the value of SAIDI as compared to that of a variation in replacement time. This is due to the fact that the repair time of a transformer is usually longer than its replacement time. Hence, it can be concluded that at times of transformer failures it is always better to replace transformers instead of repairing them. Unavailability and hence SAIDI is reduced by doing so.

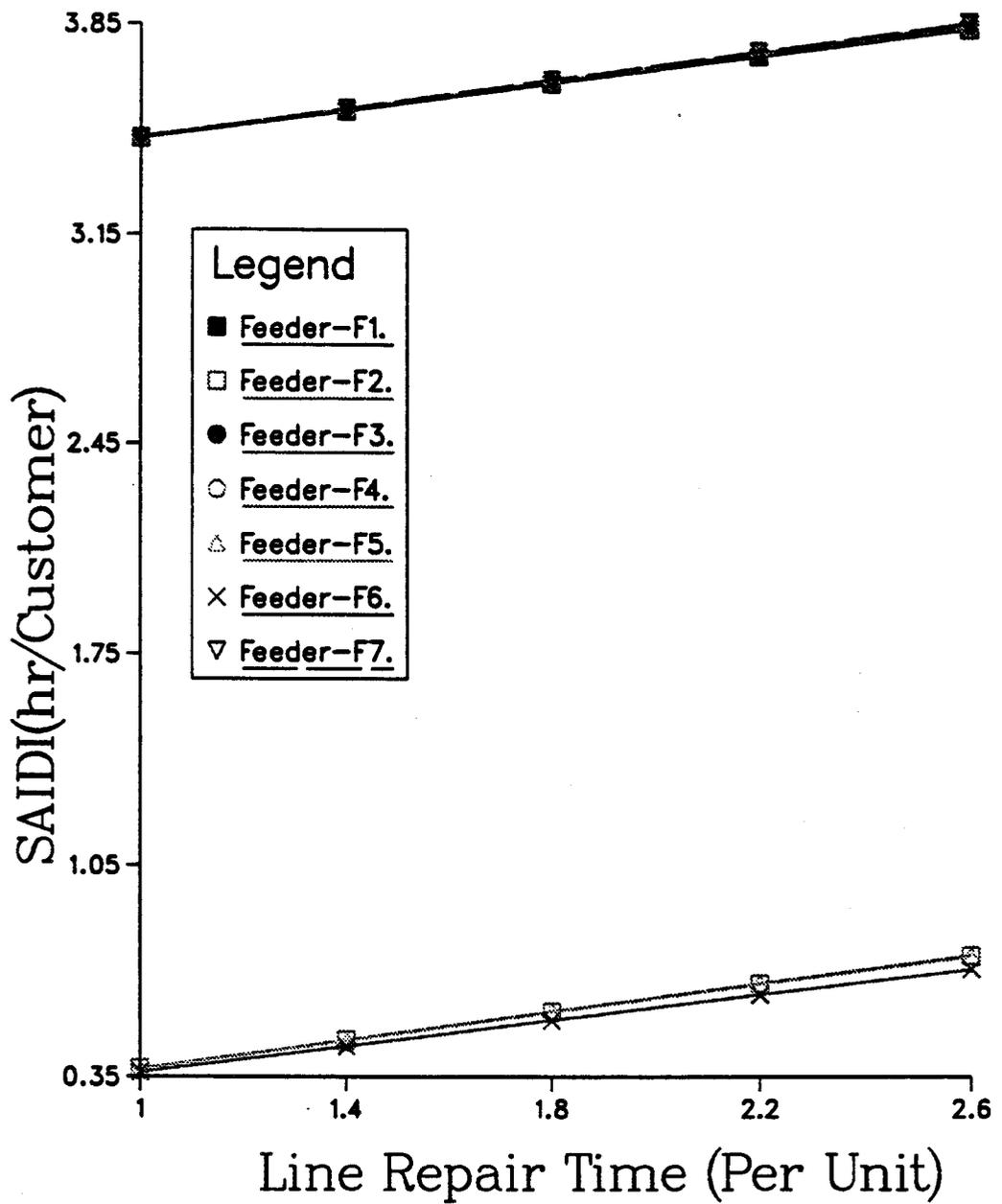


Figure 6.4: Variation in SAIDI with variation in repair time of transmission lines.

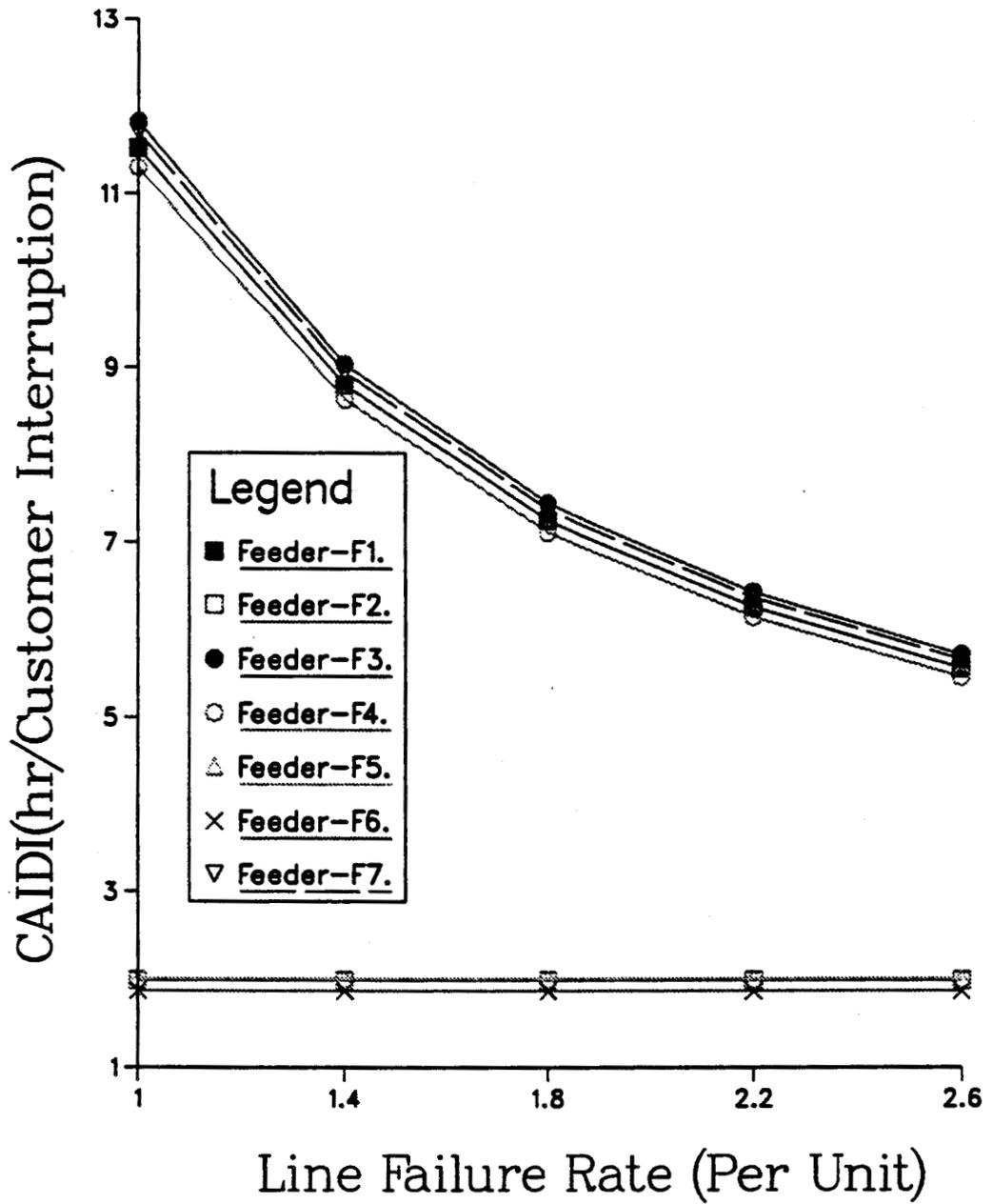


Figure 6.5: Variation in CAIDI with variation in failure rates of transmission lines.

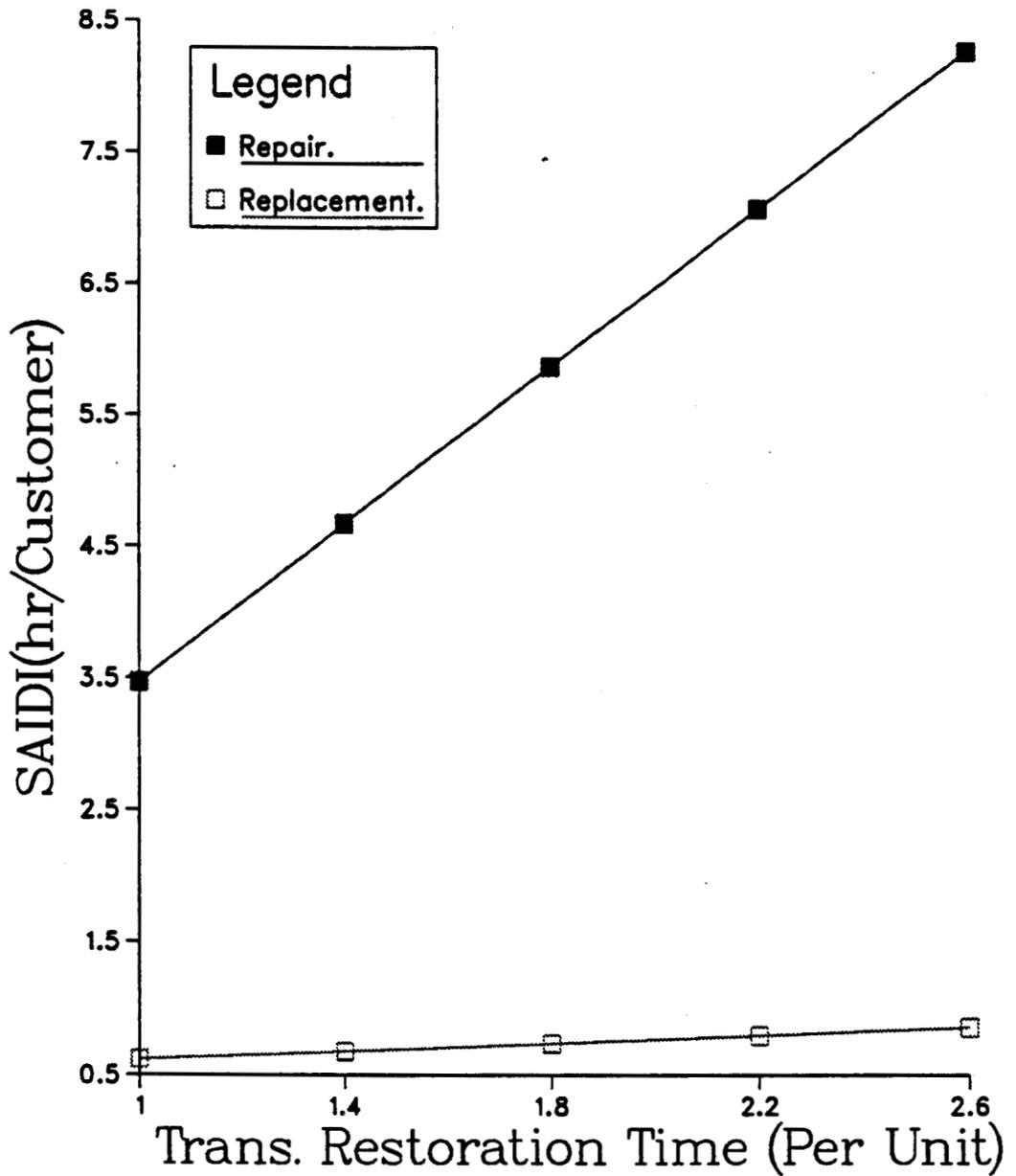


Figure 6.6: Variation in SAIDI of feeder F1 with increments in restoration rates of transformer.

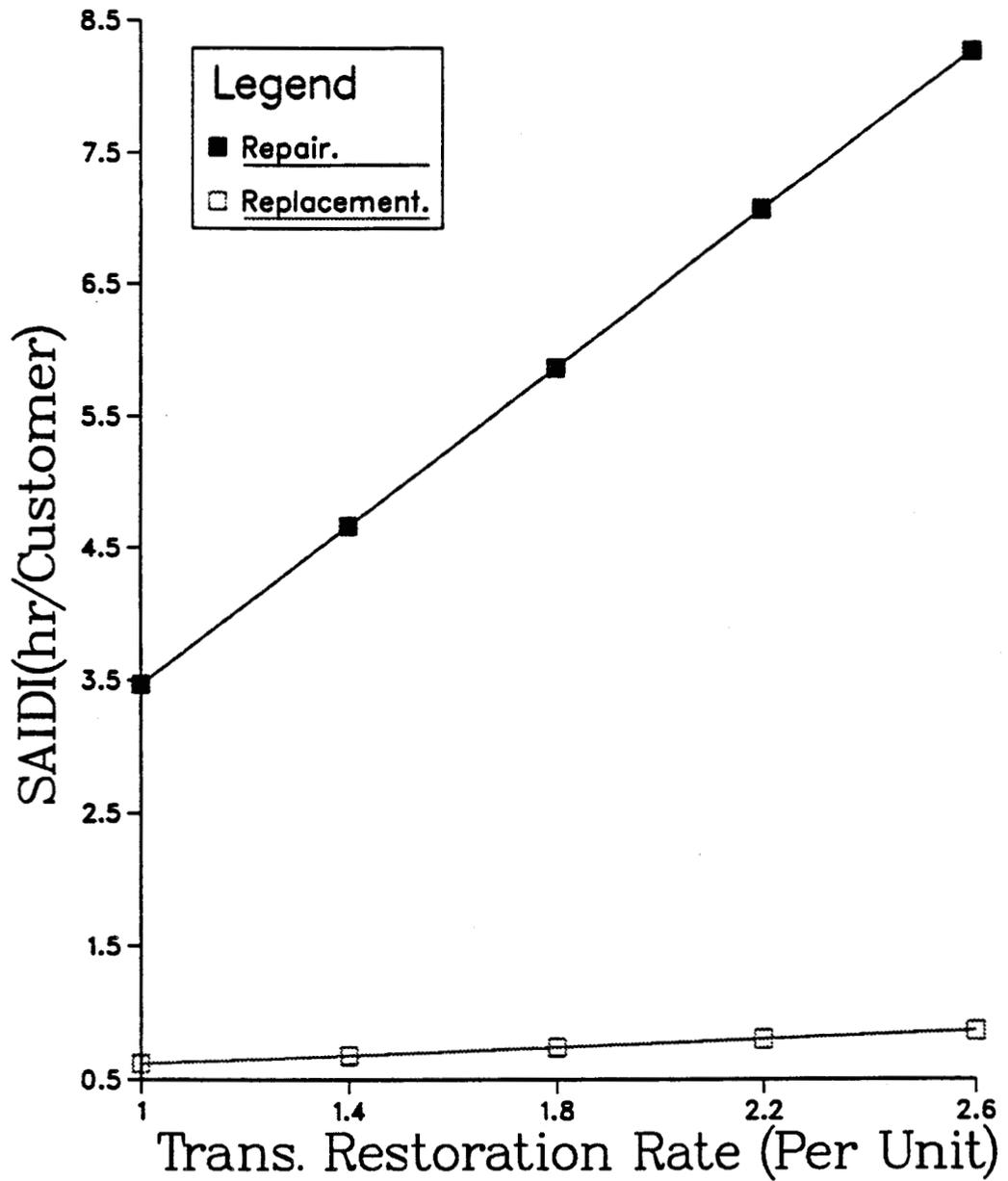


Figure 6.7: Variation in SAIDI of feeder F3 with increments in restoration rates of transformer.

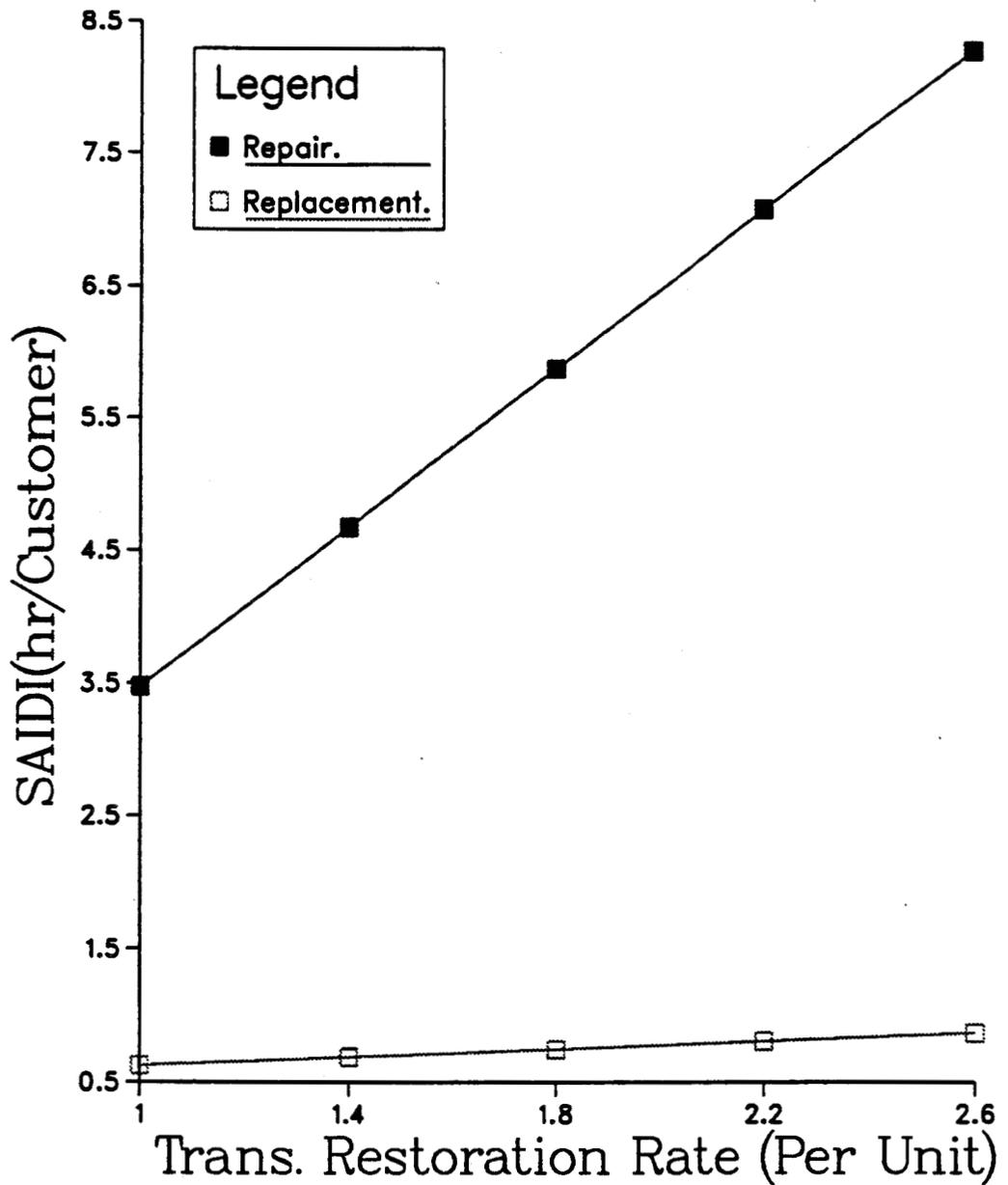


Figure 6.8: Variation in SAIDI of feeder F4 with increments in restoration rates of transformer.

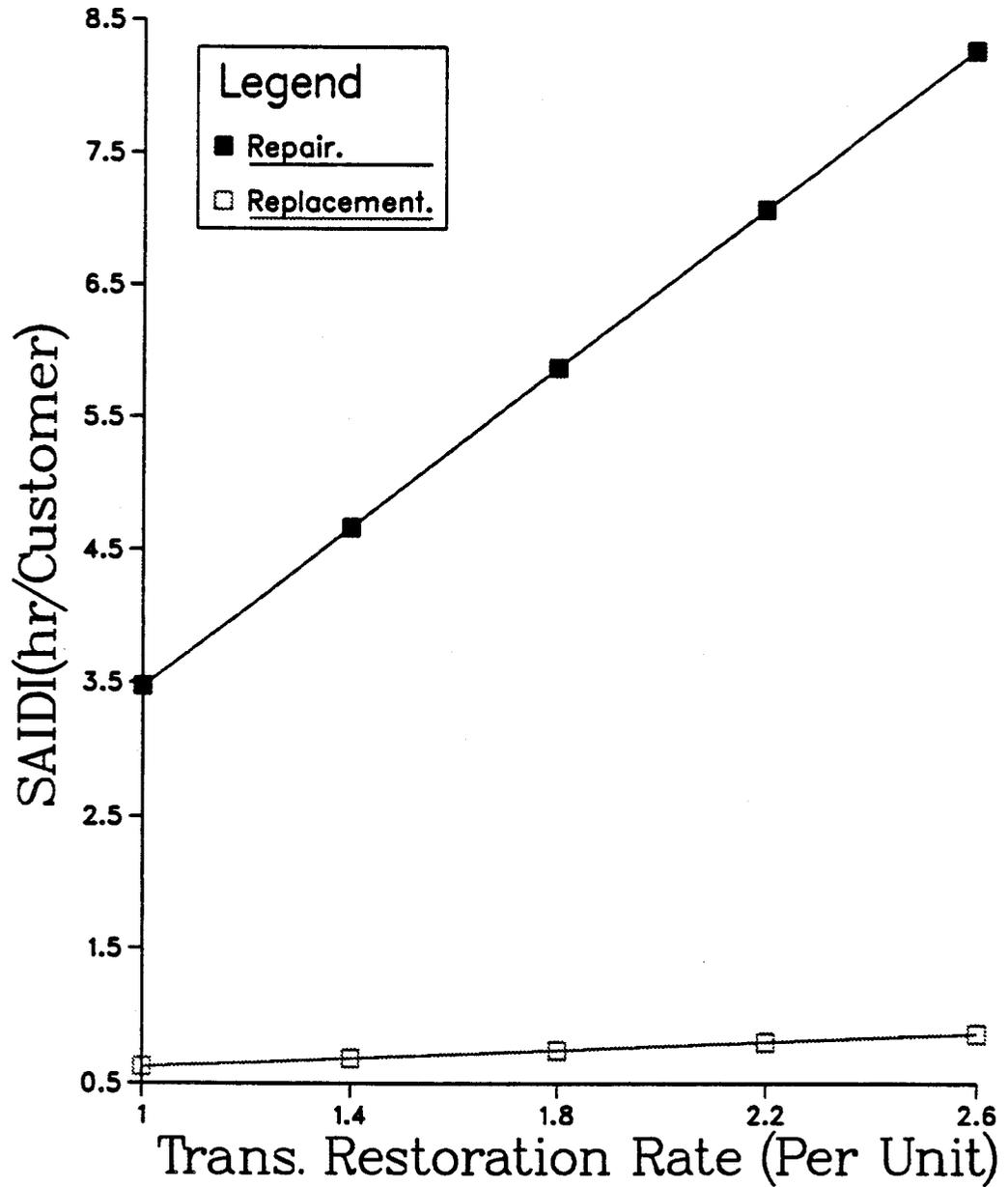


Figure 6.9: Variation in SAIDI of feeder F7 with increments in restoration rates of transformer.

6.4.5. Effect of switching times on the value of SAIDI

Switching times have similar effects on the value of SAIDI as those of repair times. Figure 6.10 shows that the value of SAIDI increases with an increase in the switching times.

6.5. Comparison Between a Subtransmission System and a Radial Portion of the Distribution System

A very high percentage of load point failures of a distribution system comes from the radial portion of the system. In order to verify this statement, a subtransmission portion is compared with radial portion of a distribution system on the basis of reliability indices. Table 6.4 shows the failure rates and unavailabilities of a radial portion and a subtransmission portion of the RBTS Bus-4 distribution system. From Table 6.4 it can be observed that the percentile failure rate of most of the load points in the case of the radial portion is higher than that of the subtransmission portion. Load points 1 through 17 obtain power from SP1. The subtransmission portion of this network has no transmission lines. Reliability indices, therefore, are not affected by adverse weather. The subtransmission system reliability indices are, thus, very small as compared to the radial system reliability indices. SP2 and SP3 supply power to load points 18 through 28 and load points 29 through 38 respectively. Transmission lines are present in the subtransmission portion of these circuits. Reliability indices are, therefore, affected by adverse weather. In the case of SP2 there are 16 second order minimal cuts in the subtransmission portion. The contribution of failure rates of load points 18 to 25 coming from the subtransmission portion are comparable to those coming from the radial portion of the distribution system. In the case of load points 26 to 28, the contribution of reliability indices coming from the subtransmission portion is more than those coming from the radial portion of the distribution system. Feeder F5 is shorter than the other feeders and as a consequence its exposure to failures is less than the others. This is evident in the lower failure rates of load points 26 to 28 which are radially connected to feeder F5. The lower unavailabilities of the radial portion of the system in the case of load points 26 to 28 is due to the exclusion of load point transformers. In the SP3 circuit, there are no second order outages which involve transmission lines, but there are third order outages which involve transmission

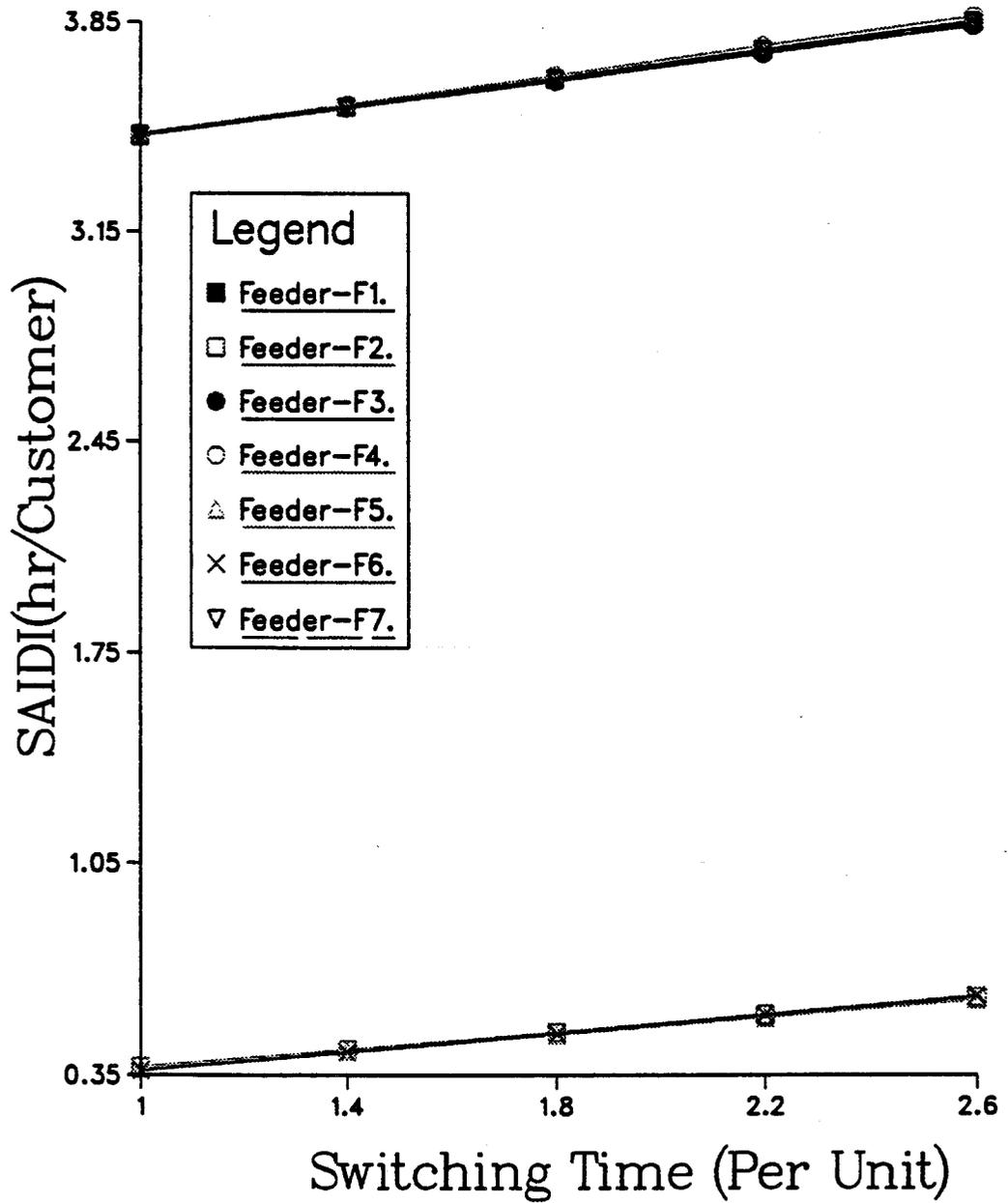


Figure 6.10: Variation in SAIDI with increments in switching time.

Table 6.4: Failure rates and unavailabilities of a subtransmission system and a radial distribution system.

LP	Failure Rate(f/yr)		Unavailability(hr/yr)	
	Radial	Subtran.	Radial	Subtran.
1	0.29450	0.0822	0.5855	0.0701
2	0.30425	0.0822	0.6342	0.0701
3	0.29450	0.0822	0.5855	0.0701
4	0.30750	0.0822	0.6505	0.0701
5	0.30425	0.0822	0.6342	0.0701
6	0.30750	0.0822	0.6505	0.0701
7	0.30425	0.0822	0.6342	0.0701
8	0.18200	0.0822	0.3380	0.0701
9	0.19175	0.0822	0.3867	0.0701
10	0.19500	0.0822	0.4030	0.0701
11	0.29775	0.0822	0.6407	0.0701
12	0.29450	0.0822	0.6245	0.0701
13	0.29450	0.0822	0.6245	0.0701
14	0.28475	0.0822	0.5757	0.0701
15	0.29450	0.0822	0.6245	0.0701
16	0.29450	0.0822	0.6245	0.0701
17	0.28475	0.0822	0.5757	0.0701
18	0.31075	0.2634	0.6407	0.7391
19	0.30100	0.2634	0.5920	0.7391
20	0.31075	0.2634	0.6407	0.7391
21	0.31075	0.2634	0.6407	0.7391
22	0.30100	0.2634	0.5920	0.7391
23	0.31075	0.2634	0.6407	0.7391
24	0.31075	0.2634	0.6407	0.7391
25	0.30100	0.2634	0.5920	0.7391
26	0.18850	0.2634	0.3835	0.7391
27	0.19175	0.2634	0.3997	0.7391
28	0.17875	0.2634	0.3348	0.7391
29	0.19175	0.1701	0.3477	0.2706
30	0.20150	0.1701	0.3965	0.2706
31	0.19175	0.1701	0.3477	0.2706
32	0.30100	0.1701	0.6440	0.2706
33	0.30100	0.1701	0.6440	0.2706
34	0.28800	0.1701	0.5790	0.2706
35	0.30100	0.1701	0.6440	0.2706
36	0.28800	0.1701	0.5790	0.2706
37	0.30100	0.1701	0.6440	0.2706
38	0.28800	0.1701	0.5790	0.2706

where,

Subtran= Subtransmission system

Radial = Radial system

LP = Load point number

lines. The contribution of failure rates coming from the subtransmission portion is, therefore, comparable to that coming from the radial portion.

Network distribution system reliability indices have a considerable effect on system reliability indices. It should, therefore, be included in the evaluation of load point indices.

6.6. Summary

The digital computer program, 'DISREL', developed previously for analyzing radial distribution systems has been discussed in this chapter. Some sensitivity analyses on the RBTS Bus-4 radial distribution system have been performed considering the radial connection to be overhead lines and the results of these analyses have been explained. Finally, a comparison of the reliability performance between the RBTS Bus-4 radial distribution system and the subtransmission system has been done. It has been observed that the contribution of the reliability indices from the subtransmission portion of the distribution system is quite significant. Both types of distribution system, i.e. radial and subtransmission system, therefore, have to be taken into consideration in order to obtain a realistic set of reliability indices.

7. SUMMARY AND CONCLUSIONS

Power system utilities are increasingly interested in the quantitative assessment of system reliability. A power system as a whole is an enormous entity. It is very difficult to evaluate the reliability of a complete power system on this basis. Independent analyses are usually conducted on the three functional zones namely, generation, transmission and distribution, and also at HL-I and HL-II levels. If required, the overall reliability of a complete system can be evaluated by combining the appropriate analyses. A distribution system can be subdivided into subtransmission systems and radial distribution systems. Computer programs have been developed previously at the University of Saskatchewan for analysing radial distribution systems.

An analysis of a subtransmission system involves the identification of individual component failure modes. Load point failure events and restoration modes are then assessed from the component failure modes. Permanent, temporary and maintenance outages are the three types of component failure modes considered in this thesis. In addition, adverse weather effects and active failure events are also considered for the reliability evaluation.

In the past, the effects of overlapping outages of three or more components were usually ignored in the reliability evaluation of distribution systems. This research work was aimed to study the effects of higher order outage events on system reliability indices. A set of equations for the evaluation of interruptions due to third order overlapping permanent, temporary and maintenance outages are developed and illustrated in this thesis. The failure characteristics of components exposed to a changing environment are considered by utilizing a two-state weather model.

One of the objectives of the research work described in this thesis was to develop a

computer program to analyse subtransmission distribution systems. A computer program 'SUBTREL' was developed to analyse subtransmission distribution systems. The program takes into account some of the factors that are known to system planners and operators which affect reliability of subtransmission systems. In this thesis, the RBTS Bus-2 and Bus-4 have been utilized as the test systems. The computer program 'SUBTREL' evaluates the basic reliability indices which includes failure rate, load point outage duration, annual unavailability and the system performance indices such as SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS. The basic steps in the program involve:

1. the determination of events and their possible combinations that can cause outage to the designated load point. The mode of service restoration corresponding to each failure event is also determined.
2. the calculation of outage frequency and duration indices using appropriate equations which are permanently stored in the computer memory.
3. the calculation of performance indices using the basic reliability indices and the number of customers per connected at each load point in the system.

It is cumbersome to take into account the effects of third order outages and adverse weather contributions to the final reliability indices. The results thus obtained by hand calculations, which usually neglect these effects, are optimistic. Reliability calculations up to third order outages can be evaluated by 'SUBTREL'. Most of the outage contributions known to power utilities are taken into account in developing 'SUBTREL'. It is shown in the thesis that third order outages have a considerable effect on the final values of the reliability indices and, therefore, cannot be neglected in the analysis of a system especially when the adverse weather effect is taken into consideration.

In order to increase the reliability of a distribution system, appropriate locations to install additional facilities have to be determined. An attempt has been made to determine the part(s) per of the system which contribute most to the system unreliability indices. This is achieved by utilizing the results of selected sets of sensitivity studies and is illustrated in this thesis in detail. The results obtained from an appropriate set of sensitivity studies will enable the power system engineer to have flexible decision strategies which involve adding the right equipment, at the right time and in the right location so as to derive optimum economic benefits at increased reliability levels.

A distribution network or system is composed of many circuits or feeders that originate at bulk substations and spread out to serve individual customers within a given geographical area. It normally uses primary or main feeders and lateral distributors. A main feeder originates from the substation and passes through the major load centres. The individual load points are connected to the main feeder by lateral distributors with distribution transformers at their ends. Many distribution systems have a single circuit main feeder which are defined as radial distribution systems. Radial systems are popular because of their simple design and generally low cost. In this thesis, a typical radial system is described briefly. Radial distribution systems of the RBTS are analysed by utilizing the computer program 'DISREL' and the results are illustrated in the thesis. Some sensitivity studies are also performed on this system using the same computer program.

References 1 and 5 have shown that more than 80% of the customer unavailability originates from outages in distribution systems. Furthermore, a very high percentage of these occur in the radial part of distribution systems. In this thesis, a comparison of the reliability performance has been made between a subtransmission distribution system and a radial distribution system. It has been found that the contribution of the indices from the subtransmission part of a distribution system is quite significant. In some cases it becomes more than the contribution from a radial distribution as observed in the RBTS Bus-4 system. Both types of distribution system, i.e. radial and subtransmission system, therefore, have to be taken into consideration in order to obtain a dependable set of reliability indices.

The computer program 'SUBTREL' is suitable for analysing a wide range of network subtransmission systems of sizes normally encountered in actual systems. It will enable electric power utilities and consultants to make decisions regarding system planning and operation.

REFERENCES

1. Billinton, R. and Allan, R.N., *Reliability Evaluation of Power Systems*, Plenum Publishing (New York), 1984.
2. Billinton, R. and Allan, R.N., "Probabilistic Methods Applied to Electric Power Systems", Proceedings of the First International Symposium, Toronto, Canada, 11-13 July 1986.
3. Billinton, R. and Allan, R.N., "Basic Power System Reliability Concepts", Reliability Engineering and System Safety 27 1990 365-384, Elsevier Science Publishers Ltd., England.
4. Billinton, R. and Allan, R.N., "Power System Reliability in Perspective", IEE Electronics and Power, March 1984, pp. 231-236.
5. Billinton, R. and Allan, R.N., *Reliability Assessment of Large Electric Power Systems*, Kluwer Academic Publishers, Boston, Massachusetts, 1988.
6. Grover, M.S., "Distribution System Reliability Assessment", MSc. Thesis, University of Saskatchewan, October 1972.
7. Billinton, R., "Distribution System Reliability Performance and Evaluation", Butterworth & Co (Publishers) Ltd., Electrical Power and Energy Systems, vol 10, no. 3, July 1988.
8. Bhavaraju, Murty P., "Application of Contingency Evaluation Techniques to Practical Systems", IEEE Tutorial Course on Reliability Assessment of Composite Generation and Transmission Systems, Course Text no. 90EH0311-1-PWR.
9. Billinton, R. and Allan, R.N., *Reliability Evaluation of Engineering Systems: Concepts & Techniques*, Plenum Publishing (New York), 1983.
10. Goel, R., "Evaluation of Probability Distributions Associated with the Reliability Indices of Electric Distribution Systems", MSc. Thesis, University of Saskatchewan, July 1985.
11. Billinton, R., Kumar, S., Chowdhury, N., Chu, K., Debnath, K., Goel, L., Khan, E., Kos, P., Nourbakhsh, G. and Oteng-Adjei, J., "A Reliability Test for Educational Purposes - Basic Data", IEEE Trans. on Power Systems, PWRS-4, 1989, pp 1238-1244.
12. Billinton, R. and Billinton, J.E., "Distribution System Reliability Indices", IEEE PES Winter Power Meeting, New York, Paper No. 88 WM 068-9, Feb. 1988.
13. IEEE Working Group on Distribution System Reliability of the Distribution Subcommittee of the Transmission & Distribution Committee, "Bibliography on Distribution System Reliability", IEEE Transactions on Power Apparatus and Systems, vol. PAS-97, no. 2, March/April 1978.
14. Singh, C. and Billinton, R., *System Reliability Modelling and Evaluation*, Hitchinson & Co. (Publishers) Ltd., London, 1977.

15. Grover, M.S., "Reliability Evaluation in Substation, Switching Station and Distribution Systems", Phd. Thesis, University of Saskatchewan, June 1974.
16. Allan, R.N., Dialynas, E.N. and Homer, I.R., "Modelling and Evaluating the Reliability of Distribution Systems", IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, no. 6, Nov./Dec. 1979.
17. Allan, R.N., Billinton, R. and DeOliveira, M.F., "Reliability Evaluation of Electrical Systems with Switching Actions", Proc. IEE, 123 1976.
18. Allan, R.N., Billinton, R. and DeOliveira, M.F., "Reliability Evaluation of the Auxiliary Electrical Systems of Power Stations", IEEE Transactions on Power Apparatus and Systems, vol. PAS-96, no. 5, Sept/Oct 1977.
19. Allan, R.N., Billinton, R. and DeOliveira, M.F., "An Efficient Algorithm for Deducing the Minimal Cuts and Reliability Indices of a General Network Configuration", IEEE Transactions on Reliability, vol. R-25, no. 4, Oct 1976.
20. Billinton, R. and Grover, M.S., "Quantitative Evaluation of Permanent Outages in Distribution System", IEEE Transactions on Power Apparatus and Systems, vol. PAS-94, no. 3, May/June 1975.
21. Allan, R.N. and DeOliveira, M.F., "Reliability Modelling and Evaluation of Transmission and Distribution Systems", Proc. IEE 124 1977.
22. Grover, M.S. and Billinton, R., "A Computerized Approach to Substation and Switching Station Reliability Evaluation", IEEE PES Winter Meeting, New York, Jan 27 - Feb 1, 1974.
23. Billinton, R. and Bollinger, K.E., "Transmission System Reliability Evaluation Using Markov Process", IEEE Transactions, PAS-87, Feb-1968.
24. Billinton, R., Kumar, S., Chowdhury, N., Chu, K., Debnath, K., Goel, L., Khan, E., Kos, P., Nourbakhsh, G. and Oteng-Adjei, J., "A Reliability Test for Educational Purposes - Basic Results", IEEE Trans on Power Systems, PWRS-4, 1989, pp 1238-1244.
25. IEEE Committee Report, "IEEE Reliability Test System", IEEE Transactions, vol. PAS-98, 1979, pp 2047-2054.
26. Allan, R.N., Billinton, R., Sjarief, I., Goel, L. and So, K.S., "A Reliability Test System for Educational Purposes - Basic Distribution System Data and Results", IEEE Transaction on Power Systems, vol. 6, No. 2, May 1991, pp. 813-820.
27. Billinton, R., Gupta, R. and Goel, L., "Reliability Evaluation of Sub-transmission Systems", Proceedings at the IEEE WESCANEX, pp. 260-266, May 29-30, 1991, Regina, Canada.
28. Billinton, R. and Grover, M.S., "Reliability Assessment of Transmission and Distribution Schemes", IEEE Transactions on Power Apparatus and Systems, vol. PAS-94, no. 3, May/June 1975.
29. Koval, D.O., "Evaluation of Distribution System Reliability", Phd. Thesis, University of Saskatchewan, June 1978.

30. Koval, D.O. and Billinton, R., "Evaluation of Distribution Circuit Reliability", IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, no. 2, March/April 1979.
31. Yuan-Yih, Hsu, Li-Ming, chen, Mou-Chih, Hsueh, Lin, C.T., Tom, S.S. Liu and W.C. Chen, "Application of a Microcomputer-Based DATABASE Management System to Distribution System Reliability Evaluation", IEEE PES Summer Meeting, Long Beach, California, July 9 - 14, 1989.
32. Goel, L., Billinton, R. and Gupta, R., "Basic Data and Evaluation of Distribution System Reliability Worth", Proceedings at the IEEE WES-CANEX, pp. 271-277, May 29-30, 1991, Regina, Canada.

A. SYSTEM PERFORMANCE INDICES

A.1. System Average Interruption Frequency Index - SAIFI

SAIFI is defined as the average number of interruptions per customer served per unit time.

$$SAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}}$$

$$SAIFI = \frac{\sum_i \lambda_i N_i}{\sum_i N_i}$$

where λ_i is the failure rate and N_i is the number of customers of load point i .

A.2. System Average Interruption Duration Index - SAIDI

SAIDI is defined as the average interruption duration for customers served during a year.

$$SAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customers}}$$

$$SAIDI = \frac{\sum_i U_i N_i}{\sum_i N_i}$$

where U_i is the annual outage time and N_i is the number of customers of load point i .

A.3. Customer Average Interruption Duration Index - CAIDI

CAIDI is defined as the interruption duration for customers interrupted during a year.

$$CAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customer interruptions}}$$

$$CAIDI = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i}$$

where λ_i is the failure rate, U_i is the annual outage time and N_i is the number of customers of load point i .

A.4. Average Service Availability Index - ASAI

ASAI is defined as the ratio of the total number of customer hours that service was available during a year to the total customer hours demanded.

$$ASAI = \frac{\text{customer hours of available service}}{\text{customer hours demanded}}$$

$$ASAI = \frac{\sum N_i \times 8760 - U_i N_i}{\sum N_i \times 8760}$$

where 8760 is the number of hours in a calendar year, U_i is the annual outage time and N_i is the number of customers of load point i .

A.5. Average Service Unavailability Index - ASUI

ASUI is defined as the ratio of the total number of customer hours that service was unavailable during a year to the total customer hours demanded.

$$ASUI = \frac{\text{customer hours of unavailable service}}{\text{customer hours demanded}}$$

$$ASUI = \frac{\sum_i U_i N_i}{\sum_i N_i \times 8760}$$

where 8760 is the number of hours in a calander year, U_i is the annual outage time and N_i is the number of customers of load point i.

A.6. Energy Not Supplied - ENS

ENS is the total energy not supplied by the system.

$$ENS = \sum_i L_{a(i)} U_i$$

where $L_{a(i)}$ is the average load connected to the load point i and U_i is the annual outage time.

A.7. Average System Curtailment Index - ASCI

ASCI is the ratio of the total energy not supplied to the total number of customers served.

$$ASCI = \frac{\text{total energy not supplied}}{\text{total number of customers served}}$$

$$ASCI = \frac{\sum_i L_{a(i)} U_i}{\sum_i N_i}$$

where $L_{a(i)}$ is the average load connected to the load point i, U_i is the unavailability of the load point i and N_i is the number of customers of load point i.

A.8. Average Customer Curtailment Index - ACCI

ACCI is the ratio of the total energy not supplied to the total number of customers affected.

$$ACCI = \frac{\text{total energy not supplied}}{\text{total number of customers affected}}$$

$$ACCI = \frac{\sum_i L_{a(i)} U_i}{N_a}$$

where $L_{a(i)}$ is the average load connected to the load point i , U_i is the unavailability of the load point i and N_a is the total number of customers affected.

B. RELIABILITY EQUATIONS

This appendix presents some equations, developed during this research work, that relate to second order and third order overlapping events. All the equations have been deduced logically using the concepts of overlapping outages described in Reference [1]. The assumptions and conditions are also given in Reference [1].

B.1. Permanent Failure Overlapping a Temporary Outage in Adverse Weather

The system indices are given by combining the tabulated contributions ($i=1$ to $i=4$) as follows:

$$\lambda = \lambda_a + \lambda_b \quad (B.1)$$

$$U = r_a(\lambda_{11} + \lambda_{31}) + r_b(\lambda_{21} + \lambda_{41}) + r_c(\lambda_{12} + \lambda_{32}) + r_d(\lambda_{22} + \lambda_{42}) \quad (B.2)$$

$$r = \frac{U}{\lambda} \quad (B.3)$$

where,

$$\lambda_a = \sum_{i=1}^4 \lambda_{i1}$$

$$\lambda_b = \sum_{i=1}^4 \lambda_{i2}$$

$$r_a = \frac{r_{11}r_2}{r_{11} + r_2}$$

$$r_b = \frac{r_{11}r_2}{r_{11} + r_2} + S$$

$$r_c = \frac{r_1r_2}{r_1 + r_2}$$

$$r_d = \frac{r_1r_2}{r_1 + r_2} + S$$

No. (i)	Failure mode 1st-2nd	Contribution to the system failure rate (λ_{11})	(λ_{12})
1	N - N	$\frac{N}{(N+S)} (\lambda_{11}\lambda_2r_{11} + \lambda_2\lambda_{11}r_2)$	$\frac{N}{(N+S)} (\lambda_2\lambda_2r_2 + \lambda_1\lambda_2r_1)$
2	N - A	$\frac{N}{(N+S)} (\lambda_{11}\frac{(r_{11})}{(N)}(\lambda_2'S)$ $+ \lambda_2\frac{(r_2)}{(N)}(\lambda_{11}'S))$	$\frac{N}{(N+S)} (\lambda_2\frac{(r_2)}{(N)}(\lambda_1'S)$ $+ \lambda_1\frac{(r_1)}{(N)}(\lambda_2'S))$
3	A - N	$\frac{S}{(N+S)} (\lambda_{11}\lambda_2r_{11} + \lambda_2\lambda_{11}r_2)$	$\frac{S}{(N+S)} (\lambda_2\lambda_1r_2 + \lambda_1\lambda_2r_1)$
4	A - A	$\frac{S}{(N+S)} (\lambda_{11}\lambda_2'S + \lambda_2\lambda_{11}'S)$	$\frac{S}{(N+S)} (\lambda_2\lambda_1'S + \lambda_1\lambda_2'S)$

B.2. Temporary Failure Overlapping a Maintenance Outage in Adverse Weather

$$\lambda = \lambda_1''(\lambda_{a2}r_1'') + \lambda_2''(\lambda_{a1}r_2'') + \lambda_1''\left(\frac{r_1''}{N}\right)(\lambda_{r2}'S) + \lambda_2''\left(\frac{r_2''}{N}\right)(\lambda_{r1}'S) \quad (B.4)$$

$$U = \lambda_{a1}R_1 + \lambda_{a2}R_2 + \lambda_{b1}(R_1 + S) + \lambda_{b2}(R_2 + S) \quad (B.5)$$

$$r = \frac{U}{\lambda} \quad (B.6)$$

where,

$$\lambda_{a1} = \lambda_1''(\lambda_{a2}r_1'')$$

$$\lambda_{a2} = \lambda_2''(\lambda_{a1}r_2'')$$

$$\lambda_{b1} = \lambda_1''\left(\frac{r_1''}{N}\right)(\lambda_{r2}'S)$$

$$\lambda_{b2} = \lambda_2''\left(\frac{r_2''}{N}\right)(\lambda_{r1}'S)$$

$$R_1 = \frac{r_1''r_2''}{r_1'' + r_2''}$$

$$R_2 = \frac{r_2''r_1''}{r_2'' + r_1''}$$

B.3. Two Permanent Forced Outages Overlapping a Maintenance Outage in Adverse Weather

The system indices are given by combining the tabulated contributions (i=1 to i=4) as follows:

$$\lambda = \lambda_a + \lambda_b \quad (B.7)$$

$$U = \lambda_a r_a + \lambda_b r_b \quad (B.8)$$

$$r = \frac{U}{\lambda} \quad (B.9)$$

where,

$$\lambda_a = \sum_{i=1}^2 \lambda_i$$

$$\lambda_b = \sum_{i=3}^4 \lambda_i$$

$$r_a = \frac{r_1'' r_2 r_3}{r_1'' r_2 + r_2 r_3 + r_1'' r_3}$$

$$r_b = \frac{r_1'' r_2 r_3}{r_1'' r_2 + r_2 r_3 + r_1'' r_3} + S$$

$$R_{11} = \frac{r_1'' r_2}{r_1'' + r_2}$$

$$R_{12} = \frac{r_1'' r_3}{r_1'' + r_3}$$

No. (i)	Failure mode 1st-2nd-3rd	Contribution to the system failure rate (λ_1)
1	N - N - N	$\lambda_1 \cdot (\lambda_2 r_1) (\lambda_3 R_{11}) + \lambda_1 \cdot (\lambda_3 r_1) (\lambda_2 R_{12})$ <i>+ similar terms for components 2 and 3</i>
2	N - A - N	$\lambda_1 \cdot \left(\frac{r_1}{N}\right) (\lambda_2' S) (\lambda_3 R_{11}) + \lambda_1 \cdot \left(\frac{r_1}{N}\right) (\lambda_3' S) (\lambda_2 R_{12})$ <i>+ similar terms for components 2 and 3</i>
3	N - A - A	$\lambda_1 \cdot \left(\frac{r_1}{N}\right) (\lambda_2' S) (\lambda_3' S) + \lambda_1 \cdot \left(\frac{r_1}{N}\right) (\lambda_3' S) (\lambda_2' S)$ <i>+ similar terms for components 2 and 3</i>
4	N - N - A	$\lambda_1 \cdot (\lambda_2 r_1) \left(\frac{R_{11}}{N}\right) (\lambda_3' S) + \lambda_1 \cdot (\lambda_3 r_1) \left(\frac{R_{12}}{N}\right) (\lambda_2' S)$ <i>+ similar terms for components 2 and 3</i>

B.4. Temporary Failure Overlapping Two Permanent Outages in Adverse Weather

The system indices are given by combining the tabulated contributions ($i=1$ to $i=8$) as follows:

$$\lambda = \lambda_a + \lambda_b \quad (B.10)$$

$$U = \lambda_a r_a + \lambda_b r_b \quad (B.11)$$

$$r = \frac{U}{\lambda} \quad (B.12)$$

where,

$$\lambda_a = \sum_{i=1}^4 \lambda_i$$

$$\lambda_b = \sum_{i=5}^8 \lambda_i$$

$$r_a = \frac{r_1 r_2 r_3}{r_1 r_2 + r_2 r_3 + r_1 r_3}$$

$$r_b = \frac{r_1 r_2 r_3}{r_1 r_2 + r_2 r_3 + r_1 r_3} + S$$

$$R_{11} = \frac{r_{11}r_2}{r_{11} + r_2}$$

$$R_{12} = \frac{r_{11}r_3}{r_{11} + r_3}$$

$$R_{13} = \frac{r_2r_3}{r_2 + r_3}$$

No. (i)	Failure mode 1st-2nd-3rd	Contribution to the system failure rate (λ_i)
1	N - N - N	$\frac{N}{(N+S)} (\lambda_{11} \lambda_2 \lambda_3 (r_{11} r_2 + r_2 r_3 + r_3 r_{11})$ <p>+ similar terms for components 2 and 3)</p>
2	N - A - N	$\frac{N}{(N+S)} (\lambda_{11} (\frac{r_{11}}{N}) (\lambda_2' S) (\lambda_3 R_{11}) + \lambda_{11} (\frac{r_{11}}{N}) (\lambda_3' S) (\lambda_2 R_{12})$ $+ \lambda_2 (\frac{r_2}{N}) (\lambda_{11}' S) (\lambda_3 R_{11}) + \lambda_2 (\frac{r_2}{N}) (\lambda_3' S) (\lambda_{11} R_{13})$ $+ \lambda_3 (\frac{r_3}{N}) (\lambda_{11}' S) (\lambda_2 R_{12}) + \lambda_3 (\frac{r_3}{N}) (\lambda_2' S) (\lambda_{11} R_{13})$ <p>+ similar terms for components 2 and 3)</p>
3	A - N - N	$\frac{S}{(N+S)} (\lambda_{11}' (\lambda_2 r_{11}) (\lambda_3 R_{11}) + \lambda_{11}' (\lambda_3 r_{11}) (\lambda_2 R_{12})$ $+ \lambda_2' (\lambda_{11} r_2) (\lambda_3 R_{11}) + \lambda_2' (\lambda_3 r_2) (\lambda_{11} R_{13})$ $+ \lambda_3' (\lambda_{11} r_3) (\lambda_2 R_{12}) + \lambda_3' (\lambda_2 r_3) (\lambda_{11} R_{13})$ <p>+ similar terms for components 2 and 3)</p>
4	A - A - N	$\frac{S}{(N+S)} (\lambda_{11}' (\lambda_2' S) (\lambda_3 R_{11}) + \lambda_{11}' (\lambda_3' S) (\lambda_2 R_{12})$ $+ \lambda_2' (\lambda_{11}' S) (\lambda_3 R_{11}) + \lambda_2' (\lambda_3' S) (\lambda_{11} R_{13})$ $+ \lambda_3' (\lambda_{11}' S) (\lambda_2 R_{12}) + \lambda_3' (\lambda_2' S) (\lambda_{11} R_{13})$ <p>+ similar terms for components 2 and 3)</p>

No. (i)	Failure mode 1st-2nd-3rd	Contribution to the system failure rate (λ_i)
5	A - A - A	$\frac{S}{(N+S)} (\lambda_{11}'(\lambda_2'S)(\lambda_3'S) + \lambda_{11}'(\lambda_3'S)(\lambda_2'S)$ $+ \lambda_2'(\lambda_{11}'S)(\lambda_3'S) + \lambda_2'(\lambda_3'S)(\lambda_{11}'S)$ $+ \lambda_3'(\lambda_{11}'S)(\lambda_2'S) + \lambda_3'(\lambda_2'S)(\lambda_{11}'S)$ $+ \text{similar terms for components 2 and 3})$
6	A - N - A	$\frac{S}{(N+S)} (\lambda_{11}'(\lambda_2'r_{11})(\frac{R_{11}}{N})(\lambda_3'S)$ $+ \lambda_{11}'(\lambda_3'r_{11})(\frac{R_{12}}{N})(\lambda_2'S)$ $+ \lambda_2'(\lambda_{11}'r_2)(\frac{R_{11}}{N})(\lambda_3'S) + \lambda_2'(\lambda_3'r_2)(\frac{R_{13}}{N})(\lambda_{11}'S)$ $+ \lambda_3'(\lambda_{11}'r_3)(\frac{R_{12}}{N})(\lambda_2'S) + \lambda_3'(\lambda_2'r_3)(\frac{R_{13}}{N})(\lambda_{11}'S)$ $+ \text{similar terms for components 2 and 3})$
7	N - N - A	$\frac{N}{(N+S)} (\lambda_{11}'(\frac{r_{11}}{N})(\lambda_2'S)(\lambda_3'S)$ $+ \lambda_{11}'(\frac{r_{11}}{N})(\lambda_3'S)(\lambda_2'S)$ $+ \lambda_2'(\frac{r_2}{N})(\lambda_{11}'S)(\lambda_3'S) + \lambda_2'(\frac{r_2}{N})(\lambda_3'S)(\lambda_{11}'S)$ $+ \lambda_3'(\frac{r_3}{N})(\lambda_{11}'S)(\lambda_2'S) + \lambda_3'(\frac{r_3}{N})(\lambda_2'S)(\lambda_{11}'S)$ $+ \text{similar terms for components 2 and 3})$
8	N - N - A	$\frac{N}{(N+S)} (\lambda_{11}'(\lambda_2'r_{11})(\frac{R_{11}}{N})(\lambda_3'S)$ $+ \lambda_{11}'(\lambda_3'r_{11})(\frac{R_{12}}{N})(\lambda_2'S)$ $+ \lambda_2'(\lambda_{11}'r_2)(\frac{R_{11}}{N})(\lambda_3'S) + \lambda_2'(\lambda_3'r_2)(\frac{R_{13}}{N})(\lambda_{11}'S)$ $+ \lambda_3'(\lambda_2'r_{11})(\frac{R_{12}}{N})(\lambda_2'S) + \lambda_3'(\lambda_2'r_3)(\frac{R_{13}}{N})(\lambda_{11}'S)$ $+ \text{similar terms for components 2 and 3})$

B.5. Temporary Failure Overlapping Permanent and Maintenance Outages in Adverse Weather

The system indices are given by combining the tabulated contributions ($i=1$ to $i=4$) as follows:

$$\lambda = \lambda_a + \lambda_b + \lambda_c + \lambda_d \quad (B.13)$$

$$U = \lambda_a r_a + \lambda_b r_b + \lambda_c r_c + \lambda_d r_d \quad (B.14)$$

$$r = \frac{U}{\lambda} \quad (B.15)$$

where,

$$\lambda_a = \sum_{i=1}^2 \lambda_{i1}$$

$$\lambda_b = \sum_{i=3}^4 \lambda_{i1}$$

$$\lambda_c = \sum_{i=1}^2 \lambda_{i2}$$

$$\lambda_d = \sum_{i=3}^4 \lambda_{i2}$$

$$r_a = \frac{r_1 r_2 r_3}{r_1 r_2 + r_2 r_3 + r_1 r_3}$$

$$r_b = \frac{r_1 r_2 r_3}{r_1 r_2 + r_2 r_3 + r_1 r_3} + S$$

$$r_c = \frac{r_1'' r_2 r_3}{r_1'' r_2 + r_2 r_3 + r_1'' r_3}$$

$$r_d = \frac{r_1'' r_2 r_3}{r_1'' r_2 + r_2 r_3 + r_1'' r_3} + S$$

$$R_1 = \frac{r_1'' r_2}{r_1'' + r_2}$$

$$R_2 = \frac{r_1'' r_3}{r_1'' + r_3}$$

$$R_3 = \frac{r_1'' r_3}{r_1'' + r_3}$$

$$R_4 = \frac{r_1'' r_2}{r_1'' + r_2}$$

No. (i)	Failure mode 1st-2nd-3rd	Contribution to the system failure rate (λ_{i1})	(λ_{i2})
1	N - N - N	$\lambda_1 (\lambda_{12} r_1) (\lambda_3 R_1)$ $+ \lambda_1 (\lambda_3 r_1) (\lambda_{12} R_2)$ <i>+ similar terms for components 2 and 3</i>	$\lambda_1 (\lambda_{13} r_1) (\lambda_2 R_3)$ $+ \lambda_1 (\lambda_2 r_1) (\lambda_{13} R_4)$ <i>+ similar terms for components 2 and 3</i>
2	N - A - N	$\lambda_1 \left(\frac{r_1}{N}\right) (\lambda_{12}' S) (\lambda_3 R_1)$ $+ \lambda_1 \left(\frac{r_1}{N}\right) (\lambda_3' S) (\lambda_{12} R_2)$ <i>+ similar terms for components 2 and 3</i>	$\lambda_1 \left(\frac{r_1}{N}\right) (\lambda_{13}' S) (\lambda_2 R_3)$ $+ \lambda_1 \left(\frac{r_1}{N}\right) (\lambda_2' S) (\lambda_{13} R_4)$ <i>+ similar terms for components 2 and 3</i>
3	N - A - A	$\lambda_1 \left(\frac{r_1}{N}\right) (\lambda_{12}' S) (\lambda_3' S)$ $+ \lambda_1 \left(\frac{r_1}{N}\right) (\lambda_3' S) (\lambda_{12}' S)$ <i>+ similar terms for components 2 and 3</i>	$\lambda_1 \left(\frac{r_1}{N}\right) (\lambda_{13}' S) (\lambda_2' S)$ $+ \lambda_1 \left(\frac{r_1}{N}\right) (\lambda_2' S) (\lambda_{13}' S)$ <i>+ similar terms for components 2 and 3</i>
4	N - N - A	$\lambda_1 (\lambda_{12}' r_1) \left(\frac{R_1}{N}\right) (\lambda_3' S)$ $+ \lambda_1 (\lambda_3' r_1) \left(\frac{R_2}{N}\right) (\lambda_{12}' S)$ <i>+ similar terms for components 2 and 3</i>	$\lambda_1 (\lambda_{13}' r_1) \left(\frac{R_3}{N}\right) (\lambda_2' S)$ $+ \lambda_1 (\lambda_2' r_1) \left(\frac{R_4}{N}\right) (\lambda_{13}' S)$ <i>+ similar terms for components 2 and 3</i>

C. DIGITAL COMPUTER PROGRAM

C.1. Input Data Files

A computer program, used for evaluation of subtransmission systems, has been explained briefly in chapter 4. As earlier mentioned this computer program utilizes two input data files. Both the input data files are unformatted for convenience and simplicity. The detailed structure of these two input data files are described below:

C.1.1. Data file for evaluation of minimal cuts and active failures

STEP-1 Provide a heading for all calculations, e.g. Reliability evaluation of subtransmission system. Number and sum all breakers, bus-section, transformers and lines of the system.

The first line includes the heading.

Next line contains:

NTOT

NTOT = total number of elements which includes busbars, transformers, breakers and lines in the system.

STEP-2 Count the number of load points in the system

Next line has :

NL

NL = Total number of load points in the system.

STEP-3 Next line has

CUS(J) LOAD(J)

CUS(J) = Number of customers at each load point.

LOAD(J) = load connected at each load point in KW.

This step is repeated NL times.

STEP-4 Consider the failure mode of each element of the system individually and note all elements which are affected by the failure of that particular element.

The next 2XNTOT lines include (for each components there are two lines):

NT(LKP)

AF(LKP,IH)

NT(LKP) = total number of elements which are effected by the active failure of a particular element, including the element itself.

AF(LKP,IH) = the first column contains the element number which undergoes failure followed by all the element numbers which are affected by the failure of the first element.

STEP-5 Find out the number of paths from the supply to the load point j.

The next line has :

$N(IKU)$

$N(IKU)$ = number of paths for each load point, where IKU = number of load points.

STEP-6 Calculate the total number of elements in each of the paths evaluated in step-4, for load point j .

This line includes :

NC

NC = Total number of elements in each path.

STEP-7 Find out all the elements in a path from the supply to load point for each load point.

The next line has :

$VAR(IKU, K, L)$

$VAR(IKU, K, L)$ = Element number in a path from the supply to load point for each load point.

Repeat steps 5 & 6 for all remaining paths of load point j . Repeat steps 4-6 for all remaining load points.

C.1.2. Data file containing component reliability data for calculating the basic reliability indices

This input file includes the basic values, i.e. average failure rate, average repair time of each element. In addition it also has a code for each element depending upon its type.

STEP-1 The first line contains

ZS, ZN

where, ZS = Duration of adverse weather

ZN = Duration of normal weather

STEP-2 The next 2 X IH lines contain the following information
SL(IH),STL(IH),SML(IH),SR(IH),STR(IH),SMR(IH),LEACT(IH),RACT(IH)

ZL(IH),ZTL(IH),ZML(IH),ZAL(IH),ZATL(IH),ZR(IH),
ZTR(IH),ZMR(IH),CODE(IH)

where IH = number of components

There are two lines for each component.

Single weather state

SL(IH) = Permanent failure rate (f/yr)

STL(IH) = Temporary failure rate (f/yr)

SML(IH) = Maintenance outage rate (out/yr)

SR(IH) = Replacement time by a spare (hr) or Repair time (hr)

STR(IH) = Reclosure time (hr)

SMR(IH) = Maintenance outage time (hr)

LEACT(IH) = Active failure rate (f/yr)

RACT(IH) = Switching time (hr)

Two weather states

ZL(IH) = Permanent failure rate in normal weather (f/yr)

ZTL(IH) = Temporary failure rate in normal weather (f/yr)

ZML(IH) = Maintenance outage rate in normal weather (out/yr)

ZAL(IH) = Permanent failure rate in adverse weather (f/yr)

ZATL(IH) = Temporary failure rate in adverse weather (f/yr)

ZR(IH) = Replacement time by a spare (hr) or Repair time (hr)

ZTR(IH) = Reclosure time (hr)

ZMR(IH) = Maintenance outage time (hr)

CODE(IH) = Element code which are given as follows

CODE(IH) = 1, for line

CODE(IH)= 2, for busbar

CODE(IH)= 3, for breaker

CODE(IH)= 4, for transformer

If any value for any element is not available or is not to be considered, then it should be input as zero.

C.2. User Friendly Program

The computer program 'subtre1' is highly interactive and user friendly. During the execution of the program following questions appear on screen:-

Q1. Please give the I/P filename for basic values.

The input filename is specified by the user. This file contains values of failure rate, repair rate and code for each element of the system.

Q2. Please give the I/P filename for mincuts.

The input file is specified by the user. This file consists of data for the determination of mincuts and active failures/events.

Q3. Please give the O/P filename ?

Any output filename as described by the user may be specified. This file will eventually provide the following:-

1. The basic reliability indices of selected module.
2. The total values of the indices for selected load point(s).
3. The percentage contribution of the Ist, IInd & IIIrd order outages in the load point selected.
4. The system performance indices of the load point selected.

Q4. Please give the output filename (for individual basic values).

Another output filename is selected. The file is comprised of the individual basic reliability indices of each outage event considered.

Q5. Do you want to consider sensitivity studies also (Y/N) ?

If the answer to this question is 'N' or 'n' then the program skips all the questions relating sensitivity studies and reaches directly to Q13. 'Y' or 'y' should be entered if sensitivity studies are required to be done.

Q6. Input the name of the O/P file for sensitivity studies.

If the answer to the previous question, i.e. Q5, is 'Y' or 'y' then only this question appears on the screen. An output file name, for sensitivity studies, has to be entered as an answer to this question.

SELECT ANY NUMBER FOR SENSITIVITY STUDY

-
1. VARIATION OF PERMANENT FAILURE RATE OF ALL COMPONENTS
 2. VARIATION OF TEMPORARY FAILURE RATE OF ALL COMPONENTS
 3. VARIATION OF MAINTENANCE OUTAGE RATE OF ALLCOMPONENTS
 4. VARIATION OF ACTIVE FAILURE RATE OF ALL COMPONENTS
 5. VARIATION OF REPAIR TIME OF ALL COMPONENTS
 6. VARIATION OF RECLOSURE TIME OF ALL COMPONENTS
 8. VARIATION OF SWITCHING TIME OF ALL COMPONENTS
 9. VARIATION OF ADV. WEATHER DURATION
 10. VARIATION OF ADV. PERM. FAIL. RATE OF ALL COMPONENTS
 11. VARIATION OF ADV. TEMP. FAIL. RATE OF ALL COMPONENTS
 12. VARIATION OF NOR. WEATHER DURATION
 13. VARIATION OF PER. FAILURE RATE IN ALL LINES
 14. VARIATION OF PER. FAILURE RATE IN ALL BREAKERS
 15. VARIATION OF PER. FAILURE RATE IN ALL BUSBARS
 16. VARIATION OF PER. FAILURE RATE IN ALL TRANSFORMERS
 17. VARIATION OF NOR. WEATHER DURATION KEEPING N/(N+S) CONSTANT
 18. MORE CHOICES

This menu will automatically appear on the screen on entering the output file name in the previous question.

Q7. Choose any one number.

Any one option has to be chosen by the user from the above menu. If the user chooses any option between '1' and '17' inclusive then the program reaches directly to Q10. skipping all questions in the path. If the choice is '18', another menu appears on the screen.

ENTER ANY ONE CHOICE

1. SYSTEM FAILURE RATE REQUIRED(%)
2. SYSTEM UNAVAILABILITY REQUIRED(%)
3. OTHER SYSTEM INDICES (SAIFI, SAIDI, CAIDI, ASAI, ENS)

This menu will appear on the screen in case choice '18' is selected for Q7.

Q8. Enter any one choice.

A number is selected from the above menu which results in the appearance of another menu.

19. VARIATION OF PERMANENT FAILURE RATE OF ALL COMPONENTS
20. VARIATION OF TEMPORARY FAILURE RATE OF ALL COMPONENTS
21. VARIATION OF MAINTENANCE OUTAGE RATE OF ALL COMPONENTS
22. VARIATION OF ACTIVE FAILURE RATE OF ALL COMPONENTS
23. VARIATION OF REPAIR TIME OF ALL COMPONENTS
24. VARIATION OF RECLOSURE TIME OF ALL COMPONENTS
25. VARIATION OF MAINTENANCE OUTAGE TIME OF ALL COMPONENTS
26. VARIATION OF SWITCHING TIME OF ALL COMPONENTS
27. VARIATION OF ADV. PERM. FAIL. RATE OF ALL COMPONENTS
28. VARIATION OF ADV. TEMP. FAIL. RATE OF ALL COMPONENTS
29. VARIATION OF PER. FAILURE RATE IN LINE
30. VARIATION OF PER. FAILURE RATE IN BREAKER
31. VARIATION OF PER. FAILURE RATE IN BUSBAR
32. VARIATION OF PER. FAILURE RATE IN TRANSFORMER

Q9. Choose any one number.

Any one option has to be chosen and the corresponding number has to be entered.

Q10. Enter the number of sensitivity studies to be done.

This question will automatically appear on the screen no matter Q8 and Q9 appear or do not appear, i.e. the choice to Q7 is '18', on the screen. The number of times a particular sensitivity study has to be done is entered by the user.

TYPE OF INCREMENT IN SENSITIVITY STUDIES

1. FIXED INCREMENT FOR ALL VALUES
(INCREASING ALL VALUES BY .001 etc.).
2. INCREMENTING THE VALUES IN GEOMETRIC
PROGRESSION (DOUBLING THE VALUES).

Q11. Input any one number.

Two options are given in the menu, above, regarding the type of increments in the sensitivity studies. Any one type of increment is chosen and the corresponding number is entered.

Q12. Enter the rate of increment.

This question appears only if the answer to Q11 is '1'. Rate of increment of a particular variable is provided.

Q13. Do you want to consider all load points (Y/N) ?

The primary condition for this question to appear on the screen is that there are more than one load points (supply points) in the system being studied. The secondary conditions for it to appear are the following :

1. The answer to Q11 is '2'.
2. The answer to Q5 is 'N' or 'n'.

The user then has the choice of selecting all the load points or only one. 'Y' or 'y' should be entered if all load points are to be considered. If not 'N' or 'n' should be entered.

Q14. Please put the load point number which has to be considered.

The question appears only if the system has more than one load point and if the user has selected 'N' or 'n' in Q13. The user is now required to enter the load point number (1,2,.....). Upon inputting the loadpoint the load point number the following menu appears on the screen.

SELECT ANY NUMBER FOR LOAD POINT

1. PERMANENT(Ist+IInd+IIIrd ORDER)
2. MAINTENANCE+PERMANENT FAILURE
3. TEMPORARY+PERMANENT FAILURE
4. TEMPORARY+MAINTENANCE OUTAGE

THIRD ORDER OUTAGES

5. MAINTENANCE+PERMANENT+PERMANENT
6. TEMPORARY+PERMANENT+PERMANENT
7. TEMPORARY+PERMANENT+MAINTENANCE

WEATHER EFFECT (SECOND ORDER)

8. PERMANENT+PERMANENT FAILURE
9. MAINTENANCE+PERMANENT FAILURE
10. TEMPORARY+PERMANENT FAILURE
11. TEMPORARY+MAINTENANCE OUTAGE

WEATHER EFFECT (THIRD ORDER)

12. PERMANENT+PERMANENT+PERMANENT
13. MAINTENANCE+PERMANENT+PERMANENT
14. TEMPORARY+PERMANENT+PERMANENT
15. TEMPORARY+PERMANENT+MAINTENANCE

COMBINATIONS

16. SECOND ORDER OUTAGES

17. THIRD ORDER OUTAGES
18. SECOND ORDER OUTAGES (WEATHER)
19. THIRD ORDER OUTAGES (WEATHER)
20. ALL THE COMBINATIONS

This menu will automatically appear on the screen in case Q13 and/or Q14 do not appear.

Q15. Enter the total number of choices.

The user, then, has to decide the number of options, which are displayed on the screen, to be considered. This number is then entered by the user. For instance, the user may enter any number between 1 to 20. Let us assume, that this number is denoted by NCHOICE.

Q16. CHOICE:

This question is repeated NCHOICE times. The option number from the previous menu (of Q6.) has to be entered by the user one by one until NCHOICE number of options are entered. The heading 'CHOICE' appear on the screen NCHOICE times in the process.

Q17. Any more choices ? (for yes type 1 for no type 2)

If the choice selected in Q16 is '20' then this question does not appear on the screen and the program reaches directly to the note below. If the user still wishes to enter some more choices, this option allows him/her to do just that. If a '2' is entered, the next question appears. If the user enters '1' in this question then questions 15 & 16 are repeated. This process goes on until the answer for Q17. is '2'. If the answer to Q13. is 'y' or 'Y' then after entering '2' for Q17. the following message appears on the screen.

NOTE: THE SAME CHOICES AS SELECTED BY LOAD POINT 1 WILL BE CONSIDERED FOR OTHER LOAD POINT(S).

Same choices as that selected for load point 1 will be entered for the remaining load points automatically. The program, then, reaches directly to Q19.

Q18. Any other load point to be considered (Y/N) ?

This question appears only

1. If there are more than one load points in the system
2. If the user had not entered 'Y' or 'y' in response to Q6.
3. If the user had not entered 'Y' or 'y' in response to Q13.

If the user selects 'Y' or 'y' in this question then Q14 reappears on the screen and the same process is repeated. The cycle goes on until the answer to this question is 'N' or 'n' or when all the load points are taken into consideration.

Q19. Do you want to evaluate the system performance indices (Y/N) ?

This question appears only

1. If the answer to Q13. is 'Y' or 'y', i.e. when all the load points are taken into consideration
2. If Q13 does not appear at all, i.e. when there is only one load point in the system
3. If the answer to Q6 is 'N' or 'n', i.e. sensitivity studies are not required to do.

If the answer to this question is 'Y' or 'y' then the system performance indices are evaluated and stored in the O/P file entered in Q3.

At the end of the program run, all the input and output files are displayed on the screen. Finally, time spent by the CPU in execution of the program is given on the screen.

C.3. Program Modules/Subroutines

In order to debug the program and for simplicity in usage, it has been divided into fifteen modules or subroutines. These modules are based on the different conditions which are imposed on the system and finally basic values are calculated in each of the module selected by the user, considering the number of minimal cuts for each order.

MODULE-1 : SUBROUTINE CAL

In this module Ist, IInd & IIIRD order permanent outage calculations are done without taking into consideration the weather effect. Finally all the three values of the basic indices are summed up and the total value of failure rate, repair rate and unavailability for a load point is calculated.

MODULE-2 : SUBROUTINE MM

This subroutine calculates the reliability indices due to permanent failures overlapping maintenance outages. Maintenance will not take place if it causes the isolation of the load point. This assumption is used here. Final values are calculated and written in the output file.

MODULE-3 : SUBROUTINE TP1

In this module Ist order transient failure & transient failure overlapping a permanent failure calculations are done. These two sets of values are then combined and final set of values are obtained. Overlapping of two temporary/transient failures is neglected because the probability is small and contributes very little to the overall result.

MODULE-4 : SUBROUTINE TM

This module evaluates the basic reliability indices for the combination of the transient failure overlapping a maintenance outage. First order transient failure is not considered as it has already been considered in the last module.

MODULE-5 : SUBROUTINE PPM

This module evaluates the reliability indices of the third order maintenance outage, i.e. two permanent failures overlapping a maintenance outage. Basic reliability indices are calculated. It is assumed that the first component in each sequential outage event is on scheduled maintenance, i.e. a component is not taken out of service for scheduled maintenance if a forced outage in the related event has already occurred.

MODULE-6 : SUBROUTINE TPP

This module evaluates the reliability indices of the two permanent failures overlapping a temporary/transient outage. In this event one component suffers either a transient or a temporary failure and the other two components are forced out of service as a result of permanent failure. The equations neglect any contribution due to two transient/temporary failures.

MODULE-7 : SUBROUTINE TPM

It evaluates the reliability indices of the permanent failure overlapping temporary/transient and maintenance outages. This is a third order event in which one component is out on scheduled maintenance, one component suffers a transient/temporary failure and one component is forced out of service as a result of a permanent failure. It is assumed that the first component in each sequential outage event is on scheduled maintenance, i.e. a component is not taken out of service for scheduled maintenance if a forced outage in the related event has already occurred.

MODULE-8 : SUBROUTINE WPP

This module includes weather effect while calculating the reliability indices of overlapping of two permanent outages. An assumption is taken that repair can not be done during adverse weather.

MODULE-9 : SUBROUTINE WPM

This module calculates the reliability indices of the second order permanent failure overlapping maintenance outage taking into consideration the weather effect. Two assumptions are taken into account

1. Repair cannot be done during adverse weather
2. Maintenance cannot be started in the adverse weather

MODULE-10 : SUBROUTINE WTP

This module includes weather effect while calculating the reliability indices of temporary/transient failure overlapping permanent outage. An assumption is taken that repair can not be done during adverse weather.

MODULE-11 : SUBROUTINE WTM

This module calculates the reliability indices of the second order temporary/transient failure overlapping maintenance outage taking into consideration the weather effect. Two assumptions are taken into account

1. Repair cannot be done during adverse weather
2. Maintenance cannot be started in the adverse weather

MODULE-12 : SUBROUTINE WPPP

In this module overlapping of three permanent outages is taken into consideration. Reliability indices are calculated taking into consideration that the three components share a common environment which can vary between normal weather and adverse weather. Repair cannot be done during adverse weather condition.

MODULE-13 : SUBROUTINE WPPM

This module considers two permanent failures overlapping a maintenance outage.

Reliability indices are calculated taking into consideration the adverse weather effect. Repair cannot be done during adverse weather condition and maintenance cannot be started when the weather is adverse.

MODULE-14 : SUBROUTINE WTPP

This module considers two permanent failures overlapping a temporary/transient outage. Reliability indices are calculated taking into consideration the adverse weather effect. Repair cannot be done during adverse weather condition.

MODULE-15 : SUBROUTINE WTMP

This module evaluates the reliability indices of permanent failure overlapping temporary/transient and maintenance outages taking into account the adverse weather effect. Repair cannot be done during adverse weather condition and maintenance cannot be started when the weather is adverse.

The following points are to be noted :

1. In case of adverse weather condition reliability indices of a particular module are calculated only when the CODE(IH) for that module is 1, i.e. when a line is considered for that module.
2. In case of the percentage contribution active failures are included in the first order mincuts.

D. HAND CALCULATIONS OF RBTS BUS-4 (UPTO SECOND ORDER OUTAGES ONLY)

In Chapter 4, evaluation of RBTS Bus-4 is conducted by making use of the computer program 'SUBTREL'. In order to check the correctness of the program implementation, reliability indices of RBTS Bus-4 are evaluated by using hand calculations, given below:

Table D.1: Overlapping permanent forced outages for supply point 1.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	1	.001	2	.002
2	2	.001	2	.002
3	5-6	7.7054E-07	7.5	5.7791E-06
4	3-6	1.9520E-07	3.157	6.1643E-07
5	4-5	1.9520E-07	3.157	6.1643E-07
6	3-4	3.2876E-08	2	6.5753E-08
	TOTAL	2.00119E-03	2.002	4.00707E-03

Table D.2: Permanent failure overlapping maintenance outage for supply point 1.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	5-6	4.1095E-04	13.33	5.4794E-03
2	3-6	2.0547E-04	8.99	1.8486E-03
3	4-5	2.0547E-04	8.99	1.8486E-03
4	3-4	9.8630E-05	3.78	3.7375E-04
	TOTAL	9.2054E-04	10.37	9.5504E-03

Table D.3: Permanent failure overlapping temporary outage for supply point 1.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	1	.01	0.083	.00083
2	2	.01	0.083	.00083
3	5-6	2.5827E-06	0.082	2.1318E-07
4	3-6	1.6894E-06	0.082	1.3928E-07
4	4-5	1.6894E-06	0.082	1.3928E-07
6	3-4	3.3558E-07	0.081	2.7287E-08
	TOTAL	2.0006E-02	0.083	1.6605E-03

Table D.4: Temporary failure overlapping maintenance outage for supply point 1.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	5-6	1.3698E-03	0.082	8.1768E-05
2	3-6	1.2328E-03	0.082	1.0224E-04
3	4-5	1.2328E-03	0.082	1.0224E-04
4	3-4	9.8630E-04	0.082	8.1768E-05
	TOTAL	4.8219E-03	0.082	3.9987E-04

Table D.5: Overlapping permanent outages for supply point 2.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	2	0.001	2	0.002
1	30	0.001	2	0.002
3	31	0.001	2	0.002
4	32-33	7.7054E-07	7.5	5.7791E-06
5	32-35	1.9520E-07	3.157	6.1643E-07
6	33-34	1.9520E-07	3.157	6.1643E-07
7	34-35	3.2876E-08	2	6.5753E-08
8	(15+9+ 29)*19	5.2785E-07	1.596	8.4286E-07
9	(15+9+ 29)*(27 +18+28)	3.9153E-04	3.98	1.5594E-03
10	(13+17+ 8)*(14+ 16+7)* (15+29+ 9)	5.5543E-07	2.657	1.476E-06
	TOTAL	3.39381E-03	2.2301	7.5688E-03

Table D.6: Permanent failure overlapping maintenance outage for supply point 2.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	18-9	2.1917E-05	3.840	8.4164E-05
2	18-15	2.5214E-03	7.382	1.8615E-02
3	18-29	2.1917E-05	3.84	8.4164E-04
4	19-9	6.3926E-06	2.060	1.3170E-05
5	19-15	2.1050E-04	3.994	8.4091E-04
6	19-29	6.3926E-06	2.060	1.3170E-05
7	27-9	2.5214E-03	7.382	1.8615E-02
8	27-15	4.2009E-04	4.000	1.6803E-03
9	27-29	2.5214E-03	7.382	1.8615E-02
10	28-9	2.1917E-05	3.840	8.4164E-05
11	28-15	2.5214E-03	7.382	1.8615E-02
12	28-29	2.1917E-04	3.840	8.4164E-05
13	32-33	4.1095E-04	13.333	5.4794E-03
14	32-35	2.0547E-04	8.996	1.8486E-03
15	34-33	2.0547E-04	8.996	1.8486E-03
16	34-35	9.8630E-05	3.789	3.7375E-04
	TOTAL	1.17374E-02	7.403	8.6897E-02

Table D.7: Temporary failure overlapping permanent outage for supply point 2.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	2	0.001	0.083	0.00083
2	30	0.001	0.083	0.00083
3	31	0.001	0.083	0.00083
4	18-9	3.7287E-08	0.0813	3.0319E-08
5	18-15	9.0483E-06	0.0821	7.4283E-07
6	18-29	3.7287E-08	0.0813	3.0319E-08
7	19-9	1.4077E-08	0.0808	1.1369E-09
8	19-15	4.3871E-06	0.0821	3.6004E-06
9	19-29	1.4077E-08	0.0808	1.1369E-09
10	27-9	9.0483E-06	0.0821	7.4283E-07
11	27-15	5.0933E-03	0.0821	4.1841E-04
12	27-29	9.0483E-06	0.0821	7.4283E-07
13	28-9	3.7287E-08	0.0813	3.0319E-08
14	28-15	9.0483E-06	0.0821	7.4283E-07
15	28-29	3.7287E-08	0.0813	3.0319E-08
16	32-33	2.5827E-06	0.0825	2.1318E-07
17	32-35	1.6894E-06	0.0824	1.3928E-06
18	34-33	1.6894E-06	0.0824	1.3928E-06
19	34-35	3.3558E-07	0.0813	2.7287E-08
	TOTAL	3.0556E-02	0.0829	2.5357E-03

Table D.8: Temporary failure overlapping maintenance outage for supply point 2.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	18-9	0.2191E-03	0.0829	0.1817E-04
2	18-15	0.3296E-02	0.0829	0.2733E-03
3	18-29	0.2191E-03	0.0829	0.1817E-04
4	19-9	0.6392E-04	0.0828	0.5294E-05
5	19-15	0.2785E-04	0.0821	0.2288E-04
6	19-29	0.6392E-04	0.0828	0.5294E-05
7	27-9	0.3296E-02	0.0829	0.2733E-03
8	27-15	0.5479E-03	0.0821	0.4501E-04
9	27-29	0.3296E-02	0.0829	0.2733E-03
10	28-9	0.2191E-03	0.0829	0.1817E-04
11	28-15	0.3296E-02	0.0829	0.2733E-03
12	28-29	0.2191E-03	0.0829	0.1817E-04
13	32-33	0.1369E-02	0.0829	0.1136E-03
14	32-35	0.1232E-02	0.0829	0.1022E-03
15	34-33	0.1232E-02	0.0829	0.1022E-03
16	34-35	0.9863E-03	0.0829	0.8176E-04
	TOTAL	0.0198401	0.08289	1.6446E-03

Table D.9: Overlapping permanent outages for supply point 3.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	2	0.001	2	0.002
2	19	0.001	2	0.002
3	20	0.001	2	0.002
4	21-22	7.7054E-07	7.5	5.7791E-06
5	21-24	1.9520E-07	3.157	6.1643E-07
6	22-23	1.9520E-07	3.157	6.1643E-07
7	23-24	3.2876E-08	2	6.5753E-08
8	(13+8+ 17)*(7+ 14+16)* 30	5.9964E-10	1.332	7.9875E-10
10	(13+17+ 8)*(14+ 16+7)* (15+29+ 9)	5.5540E-07	2.657	1.476E-06
11	(13+17+ 8)*(14+ 16+7)* (27+18+ 28)	5.5540E-07	2.657	1.476E-06
	TOTAL	3.0023E-03	2.0018	6.01003E-03

Table D.10: Permanent failure overlapping maintenance outage for supply point 3.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	21-22	4.1095E-04	13.333	5.4794E-03
2	21-24	2.0547E-04	8.996	1.8486E-03
3	22-23	2.0547E-04	8.996	1.8486E-03
4	23-24	9.8630E-05	3.78	3.7375E-04
	TOTAL	9.2054E-04	10.374	9.5504E-03

Table D.11: Permanent failure overlapping temporary outage for supply point 3.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	2	0.01	0.083	0.00083
2	19	0.01	0.083	0.00083
3	20	0.01	0.083	0.00083
4	21-22	2.5827E-06	0.082	2.1318E-07
2	21-24	1.6894E-06	0.082	1.3928E-07
3	22-23	1.6894E-06	0.082	1.3928E-07
4	23-24	3.3558E-07	0.081	2.7287E-08
	TOTAL	0.0300062	0.0829	2.4905E-03

Table D.12: Temporary failure overlapping maintenance outage for supply point 3.

No.	Event (element number)	Failure Rate (f/yr)	Repair Time (hr)	Annual Unavailability (hr/yr)
1	21-22	1.3698E-03	0.0829	1.1362E-04
2	21-24	1.2328E-03	0.0829	1.0224E-04
3	22-23	1.2328E-03	0.0829	1.0224E-04
4	23-24	9.8630E-04	0.0829	8.1768E-05
	TOTAL	4.8219E-03	0.0829	3.9987E-04