RELIABILITY EVALUATION OF ELECTRICAL SYSTEMS

A THESIS SUBMITTED

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BY

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- APRIL 1976 -
TO

MARIA TERESA

MIGUEL HENRIQUE and LUIS MANUEL.

and to my parents, brothers and sister
PERSONAL HISTORY

Born in Fajões - Oliveira de Azeméis, Portugal, in 1948 the author completed his secondary school education in 1966 with the final mark of 85% (17 out of 20). In the same year he entered the University of Porto and completed his degree in Electrical Engineering in 1971 after a five year course with the final mark of 85% (17 out of 20).

Since October 1971 he has been Assistant Lecturer at the Faculty of Engineering of the University of Porto where up to July 1973 he lectured several topics of power systems.

In February 1972 he joined the Portuguese Goverment Electricity Board (Direcção Geral dos Servicos Eléctricos) where after training he was one of the engineers responsible for the licensing and inspection of all important electrical systems in the North of Portugal.

He was granted leave by the University of Porto (supported by INVOTAN) in October 1973 to join the Department of Electrical Engineering and Electronics at UMIST to study for the degree of Doctor of Philosophy. In October 1974 he completed his M. Sc. degree (by examination and dissertation) in Power Engineering and started work on the research project described in this thesis. As a result of his research at UMIST the following papers have been published or are accepted for publication:

- RELIABILITY ASSESSMENT OF POWER SYSTEM NETWORKS,
  R.N. Allan, R. Billinton and M. F. De Oliveira, 5th PSCC (Power System Computation Conference), paper 1.2/4, Cambridge, September 1975

- RELIABILITY EVALUATION OF AUXILIARY ELECTRICAL SYSTEMS OF POWER STATIONS,
  R.N. Allan, R. Billinton and M.F. De Oliveira, IEEE (Institute of Electrical and Electronics Engineers - United States), Winter Power Meeting, New-York, 1976, paper A76018-2
- EFFECT OF PLANT RELIABILITY IN TRANSMISSION AND DISTRIBUTION SYSTEMS,
R.N. Allan and M.F. De Oliveira, 11th University Power Engineering
Conference, Portsmouth, April 1976

- THREE STATE RELIABILITY MODELLING OF ELECTRICAL NETWORKS,
R.N. Allan and M.F. De Oliveira, Advances in Reliability Technology
Symposium, Bradford, April 1976

- RELIABILITY EVALUATION OF ELECTRICAL SYSTEMS WITH SWITCHING ACTIONS,
R.N. Allan, R. Billinton and M. F. De Oliveira, Proceedings of IEE
(Institution of Electrical Engineers - U.K.), vol. 123, no. 4,
April 1976

- EVALUATING THE RELIABILITY OF AUXILIARY ELECTRICAL SYSTEMS OF GENERATING STATIONS,
R.N. Allan, R. Billinton and M.F. De Oliveira, CEA (Canadian Electrical
Association) Thermal Power Section, Spring Meeting, Toronto, 1976

- AN EFFICIENT ALGORITHM FOR DEDUCING THE MINIMAL CUTS AND RELIABILITY INDICES OF A GENERAL NETWORK CONFIGURATION,
R.N. Allan, R. Billinton and M.F. De Oliveira, IEEE (Institute of
Electrical and Electronics Engineers - United States) Transactions on Reliability, paper TR75-63 (to be published)

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197
214
235
260
SUMMARY

The research described in this thesis is concerned with the reliability evaluation of general electrical systems. The minimal cut set approach to the reliability problem is accepted and its application to large electrical systems was made possible by developing efficient techniques and incorporating features that are typical in electrical networks and are currently neglected in other kinds of networks.

The electrical auxiliary system of power stations is analysed in detail. The corresponding reliability model proposed in this thesis was tested against several practical systems and its usefulness is shown; It allows an easy evaluation of a reliability cost associated with a given design and permits the evaluation of the reliability indices of every busbar considering all realistic failure modes and restoration procedures.

The minimal cut set theory is also applied to the reliability evaluation of transmission and distribution systems. The model developed is realistic and the efficiency of the corresponding techniques allows its application to practical systems.
I

INTRODUCTION

1.1 - General Considerations

The application of probability theory to evaluate quantitatively the reliability of power systems has been rapidly increasing. In fact most of the energy consumed in industrial societies is in the form of electricity and our standard of living is highly affected by its reliability. Industry depends so much on electricity that any potential industrial consumer gives to the reliability of electrical supply a high place in his list of priorities for proposed factory locations. But more important than quality of life or industrial development is human safety and there are plenty of electrical systems whose reliability is imposed by security reasons.

To assess the reliability of any electrical system is much more than a mathematical exercise. It is the only way available to check whether or not the required reliability constraints are expected to be met. It is also an objective way for comparing alternative design proposals and different operating policies. The evaluation of a reliability cost of any proposed design, although a difficult exercise, is the most sound criterion to decide whether or not an acceptable reliability level should be increased.

The level of reliability of any system is usually affected by its operating policies but it must be built in at the design stage since it cannot be economically added at a later point in time. The work reported in this thesis is mainly applicable at the design stage of some electrical systems. Fig. 1.1 shows a basic reliability program for a disciplined design approach(1).
In the design stage reliability techniques are used to predict the future performance of the system. In general prediction techniques can be used to:

- Identify weak design areas
- Compare alternative configurations
- Compare conceptual design approaches
- Assist in partitioning corrective design effort
- Identify areas requiring redundancy
- Determine the need for additional test information
- Translate maintainability requirements into specific design criteria
The techniques described in this thesis can be directly used for any of the purposes referred to above.

1.2 - Philosophy of a Reliability Study

A widely accepted definition of reliability is as follows:

"Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered".

Reference (3) presents a very similar definition of reliability:

"Reliability is that characteristic of an item expressed by the probability that it will perform its required function in the desired manner under all the relevant conditions and on the occasions or during the time intervals when it is required so to perform".

Both definitions can be broken down into four parts: probability, adequate performance, time and operating conditions. Any reliability study is only valid for the assumed operating conditions and for the period of time intended; It requires the investigation of the modes of failure for each component and for the system followed by the appropriate probability calculations. The following can be considered typical steps in the reliability analysis of any complex system:

(i) Identification of the component failure modes
(ii) Identification of the failure events
(iii) Identification of the restoration process for every failure event
(iv) Calculation of the reliability indices

Steps (ii) and (iii) are a matter of engineering appraisal and appreciation; The corresponding effort increases dramatically with the system size and they require the development of computational techniques involving complex logic. Step (i) is associated with the understanding of the component design and step (iv) requires the use of probabilistic models accurate
enough for the purpose of reliability evaluation, but as simple as possible to allow large systems to be analysed with an acceptable computing time.

1.3 - Historical Review

It appears that the first papers\(^{(4),(5)}\) applying probability methods to the study of spare generation capacity were published in 1933/34; Their authors received the credit for the first proposals to utilize such methods and so they can be considered as the introducers of quantitative techniques to evaluate the reliability of power systems. In the 1950's and 1960's many papers\(^{(6)}\) consolidated the techniques now widely accepted for the reliability evaluation of generating systems.

In 1964\(^{(7),(8)}\) two papers introduced the basic concepts for the reliability assessment of permanent outages in power system networks. The effects of switching actions were first clearly considered in 1973\(^{(9)}\) and in 1974\(^{(10)}\); the latter of these publications is applied to the reliability evaluation of substations and switching stations.

The basic concepts of composite system reliability evaluation were first reported in a 1969\(^{(11)}\) paper and the first important paper\(^{(12)}\) on short term reliability evaluation of generating systems was published in 1970.

It can be seen from this short historical review that nearly all topics of power systems reliability were already considered in some studies, but it is evident that some of them are still in their infancy.

1.4 - The State of the Knowledge

Any power system reliability topic can be classified into one of the following areas:

a) Static generating capacity

b) Spinning generating capacity
c) Transmission and distribution

d) Composite System

e) Electrical networks

The comments that follow are for each of these areas:

a) A lot of work has been done in static generating capacity reliability evaluation. The loss of load probability method (L.O.L.P.) is widely used, is easy to program and suitable for incorporating maintenance, unit derated states and interconnected systems. The frequency and duration method (30) is still in its infancy; There are no reports of practical applications of this method although it gives results much more easy to understand by engineers and much more meaningful than the L.O.L.P. method. The lack of realistic data may be the reason why this method has not been used (it requires failure rates and average repair times of the states of the units and not simply their forced outage rates).

Both methods assume that the transmission system does not introduce any constraint into the problem of static capacity evaluation

b) The methods referred to in a), slightly modified, are also applied to short term reliability evaluation. The amount of work reported in this area is increasing in the last few years, but there are no reports in the open literature of practical applications. The basic assumption of neglecting transmission limitations is being argued and it seems that there are some utilities (13) prepared to use these methods together with the conventional security assessment.

c) As from 1964 many papers on transmission and distribution reliability evaluation (6) have been published. The techniques that have been proposed in this area are not suited for efficient programming even without considering all realistic failure modes and, as a consequence, they are limited in their application to relatively simple systems. The probabilistic formulation that has been proposed is an approximation of the Markov approach which, by itself, can only be applied to very simple systems.
d) To calculate composite reliability indices (i.e., including the
effects of the generating and of the transmission system) has not been of
great concern in the past. This might have been due more to computational
limitations than to the non interest of such studies. Indeed they have
been calculated manually for small systems (or simplified systems) for
practical purposes. Recent information (31) seems to suggest that this is
an area where research is now being concentrated. There are only a few
papers (11), (14), (15) dealing with this topic in an analytical way. Some
interesting papers have been published (16), (17) using Monte Carlo techni-
ques to simulate a random sequence of system states; They have been
written by researchers from Italy and France where Monte Carlo techniques
are widely used in power systems reliability studies.

e) Most of the concepts developed for transmission and distribution
systems can be applied to other electrical networks but these usually have
some specific features that have to be considered in detail. Only very
general papers (18) have been published in this area and the limitations
referred to in c) are also applicable to the analysis of electrical
networks.

1.5 - Considerations About Reliability Data

The existence of reliability data is often considered a prerequisite
for any reliability study. Most power utilities do not have the data required
for these kind of studies because their outage reports are not component
orientated. However there is a general agreement about the range of values
for the reliability data of power system components. This experience can be
exploited when data is not available, but to exploit such experience
efficient programming techniques are required to do the necessary sensiti-

vity studies.

A component orientated data collection scheme requires that all
component data is collected even if the outage does not result in any kind
of interruption of service. Failure reports do provide historical data on the system adequacy but they cannot provide the data required to predict the adequacy associated with changes in design, operating and maintenance policies. The uncertainty associated with predicting future performance of the system decreases as the recording period increases and as the data on similar components are combined. The personnel initiating the data must be aware of the proposed usage of this data and of the benefits that can be obtained from factual reports. This is particularly important when computers are then used to process the raw data into a usable form.

1.6- The Scope of the Present Work

In October 1974 C.E.G.B. (Central Electricity Generating Board) requested UMIST to carry out the mathematical modelling (i.e. the formulation of mathematical equations and methods of solution) and the production of a computer program to obtain the technical and economical solution to the problem of reliability on a system comprising, in the general case, a mesh network of electrical connectors inside a power station and ties from the station to the national grid. This was the main aim of the research described in this thesis. Most of the concepts and techniques developed can be applied to other systems rather than the electrical auxiliary system of power stations and this is stressed throughout the thesis.

After having satisfied the requirements referred to above other computational techniques were developed to evaluate the reliability of transmission and distribution systems. Novel concepts are also introduced in this part of the work and it is shown that the results obtained are of high practical application.

An electrical system is always represented by a graph which is a picture of the real system. Any reliability analysis requires a previous establishment of a reliability diagram which may or may not be a picture of the
system it represents; Actually most reliability studies are based upon reliability diagrams that are very difficult to establish and do not have any simple relationship with the real system. One of the merits of the work described in this thesis is the identification of the reliability diagram from the graph that represents an electrical system. Generally power networks are meshed and have branches allowing flow of energy either in both directions or in a specified direction. The number of paths available from the sources of supply to the load points are directly associated with the reliability of the load points and the "success" of a load point is the "success" of its feeding paths or conversely, the "failure" of a load point is the "failure" of the corresponding feeding paths. Throughout this thesis the reliability indices considered are a measure of the load point failures and are obtained from a knowledge of the failure events associated with the available paths of supply; These failure events are called cuts of the network (identified with the reliability diagram). The work described in this thesis is based upon the general cut set theory (see Appendix I) which was successfully applied to the reliability analysis of power system networks.

1.7- The Structure of the Thesis

This thesis can be divided into three parts: A, B and C. Part A comprises four chapters (II, III, IV & V) where all the main concepts and techniques developed are described and their general applications stressed; Simple examples are considered to clarify the content of these chapters and to show the type of results that can be obtained when the techniques described are applied. Part B (chapters VI and VII) deals with the reliability modelling and evaluation of the electrical auxiliary system of power stations; It is based upon the contents of part A and practical examples are analysed in detail. Part C (chapters VIII and IX), also based upon part A, offers a contribution to the reliability evaluation of transmission and distribu-
tion systems; Some examples are analysed to show how the work developed can be applied to practical systems.
II

AN EFFICIENT ALGORITHM FOR DEDUCING THE MINIMAL CUTS
AND RELIABILITY INDICES OF A GENERAL NETWORK CONFIGURATION

2.1 - Introduction

The method most often suggested for determining the reliability of a system is to construct a reliability network, enumerate from the network all mutually exclusive working states of the system, calculate the probability of occurrence of each working state, and sum the probabilities. This approach is computationally infeasible for large systems, since the number of systems states \((=2^n, \text{ where } n \text{ is the number of system components})\) from which the working states are selected overcomes the power of any computer for a system with a moderate size. This computational problem is alleviated by an approximation technique\(^{(19)}\), which by considering a much smaller set of states, called the set of minimal cuts, obtains a good lower bound to the system reliability. It is called the minimal cut set approximation to reliability and is described in detail in APPENDIX 1.

Several papers have been published containing algorithms for calculating the reliability of networks. Reference \((20)\) describes a sequential method for analysing the reliability of transmission and distribution systems. This method is based on the minimal cut set theory and proposes equations to calculate three reliability indices, average outage rate, average outage duration and average annual outage time, for each minimal cut. References \((21)\) to \((25)\) describe algorithms similar to the present one but they are restricted to networks which contain either elements that are bidirectional \((21),(23),(25)\), i.e. it is possible to communicate over all elements in both directions, or elements that are unidirectional \((22)\). The system nodes are generally assumed to be perfectly reliable. In reference \((23)\) they are realistically taken into account but the method is
unattractive because a large number of subnetworks of the system have to be considered. Reference (25) also considers a large number of subnetworks, the nodes (or the branches) are assumed 100% reliable and the network cannot contain pendant nodes. The algorithm described in reference (24) assumes that the minimal paths and therefore the reliability network are already known and requires the physical system to be simplified by eliminating parallel links.

The algorithm described in this chapter has the following advantages over those previously published:

(i) It is very efficient computationally and is easy to program

(ii) It permits the minimal cut sets to be deduced for every output node of the system from a single description of the system topology without requiring any simplification in the system configuration.

(iii) The system may have any number of input and output nodes

(iv) It permits any element of the system to be either unidirectional or bidirectional and allows any element to be multi-ended. This is vital if the nodes themselves are not 100% reliable

(v) It permits the reliability of the various output nodes to be combined so that the overall system indices can be calculated. This is a powerful technique, particularly for comparing alternative system designs.

2.2 - Definitions

The following definitions hold for any kind of network:

Path - set of components connecting any input node to the output node to which it is associated

Minimal path - Path that does not contain any node twice. It is also called simple path or tie set.

Cut set - set of components which literally cuts all minimal paths; that is, it breaks the line of communication between input and output.

Minimal cut set - Smallest (minimal) set of components such that the elimination of any one component would no longer make it a cut
It is important to note that a set of minimal cut sets is always associated with a set of minimal paths; this means that every time a minimal cut set is considered the corresponding minimal paths have to be defined, unless they are implicit in the reference to an output node.

2.3 - Data Requirements

The topology of the system is described by the branches of the network and each branch is defined by the series-connected components in the branch and by its two ends. Each branch end may be either a multi-ended component if it is less than 100% reliable or simply a system node if it is assumed to be completely reliable.

The input data consists of:

i) Branch numbers, numbers of the components in the branch and numbers of the branch ends

ii) All input and output nodes

iii) Unidirectional branches

iv) For each component, including the appropriate branch ends, the relevant reliability data such as failure rate, maintenance rate, average repair time and average maintenance time

To illustrate these data requirements consider the system shown in fig. 2.1 for which nodes 5, 7 and 11 are considered less than 100% reliable and branches 1 and 2 are unidirectional. The data required to compute the reliability indices for each output node and for the overall system are shown in table 2.1. In this example all components are assumed identical and have the reliability data shown. However the reliability data for each component can be different and specified separately.

2.4 - The Algorithm

The algorithm which is discussed in detail in the following sections and in its formal form in section 4.5, is best described by the flowchart in fig. 2.2.
FIG. 2.1 - General network

- Component or node number
- Branch number
- Unidirectional branch

| TABLE 2.1 - Required Data |

### a) System topology

<table>
<thead>
<tr>
<th>branch number</th>
<th>branch ends</th>
<th>components</th>
<th>branch type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 - 7</td>
<td>5, 6, 7</td>
<td>Unidirectional</td>
</tr>
<tr>
<td>2</td>
<td>7 - 17</td>
<td>7, 10</td>
<td>Unidirectional</td>
</tr>
<tr>
<td>3</td>
<td>11 - 17</td>
<td>11, 12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1 - 5</td>
<td>1, 2, 5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5 - 11</td>
<td>5, 8, 9, 11</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>11 - 15</td>
<td>11, 13, 15</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>17 - 16</td>
<td>14, 16</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3 - 7</td>
<td>3, 4, 7</td>
<td></td>
</tr>
</tbody>
</table>

### b) Reliability data

(all components assumed identical)

- Failure rate: 0.01 f/yr
- Repair time: 20.00 hr
- Maintenance rate: 0.10 outages/yr
- Maintenance time: 10.00 hr
FIG. 2.2 - Simplified flowchart of the algorithm
2.4.1 - Preparing the Network Topology

This part of the algorithm prepares the network topology for each output node being considered. First the algorithm identifies unidirectional branches in addition to those specified in the data. These additional branches are those connected to the input nodes and to the particular output node being considered. All bidirectional branches are then duplicated so that flows can be considered in both directions. This new set of branches is then re-ordered for each output node and the original branch numbers are retained. Using this technique, Table 2.2 shows the new branch list obtained for output node 5 of the system shown in fig. 2.1. In Table 2.2 input nodes are defined as -1 and the output nodes as 0.

<table>
<thead>
<tr>
<th>New branch number</th>
<th>Original branch number</th>
<th>Sending end</th>
<th>Receiving end</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>Specified unidirectional branches</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>7</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-1</td>
<td>5</td>
<td>Input node branches</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>-1</td>
<td>7</td>
<td>- unidirectional</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>-1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>Branches connected to the output node-unidirectional</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>11</td>
<td>17</td>
<td>Bidirectional branches</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>5</td>
<td>0</td>
<td>Output node branch</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>16</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>17</td>
<td>11</td>
<td>Duplicated branches</td>
</tr>
</tbody>
</table>
2.4.2 - Preparing a List of Predecessors

Defining a predecessor of branch \( k \) as any branch of which the receiving end is coincident with the sending end of branch \( k \), an array of predecessors is prepared from the array shown in Table 2.2. Care must be taken to prevent a branch of having a predecessor which has an original branch number equal to its own original branch number, i.e., a duplicated branch cannot be a predecessor of itself.

The predecessors of a branch are deduced as follows:

(i) Consider each branch in turn, say new branch 2; identify its sending end number, 7 in this case.

(ii) Detect the branches that have a receiving end number equal to the sending end number of the branch for which the predecessors are being deduced; branches 1 and 4 for branch 2.

(iii) Repeat (i) and (ii) for all branches of the system.

To prevent a duplicated branch being considered a predecessor of itself, the following logic was used in the numbering scheme of the duplicated branches:

New number of a bidirectional branch + new number of the corresponding duplicated branch = 2 \( \times \) new number of the output node branch

Considering new branch 8, the predecessors would be initially detected as branches 2, 7 and 10. However, because \( 8 + 10 = 2 \times 9 \), branch number 10 is not considered as a predecessor of branch number 8.

Some previously published algorithms (for example, reference (22)) require a set of predecessors prepared manually as input data. In the case of bidirectional components they require one such set for each combination of such components. The array of predecessors for output node 5 of fig. 2.1 is shown in table 2.3.

2.4.3 - Deducing the Minimal Paths

The minimal paths from all the input nodes to the output node being considered are evaluated from the array of predecessors. Commencing
TABLE 2.3 - Array of predecessors for node 5

<table>
<thead>
<tr>
<th>new branch number</th>
<th>predecessors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

from the branch representing the output, branch 9 in the present example, the paths are traced in terms of branches back to the input nodes. If a loop is established in this process, the path being created is eliminated. For output node 5 of fig. 2.1, the array shown in table 2.4 is obtained, where the number -1 represents the end of the path, i.e. it is the point where the path reaches an input node.

TABLE 2.4 - Path tracing for node 5

<table>
<thead>
<tr>
<th>paths</th>
<th>branch numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9   3  -1</td>
</tr>
<tr>
<td>2</td>
<td>9   6  11  2  1 3  - path eliminated</td>
</tr>
<tr>
<td>3</td>
<td>9   6  5  -1</td>
</tr>
<tr>
<td>4</td>
<td>9   6  11  10  0  - path eliminated</td>
</tr>
<tr>
<td>5</td>
<td>9   6  11  2  4  -1</td>
</tr>
<tr>
<td>6</td>
<td>9   6  11  2  1  6  - path eliminated</td>
</tr>
</tbody>
</table>
In this array path 4 is eliminated because branch 10 has no predecessor and path 6 is eliminated because branch 6 appears twice indicating that a loop has been created. The loop of path 6 is closed, not by branch 6, but by the previous branch, i.e. branch 1. This implies that path 2 is also a closed loop since up to this point paths 2 and 6 are identical. Therefore path 2 is also eliminated.

The new branches are now replaced by their original numbers and the array of minimal paths is then obtained. For node 5 of fig 2.1 this array is shown in table 2.5.

<table>
<thead>
<tr>
<th>TABLE 2.5 - Minimal paths for node 5 in terms of branches</th>
</tr>
</thead>
<tbody>
<tr>
<td>branch numbers</td>
</tr>
<tr>
<td>path</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The minimal paths, presently defined in terms of branches, are then obtained in terms of system components by replacing each branch by its constituent components using table 2.1. During this process it is necessary to prevent a component being duplicated in the same path. Replacing the branches shown in table 2.5 by the appropriate components gives table 2.6.

<table>
<thead>
<tr>
<th>TABLE 2.6 - Minimal paths for node 5 in terms of components</th>
</tr>
</thead>
<tbody>
<tr>
<td>components</td>
</tr>
<tr>
<td>paths</td>
</tr>
<tr>
<td>path 1</td>
</tr>
<tr>
<td>path 2</td>
</tr>
<tr>
<td>path 3</td>
</tr>
</tbody>
</table>

Note: In path 2 component 11 appears twice and one is eliminated.

In path 3 components 11 and 7 appear twice and one of each is eliminated.

It is worth noting that in deducing these paths unidirectional, bidirectional, multi-ended components and multi-input nodes have been
considered. In the case of multi-ended components, these have been included by defining them as system nodes and also as system components (see table 2.1 and fig. 2.2). The advantage of this is illustrated by considering the network shown in fig. 2.3

![Network Diagram](image)

**Fig. 2.3** - Multi-ended components

5 component number

2 branch number

The unique path as defined by branches between the input and output of this network is 1-4. Replacing each branch by its components gives a path 1-2-3-3-7, i.e., 1-2-3-7. It is clear therefore that multi-ended components are easily incorporated.

Most published algorithms permit the minimal paths to be deduced. However, the present algorithm enables both unidirectional and bidirectional branches to be included and also enables multi-ended components to be assessed. Furthermore, tracing paths by means of branches instead of components reduces the computation time very significantly particularly when many components exist in each branch.

### 2.4.4 - Deducing the Minimal Cut Sets

In a typical system the number of nodal minimal cut sets is considerable greater than the number of associated paths. For the system shown in fig. 2.1, there are 3 minimal paths for node 5 creating 7 minimal cut sets; for node 11 there are 4 minimal paths and 43 minimal cuts of third order or less. Normally
therefore the storage requirements for the minimal cuts in binary form is
very large, particularly when all minimal cut sets of all output nodes have
to be stored in order to evaluate the overall system minimal cut sets.

Computationally, the easiest way of calculating the minimal cut sets is
by representing all the minimal paths in a binary form as well as the cuts
that are subsequently generated. The correspondence between a path (or a cut)
in compact form and in binary form is best understood by considering a set
of components, say \( \{2, 5, 7\} \), which may represent a path (or a cut). These
are stored in compact and in binary forms as follows:

<table>
<thead>
<tr>
<th>2</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>...</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \( n \) = total number of system components

Because the storage required for the compact form is dramatically decreased,
particularly for large systems, the minimal cut sets have been stored in
a compact form in the programs developed

2.4.4.1 - Minimal Paths in Binary Form

When the algorithm was firstly programmed it was decided not to
compact the nodal path array since the reduction in storage would have been*outweighed by the increase in computation time of evaluating the minimal
cut sets.

To deduce the minimal cut sets the previous minimal path array is
overwritten by the paths represented in binary form. For node 5 of fig. 2.1,
the new path array is shown in table 2.7

**TABLE 2.7 - Minimal paths for node 5 in binary form**

<table>
<thead>
<tr>
<th>components</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>paths 1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
To deduce the first order minimal cuts the program searches for columns in which every element is equal to unity. These are then replaced by zeros to prevent non-minimal cuts containing first order minimal cuts being detected. The maximum order of the minimal cuts is equal to the number of minimal paths, i.e. third order in the present example.

The second order minimal cuts are calculated by adding logically two columns at a time of the path array. If any of the resulting vectors has every element equal to unity, the combined columns (components) form a second order minimal cut.

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

Consider two cuts, \( I \) and \( J \); \( I \) being a minimal cut set of order \( n_i \) and \( J \) a cut set of order \( n_j \) where \( n_i < n_j \). Consider the following sets:

\[
I = \{a_i, b_i, c_i, \ldots\} \text{ with } n_i \text{ elements}
\]

\[
J = \{a_j, b_j, c_j, \ldots\} \text{ with } n_j \text{ elements}
\]

Create a set \( \{ A \} = \{ I \} \cap \{ J \} \). If the number of non-zero elements of \( \{ A \} \) is equal to \( n_i \), then \( J \) is non-minimal and is rejected.

For node 5 of fig. 2.1, the minimal cut sets obtained using this technique are:

5, 1-8, 1-9, 1-11, 2-8, 2-9, 2-11
2.4.4.2 - Minimal Paths in Compact Form

When the algorithm was applied to large practical systems having about 400 components and more than 100 paths to some output nodes, it was found that the storage required for the minimal paths became excessive and increased dramatically with increasing number of system components. For such cases, the algorithm was programmed so that the minimal paths were also compacted. A new procedure for deducing the minimal cut sets had to be devised with this method of storage.

To deduce the first order minimal cut sets, every component is considered, one at a time, and checked whether it belongs to every path; if it does it is a first order cut set. This component is then negated to prevent non-minimal cut sets containing first order minimal cut sets being detected. If the paths are required for further analyses then the negated components are re-set positive after all cut sets of the required order have been deduced.

To deduce the second order minimal cut sets, all combinations of two components \( \{i, j\} \) for \( i = 1 \) to \( n-1 \) and \( j = i+1 \) to \( n \) where \( n \) is the total number of system components are considered. If any of these combinations are found to break all minimal paths, the combination is a second order minimal cut.

To deduce the third order minimal cut sets, all combinations of three components \( \{i, j, k\} \) for \( i = 1 \) to \( n-2 \), \( j = i+1 \) to \( n-1 \) and \( k = j+1 \) to \( n \) are considered. If any of these combinations are found to break all minimal paths, the combination is a third order cut. It is then necessary to check whether these cuts are minimal cuts using the technique described in section 2.4.4.1.

For a higher order cuts a similar procedure can be adopted.

2.4.5 - Formal Presentation of the Algorithm

Let \( n \) be the number of branches in the system.

a) Consider one output node
b) Consider all branches connected to the input nodes and connected to the output node to be unidirectional in addition to those specified in the input data. Let \( p \) be the total number of unidirectional branches including those specified and assumed.

c) Re-order the branch list so that all unidirectional branches are the first \( p \) branches in the list. Retain the correspondence between the new branch numbers and their original numbers.

d) Create an additional branch, number \( (n+1) \) in the branch list, to represent the output node; its sending end is the output node number and its receiving end is given the value zero \( (0) \).

e) Duplicate all bidirectional branches which appear as \( p + 1,\ p + 2, \ldots n \) in the branch list. Each duplicated branch has a sending end number equal to the receiving end number and a receiving end number equal to the sending end number of the real branch. The duplicated branch is given a number \( n_2 \) where \( n_2 = 2(n+1) - n_1 \), and \( n_1 \) is the branch number of the real branch.

f) Deduce the predecessors of every branch by identifying the branches whose receiving end numbers are equal to the sending end number of the branch being considered.

g) Eliminate as predecessors those branches which have a branch number equal to \( 2(n+1) - n_1 \) where \( n_1 \) is the branch number for which the predecessors are being deduced.

h) Deduce all minimal paths starting from the branch representing the output node to all input nodes using the list of predecessors. A path is completed when the value \( (-1) \), i.e. an input node, is reached. During the identification of these paths reject those paths that are found not to have a branch predecessor and eliminate those paths that form closed loops. This is achieved by

(i) eliminating those paths in which a branch number occurs twice

(ii) eliminating those paths that are identical to the paths eliminated
under (i) up to, but not including, the branch number that occurred twice

(iii) eliminating those paths in which a branch number, \( n_2 \), is equal to \( 2(n+1)-n_1 \), where \( n_1 \) is the numbers of branches that precede \( n_2 \)
(iv) eliminating those paths that are identical to the paths eliminated under (iii) up to, but not including, branch number \( n_2 \).

i) Replace the new branch number by their original numbers in the identified minimal paths.

j) Replace each branch by the components that it contains including the sending end node and/or the receiving end node if these are less than 100\% reliable. Prevent the same component number to appear twice in a path

k) Deduce the minimal cut sets of the minimal paths as explained in detail in section 2.4.4

l) Evaluate the reliability indices for each cut and for the output node

m) Repeat a) to l) for each output node

2.5 - Calculating the Output Node Reliability Indices

Having deduced the minimal cut sets for the output node being considered, the reliability indices for that node can be evaluated. Firstly all second and higher order minimal cut sets are reduced to an equivalent first order cut; then all real and equivalent first order minimal cuts are combined "in series" to obtain the output node reliability indices.

The basic equations needed to evaluate the outage rate and duration of second and third order minimal cut sets are given below where

\[ \lambda_i = \text{failure rate of component } i \text{ (failures/year)} \]
\[ r_i = \text{expected repair time of component } i \text{ (years)} \]
\[ \lambda_i'' = \text{maintenance outage rate of component } i \text{ (outages/year)} \]
\( r_{i}^n = \) expected maintenance time for component \( i \) (years)

a) Second order cut (components 1 and 2)

(i) overlapping forced outages

\[
\lambda_{eq} = \lambda_1 (\lambda_2 r_1) + \lambda_2 (\lambda_1 r_2)
\]

\[
r_{eq} = \frac{r_1 r_2}{r_1 + r_2}
\]

(ii) forced outages overlapping a maintenance outage

\[
\lambda_{eq}'' = \lambda_1 (\lambda_2 r_1'') + \lambda_2 (\lambda_1 r_2'')
\]

\[
r_{eq}'' = \frac{\lambda_1 (\lambda_2 r_1'') x \frac{r_1''}{r_1 + r_2} + \lambda_2 (\lambda_1 r_2'') x \frac{r_2''}{r_2 + r_1}}{\lambda_{eq}''}
\]

b) Third order cut (components 1, 2 and 3)

(i) overlapping forced outages

\[
\lambda_{eq} = \lambda_1 \lambda_2 \lambda_3 (r_1 + r_2 + r_1 r_2 + r_2 r_3)
\]

\[
r_{eq} = \frac{r_1 r_2 r_3}{r_1 r_2 + r_1 r_3 + r_2 r_3}
\]

(ii) forced outages overlapping a maintenance outage

\[
\lambda_{eq}'' = A + B + C
\]

where

\[
A = \lambda_1'' \lambda_2 \lambda_3 x^n (\frac{r_2}{r_1 + r_2} + \frac{r_3}{r_1 + r_3})
\]

\[
B = \lambda_2'' \lambda_1 \lambda_3 x^n (\frac{r_1}{r_2 + r_1} + \frac{r_3}{r_2 + r_3})
\]

\[
C = \lambda_3'' \lambda_1 \lambda_2 x^n (\frac{r_1}{r_3 + r_1} + \frac{r_2}{r_3 + r_2})
\]
\[
\begin{align*}
\mathbf{r}_{eq}^n &= \frac{A}{\lambda_{eq}} \left( \frac{r_1^n}{r_1} + \frac{r_2^n}{r_2} + \frac{r_3^n}{r_3} \right) + \frac{B}{\lambda_{eq}} \left( \frac{r_1^m}{r_1} + \frac{r_2^m}{r_2} + \frac{r_3^m}{r_3} \right) + \\
&\quad + \frac{C}{\lambda_{eq}} \left( \frac{r_1}{r_1} + \frac{r_2}{r_2} + \frac{r_3}{r_3} \right)
\end{align*}
\]

If there are \( n \) first order minimal cuts, including the equivalent ones evaluated using the above equations the output node reliability indices are:

(i) overlapping forced outages

\[
\lambda_L = \sum_{i=1}^{n} \lambda_i \\
\mathbf{r}_L = \frac{\sum_{i=1}^{n} \lambda_i}{\lambda_L} \mathbf{r}_i
\]

(ii) forced outages overlapping a maintenance outage

\[
\lambda''_L = \sum_{i=1}^{n} \lambda''_i \\
\mathbf{r}''_L = \frac{\sum_{i=1}^{n} \lambda''_i}{\lambda''_L} \mathbf{r}''_i
\]

Finally the output node reliability indices can be evaluated from:

\[
\lambda = \lambda_L + \lambda''_L \quad \text{expected outage rate}
\]

\[
\mathbf{U} = \lambda_L \mathbf{r}_L + \lambda''_L \mathbf{r}''_L \quad \text{expected outage time per year}
\]

\[
\mathbf{r} = \mathbf{U}/\lambda \quad \text{average outage duration}
\]

2.6 - Calculating the System Minimal Cut Sets

Having calculated the minimal cut sets of each output node in turn and the reliability indices of each of these nodes, it is often necessary to compare different alternative system designs. With previously published algorithms by which the indices for only one output node can be computed for each set of input data, this was particularly difficult especially when comparing large systems.
This problem is partly overcome with the present algorithm since all output nodes are evaluated sequentially in one computer run from a single set of input data describing the network topology. The problem is further overcome by developing a technique which expresses each failure event at each node by its consequences and evaluating the system minimal cut sets from the nodal minimal cuts. This then permits the overall system reliability indices to be calculated. To achieve this it is necessary to define a system failure and whether the loss of an output node causes a total system failure, a partial system failure or no failure in the system.

The easiest and perhaps the most general application of this technique is described in this section. Assuming that the loss of any output node causes either a total failure of the system or no system failure the following steps enable the system reliability indices to be evaluated:

a) eliminate the nodal minimal cuts of the redundant output nodes, i.e., those that do not cause system failure

b) consider all the remaining nodal minimal cuts as non-minimal system cuts. Using the technique described in section 2.4.4, i.e., checking whether one cut set is included in any other, the system minimal cuts are established and, from these, the system reliability indices are evaluated.

2.7. - Application of the Techniques

2.7.1 - Application to General Networks

Applying the techniques presented in the previous sections and the concepts described in reference 20 to the system shown in Fig. 1.1 and the data given in Table 2.1 gives the results shown in Table 2.8 and 2.9. In this example all components were assumed to have the same reliability data. The overall system indices were calculated by considering that the loss of any busbar causes total system failure.
## TABLE 2.8 - Reliability indices for output nodes of Fig. 2.1

<table>
<thead>
<tr>
<th>Cuts or Nodes</th>
<th>A (f/yr)</th>
<th>B (hr)</th>
<th>C (hr/yr)</th>
<th>D (out/yr)</th>
<th>E (hr)</th>
<th>F (hr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st order cut</td>
<td>0.010</td>
<td>20.0</td>
<td>0.20</td>
<td>0.10</td>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2nd &quot; &quot;</td>
<td>0.4566x10^{-6}</td>
<td>10.0</td>
<td>0.4566x10^{5}</td>
<td>0.2283x10^{5}</td>
<td>6.667</td>
<td>0.1522x10^{4}</td>
</tr>
<tr>
<td>3rd &quot; &quot;</td>
<td>0.1303x10^{-10}</td>
<td>6.667</td>
<td>0.8687x10^{10}</td>
<td>0.5212x10^{-10}</td>
<td>5.0</td>
<td>0.2606x10^{9}</td>
</tr>
<tr>
<td>Node 5</td>
<td>0.1000x10^{1}</td>
<td>19.997</td>
<td>0.20003</td>
<td>0.10001</td>
<td>9.9995</td>
<td>1.0001</td>
</tr>
<tr>
<td>Node 7</td>
<td>0.1000x10^{1}</td>
<td>19.998</td>
<td>0.20002</td>
<td>0.10001</td>
<td>9.9997</td>
<td>1.0001</td>
</tr>
<tr>
<td>Node 11</td>
<td>0.010</td>
<td>20.0</td>
<td>0.20</td>
<td>0.10</td>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Node 16</td>
<td>0.2000x10^{-1}</td>
<td>19.999</td>
<td>0.40002</td>
<td>0.20001</td>
<td>9.9998</td>
<td>2.0001</td>
</tr>
<tr>
<td>Node 17</td>
<td>0.1827x10^{5}</td>
<td>9.99</td>
<td>0.1827x10^{-4}</td>
<td>0.9135x10^{5}</td>
<td>6.6662</td>
<td>0.6089x10^{4}</td>
</tr>
</tbody>
</table>

## TABLE 2.9 - Nodal and System indices for system of Fig. 2.1

<table>
<thead>
<tr>
<th>Node number or system</th>
<th>Number of Minimal Cuts</th>
<th>( \lambda_t ) (outs/yr)</th>
<th>( r_t ) (hr)</th>
<th>( U_t ) (hr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st order</td>
<td>2nd order</td>
<td>3rd order</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
<td>20</td>
<td>0.1102</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>4</td>
<td>20</td>
<td>0.11001</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>0</td>
<td>42</td>
<td>0.11000</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>4</td>
<td>44</td>
<td>0.22001</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>4</td>
<td>44</td>
<td>0.1096x10^{4}</td>
</tr>
<tr>
<td>System</td>
<td>5</td>
<td>7</td>
<td>84</td>
<td>0.55002</td>
</tr>
</tbody>
</table>
In Tables 2.8 and 2.9, the column headings represent:

A - Contribution to the total failure rate due to forced outages
B - Average duration of an outage due to forced outages
C - Average annual outage time due to forced outages
D - Contribution to the total failure rate due to forced outages
   overlapping a maintenance outage
E - Average duration of an outage due to forced outages overlapping
   a maintenance outage
F - Average annual outage time due to forced outages overlapping a
   maintenance outage

$\lambda_t$ - Total failure rate

$\tau_t$ - Average duration of an outage

$\nu_t$ - Average annual outage time

The details of the first and second order minimal cut sets for the
system shown in Fig. 2.1 are specified in Table 2.10

**TABLE 2.10- 1st and 2nd order cuts for the system of Fig. 2.1**

<table>
<thead>
<tr>
<th>node number or system</th>
<th>component numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5, 1-8, 1-9, 1-11, 2-8, 2-9, 2-11.</td>
</tr>
<tr>
<td>7</td>
<td>7, 3-5, 3-6, 4-5, 4-6.</td>
</tr>
<tr>
<td>11</td>
<td>11, no 2nd order cuts</td>
</tr>
<tr>
<td>16</td>
<td>14, 16, 7-11, 7-12, 10-11, 10-12.</td>
</tr>
<tr>
<td>17</td>
<td>no 1st order cuts, 7-11, 7-12, 10-11, 10-12.</td>
</tr>
<tr>
<td>system</td>
<td>5, 7, 11, 14, 16, 1-8, 1-9, 2-8, 2-9, 2-11, 3-6, 4-6, 10-12.</td>
</tr>
</tbody>
</table>
2.7.2 - Application to an Electrical Network

A typical electrical network is shown in Fig. 2.4. The reliability indices discussed for the previous examples were again evaluated using the criterion that system failure is caused by the loss of any one busbar. The assumed reliability data is shown in Table 2.11. It should be noted that maintenance of the busbars and of components 3, 4 and 10 is not included since these create first order minimal cuts. It is assumed that maintenance of such components is made only when the system is not required to operate.

FIG. 2.4 - Typical electrical system

unidirectional branches
TABLE 2.11 - Reliability data for system of Fig. 2.4

<table>
<thead>
<tr>
<th>Component</th>
<th>failure rate f/yr</th>
<th>repairtime hr</th>
<th>maintenance rate out/yr</th>
<th>maintenance time hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>breakers</td>
<td>0.02</td>
<td>20.0</td>
<td>0.50</td>
<td>10.0</td>
</tr>
<tr>
<td>transformers</td>
<td>0.02</td>
<td>600.0</td>
<td>1.0</td>
<td>20.0</td>
</tr>
<tr>
<td>busbars</td>
<td>0.05</td>
<td>10.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>cables</td>
<td>0.02</td>
<td>20.0</td>
<td>0.50</td>
<td>10.0</td>
</tr>
<tr>
<td>breakers 3 and 10</td>
<td>0.01</td>
<td>20.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>transformer 4</td>
<td>0.02</td>
<td>100.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The reliability indices $A$, $B$, $C$, $D$, $E$, $F$ discussed previously for each busbar are shown in Table 2.12, the total indices $\lambda_t$, $r_t$, $U_t$ for each busbar and for the overall system are shown in Table 2.13 and the details of the first and second order minimal cuts for every busbar and for the overall system are shown in Table 2.14. The number of third order minimal cuts are also given in Table 2.14.

TABLE 2.12 - Reliability indices for busbars of Fig. 2.4

<table>
<thead>
<tr>
<th>busbar number</th>
<th>$A$ f/yr</th>
<th>$B$ hr</th>
<th>$C$ hr/yr</th>
<th>$D$ out/yr</th>
<th>$E$ hr</th>
<th>$F$ hr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.140</td>
<td>24.282</td>
<td>3.40</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.19016</td>
<td>20.522</td>
<td>3.9023</td>
<td>0.4111x10^3</td>
<td>7.6712</td>
<td>0.3153x10^2</td>
</tr>
<tr>
<td>6</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
<td>0.1775x10^6</td>
<td>5.9349</td>
<td>0.1054x10^5</td>
</tr>
<tr>
<td>7</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
<td>0.8123x10^7</td>
<td>5.1404</td>
<td>0.4176x10^6</td>
</tr>
<tr>
<td>8</td>
<td>0.19016</td>
<td>20.522</td>
<td>3.9023</td>
<td>0.4111x10^3</td>
<td>7.6712</td>
<td>0.3153x10^2</td>
</tr>
<tr>
<td>9</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
<td>0.1775x10^6</td>
<td>5.9349</td>
<td>0.1054x10^5</td>
</tr>
</tbody>
</table>
### TABLE 2.13 - Reliability indices for system of Fig. 2.4

<table>
<thead>
<tr>
<th>busbar number</th>
<th>$\lambda_t$ f/yr</th>
<th>$r_t$ hr</th>
<th>$U_t$ hr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.140</td>
<td>24.286</td>
<td>3.40</td>
</tr>
<tr>
<td>5</td>
<td>0.19057</td>
<td>20.494</td>
<td>3.9055</td>
</tr>
<tr>
<td>6</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
</tr>
<tr>
<td>7</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
</tr>
<tr>
<td>8</td>
<td>0.19057</td>
<td>20.494</td>
<td>3.9055</td>
</tr>
<tr>
<td>9</td>
<td>0.190</td>
<td>20.526</td>
<td>3.90</td>
</tr>
<tr>
<td>system</td>
<td>0.39064</td>
<td>15.122</td>
<td>5.9074</td>
</tr>
</tbody>
</table>

### TABLE 2.14 - Minimal cut sets for system of Fig. 2.4

<table>
<thead>
<tr>
<th>busbar number</th>
<th>number of 3rd order cuts</th>
<th>1st and 2nd order minimal cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>1, 2, 3, 4, 10.</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>1, 2, 3, 4, 10, 5, 6-14, 6-15, 6-16, 14-29, 14-30, 14-31, 15-29, 15-30, 15-31, 16-29, 16-30, 16-31.</td>
</tr>
<tr>
<td>6</td>
<td>84</td>
<td>1, 2, 3, 4, 10, 6.</td>
</tr>
<tr>
<td>7</td>
<td>84</td>
<td>1, 2, 3, 4, 10, 7.</td>
</tr>
<tr>
<td>9</td>
<td>84</td>
<td>1, 2, 3, 4, 10, 9.</td>
</tr>
</tbody>
</table>
2.8 - Conclusions

An efficient algorithm that enables the minimal paths and minimal cut sets of any complex system to be evaluated has been described. It can be used to calculate the modal output reliability indices of any system. Its computational efficiency is clearly indicated by the fact that the times required to analyse the systems shown in figs. 2.1 and 2.4 on a CDC 7600 were 0.7 and 3.0 seconds respectively. The storage required for the appropriate arrays dimensioned for a system having 100 components and up to 125 minimal cuts per output node is 15 kwords. These times and storage include the incorporation of the overall system reliability analysis.

The main and most important new features of the present algorithm include the ability to express the reliability of the overall system by appropriate indices and therefore to compare easily and efficiently different designs, the ability to deduce the minimal paths and cuts for all nodes from one set of topological input data and the ability to include simply unidirectional, bidirectional, multi-ended components and any number of input nodes. The concept of overall indices is presented in its simplest formulation and will be developed in the following chapters.
THREE STATE RELIABILITY MODELLING OF

ELECTRICAL NETWORKS

3.1 - Introduction

Most literature on reliability evaluation of electrical systems does not include the effects of switching actions after a component fault has occurred. However faults usually cause outages of other healthy components which can be reenergised after isolating the faulty component. Therefore the electrical system can be found in one of three states: the operating state, the state requiring switching actions and the state after switching actions.

The first paper (26) to recognise the three state model of electrical networks was published in 1970. Thereafter only a few papers (10), (27) in this area have been published. However if the expected failure rate of a load point is to be calculated with minimum inaccuracy, a three state model must be considered. On the other hand, the load point average annual outage time may not be influenced by the consideration of a three-state model since the duration of the second state is only the switching time (time required to isolate a faulty component and to restore to service all healthy components); this being of short duration, compared with the repair times.

If the three reliability indices, expected failure rate, average outage duration and average annual outage time, are required for the load points of the system with the same degree of accuracy then a three state model is the most realistic reliability representation of any electrical network.
3.2 - Component States

In most of the literature concerning repairable systems, the reliability techniques are based on a two state representation of each component in which each component has an operating history consisting of periodic cycles between the "in service" and "failed" states. This is illustrated in Fig. 3.1.

FIG. 3.1 - Operating history of a two state component

Figs. 3.2 and 3.3 show the models for a one component and two component system, where \( \lambda_k \) and \( \mu_k \) represent the failure and repair rates of component \( k \); \( \mu_k \) is the inverse of the average repair time of component \( k \).

FIG. 3.2 - 2 states, 1 component

FIG. 3.3 - 2 states, 2 components
Analysing these models and a similar one for a three component system the equations presented in section 2.5 are obtained for first, second and third order cuts.

If a component can develop several types of failures, it does not follow that these failures necessarily constitute as many failure modes. Often they are independent of each other but cause identical system effects. In such cases these failures can be pooled together and the component can be regarded as having a single failure mode. The expected component failure rate in this mode is the sum of the rates of occurrence of the constituent failures and the component can be represented as a two state component.

If the above conditions do not hold for some components these components must be considered to have several failure modes. The failures in each of the modes occur under the same conditions and have the same system effects. The number of component states is equal to the number of component failure modes plus one (corresponding to the up state).

Consider, as an example, the three modes in which a normally closed circuit breaker can fail. These are:

i) false breaker operation (opening)

ii) ground faults

iii) failures to operate (expressed by a stuck probability)

The failure mode i) usually results only in a break in the circuit, whereas the failure modes ii) and iii) will cause the operation of the entire protection zone around the breaker. There is also a difference in the conditions in which these failures can occur: ground faults and false operations occur "at random" and failures to operate manifest themselves only when a need for operation arises, i.e. when a failure occurs in a component protected by the breaker.

For any other electrical component two failure modes can be identified: failures that result in the removal of certain other healthy components
from service and failures that do not cause the operation of circuit breakers. These failure modes were called\(^{(10)}\) active and passive, respectively and the corresponding rates of failure were designated by passive failure rate and active failure rate. Neglecting, at this stage, the stuck probability of the circuit breakers it can be assumed that every electrical component has two failure modes, although for some components the rate of occurrence of one of them may be zero, e.g., the busbars have usually a passive failure rate equal to zero.

Fig. 3.4 shows the cycle of events that happen after a passive and an active failure.

---

**FIG. 3.4** - Sequence of events after a passive and an active failure

For passive failures the electrical components are represented as two state components but for active failures a three state model is considered. Figs. 3.5 and 3.6 show the models for a one component and a two component system where \( \lambda_k, \mu_k \) and \( s_k \) represent the active failure rate, the repair rate and the switching rate of component \( k \); \( s_k \) is the inverse of the switching time of component \( k \).
The stuck probability of the circuit breakers can only be taken into account in conjunction with the failure of a component protected by the breaker. Let \( p \) be the stuck breaker probability (probability of the breaker failing to open when called upon to operate), \( \lambda_{pc} \) and \( \lambda_{ac} \) the passive and active failure rate of a component, \( \lambda_{pb} \) and \( \lambda_{ab} \) the passive and the active failure rate of the breaker; \( \mu_{p} \) and \( \mu_{c} \) are the repair rates of the breaker and of the component, respectively. Fig. 3.7 shows the model for a circuit breaker protecting a component C
3.3 - System States

It is clearly evident from the previous section that, as the number of components increase, the number of system states increases dramatically. For example, for a relatively small system of 100 components, there will be \(2^{100} \approx 10^{30}\) states for the 2-state model and \(3^{100} \approx 10^{48}\) states for the 3-state model. Since the techniques developed were to be used for systems having several hundred components some simplifications have to be made. However the errors introduced by these simplifications are negligible.

The first assumption is that the probability of occurrence of two simultaneous active faults is negligible. Therefore, referring to fig. 3.6 for a 2 component system, the state in which both components are failed but not isolated, \((i_s, j_s)\), is neglected. This is justified because the component switching times are relatively very small, even including the corresponding decision time. The exposure time of the system to a second active failure is small and therefore the probability of two overlapping active failures is negligible.

A second assumption is that the probability of two simultaneous
stuck breaker conditions in the system is also negligible. This is evident since the stuck breaker probability is around $10^{-3}$.

The third assumption is that, for a given system configuration (defined by the healthy components "in service"), the independent load point failure events are the minimal cut sets associated with the minimal paths from the load point to the system sources. This is valid because the components of an electrical system always have high availabilities (see Appendix 1).

The assumptions indicated simplify very much the modelling of an electrical network in its three states, mainly because it is possible to simulate directly the active failures and the active failures overlapping a stuck breaker condition. Fig. 3.8 shows the possible system states and the transitions between them.

![Diagram of system states](image)

1 - System without active or passive failures
2 - System after an active failure but before switching
3 - System after switching or after a passive failure

**FIG. 3.8 - System states**

The system states indicated in fig. 3.8 can be easily observed in the electrical system shown in fig. 3.9. The fault indicated causes changes of system states according to the sequence shown in fig. 3.8.
It was stated before that active and passive failures are independent failures. So the analysis of a system can be divided into the following parts:

a) Analysis considering only passive failures and consequently accepting a two state model for the system. The minimal cut set theory can be applied as described in chapter II.

b) Analysis considering only active failures and active failures overlapping passive failures. A three state model of the system is considered changing the system configuration for each simulation of active failures and active failures overlapping a stuck breaker condition. For each system configuration the corresponding failure events are associated with its minimal cut sets.

c) Combining the results obtained in a) and b)

This approach is applied to evaluate the failure events of the load point L₂ in the system represented in fig. 3.9, assuming the busbars to be 100% reliable.

In this example a P, A or S after a component number indicates its
failure mode, passive, active or stuck, respectively.

a) 1E, 2E, 3E, 10E, 11P and 12P are failure events of the load point; they are the minimal cut sets associated with the unique path 1-2-3-10-11-12

b) 1A, 2A, 3A, 10A, 11A and 12A are also failure events of the load point; in fact if a passive failure causes a load failure, an active failure in the same component also causes the loss of continuity to the load. Therefore the events detected in a) but with the components actively failed are also load point failure events.

4A and 7A cause the loss of L2 because breaker 3 trips and all paths to the load are broken (in this example there is only one path). There is no need to simulate a stuck breaker condition of breaker 3 overlapping 4A or 7A because the active failure by itself is a failure event.

5A, 6A, 8A and 9A do not cause a failure of L2 and therefore these active failures are combined with stuck breaker conditions.

5A and 4S, 6A and 4S, 8A and 7S, 9A and 7S would trip breaker 3 and, as a consequence, all paths to the load point are broken. Therefore these events are also load point failure events.

5A and 6S, 6A and 9S, 8A and 9S, 9A and 6S do not break any path to the load point under consideration; these events are not considered failure events.

c) The load point failure events are summarized below:

1(P+A), 2(P+A), 3(P+A), 10(P+A), 11(P+A), 12(P+A), 4A, 7A, 5A-4S, 8A-7S, 6A-4S, 9A-7S

The objective of the previous example was to show that in a practical reliability analysis the passive failures lose their identity since they are always combined with active failures. This leads to the consideration of the component total failure rate as well as its active failure rate; the first includes passive and active failures. When considering total failures there is no need to analyse the change of the system configuration
after the failures; For active failures (simulated one at a time) the sequence of system states has to be taken into account.

3.4 - Application

Consider as a second simple example the electrical system shown in fig. 3.10

![Diagram of electrical system]

Fig. 3.10 - Application example

The busbars are assumed to be 100% reliable and the aim of this example is to show a systematic logic to identify the failure events of a load point, taking into account the change of the network configuration after an active failure. A, S & F after a component number mean actively failed, stuck and failed (passively or actively), respectively.

Consider the load point \( L_2 \); Its failure events are deduced as follows:

(i) Calculate the minimal paths to \( L_2 \). These are:

1, 2, 3, 7, 8, 9 - path 1

10, 11, 12 - path 2

(ii) Calculate the minimal cut sets associated with the paths found in (i). These are:
1-10, 2-10, 3-10, 7-10, 8-10, 9-10
1-11, 2-11, 3-11, 7-11, 8-11, 9-11
1-12, 2-12, 3-12, 7-12, 8-12, 9-12

(iii) Identify the minimal cut sets found in (ii) with load point failure events; the following are independent load point failure events:
F-10F, 2F-10F, 3F-10F, 7F-10F, 8F-10F, 9F-10F
F-11F, 2F-11F, 3F-11F, 7F-11F, 8F-11F, 9F-11F
F-12F, 2F-12F, 3F-12F, 7F-12F, 8F-12F, 9F-12F

(iv) Simulate one active failure in every system component. Table 3.1 shows the deductions made after each simulation. Active failures of components 4 and 7 are considered in more detail:

a) 4A causes the opening of breakers 3 and 7 but L2 is still fed by the path 10, 11, 12. The minimal cut sets of the system after the active failure of component 4 are those associated with the remaining path, i.e., 10, 11 & 12 and the corresponding failure events are 10F, 11F & 12F. These failure events overlapping the active failure being simulated are failure events of the load point L2, that is, 4A-10F, 4A-11F and 4A-12F cause loss of continuity to L2.

Then it is necessary to check whether the failure events that were deduced are included in those indicated in (iii). In this example they are not included and so are considered as load point independent failure events.

Breaker 3 is then assumed stuck and so an active failure of component 4 trips breakers 1 and 7. It causes the same system effects as 4A alone and no more load point failures are evaluated.

When breaker 7 is stuck 4A trips breakers 3 and 9. Again no more load point failure events are evaluated. Because the remaining paths after this simulation are the same as if 4A alone was simulated it can be immediately concluded that it has the same system effects as 4A alone.

b) 7A causes the opening of breakers 3 and 2. L2 is fed by the remaining path 10, 11, 12 and its failure events are 10F, 11F and 12F. These events
### TABLE 3.1 - Effects of active failures

<table>
<thead>
<tr>
<th>Component actively failed</th>
<th>Component stuck</th>
<th>Remaining paths</th>
<th>Failure events</th>
<th>Independent failure events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>2</td>
<td>1A-10F, 1A-11F, 1A-12F</td>
<td>none</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>same system effects as 1A</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>2</td>
<td>2A-10F, 2A-11F, 2A-12F</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>1 or 3</td>
<td>2</td>
<td>same system effects as 2A</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>2</td>
<td>3A-10F, 3A-11F, 3A-12F</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>1 or 7</td>
<td>2</td>
<td>same system effects as 3A</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>2</td>
<td>4A-10F, 4A-11F, 4A-12F</td>
<td>4A-10F, 4A-11F, 4A-12F</td>
</tr>
<tr>
<td>4</td>
<td>3 or 7</td>
<td>2</td>
<td>same system effects as 4A</td>
<td>none</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>1, 2</td>
<td>does not break any path to the load</td>
<td>none</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>5A-4S-10F, 5A-4S-11F, 5A-4S-12F, 5A-4S-11F, 5A-4S-12F</td>
<td>none</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>1, 2</td>
<td>does not break any path to the load</td>
<td>none</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2</td>
<td>6A-4S-10F, 6A-4S-11F, 6A-4S-12F, 6A-4S-11F, 6A-4S-12F</td>
<td>none</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>2</td>
<td>7A-10F, 7A-11F, 7A-12F</td>
<td>none</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>2</td>
<td>same system effects as 7A</td>
<td>none</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>none</td>
<td>7A - 9S</td>
<td>7A - 9S</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>2</td>
<td>8A-10F, 8A-11F, 8A-12F</td>
<td>none</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>2</td>
<td>same system effects as 8A</td>
<td>none</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>none</td>
<td>8A - 9S</td>
<td>8A - 9S</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>none</td>
<td>9A</td>
<td>9A</td>
</tr>
<tr>
<td>9</td>
<td>7 or 12</td>
<td>none</td>
<td>same system effects as 9A</td>
<td>none</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>1</td>
<td>same systems effects as 10A</td>
<td>none</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>1</td>
<td>same system effects as 11A</td>
<td>none</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>none</td>
<td>11A-12S</td>
<td>11A-12S</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>none</td>
<td>12A</td>
<td>12A</td>
</tr>
<tr>
<td>12</td>
<td>9 or 10</td>
<td>none</td>
<td>same system effects as 12A</td>
<td>none</td>
</tr>
</tbody>
</table>
together with 7A are load point failure events. The events deduced are:

7A-10F, 7A-11F and 7A-12F

However these events are already included in 7F-10F, 7F-11F and 7F-12F deduced in (iii) and so are rejected as independent load point failures.

When breaker 3 is assumed stuck the event 7A-3S has the same system effects as 7A and so no more analysis is required.

When breaker 9 is stuck, breaker 12 would trip and the event 7A-9S breaks all paths to the load point and because it is not included in those deduced in (iii) it is an independent load point failure event.

A similar logic is applied every time an active failure is simulated; Table 3.1 shows the results of its application in the system given in fig. 3.10.

3.5 - Conclusions

This chapter has shown the complexity involved in modelling each component of an electrical system by three residence states. Even modelling each component by its two conventional states would be prohibitive for systems with more than a few components. This is overcome by using the minimal cut set approach. It was shown that, for some faults (active), an electrical component must be represented by a three state reliability model. Because these faults have a small duration it was assumed that the probability of having two overlapping active faults is negligible. This assumption permits direct computer simulation of active faults. Each time an active failure or an active failure plus a stuck breaker condition is simulated, a new system configuration is found and the failure events associated with this new system are evaluated using again the minimal cuts associated with each output node.

The logic described in the application example to detect the load point failure events is completely original and leads to very efficient programming techniques compared to those already published (10), (27).
4.1 - Introduction

Recent literature\(^{(9)}\), \(^{(10)}\) describe computer programs that assess the reliability of electrical systems and permit the effect of switching actions to be included. Grover and Billinton\(^{(10)}\) describe a technique that incorporates all realistic component failure modes in the reliability predictions and state the limitations of the computerized approach presented by Endrenyi et al\(^{(9)}\). However the technique\(^{(10)}\) was not designed for and therefore cannot handle easily systems with more than one load point. Also the input data required increases dramatically as the number of non-unidirectional system components increases.

This chapter describes computational techniques that overcome these limitations and introduces a completely new concept of overall system reliability indices. The usefulness of these system indices is shown by the numerical examples considered in this chapter. A program based on these techniques does not limit the number of load points and is very efficient computationally.

4.2 - Reliability Concepts

The reliability techniques are based on the concept of expected failure rate and average outage duration method\(^{(28)},\(^{(29)}\). For each load point the expected failure rate, average outage duration and average annual outage time are evaluated. These indices are easily understood and have a much more meaningful engineering significance than the mathematical concept of probability of failure.

In order to indicate the critical areas of failure, it is necessary
to deduce the individual contributions of each failure event to the reliability indices of each load point. These contributions are the expected failure rate, the average outage duration and the average annual outage time due to:

(a) overlapping forced outages

(b) forced outages overlapping a maintenance outages

The individual contributions and the load point indices are evaluated using the equations given in Appendix 2 after the failure modes for the load point under consideration have been deduced.

It is not easy to compare the reliability of different system designs from a knowledge of the load point indices only, particularly when many load points exist and when their indices change in different ways by different amounts. Furthermore the indices at different load points may not be independent due to common mode failures and therefore cannot be realistically summed. To overcome these difficulties a concept of system reliability in contrast to load point reliability has been developed. To apply this concept rigorously it is necessary to define what is a system failure. The present algorithm as described in section 4.5 considers that the system fails when at least one of the load points fails. If only one kind of failure mode exists then this concept becomes a simple extension of the minimal cut set theory applied to a multiple output system; This was considered in chapter II. However in an electrical system a number of different failure modes exist, as described in Section 4.4, and the technique therefore becomes much more complex.

4.3 - Reliability Input Data

To evaluate the reliability indices described in Section 4.2 for each failure event, for each load point and for the overall system, the following component data is required:
a) total failure rate - average total number of component failures per year that require the component to be removed from service for repair due to any of its failure modes.

b) active failure rate - average number of component failures per year that cause breakers to open and therefore tripping of other healthy components. The healthy components can be re-energised after isolating the actively failed component. It should be noted that an actively failed component may cause a temporary outage of several healthy components.

c) average repair time - average time taken to repair all kinds of component failures modes.

d) switching time - average time between the occurrence of an active failure and the instant when the failed component is isolated and all possible healthy components are restored to service. It should be noted that the actively failed component itself can only be restored to service following a repair or replacement action.

e) maintenance outage rate - average number of occasions per year that a component is taken out of service for preventative or scheduled maintenance. It is assumed that maintenance is not commenced if an outage already exists in a related part of the system.

f) average maintenance time - average duration of all preventative maintenance outages.

g) stuck probability - probability of a breaker or a switch failing to open or close when called upon to operate. It should be noted that when a breaker fails to open following an active failure, a considerably greater number of healthy components may suffer a temporary outage due to back-up protection operating.

4.4 - Failure Modes of an Electrical System

It was shown in chapters II and III how the minimal cut set theory
can be used to deduce the load point failure events. The minimal cuts were differentiated according to the type of failure they represent; This is a new approach to the analysis of electrical systems and its application in a computer program developed is one of the main reasons why it is far more efficient than the programs described in the literature \(^{(10),(27)}\).

In an electrical system with switching actions there are four kinds of minimal cut sets if the probability of two overlapping active failures and two stuck breakers are considered negligible. These are:

a) a cut set of which all components are out either for repair or for maintenance. Service can be restored only by replacing at least one component.

b) a cut set of which all components are out either for repair or maintenance but service can be restored by closing a normally open path.

c) a cut set of which one component is actively failed and the other components are out either for repair or maintenance. Service is restored by isolating the actively failed component and re-energising the rest of the system.

d) a cut set similar to type c) but including a stuck breaker.

To illustrate these failure modes consider the system shown in Fig. 4.1 All the load points failure modes for this system are shown in Table 4.1. These load point failure modes can be deduced using the following procedure:

a) deduce all minimal paths from the sources to the load point including normally open paths

b) separate the normally closed paths and the normally open paths

c) deduce the minimal cut sets associated with the normally closed minimal paths. Identify which of these failure events can be eliminated by closing a normally open path.

d) simulate an active failure in every component unless it constitutes a first order failure event. Simultaneously consider operation of firstly, the primary protection breakers and secondly, the back-up protection
FIG. 4.1 - System used to illustrate failure modes

TABLE 4.1 - Failure modes for system in Fig. 4.1

<table>
<thead>
<tr>
<th>load point</th>
<th>failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1*, 2*, 3*, 4, 10, 11(10), 12(10), 14, 15(14), 16(14)</td>
</tr>
<tr>
<td>8</td>
<td>5*, 6*, 7*, 8, 17, 18(17), 19(17)</td>
</tr>
<tr>
<td>13</td>
<td>1*, 2*, 3*, 4, 13, 10+14, 10+15, 10+16, 11+14, 11+15, 11+16, 12+14, 12+15, 12+16, 10, 11(10), 11(12), 12, 14, 15(14), 15(16), 16</td>
</tr>
<tr>
<td>20</td>
<td>5*, 6*, 7*, 8, 17, 18, 19, 20</td>
</tr>
</tbody>
</table>

| system     | 1*, 2*, 3*, 4, 10, 11(10), 14, 15(14), 15(16), 11(12), 5*, 6*, 7*, 8, 13, 10+14, 10+15, 10+16, 11+14, 11+15, 11+16, 12+14, 12+15, 12+16, 12, 16, 17, 18, 19, 20 |

where:
- underlined numbers are actively failed components
- numbers in parentheses are stuck breakers
- asterisked numbers are failed components but service can be restored by closing a normally open path (breaker 9)
breakers. In both simulations identify the normally closed paths that are broken. If all these paths are broken the active failure or active failure plus stuck breaker event is a load point failure mode. If none of the normally closed paths is broken the event is ignored. If some paths are broken the minimal cut sets associated with the remaining paths are evaluated; these together with the primary event form a load point failure mode. Each time such a failure event is detected it is checked for independence; if already included in previous events, it is ignored.

The reliability indices of these load point failure modes can be evaluated using the equations given in appendix 2 which are based on those published previously(28),(29),(10).

4.5 - The Overall System Indices

It is evident from Table 4.1 that some failure modes are common to more than one load point. The load point indices are therefore dependent. To evaluate the system reliability indices the independent system failure modes must be deduced from the independent failure modes of all the load points. The algorithm developed to achieve this objective is described in this section. Briefly it involves comparing two load point failure modes at a time and deciding whether they are independent events. Using this algorithm the system failure modes can be determined for the system shown in Fig. 4.1. These are also shown in Table 4.1. It is clearly evident that there is a total of 47 cuts associated with all the load points but only 30 of these are independent events for the system.

In the description of the algorithm it is assumed that the loss of any busbar causes the loss of the system. This is so because the busbars specified as redundant are simply not taken into account when the algorithm is applied. In the formulation presented in this section the busbars are assumed to be grouped into two categories: those that are absolutely essential and those that are redundant, i.e. those that, when lost, cause 100% reduction of the
system objective and those that, when lost, cause 0% reduction of the
system objective.

4.5.1 - The Algorithm (Algorithm 1)

1. Assumption
   It is assumed that the loss of any busbar causes the loss of the
   system

2. Identification of a minimal cut set
   Each cut is defined by a set of 5 values having the following
   meaning:

   \[
   \begin{array}{|c|c|c|c|c|}
   \hline
   x & N & a & b & c \\
   \hline
   \end{array}
   \]

   \(x\) defines the kind of cut
   \(N\) defines the busbar to which the minimal cut is
   attached
   \(a, b, c\) are the elements of the cut, where \(b\) and/or \(c\)
   may be zero

   The value of \(x\) may be:
   - 1 a cut in which every component is out, and service is restored
     by a repair action
   - 2 a cut in which every component is out, but the cut may be
     eliminated by closing a normally open path
   - 3 a cut in which component \(a\) is actively failed and every other
     component is out; this cut may be eliminated by switching
     component \(a\) out of the system
   - 4 a cut as defined by -3, but where breaker \(k\) is stuck

3. Aim of the algorithm

Given two busbar minimal cuts it is necessary to decide whether or not
one is included within the other, that is whether both are system minimal cuts. The complexity of the procedure is due to the need to compare cuts of different kinds.

4. Algorithm

Consider two minimal cuts, say cuts i and j

\[
\begin{array}{c|c|c|c}
  i & x_i & N_i & a_i & b_i & c_i \\
\end{array}
\]

\[
\begin{array}{c|c|c|c}
  j & x_j & N_j & a_j & b_j & c_j \\
\end{array}
\]

Let I and J be a set of three numbers defined as follows:

\[
I = \{a_i, b_i, c_i\} \quad \text{and} \quad J = \{a_j, b_j, c_j\}
\]

\[
n_i = n^c \text{ of non-zero elements of } I
\]

\[
n_j = n^c \text{ of non-zero elements of } J
\]

\[
n_m = \text{minimum of } n_i \text{ and } n_j
\]

Define the set \( A = I \cap J \) and consider that \( n_a \) is the number of non-zero elements of \( A \), which is necessarily less than or equal to \( n_m \).

The algorithm can then be described by the following steps:

(i) If \( N_i = N_j \) the cuts are considered independent

(ii) If \( n_a < n_m \) the cuts are considered independent

So if \( N_i \neq N_j \) and \( n_a = n_m \) the analysis proceeds in the following sequence:

(iii) \( x_i = x_j \)

a) \( x_i = x_j = -1 \) or \( -2, n_i = n_j \)

reject either of the cuts; the program retains the cut that minimises the execution time in future comparisons of different pairs of cuts
b) \( x_i = x_j = -1 \) or \(-2\), \( n_i \neq n_j \)
   reject the cut with most elements

c) \( x_i = x_j \neq -1 \) or \(-2\)
   c-1) \( a_i = a_j, n_i = n_j \)
        As case a)
   c-2) \( a_i = a_j, n_i \neq n_j \)
        As case b)
   c-3) \( a_i \neq a_j \)
        Reject the cut with minimum total outage time per year

iv) \( x_i \neq x_j \)
   a) \( n_i \neq n_j \)
   Cuts considered independent
   b) \( n_i = n_j \)
   Decision taken according to the following table
   The cut indicated in the table is eliminated

<table>
<thead>
<tr>
<th></th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td>j</td>
<td>i</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>j</td>
<td>j</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>j</td>
<td>j</td>
<td>j</td>
<td>a</td>
</tr>
</tbody>
</table>

values of \( x_i \)

values of \( x_j \)

(a) both \( i \) and \( j \) are independent and are retained

4.5.2 - Application of the Algorithm

To exemplify the application of the algorithm described in section 4.5.1
consider two failure events - 17 and 17 - associated with busbars 20 and 8, respectively. These events are: Component 17 failed (actively or passively) and component 17 actively failed. They are represented as follows:

\[
\begin{array}{cccc}
-1 & 20 & 17 & 0 \\
17 & 0 & 0 & 0
\end{array}
- \text{ cut i}
\]

\[
\begin{array}{cccc}
-3 & 8 & 17 & 0 \\
17 & 0 & 0 & 0
\end{array}
- \text{ cut j}
\]

The following is done before applying the algorithm (the symbols are the same as those used in the description of the algorithm):

\[
I = \{17, 0, 0\} \quad J = \{17, 0, 0\}
\]

\[
n_i = n_j = n_m = 1
\]

\[
A = I \cap J = \{17, 0, 0\} \quad n_a = 1
\]

Steps (i) - (iv) of the algorithm are then followed sequentially and every time the topology of the cuts is not accommodated in any step the next step is tried:

step (i) \quad N_i \neq N_j

step (ii) \quad n_a = n_m

step (iii) \quad x_i \neq x_j

step (iv) a) \quad n_i = n_j

b) The cuts satisfy the conditions specified in (iv), b). So the decision is taken according to (iv), b) and cut j is eliminated.

The elimination is correct since every time the event defined by cut j happens the event defined by cut i also happens; So cut j is contained in cut i.
4.6 - Computational Aspects

A computer program was developed that incorporates all the previous concepts.

The following aspects are evaluated:

a) the failure events for every system node from a description of the network topology and of the protection zones. The most important and novel features of the present computerized approach are that the system can be either radial or highly meshed, can have unidirectional and/or bidirectional components, can have multiended components that are not 100% reliable (busbaks) and can be a multiple input/multiple output system.

b) the expected failure rate, average outage duration and average annual outage time of each load point failure event and for each load point

c) the overall system independent failure events assuming that the system fails when at least one load point fails.

d) the overall system reliability indices

The computer storage requirement is given approximately by:

\[
\text{storage} = k + 4 n_c + 29 n_e + 3 n_c n_n
\]

where \( k = 12 \) k words

\( n_c = \) maximum number of minimal cut sets for a system load point

\( n_e = \) number of system components

\( n_n = \) number of system load points

For a system having 100 components, 250 failure modes per output node and 10 load points, the required storage is approximately 23 k words.

The computing time is a function of the system complexity, the total number of failure modes detected and the number of output nodes. The time taken to analyse the systems shown in Figs. 4.1 and 4.2 were 0.185s and 6.481s respectively using a CDC 7600 computer.
4.7 - Analysis of Typical System

4.7.1 - Busbar Analysis

To illustrate the application of the concepts described in the previous sections and the type and depth of the results that can be obtained, the system shown in Fig. 4.2 was analysed. This system may reasonably be considered as basically a radial distribution network with interconnections between the l.v. busbars. The component reliability data used in this analysis is shown in Table 4.2.

**TABLE 4.2 - Component reliability data**

<table>
<thead>
<tr>
<th>Component</th>
<th>failure rate</th>
<th>repair time</th>
<th>switching time</th>
<th>stuck probability</th>
<th>maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total f/yr</td>
<td>active f/yr</td>
<td></td>
<td></td>
<td>rate o/yr</td>
</tr>
<tr>
<td>1,2,5,6</td>
<td>0.024</td>
<td>0.024</td>
<td>3</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>7,8,9</td>
<td>0.23</td>
<td>0.10</td>
<td>15</td>
<td>2</td>
<td>0.005</td>
</tr>
<tr>
<td>3,10</td>
<td>0.10</td>
<td>0.10</td>
<td>24</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.23</td>
<td>0.10</td>
<td>20</td>
<td>1</td>
<td>0.005</td>
</tr>
<tr>
<td>11,13,14,16,17,19,20,22,23,25,26,28,29,31,32,34,35,37</td>
<td>0.12</td>
<td>0.12</td>
<td>10</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>27,30,33,36</td>
<td>0.10</td>
<td>0.10</td>
<td>500</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>12,15,18,21,24</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the reliability data shown in Table 4.2, all the failure events up to third order, i.e. up to three overlapping outages plus, if applicable, a stuck breaker, were deduced for each busbar. The reliability indices of
each event and the overall indices of each busbar were also calculated. As discussed previously it was assumed that a component is not taken out for maintenance if it causes a busbar failure or if an outage already exists in a related part of the system. Therefore maintenance details are not given for some components in Table 4.2 as these were not required.

![Diagram](image)

**FIG. 4.2 - Typical distribution network**

From this analysis, 20 failure events up to third order were deduced for busbar 2, 133 failure events for busbar 5 and busbar 8 and 217 failure events for busbar 6, busbar 7 and busbar 9, that is, a total of 937 events.

Clearly it is not possible to specify all these in detail but a summary of the type and order of cut is shown in Table 4.3.
TABLE 4.3 - Summary of failure events

<table>
<thead>
<tr>
<th>busbar number</th>
<th>no. of paths</th>
<th>failure events of order 1, 2 and 3</th>
<th>overlapping outages</th>
<th>active failures</th>
<th>active plus stuck breaker</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 2 3 total</td>
<td>1 2 3 total</td>
<td>1 2 3 total</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>5 - - 5 5 - - 5 10 - - 10</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5, 8</td>
<td>5</td>
<td>6 12 36 54 6 18 31 12 9 27 48 133</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6, 7, 9</td>
<td>5</td>
<td>6 - 84 90 8 - 42 50 14 - 63 77 217</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>system</td>
<td>-</td>
<td>10 18 135 165 18 - 18 18 3 33 54 235</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To illustrate the type of failure events and reliability indices obtained from this part of the analysis, consider the first and second order failure events associated with busbar 5. Details of these events are shown in Table 4.4; the overall indices given for this busbar are those for the first and second order events only and also those including the third order events. These overall indices will also apply to busbar 8.

TABLE 4.4 - Reliability indices associated with busbar 5

<table>
<thead>
<tr>
<th>failure event</th>
<th>forced outages</th>
<th>maintenance overlapping forced outages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f/yr</td>
<td>hr</td>
</tr>
<tr>
<td>1</td>
<td>.24000E(-01)</td>
<td>3.0000</td>
</tr>
<tr>
<td>2</td>
<td>.24000E(-01)</td>
<td>3.0000</td>
</tr>
<tr>
<td>3</td>
<td>.23000E(+00)</td>
<td>15.0000</td>
</tr>
<tr>
<td>4</td>
<td>.10000E(+00)</td>
<td>24.0000</td>
</tr>
<tr>
<td>5</td>
<td>.24000E(-01)</td>
<td>3.0000</td>
</tr>
<tr>
<td>10</td>
<td>.23000E(+00)</td>
<td>15.0000</td>
</tr>
<tr>
<td>subtotal</td>
<td>.63200E(+00)</td>
<td>15.0570</td>
</tr>
<tr>
<td>failure event</td>
<td>forced outages</td>
<td>maintenance overlapping forced outages</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td></td>
<td>$f/yr$</td>
<td>$hr$</td>
</tr>
<tr>
<td>6, 14</td>
<td>$14493E(-04)$</td>
<td>2.6087</td>
</tr>
<tr>
<td>6, 15</td>
<td>$13781E(-03)$</td>
<td>2.9821</td>
</tr>
<tr>
<td>6, 16</td>
<td>$14493E(-04)$</td>
<td>2.6087</td>
</tr>
<tr>
<td>14, 29</td>
<td>$24155E(-03)$</td>
<td>10.0000</td>
</tr>
<tr>
<td>14, 30</td>
<td>$94521E(-04)$</td>
<td>6.6667</td>
</tr>
<tr>
<td>14, 31</td>
<td>$24155E(-03)$</td>
<td>10.0000</td>
</tr>
<tr>
<td>15, 29</td>
<td>$13653E(-02)$</td>
<td>19.2310</td>
</tr>
<tr>
<td>15, 30</td>
<td>$69863E(-03)$</td>
<td>9.8039</td>
</tr>
<tr>
<td>15, 31</td>
<td>$13653E(-02)$</td>
<td>19.2310</td>
</tr>
<tr>
<td>16, 29</td>
<td>$24155E(-03)$</td>
<td>10.0000</td>
</tr>
<tr>
<td>16, 30</td>
<td>$94521E(-04)$</td>
<td>6.6667</td>
</tr>
<tr>
<td>16, 31</td>
<td>$24155E(-03)$</td>
<td>10.0000</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$47513E(-02)$</td>
<td>14.8950</td>
</tr>
<tr>
<td>11</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>14</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>16</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>17</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>20</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>23</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>29</td>
<td>$10000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$70000E(+00)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>12, 14</td>
<td>$55137E(-04)$</td>
<td>0.95238</td>
</tr>
<tr>
<td>12, 15</td>
<td>$57192E(-03)$</td>
<td>0.99800</td>
</tr>
<tr>
<td>12, 16</td>
<td>$55137E(-04)$</td>
<td>0.95238</td>
</tr>
<tr>
<td>12, 15</td>
<td>$57192E(-03)$</td>
<td>0.99800</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>$13644E(-02)$</td>
<td>0.99063</td>
</tr>
<tr>
<td>12, (11)</td>
<td>$50000E(-03)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>13, (11)</td>
<td>$50000E(-03)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>12, (14)</td>
<td>$50000E(-03)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>15, (16)</td>
<td>$50000E(-03)$</td>
<td>1.0000</td>
</tr>
<tr>
<td>failure event</td>
<td>forced outages</td>
<td>maintenance overlapping forced outages</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td></td>
<td>f/yr</td>
<td>hr</td>
</tr>
<tr>
<td>18, (17)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>19, (17)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>21, (20)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>22, (20)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>24, (23)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>25, (23)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>30, (29)</td>
<td>60000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>31, (29)</td>
<td>50000E(-03)</td>
<td>1.0000</td>
</tr>
<tr>
<td>Subtotal</td>
<td>61000E(-02)</td>
<td>1.0000</td>
</tr>
<tr>
<td>18, 14(19)</td>
<td>27568E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>18, 15(19)</td>
<td>28596E(-05)</td>
<td>0.99800</td>
</tr>
<tr>
<td>18, 16(19)</td>
<td>27568E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>32, 14(34)</td>
<td>27568E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>32, 15(34)</td>
<td>28596E(-05)</td>
<td>0.99800</td>
</tr>
<tr>
<td>32, 16(34)</td>
<td>27568E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>32, 14(34)</td>
<td>33082E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>32, 15(34)</td>
<td>34315E(-05)</td>
<td>0.99800</td>
</tr>
<tr>
<td>32, 16(34)</td>
<td>33082E(-06)</td>
<td>0.95238</td>
</tr>
<tr>
<td>Subtotal</td>
<td>10915E(-04)</td>
<td>0.99064</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total for 1st or 2nd order</th>
<th>f/yr</th>
<th>hr</th>
<th>hr/yr</th>
<th>o/yr</th>
<th>hr</th>
<th>hr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3442</td>
<td>7.6581</td>
<td>10.294</td>
<td>.37165E(-02)</td>
<td>8.3666</td>
<td>.31094E(-01)</td>
<td></td>
</tr>
</tbody>
</table>

Total for 1st, 2nd, 3rd order

1.3443 7.6582 10.295 .37268E(-02) 8.3632 .31168E(-01)

A similar set of results to those shown in Table 4.4 can be obtained for each busbar in the system. The overall reliability indices for each busbar are
shown in Table 4.5.

<table>
<thead>
<tr>
<th>busbar</th>
<th>type of failure</th>
<th>outage rate o/yr</th>
<th>outage duration hr</th>
<th>annual outage time, hr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>a</td>
<td>1.1130</td>
<td>8.9389</td>
<td>9.9490</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.1130</td>
<td>8.9389</td>
<td>9.9490</td>
</tr>
<tr>
<td>5,8</td>
<td>a</td>
<td>1.3443</td>
<td>7.6582</td>
<td>10.2950</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>0.0037</td>
<td>8.3632</td>
<td>0.0312</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.3480</td>
<td>7.6601</td>
<td>10.3262</td>
</tr>
<tr>
<td>6,7,9</td>
<td>a</td>
<td>1.4393</td>
<td>7.1730</td>
<td>10.3240</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>1.5921x10^-5</td>
<td>6.6809</td>
<td>1.0636x10^-4</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.4393</td>
<td>7.1730</td>
<td>10.3241</td>
</tr>
</tbody>
</table>

where: a - overlapping forced outages  
       b - maintenance outage overlapping forced outages

From the results shown in Table 4.4 it is evident, at least in this example, that the lower order events dominate over higher order ones. This is made clear by the overall indices which indicate that the third order events contribute very little to the overall values. Several other interesting features can be observed from the results in Table 4.4.

The failure rate due to first order active failures (0.7 f/yr) is greater than the failure rate due to first order total failures (0.632 f/yr). This stresses the importance of studying the impact of active failures on healthy components in the system. On the other hand, the average duration of these active failures (1 hr) is significantly less than that of the total failures (15.057 hr) because the former is associated with switching actions.
and the latter with repair or replacement actions. It is evident therefore that the two types of failure events should be categorised separately otherwise an average outage duration not applicable to either would be obtained.

It can be seen from Table 4.4 that the failure rate due to an active failure plus a stuck breaker \((0.61 \times 10^{-2} \text{ f/yr})\) is greater than that for two overlapping forced outages \((0.48 \times 10^{-2} \text{ f/yr})\).

Considering the results shown in Table 4.5 it is evident that the total outage rates of busbars 5-9 are greater than that of busbar 2 due to the increased number of possible failure events. This could reasonably be expected. The average outage duration of busbars 5-9 are however less than that of busbar 2. This is due to an increased number of events having a relatively small duration; the weighted average is then less than that of busbar 2.

A more surprising observation from Table 4.5 is that the annual outage time due to overlapping forced outages of busbars 6, 7, 9 is greater than that of busbars 5, 8 although there are more feeders (increased reliability?) to these three busbars. This is due to the increased number of components and therefore increased number of active failures to these busbars. Although the average duration decreases due to a larger number of small duration events, this decrease is outweighed by the increased number of failures. It cannot be concluded therefore that an increased number of feeders automatically increases the reliability; it also depends on the number of associated failure events.

These aspects, together with many other observations that can be made from these Tables, are clearly related to the assumed data. However it is readily evident that it is necessary to include all appropriate and realistic failure modes in the analysis and to deduce the breakdown of the constituent events in order to ensure a reasonable appraisal of the reliability behaviour of the system.
4.7.2 - System Analysis

Using the algorithm described in section 4.5 it can be shown that of the 937 total first, second and third order failure events associated with the 6 busbars, only 235 events are independent system events. A summary of these events is also shown in Table 4.3. From this Table it can be seen that although there are a significant number of second and third order active failure events associated with the busbars, there are no such events associated with the system. This is due to these events already being included in other failure events. For example, the failure event of breaker 19 actively failed with breaker 14 out associated with busbar 5 is not an independent event because the active failure of component 19 as a first order event causes failure of busbar 6.

Details of the various first order system failure events are shown in Table 4.6.

**TABLE 4.6 - First order system failure events**

<table>
<thead>
<tr>
<th>forced outages</th>
<th>active failures</th>
<th>active failures plus stuck breaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>12(11)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>24(25)</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>12(13)</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>27(26)</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>15(14)</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>27(28)</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>15(16)</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>30(29)</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>18(17)</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>30(31)</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>18(19)</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>33(32)</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>21(20)</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>33(34)</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>21(22)</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>36(35)</td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>24(23)</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>36(37)</td>
</tr>
</tbody>
</table>

Combining the indices for the events shown in Table 4.6 and those for the appropriate second and third order events gives the following
system reliability indices:

expected failure rates = 2.5528 f/yr
average outage duration = 4.6286 hr
average annual outage time = 11.816 hr/yr

Once again it is seen that the failure rate is greater than that of any one busbar due to the increased number of failures but the average outage duration has decreased due to an increased number of short duration outages.

4.8 - Conclusions

The inclusion of switching actions in reliability analyses of electrical systems is a vital and important feature. It necessarily imposes a three state model of the system; the state before a fault, the state after a fault but before switching and the state after switching. The second state has a small average annual outage time because its residence time is dependent on switching times although its rate of occurrence can be very large. If this state could be neglected the reliability analysis is much simpler but can only be done with the following assumptions.

- the components switching times are negligible compared with the component average outage time and
- the rate of occurrence of a down state is not required

Generally these assumptions are not valid particularly because the rate of occurrence of a down state is an important reliability indice. The inclusion of this state as described in this chapter is therefore considered necessary.

A new approach has been presented for incorporating in the reliability analysis of electrical systems the effects of switching actions following active failures.
system reliability indices:

\[
\text{expected failure rates} = 2.5528 \text{ f/yr} \\
\text{average outage duration} = 4.6286 \text{ hr} \\
\text{average annual outage time} = 11.816 \text{ hr/yr}
\]

Once again it is seen that the failure rate is greater than that of any one busbar due to the increased number of failures but the average outage duration has decreased due to an increased number of short duration outages.

4.8 - Conclusions

The inclusion of switching actions in reliability analyses of electrical systems is a vital and important feature. It necessarily imposes a three state model of the system; the state before a fault, the state after a fault but before switching and the state after switching. The second state has a small average annual outage time because its residence time is dependent on switching times although its rate of occurrence can be very large. If this state could be neglected the reliability analysis is much simpler but can only be done with the following assumptions.

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Generally these assumptions are not valid particularly because the rate of occurrence of a down state is an important reliability indice. The inclusion of this state as described in this chapter is therefore considered necessary.

A new approach has been presented for incorporating in the reliability analysis of electrical systems the effects of switching actions following active failures.
The predicted reliability indices of an electrical system in its design stage is an important feature for comparing objectively different alternative designs. The concept of overall system reliability indices facilitates these comparisons particularly when the system has many load points.
FAILURES AFTER CLOSING A NORMALLY OPEN PATH.

OVERALL SYSTEM INDICES AND INTERCONNECTED NETWORKS

5.1 - Introduction

In this chapter it is shown how the reliability of one network is affected by the interconnections to other networks; A method is described to calculate "equivalent sources" that are considered as feeding the network under consideration and represent the impact of the interconnections to other networks.

The concept of overall system indices was first introduced in chapter II and described in detail in chapter IV. In this chapter another version of the algorithm already described is presented and its usefulness is shown; It assumes that different busbars can have different impact in the system objective which is realistic in many systems.

The normally open paths have always \((9), (10), (27)\) been assumed not to fail during their required operating time. This assumption may not be acceptable in cases where the normally open paths are required to operate for a long time due to the repair time of the faulty component that caused the normally open path to be closed. A technique based on a conditional probability approach has been developed to eliminate this assumption.

The three concepts introduced in this chapter are completely original and efficient techniques were developed to implement them on a computer program. These techniques have been highly tested and their application to complex systems is shown in chapter VII and IX.

When considering a general form for the algorithm to deduce the overall system indices it was realized that a system can have several interconnected networks, each with a single objective. Therefore the need
to analyse complex systems with multiple objectives subdividing them into subsystems was evident. However in the practical systems analysed most of the interconnectors were normally open branches and the need to model them realistically led to the development of a technique to eliminate the assumption which considers that the normally open paths do not fail when in operation.

5.2  - Failure After Closing a Normally Open Path

One of the four kinds of cut sets referred to in chapter IV was that a busbar failure occurs when the components of the cut sets are out of service but the service can be restored by a switching action involving closing a normally open path. It was assumed that the normally open paths do not fail during the service restoration time of the failed normally closed paths. This may not be true particularly when the repair times of the components in such a cut set are large. Furthermore it was assumed that the stuck breaker probability of the normally open breakers was zero. The technique described in this section is a method that eliminates these restrictive assumptions.

Define the following two events, A & B:

Event A = failure event that can be eliminated closing any of the normally open paths k, j, l ...m.

Event B = event defined as "at least one of the normally open paths k, j, l, ...m does not fail before restoring to service one component of the failure event A".

The following equation can be written:

\[ P(A) = P(A|B) \times P(B) + P(A|\bar{B}) \times P(\bar{B}) \]

\[ P(A|B) \] is the probability of event A assuming that at least one of the normally open paths is always available and \[ P(A|\bar{B}) \] is the probability of event A assuming that none of them is available to restore the service
by closing a normally open path. For each of the events $A \mid B$ and $A \mid \overline{B}$ the contribution to the average failure rate, the average outage duration and the total outage time per year due to forced outages ($\lambda$, $r$, $U$) and forced outages overlapping a maintenance outage ($\lambda'$, $r'$, $U'$) are evaluated.

The appropriate indices are:

$$A \mid B \rightarrow \lambda_1 \& \lambda'_1, r_1 \& r'_1, U_1 \& U'_1$$

$$A \mid \overline{B} \rightarrow \lambda_2 \& \lambda'_2, r_2 \& r'_2, U_2 \& U'_2$$

(note that $\lambda_1 = \lambda_2$ and $\lambda'_1 = \lambda'_2$)

To calculate the same indices for the event represented by $\overline{B}$ the minimal cut sets of the paths $k$, $j$, $l$ ... $m$ are evaluated. From these cuts those that are also load point minimal cut sets are eliminated. These minimal cut sets are evaluated up to second order if event $A$ is of first order, up to first order if event $A$ is of second order and are not evaluated if event $A$ is of third order.

From the remaining minimal cut sets the reliability indices of the "element" equivalent to the normally open paths are evaluated. These being $\lambda'_e \& \lambda''_e, r'_e \& r''_e, U'_e \& U''_e$. The normally open breakers which are first order cut sets of the minimal paths $k$, $j$, $l$ ... $m$ are considered "in series" in order to evaluate the stuck probability ($P_s$) of this equivalent "element".

Noting that the average annual outage time of event $A$, when expressed in years/year, represents $P(A)$ the following equations are obtained:

$$U_A = U_1 \times \left[1 - (U'_e + P_s)\right] + U_2 \times (U'_e + P_s)$$

$$U''_A = U''_1 \times \left[1 - U''_e\right] + U''_2 \times U''_e$$

The following equations can also be obtained:

$$\lambda_A = \lambda_2 \left(1 + \lambda'_e r_2\right)$$
\[ \lambda_A'' = \lambda_2'' (1 + \lambda_e'' r_2'' \) \\
\]

\[ r_A = \frac{u_A}{\lambda_A'} = \frac{u_A''}{\lambda_A''} \]

This technique is applied to every cut set that may be eliminated by closing a normally open breaker. The increase in associated computing time is a function of the number of normally open paths available to eliminate the cut set under consideration. It is also, as expected, a function of the number of cut sets that may be eliminated by closing a normally open path. It is worth noting that by closing a single normally open breaker more than one normally open path may be closed.

5.3 - Application Example

Consider the simple system shown in fig. 5.1 and the data given in Table 5.1

![Diagram of simple electrical system](image)

**FIG. 5.1 - Simple electrical system**

- normally open breaker
- busbar number

**TABLE 5.1 - Data for the system shown if Fig. 5.1**

<table>
<thead>
<tr>
<th></th>
<th>Total failure rate (f/yr)</th>
<th>Active failure rate (f/yr)</th>
<th>Repair time (hr)</th>
<th>Switching time (hr)</th>
<th>Stuck Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Busbars</strong></td>
<td>0.005</td>
<td>0.005</td>
<td>10.0</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td><strong>Breakers</strong></td>
<td>0.020</td>
<td>0.015</td>
<td>20.0</td>
<td>1.0</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Transformers</strong></td>
<td>0.020</td>
<td>0.015</td>
<td>800.0</td>
<td>1.0</td>
<td>-</td>
</tr>
</tbody>
</table>
This example is used to exemplify the application of the technique described in section 5.2 and to show the impact of the failures in the normally open paths on the reliability indices of the busbars.

Consider in particular the reliability analysis for busbar no. 4. There are 10 possible failure events for this busbar:

Component 4 failed
Components 1, 2 or 3 failed (service can be restored closing a normally open path)
Components 5 or 9 actively failed
Components 6 or 7 actively failed and 5 stuck
Components 10 or 11 actively failed and 9 stuck

Consider now the failure of breaker 1 and the subsequent restoration of supply to busbar 4 (a similar analysis exists for failures of transformer 2 and breaker 3). From table 5.1 the failure rate of this event is 0.02 f/yr and the outage time if a normally open path was not available (event $A | \overline{B}$) would be 20 hours.

Therefore:

$$\lambda_2 = 0.02 \text{ f/yr}, \quad r_2 = 20.0 \text{ hr}, \quad U_2 = 0.4 \text{ hr/yr}$$

If however at least one normally open path is available (event $A | B$) then the failure rate remains unchanged but the outage time becomes the switching time for restoring the supply.

Therefore:

$$\lambda_1 = 0.02 \text{ f/yr}, \quad r_1 = 1.0 \text{ hr}, \quad U_1 = 0.02 \text{ hr/yr}$$

The minimal cut sets of the unique normally open path to busbar 4 (there could be more than one path) are the outages of components 12, 13, 14, 15 and 16. Combining the reliability indices of these five first order minimal cut gives the reliability indices for the equivalent indices discussed in section 5.2.

Therefore:

$$\lambda_e = 0.08500 \text{ out/yr}, \quad r_e = 0.02317 \text{ years}, \quad U_e = 0.0020 \text{ yr/yr}$$
\[
\lambda''_e = 0.0 \text{ out/yr}, \ r''_e = 0.0 \text{ years}, \ U''_e = 0.0 \text{ yr/yr}
\]

\[
P_e = 0.001
\]

The reliability indices of the cut considering the possible failure of the normally open path are:

\[
\lambda_A = 0.02 \left( 1 + 0.085 \times \frac{20.0}{8760.0} \right) = 0.020004 \text{ f/yr}
\]

\[
U_A = 0.02 \left[ 1 - (0.002 + 0.001) \right] + 0.4 \times (0.002 + 0.001) = 0.02112 \text{ hr/yr}
\]

\[
r_A = \frac{U_A}{\lambda_A} = 1.056 \text{ hr}
\]

The failures of transformer 2 and breaker 3 cause loss of supply to busbar 4 but service can also be restored closing breaker 12 and so the corresponding reliability indices are obtained as exemplified previously. The reliability indices of all other failure events are obtained using the equations given in appendix 2. Combining "in series" the indices of all failure events the reliability indices of busbar 4 are obtained. Table 5.2 gives the busbar reliability indices for the system considered in fig. 5.2

**TABLE 5.2 - Reliability indices for the system shown in fig. 5.1**

<table>
<thead>
<tr>
<th>Busbar no.</th>
<th>Failure rate (outages/year) (a)</th>
<th>Average outage duration (hours) (a)</th>
<th>Average annual outage time (hr/year) (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.09506</td>
<td>1.4734</td>
<td>0.14006</td>
</tr>
<tr>
<td>8</td>
<td>0.13028</td>
<td>1.9364</td>
<td>0.25226</td>
</tr>
<tr>
<td>16</td>
<td>0.08003</td>
<td>1.5623</td>
<td>0.12503</td>
</tr>
<tr>
<td>20</td>
<td>0.13000</td>
<td>1.30.46</td>
<td>16.960</td>
</tr>
</tbody>
</table>

(a) Assuming that the n/O paths do not fail when required to operate

(b) Assuming that the n/O paths may fail when required to operate
The incorporation of the failure of the normally open paths increases the computing time (on a CDC 7600) for this example from 0.149 sec to 0.197 sec. The need for the application of this technique depends on the accuracy required for the results. Although no general conclusions can be made from this simple example, it is evident that the errors contained in the first set of indices, (a), may not be acceptable for some practical applications. In complex systems the introduction of the technique described in this section increases the computing time by approximately a factor of 3; This suggests that in practical applications it should be incorporated only when it is required.

5.4 - The Overall System Indices

The algorithm described in chapter IV to calculate the overall system indices after evaluating the reliability indices of each system load point made the following assumptions:

a) the dependence between minimal cut sets can be neglected; This being widely accepted in systems having components with a low probability of failure

b) the system load points were grouped into two categories; those having no impact on the system performance and those that, when lost, cause a system failure.

The previous algorithm was extended so that a more realistic definition of system failure can be considered. The logic of the original algorithm is much easier to understand and any reader requiring the application of the present algorithm should first understand its predecessor.

Every load point is assumed to have, when lost, a numerically defined impact on the system performance; this being expressed as a percentage of the system objective. If the system objective is not met at all when a load point fails, that load point is defined as having a 100% impact, if the system objective is only partially met, the load point is defined as
having \( x \% \) impact \((0 \leq x \leq 100\% \)) and if the system objective is met totally, the load point is defined as causing a \( 0\% \) loss of the system objective. In this way every load point in the system can be graded in terms of its importance in the system. The numerical definition of this importance may mean loss of revenue, loss of power supplied, number of consumers not supplied, etc.

The consequences of losing simultaneously two load points, each graded \( x\% \), must also be known since, when suffering an overlapping outage, the combined impact may not be equal to either of the individual impacts. The present algorithm assumes that the simultaneous loss of more than two load points, each causing an \( x\% \) loss of the system objective, is a catastrophic failure of the system, i.e. it causes a \( 100\% \) loss of the system objective.

The algorithm is described in detail in the next section. It can be easily programmed provided all the independent failure events for all load points have been identified and stored.

5.4.1 - The Algorithm (Algorithm 2)

Assumptions

The loss of any busbar causes one of the following consequences:

a) \( 100\% \) reduction of the system objective
b) \( x\% \) \((0 \leq x \leq 100\%) \) reduction of the system objective
c) no reduction of the system objective

The loss of more than two busbars from those defined by b) causes \( 100\% \) reduction of the system objective.

The loss of any combination of two busbars from those defined by b) causes a known loss of the system objective.

Identifying a Minimal Cut Set

Each cut set is defined by a set of six values as follows:
where:  \( x \) defines the type of cut
\( N \) defines the busbar to which the cut is attached
\( a, b, c \) are the components of the cut and \( b \) and/or \( c \)
may be zero
\( R \) is the reduction of the system objective due to the cut

The value of \( x \) may be:
- \(-1\): a cut for which every component is out and service is restored
  by a repair action
- \(-2\): a cut for which every component is out but service may be
  restored by closing a normally open breaker
- \(-3\): a cut for which component \( a \) is actively failed and all other
  components are out. Service is restored by isolating component \( a \)
- \( k \): a cut as defined by \(-3\) but one in which breaker \( k \) is stuck

Algorithm
Consider the two minimal cuts:

\[
i = \begin{array}{cccccc}
x_i & N_i & a_i & b_i & c_i & R_i \\
\end{array}
\]
\[
 j = \begin{array}{cccccc}
x_j & N_j & a_j & b_j & c_j & R_j \\
\end{array}
\]

Let \( I \) and \( J \) be a set of three numbers defined as:
\[
I = \{a_i, b_i, c_i\} \quad J = \{a_j, b_j, c_j\}
\]
\( n_i = \) number of non-zero elements of \( I \)
\( n_j = \) number of non-zero elements of \( J \)
\( n_m = \) minimum of \( n_i \) and \( n_j \)

Define the set \( A = I \cap J \) and let \( n_a \) be the number of non-zero element
of \( A \), then \( n_a \leq n_m \).

Let \( R(N_i) \) and \( R(N_j) \) be the output power lost when busbars \( N_i \) and \( N_j \)
are lost respectively.
Let \( l = 1 \) when \( 0 < R(N_i) < 100 \) and \( 0 < R(N_j) < 100 \) and in this case let \( R(N_i, N_j) \) represent the loss of the system objective when both busbars \( N_i \) and \( N_j \) are lost. Otherwise let \( l = 0 \).

The algorithm then proceeds as follows:

(i) if \( R(N_i) = 0 \) neglect \( i \) and if \( R_j = 0 \) set \( R_j = R(N_j) \)

(ii) if \( R(N_j) = 0 \) neglect \( j \) and if \( R_i = 0 \) set \( R_i = R(N_i) \)

(iii) if \( n_a < n_m \) the cuts are independent. The values of \( R_i \) and \( R_j \) are as in (i)

If \( N_i \neq N_j \) and \( n_a = n_m \) the algorithm proceeds as follows:

(iv) \( x_i = x_j = x \)

a) \( x = -1 \) or \( -2 \) and \( n_i = n_j \)

Reject the cut associated with the busbar causing minimum power loss, i.e. if \( R(N_i) < R(N_j) \) reject cut \( i \)

If \( l = 0 \) set \( R_j = -100 \) if \( i \) is rejected and set \( R_i = -100 \) if \( j \) is rejected

If \( l = 1 \) and \( j \) has been rejected then, if \( R_i \) or \( R_j < 0 \) set \( R_i = -100 \)

but if \( R_i \) and \( R_j \) \( 0 \) set \( R_i = -R(N_i, N_j) \). Similarly if \( i \) has been rejected the value of \( R_j \) is suitable set.

b) \( x = -1 \) or \( -2 \) and \( n_i \neq n_j \)

Reject the cut associated with the busbar causing minimum annual loss of the system objective (product of impact of the busbar in the loss of the system objective and average annual outage time).

If \( l = 0 \) or \( l = 1 \) use appropriate conditional statement in a) above

c) \( x \neq -1 \) or \( -2 \)

If \( a_i = a_j \) and \( n_i = n_j \) : as in case a).

If \( a_i = a_j \) and \( n_i \neq n_j \) : as in case b)

If \( a_i \neq a_j \) then the cuts are considered independent.
The values of \( R_i \) and \( R_j \) are set as in (i) above.

(v) \( x_i \neq x_j \)

a) if \( n_i \neq n_j \) then the cuts are considered independent and the values of \( R_i \) and \( R_j \) are set as in (i) above.

b) if \( n_i = n_j \), a decision is taken according to the following table

<table>
<thead>
<tr>
<th>( x_i )</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
<th>( k_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>i</td>
<td>i</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td>j</td>
<td>i</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>j</td>
<td>j</td>
<td>i</td>
<td></td>
</tr>
<tr>
<td>( k_j )</td>
<td>j</td>
<td>j</td>
<td>j</td>
<td>(X)</td>
</tr>
</tbody>
</table>

If \( l = 0 \), the cut indicated in the table is eliminated and the reduction of the system objective associated with the remaining cut is set to 100% but if the reduction of the system objective of the remaining cut is \( x \% \), proceed as for \( l = 1 \). If \( l = 1 \) (in the following assume that cut \( j \) is indicated, a similar reasoning exists if it is cut \( i \)), then \( R_i \) is set to -100 if previously either \( R_i \) or \( R_j \) is negative, \( R_i \) is set to \(-R(N_i, N_j)\) if previously \( R_i \) and \( R_j \) are not negative.

\( R_j \) is set to -100 if its previous value is negative.

\( R_j \) is set to \( R(N_j) \) if its previous value is not negative.

The average annual outage time of cut \( j \) is decreased by the average annual outage time of cut \( i \).

(X) - in this case the cuts are considered independent and the values of \( R_i \) and \( R_j \) are set as in (i) above.

(vi) Scan all the cuts not rejected in the above logic and make \( R_i = \mid R_i \). Combine all the cuts that lead to the same reduction of the system objective.
5.5 - Application Example

Consider the very simple example shown in fig. 5.2. This example is used to show how the system minimal cuts can be obtained from the load point minimal cuts. Having deduced the system minimal cut sets the overall reliability indices are calculated by combining the indices of the cuts leading to the same reduction of the system objective.

![Diagram](image)

**FIG. 5.2** - Simple example for deducing the system minimal cuts

- ✗ normally open component
- ● load point

It is assumed that the loss of busbars 4 or 8 causes 100% reduction of the system objective and the loss of busbar 13 causes 60% reduction of the same overall objective.

Table 5.3 gives the failure events associated with every busbar. These failure events are identified according to the method considered in section 4.4. The letters P, A and S after a component number mean failed, actively failed and stuck, respectively.
TABLE 5.3 - Failure events for the busbars of the system shown in fig. 5.2

<table>
<thead>
<tr>
<th>Busbar no.</th>
<th>Failure events</th>
<th>Type</th>
<th>Busbar no.</th>
<th>Components</th>
<th>Impact</th>
<th>Cut number</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1F (a)</td>
<td>-2</td>
<td>4</td>
<td>1 0 0</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2F (a)</td>
<td>-2</td>
<td>4</td>
<td>2 0 0</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3F (a)</td>
<td>-2</td>
<td>4</td>
<td>3 0 0</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4F</td>
<td>-1</td>
<td>4</td>
<td>4 0 0</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10A</td>
<td>-3</td>
<td>4</td>
<td>10 0 0</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>11A, 10S</td>
<td>10</td>
<td>4</td>
<td>11 0 0</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>12A, 10S</td>
<td>10</td>
<td>4</td>
<td>12 0 0</td>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>5F (a)</td>
<td>-2</td>
<td>8</td>
<td>5 0 0</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6F (a)</td>
<td>-2</td>
<td>8</td>
<td>6 0 0</td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>7F (a)</td>
<td>-2</td>
<td>8</td>
<td>7 0 0</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>8F</td>
<td>-1</td>
<td>8</td>
<td>8 0 0</td>
<td>100</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>1F (a)</td>
<td>-2</td>
<td>13</td>
<td>1 0 0</td>
<td>60</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2F (a)</td>
<td>-2</td>
<td>13</td>
<td>2 0 0</td>
<td>60</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>3F (a)</td>
<td>-2</td>
<td>13</td>
<td>3 0 0</td>
<td>60</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>4F</td>
<td>-1</td>
<td>13</td>
<td>4 0 0</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>10F</td>
<td>-1</td>
<td>13</td>
<td>10 0 0</td>
<td>60</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>11F</td>
<td>-1</td>
<td>13</td>
<td>11 0 0</td>
<td>60</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>12F</td>
<td>-1</td>
<td>13</td>
<td>12 0 0</td>
<td>60</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>13F</td>
<td>-1</td>
<td>13</td>
<td>13 0 0</td>
<td>60</td>
<td>19</td>
</tr>
</tbody>
</table>

(a) Failure events eliminated closing a normally open path

When calculating the reliability indices of each busbar, 19 failures events were deduced: 7 for busbar 4, 4 for busbar 8 and 8 for busbar 13. These failure events are stored in the form shown in Table 5.3. It is evident that not all of these failure events are independent and therefore...
the system independent failure events must be deduced.

The application of the algorithm given in section 5.4.1 starts by comparing cut number 8 with cuts 1-7. The first seven cuts are independent since they are failure events associated with the same busbar. It can be easily seen that cut 8 is not included in any of the cuts 1-7. Similarly for cuts 9, 10 and 11 (confirmed by the algorithm).

Cuts 12-19 are then compared with the non eliminated cuts (in this example all of them) 1-11. It can be seen that cuts 12, 13, 14 and 15 are the same as cuts 1, 2, 3 and 4; This means that the same failure events cause the loss of two busbars (4 and 13). In this example cuts 12, 13, 14 and 15 are eliminated since they only cause 60% reduction of the system objective and cuts 1, 2, 3 and 4 cause 100% (the algorithm does this).

Consider now in more detail the comparison of cut 16 with cuts 1-11. It is seen that there is a strong relationship between cuts 5 and 16. These are as follows:

| cut 5 | -3 4 10 0 0 100 |
| cut 16 | -1 13 10 0 0 60 |

When component 10 is failed (passively or actively) the continuity of supply is lost to busbar 13. The outage time of this event is the repair time of component 10. However, busbar 4 is only lost when component 10 is actively failed and the outage time of this event is the isolating time of component 10. During the overlapping time of the two events both busbars are lost and the reduction of the overall objective is due to the combination of the impacts of each busbar (100% in this case); After isolating component 10 only busbar 13 is lost. In this case, following the algorithm, both cuts are retained but their indices are modified. Consider $u_5$ (switching time of component 10) and $u_{16}$ (repair time of component 10) the annual outage times of cuts 5 and 16, respectively. Assume that $R_5$ and $R_{16}$ are the
reduction of the overall objective associated to each of the cuts. According to the algorithm $R_5$ becomes the reduction of the overall objective due to the loss of busbars 5 and 16 simultaneously (100% in the example) and $U_5$ is kept unchanged. $R_{16}$ is the reduction of the overall objective due to the loss of busbar 16 alone (60% in the example) and the annual outage time of cut 16 is reduced by $U_5$. This logic avoids duplication of outage times, associated with a same failure, in the overall system indices.

A similar procedure is valid for cuts 17 and 18. Cut 19 is then compared with cuts 1-11 and because it is independent of all of them it is retained as a system independent failure event.

After this analysis the number of system minimal cuts was reduced from 19 to 15 and three of the remaining cuts have their reliability indices modified. This is a very simple example and was intended to show the philosophy of the algorithm rather than its complexity; In the example only first order cut sets and only one busbar causing $x\%$ reduction of the system objective were considered. Chapter VI contains applications of this algorithm to practical systems for which more complex analysis is required.

5.6 - Interconnected Networks

The application of the techniques described in this section may be required due to two reasons:

a) The system to be analysed may have some interconnections to other systems and the impact of these interconnections in the system reliability is required. Furthermore once this impact is known all kinds of reliability studies can be made without having to consider all the systems, because each of the systems is considered independent of the others.

b) The system to be analysed may not have a single overall objective
and so the techniques described in section 5.4 are not applicable. However in many systems with multiple objectives it is possible to divide them into subsystems, each with a single objective. The overall subsystem reliability indices can be deduced if each subsystem is considered isolated of the others and this achieved using the techniques described in this section.

The description of the techniques developed is made using the terminology considered in b), i.e. system and subsystems linked through interconnectors, but is equally valid for a) simply by changing "system" into "set of systems" and "subsystem" into "system".

![Diagram](image)

**FIG. 5.3** - Example of how a complex system can be subdivided

![Diagram](image)

**FIG. 5.4** - Subsystem 1 shown isolated of the overall system

Fig. 5.3 is a schematic representation of how a complex system can be subdivided into subsystems. The subsystems may be connected via normally
open or normally closed links.

The subsystems are analysed one at a time with the interconnectors replaced by "equivalent sources" (see fig. 5.4). Having calculated these "equivalent sources", the analysis is carried out as if a subsystem was isolated from all others and so all the techniques developed so far can be applied.

The "equivalent sources" discussed above are not 100% reliable and their unreliability has to be evaluated. Several methods were studied to deduce the reliability indices of these sources and two of them led to results that were absolutely precise. The method described below is the one implemented and recommended because it is computationally more efficient. It may be best described by the following steps:

a) The input data is prepared so that the overall system is presented to the main program as a single system. The components are renumbered internally but the equivalence between the new numbers and the original ones is maintained.

b) In this overall system the busbars directly connected to interconnectors are identified and these busbars are considered as output nodes.

c) The reliability indices of the output nodes deduced in (b) are evaluated and stored. These becomes the "equivalent sources" of the relevant subsystem

d) The new component numbers are translated back to their original numbers and the analysis of each subsystem is commenced.

e) The interconnectors connected to a subsystem are assumed to be unidirectional subsystem branches; their receiving ends being the busbars in the subsystem to which the interconnectors are connected, their components being those that were defined on input as the interconnector components and their sending ends being the "equivalent sources" having the reliability indices evaluated in (c) above, i.e. the indices of the busbars belonging to other subsystems but connected to the subsystem under analysis
through the interconnectors.

f) The reliability indices of each subsystem including the interconnectors and "equivalent sources" described in e) above are evaluated. In this analysis, if a simulated active failure breaks a path to an "equivalent source", this path is still considered as available since the effect was previously taken into account when evaluating the reliability indices in (c) above.

The validity of the above logic was verified by evaluating the reliability indices of every busbar twice; firstly by considering the overall system as a single system and secondly by using the above technique of subsystems. The reliability indices obtained by both methods were exactly the same.

The detailed description of the computer techniques used to implement the steps described is given in appendix 4. These are mainly transformations of the structure of several arrays coupled with a logic to transfer output data from one run to input data of sequential runs.

5.7 - Typical Application

The system shown in fig. 5.5 was considered to exemplify the application of the techniques described in section 5.6.

FIG. 5.5 - Example considered to show a typical interconnected electrical system
The data used in this analysis is the same as that of table 5.1. The system shown in fig. 5.5 is a set of two identical systems to that shown in fig. 5.1. These two identical systems were linked as shown in fig. 5.5 via normally open interconnectors.

After a data transformation (see appendix 4) the complete system is analysed and the output nodes automatically selected are busbars 16 and 8 in both subsystems.

The reliability indices of these busbars are given in table 5.4

<table>
<thead>
<tr>
<th></th>
<th>Failure rate (outages/year)</th>
<th>Average outage duration (hr)</th>
<th>Annual outage duration (hr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Busbar 8</td>
<td>0.13028</td>
<td>1.3467</td>
<td>0.17544</td>
</tr>
<tr>
<td>(b) Busbar 16</td>
<td>0.80030x10^-1</td>
<td>1.5623</td>
<td>0.12503</td>
</tr>
<tr>
<td>(c) Busbar 8</td>
<td>0.13028</td>
<td>1.3467</td>
<td>0.17544</td>
</tr>
<tr>
<td>(d) Busbar 16</td>
<td>0.80030x10^-1</td>
<td>1.5623</td>
<td>0.12503</td>
</tr>
</tbody>
</table>

The results shown in Table 5.4 are identical for both subsystems due to the symmetrical structure of the example under consideration.

Each subsystem is then analysed and the equivalent sources are defined from the reliability view point by the results shown in table 5.4. Fig. 5.6 shows subsystem 1 as it is considered after the evaluation of the reliability indices of the "equivalent sources".

The reliability data for the sources represented by components 21 and 24 (fig. 5.6) are the reliability indices (c) and (d) shown in Table 5.4.

The analysis of the system shown in fig. 5.6 gives the results shown in table 5.5.
FIG. 5.6 - Subsystem 1 as it is considered after the evaluation of the reliability indices of the "equivalent sources"

TABLE 5.5 - Results for the system shown in fig. 5.6

<table>
<thead>
<tr>
<th>Busbar no.</th>
<th>Failure rate (outages/year)</th>
<th>Average outage duration (hr)</th>
<th>Annual average duration (hr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$0.95108 \times 10^{-1}$</td>
<td>1.6577</td>
<td>0.15766</td>
</tr>
<tr>
<td>8</td>
<td>0.13028</td>
<td>1.3467</td>
<td>0.17544</td>
</tr>
<tr>
<td>16</td>
<td>$0.80030 \times 10^{-1}$</td>
<td>1.5623</td>
<td>0.12503</td>
</tr>
<tr>
<td>20</td>
<td>0.1300</td>
<td>130.46</td>
<td>16.960</td>
</tr>
</tbody>
</table>

It is obvious that the results obtained for busbar 8 and 16 must be the same when considering the overall system or when considering subsystem 1.

For this simple example the procedure seems to complicate the analysis but its usefulness will be more evident when systems similar to the ones considered in chapter VII are analysed.

Apart from the need to consider a complex system subdivided into subsystems it was realized that this technique led to considerable savings
in computing time. As an example, the system shown in fig. 5.5 when analysed completely takes .496 sec on a CDC 7600; The same system subdivided into two systems takes only .440 sec. The saving in time is small only because the system considered is very simple. This saving is due to the smaller number of active failures that are simulated.

5.6 -- Conclusions

This chapter introduced three novel concepts in the reliability analysis of power system networks. The computational techniques required to implement them in a computer program were described and simple examples were considered to show how they can be applied. Chapter VI contains practical applications of the techniques described in this chapter applied to the reliability analysis of the electrical auxiliary system of power stations and chapter IX. contains an example where these techniques are applied to transmission and distribution systems. However these techniques can be applied to most systems (electrical or non-electrical) that can be represented by an equivalent network.
VI

RELIABILITY EVALUATION OF THE AUXILIARY ELECTRICAL SYSTEMS
OF POWER STATIONS - SINGLE UNIT SYSTEM

6.1 - Introduction

There has been considerable interest in recent years to quantify the effect of generating capacity on the reliability and long term availability of power systems. The availability of the generating unit is a fundamental element in such an analysis. However it is well known that the generating unit availability has decreased as the unit rating has been increased; large units having unavailabilities as high as 20%. These high unavailabilities are due to a rapid increase in size that resulted in many prototype designs much larger than the previous ones including many untried features without the associated background of experience. Therefore a realistic quantitative appraisal of the reliability of the unit and the components of its subsystems is necessary in the design phase from which their impact on the output availability can be evaluated. One component contributing to this unavailability is the electrical auxiliary system and its design. Although this contribution is only one factor of the overall unavailability it is nevertheless one of the most difficult to assess due to the complexity of the system and the consequences of losing parts of it. The present studies have therefore been centred on assessing the impact of such auxiliary systems on the availability of the unit.

Many factors must be considered in the design of electrical systems, one of which is the capital cost. This however cannot be the only criterion for comparing them since each design has its own expected reliability. One realistic method for comparing different designs includes the evaluation of the average annual cost of its expected unreliability. This cost together with the capital cost of the design are invaluable contributions in helping
the designer to choose objectively the "best" alternative.

The cost of the unreliability of the electrical auxiliary system can be evaluated by predicting the expected annual power not supplied by the station due to the unreliability of its electrical system. This power not supplied must therefore be supplied by another station lower down the merit order. This imposes a financial penalty which is directly related to the unreliability of the first station. Therefore the power not supplied by the station due to the electrical system not being able to perform its intended function can be considered as a sound criterion for predicting the reliability cost of different auxiliary electrical systems.

In a power station the load points or busbars have a common objective; this being the output of the unit. The consequence of losing a busbar or combination of busbars can therefore be expressed in terms of the output power reduction of the unit. However a single failure event can cause the failure of more than one busbar and so the independent failure events of the unit cannot be obtained by simply considering the failure events of all the busbars. The algorithm described in chapter V can be directly applied to deduce the unit independent failure events from a knowledge of the busbar independent failure events.

The results that can be evaluated with the techniques described in this chapter allow different electrical auxiliary systems of power stations to be compared objectively although conceptionally and operationally they can be vastly different.

6.2 - Load Point Failure Modes

The analysis is commenced by calculating the reliability indices of each busbar in the electrical auxiliary system. The component failure modes that are considered are identical to those described in chapter III. To deduce the busbar failure modes it was assumed that the probability of having simultaneously more than three faulty components is negligible and
therefore only events up to third order were considered. Also two failure events at a busbar were considered independent if the set of components defining one failure event did not include the set of components defining the other failure event. This assumption is valid because the failure probability of any electrical component is numerically very small. It was also assumed that, after a busbar failure, no other healthy component in the paths from any source to the busbar can subsequently fail during the time the paths are de-energised. This is acceptable because the components will have a much smaller failure rate when they are out of service.

All the above assumptions permit the busbar failure modes to be identified with the minimal cut sets associated with the minimal paths from all the sources of supply to the busbar under consideration. Therefore the techniques described in chapter IV can be used to deduce the load point failure events and the corresponding reliability indices. The reliability indices of the cut sets for which a busbar failure occurs when all components of the cuts are out but service can be restored by closing a normally open path may be evaluated assuming that the normally open paths may fail when required to operate. This can be done using the conditional probability approach described in chapter V.

6.3 - Representing Branches off the Busbars

To calculate the reliability indices of each busbar, the branches off the busbars cannot be ignored since they could have a significant impact on the busbar indices, particularly on its failure rate. This is due to the effect of active failures and active failures overlapping a stuck breaker condition of the components in these branches being reflected back to the breakers on the input side of the busbars. In a typical power station the number of branches off a busbar may exceed 60 or so with each branch containing at least three components, e.g. a breaker, a cable and a motor. Therefore in a typical station the number of additional components that
would need to be introduced to adequately represent these branches could exceed several hundreds. The computer time and storage requirements of a computer program are a function of the number of components. Therefore to include all these additional components would seriously degrade computational efficiency.

This difficulty was overcome by representing the branches off each busbar by an "equivalent branch". The active failure rate of each component in this equivalent branch is obtained by summing the active failure rates of the components existing in the real branches. The switching time and stuck breaker probability are the same as any one of the real components. Using this technique the reliability indices of each busbar are calculated precisely and the increase in computer time and storage requirements is a minimum.

The example considered in fig. 6.1 is an oversimplified system where it is shown how branches off the busbars are represented; \( \lambda^a_i, S_i \) and \( P_i \) represent the active failure rate, the switching time and stuck probability of component \( i \)

![Diagram](image)

\[
\begin{align*}
\lambda^a_2 &= 3 \lambda^a_a \\
S_2 &= S_a \\
P_2 &= P_a \\
\lambda^a_3 &= 3 \lambda^a_b \\
S_3 &= S_b 
\end{align*}
\]

**FIG. 6.1** - Example to show how branches off the busbars are represented
6.4 - Representing Alternative Sources of Supply

The electrical auxiliary system of each unit is normally fed from its own generator and/or from the grid system. However, alternative sources of supply such as diesel generators and gas turbines may be available either for black starts or for use when the normal feeding points are not available. In the present system model, these alternative sources of supply were represented as normal system branches connected to the system through a normally open breaker. The switching time of this normally open breaker includes the start-up time of the alternative source of supply; its stuck probability is defined as the combined probability of a stuck breaker condition and a running up failure, that is:

\[ P_{be} = P_b + P_s - P_b P_s \]

where

- \( P_{be} \) = stuck probability of the "equivalent" n/o breaker
- \( P_b \) = stuck probability of the n/o breaker
- \( P_s \) = Probability of running up failure of the alternative source

For each busbar, any such source is included as one of the normally open paths. For each failure event that does not include a component actively failed, it is checked whether it is possible to eliminate it by closing a normally open path. When the failure event under consideration involves the loss of the normal sources of supply, the normally open paths that are considered include that of the alternative source. Because these alternative sources often have very high unreliabilities, it is generally not acceptable to assume that they cannot fail when required, i.e., during the outages time of the minimal cut set. Therefore, the conditional probability techniques described previously were incorporated for these sources of supply and in fact was the main reason for their development.
6.5 - Loss of Power Due to the Unreliability of the Electrical System

The algorithm described in chapter V to calculate the overall system indices of any system with a single overall objective can be applied to evaluate the loss of power due to the unreliability of the electrical auxiliary system of a power station. In this application of the algorithm the overall system objective is to keep the generator running at its full capacity when that is required. Any failure in the electrical auxiliary system may or may not cause a reduction in the output power of the generator; if it does it causes a reduction in the objective of the electrical auxiliary system and this reduction is expressed as a percentage of the capacity of the unit.

Each busbar, when lost, is assumed to have one of the following impacts on the output power of the unit:

(i) no impact (0% reduction)

(ii) reduction of the output power to a value between 0% and 100% (x % reduction), i.e., it causes a derated state

(iii) complete shut down of the unit (100 % reduction)

The reduction of power due to the loss of any combination of two busbars is given by the power reduction states shown in Table 6.1.

The reduction of power due to the loss of three or more of the x % - type busbars is assumed to be 100%.

**TABLE 6.1 - Reduction states due to loss of two busbars**

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>x%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>busbar i</td>
<td>0%</td>
<td>0%</td>
<td>x%</td>
</tr>
<tr>
<td></td>
<td>y%</td>
<td>y%</td>
<td>z%</td>
</tr>
<tr>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

where 0% < z < 100%

After having deduced the unit independent failure events and the
reduction of power associated with each of them, the availability of the expected unit derated states is evaluated by summing the availabilities of the failure events that cause the same derated state. The expected annual reduction of power due to the unreliability of the electrical auxiliary system is obtained by

\[ R_t = \left( \sum_{i=1}^{n} R_i A_i \right) \times C \text{ Mwhr} \]

where:

- \( n \) = number of expected derated states
- \( R_i \) = reduction of power, expressed in % of the unit capacity, of derated state \( i \)
- \( A_i \) = average annual duration (hr/year) of derated state \( i \); It represents the availability of derated state \( i \)
- \( C \) = capacity of the unit (MW)

6.6 - Effect of Loss of Components Off the Busbars

The expected annual MWh lost due to the unreliability of the auxiliary electrical equipment as well as the corresponding unit derated states are normally obtained from the data that defines the consequences of busbar outages in terms of the reduction of the unit output power.

An example of an event that causes change in the consequences of busbar outages is the failure of a cooling water pump. A spare pump may be installed but fed from a busbar that normally has no impact in the reduction of the output power. During the repair time of the failed cooling water pump, the busbar that feeds the spare pump becomes a busbar that, when lost, causes a known reduction (>0%) of the output power of the unit. It is worth noting that the failure of a cooling water pump is an event outside the boundary considered for the electrical auxiliary system. This boundary was defined by the busbars although the reliability indices
incorporate the effects of active failures in the loads off the busbars.

There may be many other failure events, normally outside the system boundary, which, when they occur, create a new set of busbar impact data and consequently, different system indices. In these cases the probability of occurrence of the evaluated system indices is equal to the probability of the non-occurrence of such events. Another set of results must therefore be evaluated which considers the consequences of busbar outages whilst the particular events exist. The probability of occurrence of the new set of indices is equal to the probability of the occurrence of such events.

The expected annual MWhr lost due to the unreliability of the electrical system is obtained by weighting the annual MWhr lost associated with each set of indices by the corresponding probability of occurrence, that is:

\[ C_{av} = (1 - P) C_1 + PC_2 \]

where

- \( C_{av} \) = expected annual MWhr lost
- \( C_1 \) = expected annual MWhr lost assuming that the consequences of busbar outages are constant (associated with the normal operating condition)
- \( C_2 \) = expected annual MWhr lost assuming that the consequences of busbar outages are constant (associated with the operating condition that occurs with a probability \( P \))
- \( P \) = Probability of occurrence of events outside the system boundary that cause change in the consequences of busbar outages

The events causing changes in the consequences of busbar outages are usually outages of components off the busbars. The logic used to introduce this kind of events is shown in Fig. 6.2
From main program

All minimal cut sets stored

FLAG = 0

Duplicate the information that is lost when applying the reduction of power algorithm

Print out derated states, expected MWhr lost/yr and probability of occurrence

Calculate their availability and unavailability

Any events causing changes in reduction of power data?

Print out derated states and MWhr lost/yr

Print out derated states, expected MWhr lost/yr and probability of occurrence

Print out annual energy lost having weighted the calculated values

STOP

FIG. 6.2 - Flowchart showing inclusion of components off the busbars that cause changes in reduction of power data
6.7 - **Analysis of a Typical Auxiliary System**

To illustrate the type and significance of the results that can be obtained from the application of the techniques described in this chapter, consider the auxiliary electrical system shown in Fig. 6.3. Consider also that this system is used to supply the auxiliaries of a 500MW generating unit and that the consequences on the output of the unit due to the loss of one or more busbars are as shown in Table 6.2. Finally, for illustrative purposes consider that the component reliability data are as shown in Table 6.3.

Following the method and analysis of results presented in chapter IV, the detailed results for the base system are shown in Tables 6.4-8 inclusive. In this analysis up to three overlapping outages (failure events of third order) and the possible failure of the normally open paths when required to operate were considered. From this analysis the total energy lost is seen to be 3523.65 MWhr/yr.

The results, failure events, reliability indices and MWhr lost per year shown in Tables 6.4-8 can be considered those for the proposed base case. In practice alternative designs and various modifications should also be considered to decide whether this proposed design is the "best" design. Also, because the computational time increases dramatically if the normally open paths are assumed to be subject to failure when required to operate, a decision must be made to decide whether it is necessary to consider the possibility of such failures. Finally the computational time also increases as the number of overlapping outages (order of failure events) considered is increased. In some cases, particularly in the preliminary design stage it may be justifiable only to consider first or second order events and to consider the inclusion of third order events only in the final design stage.

For the above reasons the following sensitivity analyses have been
FIG. 6.3 - Typical electric auxiliary system

13 - number of motors

bidirectional components

55 standby generator
### TABLE 6.2 - Consequences of busbar outages

<table>
<thead>
<tr>
<th>Number of failed busbars</th>
<th>Busbar number</th>
<th>Reduction of output power %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4, 13, 24, 28</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>8, 37</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>8 + 20</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>8 + 37</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>20 + 37</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>any</td>
<td>100</td>
</tr>
</tbody>
</table>

### TABLE 6.3 - Reliability data (maintenance not considered)

<table>
<thead>
<tr>
<th>Component</th>
<th>failure rate (f/yr)</th>
<th>repair time (hr)</th>
<th>Switching time (hr)</th>
<th>Stuck Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n/c breakers</td>
<td>0.020</td>
<td>0.015</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>n/o breakers</td>
<td>0.020</td>
<td>0.015</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>transformers</td>
<td>0.020</td>
<td>0.015</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>busbars</td>
<td>0.005</td>
<td>0.005</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>standby generator</td>
<td>12.00</td>
<td>-</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>breaker 56 (a)</td>
<td>0.020</td>
<td>0.015</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>motors</td>
<td>0.050</td>
<td>0.040</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

(a) includes probability of start-up failure of standby generator

### TABLE 6.4 - Summary of failure events

<table>
<thead>
<tr>
<th>Busbar number</th>
<th>n/c</th>
<th>n/o</th>
<th>Number of paths</th>
<th>Number of failure events</th>
<th>active</th>
<th>active + stuck breaker</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3 (30)</td>
<td>3</td>
<td>5</td>
<td>12(39)</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3 (24)</td>
<td>2</td>
<td>3</td>
<td>9(30)</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>4</td>
<td>14</td>
<td>3 (30)</td>
<td>8</td>
<td>10</td>
<td>32(69)</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>3 (24)</td>
<td>4</td>
<td>6</td>
<td>18(39)</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>7</td>
<td>18</td>
<td>17 (179)</td>
<td>8</td>
<td>8</td>
<td>34(196)</td>
</tr>
<tr>
<td>28</td>
<td>2</td>
<td>7</td>
<td>18</td>
<td>17 (179)</td>
<td>8</td>
<td>8</td>
<td>34(196)</td>
</tr>
<tr>
<td>32</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>11 (173)</td>
<td>4</td>
<td>5</td>
<td>21(183)</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>11 (173)</td>
<td>4</td>
<td>5</td>
<td>21(183)</td>
</tr>
</tbody>
</table>

Note: the figures in breakers correspond to number of failure events when failure of n/o paths is considered
<table>
<thead>
<tr>
<th>Failure Event</th>
<th>λ (f/year)</th>
<th>r (hours)</th>
<th>θ (hr/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 out (a)</td>
<td>0.20001 x 10⁻¹</td>
<td>1.0039</td>
<td>0.20080 x 10⁻¹</td>
</tr>
<tr>
<td>2 out (a)</td>
<td>0.20060 x 10⁻¹</td>
<td>1.1647</td>
<td>0.23364 x 10⁻¹</td>
</tr>
<tr>
<td>3 out (a)</td>
<td>0.20001 x 10⁻¹</td>
<td>1.0039</td>
<td>0.23364 x 10⁻¹</td>
</tr>
<tr>
<td>4 out</td>
<td>0.50000 x 10⁻²</td>
<td>10.000</td>
<td>0.50000 x 10⁻¹</td>
</tr>
<tr>
<td>13 out</td>
<td>0.50000 x 10⁻²</td>
<td>10.000</td>
<td>0.50000 x 10⁻¹</td>
</tr>
<tr>
<td>10 + 14 out</td>
<td>0.18265 x 10⁻⁵</td>
<td>10.000</td>
<td>0.18265 x 10⁻⁴</td>
</tr>
<tr>
<td>10 + 15 out</td>
<td>0.37443 x 10⁻⁴</td>
<td>19.512</td>
<td>0.73059 x 10⁻³</td>
</tr>
<tr>
<td>10 + 16 out</td>
<td>0.18265 x 10⁻⁵</td>
<td>10.000</td>
<td>0.18265 x 10⁻⁴</td>
</tr>
<tr>
<td>11 + 14 out</td>
<td>0.37443 x 10⁻⁴</td>
<td>19.512</td>
<td>0.73059 x 10⁻³</td>
</tr>
<tr>
<td>11 + 15 out</td>
<td>0.73059 x 10⁻⁴</td>
<td>400.00</td>
<td>0.29224 x 10⁻¹</td>
</tr>
<tr>
<td>11 + 16 out</td>
<td>0.37443 x 10⁻⁴</td>
<td>19.512</td>
<td>0.73059 x 10⁻³</td>
</tr>
<tr>
<td>12 + 14 out</td>
<td>0.18265 x 10⁻⁵</td>
<td>10.000</td>
<td>0.18265 x 10⁻⁴</td>
</tr>
<tr>
<td>12 + 15 out</td>
<td>0.37443 x 10⁻⁴</td>
<td>19.512</td>
<td>0.73059 x 10⁻³</td>
</tr>
<tr>
<td>12 + 16 out</td>
<td>0.18265 x 10⁻⁵</td>
<td>10.000</td>
<td>0.18265 x 10⁻⁴</td>
</tr>
<tr>
<td>10 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>11 active + 10 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>11 active + 12 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>12 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>14 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>15 active + 14 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>15 active + 16 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>16 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>21 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>22 active + 21 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>23 active + 21 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>25 active</td>
<td>0.15000 x 10⁻¹</td>
<td>1.000</td>
<td>0.15000 x 10⁻¹</td>
</tr>
<tr>
<td>26 active + 25 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>27 active + 25 stuck</td>
<td>0.15000 x 10⁻⁴</td>
<td>1.000</td>
<td>0.15000 x 10⁻⁴</td>
</tr>
<tr>
<td>39 active</td>
<td>0.75000 x 10⁻³</td>
<td>1.000</td>
<td>0.75000 x 10⁻¹</td>
</tr>
<tr>
<td>40 active + 39 stuck</td>
<td>0.20000 x 10⁻³</td>
<td>1.000</td>
<td>0.20000 x 10⁻³</td>
</tr>
<tr>
<td>43 active</td>
<td>0.19500</td>
<td>1.000</td>
<td>0.19500</td>
</tr>
<tr>
<td>44 active + 43 stuck</td>
<td>0.52000 x 10⁻³</td>
<td>1.000</td>
<td>0.52000 x 10⁻³</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.43113</strong></td>
<td><strong>1.2910</strong></td>
<td><strong>0.55658</strong></td>
</tr>
</tbody>
</table>

(a) Failure events that may be eliminated closing a n/o path
### TABLE 6.6 - Events causing power reduction of unit

<table>
<thead>
<tr>
<th>Passive outages restored by repair</th>
<th>Passive outages restored by n/o paths</th>
<th>Active failures</th>
<th>Active failures plus stuck breaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>8</td>
<td>39</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>6</td>
<td>18</td>
<td>41</td>
</tr>
<tr>
<td>19</td>
<td>7</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>24</td>
<td>26</td>
<td>34</td>
<td>43</td>
</tr>
<tr>
<td>28</td>
<td>27</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>37</td>
<td>21</td>
<td>36</td>
<td>47</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>14</td>
<td>17</td>
</tr>
</tbody>
</table>

### TABLE 6.7 - Reliability indices of base system

<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity out (MW)</th>
<th>MWhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>254.36</td>
<td>16.553</td>
<td>20</td>
<td>100</td>
<td>1653.3</td>
</tr>
<tr>
<td>0.36598</td>
<td>1.7668</td>
<td>0.64661</td>
<td>30</td>
<td>150</td>
<td>96.99</td>
</tr>
<tr>
<td>0.00500</td>
<td>8.8633</td>
<td>0.04432</td>
<td>40</td>
<td>200</td>
<td>8.86</td>
</tr>
<tr>
<td>0.14036</td>
<td>2.6835</td>
<td>0.37666</td>
<td>45</td>
<td>225</td>
<td>84.75</td>
</tr>
<tr>
<td>2.3564</td>
<td>1.4257</td>
<td>3.3595</td>
<td>100</td>
<td>500</td>
<td>1679.75</td>
</tr>
</tbody>
</table>

### TABLE 6.8 - Events causing 30% derated states

<table>
<thead>
<tr>
<th>Failure event</th>
<th>Expected failure rate (f/yr)</th>
<th>Average duration (hr)</th>
<th>Annual outage time (hr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 out</td>
<td>0.00500</td>
<td>10.0</td>
<td>0.05000</td>
</tr>
<tr>
<td>34, n/o path closed</td>
<td>0.02000</td>
<td>0.53458</td>
<td>0.01069</td>
</tr>
<tr>
<td>35, n/o path closed</td>
<td>0.02017</td>
<td>12.86</td>
<td>0.25943</td>
</tr>
<tr>
<td>36, n/o path closed</td>
<td>0.02000</td>
<td>1.2837</td>
<td>0.25679</td>
</tr>
<tr>
<td>53 active</td>
<td>0.3000</td>
<td>1.00</td>
<td>0.3000</td>
</tr>
<tr>
<td>54 active + 53 stuck</td>
<td>0.00080</td>
<td>1.00</td>
<td>0.00080</td>
</tr>
</tbody>
</table>
performed on the base system shown in Fig. 6.3. In the base system analysis up to third order events were considered as well as the possibility of normally open paths failing when required to operate. In the following sensitivity analysis either modifications to the base case are made or less precise indices are evaluated. It should be noted however that only one modification is made to the base case in any given sensitivity study. Also the detailed results are not included, only the final reliability indices for each derated state of the 500MW unit and the MWhr lost per year for each derated state and for the unit.

The details of the sensitivity analysis are as follows:

a) A study of the base system including failure events up to third order but this time assuming that the normally open paths do not fail when required to operate. These results are shown in Table 6.9 from which the total MWhr lost per year is seen to be 3058.86 MWhr. In fact, under these circumstances, there are no third order events and therefore this energy lost also represents that which would be obtained if failure events up to second order only are considered.

b) A study as in a) above but this time considering failure events up to first order only. These results are shown in Table 6.10 from which it is seen that the total energy lost decreases to 3042.75 MWhr/yr. It should be noted that a component failure overlapping a stuck breaker condition is considered as a first order event.

c) A study of the base system including the assumption that normally open paths may fail when required to operate but considering failure events up to second order only. These results are shown in Table 6.11 from which the total energy lost is seen to be 3520.29 MWhr/yr.

d) A study as in c) above but considering failure events up to first order only. These results are shown in Table 6.12 from which the total energy lost is seen to be 3042.75 MWhr/yr.
<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity (MW)</th>
<th>Mwhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>258.23</td>
<td>16.785</td>
<td>20</td>
<td>100</td>
<td>1678.50</td>
</tr>
<tr>
<td>0.36580</td>
<td>1.0819</td>
<td>0.39577</td>
<td>30</td>
<td>150</td>
<td>59.37</td>
</tr>
<tr>
<td>0.00500</td>
<td>9.0000</td>
<td>0.04500</td>
<td>40</td>
<td>200</td>
<td>9.00</td>
</tr>
<tr>
<td>0.14018</td>
<td>0.89278</td>
<td>0.12515</td>
<td>45</td>
<td>225</td>
<td>28.16</td>
</tr>
<tr>
<td>2.35570</td>
<td>1.0900</td>
<td>2.5677</td>
<td>100</td>
<td>500</td>
<td>1283.85</td>
</tr>
</tbody>
</table>

**TABLE 6.10 - Reliability indices for study (b)**

<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity (MW)</th>
<th>Mwhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>258.23</td>
<td>16.785</td>
<td>20</td>
<td>100</td>
<td>1678.50</td>
</tr>
<tr>
<td>0.36580</td>
<td>1.0819</td>
<td>0.39577</td>
<td>30</td>
<td>150</td>
<td>59.37</td>
</tr>
<tr>
<td>0.00500</td>
<td>9.0000</td>
<td>0.04500</td>
<td>40</td>
<td>200</td>
<td>9.00</td>
</tr>
<tr>
<td>0.14018</td>
<td>0.89278</td>
<td>0.12515</td>
<td>45</td>
<td>225</td>
<td>28.16</td>
</tr>
<tr>
<td>2.35555</td>
<td>1.0764</td>
<td>2.5355</td>
<td>100</td>
<td>500</td>
<td>1267.75</td>
</tr>
</tbody>
</table>

**TABLE 6.11 - Reliability indices for study (c)**

<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity (MW)</th>
<th>Mwhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>254.36</td>
<td>16.534</td>
<td>20</td>
<td>100</td>
<td>1653.40</td>
</tr>
<tr>
<td>0.36598</td>
<td>1.7666</td>
<td>0.64655</td>
<td>30</td>
<td>150</td>
<td>96.98</td>
</tr>
<tr>
<td>0.00500</td>
<td>8.8652</td>
<td>0.04433</td>
<td>40</td>
<td>200</td>
<td>8.87</td>
</tr>
<tr>
<td>0.14036</td>
<td>2.6830</td>
<td>0.3766</td>
<td>45</td>
<td>225</td>
<td>84.74</td>
</tr>
<tr>
<td>2.3563</td>
<td>1.4228</td>
<td>3.3526</td>
<td>100</td>
<td>500</td>
<td>1676.30</td>
</tr>
</tbody>
</table>

**TABLE 6.12 - Reliability indices for study (d)**

<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity (MW)</th>
<th>Mwhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>258.23</td>
<td>16.785</td>
<td>20</td>
<td>100</td>
<td>1678.50</td>
</tr>
<tr>
<td>0.36580</td>
<td>1.0819</td>
<td>0.39577</td>
<td>30</td>
<td>150</td>
<td>59.37</td>
</tr>
<tr>
<td>0.00500</td>
<td>9.0000</td>
<td>0.04500</td>
<td>40</td>
<td>200</td>
<td>9.00</td>
</tr>
<tr>
<td>0.14018</td>
<td>0.89278</td>
<td>0.12515</td>
<td>45</td>
<td>225</td>
<td>28.16</td>
</tr>
<tr>
<td>2.3555</td>
<td>1.0764</td>
<td>2.5355</td>
<td>100</td>
<td>500</td>
<td>1267.75</td>
</tr>
</tbody>
</table>

**TABLE 6.13 - Reliability indices for study (e)**

<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity (MW)</th>
<th>Mwhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06500</td>
<td>254.31</td>
<td>16.530</td>
<td>20</td>
<td>100</td>
<td>1653.00</td>
</tr>
<tr>
<td>0.36604</td>
<td>1.7759</td>
<td>0.65004</td>
<td>30</td>
<td>150</td>
<td>97.51</td>
</tr>
<tr>
<td>0.06500</td>
<td>254.31</td>
<td>16.530</td>
<td>40</td>
<td>200</td>
<td>3306.00</td>
</tr>
<tr>
<td>0.14042</td>
<td>2.7069</td>
<td>0.38010</td>
<td>45</td>
<td>225</td>
<td>85.52</td>
</tr>
<tr>
<td>2.37980</td>
<td>2.9976</td>
<td>7.1336</td>
<td>100</td>
<td>500</td>
<td>3566.80</td>
</tr>
</tbody>
</table>

8708.83
<table>
<thead>
<tr>
<th>Expected encounter rate / yr</th>
<th>Average duration (hr)</th>
<th>Annual residence time (hr/yr)</th>
<th>Derated state (%)</th>
<th>Capacity out (MW)</th>
<th>MWhr lost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36580</td>
<td>46.845</td>
<td>17.136</td>
<td>30</td>
<td>150</td>
<td>2570.40</td>
</tr>
<tr>
<td>0.14018</td>
<td>120.63</td>
<td>16.910</td>
<td>45</td>
<td>225</td>
<td>3804.75</td>
</tr>
<tr>
<td>2.35610</td>
<td>8.4294</td>
<td>19.861</td>
<td>100</td>
<td>500</td>
<td>9930.50</td>
</tr>
</tbody>
</table>

TABLE 6.14 - Reliability indices for study (f)

| 0.00024                     | 131.66                 | 0.031607                      | 20                | 100              | 3.16              |
| 0.37098                     | 1.7448                 | 0.64728                       | 30                | 150              | 97.09             |
| 0.00500                     | 8.8633                 | 0.044316                      | 40                | 200              | 8.86              |
| 0.11074                     | 1.0041                 | 0.11089                       | 45                | 225              | 24.95             |
| 2.37120                     | 1.3961                 | 3.3105                        | 100               | 500              | 1655.25           |

TABLE 6.15 - Reliability indices for study (g)

| 0.06500                     | 253.87                 | 16.501                        | 20                | 100              | 1650.10           |
| 0.36610                     | 1.8537                 | 0.67865                       | 30                | 150              | 101.80            |
| 0.00500                     | 8.8461                 | 0.04423                       | 40                | 200              | 8.85              |
| 0.14048                     | 2.9100                 | 0.40879                       | 45                | 225              | 91.98             |
| 2.3562                      | 8.5170                 | 20.067                        | 100               | 500              | 11886.22          |

TABLE 6.16 - Reliability indices for study (h)
e) A study of the base system including the assumption that the normally open paths may fail when required to operate and failure events up to third order but this time without breaker 9 in the system, that is, no normally open tie breaker between busbars 4 and 8. These results are shown in Table 6.13 from which the energy lost is seen to increase to 8708.83 MWhr/yr.

f) A study similar to e) above but this time with breaker 9 but without breaker 38. These results are shown in Table 6.14 from which the energy lost is seen to increase further to 16305.64 MWhr/yr.

g) A study similar to e) but this time with breakers 9 and 38 included and also with a new branch connected between busbars 8 and 20; This being identical to the existing branch. These results are shown in Table 6.15 from which the energy lost is seen to decrease to 1789.31 MWhr/yr.

h) A study similar to e) above but this time with breaker 9 and 38 included but one of the parallel branches between busbars 4 and 13 eliminated. These results are shown in Table 6.16 from which the energy lost is seen to be 11886.22 MWhr/yr.

6.8 - General Discussion of Results

From the results presented in section 7 it can be deduced, as expected, that first order events cause the major contribution to the unreliability of the system (compare Tables 6.7, 6.11 and 6.12 and Tables 6.9 and 6.10); The imprecision between Tables 6.9 and 6.10 is only 0.53% and between Tables 6.7 and 6.11 and Tables 6.7 and 6.12 is 0.1% and 13.7% respectively. This cannot be considered as a general conclusion but does indicate that, in order to reduce computational effort, higher order events could be neglected in the preliminary design stage and included only in the final assessment when greatest precision is required.

From the results it can also be deduced that failure of normally
open paths can influence the expected energy lost by a reasonable significant amount. By comparing Tables 6.7 and 6.9 it is seen that the energy difference is 465 MWhr which represents a difference of about 13%. This value cannot be considered insignificant but again may be sufficiently small that it need only be considered during the final design stages.

Very significant increases in energy lost were found when either breaker 9 or breaker 38 were removed from the system (compare Table 6.7 with Tables 6.13 and 6.14); the increases being approximately 150% and 360% respectively. Clearly, therefore, both of these breakers can be considered important components of the system. It is also clear that breaker 38 is considerably more important than breaker 9. It should be remembered however that these results are dependent on the assumed component reliability data and may be different for other systems. Fundamentally however it illustrates the great importance of this type of analysis in detecting the critical areas of a complex network.

The reason for breaker 38 to be more critical than breaker 9 in the present example is as follows. The removal of breaker 38 seriously weakens busbar 24 which has a 100% reduction impact on the unit. Its removal creates 6 first order failure events all of which can be eliminated only by a repair action. The removal of breaker 9 however leaves those busbars having a defined 100% reduction impact still with at least one alternative source of supply.

It is seen from Tables 6.15 and 6.16 that, by introducing a new branch between busbars 8 and 20, the energy lost is decreased by 50% and, by eliminating one of the branches between busbars 4 and 13, the energy lost is increased by 237%. This again shows the importance of such branches and permits the station designer to make a totally objective engineering judgement of his various proposed designs in relation to their capital cost and their unreliability cost.
6.9 - Conclusions

To associate a cost to the reliability of a proposed design is one of the main objectives of long term reliability or availability studies. This chapter has proposed techniques that assist these objectives to be fulfilled with regard to the specific area of electrical auxiliary systems of power stations. The concept of system minimal cut sets leads to the evaluation of the reliability indices of the unit derated states due to the unreliability of the electrical auxiliary system.

The detailed results deduced and discussed in this chapter relate directly to the assumed component reliability data and the base system used as an example. Any changes to the data or to the system may cause significant changes in the relative values of the results. However it was shown that by the inclusion of this type of analysis in the design stage of auxiliary electrical systems of power stations, it is possible for the designer to make very realistic decisions based on quantitative results.
RELIABILITY EVALUATION OF THE AUXILIARY ELECTRICAL
SYSTEMS OF POWER STATIONS - MULTI-UNIT STATION

7.1 - Introduction

In the previous chapter it was shown how the reliability of the auxiliary electrical systems of power stations can be assessed, but the model described and the application considered were limited to single unit stations or to stations where the auxiliary electrical systems of the different units are independent. However most power stations have more than one unit, each with its own electrical system but with these auxiliary systems interconnected among them. The techniques described in this chapter can be used to analyse the auxiliary electrical system of any station with any number of units. These techniques have been successfully applied to solve typical problems suggested by C.E.G.B., and one of these problems is described and solved in this chapter.

7.2 - Reliability Techniques

The electrical auxiliary system of any station can always be divided into subsystems connected via normally open or normally closed links. Each of these subsystems is mainly associated with a known objective, e.g. it is the auxiliary system of one of the units or it is an electrical system that influences all station units. The loss of a busbar or combination of busbars in a subsystem causes a reduction in the output power of the station that can be expressed as a percentage of the capacity associated with the subsystem (e.g., the unit rating or the station capacity). Usually the loss of a busbar in a subsystem does not have any influence in the reduction of power of other subsystems unless the subsystem considered affects all station
units, but in this case because its associated output capacity is the station capacity such influence is automatically taken into account.

Fig. 7.1 shows how the auxiliary electrical system of a station can be divided, where $C_i$ is the capacity of unit $i$ in the station.

![Diagram of a typical division of the electrical auxiliary system of a power station](image)

**FIG. 7.1** - Typical division of the electrical auxiliary system of a power station

There are cases where a busbar although affecting all station units is best accommodated in a subsystem associated with one of the units. In other cases it is possible that the loss of a busbar causes a reduction of the output capacity of more than one unit, say of two adjacent units, without affecting all station units. Section 3.2 presents another version of the algorithm described in section 5.4 to incorporate these kind of busbars.

To analyse the reliability of an overall station the following steps were considered:

- **a)** Divide the station electrical auxiliary system into any number of electrical subsystems in order to associate with each of them an output power

- **b)** Evaluate the influence of the station interconnectors on the reliability of each electrical subsystem referred to in a). This is done using the techniques described in section 5.6.

- **c)** Calculate the reliability indices of each busbar in each of the electrical subsystems.

- **d)** In the analysis of each electrical subsystem calculate the
contribution to the station reduction of power due to the unreliability of the electrical subsystem being considered.

e) Evaluate the expected annual cost, together with its components, of the unreliability of the station electrical auxiliary equipment.

7.3 - Reduction of Power Associated with a Subsystem

It was stated in section 5.4 that the loss of any busbar could have one of the following consequences:

a) 100% reduction of output power
b) \( x\% \ (0 < x < 100) \) reduction of output power
c) no reduction of output power

When considering a multi-unit station, busbars that are associated with the auxiliary system of one unit may have an impact on other unit(s). It was decided to represent the loss of power associated with these busbars in terms of a percentage impact on the unit to which they are associated. Because of their impact on more than one unit, this led to the consideration of busbars causing, when lost, an effective power reduction of more than 100%. Consequently, the expected unit derated states may include one that represents a power loss greater than the unit rating. However, its meaning is self-evident; the annual expected MWhr lost associated with it includes the impact that it has on the reduction of power of other unit(s). The algorithm described in section 5.4 was modified to incorporate busbars causing when lost more than 100% reduction of the associated objective. This new algorithm is described in the next subsection as applied to power stations.

7.3.1 - The Algorithm (algorithm 3)

Assumptions

The loss of any busbar causes one of the following consequences:

(a) 100% reduction of output power
(b) \( x\% \) \((0 < x < 100)\) reduction of output power

(c) no reduction of output power

(d) more than 100\% reduction of power representing impact on other units.

The loss of more than two busbars from those defined by (a), (b) or (d) causes 100\% reduction of output power or the maximum of the reductions of output power associated with each of them if this value is greater than 100\%.

The loss of any combination of two busbars (from those defined by (b)) causes a known loss of output power.

**Identifying a Minimal Cut Set**

Each cut set is defined by a set of six values as follows:

\[
\begin{array}{|c|c|c|c|c|}
\hline
x & N & a & b & c & R \\
\hline
\end{array}
\]

where \( x \) defines the type of cut

\( N \) defines the busbar to which the cut is attached

\( a, b, c \) are the components of the cut and \( b \) and/or \( c \) may be zero

\( R \) is the reduction of power output of the unit due to the cut

The value of \( x \) may be:

-1 : a cut for which component is cut and service is restored by a repair action

-2 : a cut for which every component is cut but service may be restored by closing a normally open breaker

-3 : a cut for which component \( a \) is actively failed and all other components are cut. Service is restored by isolating component \( a \).

\( k \) : a cut as defined by -3 but one in which breaker \( k \) is stuck
Algorithm

Consider the two minimal cuts:

\[ i = \begin{array}{c|c|c|c|c|c} x_i & H_i & a_i & b_i & c_i & R_i \end{array} \]

\[ j = \begin{array}{c|c|c|c|c|c} x_j & H_j & a_j & b_j & c_j & R_j \end{array} \]

Let \( I \) and \( J \) be a set of three numbers defined as:

\[ I = \{ a_i, b_i, c_i \} \quad J = \{ a_j, b_j, c_j \} \]

\( n_i \) = number of non-zero elements of \( I \)

\( n_j \) = number of non-zero elements of \( J \)

\( n_m \) = minimum of \( n_i \) and \( n_j \)

Define the set \( A = I \cap J \) and let \( n_a \) be the number of non-zero elements of \( A \), then \( n_a \leq n_m \).

Let \( R(N_i) \) and \( R(N_j) \) be the output power lost when busbars \( N_i \) and \( N_j \) are lost respectively and \( \max(a, b, c) \) represent the maximum of the numbers \( a, b \) and \( c \).

Let \( l = 1 \) when \( 0 < R(N_i) < 100 \) and \( 0 < R(N_j) < 100 \) and in this case let \( R(N_i, N_j) \) represent the output power lost when both busbars \( N_i \) and \( N_j \) are lost.

Otherwise let \( l = 0 \).

The algorithm then proceeds as follows:

(i) if \( R(N_i) = 0 \) neglect \( i \) and if \( R_j = 0 \) set \( R_j = R(N_j) \)

(ii) if \( N_i = N_j \) the cuts are independent. The values of \( R_i \) and \( R_j \) are as in (i).

(iii) if \( n_a < n_m \) the cuts are independent as in (ii)
If \( N_i \neq N_j \) and \( n_a = n_m \) the algorithm proceeds as follows:

(iv) \( x_i = x_j = x \)

a) \( x = -1 \) or \( -2 \) and \( n_i = n_j \)

Reject the cut associated with the busbar causing minimum power loss, i.e., if \( R(N_i) < R(N_j) \) reject cut \( i \)

If \( l = 0 \) set \( R_j = -\max \left[ R(N_i), R(N_j) \right] \) if \( i \) is rejected and

set \( R_i = -\max \left[ R(N_i), R(N_j) \right] \) if \( j \) is rejected

If \( l = 1 \) and \( j \) has been rejected then, if \( R_i \) or \( R_j < 0 \) set \( R_i = -100 \) but if \( R_i \) and \( R_j \geq 0 \) set \( R_j = -R(N_i, N_j) \). Similarly if \( i \) has been rejected the value of \( R_j \) is suitably set

b) \( x = -1 \) or \( -2 \) and \( n_i \neq n_j \)

Reject the cut associated with the busbar causing minimum loss of energy per year (product of output power lost and average annual outage time).

If \( l = 0 \) or \( l = 1 \) use appropriate conditional statement in a) above

c) \( x \neq -1 \) or \( -2 \)

If \( a_i = a_j \) and \( n_i = n_j \): as in case a)

If \( a_i = a_j \) and \( n_i \neq n_j \): as in case b)

If \( a_i \neq a_j \) then the cuts are considered independent

The values of \( R_i \) and \( R_j \) are set as in (i) above

(v) \( x_i \neq x_j \)

a) if \( n_i \neq n_j \) then the cuts are considered independent and the values of \( R_i \) and \( R_j \) are set as in (i) above

b) if \( n_i = n_j \), a decision is taken according to the following table
If \( l = 0 \), the cut indicated in the table is eliminated and the reduction of power of the remaining cut is set to \( \max \left[ R(N_i), R(N_j) \right] \) but if the reduction of power of the remaining cut is \( \times \), proceeds as for \( l = 1 \).

If \( l = 1 \) (in the following assume that cut \( i \) is indicated, a similar reasoning exists if it is cut \( j \)), then \( R_i \) is set to \( -\max \left[ 100, R(N_i), R(N_j) \right] \) if previously either \( R_i \) or \( R_j \) is negative, \( R_i \) is set to \( -\max \left[ R(N_i), R(N_j) \right] \) if previously \( R_i \) and \( R_j \) are not negative.

\( R_j \) is set to \( -\max \left[ 100, R(N_j) \right] \) if its previous value is negative.

\( R_j \) is set to \( R(N_j) \) if its previous value is not negative.

The average annual outage time of cut \( j \) is decreased by the average annual outage time of cut \( i \).

\( (X) \)- in this case the cuts are considered independent and the values of \( R_i \) and \( R_j \) are set as in (i) above.

\( (vi) \) Scan all the cuts not rejected in the above logic and make

\[ R_i = |R_i| \]  

Combine all the cuts that lead to the same reduction of output power of the unit.

7.4 - Typical Application

Fig. 7.2 shows a four unit station with separate station supplies used to exemplify how a typical station electrical auxiliary system is analysed and to show the kind of results that are obtained. It can be seen that each of the 660.0 MW units has its own auxiliary system and that some supplies are not associated with any specific unit. If the interconnectors
Fig. 7.2 A FOUR UNIT STATION WITH SEPARATE STATION SUPPLIES

- normally open breaker
- number of motors

42° busbar number
42 component in the interconnector sub-system
were not drawn it is evident that fig. 7.2 would be split into five, separate systems: one associated with each of the four units and a fifth one fed by the 132KV system. Each of these systems has a very specific objective: the four unit systems keep the different units running and the station system is directly associated with the overall station. Since it is possible to associate an objective to each of these parts of the overall system they constitute the subsystems that will be analysed in turn after evaluating the impact of the existence of the interconnectors in each of these subsystems. Table 7.1 shows the output power associated with each of the subsystems, i.e. the power that is lost when the subsystem fails to perform its intended function. The consequences of busbar failures have to be expressed as a percentage of the output power associated with the corresponding subsystem.

**TABLE 7.1 - Output power associated with each subsystem**

<table>
<thead>
<tr>
<th>Subsystem number</th>
<th>Output power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>660.0</td>
</tr>
<tr>
<td>2</td>
<td>660.0</td>
</tr>
<tr>
<td>3</td>
<td>660.0</td>
</tr>
<tr>
<td>4</td>
<td>660.0</td>
</tr>
<tr>
<td>5</td>
<td>2640.0 (4x660.0)</td>
</tr>
</tbody>
</table>

Subsystems 1, 2, 3 and 4 are identical and their components were numbered identically, i.e. components performing the same function have the same number. Table 7.2 gives the consequences of busbar outages in all subsystems.
<table>
<thead>
<tr>
<th>Subsystem(s)</th>
<th>Busbar(s)</th>
<th>Loss of power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3, 4</td>
<td>8, 19, 21, 27, 42, 47, 49</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>9, 10, 21, 51, 52, 53, 54, 55, 56, 57, 58</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>55 and 56</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>57 and 58</td>
<td>50%</td>
</tr>
</tbody>
</table>

In this example the loss of any busbar in subsystems 1-4 causes the shutdown of the corresponding unit and the loss of any busbar in subsystem 5 does not cause any reduction in the station capacity. However the simultaneous loss of busbars 55 and 56 causes the shutdown of the station and the loss of busbars 57 and 58 causes a reduction of the station capacity to 50% of its rating (i.e. to 1320.0 MW). This is an example, although not very common, for which the algorithm described in section 7.3 cannot be applied directly. As described in detail in section 6.5, the algorithm assumes that the loss of two "0% busbars" causes 0% reduction of output power. The algorithm was developed with this assumption to minimize the amount of input data required since otherwise the consequences of losing every combination of two "0% busbars" would have to be considered and in a typical station there are many of these busbars. In order to solve problems similar to this example two methods were devised, one of which always gives accurate results:

a) The "0% busbars" that, when lost simultaneously, cause reduction of the output power may be defined as "x% busbars" by specifying that they cause, when lost, a very small reduction of power (say 0.0001%) and then any reduction of power can be associated with each combination of two of these
busbars. This method creates a 0.0001% derated state but after deducing the
unit expected derated states and before calculating the expected annual
loss of power, derated states less than 1% may be eliminated (the program
developed does this automatically). This method is accurate only when the
independent failure events of these "new x% busbars" include the indepen-
dent failure events that cause a simultaneous loss of each combination of
two "new x% busbars". This is not the case in the present example. Consider
for example the overlapping outage of transformers 32 and 37 which causes the
loss of busbars 55 and 56 and therefore causes shutdown of the station
(see tables 7.1 and 7.2). However the loss of transformer 32 is an indepen-
dent failure event associated with busbar 55 although the indices of
this failure event incorporate the effects of the loss of transformer 37
due to the use of the normally open path through breaker 49, similarly
for transformer 57 and breaker 56. This means that because the overlapping
outage of transformers 32 and 37 is not a failure event either of busbar 55
or of busbar 56, it will not be considered as causing the simultaneous loss
of both busbars. The above method of "new x% busbars" can always be applied
directly when there are no normally open breakers in the subsystem but
when such breakers exist its valid application depends on the topology
of the subsystem.

b) It is possible to introduce "dummy busbars" (100% reliable) linked
to those "0% busbars" that, when lost in combination, cause a reduction
of output power. Each of these "dummy busbars" are considered to cause,
when lost, a reduction of power equal to that caused by the simultaneous
loss of the "0% busbars" to which they are linked. Fig. 7.3 shows how this
is done for the example being considered; Busbars 67 and 68 are the "dummy
busbars" that were introduced and the output power associated with the
loss of busbar 67 is equal to that caused by the simultaneous loss of
busbars 55 and 56 (i.e. 100%) and similarly the output power associated with
busbar 68 is 50%.
FIG. 7.3 - Introduction of "dummy busbars" 67 and 68 in subsystem 5

This method always gives accurate results but requires a modification (although very simple) of the real picture of the system being analysed.

It is assumed that busbar 8 in subsystem 1 feeds a spare cooling water pump and that when this pump is required to operate the loss of busbar 8 in subsystem 1 causes complete shutdown of the station, i.e. a loss of 2640MW. It was considered that the spare pump is required on average to operate twice a year and each time for 300 hours; This means that during 6.8% of the year (\( \frac{2 \times 300}{8760} = 0.068 \)) the loss of busbar 8 in subsystem 1 causes 400% reduction of output power, expressed in terms of the output power associated with subsystem 1.

Table 7.3 gives the components data used in the reliability analysis of the system shown in fig. 7.2. The sources (feeding points) and the generators are assumed 100% reliable because the aim of this example is to evaluate the expected loss of energy due to the unreliability of the electrical auxiliary system.

7.4.1 - Busbar Indices

Tables 7.4 and 7.5 give the reliability indices for the busbars in
<table>
<thead>
<tr>
<th>Component</th>
<th>Voltage level</th>
<th>Total failure rate (f/yr)</th>
<th>Active failure rate (f/yr)</th>
<th>Repair time (hr)</th>
<th>Switching time (hr)</th>
<th>Stuck Probability</th>
<th>Maintenance rate (out/yr)</th>
<th>Maintenance time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakers</td>
<td>400 KV</td>
<td>0.221</td>
<td>0.171</td>
<td>54.0</td>
<td>1.0</td>
<td>0.001</td>
<td>1.0</td>
<td>168.0</td>
</tr>
<tr>
<td></td>
<td>132 KV</td>
<td>0.034</td>
<td>0.026</td>
<td>45.0</td>
<td>1.0</td>
<td>0.001</td>
<td>1.0</td>
<td>168.0</td>
</tr>
<tr>
<td></td>
<td>11 KV</td>
<td>0.012</td>
<td>0.005</td>
<td>48.0</td>
<td>1.0</td>
<td>0.001</td>
<td>1.0</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>3.3 KV</td>
<td>0.012</td>
<td>0.005</td>
<td>36.0</td>
<td>1.0</td>
<td>0.001</td>
<td>1.0</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>415 V</td>
<td>0.012</td>
<td>0.005</td>
<td>36.0</td>
<td>1.0</td>
<td>0.001</td>
<td>1.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Transformers</td>
<td>400/23.5KV</td>
<td>0.115</td>
<td>0.060</td>
<td>144.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>168.0</td>
</tr>
<tr>
<td></td>
<td>132/11 KV</td>
<td>0.051</td>
<td>0.027</td>
<td>196.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>168.0</td>
</tr>
<tr>
<td></td>
<td>23.5/11 KV</td>
<td>0.020</td>
<td>0.014</td>
<td>196.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>168.0</td>
</tr>
<tr>
<td></td>
<td>11/3.3 KV</td>
<td>0.020</td>
<td>0.014</td>
<td>120.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>72.0</td>
</tr>
<tr>
<td></td>
<td>3.3/415KV</td>
<td>0.020</td>
<td>0.014</td>
<td>120.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>72.0</td>
</tr>
<tr>
<td>Busbars</td>
<td>11 KV</td>
<td>0.005</td>
<td>0.005</td>
<td>120.0</td>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>3.3 KV</td>
<td>0.005</td>
<td>0.005</td>
<td>48.0</td>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>415 V</td>
<td>0.005</td>
<td>0.005</td>
<td>24.0</td>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Cables</td>
<td>23.5 KV</td>
<td>0.005</td>
<td>0.005</td>
<td>120.0</td>
<td>1.0</td>
<td>-</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>11 KV</td>
<td>0.005</td>
<td>0.005</td>
<td>48.0</td>
<td>1.0</td>
<td>-</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>3.3 KV</td>
<td>0.005</td>
<td>0.005</td>
<td>36.0</td>
<td>1.0</td>
<td>-</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Motors</td>
<td>11 KV</td>
<td>0.013</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.3 KV</td>
<td>0.01</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>415 V</td>
<td>0.004</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The stuck probability of a normally open breaker is 0.013

23.5KV is the output voltage of the generator
subsystems 1 and 5, respectively. In these tables A, B, C and D have the following meaning:

A - Contribution to the total indices due to cuts eliminated by a repair action

B - Contribution to the total indices due to cuts that may be eliminated closing a normally open path

C - Contribution to the total indices due to active failures

D - Contribution to the total indices due to active failures overlapping a stuck breaker condition

From the analysis of tables 7.4 and 7.5 it can be seen that in this example the most important contribution to the total reliability indices of the busbars is that represented by (B); This conclusion was expected since most of the failures can be eliminated closing a normally open path either through the interconnectors or through the normally open breakers that exist in both subsystems. The effects of active failures (represented

<table>
<thead>
<tr>
<th>Busbar no.</th>
<th>Failure rate (f/year)</th>
<th>Average outage duration (hrs)</th>
<th>Average Annual outage time (hrs/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55, 56, 57 and 58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.00500</td>
<td>24.000</td>
<td>0.12000</td>
</tr>
<tr>
<td>B</td>
<td>0.11234</td>
<td>1.0638</td>
<td>0.11951</td>
</tr>
<tr>
<td>C</td>
<td>0.04521</td>
<td>0.9999</td>
<td>0.04521</td>
</tr>
<tr>
<td>D</td>
<td>0.00014</td>
<td>0.9999</td>
<td>0.00014</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.16269</td>
<td>1.7509</td>
<td>0.28486</td>
</tr>
</tbody>
</table>

| 67 and 68 |                      |                              |                                   |
| A         | 0.00318              | 26.242                       | 0.08347                           |
| B         | 0.01155              | 0.9862                       | 0.011391                          |
| C         | 0.007629             | 0.99107                      | 0.007561                          |
| D         | 0.000039             | 0.99444                      | 0.0000387                         |
| TOTAL     | 0.022398             | 4.5741                       | 0.102461                          |

**TABLE 7.5 - Busbar indices for subsystem 5**
by (G) are also significant, particularly in their contribution to the total failure rate. The contribution represented by (A) although representing in all cases less than 10% of the total failure rate, causes in all cases more than 50% of expected average annual outage time. As in previous examples, the contribution due to active failures overlapping a stuck breaker condition is negligible; This suggests that in most practical applications the effects of stuck breakers could be neglected.

Table 7.6 gives the busbar indices for subsystems 1 and 5 calculated assuming that the normally open paths do not fail when required to operate. Comparing these results with those given by tables 7.4 and 7.5 (calculated assuming that the normally open paths may fail) it can be concluded that there is no significant difference between both sets of results.

**TABLE 7.6 - Busbar indices for subsystems 1 and 5 (normally open paths do not fail)**

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Busbar</th>
<th>Failure rate (f/yr)</th>
<th>Average outage duration (hrs)</th>
<th>Average Annual outage time (hrs/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.42314</td>
<td>2.4062</td>
<td>1.0181</td>
</tr>
<tr>
<td></td>
<td>19 and 21</td>
<td>0.50219</td>
<td>2.6528</td>
<td>1.3322</td>
</tr>
<tr>
<td></td>
<td>47 and 49</td>
<td>0.55122</td>
<td>2.5058</td>
<td>1.3812</td>
</tr>
<tr>
<td></td>
<td>40 and 42</td>
<td>0.61121</td>
<td>2.1616</td>
<td>1.3212</td>
</tr>
<tr>
<td>5</td>
<td>55,56,57 &amp; 58</td>
<td>0.16264</td>
<td>1.7065</td>
<td>0.27755</td>
</tr>
<tr>
<td></td>
<td>67 and 68</td>
<td>0.022398</td>
<td>4.5741</td>
<td>0.102461</td>
</tr>
</tbody>
</table>

This conclusion is only valid for this particular example and for the data assumed and it is due to the low repair times assumed for the components and to the existence of many normally open paths from each load point to the sources. Actually the lower the components repair times the less is the required working time of the normally open paths and the higher the number of available normally open paths the less is their probabili-
ty of failure.

7.4.2 - Reduction of Power

Table 7.7 gives the expected annual loss of energy due to the unreliability of the electrical auxiliary system of the station shown in Fig. 7.2 together with the reliability indices of the derated states caused by the auxiliary system. These data are for the condition that the normally open paths may fail when required to operate and for the condition that they do not fail when in operation. Again the differences observed in both sets of results are not very significant due to the same reasons as those given in the previous sub-section.

It can be argued that the total expected annual loss of energy of the station due to the unreliability of its electrical auxiliary system is not significant compared with the total unavailability of 660 MW units which may have forced outage rates of 10% or more. However the evaluated energy lost is an index from which the true cost penalty of the auxiliary electrical system can be deduced and is a simple and meaningful index for comparing alternative designs from which the present worth cost of a system can be deduced and even reduced without adversely affecting the system reliability.

7.5 - The Computer Program RELAPSE

A computer program was developed to analyse the reliability of the electrical auxiliary systems of power stations. It incorporates all the techniques described in the previous chapters (II to VII) and has been extensively tested with practical systems. Its versatility is shown in Appendix 5 in the introduction to its user's manual.

The storage requirements of this computer program are a function of the system size and complexity to which it is dimensioned. In its present
<table>
<thead>
<tr>
<th>Sub-system no.</th>
<th>Derated state (a)</th>
<th>Rate of occurrence (occurrences/year)</th>
<th>Average duration (hrs)</th>
<th>Annual residence time (hours/yr)</th>
<th>Expected loss of energy (MWHr/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normally open paths may fail when required to operate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100% 932%</td>
<td>0.89747</td>
<td>2.9925</td>
<td>2.6857</td>
<td>1651.15</td>
</tr>
<tr>
<td></td>
<td>100% 6.8%</td>
<td>0.38632</td>
<td>4.0609</td>
<td>1.5688</td>
<td>70.91</td>
</tr>
<tr>
<td></td>
<td>400% 6.8%</td>
<td>0.51115</td>
<td>2.1850</td>
<td>1.1168</td>
<td>201.94</td>
</tr>
<tr>
<td>2</td>
<td>100% 100%</td>
<td>0.89747</td>
<td>2.9925</td>
<td>2.6857</td>
<td>1772.53</td>
</tr>
<tr>
<td>3</td>
<td>100% 100%</td>
<td>0.89747</td>
<td>2.9925</td>
<td>2.6857</td>
<td>1772.53</td>
</tr>
<tr>
<td>4</td>
<td>100% 100%</td>
<td>0.89747</td>
<td>2.9925</td>
<td>2.6857</td>
<td>1772.53</td>
</tr>
<tr>
<td>5</td>
<td>100% 100%</td>
<td>0.025118</td>
<td>4.3105</td>
<td>0.10827</td>
<td>285.83</td>
</tr>
<tr>
<td></td>
<td>50% 100%</td>
<td>0.002889</td>
<td>11.702</td>
<td>0.03381</td>
<td>44.63</td>
</tr>
<tr>
<td></td>
<td>Normally open paths do not fail when in operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100% 932%</td>
<td>0.89735</td>
<td>2.9669</td>
<td>2.6623</td>
<td>1636.77</td>
</tr>
<tr>
<td></td>
<td>100% 6.8%</td>
<td>0.38626</td>
<td>4.0291</td>
<td>1.5563</td>
<td>70.35</td>
</tr>
<tr>
<td></td>
<td>400% 6.8%</td>
<td>0.51109</td>
<td>2.1642</td>
<td>1.1061</td>
<td>200.00</td>
</tr>
<tr>
<td>2</td>
<td>100% 100%</td>
<td>0.89735</td>
<td>2.9669</td>
<td>2.6623</td>
<td>1757.15</td>
</tr>
<tr>
<td>3</td>
<td>100% 100%</td>
<td>0.89735</td>
<td>2.9669</td>
<td>2.6623</td>
<td>1757.15</td>
</tr>
<tr>
<td>4</td>
<td>100% 100%</td>
<td>0.89735</td>
<td>2.9669</td>
<td>2.6623</td>
<td>1757.15</td>
</tr>
<tr>
<td>5</td>
<td>100% 100%</td>
<td>0.025118</td>
<td>4.3105</td>
<td>0.10827</td>
<td>285.83</td>
</tr>
<tr>
<td></td>
<td>50% 100%</td>
<td>0.002889</td>
<td>11.702</td>
<td>0.03381</td>
<td>44.63</td>
</tr>
</tbody>
</table>

(a) % of annual time for which the data associated with consequences of busbar outages is valid

1924.00

330.46

7572.05

1907.13

330.46

7509.04
form it is prepared to analyse systems having up to:

- 5 subsystems
- 450 components
- 120 branches
- 10 components per branch
- 5 components tripping following an active failure of any other component
- 120 paths from any load point to the sources
- 150 minimal cut sets associated with any system configuration
- 7 sources per subsystem
- 10 load points per subsystem
- 30 interconnectors
- 1000 independent failure events for all load points per subsystem

The storage required by the program in its present form is 53.5 Kwords which is very much less than that referred to in the most recent publications\(^{(10),(27)}\) describing programs much less powerful than the program developed to incorporate the techniques described in this thesis. In reference \((10)\) it is stated that for an 80 component system the storage required is 110 Kwords and the program described in reference \((27)\) for a 198 component system requires 250 Kwords. The saving in storage was achieved by compacting the arrays that occupied most of the storage and developing techniques that could be efficiently programmed.

The computing time is also a function of the system size and complexity. The use of the technique to consider that the normally open paths may fail when they are required to operate may increase dramatically the computing time. The system considered in section 6.7 takes 1.090 sec to be analysed (on a CDC 7600) if the normally open paths are assumed not to fail and 8.996 sec if they are assumed to fail. A three unit station formed by three subsystems identical to that analysed in section 6.7 interconnec-
START

Read data: network topology, component reliability data, switching effects due to active failures and consequences of busbar outages

? Are there more than one subsystem?

No

Yes

Prepare the network topology to consider the overall system

Calculate impact between subsystems

Consider one subsystem

Consider one output node

Set output node reliability indices to zero

Deduce a failure event

Calculate its indices and store

Print the failure event and its indices

Update output node reliability indices

? Any other failure event?

Yes

No
FIG. 7.4 - Simplified flowchart of the program RELAPSE
ted at the 11kV and 3.3kV levels by 6 interconnectors took 6.568 sec. and 74.047 sec to be analysed considering both of these options. The example considered in this chapter analysed completely (i.e. assuming all 5 subsystems different) took 40.544 sec and 44.512 sec. when the normally open paths were assumed not to fail and assumed may fail, respectively. It is believed that the computational requirements of the computer program developed are well within the restrictions imposed by any computing facility when practical systems are analysed.

Fig. 7.4 shows a simplified flowchart of the computer program RELAPSE.

7.6 - Conclusions

A practical and realistic electrical auxiliary system of a four unit station with 302 components and 98 branches was analysed using a computer program developed to incorporate all the techniques described in the present and previous chapters. The efficiency of these techniques can be easily proved by the computing times quoted in this chapter.

A new form of the algorithm was developed to deduce the overall system indices and was described in this chapter. This algorithm in its present form incorporates all practical requirements that can be considered in the analysis of the auxiliary electrical systems of power stations.

The method used to analyse a multi-unit station is completely original and allows any kind of auxiliary electrical system of power stations to be easily and efficiently analysed with the techniques developed.
8.1 - Introduction

After the publication of two papers(7),(8) in 1964, considerable interest has been focussed on the evaluation of the reliability in power system networks. One paper(8) presented the basic logic for deducing the equations needed to calculate the busbar (load point) reliability indices.

In 1968 it was shown by Billinton and Bollinger(32) that these equations(8) gave inconsistent results when compared with the Markov approach; this being accepted as a theoretically accurate reliability model for power system networks. Unfortunately the Markov approach can be applied only to very simple systems due to computational limitations that are virtually impossible to overcome. In 1975 two papers(28),(29) presented modified versions of the previous equations(8) which gave results very similar to those obtained from the Markov approach. Another paper(33) showed how the minimal cut set theory could be used to evaluate the reliability indices of the load points in transmission and distribution systems from the modified equations(28),(29).

Chapter IV described a systematic technique to evaluate the reliability indices of any electrical system in which switching actions may take place following a fault. It was assumed however that component failures were independent of the weather state and failures eliminated by reclosure action were neglected. This chapter shows how these features can be taken into account and how the techniques described in chapter V are applied to transmission and distribution systems.

In the previous chapters the criterion for unreliability was based entirely on continuity, i.e. the system is successful if at least one
path exists between any source and the load point of interest. This means that all system branches are essentially considered to be of unlimited capacity. In previous papers \[ (7-10), (15), (20), (28), (29), (32), (33) \] this criterion has also been assumed. Clearly in transmission and distribution systems continuity is not the only criterion for unreliability and in this chapter it is shown how the overload probability and the probability of violation of voltage limits (designated by probability of "loss of quality" as opposed to loss of continuity) can be included in the minimal cut set method so that failure events caused by loss of quality as well as loss of continuity can be included.

It is believed that the concepts and techniques described in this chapter lead to a realistic modelling of transmission and distribution systems. The approach described is original and a computer program that incorporates all its concepts and techniques has been developed and was used to analyse the typical system considered in chapter IX.

8.2 - Component Reliability Data

Many power utilities do not keep detailed records associated with component failures unless the failures lead to consumer interruption, i.e. the data collection schemes tend to be consumer-interruption oriented and not component-failure oriented. However all reliability studies must be based on components data since, from the quantitative knowledge of the expected reliability of the system components, the expected performance of the system can be evaluated.

The reliability model described in this chapter requires a considerable amount of components reliability data some of which may be considered not to be available for practical applications. However the techniques described are ideally suited for efficient programming which allows a wide range of sensitivity studies to be easily done when some data either is not available or is considered imprecise. In addition the existence of techniques that
realistically model the system behaviour but require data not readily available can lead to and encourage a component oriented data collection scheme, particularly if the application of such techniques can be shown to give meaningful results to system designers and those responsible for making engineering judgements on investment, system expansion and reinforcement.

The component reliability data considered and defined in chapter IV were the total failure rate, the active failure rate, the maintenance rate, the switching time, the repair time, the maintenance time and the probability of a breaker failing to operate (stuck probability). In the present model the following additional data is also required:

a) Temporary failure rate - number of temporary component outages per year. This failure rate models a system failure which does not require any repair after the outage but is immediately reclosed either manually or automatically, eg. opening and reclosing of a breaker following a flashover due to lightning surges.

b) Reclosure time - time during which the component is not available due to a temporary failure.

c) Two-state weather model data - in order to incorporate a two-state weather model, the average durations of normal and adverse weather periods must be known. In addition the average total failure, active failure and temporary failure rates must be subdivided into the respective rates experienced during normal and adverse weather. As an example consider the average total failure rate(\( \lambda_{av} \)) of a component and its two subdivided rates \( \lambda \) and \( \lambda' \). The relationship between these outage rates is:

\[
\lambda_{av} = \frac{N}{N+S} \lambda + \frac{S}{N+S} \lambda'
\]

where

\( \lambda \) = failure rate during normal weather expressed in failures per year of normal weather
\[ \lambda' = \text{failure rate during adverse weather expressed in failures per year of adverse weather} \]

\[ N_S = \text{average duration of normal and adverse weather periods, respectively} \]

Although the two-state model presented in this chapter is discussed in relation to weather, the technique may clearly be related to any two-state environmental stress model provided the appropriate failure rates and average durations of the two environmental stresses are known. In power system network problems the environmental stress is mainly related to weather but in many other systems the stress may be associated with temperature, humidity, vibration, etc. Furthermore it may be considered that the reliability of underground cables is not directly related to weather variations but instead to high and low loading levels, i.e. high and low operating temperatures. In such cases the techniques can be very easily adapted.

8.3 - Reliability Analysis

Billinton and Grover\(^{(33)}\) presented equations for evaluating the reliability indices of first, second and third order minimal cut sets considering single-state and two-state weather models. These equations are presented in Appendix 3 where it is also shown how they are modified to suit the model described in this chapter. There are five ways of using these equations depending on the assumptions specified by the user. In all cases it is assumed that maintenance is started only during normal weather and that, by itself, it does not cause the failure of any load point. With this basic assumption, the five ways are:

(i) Repair may be started during normal and adverse weather; weather may change during maintenance; repair and maintenance started are continued during adverse weather.

(ii) Repair may be started during normal and adverse weather; weather
is assumed not to change during maintenance.

(iii) Repair is not started during adverse weather; weather may change during maintenance; repair and maintenance started during normal weather are continued during adverse weather.

(iv) As in (iii) but repair and maintenance are discontinued during adverse weather.

(v) Repair is not started during adverse weather; weather is assumed not to change during maintenance.

As described in section 4.4 the failure events of any load point can be identified with the minimal cut sets 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 (or failure events), including those caused by switching actions, can be evaluated using the techniques described in section 4.4. In the present model the following procedure is adopted every time the reliability indices of the failure events are evaluated:

a) identify the components in the minimal cut set

b) identify the possible outage modes (i.e. maintenance, actively failed, passively failed, temporarily failed or causing breach of quality of supply) of each component in the minimal cut set.

c) identify the corresponding restoration mode (i.e. repair, replacement, switching, reclosure or load scheduling)

d) apply the appropriate equations for the modes of failure and restoration and the order of cut set.

e) repeat steps (b-d) as many times as there are combinations of component outage modes for the particular cut set being considered

f) repeat steps (a-e) as many times as there are cut sets associated with each load point

g) repeat steps (a-f) as many times as there are load points in the system being considered.
In any reliability study it is essential to maintain as much detail as possible throughout the analysis in order to appraise the causes of the overall reliability of a load point; this clearly cannot be assessed from the overall indices of a load point. Therefore it was considered that the reliability indices of each failure event and consequently of each load point should be permanently recorded and subdivided into four groups of indices that are based on the restoration mode. These four subdivisions are:

(i) failure modes eliminated by a working action. These are the failure events associated with forced outages and forced outages overlapping a maintenance outage that can only be eliminated by restoring to service one of the components that are out. The restoration may be due to repair, replacement or completion of maintenance.

(ii) failure modes eliminated by a switching action. This may involve switching some components into or out of the system and includes restoration of service by closing a normally open path or isolating an actively failed component

(iii) failure modes eliminated by a reclosure action. These represent the impact of temporary outages

(iv) failure modes eliminated by load scheduling. These include failures that, without breaking continuity of supply, cause a violation of quality of supply defined by an overload in any of the remaining components or a voltage fluctuation outside specified limits at any system load point.

The total load point indices are obtained by first combining the indices associated with each of the above four types of failure mode and secondly combining these four subdivided indices.

The failure modes of each of the four types of minimal cut sets previously described in section 4.4 are defined in the next four subsections, where the symbols used have the following meaning:

PAF - Component passively or actively failed (total failure rate)
AF - Component actively failed (active failure rate)
M - Component out for maintenance (maintenance outage rate)
TF - Component temporarily failed (temporary failure rate)

8.3.1 - Cut Set For Which All Components Are Cut (but service cannot be restored by closing a normally open path)

a) 1st order cuts

When one of these cuts is identified it gives two contributions to the load point reliability indices: one associated with a failure mode eliminated by a working action and the other associated with a failure mode eliminated by a reclosure action. This is schematically represented in fig. 8.1

![Diagram](image)

**FIG. 8.1 - Failure modes of a 1st order cut**

(8.3.1)

b) 2nd order cuts

These cuts give three contributions to the load point reliability indices as shown in fig. 8.2. These contributions are due to failure modes eliminated by a working action, by a reclosure action and by load scheduling

c) 3rd order cuts

The failure modes associated with third order cut sets are similarly deduced and give the same contributions to the load point indices as the second order cut sets
FIG. 8.2 - Failure modes of a 2nd order cut set (8.3.1)

8.3.2 - Cuts Restored By Closing a Normally Open Path

a) 1st order cuts

First order cut sets that are eliminated by closing a normally open path may give three contributions to the load point reliability indices. One is due to a failure mode eliminated by a switching action, the second is associated with a failure mode eliminated by a reclosure action and the third one, eliminated by load scheduling, may exist when the transfer capacity of the normally open path is less than the capacity of the normally closed path.

These failure modes are schematically represented in fig. 8.3

FIG. 8.3 - Failure modes of a 1st order cut set (8.3.2)
b) 2nd order cuts

These cuts give three contributions to the load point reliability indices as shown in fig. 8.4. These contributions are due to failure modes eliminated by a switching action, by a reclosure action and by load scheduling. It is assumed that the normally open path has a transfer capacity at least equal to the capacity of any of the normally closed paths; however, if required, this assumption can be easily eliminated.

c) 3rd order cuts

The failure modes associated with third order cut sets are similarly deduced and give the same contributions to the load point indices as the second order cut sets.

![Diagram](image)

FIG. 8.4 — Failure modes of a 2nd order cut (8.3.2)

8.3.3 — Cut Sets Due To An Active Failure (component 1 actively failed)

a) 1st order cut

A first order cut set originated by an active failure give two contributions to the load point reliability indices; one is associated with a failure mode eliminated by a switching action and the other is due to a failure mode eliminated by a reclosure action. This is schematically shown in fig. 8.5
b) 2nd order cut set

These cuts give two contributions to the load point reliability indices as shown in fig. 8.6. These contributions are due to failure modes eliminated by switching and reclosure actions.

![Diagram of 2nd order cut set]

FIG. 8.6 - Failure modes of a 2nd order cut (8.3.3)

c) 3rd order cut set

The failure modes associated with third order cut sets are similarly deduced and give the same contributions to the load point indices as the second order cuts.

8.3.4 - Cut Sets Due To An Active Failure And A Stuck Breaker Condition

The failure modes are the same as those described in section 8.3.3 for first, second and third order cut sets.
The existence of a stuck breaker condition simply changes the effects of the active failure being simulated and the corresponding active failure rate is multiplied by the stuck probability of the breaker assumed stuck. Everything else is identical to that considered for cut sets in which an active failure does not overlap a stuck breaker condition.

8.4 - Failure Events Causing Breach of Quality of Supply

When a load point is fed by more than one path, the paths are not always fully redundant; this being particularly the case with power system networks. In such cases the failure of a set of components that do not break all the minimal paths to a load point may cause a system failure due to a "loss of quality". This type of failure may occur at all load levels or only at some of the load levels due either to overloading all or some of the remaining system components or to an unacceptable voltage fluctuation. This section describes how these types of failure may be taken into account in the present reliability model.

The present approach is based on the assumption that individual bus loads are directly proportional to the total system load. The annual load characteristic is divided into any number of load levels; The greater the number of load levels the greater the accuracy of the method, but the computational effort is expected to increase dramatically with the number of load levels considered although the corresponding gain in accuracy could be very small.

Consider one of the load levels, say load level $x$. The rate of occurrence of load levels greater than $x$ ($\lambda_x$), the average duration of load levels greater than $x$ ($r_x$) and the probability of the load being greater than the load level $x$ ($P_x$) must be evaluated. These data are considered as input data in the reliability model being described. $\lambda_x$, $r_x$ and $P_x$ for load level $x$ can be obtained from a hourly load characteristic (recorded or forecasted) associated with any period of time, say a year.
From the load characteristic considered the following values can be easily obtained, where \( l(t) \) represents the load at hour \( t \):

- \( N_t \) - number of transitions from the "less or equal than \( x\)" load level to the "greater than \( x\)" load level
- \( D_1 \) - Number of hours for which \( l(t) \leq x \)
- \( D_h \) - Number of hours for which \( l(t) > x \) [\( = 8760 - D_1 \)]

Fig. 8.7 shows how these values can be obtained from a typical hourly load characteristic.

\[
D_1 = \sum_{i=1}^{N_t} D_{1i} \quad ; \quad D_h = \sum_{i=1}^{N_t} D_{hi}
\]

For a fixed load level \( x \) define high load as any load greater than \( x \); the load is then assumed as oscillating between a high load and a low load state; This is represented in the diagram of fig. 8.8.

**FIG. 8.7** - Derivation of indices for load level \( x \)

- \( D_{1i} \) - duration of \( i^{th} \) transition from the "less or equal than \( x\)" load level to the "greater than \( x\)" load level
- \( D_{hi} \) - duration of \( i^{th} \) "greater than \( x\)" load level
- \( D_{1i} \) - duration of \( i^{th} \) "less or equal than \( x\)" load level
FIG. 8.8 - Diagram associated with load level x

H - "high load" state
L - "low load" state

It is known that the rate of departure from a state is equal to the inverse of its average duration. Therefore the required indices for load level x are as follows:

$$P_x = \frac{D_h}{D_h + D_l} \quad \lambda_x = \frac{D_h}{N_t} \quad \text{hours} \quad \lambda_x = \frac{8760 N_t}{D_l} \quad \text{occurrences/} \text{year}$$

It is also assumed that the maximum load level which the system can withstand without violation of specified limits of line loads or voltage fluctuations has been established previously from a security assessment study or probabilistic load flow analysis for the required single and double outages. These outages are branch outages not component outages. When the line loadings or busbar voltages violate pre-specified limits during an outage study at the load level under consideration, it is necessary to establish whether a redispaching action eliminates the failure before considering the outage as a system failure; If it can be eliminated, this means that the system can withstand the outage being considered at the load level under study.

First order minimal cuts can be ignored in the analysis of "loss of quality" as these lead directly to loss of continuity. Similarly only the loss of one component at a time of a second order minimal cut need be considered when analyzing "loss of quality" since the loss of both compo-
ments leads to loss of continuity. For second order events that cause loss of continuity to a load point, the reliability indices due to loss of quality of supply when one of the components of the cut set fails are obtained using the following equations:

Annual failure rate \( \lambda = A + B \)

Average duration of the failure event

\[
 r = \frac{A}{A+B} \left( \frac{r_{i} r_{l_i}}{r_{i} + r_{l_i}} \right) + \frac{B}{A+B} \left( \frac{r_{j} r_{l_{j}}}{r_{j} + r_{l_{j}}} \right)
\]

where

\[
 A = \lambda_{i} \lambda_{l_i} \left[ 1 - P(1(t) > l_{i}) \right] + \lambda_{i} P(1(t) > l_{i})
\]

\[
 B = \lambda_{l_j} \lambda_{j} \left[ 1 - P(1(t) > l_{j}) \right] + \lambda_{j} P(1(t) > l_{j})
\]

\[ l_{i} \] maximum load level that the system can withstand with component \( i \) out

\[ \lambda_{i} \] failure rate of component \( i \)

\[ r_{i} \] average repair time of component \( i \)

\[ l_{i}(t) \] system load level at time \( t \)

\[ \lambda_{l_i} \] rate of occurrence of load levels greater than \( l_{i} \)

\[ r_{l_i} \] average duration of load levels greater than \( l_{i} \)

\[ P(1(t) > l_{i}) \] probability of load level \( 1(t) \) greater than \( l_{i} \)

Similar equations are deduced for third order events. In the formulation of these third order equations it was assumed that the system is partially redundant and the loss of only one of the three components does not cause any system failure due to "loss of quality". If, however, this assumption is not valid for some systems the equations given below can be easily modified. These equations are (the symbols are the same as those defined for 2nd order cuts):

Annual failure rate \( \lambda = A + B + C \)

Average duration of the failure event

\[
 r = \frac{A}{A+B+C} \left( \frac{r_{j-k} r_{l_i}}{r_{j-k} + r_{l_i}} \right) + \]

\[ + \frac{B}{A+B+C} \frac{r_{1-k} r_{1-j}}{r_{1-k} + r_{1-j}} + \frac{C}{A+B+C} \frac{r_{1-j} r_{1-k}}{r_{1-j} + r_{1-k}} \]

where

\[ A = \lambda_{1i} \left[ 1 - P(1(t) > l_i) \right] \left( \lambda_{j-k} r_{j-k} \right) + \lambda_{j-k} P(1(t) > l_i) \]

\[ B = \lambda_{1j} \left[ 1 - P(1(t) > l_i) \right] \left( \lambda_{i-k} r_{i-k} \right) + \lambda_{i-k} P(1(t) > l_j) \]

\[ C = \lambda_{1k} \left[ 1 - P(1(t) > l_i) \right] \left( \lambda_{i-j} r_{i-j} \right) + \lambda_{i-j} P(1(t) > l_k) \]

\[ r_{i-j} = \frac{r_i}{r_i + r_j}, \text{ similarly for } r_{i-k} \text{ and } r_{j-k} \]

\[ \lambda_{i-j} = \lambda_i \lambda_j (r_i + r_j), \text{ similarly for } \lambda_{i-k}, \lambda_{j-k} \]

8.5 - Consideration of Normally Open Paths

To calculate the reliability indices of every load point, the failure events were grouped (section 4.4) into four kinds of cut sets. One of these was that a load point failure occurs when the components of the cut set are out but service can be restored by a switching action involving the closure of a normally open path. The reliability indices of these cut sets when they exist in transmission and distribution systems can be evaluated using the conditional probability approach described in section 5.2.

However, in order to keep the indices of the cut sets that may be eliminated by closing a normally open path subdivided according to the possible restoration modes it was necessary to formulate another approach to take into account the failure of the normally open paths when they are required to operate. Fig. 8.9 shows a simplified system considered to deduce the indices of a cut set that may be eliminated by closing a normally open path.
FIG. 8.9 - Simplified system considered to deduce the indices of a cut set that may be eliminated by closing a normally open path

Component A is a component "equivalent" to the cut set under consideration, i.e. it has the same reliability indices as those calculated for the associated cut set as if the normally open path were not available.

Component B is a component "equivalent" to the normally open paths. To calculate the reliability indices of component B it is necessary to deduce the first order cut sets associated with the normally open paths that may be closed to restore the continuity of supply to the load point when the cut set represented by component A fails. Second order cut sets associated with these paths could also be deduced but their contribution to the load point indices would be negligible. The reliability indices of component B are obtained by combining "in series" the indices associated with the cut sets deduced.

Breaker b is a component that represents the stuck probability of the normally open components in the path that is required to close, i.e. if there are two normally open components in the path referred to with stuck probabilities $p_1$ and $p_2$ the stuck probability of breaker b would be

$$p = p_1 + p_2 - p_1 p_2$$

The switching time of breaker b is the time taken to close the normally open path. Let this switching time be $s$. 
Assume that component A has the following calculated indices:

\[ \lambda_{pA} = \text{failure rate due to permanent forced outages} \]

\[ \lambda''_{pA} = \text{failure rate due to permanent forced outages overlapping a maintenance period} \]

\[ r_{pA} = \text{average outage time due to permanent forced outages} \]

\[ r''_{pA} = \text{average outage time due to permanent outages overlapping a maintenance period} \]

\[ \lambda_{tA} = \text{failure rate due to temporary forced outages} \]

\[ \lambda''_{tA} = \text{failure rate due to temporary forced outages overlapping a maintenance period} \]

\[ r_{tA} = \text{average outage time due to temporary forced outages} \]

\[ r''_{tA} = \text{average outage time due to temporary forced outages overlapping a maintenance period} \]

Assume that the calculated indices for component B are \( \lambda_{pB}, \lambda''_{pB}, r_{pB}, r''_{pB}, \lambda_{tB}, \lambda''_{tB}, r_{tB}, r''_{tB} \) with similar meaning.

To calculate the contribution to the load point indices due to the cut set represented by component A assume firstly that the stuck probability of breaker B is zero (i.e. it is always possible to close successfully the normally open path) and then that the stuck probability of breaker B is 1 (i.e. the normally open path is never closed).

a) Breaker B never fails to close (p=0)

The indices of the cut set represented by component A would be:

\[ \lambda_t = A + B, \text{ where} \]

\[ A = \lambda_{tA} + \lambda''_{tA} \]

\[ B = (\lambda_{tB} + \lambda''_{tB}) \times (\lambda_{pA} + \lambda''_{pA}) \frac{\lambda_{pA} r_{pA} + \lambda''_{pA} r''_{pA}}{r_{pA} + r''_{pA}} \]
\[ r_t = A \frac{\lambda_{tA} r_A + \lambda_{tA}'' r_{tA}}{r_{tA} + r_{tA}''} + B \frac{\lambda_{tB} r_B + \lambda_{tB}'' r_{tB}}{r_{tB} + r_{tB}''} \]

2 - Events restored by a switching action

\[ \lambda_S = \lambda_{pA} + \lambda_{pA}'' \]

\[ r_S = s \]

3 - Events restored by a working action

\[ \lambda_w = (\lambda_{pB} + \lambda_{pB}'') (\lambda_{pA} + \lambda_{pA}'') \frac{\lambda_{pA} r_{pA} + \lambda_{pA}'' r_{pA}}{r_{pA} + r_{pA}''} \]

\[ r_w = \frac{r_1 r_2}{r_1 + r_2} \text{ where } r_1 = \frac{\lambda_{pA} r_{pA} + \lambda_{pA}'' r_{pA}}{r_{pA} + r_{pA}''} \]

\[ r_2 = \frac{\lambda_{pB} r_{pB} + \lambda_{pB}'' r_{pB}}{r_{pB} + r_{pB}''} \]

4 - Events restored by load scheduling

Indices calculated as explained in sections 8.3.2 and 8.4

for the cut set represented by component A

b) Breaker b is always stuck \( (p = 1) \)

The indices of the cut set represented by component A would be:

1 - Events restored by reclosure action

\[ \lambda_{t1} = \lambda_{tA} + \lambda_{tA}'' \]

\[ r_{t1} = \frac{\lambda_{tA} r_{tA} + \lambda_{tA}'' r_{tA}''}{r_{tA} + r_{tA}''} \]

2 - Events restored by a switching action

\[ \lambda_{S1} = 0 \]

\[ r_{S1} = 0 \]
3 - Events restored by a working action

\[ \lambda_{w1} = \lambda_{pA} + \lambda_{pA}'' \]

\[ r_{w1} = \frac{\lambda_{pA} r_{pA} + \lambda_{pA}'' r_{pA}''}{r_{pA} + r_{pA}''} \]

4 - Events restored by load scheduling

Indices calculated as explained in section 8.3.1 and 8.4 for the cut set represented by component A.

Having calculated the reliability indices as indicated in a) and b) the contributions to the load point indices associated with each restoration mode are evaluated from the following conditional probability equation:

\[ P(X) = P(X \mid \text{breaker b is not stuck}) \cdot P(\text{breaker b is not stuck}) + \]

\[ + P(X \mid \text{breaker b is stuck}) \cdot P(\text{breaker b is stuck}) \]

Where \( X \) is any of the events associated with the restoration modes considered previously.

For the events restored by a working action the following indices are obtained:

\[ \lambda_{wf} = \lambda_{w} (1-p) + \lambda_{w1} P \]

\[ U_{wf} = \lambda_{wf} r_{wf} = \lambda_{w} r_{w} (1-p) + \lambda_{w1} r_{w1} P \]

For the other events similar equations can be written to calculate \( \lambda_{tf}, r_{tf}, \lambda_{sf}, r_{sf}, \lambda_{lqf}, r_{lqf} \), where \( \lambda_{lqf} \) and \( r_{lqf} \) are the failure rate and the average duration of the events that can be eliminated by load scheduling, i.e., they are associated with "loss of quality" failures.

The overall cut set reliability indices are obtained from this four contributions to the load point indices, i.e.

\[ \lambda_{cut} = \lambda_{tf} + \lambda_{sf} + \lambda_{wf} + \lambda_{lqf} \]

\[ U_{cut} = \lambda_{tf} r_{tf} + \lambda_{sf} r_{sf} + \lambda_{wf} r_{wf} + \lambda_{lqf} r_{lqf} \]

\[ r_{cut} = U_{cut} / \lambda_{cut} \]
8.6 - Variable Repair Times

Previously the average repair time of a component has always been considered [references (8), (28), (29), (33), etc.] as a fixed value. However in practice this is not necessarily true and the repair time of a component may depend very much on the impact of that component in the system when a failure occurs. For instance, if a component failure causes a load point failure, the repair action is performed in the shortest possible time, but if it is seriously weakens the system reliability without causing a load point failure, its repair time may be longer though still less than that if it only slightly weakens the system. This philosophy has led to the development of a concept of multi-average repair times for each component; The number of repair times being limited realistically to three values. These values, for which any two or all three can be equal if this is considered more realistic in any given practical situation, are defined as:

a) If the loss of a single component causes a load point failure, i.e. a first order cut set, the associated reliability indices are evaluated by considering the shortest repair time.

b) If the overlapping outage of two components causes a load point failure, i.e. a second order cut set, the associated reliability indices are evaluated by considering the medium and shortest repair times. These values are used as follows:

(i) after the first component fails, its medium repair time is taken as the exposure time during which a load point failure occurs if the second component fails. Therefore this value of repair time is used to evaluate the rate of occurrence of the second order outage.

(ii) the shortest repair time of the second component to fail is used as its repair time and therefore used to evaluate the expected duration of the double outage. This average outage duration will therefore consist of two values depending on which component is assumed to fail first; The two values being weighted by the probability of occurrence of the second component to fail.
The minimal cut set equations used to evaluate the reliability indices of second order failure events can be adapted readily to accommodate these variable repair times, e.g., for a single state weather model:

annual failure rate \( \lambda = \lambda_i \lambda_j (r_{i2} + r_{j2}) \)

average duration \( r = \frac{\lambda_i \lambda_j r_{i2}}{\lambda} \frac{r_{i2}}{r_{i2} + r_{j1}} + \frac{\lambda_i \lambda_j r_{j2}}{\lambda} \frac{r_{j2}}{r_{j2} + r_{j1}} \)

where

\( \lambda_i = \text{failure rate of component } i \)

\( r_{i1} = \text{shortest repair time of component } i \)

\( r_{i2} = \text{medium repair time of component } i \)

c) If the overlapping outage of three components causes a load point failure, i.e., a third order cut set, the associated reliability indices are calculated by considering all three repair times for each component. The first component to fail is associated with its longest repair time (it slightly weakens the system), the second component to fail is associated with its medium repair time (it seriously weakens the system) and the third component to fail is associated with its shortest repair time (it causes a load point failure). All sequences of component failures must be considered and are evaluated using the following equations, valid for a single-state weather model:

annual failure rate \( \lambda = A + B + C + D + E + F \)

average duration \( r = \frac{A}{\lambda} \frac{r_{i3} r_{j2} r_{k1}}{r_{i3} r_{j2} + r_{i3} r_{k1} + r_{j2} r_{k1}} + \frac{B}{\lambda} \frac{r_{i3} r_{j1} r_{k2}}{r_{i3} r_{j1} + r_{i3} r_{k2} + r_{j1} r_{k2}} + \frac{C}{\lambda} \frac{r_{j3} r_{i2} r_{k1}}{r_{j3} r_{i2} + r_{j3} r_{k1} + r_{i2} r_{k1}} + \frac{D}{\lambda} \frac{r_{j3} r_{k2} r_{i1}}{r_{j3} r_{k2} + r_{j3} r_{i1} + r_{k2} r_{i1}} + \frac{E}{\lambda} \frac{r_{k3} r_{i2} r_{j1}}{r_{k3} r_{i2} + r_{k3} r_{j1} + r_{i2} r_{j1}} \)
\[ \frac{1}{\lambda} \frac{r_{k3} r_{j2} r_{i1}}{r_{k3} r_{j2} + r_{k3} r_{i1} + r_{j2} r_{i1}} \]

where

\[ A = \lambda_i (\lambda_j r_{i3}) \left( \lambda_k \frac{r_{i3} r_{j2}}{r_{i3} + r_{j2}} \right) \]; \quad B = \lambda_i (\lambda_k r_{i3}) \left( \lambda_j \frac{r_{i3} r_{k2}}{r_{i3} + r_{k2}} \right) \]

\[ C = \lambda_j (\lambda_i r_{i3}) \left( \lambda_k \frac{r_{j3} r_{i2}}{r_{j3} + r_{i2}} \right) \]; \quad D = \lambda_j (\lambda_k r_{j3}) \left( \lambda_i \frac{r_{j3} r_{k2}}{r_{j3} + r_{k2}} \right) \]

\[ E = \lambda_k (\lambda_i r_{i3}) \left( \lambda_j \frac{r_{k3} r_{i2}}{r_{k3} + r_{i2}} \right) \]; \quad F = \lambda_k (\lambda_j r_{k3}) \left( \lambda_i \frac{r_{k3} r_{j2}}{r_{k3} + r_{j2}} \right) \]

\( \lambda_i, r_{i1}, r_{i2} \) as in b) above

\( r_{i3} \) = longest repair time of component i

Similar equations can be written to incorporate a two-weather state model and the effects of maintenance outages using the logic behind the equations given in Appendix 3.

8.7 - The Overall System Indices

Three algorithms were described (sections 4.5, 5.4 and 7.3) to calculate the overall system indices from the knowledge of the load points failure events. They can be applied in the analysis of any system in which the consequences of losing a load point or combination of load points can be expressed in terms of reduction of a system objective. In most transmission and distribution systems this can be done and the application of the appropriate algorithm offers a very simple means for comparing objectively alternative design, reinforcement or expansion proposals.

8.8 - Application Example

Fig. 8.10 shows a very simple system considered to exemplify the possible failure modes of the load point represented by busbar 12.
FIG. 8.10 - Simple example to show the failure modes of busbar 12

Table 8.1 gives the failure modes of the load L in fig. 8.10. Firstly the load point failure events are identified (using the techniques described in chapter IV) and then the failure modes of each failure event are deduced.

<table>
<thead>
<tr>
<th>Type of failure event</th>
<th>Failure event</th>
<th>FAILURE MODES ASSOCIATED WITH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>working action</td>
</tr>
<tr>
<td>A</td>
<td>1 Cut</td>
<td>1 PAF</td>
</tr>
<tr>
<td></td>
<td>2 Cut</td>
<td>2 PAF</td>
</tr>
<tr>
<td></td>
<td>12 Cut</td>
<td>12 PAF</td>
</tr>
<tr>
<td>B</td>
<td>4 Cut</td>
<td>4 PAF</td>
</tr>
<tr>
<td></td>
<td>6 Cut</td>
<td>6 PAF</td>
</tr>
<tr>
<td></td>
<td>8 Cut</td>
<td>8 PAF</td>
</tr>
<tr>
<td></td>
<td>10 Cut</td>
<td>10 PAF</td>
</tr>
<tr>
<td>C</td>
<td>3 A</td>
<td>3 AF</td>
</tr>
<tr>
<td>D</td>
<td>5A,3S</td>
<td>5AF,3S</td>
</tr>
<tr>
<td></td>
<td>7A,3S</td>
<td>7AF,3S</td>
</tr>
<tr>
<td></td>
<td>9A,3S</td>
<td>9AF,3S</td>
</tr>
</tbody>
</table>
In table 8.9 the symbols used have the following meaning:

A - Cut sets (failure events) for which all component are out and service cannot be restored by closing a normally open path

B - As A but service can be restored closing a normally open path; In this case closing breaker 13

C - Cut sets due to a component active failure

D - Cut sets due to a stuck breaker condition

A - Failure causing switching of other healthy components

PAF - Component passively or actively failed

TF - Component temporarily failed

AF - Component actively failed

S - Breaker stuck

LQ - "loss of quality" after an outage

Having deduced the load point failure modes the associated reliability indices are evaluated using the appropriate equations given in appendix 3 and in sections 8.4 and 8.6. These equations include the effects of a two-weather state model and "loss of quality" of supply as well as variable repair times.

8.9 - Conclusions

A new reliability model for transmission and distribution systems was described in this chapter. It takes into account the weather dependency of component outages, incorporates the effects of switching after failures, considers the impact of temporary outages and allows up to three average repair times for each component to be specified according to the effects that a loss of a component has in the system. Failure events causing breach of "quality of supply" were introduced including failures due to line overloads after an outage and due to excessive voltage fluctuations. A new approach was presented to incorporate the failure of the normally open paths when they are required to operate.
The realistic model described in this chapter was implemented in a computer program and its application to analyse typical systems is shown in the following chapter.
RELIABILITY EVALUATION OF TRANSMISSION AND DISTRIBUTION SYSTEMS

9.1 - Introduction

Reliability evaluation of transmission and distribution systems is an important prerequisite for comparing alternative system designs and different operating policies, for quantifying the quality of supply and for objectively assessing the impact of the components on the overall system performance. The first three aspects are achieved by evaluating the reliability indices of the system busbars and, when possible, the overall system indices in a similar way to that shown in the example considered in chapter VI. The latter aspect is achieved through sensitivity studies and from such studies the manufacturer and customer can assess the degree of reliability needed in the component under consideration; They give a sound criterion to decide whether to implement or improve a component design and the cost of component reliability can be assessed from the change in the service quality.

In this chapter a typical subtransmission network is considered to show the kind of results obtained when the reliability model described in the previous chapter is applied to any practical system. The same network, assuming some simplifications in the reliability data is used to show how the effect of plant reliability in transmission and distribution systems can be assessed.

9.2 - The Reliability Data

Fig. 9.1 shows the network analysed and discussed in this chapter where components 14 and 27 are normally open breakers.
FIG. 9.1 - Network analysed

Table 9.1 gives the reliability data assumed for the components in the system shown in fig. 9.1. The failure rates given (total, active and temporary) are average values expressed in failures per calendar year. If the component average annual failure rate, $\lambda_{av}$, and the fraction of its failure $p$ in adverse weather are known, the normal and adverse weather failure rates can be calculated from the following equations:

$$\lambda = \lambda_{av} \frac{N+S}{N} (1-p) \quad \text{in failures/year of normal weather}$$

$$\lambda' = \lambda_{av} \frac{N+S}{S} p \quad \text{in failures/year of adverse weather}$$

where $N$ is the average duration of a normal weather period and $S$ is the average duration of an adverse weather period. In this example it is assumed that

$$N = 200.0 \text{ hours}$$

$$S = 2.5 \text{ hours}$$
<table>
<thead>
<tr>
<th>Components</th>
<th>Average total failure rate (f/yr)</th>
<th>Average active failure rate (f/yr)</th>
<th>Minimum repair time (hrs)</th>
<th>Medium repair time (hrs)</th>
<th>Maximum repair time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 7</td>
<td>0.004</td>
<td>0.004</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>8, 9</td>
<td>0.030</td>
<td>0.020</td>
<td>20.0</td>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>10, 11</td>
<td>0.025</td>
<td>0.015</td>
<td>20.0</td>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>12-22, 25-27</td>
<td>0.020</td>
<td>0.015</td>
<td>600.0</td>
<td>650.0</td>
<td>700.0</td>
</tr>
<tr>
<td>23, 24</td>
<td>0.025</td>
<td>0.015</td>
<td>500.0</td>
<td>550.0</td>
<td>600.0</td>
</tr>
<tr>
<td>28 - 30</td>
<td>0.050</td>
<td>0.020</td>
<td>10.0</td>
<td>12.0</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Switching time for all components = 1 hr
Reclosure time for all components = 0.08 hrs
Stuck breaker probability = 0.002
Maintenance not considered
and that the failure rates of busbars, breakers and transformers are independent of the weather state, i.e. their failure rates under normal weather are equal to their failure rates under adverse weather (and therefore equal to their average failure rates given in table 9.1). Lines 28, 29 and 30 are considered as having 50% of their failures (passive, active and temporary) during adverse weather periods. Therefore:

$$\lambda_t \text{ (total normal weather failure rate)} = 0.4 \frac{200+2.5}{200} (1-0.5) = 0.2025 \text{ failures per year of normal weather}$$

$$\lambda'_t \text{ (total adverse weather failure rate)} = 0.4 \frac{200+2.5}{2.5} 0.5 = 16.2 \text{ failures per year of adverse weather}$$

and similarly

$$\lambda_a \text{ (active normal weather failure rate)} = 0.1772 \text{ f/yr of normal weather}$$

$$\lambda'_a \text{ (active adverse weather failure rate)} = 14.175 \text{ f/yr of adverse weather}$$

$$\lambda_{tp} \text{ (temporary normal weather failure rate)} = 1.0125 \text{ f/yr of normal weather}$$

$$\lambda'_{tp} \text{ (temporary adverse weather failure rate)} = 81.0 \text{ f/yr of adverse weather}$$

It is also assumed that repair may be started during normal and adverse weather, i.e. it is started as soon as a failure occurs.

9.3 - Load Data

Table 9.1 gives the load data which was assumed in order to consider the effects of "loss of quality" after component outages in the system shown in fig. 9.1. It is worth noting that the inverse of the rate of occurrence of load levels greater than load level i is the average duration of load levels less than load level i; From table 9.1 it can be seen that the average duration of load levels greater than load level 2 (55% of system peak load) is 21.0 hours and the average duration of load levels less than load level 2 is 6.09 hours ($$\frac{1}{1439.2} \times 8760 = 6.087$$); Therefore the average pattern is a 21-hour period of loads greater than 55% of the peak followed by a 6-hour period of loads less than 55% of the peak.
TABLE 9.1 - Load data assumed for the system shown in fig. 9.1

<table>
<thead>
<tr>
<th>load levels number</th>
<th>% of system peak load</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>3406.5</td>
<td>1248.0</td>
<td>0.9979</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>1439.2</td>
<td>21.0</td>
<td>0.7753</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>646.8</td>
<td>13.5</td>
<td>0.4992</td>
</tr>
<tr>
<td>4</td>
<td>85</td>
<td>152.3</td>
<td>4.2</td>
<td>0.0681</td>
</tr>
<tr>
<td>5</td>
<td>98</td>
<td>3.0</td>
<td>1.7</td>
<td>0.0006</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0001</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A - rate of occurrence of load levels greater than load level i
B - average duration of load levels greater than load level i (hours)
C - Probability of load l(t) being greater than load level i

The reliability model described in chapter VIII requires the knowledge of the maximum load level that the system can withstand after the relevant outages. Table 9.3 gives this assumed data.

TABLE 9.3 - Maximum load levels withstand after outages

<table>
<thead>
<tr>
<th>Busbar outage</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load level</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Branch outage</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Maximum load level</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>
9.4 - Busbar indices

Using the computer program developed (program RELNET 2) to incorporate the reliability model described in the previous chapter the reliability indices of busbars 4, 5, 6 and 7 were evaluated. The total number of identified failure events was 426 (97 for busbar 4, 133 for busbar 5 and 98 each for busbars 6 and 7) each having two, three or even four failure modes. The failure events are identified as described in chapters III and IV and the corresponding failure modes as detailed in chapter VIII. Tables 9.4 and 9.5 give the reliability indices of the relevant busbars for the system shown in fig. 9.1 assuming that the normally open paths may fail and that they do not fail, respectively. The usefulness of dividing the reliability indices according to the load point restoration modes is evident from the results shown in tables 9.4 and 9.5. The total indices are obtained from partial indices associated with failures having completely different system effects and therefore do not have a meaning easy to understand. The partial indices show, among other things, that most of the failures are temporary failures with a very small outage time; Failures due to "loss of quality" of supply have an important contribution to the overall indices although they do not represent catastrophic events; Permanent failures eliminated by a repair action have a very low contribution to the load point outage rate, although, as expected, they have a significant average outage duration and failures eliminated by switching although with negligible contribution to the total indices, represent a significant contribution to the total catastrophic load point failure rate.
### TABLE 9.4 - Reliability indices for busbars 4, 5, 6 and 7
(n/o paths may fail)

| Failure modes | Busbar 4 | | | Busbar 5 | | | Busbar 6 and 7 | | |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|
|               | A       | B       | C       | A       | B       | C       | A       | B       | C       |
|               | f/yr    | hrs     | hrs/yr  | f/yr    | hrs     | hrs/yr  | f/yr    | hrs     | hrs/yr  |
| D             | 0.02707 | 8.5035  | 0.23020 | 0.02707 | 8.5035  | 0.23020 | 0.03138 | 10.159  | 0.31880 |
| E             | 0.10521 | 0.99971 | 0.10518 | 0.07519 | 0.99956 | 0.07516 | 0.16500 | 0.99982 | 0.16497 |
| F             | 8.0287  | 0.080   | 0.64230 | 6.0207  | 0.080   | 0.48166 | 11.032  | 0.080   | 0.88259 |
| G             | 4.6958  | 5.949   | 27.935  | 3.0554  | 5.8566  | 17.894  | 4.6958  | 5.9490  | 27.935  |
| **Total indices** | **12.857** | **2.2489** | **28.913** | **9.1784** | **2.03554** | **18.681** | **15.925** | **1.840** | **29.302** |

### TABLE 9.5 - Reliability indices for busbars 4, 5, 6 and 7
(n/o paths do not fail)

| Failure modes | Busbar 4 | | | Busbar 5 | | | Busbar 6 and 7 | | |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|
|               | A       | B       | C       | A       | B       | C       | A       | B       | C       |
|               | f/yr    | hrs     | hrs/yr  | f/yr    | hrs     | hrs/yr  | f/yr    | hrs     | hrs/yr  |
| D             | 0.02706 | 8.5093  | 0.23013 | 0.02706 | 8.5093  | 0.23013 | 0.03106 | 8.6956  | 0.27013 |
| E             | 0.10522 | 0.99971 | 0.10518 | 0.07520 | 0.99956 | 0.07516 | 0.16516 | 0.99982 | 0.16512 |
| F             | 8.0287  | 0.080   | 0.64230 | 6.0207  | 0.080   | 0.48166 | 11.025  | 0.080   | 0.88198 |
| G             | 4.6958  | 5.949   | 27.935  | 3.0554  | 5.8566  | 17.894  | 4.6958  | 5.9490  | 27.935  |
| **Total indices** | **12.857** | **2.2489** | **28.913** | **9.1784** | **2.03553** | **18.681** | **15.917** | **1.8379** | **29.253** |

A - failure rate, B - average outage duration, C - annual outage time
D - eliminated by working action, E - eliminated by switching action
F - eliminated by reclosure action, G - eliminated by load scheduling
Comparing tables 9.4 and 9.5 it can be immediately concluded that the failure of normally open paths during their operating time do not represent any significant contribution to the total busbar indices in the example being considered. This is because the main contribution to the total indices (temporary outages and failures due to "loss of quality") are not practically affected by the failures of the normally open paths. Failures eliminated by switching and by repair action have slightly different indices, these differences being more significant for events associated with busbars 6 and 7. It can, however, be concluded that the differences observed do not justify the corresponding increase in computing time for this particular example. This conclusion is however only valid for the example being considered and for the data assumed.

A detailed analysis of the failure events and reliability indices associated with busbar 7 (in fig. 9.1) is given in appendix VII.

9.5 - Sensitivity Studies

In the sensitivity studies presented in this section it was assumed that the failure rates of lines 28, 29 and 30 (in fig. 9.1) were not dependent on the weather state and the effects of temporary outages and of failure due to "loss of quality" of supply were not considered. Only one average repair time was considered for each component and it was assumed equal to the average minimum repair time indicated in table 9.1. With these data simplifications the reliability indices for busbars 4, 5, 6 and 7 in fig. 9.1 are given in table 9.6. These results were obtained considering that
TABLE 9.6 - Reliability indices after data simplifications

<table>
<thead>
<tr>
<th>Busbars</th>
<th>Expected failure rate (f/yr)</th>
<th>Average outage duration (hrs)</th>
<th>Annual outage time (hrs/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.11425</td>
<td>2.0347</td>
<td>0.23247</td>
</tr>
<tr>
<td>5</td>
<td>0.08422</td>
<td>2.4038</td>
<td>0.20244</td>
</tr>
<tr>
<td>6 and 7</td>
<td>0.17835</td>
<td>2.1350</td>
<td>0.38078</td>
</tr>
</tbody>
</table>

the normally open paths may fail during their required operating time.

9.5.1 - Effect of Repair Time

Fig. 9.2 shows how the reliability indices of node 6 change when the repair time of every system component if changed from 30% to 180% of its original value. The change in expected failure rate is not shown but was found to vary very little with the value of component repair times. The results for the other nodes were found to vary in a similar manner.

Fig. 9.2 also shows the effect of the repair times of the breakers and the transformers on the load point indices. It can be seen that most of the effects are due to the repair times of the transformers; the original value of which was assumed to be very long.
Fig. 32 Effect of repair time

- a - all components
- b - breakers only
- l - lines only
- t - transformers only
9.5.2 - Effect of Total Failure Rate

The total failure rate of every component was changed from 30% to 180% of its original value but maintaining the ratio of active failure rate to total failure rate constant. The effect of changing the total failure rate of every component, of the breakers, of the transformers and of the lines on the reliability indices of node 6 is shown in Fig. 9.3. Similar results were obtained for the other load points. These results clearly show that the expected failure rate is mostly affected by the failure rate of the breakers whilst the annual outage time is primarily affected by the failure rate of the transformers but is also affected by the failure rate of the breakers. The results also show that the lines had a negligible effect.

9.5.3 - Effect of Stuck Breaker Probability

The stuck breaker probability of every breaker was changed from 10 to 10⁻¹. The effect of this change on the reliability indices of all nodes is shown in Fig. 9.4. The most important conclusion is that the stuck probability can affect significantly the annual outage time of some load points. In this study the probability of failing to trip was assumed equal to the probability of failing to close. It appears that the probability of failing to close can be much higher than that of failing to trip in which case the effect shown for nodes 6 and 7 will be greater. These nodes are more affected than the others due to the cumulative effects of the two normally open breakers, but particularly due to breaker 27. Actually if breaker 27 was permanently stuck (stuck probability = 1) three new first order cut sets only eliminated by a working action would be originated for busbars 6 and 7 (failures of breakers 21 and 25 and transformer 23 for busbar 6 and similarly for busbar 7). Although these new cut sets would not cause any important increase in the load point failure rate they would cause a dramatic increase in the expected annual outage time and consequently in the
Fig. 9.3 Effect of total failure rate
Fig. 94 Effect of stuck probability
average outage duration. This is clearly seen in fig. 9.4.

9.5.4 - Effect of Active Failures

The total failure rate of every system component was kept constant but its active failure rate was changed from 0% to 100% of the corresponding total failure rate. The effect of this change on the reliability indices of node 6 are shown in Fig. 9.5. From these results it is evident that separating active failures from total failures in reliability studies is vitally important since the failure rate of the system increases and the average outage duration decreases. This latter aspect is due to an increased number of short duration outages.

It is also seen from Fig. 9.5 that the reliability of the breakers has an important effect on the load point indices since most of the effects observed are due mainly to the impact of the breakers.

9.5.5 - Impact of Results in the Design Phase

It should be noted that the results shown in the previous subsections relate in detail only to the system being studied and the data that was assumed. Both aspects may vary considerably. However the philosophy and general conclusions concerning the impact of components on the system reliability are perfectly valid for all situations.

Bearing these points in mind it is evident from the results that different components can have very different degrees of impact on the system. For instance the lines had a negligible impact despite very large changes in their indices. In general plant having such a negligible impact on the system should be considered relatively inconsequential and little effort need be placed on improving their reliability, repairability or maintainability in the design phase. Reasonable maintenance is still required however to prevent their indices deteriorating to such values that their effect does become significant.
Fig. 95 Effect of active failures
The results also showed that some components may have a significant effect on the outage duration but little effect on the failure rate whilst others may have an opposite effect. Clearly in such cases, the repairability (ease of repair or replacement) of the former components may be the important aspect to consider in the design stage whilst for other components it may be more cost effective to consider only their reliability, i.e. ability of not failing.

For situations in which it is found that stuck breaker probability is important, the operating ability of the breaker and the associated protection equipment must be thoroughly assessed in the design phase. This is likely to necessitate a reliability analysis of this part of the system to maximise the cost benefit. However if it is ascertained that the effect is negligible it would be very cost ineffective to place too much effort in the design phase on improving the functioning of such plant.

9.6 - The Computer Program RELNET 2

The structure and the general philosophy of the computer program RELNET 2 is very similar to that described for the program RELAPSE. The user's manual given in appendix VI shows the versatility of the program developed and describes its main features. The storage requirements with the arrays dimensioned as described in section 7.5 are 60 Kwords and the computing time taken to analyse the system shown in fig. 9.1 was 3.508 sec. assuming that the normally open paths do not fail and 4.744 sec. when the normally open paths are considered as may fail during their required operating time. These figures clearly show the computational efficiency of the techniques incorporated in the program RELNET 2.

9.7 - Conclusions

This chapter has shown the kind of results obtained when the reliability model described in chapter VIII is applied to practical systems. These
results can be used in the assessment of the merits of different proposed
designs or operating policies. The division of the total busbar indices
according to the possible restoration modes gives useful information about
the expected behaviour of the system being analysed and is a clear and
objective way of quantifying the quality of supply at the different system
busbars.

It was also shown how reliability studies can be used to assess the
impact of plant reliability in power system networks. The specific results
presented are clearly dependent on the initial data and on the network
considered. However the philosophy of the conclusions is that for any set
of data and network, it is possible to compute the quality of the plant
required for a certain overall objective. It is then possible to assess
from a cost effective analysis the degree of reliability that should be
in-built into the various system components in the design stage.
CONCLUSIONS

This thesis provides an addition to the literature on the topological and probabilistic aspects of reliability analysis of electrical systems. The general approach developed in the reliability analysis problem can be summarised as follows:

- Identification of the component states
- Evaluation of the load point failure events
- Calculation of the load point reliability indices
- Evaluation of the system failure events
- Calculation of the system reliability indices

This procedure, although very simple to describe, becomes extremely complex when applied to realistic problems. Some assumptions were introduced to arrive at a compromise between accuracy and usefulness. The most important of these assumptions is the identification of the load point independent failure events with the minimal cut sets associated with the minimal paths from the sources to each of the load points. The algorithm described in chapter II to evaluate the minimal cuts of any general network represents one of the most important contributions presented in this thesis since it is implicit in most of the techniques described throughout the thesis; its simplicity and its efficiency are the basic reasons for the computational efficiency of the methods introduced to analyse different kinds of electrical networks.

The effects of failures causing switching of other healthy components (active failures) were considered in all applications described in this thesis. This kind of failures are not taken into account in most previous publications although it was clearly shown in the present work that they may represent an important contribution to the unreliability of electrical systems. A systematic and efficient method to consider the effects of active
failures was developed and successfully applied to practical systems. One of the most important conclusions from this research is that active failures should be considered in the reliability analysis of most electrical systems and never neglected without a quantitative knowledge of their impact in the busbar indices.

Failures between switching and repair, when the continuity of supply can be obtained by closing a new path after a failure, have been considered in this thesis. This represents a contribution to the available analytical methods to assess the reliability of electrical networks that may or may not be of great interest depending on the topology of the system being analysed and on the data considered. However, if alternative sources of supply need to be represented this technique seems to be the only method available to represent them with acceptable inaccuracy.

The initial aim of the research described in this thesis was to develop the techniques required for a reliability assessment of power station electrical auxiliary systems. These electrical auxiliary systems provide three main functions; powering the main unit drives (main systems), supplying computers, instruments, etc. (guaranteed supply systems), and powering the essential supplies (diesel and gas turbines) for safe operation of nuclear reactors. The methods developed provide reliability indices which permit the comparison of the merits of various alternative design proposals including the evaluation of the reliability cost associated with each design. The completely new concept of overall system indices represents a valuable tool in the reliability assessment of auxiliary systems. Furthermore, the ability to model all failure modes and restoration procedures realistically is considered essential in the analysis of nuclear powered generating stations. By quantifying the reliability indices of the relevant busbars without any unnecessary simplification of the system or its modes of operation, it is possible to compare objectively the expected safety performance of the essential supplies with pre-specified and statutory requirements.
To evaluate the reliability of transmission and distribution systems is of extreme value either for the consumer or for the system engineer. The last two chapters of this thesis represent a contribution in this field where the techniques described in the previous chapters are applied to transmission and distribution systems. Several modifications were introduced in the previous techniques and new concepts were developed to obtain a realistic model of transmission and distribution systems. The effects of failures eliminated by reclosure action (temporary failures), and weather dependent failures were taken into account. Failures due to "loss of quality" of supply were also introduced in a general form but it was assumed that the maximum load level that the system can withstand after an outage or combination of outages is known from a previous study. The automatic and realistic evaluation of this maximum load level must incorporate the system operating policies and is still a problem that remains open for future investigation.
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MINIMAL CUT SET THEORY

"A very efficient method for comparing the reliability of any system not containing dependent failures can be developed from the properties of the reliability graph." (36). A reliability graph is defined by a set of branches (each representing a component) tied together by the nodes of the graph to form a structure. The probability of component success is written above each branch (see Fig. I.1)

![Diagram](image-url)

**FIG. I.1** - (a) - Simple functional logic diagram
(b) - Reliability graph corresponding to the functional logic diagram (element 5 is bidirectional)

**Definitions:**

Tie set (or path) - group of branches which forms a connection between input and output when traversed in the arrow direction.

Minimal tie set - Tie set containing a minimal number of elements. If no node is traversed more than once in tracing out a tie set, the tie set is minimal.

Cut set - Set of branches which interrupts all connections between input and output when removed from the graph.

Minimal cut set - Cut set containing a minimum number of terms. All system failures can be represented by the removal of at least one minimal cut set from the graph.
If a system has $i$ minimal tie sets, $T_1, T_2 \ldots T_i$, then the system has a connection between input and output if at least one tie set is intact. The system reliability is given by

$$R = P\left(T_1 + T_2 + T_3 + \ldots + T_i\right) \quad (1)$$

Let $C_1, C_2 \ldots C_j$ represent the $j$ minimal cut sets and $\overline{C}_j$ the failure of the $j^{th}$ cut set. The system reliability is also given by:

$$P_f = P\left(\overline{C}_1 + \overline{C}_2 + \overline{C}_3 + \ldots + \overline{C}_j\right)$$

$$R = 1 - P_f = 1 - P\left(\overline{C}_1 + \overline{C}_2 + \overline{C}_3 + \ldots + \overline{C}_j\right) \quad (2)$$

In the example shown in Fig. 1.1 there are 4 minimal tie sets and 4 minimal cut sets:

$$T_1 = x_1 x_2 \quad C_1 = x_1 x_3$$

$$T_2 = x_3 x_4 \quad C_2 = x_2 x_4$$

$$T_3 = x_1 x_5 x_4 \quad C_3 = x_1 x_5 x_4$$

$$T_4 = x_3 x_5 x_2 \quad C_4 = x_2 x_5 x_3$$

The system reliability is given by:

(a) - from equation (1)

$$R = P\left(x_1 x_2 + x_2 x_4 + x_4 x_5 x_4 + x_3 x_5 x_2\right) \quad (3)$$

(b) - from equation (2)

$$R = 1 - P\left(\overline{x}_1 x_3 + \overline{x}_2 x_4 + \overline{x}_4 x_5 x_4 + \overline{x}_3 x_5 x_3\right) \quad (4)$$

The inclusion of non-minimal tie sets or non-minimal cut sets in equations (3) and (4) do not affect the result obtained for $R$ but the algebra required to evaluate $R$ would become more difficult.

Consider now the following expression

$$P\left(A\overline{B}+C\right) = P(A)4P(B)+P(C)+P(AB)-P(AC)-P(BC)+P(ABC) \quad (5)$$
If events $A$, $B$ and $C$ are disjoint equation (5) is greatly simplified:

$$P(A+B+C) = P(A) + P(B) + P(C)$$  \hspace{1cm} (6)

If we assume the disjoint property of events $A$, $B$ and $C$ it is possible to show that

$$P(A+B+C) \leq P(A) + P(B) + P(C)$$  \hspace{1cm} (7)

So the disjoint approximation yields to an upper bound. The approximation represented by (7) is good for any set of events and is a close bound for events that have a small probability of occurrence. Combining the above results with equations (1) we conclude that

$$R \leq P(T_1) + P(T_2) + \ldots + P(T_l)$$  \hspace{1cm} (8)

The upper bound for $R$ given by (8) becomes a good approximation in the low-reliability region.

Similarly from equation (2):

$$P_f \leq P(\overline{C}_1) + P(\overline{C}_2) + \ldots + P(\overline{C}_j)$$  \hspace{1cm} (9)

The upper bound given by (9) should be good where the failure probability of the system elements is small, i.e., in the high-reliability region. Manipulating the inequality (9) we obtain

$$R \geq 1 - \left[ P(\overline{C}_1) + P(\overline{C}_2) + \ldots + P(\overline{C}_j) \right]$$  \hspace{1cm} (10)

The lower bound given by (10) is good in the high-reliability region.

The minimal cut set theory is based on equation (10) and gives a lower bound (a pessimistic answer) for the system reliability. This lower bound is a close bound in the high-reliability region. The probability of failure of most electrical components (particularly those existing in the type of systems considered in this thesis) is very low, i.e. $p^2 \ll p$, where $p$ is the probability of a component failure, and so the minimal cut set approximation can be used to evaluate the reliability of electrical systems and, in fact, has been widely used.
APPENDIX I I

EQUATIONS TO CALCULATE THE RELIABILITY INDICES IN SYSTEMS FOR WHICH THE COMPONENT DATA IS INDEPENDENT OF THE WEATHER STATE

The following equations were used to calculate $\lambda$, $\mu$, $U$, $\lambda''$, $\mu''$ and $U''$ for cut sets up to third order, where

$\lambda = \text{Contribution to the total failure rate due to forced outages or to overlapping forced outages}$

$\mu = \text{Average outage time due to forced outages}$

$U = \text{Average total outage time per year due to forced outages}$

$\lambda'' = \text{Contribution to the total failure rate due to a forced outage overlapping a maintenance outage}$

$\mu'' = \text{Average outage time due to a forced outage overlapping a maintenance outage}$

$U'' = \text{Average total outage time per year due to a forced outage overlapping a maintenance outage}$

The component data required is:

$\lambda_i = \text{Total failure rate of component } i$

$\mu_i = \text{Average repair time of component } i$

$\lambda''_i = \text{Maintenance rate of component } i$

$\mu''_i = \text{Average maintenance time of component } i$

$\lambda_{a_i} = \text{Active failure rate of component } i$

$S_i = \text{Switching time of component } i$

$P_i = \text{Probability of breaker } i \text{ being stuck when called on to operate}$
I - Non Temporary Cutages (eliminated by a repair action)

a) Component i is failed (1st order cut):
\[
\lambda = \lambda_i \\
\mathbf{r} = r_i \\
\mathbf{u} = \lambda \mathbf{r} \\
\lambda'' = 0 \\
r'' = 0 \\
u'' = 0
\]

b) Components i and j are out (2nd order cut):
\[
\lambda = \lambda_i \left( \lambda_j r_i \right) + \lambda_j \left( \lambda_i r_j \right) \\
\mathbf{r} = \frac{r_i r_j}{r_i + r_j} \\
\mathbf{u} = \lambda \mathbf{r} \\
\lambda'' = \lambda''_i \left( \lambda_j r''_i \right) + \lambda''_j \left( \lambda_i r''_j \right) \\
r'' = \frac{\lambda''_i \left( \lambda_j r''_i \right)}{\lambda''} \cdot \frac{r''_i r_j}{r''_i + r_j} + \frac{\lambda''_j \left( \lambda_i r''_j \right)}{\lambda''} \cdot \frac{r''_j r_i}{r''_j + r_i} \\
u'' = \lambda''. \mathbf{r}''
\]

c) Components i, j and k out (3rd order cut):
\[
\lambda = \lambda_i \left( \lambda_j r_i \right) \left( \lambda_k \frac{r_i r_j}{r_i + r_j} \right) + \lambda_i \left( \lambda_k r_i \right) \left( \lambda_j \frac{r_i r_k}{r_i + r_k} \right) + \lambda_j \left( \lambda_k r_j \right) \left( \lambda_i \frac{r_j r_k}{r_j + r_k} \right) + \lambda_j \left( \lambda_i r_j \right) \left( \lambda_k \frac{r_j r_i}{r_j + r_i} \right) + \lambda_k \left( \lambda_i r_k \right) \left( \lambda_j \frac{r_k r_i}{r_k + r_i} \right) + \lambda_k \left( \lambda_j r_k \right) \left( \lambda_i \frac{r_k r_j}{r_k + r_j} \right) + \lambda_k \left( \lambda_i r_k \right) \left( \lambda_j \frac{r_k r_i}{r_k + r_i} \right) + \lambda_k \left( \lambda_j r_k \right) \left( \lambda_i \frac{r_k r_j}{r_k + r_j} \right)
\]
\[ r = \frac{r_1 r_j r_k}{r_i r_j + r_i r_k + r_j r_k} \]

\[ U = \lambda r \]

\[ \lambda' = A + B + C, \text{ where} \]

\[ A = \lambda''_i \left( \lambda_j r''_i \right) \left( \lambda_k \frac{r''_i}{r''_i + r_j} \right) + \lambda''_i \left( \lambda_k r''_i \right) \left( \lambda_j \frac{r_i}{r_i + r_k} \right) \]

\[ B = \lambda''_j \left( \lambda_k r''_j \right) \left( \lambda_i \frac{r''_j}{r''_j + r_k} \right) + \lambda''_j \left( \lambda_i r''_j \right) \left( \lambda_k \frac{r_j}{r_j + r_i} \right) \]

\[ C = \lambda''_k \left( \lambda_i r''_k \right) \left( \lambda_j \frac{r''_k}{r''_k + r_i} \right) + \lambda''_k \left( \lambda_j r''_k \right) \left( \lambda_i \frac{r_k}{r_k + r_j} \right) \]

\[ r = \frac{A}{\lambda''} \times \frac{r''_i r_j r_k}{r''_i r_j + r''_i r_k + r_j r_k} + \frac{B}{\lambda''} \times \frac{r''_j r_i r_k}{r''_j r_i + r''_j r_k + r_i r_k} + \frac{C}{\lambda''} \times \frac{r''_k r_i r_j}{r''_k r_i + r''_k r_j + r_i r_j} \]

\[ U'' = \lambda'' r'' \]

II - **Temporary Outage** : due to service being restored by closing a normally open path (time to close a normally open path = \( t_c \))

a) Component \( i \) is failed (1st order cut):

\[ \lambda = \lambda_i \]
r = \tau_c \\
u = \lambda \cdot r \\
\lambda'' = r'' = u'' = 0

b) Components i and j are out (2nd order cut): 
\lambda = \lambda_i (\lambda_j r_i) + \lambda_j (\lambda_i r_j) \\
r = \frac{\lambda_i(\lambda_j r_i)}{\lambda} \cdot \frac{r_i t_c}{r_i + t_c} + \frac{\lambda_j(\lambda_i r_j)}{\lambda} \cdot \frac{r_j t_c}{r_j + t_c} \\
u = \lambda \cdot r \\
\lambda'' = \lambda_i'' (\lambda_j r_i'') + \lambda_j'' (\lambda_i r_j'') \\
r'' = \frac{\lambda_i''(\lambda_j r_i'')}{\lambda} \cdot \frac{r_i'' t_c}{r_i'' + t_c} + \frac{\lambda_j''(\lambda_i r_j'')}{\lambda} \cdot \frac{r_j'' t_c}{r_j'' + t_c} \\
u'' = \lambda'' \cdot r''

c) Components i, j and k are out (3rd order cut): 
\lambda = A + B + C, where 
\begin{align*}
A &= \lambda_i (\lambda_j r_i) (\lambda_k \frac{r_i}{r_i + r_j}) + \lambda_j (\lambda_i r_j) (\lambda_k \frac{r_j}{r_j + r_i}) \\
B &= \lambda_j (\lambda_k r_j) (\lambda_i \frac{r_j}{r_j + r_k}) + \lambda_k (\lambda_j r_k) (\lambda_i \frac{r_k}{r_k + r_j}) \\
C &= \lambda_k (\lambda_i r_k) (\lambda_j \frac{r_k}{r_k + r_i}) + \lambda_i (\lambda_k r_i) (\lambda_j \frac{r_i}{r_i + r_k}) \\
r &= \frac{A}{\lambda} \frac{r_i r_j t_c}{r_i r_j + r_i t_c + r_j t_c} + \frac{B}{\lambda} \frac{r_j r_k t_c}{r_j r_k + r_j t_c + r_k t_c}
\end{align*}
\[ U = \lambda \cdot r \]

\[ \lambda'' = A + B + C + D + E + F, \text{ where} \]

\[ A = \lambda'' \left( \lambda_j r''_j \right) \left( \lambda_k \frac{r_j r''_j}{r_i + r_j} \right) \]

\[ B = \lambda'' \left( \lambda_k r''_j \right) \left( \lambda_i \frac{r_j r''_j}{r_i + r_k} \right) \]

\[ C = \lambda'' \left( \lambda_j r''_j \right) \left( \lambda_k \frac{r_j r''_j}{r_k + r_i} \right) \]

\[ D = \lambda'' \left( \lambda_i \frac{r_j r''_j}{r_i + r_k} \right) \]

\[ E = \lambda'' \left( \lambda_j r''_j \right) \left( \lambda_k \frac{r_j r''_j}{r_j + r_i} \right) \]

\[ F = \lambda'' \left( \lambda_i r''_i \right) \left( \lambda_k \frac{r_j r''_i}{r_k + r_j} \right) \]

\[ r'' = \frac{A}{\lambda''} \frac{r''_i r_j t_c}{r''_i r_j + r''_i r_j t_c + r''_j t_c} + \frac{B}{\lambda''} \frac{r''_i r_k t_c}{r''_i r_k + r''_j r_k t_c + r''_k t_c} + \frac{C}{\lambda''} \frac{r''_k r_i t_c}{r''_k r_i + r''_k r_i t_c + r''_i t_c} + \frac{D}{\lambda''} \frac{r''_j r_k t_c}{r''_i r_k + r''_j r_k t_c + r''_k t_c} + \frac{E}{\lambda''} \frac{r''_j r_i t_c}{r''_i r_j + r''_j r_i t_c + r''_i t_c} + \frac{F}{\lambda''} \frac{r''_k r_j t_c}{r''_k r_j + r''_k r_j t_c + r''_j t_c} \]

\[ \lambda'' = \lambda' \cdot r'' \]

**III - Temporary Outages Due to:**

- An active fault
- An active fault overlapping any existing outage

a) Component i is actively faulted (1st order cut):

\[ \lambda = \lambda^a_i \]

\[ r = S_i \]
\[ U = \lambda . r \]
\[ \lambda'' = r'' = U'' = 0 \]

b) Component \( i \) is actively failed and component \( j \) is out (2nd order cut):

\[ \lambda = \lambda_i^a (\lambda_j^s s_i) + \lambda_j^a (\lambda_i^s r_j) \]
\[ r = \frac{s_i r_i}{s_i + r_j} \]

\[ U = \lambda . r \]
\[ \lambda' = \lambda_i'' (\lambda_j^a r''_j) \]
\[ r'' = \frac{s_i r''_i}{s_i + r''_j} \]
\[ U'' = \lambda''. r'' \]

c) Component \( i \) is actively failed and components \( j \) and \( k \) are out (3rd order cut):

\[ \lambda = \lambda_i^a (\lambda_j^s s_i) (\lambda_k^s \frac{s_i r_j}{s_i + r_j}) + \lambda_i^a (\lambda_k^s s_i) (\lambda_j^s \frac{s_i r_k}{r_k + s_i}) + \]
\[ + \lambda_j^a (\lambda_i^s r_j) (\lambda_k^s \frac{s_i r_j}{s_i + r_j}) + \lambda_j^a (\lambda_k^s r_j) (\lambda_i^s \frac{r_j r_k}{r_j + r_k}) + \]
\[ + \lambda_k^a (\lambda_i^s r_k) (\lambda_j^s \frac{s_i r_k}{s_i + r_k}) + \lambda_k^a (\lambda_j^s r_k) (\lambda_i^s \frac{r_i r_k}{r_i + r_k}) \]
\[ r = \frac{s_i r_j r_k}{s_i r_j + s_i r_k + r_j r_k} \]
\[ U = \lambda \cdot r \]

\[ \lambda'' = A + B, \]  
where

\[ A = \lambda'' \left( \lambda_i^a r'' \right) \left( \lambda_j^a \frac{S_i r''_j}{S_i r''_j + r''_{j+k}} \right) + \lambda'' \left( \lambda_k^a \frac{S_i r''_j}{r''_{j+k} + r''_{j+k}} \right) \]

\[ B = \lambda'' \left( \lambda_i^a r'' \right) \left( \lambda_j^a \frac{S_i r''_k}{S_i r''_j + r''_{j+k}} \right) + \lambda'' \left( \lambda_j^a \frac{S_i r''_k}{r''_{j+k} + r''_{j+k}} \right) \left( \lambda_i^a \frac{S_i r''_k}{r''_{j+k} + r''_{j+k}} \right) \]

\[ r'' = \frac{A}{\lambda''} \frac{S_i r''_j r_k}{S_i r''_j + S_i r_k + r''_{j+k}} + \frac{B}{\lambda''} \frac{S_i r_j r''_k}{S_i r_j + S_i r_k + r''_{j+k}} \]

\[ U'' = \lambda''.r'' \]

**IV - Temporary Outages Due to:**

- An active fault overlapping a stuck breaker condition
- An active fault overlapping any existing outage and a stuck breaker condition

a) Component \( i \) is actively faulted and breaker \( j \) is stuck (1st order cut):

\[ \lambda = \lambda_i^a \lambda_j^p \]

\[ r = S_i \]

\[ U = \lambda \cdot r \]

\[ \lambda'' = r'' = U'' = 0 \]

b) Component \( i \) is actively faulted, breaker \( j \) is stuck and component \( k \) is out (2nd order cut):

\[ \lambda = \lambda_i^a \lambda_j^p \left( \lambda_k^a S_i \right) + \lambda_k^a \left( \lambda_i^a \lambda_j^p r_k \right) \]
\[
\begin{align*}
\lambda &= \lambda^a_{i_m} (\lambda^a_{j_s} S_i) (\lambda^a_{i} S_i \frac{r_j}{S_i + r_j}) + \lambda^a_{i_m} (\lambda^a_{k_k} S_i) (\lambda^a_{j_s} S_i \frac{r_k}{S_i + r_k}) + \\
&+ \lambda^a_{i_m} (\lambda^a_{k_k} S_i \frac{r_j}{S_i + r_j}) + \lambda^a_{j_s} (\lambda^a_{k_k} S_i \frac{r_j}{S_i + r_k}) + \\
&+ \lambda^a_{i_m} (\lambda^a_{k_k} S_i \frac{r_j}{S_i + r_j}) + \lambda^a_{j_s} (\lambda^a_{k_k} S_i \frac{r_j}{S_i + r_k})
\end{align*}
\]

\[
r = \frac{S_i r_j r_k}{S_i r_j + S_i r_k + r_j r_k}
\]

\[
u = \lambda^a r
\]

\[
\lambda' = A + B, \text{ where}
\]

\[
A = \lambda^a_{j_s} (\lambda^a_{i_m} r_j) (\lambda^a_{i_m} S_i \frac{r_j}{S_i + r_j}) + \lambda^a_{j_s} (\lambda^a_{k_k} S_i \frac{r_j}{S_i + r_j}) (\lambda^a_{i_m} \frac{r_j r_k}{S_i + r_j})
\]
\[ B = \frac{\lambda''}{k} \left( \lambda''_a \frac{r^n_k}{r^n_m} \right) \left( \lambda''_j \frac{S_i r^n_k}{S_i + r^n_k} \right) + \frac{\lambda''}{k} \left( \lambda''_j r''_k \right) \left( \lambda''_a \frac{r''_k}{r''_m} \right) \]

\[ r'' = \frac{A}{\lambda''} \left( \frac{S_i r''_j r_k}{S_i r''_j + S_i r_k + r''_j r_k} \right) + \frac{B}{\lambda''} \left( \frac{S_i r_j r''_k}{S_i r_j + S_i r''_k + r_j r''_k} \right) \]

\[ U'' = \lambda'' \cdot r'' \]

**V - Overall Values (for n cut sets)**

\[ \lambda_t = \sum_{i=1}^{n} \lambda_i \]

\[ \lambda''_t = \sum_{i=1}^{n} \lambda''_i \]

\[ U_t = \sum_{i=1}^{n} U_i \]

\[ U''_t = \sum_{i=1}^{n} U''_i \]

\[ r_t = \frac{U_t}{\lambda_t} \]

\[ r''_t = \frac{U''_t}{\lambda''_t} \]

To calculate the three main reliability indices the following equations are used:

\[ \lambda_T (total \ failure \ rate) = \lambda_t + \lambda''_t \]

\[ U_T (total \ outage \ time \ per \ year) = U_t + U''_t \]

\[ r_T (average \ outage \ time) = \frac{U_T}{\lambda_T} \]
Appendix III

Equations to Calculate the Reliability Indices in Systems Where the Component Data Is Dependent of the Weather State

The following equations were used to calculate $\lambda$, $r$, $\lambda''$, and $r''$ for cuts up to 3rd order, where:

$\lambda = \text{Contribution to the total failure rate due to forced outages or to overlapping forced outages (incorporates $\lambda$, $\lambda_t$, and $\lambda_a$)}$

$r = \text{Average outage time due to forced outages (incorporates $r$, $r_t$, and $r_a$)}$

$\lambda'' = \text{Contribution to the total failure rate due to forced outages overlapping a maintenance outage (incorporates $\lambda''$, $\lambda''_t$, and $\lambda''_a$)}$

$r'' = \text{Average outages time due to forced outages overlapping a maintenance outage (incorporates $r''$, $r''_t$, and $r''_a$)}$

The component data required is:

$\lambda_i = \text{Normal weather total failure rate of component } i$

$\lambda'_i = \text{Adverse weather total failure rate of component } i$

$\lambda''_i = \text{Maintenance outage rate of component } i$

$\lambda'_it = \text{Normal weather temporary outage rate of component } i$

$\lambda'_it = \text{Adverse weather temporary outage rate of component } i$

$\lambda'_ia = \text{Normal weather active failure rate of component } i$

$\lambda'_ia = \text{Adverse weather active failure rate of component } i$

$r_i = \text{Expected repair time of component } i$

$r''_i = \text{Expected maintenance time of component } i$

$R_i = \text{Reclosure time of component } i$

$S_i = \text{Switching time of component } i$

$P_i = \text{Stuck probability of component } i$

The weather data required is:

$N = \text{Average duration of a normal weather period}$

$S = \text{Average duration of an adverse weather period}$
1 - Equations to calculate the reliability indices due to component permanent forced outages

1.1 - Repair during adverse weather

a) First order cut set

Let $i$ be the component contained in the cut set, then

$$\lambda = \frac{N}{N+S} \lambda_i + \frac{S}{N+S} \lambda'_i$$

b) Second order cut set

Let the components contained in the cut set be $i$ and $j$, then

$$\lambda = \frac{N}{N+S} \left[ \lambda_i \lambda_j (r_i + r_j) + \frac{S}{N} \left( \lambda'_i \lambda'_j \frac{r_i^2}{r_i + r_j} + \lambda'_i \lambda_j \frac{r_j^2}{r_i + r_j} \right) \right] +$$

$$+ \frac{S}{N+S} \left[ \lambda'_i \lambda_j \frac{r_i}{r_i + r_j} + \lambda'_j \lambda_i \frac{r_j}{r_i + r_j} + \lambda'_i \lambda'_j \frac{r_i r_j}{r_i + r_j} \right]$$

$$+ r = \frac{r_i r_j}{r_i + r_j}$$

c) Third order cut set

Let the components contained in the cut set be $i$, $j$ and $k$, then

$$\lambda = A + B$$

where

$$A = \frac{N}{N+S} \left[ \lambda_i \left[ \lambda'_j \lambda'_k \frac{r_i^2}{r_i + r_j} + \frac{r_k}{r_i + r_k} + \frac{Sr_j^2}{S+r_i} \right] + \lambda'_i \lambda'_j \frac{r_j}{r_i + r_j} \right]$$

$$+ \lambda_j \lambda'_i \lambda'_k \frac{r_k}{N r_i + N r_j + r_i r_j} \right] + \text{similar terms for components } j \text{ and } k \right] +$$

$$+ \frac{S}{N+S} \left[ \lambda'_i \lambda'_j \lambda'_k \left[ \frac{N^2 r_i^2}{N+r_i} \left( \frac{r_i}{N r_i + N r_j + r_i r_j} \right) + \frac{r_k}{N r_i + N r_j + r_i r_j} \right] \right] +$$

$$+ \frac{N S r_i^2}{S + r_i} \left( \lambda'_i \lambda'_j \frac{r_i}{N r_i + N r_j + r_i r_j} + \lambda'_j \lambda'_k \frac{r_k}{N r_i + N r_j + r_i r_j} \right) +$$
and
\[
B = \frac{N}{N+S} \left[ \lambda_i \left[ \lambda_j' \lambda_k' \frac{S^2 r_i^3}{(S+r_i)N} \left( \frac{r_j}{r_i^2 S r_j + r_j r_i} + \frac{r_k}{r_i^2 S r_k + r_k r_i} \right) + \right. \right.
\]
\[
+ \frac{S r_i^3}{N} \left( \frac{r_j^2}{(r_i+r_j)(S r_j + S r_j r_i)} + \frac{r_k^2}{(r_i+r_k)(S r_k + S r_k r_i)} \right) \left. \right] \right]
\]
\[
+ \text{similar terms for component } j \text{ and } k \right]
\]
\[
+ \frac{S}{N+S} \left[ \lambda_i' \left[ \lambda_j' \lambda_k' \frac{S^2 r_i^2}{S r_i + S r_j + r_i r_j} \left( \frac{r_i}{S r_i + S r_j + r_i r_j} + \frac{r_k}{S r_k + S r_k + r_k r_k} \right) + \right. \right.
\]
\[
+ \frac{S r_i^3}{N+S} \left( \frac{r_j^2}{(S r_j + S r_j r_i)(N r_i + N r_j + r_i r_j)} + \frac{r_k^2}{(S r_k + S r_k r_i)(N r_i + N r_j + r_i r_j)} \right) \left. \right] \right]
\]
\[
+ \text{similar terms for components } j \text{ and } k \right]
\]
\[
r = \frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k}
\]

1.2 - No repair during adverse weather

a) First order cut set

Let the component contained in the cut set be \( i \), then
\[
\lambda = \frac{N}{N+S} \lambda_i + \frac{S}{N+S} \lambda_i'
\]
\[
r = \frac{N r_i \lambda_i + S(S+r_i) \lambda_i'}{\lambda_i N + \lambda_i' S}
\]
b) Second order cut set

Let the components contained in the cut set be i and j, then

$$\lambda = A + B$$

where

$$A = \frac{N}{N+S} \left[ \lambda_i \lambda_j (r_i + r_j) + \frac{S}{N} (\lambda_i' \lambda_j' r_i + \lambda_i' \lambda_j r_j) \right]$$

$$B = \frac{S}{N+S} \left[ 2 \lambda_i' \lambda_j' S + \lambda_i \lambda_j' r_i + \lambda_i' \lambda_j r_j \right]$$

$$r = \frac{A}{A+B} \left[ \frac{r_i}{r_i + r_j} \right] + \frac{B}{A+B} \left[ \frac{r_i}{r_i + r_j} + S \right]$$

c) Third order cut set

Let the components contained in the cut set be i, j and k, then

$$\lambda = A + B$$

where

$$A = \frac{N}{N+S} \left[ \lambda_i \lambda_j \lambda_k r_i^2 \left( \frac{r_j}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right) + \right.$$

$$\left. + \frac{S}{N} \lambda_j' \lambda_k \lambda_j \frac{r_j}{r_i + r_j} + \lambda_j \lambda_k' \frac{r_k}{r_i + r_k} \right] + \text{similar terms for components j and k}$$

$$+ \frac{S}{N+S} \left[ \lambda_i' \lambda_j \lambda_k r_i^2 \left( \frac{r_i}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right) + \right.$$

$$\left. + S r_i \left( \lambda_j' \lambda_k \frac{r_j}{r_i + r_j} + \lambda_j \lambda_k' \frac{r_k}{r_i + r_k} \right) \right] + \text{similar terms for components j and k}$$

$$B = \frac{N}{N+S} \left[ \lambda_i' \lambda_j' \lambda_k' \left( \frac{2}{N} \frac{r_i}{r_i + r_j} + \frac{S r_i}{N} \left( \lambda_j \lambda_k \frac{r_i}{r_i + r_j} + \lambda_j' \lambda_k' \frac{r_i}{r_i + r_k} \right) \right] + \right.$$

$$\left. + \text{similar terms for components j and k} \right]$$
\[
+ \frac{S}{N+S} \left[ \lambda_i' \left( \lambda_j \lambda_k \right) S^2 + \frac{S}{N} r_i^2 \left( \lambda_j' \lambda_k + \frac{r_i}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right) \right] + \\
+ \text{similar terms for components } j \text{ and } k
\]

\[
r = \frac{A}{A+B} \left( \frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k} \right) + \frac{B}{A+B} \left( \frac{r_i r_j r_k}{r_i r_j + r_i r_k + r_j r_k} + S \right)
\]

2 - Equations to calculate the reliability indices due to component permanent outages overlapping maintenance periods

2.1 - Weather cannot change during the maintenance period

a) Second order cut set

Let the components contained in the cut set be \( i \) and \( j \), then

\[
\lambda'' = \lambda''_i \lambda''_j + \lambda''_i \lambda''_j
\]

\[
r'' = \lambda''_i \lambda''_j \frac{r''_i}{r''_i + r''_j} + \lambda''_i \lambda''_j \frac{r''_i}{r''_i + r''_j}
\]

\[= \lambda''_i \lambda''_j \frac{r''_i}{r''_i + r''_j} + \lambda''_i \lambda''_j \frac{r''_i}{r''_i + r''_j} \]

\[\lambda'' (r''_i + r''_j)
\]

b) Third order cut set

Let the component contained in the cut set be \( i \), \( j \) and \( k \), then

\[
\lambda''' = A + B + C
\]

where

\[
A = \lambda''_i \lambda''_j \lambda''_k \frac{r''_i}{r''_i + r''_j} + \frac{r''_k}{r''_i + r''_k}
\]

\[
B = \lambda''_j \lambda''_i \lambda''_k \frac{r''_i}{r''_i + r''_j} + \frac{r''_k}{r''_i + r''_k}
\]

\[
C = \lambda''_k \lambda''_i \lambda''_j \frac{r''_k}{r''_k + r''_i} + \frac{r''_k}{r''_k + r''_j}
\]
\[ r^n = \frac{A}{\lambda^n} \left( \frac{r''_i r_j r_k}{r''_i + r''_j + r''_k} \right) + \frac{B}{\lambda^n} \left( \frac{r_i r''_j r_k}{r_i + r_j + r_k} \right) + \frac{C}{\lambda^n} \left( \frac{r_i r_j r''_k}{r_i r_j + r_i r''_j + r_j r''_k} \right) \]

2.2 - Weather can change during the maintenance period

2.2.1 - Repair and maintenance started in normal weather is carried on in adverse weather

a) Second order cut set

Let the components contained in the cut set be i and j, then

\[ \lambda^n = A + B \]

where

\[ A = \lambda^n \lambda_i \lambda_j \frac{r''_{ij}}{N} \frac{S}{S + r''_i} \]

\[ B = \lambda^n \lambda_i \lambda_j \frac{r''_{ij}}{N} \frac{S}{S + r''_j} \]

\[ r^n = \frac{A}{\lambda^n} \left( \frac{r''_{ij}}{r''_i + r''_j} \right) + \frac{B}{A+B} \left( \frac{r_i r''_j}{r_i + r''_j} \right) \]

b) Third order cut set

Let the components contained in the cut set be i, j and k, then

\[ \lambda^n = A + B + C \]

where

\[ A = \lambda^n \left[ \lambda_i \lambda_j \frac{r''_{ij}}{N} \left( \frac{r_j}{r''_i + r''_j + r''_k} + \frac{r_k}{r''_i + r''_j + r''_k} \right) + \right. \]

\[ + \frac{S}{N} \frac{r''_{ij} r''_k}{r_i + r_j} \left( \frac{S r''_{ij} + S r''_j}{r''_i + r''_j + r''_k} \right) \]

\[ + \frac{B}{A+B} \left( \frac{r_i r''_j}{r_i + r''_j} \right) \]
\[ + \lambda'_j \lambda_k \frac{r_i^2}{(r_i^2 + r_j^2)} \left( \frac{S}{r_i^2 + r_j^2} + \frac{S}{r_i^2 + r_j^2} \right) + \]

\[ + \frac{S r_i^3}{S + r_i^2} \frac{\lambda'_j \lambda_k r_j + \lambda'_k \lambda_j r_k}{N r_i + N r_j + r_i r_j} + \frac{\lambda'_k \lambda_j r_i}{N r_k + N r_k + r_i r_k} \]

\[ + \lambda'_j \lambda_k \frac{S^2 r_i^3}{N(S + r_i^2)} \left( \frac{r_j}{S r_i + S r_j + r_i r_j} + \frac{r_k}{S r_k + S r_k + r_i r_k} \right) \]

B and C are similar to A but for components j and k respectively

\[ r_i = \frac{A}{\lambda''} \left( \frac{r_i^2}{r_i^2 + r_j^2} + \frac{r_i r_k}{r_i r_j + r_i r_k + r_j r_k} \right) + \frac{B}{\lambda''} \left( \frac{r_i r_j}{r_i r_j + r_i r_k + r_j r_k} + \frac{r_i r_k}{r_i r_j + r_i r_k + r_j r_k} \right) + \]

\[ + \frac{C}{\lambda''} \left( \frac{r_i r_j}{r_i r_j + r_i r_k + r_j r_k} + \frac{r_i r_k}{r_i r_j + r_i r_k + r_j r_k} \right) \]

### 2.2.2. - Repair and maintenance started in normal weather is discontinued in adverse weather

**a) Second order cut set**

Let the components contained in the cut set be i and j, then

\[ \lambda'' = \lambda_i \lambda_j \frac{r_i^2}{r_i^2 + r_j^2} + \lambda'_j \lambda'_k \frac{S}{r_i^2 + r_j^2} \]

where

\[ A = \lambda'' \lambda_j \frac{r_i^2}{r_i^2 + r_j^2} \]

\[ B = \lambda'' \lambda'_j \frac{S}{N r_i} \]

\[ C = \lambda'' \lambda_i \frac{r_i^2}{r_i^2 + r_j^2} \]

\[ D = \lambda'' \lambda'_i \frac{S}{N r_j} \]

\[ r_i = \frac{A}{\lambda''} \left( \frac{r_i^2}{r_i^2 + r_j^2} + \frac{r_i r_j}{r_i r_j + r_i r_k + r_j r_k} + S \right) + \]

\[ + \frac{C}{\lambda''} \left( \frac{r_i r_j}{r_i r_j + r_i r_k + r_j r_k} + \frac{r_i r_k}{r_i r_j + r_i r_k + r_j r_k} + S \right) \]
b) Third order cut set

Let the components contained in the cut set be \(i\), \(j\) and \(k\), then

\[ \lambda'' = A + B + C + D + E + F \]

where

\[
A = \lambda'' \left[ \lambda_i \lambda_j \lambda_k \frac{r_j^2}{r_i + r_j} + \frac{r_k}{r_i + r_k} \right] \]

\[
+ \lambda_j \lambda_k \left( \frac{r_i}{r_i + r_j} \right) \]

\[
B = \lambda'' \left[ \frac{r_i^2}{N} \left( \lambda_j \lambda_k \frac{r_j}{r_i + r_j} + \lambda_j \lambda_k \frac{r_i}{r_i + r_k} \right) + 2 \lambda_j \lambda_k \frac{r_i}{N} \frac{r_i}{r_j} \right] \]

\(C\) and \(E\) are similar to \(A\) but for components \(j\) and \(k\), respectively

\(D\) and \(F\) are similar to \(B\) but for components \(j\) and \(k\), respectively

3 - Equations to calculate the reliability indices due to component temporary outages

3.1 - Component temporary outages overlapping component permanent outages

a) First order cut set

Let the component contained in the cut set be \(i\), then

\[ \lambda_t = \frac{N}{N+S} \lambda_{it} + \frac{S}{N+S} \lambda'_{it} \]

\[ x_t = R_i \]

b) Second order cut set

Let the components in the cut set be \(i\) and \(j\), then

b-1) No repair during adverse weather

\[ \lambda_t = A + B \]
where
\[ A = \frac{N}{N+S} \left[ \lambda_i \lambda_i \lambda_j t r_i + \frac{S}{N} \lambda_i \lambda_j t r_i \right] + \]
\[ + \frac{S}{N+S} \left[ \lambda_i \lambda_i r_i + \lambda_i \lambda_j t r_i \right] \]
\[ B = \frac{N}{N+S} \left[ \lambda_j \lambda_j r_j + \frac{S}{N} \lambda_j \lambda_j r_j \right] + \]
\[ + \frac{S}{N+S} \left[ \lambda_j \lambda_j r_j + \lambda_j \lambda_j r_j \right] \]
\[ r_t = \frac{A}{A+B} R_i + \frac{B}{A+B} R_j \]

b-2) Repair is carried on during adverse weather
\[ \lambda_t = A + B \]

where
\[ A = \frac{N}{N+S} \left[ \lambda_i \lambda_i \lambda_j t r_i + \frac{S}{N} \lambda_i \lambda_j t \frac{N r_i}{N + r_i} \right] + \]
\[ + \frac{S}{N+S} \left[ \lambda_i \lambda_i \frac{S r_i}{S + r_i} + \lambda_i \lambda_j \frac{S r_i}{S + r_i} \right] \]
\[ B = \frac{N}{N+S} \left[ \lambda_j \lambda_j r_j + \frac{S}{N} \lambda_j \lambda_j \frac{N r_i}{N + r_j} \right] + \]
\[ + \frac{S}{N+S} \left[ \lambda_j \lambda_j \frac{S r_j}{S + r_j} + \lambda_j \lambda_j \frac{S r_j}{S + r_j} \right] \]
\[ x_t = \frac{A}{A+B} R_i + \frac{B}{A+B} R_j \]

c) Similar equations can be written for third order cut sets
3.2 - Component temporary outages overlapping component maintenance periods

3.2.1 - Weather cannot change during maintenance periods

a) Second order cut set

Let the components in the cut set be i and j, then

\[ \lambda''_t = \lambda''_i \lambda_{jt} r''_i + \lambda''_j \lambda_{it} r''_j \]

\[ r''_t = \frac{\lambda''_i \lambda_{jt} r''_i}{\lambda''_t} R_j + \frac{\lambda''_j \lambda_{it} r''_i}{\lambda''_t} R_i \]

b) Third order cut set

Let the components in the cut set be i, j and k, then

\[ \lambda''_t = A + B + C \]

where

\[ A = \lambda''_i \lambda_j \lambda_{kt} \frac{r''_j r''_i}{r''_1 + r''_j} + \lambda''_j \lambda_{kt} \lambda_i \frac{r''_j^2}{r''_j + r''_i} \]

\[ B = \lambda''_i \lambda_{jt} \lambda_k \frac{r''_j^2 r''_k}{r''_1 + r''_k} + \lambda''_k \lambda_{jt} \frac{r''_i}{r''_i + r''_k} \]

\[ C = \lambda''_j \lambda_k \lambda_{it} \frac{r''_j^2 r''_k}{r''_j + r''_k} + \lambda''_k \lambda_{it} \frac{r''_j}{r''_j + r''_k} \]

\[ r''_t = \frac{A}{A + B + C} R_k + \frac{B}{A + B + C} R_j + \frac{C}{A + B + C} R_i \]

3.2.2 - Weather can change during the maintenance period

a) Second order cut set

Let the components in the cut set be i and j, then

a-1) Maintenance is continued in adverse weather

\[ \lambda''_t = A + B \]
where

\[ A = \lambda'' \left[ \lambda'_{jt} r''_{jt} + \lambda'_{jt} \frac{S r''_i}{N(S+r''_i)} \right] \]

\[ B = \lambda'' \left[ \lambda'_{jt} r''_{jt} + \lambda'_{jt} \frac{S r''_j}{N(S+r''_j)} \right] \]

\[ r''_t = \frac{A}{A+B} R_j + \frac{B}{A+B} R_i \]

\( a-2) \) Maintenance is discontinued in adverse weather

\[ \lambda''_t = A + B \]

where

\[ A = \lambda'' \left[ \lambda'_{jt} r''_{jt} + \lambda'_{jt} \frac{S r''_i}{N} \right] \]

\[ B = \lambda'' \left[ \lambda'_{jt} r''_{jt} + \lambda'_{jt} \frac{S r''_j}{N} \right] \]

\[ r''_t = \frac{A}{A+B} R_j + \frac{B}{A+B} R_i \]

\( b) \) Similar equations can be written for third order cut sets

4 - **Equations to calculate the reliability indices due to component active failures (COMPONENT i IS ACTIVELY FAILED)**

4.1 - **Component active failures overlapping permanent outages**

4.1.1 - **Repair during adverse weather**

a) **First order cut set**

Let \( i \) be the component contained in the cut set, then

\[ \lambda'_a = \frac{N}{N+S} \lambda'_{ia} + \frac{S}{N+S} \lambda''_{ia} \]
\[ r_a = S_i \]

b) Second order cut set

Let the components contained in the cut set be \( i \) and \( j \), then

\[
a = \frac{N}{N+S} \left[ \lambda'_{ia} \lambda_j \left( S_i + r_j \right) + \frac{S}{N} \left( \lambda'_{ia} \lambda_j S_i \frac{S_i}{N+S} + \lambda'_{ia} \lambda_j \frac{r_j^2}{N+S} \right) \right] +
\]

\[
+ \frac{S}{N+S} \left[ \lambda'_{ia} \lambda_i S_i + \lambda'_{ia} \lambda_j r_j + \lambda'_{ia} \lambda_j S \left( \frac{S_i}{N+S} + \frac{r_j}{N+S} \right) \right] \]

\[ r_a = \frac{S_i r_j}{S_i + r_j} \]

c) Similar equations can be written for 3rd order cut sets

4.1.2 - No repair during adverse weather

a) First order cut set

As in 4.1.1

b) Second order cut set

Let the components contained in the cut set be \( i \) and \( j \), then

\[ \lambda_a = A + B \]

where

\[
A = \frac{N}{N+S} \left[ \lambda'_{ia} \lambda_j \left( S_i + r_j \right) + \frac{S}{N} \left( \lambda'_{ia} \lambda_j S_i + \lambda'_{ia} \lambda_j r_j \right) \right] + \frac{S}{N+S} \left( \lambda'_{ia} \lambda_j S_i \right) \]

\[
B = \frac{S}{N+S} \left[ \lambda'_{ia} \lambda_j S_i + \lambda'_{ia} \lambda_j r_j \right] \]

\[ r_a = \frac{A}{A+B} \left[ \frac{S_i r_j}{S_i + r_j} \right] + \frac{B}{A+B} \left[ \frac{S_i r_j}{S_i + r_j} + S \right] \]

c) Similar equations can be written for 3rd order cut sets
4.2 - Component active failures overlapping maintenance periods

4.2.1 - Weather cannot change during maintenance

a) Second order cut set

Let the components contained in the cut set be i and j, then

\[ \lambda_a = \lambda_j^i \lambda_{ia}^j r^i \]

\[ r^i = \frac{S_i r_j^i}{S_i + r_j^i} \]

b) Similar equations can be written for 3rd order cut sets

4.2.2 - Weather can change during the maintenance period

4.2.2.1 - Repair and maintenance started in normal weather is carried on in adverse weather

a) Second order cut set

Let the components in the cut set be i and j, then

\[ \lambda_a = \lambda_j^i \lambda_{ia}^j r^i + \lambda_j^i \lambda_{ia}^j \frac{r_j^i}{N} \frac{S}{S + r_j^i} \]

\[ r^i = \frac{S_i r_j^i}{S_i + r_j^i} \]

b) Similar equations can be written for 3rd order cut sets

4.2.2.2 - Repair and maintenance started in normal weather is discontinued in adverse weather

a) Second order cut set

\[ \lambda_a = A + B \]

where

\[ A = \lambda_j^i \lambda_{ia}^j r^i \]

\[ B = \lambda_j^i \lambda_{ia}^j \frac{S}{N} r^i \]
\[ r^n_a = \frac{A}{A+B} \left[ \frac{S_i r^n_j}{S_i + r^n_j} \right] + \frac{B}{A+B} \left[ \frac{S_i r^n_j}{S_i + r^n_j} + S \right] \]

b) Similar equations can be written for 3rd order cut sets

5 - **Equations to calculate the reliability indices due to a component active failure overlapping a stuck breaker condition**

These equations are absolutely identical to those given in section 4 of this appendix. The only required modification is the change of \( \lambda_{ia} \) and \( \lambda'_{ia} \) into \( \lambda_{ia \ k} \) and \( \lambda'_{ia \ k} \), where \( P_k \) is the stuck probability of breaker \( k \) which when stuck after an active failure of component \( i \) causes a load point failure.

6 - **Equations to calculate the reliability indices due to "loss of quality"**

These equations were given in chapter VIII (section 8.4). In section 8.6 it is shown how multi-average repair times for each component can be introduced in the equations given in this appendix.
APPENDIX IV

INTERCONNECTED SYSTEMS

To calculate the reliability indices of a load point in any electrical system the following data is required:

- Network structure data (branches, components in the branches, sources, normally open components, etc.)
- Effects of active failures (protection zones for every component for which an active failure is to be simulated)
- Reliability data for every component

To analyse an interconnected system it is necessary:

(i) to analyse the overall system to evaluate the "equivalent sources" that represent the impact between subsystems. These "equivalent sources" are evaluated calculating the reliability indices of some busbars (see chapter V) in the overall system.

(ii) to analyse each subsystem in turn

Assume that $n_1$ represent the number of columns of one of the arrays, say array $A$, required to store data associated with subsystem $i$. The following applies to all arrays containing input data and is described only for array $A$ (the value of $n_1$ changes with the array being considered but the logic is the same).

When reading in the data to be stored in array $A$ this array is filled sequentially with data from every subsystem, i.e. the data for subsystem 1 is stored between $A(1)$ and $A(n_1)$, the data for subsystem 2 is stored between $A(n_1+1)$ and $A(n_1+n_2)$, etc.
FIG. IV.1 - array A for a system with three subsystems

\( n_1 \) - number of columns required to store data associated with subsystem i

\( n_{int} \) - number of columns required to store data associated with the interconnector system

\( p \) - no. of columns of array A

The data stored in array A contain either component numbers or are directly associated to them. These component numbers are numbered sequentially from 1 to \( C_i \), where \( C_i \) is the number of components in subsystem i. Each component has a new number during the analysis of the overall system; this new number is obtained by

\[
n_{new}(i) = \sum_{j=1}^{i-1} C_j + n(i), \quad \text{where } n_{new}(i) \text{ is the new number for the } n^{th} \text{ component of subsystem } i \text{-} n(i)
\]

With the components renumbered as shown and with array A filled as indicated in fig. IV-1 (and similarly all other arrays storing input data) the overall system is analysed to evaluate the reliability indices of the busbars that are "ends" of the interconnectors. These indices are then stored.

Before starting the analysis of the subsystems, array A is modified (as well as all arrays containing input data) as indicated in fig. IV-2 for the same system as that considered in fig. IV-1
Array A is divided into identical blocks each storing the data associated with one subsystem; The data associated with the interconnector system is stored in the last columns of array A. The component numbers are then changed back to their original numbers in the appropriate subsystem and the analysis of the subsystems starts. After analysing any subsystem array A (and all identical arrays) is modified back to the form shown in Fig. IV.2.

Consider now the analysis of subsystem i. To analyse a subsystem only the first block of array A is considered as data and therefore the positions of the 1st and i\textsuperscript{th} blocks are interchanged. The first \( n_1 \) columns of array A containing the data associated with subsystem i stored in array A define, with all other similar arrays, the subsystem to be analysed. The non-occupied columns of the first block are then used to store the data associated with the components that belong to the interconnectors which have one "end" in the subsystem being analysed; these data is transferred from the last \( n_{\text{int}} \) columns of array A. The other "end" of the interconnectors with one "end" in the i\textsuperscript{th} subsystem is assumed an "equivalent source" not 100\% reliable and its reliability indices are transferred from the array where they were stored during the analysis of the overall system.
APPENDIX V

USERS MANUAL

FOR

RELAPSE

Reliability Evaluation of Auxiliary Electrical Systems of Power Stations
1 - Introduction

This manual describes the use of a digital computer program for evaluating the reliability of the auxiliary electrical system of any power station. The program evaluates the three main reliability indices (expected failure rate, average outage duration and expected annual outage time) for each busbar (i.e. load point) in the system and the expected annual loss of energy from the station due to the unreliability of the auxiliary electrical system.

The program incorporates all realistic failure modes including passive and active failures up to third order, stuck breaker conditions and the effect of maintenance and all realistic restoration modes including repair, replacement, switching, alternative sources of supply and standby plant such as gas turbines and diesel generators.

The program, written in Fortran IV, can perform several functions depending on the parameters specified in the control cards. This versatility is illustrated by the simplified flowchart shown in Fig. 1; any one of the paths being permissible.

The dimensioning of the program can be varied at will; the method by which this can be achieved is explained in the comment cards at the beginning of the program. To analyse a system of 450 components a storage requirement of 51.5 kwords is required.

2 - Main Features of the Program

The program has been developed primarily to evaluate the unreliability of the auxiliary electrical system of a power station in terms of the expected annual MW hr. lost. Many other important calculations are made during this evaluation and the program can be used to evaluate any or all of these subcalculations only.

The most important of these subcalculations are:
FIG. 1 - Simplified flowchart showing program versatility

Any path between START and END may be used
a) the failure modes up to three overlapping outages and the
reliability indices detailed in Section 1 for each specified busbar
b) the independent failure modes of the generating units and the
expected encounter rate, average duration and annual residence time of
each derated state.

The main features included in the program are failures due to
passive events, active events, stuck breakers and maintenance outages
and restoration due to repair, replacement, closing of normally open
paths and use of standby plant. The program can also include the impact
due to the failure of the normally open paths when they are required to
operate.

The program automatically simulates the impact of active failures
and the impact of stuck breakers. In the latter case back-up protection
zones are evaluated internally as required.

The program permits a complex system to be decomposed into subsystems
linked via normally open or normally closed interconnectors. The program
automatically replaces these interconnectors by "equivalent sources" and
analyzes each subsystem in turn. It then recomposes the complete system to
evaluate the overall indices.

3 - Assumptions

The following assumptions were made when developing and programming
the techniques required to analyze the auxiliary electrical system of a
power station:

a) the criterion for success was assumed to be one of continuity only.
This means that a busbar failure occurs only when there is no path between-
it and any source and the outage time is equal to the time taken to re-
establish one of these paths.

b) the failure events were identified as the minimal cut sets
associated with the minimal paths between the busbar of interest and all
sources. Briefly a minimal path is a path between a source and the busbar in which a given component or branch appears only once, i.e. paths containing loops are ignored. A minimal cut set is a set of components which, when failed, causes failure of all minimal paths and therefore the busbar but, when any one component of that cut is restored, at least one minimal path is established.

c) when more than two busbars, each of which by itself causes a derated state, fail in a subsystem (or the complete system if it is not decomposed into subsystems), the loss of power associated with that subsystem is assumed to be 100%.

4 - Theory

The user is referred to the thesis "Reliability Evaluation of Electrical Systems" by M. F. De Oliveira, UMIST, 1976 for complete details of the theory, concepts and techniques that have been developed and used in this program.

5 - Output of Program

Used in its most complete form, the program will evaluate and print out the following information.

a) all the input information and data

b) all the independent failure modes of each specified busbar (i.e. load point)

c) the reliability indices (expected failure rate, average outage duration and expected annual outage time) due to overlapping forced outages and forced outages overlapping a maintenance outage for each busbar failure mode and for each specified busbar.

d) the independent failure modes and the reliability indices for each subsystem together with the loss of output power associated with each failure mode.
e) the expected encounter rate, average duration and expected annual residence time for each of the derated states caused by the unreliability of each of the subsystems

f) the expected annual loss of energy due to the unreliability of each subsystem.

g) the expected annual loss of energy due to the unreliability of the complete auxiliary electrical system

In all cases the output information is printed out under self-explanatory and appropriate headings.

6 - Data Preparation

6.1 - General

To prepare the data for presentation to the program, the system to be analysed is divided into a number of subsystems and an interconnector system. It is recommended, but not essential, for each subsystem to be the auxiliary system associated with each unit of the power station plus one or more subsystems, if required, that are associated with supplies that are common to more than one or to all units. If the system is not divided into subsystems, there is no interconnector system and the data preparation for the complete system is identical to that described below for one subsystem of a complex system.

6.2 - Subsystem

Each subsystem of the auxiliary electrical system of a power station would normally be the electrical system associated with each unit or a part of the overall system that affects or has an impact on either more than one unit or on the complete station

a) Network topology

All the components to be considered in the analysis must be identified.
These components should include all sources (input feeding points) and all busbars even if they are to be considered as 100% reliable. The components so identified in each subsystem are consecutively numbered starting from 1 (i.e. 1, 2, ... p where p is the number of identified components in the subsystem). These numbers may be freely associated with any component. The reliability indices for all of these components must be ascertained and specified in the input data; those for components that are considered 100% reliable being specified as zero.

The branches of the subsystem must be identified where a branch is defined as a set of components connected in series and usually terminating at two busbars. Branches through which the power is permitted to flow in one direction only are defined as unidirectional branches and those through which power is permitted to flow in either direction are defined as bidirectional branches. The branches so identified in each subsystem must be consecutively numbered starting from 1 (i.e. 1, 2, ... n, where n is the total number of branches in the subsystem). The unidirectional branches must have the lowest branch numbers, i.e. the unidirectional branches should be numbered (1, 2, ... m, where m is the number of unidirectional branches) and the bidirectional branches should be numbered (m+1, m+2, ... n). The sources and all busbars must be designated as ends of branches.

b) Components connected off the busbars

The loads off the busbars, i.e. motors, etc., that are fed by the busbar to which they are attached, are modelled using an "equivalent component" concept. Generally, each of these loads are fed by branches that may contain three components: a breaker, a cable and a motor or other load. Identical branches connected to the same busbar are identified. Each group of identical branches is numbered as if it were only one branch, i.e. the group is allocated only one branch number and this would normally be a unidirectional branch number. This branch is therefore an "equivalent
branch" and contains the same number of components as each of the individual branches it represents, e.g. a breaker, a cable and a motor.

The components of the individual branches are defined as "real components" and those of the equivalent branch are defined as "equivalent components". Only the equivalent components are numbered as components of the subsystem. The real components are therefore ignored in the component numbering scheme although the number of individual branches forming the equivalent branch must be identified and the reliability indices of the real components ascertained.

(c) **Protection zones**

The breakers that would trip following an active failure on each component (including breakers) must be identified and specified. In this section it is recommended that breakers which may trip but are not in a normally closed path between a normal source of supply and the failed component should not be specified; to include them increases both the execution time and the required storage. At present the program is dimensioned so that up to 5 breakers can be specified for each actively failed component. Back-up protection zones are deduced automatically by the program.

(d) **Output power of subsystem**

Each subsystem is associated with an output power expressed in MW. This is either the rating of the unit with which the subsystem is associated, the combined rating of the units if it is associated with more than one unit or the overall output capacity of the station if it is associated with all units.

(e) **Derating effect of busbar failures**

Every busbar in the subsystem must be associated with a reduction of power expressed as a percentage which represents the percentage loss of subsystem output power when that busbar fails.

The percentages associated with single busbar outages will generally
be 0% (no impact on the subsystem), 100% (total failure of the subsystem) or \( x\% \) where \( 0 < x < 100 \) (partial failure of the subsystem).

There may however be instances where a busbar is best associated with one of the subsystems but which has an impact on other subsystems. In such cases the output power that should be associated with the busbar is therefore the sum of the output powers associated with each affected subsystem. Consequently the reduction of power associated with such busbars expressed as a percentage of the output power of the subsystem in which it resides may be greater than 100%.

The percentage impact of all busbars defined as load point busbars (see point f) must be specified even if they are 0% busbars. No other busbars should be included.

All busbars that are specified as having an \( x\% \) impact when considering single busbar outages must be identified and all combinations of two such busbars must be deducted. The percentage impact of each combination must be specified as \( y\% \) where \( y \) must be greater than zero.

There may be instances where busbars are known to have a 0% impact when forming a single busbar outage but are known to have an impact greater than zero when in combination with another busbar specified as having a 0% or \( x\% \) impact. In such cases, the percentage impact of all such busbars should be specified, not as zero, but as an extremely small value (0.0001%)

f) **Load point busbars**

Busbars for which the failure events or failure events and reliability indices are to be evaluated are defined as load point busbars. All such load points must be identified and specified. It should be noted that all busbars having a specified impact on the output of a subsystem must be specified as load point busbars.

g) **Changes in derating effect of busbars**

There are some systems in which the percentage impact of some busbars change when a spare motor is connected to a 0% busbar, say, and is used only
when the main motor connected to another busbar fails. During the outage
time of the main motor, the busbar to which the spare motor is connected
becomes a 100% busbar, say. Two such components can be modelled in each
subsystems; the only additional data being the unavailability data of
the main components and the new percentage impact on the busbars.

h) Standby plant

Standby plant should be modelled as a source connected to the
appropriate busbar(s) through a normally open breaker with both numbered
within the component numbering scheme. The stuck probability of the normally
open breaker is the combined probability of a stuck breaker condition and
a running-up failure; the switching time of the normally open breaker is its
own switching time plus the start-up time of the standby plant. The total
failure rate of the standby plant is its running failure rate; the active
failure rate and switching time of the standby source are not required and
can be inserted as blank.

i) Subsystems to be analysed

There are some occasions when it is not required to analyse all of
the subsystems. The control data permits the user to select only those
subsystems that he requires to be analysed.

6.2 - Interconnector System

An interconnector is defined as a link between subsystems. The compo-
nents of an interconnector do not belong to any of the subsystems. All the
interconnectors in the auxiliary electrical system form one interconnector
system. The components of the interconnector system are consecutively
numbered starting from 1 (i.e. 1, 2, ... 1, where 1 is the total number
of components in the interconnector system). Each interconnector is also
consecutively numbered starting from 1 (i.e., 1, 2, ... k, where k is the
total number of interconnectors in the interconnector system, i.e. in the
auxiliary electrical system). All interconnectors are automatically assumed
to be bidirectional system branches, i.e. branches through which the power is permitted to flow in either direction.

7 - Data Cards

Having defined the subsystems and the interconnector system as described in Section 6, the data cards are produced and ordered as described in this section. These are grouped as sets of data, the order of which must be strictly adhered to. The organization of these data sets and their preparation are shown in the flowchart of Fig. 2. The input data are defined either as integer variables (I) or real (decimal) variables (F) where for example:

I5 indicates that 5 columns have been allocated for this integer variable and therefore up to 5 integer numbers, right justified, can be specified. A decimal point must not be included.

F10.3 indicates that 10 columns have been allocated for this real variable and therefore up to 10 digits including the decimal point can be specified. It is recommended that the decimal point should always be punched, e.g. 100 MW should be punched 100.0 or 100.0. If the decimal point is included, the variable may be punched in any of the columns allocated. If the decimal point is omitted the computer will assume a number of decimal digits as indicated by the second figure in the designated F field, e.g. F10.3 will assume that the variable entered has 3 decimal places counting from last column allocated. If a given variable to be specified is zero, it can be punched as 0 or 0.0 or preferably, the entry left blank.

(i) Title and Comments (optional) - as many cards as required

Any alphanumeric title and comments may be punched in columns 1-80 of as many cards as required. This will be printed on the first page of
the computer output.

(ii) Title Termination (obligatory) - 1 card

*END OF COMMENTS must be punched in columns 1-16

(iii) Control Data (obligatory) - 2 cards

a) Card 1

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>number of subsystems</td>
<td>1</td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>total number of interconnectors in the interconnector system</td>
<td>0</td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>total number of normally open breakers in all the interconnectors, i.e. in the interconnectors system</td>
<td>0</td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>total number of components in all the interconnectors, i.e in the interconnector system</td>
<td>0</td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>control: 0 or 1 (see note a)</td>
<td>0</td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>control: 0 or 1 (see note b)</td>
<td>1</td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>control: 0 or 1 (see note c)</td>
<td>0</td>
</tr>
<tr>
<td>36 - 40</td>
<td>I 5</td>
<td>control: 0 or 1 (see note d)</td>
<td>0</td>
</tr>
<tr>
<td>41 - 45</td>
<td>I 5</td>
<td>maximum number of overlapping outages to be considered (1, 2 or 3)</td>
<td>3</td>
</tr>
<tr>
<td>46 - 50</td>
<td>I 5</td>
<td>0 = stuck breakers considered 0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 = stuck breakers not considered</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>51 - 55</td>
<td>I 5</td>
<td>control: 0 or 1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note c)</td>
<td></td>
</tr>
<tr>
<td>56 - 60</td>
<td>I 5</td>
<td>control: 0 or 1 or 2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note f)</td>
<td></td>
</tr>
<tr>
<td>65 - 70</td>
<td>I 5</td>
<td>maximum number of overlapping failures considered in n/o paths (1 or 2)</td>
<td>2</td>
</tr>
</tbody>
</table>

**Notes**

(note a) if = 0 : the normally open paths are assumed may fail when required to operate

if = 1 : the normally open paths are assumed not to fail when required to operate

(note b) if = 1 : the normally open paths are assumed may fail when the "equivalent sources" required to analyse a subsystem are evaluated

if = 0 : the normally open paths are assumed not to fail when the "equivalent sources" are evaluated. This option is recommended when analysing a large system in order to reduce computing time

if the option under (note a) is = 1, the program automatically considers the option under (note b) to be = 0 irrespective of the input value. If the option under (note a) is = 0, however, the program accepts the input value under note (b)

(note c) if = 0 : the reduction of power associated with each subsystem and the overall reduction of power of the station is evaluated

if = 1 : the reduction of power is not evaluated

(note d) if = 0 : the reliability indices are evaluated and therefore component reliability data must be inputted
if = 1 : the reliability indices are not evaluated and no component reliability data is required. The program deduces and prints out all the failure events however but not more than one subsystem can be considered when using this option

(note c) if = 0 : the list of normally open paths is not printed out
if = 1 : the list of all normally open paths is printed out

(note f) if = 0 : the subcalculations made to evaluate the "equivalent sources" for analysing each subsystem are not printed out
if = 1 : the subcalculations made to evaluate the "equivalent sources" are printed out
if = 2 : the subcalculations made to evaluate the "equivalent sources" are not printed out nor are the details of the individual failure modes for each busbar. Only the overall reliability indices for each busbar and for the subsystem are printed out

b) Card 2

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>subsystem number to be analysed</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>subsystem number to be analysed</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all subsystems to be analysed have been included

NOTE : if all subsystems are to be analysed, insert a blank card.

(iv) Subsystem Data (one group of cards for each subsystem)

a) Control data (obligatory) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>subsystem number</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(program error)</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>total number of components</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in subsystem including</td>
<td>(program error)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&quot;equivalent components&quot;</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>total number of &quot;equivalent components&quot; off the busbars in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>total number of branches in the subsystem including &quot;equivalent branches&quot; (program error)</td>
<td>0</td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>number of unidirectional branches in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>number of components on which an active failure is to be simulated</td>
<td>0</td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>number of sources in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>36 - 40</td>
<td>I 5</td>
<td>number of busbars at which the reliability indices are to be evaluated</td>
<td>0</td>
</tr>
<tr>
<td>41 - 45</td>
<td>I 5</td>
<td>number of normally open breakers in the subsystem</td>
<td>0</td>
</tr>
</tbody>
</table>

b) **Source data (obligatory) - 1 card**

1 - 5     I 5     source number

6 - 10    I 5     source number

... sequentially until all source numbers are included

c) **Load point busbar data (obligatory) - 1 card**

1 - 3     I 3     busbar number at which reliability indices are to be evaluated

4 - 6     I 3     ditto

... sequentially until all load point busbars are included
d) **network topology data (obligatory)** - 1 card for each branch in the subsystem including "equivalent branches"

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>branch number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>sending end number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note a)</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>receiving end number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note a and note b)</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>branch component number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>nearest sending end</td>
<td></td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>next branch component number</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all branch components are included

(note a) for bidirectional branches, the sending end and receiving end are chosen arbitrarily; for unidirectional branches, the sending and receiving ends define the direction of power flow

(note b) if a branch has only one of its ends in the subsystem being considered, the receiving end number is punched as zero (0) or left blank

e) **normally open component data (obligatory if normally open components exist)** - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>normally open component number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all normally open components are included
f) **active failure and protection data** (obligatory if active failures are to be considered) - 1 card for each actively failed component

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number where active failure is to be simulated</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>breaker number that protects the actively failed component</td>
<td></td>
</tr>
<tr>
<td>16 - 15</td>
<td>I 5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all relevant breakers are included

g) **component reliability data** (obligatory if reliability indices are to be evaluated) - 1 card for each component but not including "equivalent components" off the busbars

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number</td>
<td></td>
</tr>
<tr>
<td>6 - 15</td>
<td>F10.3</td>
<td>total failure rate in f/yr</td>
<td></td>
</tr>
<tr>
<td>16 - 25</td>
<td>F10.3</td>
<td>active failure rate in f/yr</td>
<td></td>
</tr>
<tr>
<td>26 - 35</td>
<td>F10.3</td>
<td>average repair time in hrs</td>
<td></td>
</tr>
<tr>
<td>36 - 45</td>
<td>F10.3</td>
<td>switching time in hrs</td>
<td></td>
</tr>
<tr>
<td>46 - 55</td>
<td>F10.3</td>
<td>stuck probability</td>
<td></td>
</tr>
<tr>
<td>56 - 65</td>
<td>F10.3</td>
<td>maintenance rate in outages/yr</td>
<td></td>
</tr>
<tr>
<td>66 - 75</td>
<td>F10.3</td>
<td>average maintenance time in hrs</td>
<td></td>
</tr>
<tr>
<td>76 - 80</td>
<td>I 5</td>
<td>N (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The integer N indicates that the next N cards define components having the same reliability indices as those just read. In the next N cards, columns 6-80 may be left blank which reduces data preparation for identical components. If new data is to be inputted then N is punched zero or left blank.
h) "equivalent components" reliability data (obligatory if components off the busbars are to be evaluated as "equivalent components") - 1 card for each "equivalent component"

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>number of real components that the &quot;equivalent component&quot; represents</td>
<td></td>
</tr>
<tr>
<td>16 - 25</td>
<td>F10.3</td>
<td>active failure rate of a real component in f/yr</td>
<td></td>
</tr>
<tr>
<td>36 - 45</td>
<td>F10.3</td>
<td>switching time in hrs</td>
<td></td>
</tr>
<tr>
<td>46 - 55</td>
<td>F10.3</td>
<td>stuck probability</td>
<td></td>
</tr>
<tr>
<td>76 - 80</td>
<td>I 5</td>
<td>M (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The integer M indicates that the next M cards define "equivalent components" having the same reliability indices as that just read. In the next M cards, columns 11-80 may be left blank. If new data is to be inputted then M is punched zero or left blank.

(v) Interconnector data (obligatory if the system has more than one subsystems)

a) interconnector branch data (obligatory) - 1 card for each interconnector

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>interconnector number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>subsystem number in which one end of the interconnector belongs</td>
<td></td>
</tr>
<tr>
<td>11 - 18</td>
<td>I 5</td>
<td>busbar number to which this end of interconnector is connected</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>subsystem number in which the other end of the interconnector belongs</td>
<td></td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>busbar number to which this end of interconnector is connected</td>
<td></td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>component number of interconnector nearest end defined in columns 6-10</td>
<td></td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>next component number</td>
<td></td>
</tr>
</tbody>
</table>

...... sequentially until all components of interconnector are included

b) normally open component data (obligatory if normally open components exist) - 1 card

1 - 5    I 5    normally open component number

6 - 10   I 5    ditto

...... sequentially until all normally open components are included

c) component reliability data (obligatory) - 1 card for each component data format as for data set (iv g)

(vi) Subsystem output power data (obligatory if reduction of power is to be evaluated) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>F10.2</td>
<td>output power (MW) associated with subsystem 1</td>
<td></td>
</tr>
<tr>
<td>11 - 20</td>
<td>F10.2</td>
<td>output power (MW) associated with subsystem 2</td>
<td></td>
</tr>
</tbody>
</table>

...... sequentially until all output powers have been included

(vii) Reduction of output power data (obligatory if reduction of power is to be evaluated) - 1 group of cards for each subsystem

NOTE: order of insertion of each group of cards:
- if a restricted number of subsystems to be analysed have been specified in data set (iii b), the order of insertion must be as specified in data set (iii b)

- if all subsystems are to be analysed and data set (iii b) is blank, the order of insertion must be subsystem 1, subsystem 1, etc, i.e. in ascending order of subsystem number

(a) single busbar outages - as many cards as required

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>F 5.2</td>
<td>reduction of power expressed as a percentage of the subsystem output power</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>F 5.2</td>
<td>reduction of power in %</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all single busbar outages have been included

(b) combination of 2 busbar outages - as many cards as required - Card 1

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>number of combinations of two busbars (each causing an x% reduction) to be considered</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>F 5.2</td>
<td>reduction of power expressed as percentage of the subsystem output power caused by combined outage of the two above busbars</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all combinations have been included or the card is completed
card 2 and following

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>F 5.2</td>
<td>reduction of power</td>
<td></td>
</tr>
</tbody>
</table>

...... sequentially until all combinations have been included or column 75 has been reached

(c) Change of busbar consequences - unavailability data (obligatory) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>F10.3</td>
<td>outage rate of component 1 in outages/yr</td>
<td></td>
</tr>
<tr>
<td>11 - 20</td>
<td>F10.3</td>
<td>average repair time of component 1 in hrs</td>
<td></td>
</tr>
<tr>
<td>21 - 30</td>
<td>F10.3</td>
<td>outage rate of component 2 in outages/yr</td>
<td></td>
</tr>
<tr>
<td>31 - 40</td>
<td>F10.3</td>
<td>average repair time of component 2 in hrs</td>
<td></td>
</tr>
</tbody>
</table>

This card defines the two components which, when lost, causes a change in the impact of some busbars. If this change is not to be considered, a blank card must be inserted

(d) new busbar consequences (obligatory if above card is not blank) data format as for data sets (vii a and b)

(viii) Continuation or termination card (obligatory) - 1 card

If further systems to be analysed punch *CONTINUE in columns 1-9

If no further systems to be analysed punch *END OF RUN in columns 1-11
FIG. 2 - Flowchart showing data preparation
APPENDIX VI

USERS MANUAL

FOR

RELNET 2

Reliability Evaluation of Power System Networks
1 - Introduction

This manual describes the use of a digital computer program for evaluating the reliability of power system networks, e.g. transmission and distribution systems. The program evaluates the three main reliability indices (expected failure rate, average outage duration and expected annual outages time) for each load point in the system and, when required, the overall system reliability indices.

The program incorporates all realistic failure modes including passive and active failures, temporary failures, stuck breaker conditions, the effects of weather dependent failures and the effect of maintenance. The restoration modes include repair, replacement, switching, reclosure and load scheduling.

The program, written in Fortran IV, can perform several functions depending on the parameters specified in the control cards. This versatility is illustrated by the simplified flowchart shown in fig. 1; any one of the paths being permissible.

The dimensioning of the program can be varied at will; the method by which this can be achieved is explained in the comment cards at the beginning of the program. To analyse a system of 450 components a storage requirement of 60 kwords is required.

2 - Main Features of the Program

The program has been developed primarily to evaluate the load point reliability indices of transmission and distribution systems. Many other important calculations are made during this evaluation and the program can be used to evaluate any or all of these sub-calculations only. The most important of these subcalculations are:

a) Identification of the load point failure events
b) Identification of the possible restoration modes following a failure
c) Evaluation of the contributions to the load point reliability indices
FIG. 1 - Simplified flowchart showing program versatility
(a) any path between START and END may be used
due to failures that can be eliminated by:
- working action
- switching action
- reclosure action
- load scheduling

d) Evaluation of the overall system failure events when a single overall objective is defined and the corresponding reliability indices.

The main features included in the program are failures due to passive events, active events, temporary events, stuck breakers and maintenance outages and the possibility of incorporating a two-weather state model according to five specified options (see section 7, (iii), note a). The restoration modes considered include the possible use of standby plant assuming that it is connected to the system through a normally open breaker. The program can also include the impact due to failures of the normally open paths when they are required to operate.

The program automatically simulates the impact of active failures and the impact of stuck breakers. In the latter case back-up protection zones are evaluated internally as required.

The program permits a complex system to be decomposed into subsystems linked via normally open or normally closed interconnectors. The program automatically replaces these interconnectors by "equivalent sources" and analyses each subsystem in turn. It then recomposes the complete system to evaluate the overall indices when each of the subsystems has a single overall objective.

3 - Assumptions

The following assumptions were made when developing and programming the techniques required to analyse transmission and distributions systems:

a) The maximum load level that the system can withstand after single and required double outages is considered to be known from a previous security
assessment study or probabilistic load flow analysis. For each load level \( x \), the average duration of a load level greater than \( x \) and the probability of occurrence of a load level greater than \( x \) are assumed as input data for the present program.

b) If the data referred to in a) is not available the criterion for success is assumed to be one of continuity only. This means that a busbar failure occurs only when there is no path between it and any source and the outage time is equal to the time taken to re-establish one of these paths.

c) The failure events were identified as the minimal cut sets associated with the minimal paths between the busbars of interest and all sources. "Loss of quality" is taken into account, when the data referred to in a) is available, by considering partial loss of the minimal cut sets.

d) To calculate the overall system reliability indices the loss of more than two busbars, each causing a partial loss of the system objective, in a subsystem (or in the complete system if it is not decomposed into sub-systems) is considered to cause 100% reduction of the system objective.

4 - Theory

The user is referred to the thesis "Reliability Evaluation of Electrical Systems" by M.F. De Oliveira, UMIST, 1976 for complete details of the theory, concepts and techniques that have been developed and used in this program.

5 - Output of Program

Used in its most complete form, the program will evaluate and print out the following information:

a) all the input information and data

b) all the independent failure events of each specified busbar (i.e. load point)

c) for each failure event considered in b) the reliability indices associated with its possible restoration modes (i.e. switching, repair,
reclosure and load scheduling)

d) the reliability indices (expected failure rate, average outage duration and expected annual outage time) due to overlapping forced outages and forced outages overlapping a maintenance outage for each busbar restoration mode and for each specified busbar

e) the expected encounter rate, average duration and expected annual residence time for each system state caused by the unreliability of each of the subsystems

f) the expected annual loss of the system objective due to the unreliability of each subsystem

g) the expected annual loss of the system objective due to the unreliability of the complete system

In all cases the output information is printed out under self-explanatory and appropriate headings.

6 - Data Preparation

6.1 - General

To prepare the data for presentation to the program, the system to be analysed is divided into a number of subsystems and an interconnector system. Each subsystem should be associated with a single known objective if the overall system indices are required. If the system is not divided into subsystems, there is no interconnector system and the data preparation is identical to that described below for one subsystem of a complex system.

6.2 - Subsystem

Each subsystem would normally be associated with a geographical area but any criteria can be used to define a subsystem
a) Network Topology

All the components to be considered in the analysis must be identified. These components should include all sources (input feeding points) and all busbars even if they are to be considered as 100% reliable. The components so identified in each subsystem are consecutively numbered starting from 1 (i.e., 1, 2 ... p where p is the number of identified components in the subsystem). These numbers may be freely associated with any component. The reliability indices for all of these components must be ascertained and specified in the input data; those for components that are 100% reliable being specified as zero.

The branches of the subsystem must be identified where a branch is defined as a set of components in series and usually terminating at two busbars. Branches through which the power is permitted to flow in one direction only are defined as unidirectional branches and those through which power is permitted to flow in either direction are defined as bidirectional branches. The branches so identified in each subsystem must be consecutively numbered starting from 1 (i.e., 1, 2 ... n where n is the total number of branches in the subsystem). The unidirectional branches must have the lowest branch numbers, i.e., the unidirectional branches should be numbered 1, 2, ... m where m is the number of unidirectional branches and the bidirectional branches should be numbered m+1, m+2, ... n. The sources and all busbars must be designated as ends of branches.

b) Components off the busbars

The loads off the busbars not included within the system boundary are modelled using an "equivalent component" concept. Generally, each of these loads are fed by branches that contain only a few components, say a breaker, a cable (or a line) and a motor or other load. Identical branches connected to the same busbar are identified. Each group of identical branches is numbered as if it were only one branch, i.e., the group is allocated only one branch number and this would normally be a unidirectional
branch number. This branch is therefore an "equivalent branch" and contains the same numbers of components as each of the individual branches it represents, e.g. a breaker, a cable (or a line) and a motor or other load.

The components of the individual branches are defined as "real components" and those of the equivalent branch are defined as "equivalent components". Only the equivalent components are components of the subsystem. The real components are therefore ignored in the component numbering scheme although the number of individual branches forming the equivalent branch must be identified and the reliability indices of the real components ascertained.

d) **Protection zones**

The breakers that would trip following an active failure on each component (including breakers) must be identified and specified.

In this section it is recommended that breakers which may trip but are not in a normally closed path between a normal source of supply and the failed component should not be specified; to include them increases both the execution time and the required storage. At present the program is dimensioned so that up to 5 breakers can be specified for each actively failed component. Back-up protection zones are deduced automatically by the program.

d) **Subsystem objective**

When the overall system indices are required each subsystem is associated with a number that quantifies the system objective, e.g. total load expected to be supplied, total number of consumers supplied, total revenue associated with the system as if it was 100% reliable, etc.

e) **Effects of busbar failures**

Every busbar in the subsystem must be associated with a reduction of the subsystem objective expressed as a percentage which represents the percentage loss of the subsystem objective when that busbar fails.

The percentages associated with single busbar outages will generally be 0% (no impact on the subsystem), 100% (total failure of the subsystem)
or \( x\% \) where \( 0 < x < 100 \) (partial failure of the subsystem)

There may however be instances where a busbar is best associated with one of the subsystems but which has a impact on other subsystems. In such cases the loss of the system objective that should be associated with the busbar is therefore the sum of the effects associated with each affected subsystem. Consequently the reduction of the system objective associated with such busbars expressed as a percentage of the objective of the subsystem in which it resides may be greater than 100%.

The percentage impact of all busbars defined as load point busbars (see point f) must be specified even if they are 0% busbars. No other busbars should be included.

All busbars that are specified as having as \( x\% \) impact when considering single busbar outages must be identified and all combinations of two such busbars must be deduced. The percentage impact of each combination must be specified as \( y\% \) where \( y \) must be greater than zero.

There may be instances where busbars are known to have a 0% impact when forming a single busbar outage but are known to have an impact greater than 0% when in combination with another busbar specified as having a 0% or \( x\% \) impact. In such cases, the percentage impact of all such busbars should be specified, not as zero, but as an extremely small value (0.0001%).

f) Load point busbars

Busbars for which the failure events or failure events and reliability indices are to be evaluated are defined as load point busbars. All such load points must be identified and specified. It should be noted that all busbars having a specified impact on the system objective must be specified as load point busbars.

g) Changes in the effects of loss of busbars

There are some systems in which the percentage impact of some busbars change due to an event outside the system boundary (i.e. an event that does not affect the busbar indices). Two such events can be modelled in each
subsystem; the only additional data being the rate of occurrence and the average duration of these events and the new percentage impact on the busbars.

h) Standby plants

Standby plants should be modelled as sources connected to the appropriate busbar(s) through a normally open breaker with both numbered within the component numbering scheme. The stuck probability of the normally open breaker is the combined probability of a stuck breaker condition and a running-up failure; the switching time of the normally open breaker is its own switching time plus the start-up time of the standby plant. The total failure rate of the standby plant is its running failure rate; the active failure rate and the switching time of a standby source are not required and can be inserted as blank.

i) Subsystems to be analysed

There are some occasions when it is not required to analyse all of the subsystems. The control data permits the user to select only those subsystems that he requires to be analysed.

6.2 - Interconnector System

An interconnector is defined as a link between subsystems. The components of an interconnector do not belong to any of the subsystems. All the interconnectors in the overall system form one interconnector system. The components of the interconnector system are consecutively numbered starting from 1 (i.e. 1, 2 ... 1 where 1 is the total number of components in the interconnector system). Each interconnector is also consecutively numbered starting from 1 (i.e. 1, 2 ... k where k is the total number of interconnectors in the interconnector system). All interconnectors are automatically assumed to be bidirectional system branches, i.e. branches through which the power is permitted to flow in either direction.
7 - **Data Cards**

Having defined the subsystems and the interconnector system as described in section 6, the data cards are produced and ordered as described in this section. These are grouped as sets of data, the order of which must be strictly observed. The organization of these data sets and their preparation are shown in the flowchart of fig. 2. The input data are defined either as integer variables (I) or real (decimal) variables (F).

(i) **Title and Comments (optional)** - as many cards as required. Any alphanumeric title and comments may be punched in columns 1-80 of as many cards as required. This will be printed on the first page of the computer output.

(ii) **Title Termination (obligatory)** - 1 card

*END OF COMMENTS must be punched in columns 1-16

(iii) **Control Data (obligatory)** - 2 cards or 2 cards + as many cards as load levels + 1

a) **Card 1**

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>control: 1,2,3,4 or 5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note a)</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>control: 0 or 1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note b)</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>number of subsystems</td>
<td>1</td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>total number of interconnectors in the interconnector system</td>
<td>0</td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>total number of normally open breakers in all the interconnectors, i.e. in the interconnector system</td>
<td>0</td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>-------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>total number of components in all the interconnectors, i.e. in the interconnector system</td>
<td>0</td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>control: 0 or 1 (see note c)</td>
<td>0</td>
</tr>
<tr>
<td>36 - 40</td>
<td>I 5</td>
<td>control: 0 or 1 (see note d)</td>
<td>1</td>
</tr>
<tr>
<td>41 - 45</td>
<td>I 5</td>
<td>control: 0 or 1 (see note e)</td>
<td>0</td>
</tr>
<tr>
<td>46 - 50</td>
<td>I 5</td>
<td>control: 0 or 1 (see note f)</td>
<td>0</td>
</tr>
<tr>
<td>51 - 55</td>
<td>I 5</td>
<td>maximum number of overlapping outages to be considered (1, 2 or 3)</td>
<td>3</td>
</tr>
<tr>
<td>56 - 60</td>
<td>I 5</td>
<td>0 = stuck breakers considered 1 = stuck breakers not considered</td>
<td>0</td>
</tr>
<tr>
<td>61 - 65</td>
<td>I 5</td>
<td>control: 0 or 1 (see note g)</td>
<td>0</td>
</tr>
<tr>
<td>66 - 70</td>
<td>I 5</td>
<td>control: 0 or 1 or 2 (see note h)</td>
<td>0</td>
</tr>
<tr>
<td>71 - 75</td>
<td>F 5.1</td>
<td>average duration of a normal weather period (hours)</td>
<td>8760.0</td>
</tr>
<tr>
<td>76 - 80</td>
<td>F 5.1</td>
<td>average duration of an adverse weather period (hours)</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Notes

(note a) if = 1: repair may be started during normal and adverse weather; weather may change during maintenance; repair and maintenance started are continued during adverse weather.

if = 2: repair may be started during normal and adverse weather; weather is assumed not to change during maintenance.

if = 3: repair is not started during adverse weather; weather may change during maintenance; repair and maintenance started during normal weather are continued during adverse weather.

if = 4: repair is not started during adverse weather; weather may change during maintenance; repair and maintenance started during normal weather are discontinued during adverse weather.

if = 5: repair is not started during adverse weather; weather is assumed not to change during maintenance.

If a single state is to be considered insert 1.

(note b) if = 0: the criterion for success is continuity of supply, i.e.

"loss of quality" is not considered.

if = 1: "loss of quality" is taken into account as well as "loss of continuity".

(note c) if = 0: the normally open paths are assumed may fail when required to operate.

if = 1: the normally open paths are assumed not to fail when required to operate.

(note d) if = 1: the normally open paths are assumed may fail when the "equivalent sources" required to analyse a subsystem are evaluated.

if = 0: the normally open paths are assumed not to fail when the "equivalent sources" are evaluated. This option is recommended when analysing a large system in order to reduce computing time.
If the option under (note c) is = 1 the program automatically considers the option under (note d) to be = 0 irrespective of the input value. If the option under (note c) is = 0, however, the program accepts the input value under (note d).

(note e) if = 0 : the overall system indices associated with each subsystem and the overall reduction of the system objective are evaluated

if = 1 : the overall system indices are not evaluated

(note f) if = 0 : the reliability indices are evaluated and therefore component reliability data must be inputted

if = 1 : the reliability indices are not evaluated and no component reliability data is required. The program deduces and prints out all the failure events however but not more than one subsystem can be considered when using this option.

(note g) if = 0 : the list of normally open paths is not printed out

if = 1 : the list of all normally open paths is printed out

(note h) if = 0 : the subcalculations made to evaluate the "equivalent sources" for analysing each subsystem are not printed out

if = 1 : the subcalculations made to evaluate the "equivalent sources" are printed out

if = 2 : the subcalculations made to evaluate the "equivalent sources" are not printed out nor are the details of the individual failure events for each busbar. Only the overall reliability indices for each busbar and for the subsystem are printed out.

(note i) If a single weather state is to be considered leave these columns blank (or insert 0)
b) **Card 2**

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>Subsystem number to be analysed</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>Subsystem number to be analysed</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all subsystems to be analysed have been included

**Note:** if all subsystems are to be analysed, insert a blank card

c) **Load Data** *(obligatory if in card 1 the option under (note b) is = 1)* - as many cards as load levels + 1; One card for each load level

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>number of the load level (x)</td>
<td></td>
</tr>
<tr>
<td>6 - 15</td>
<td>F 10.3</td>
<td>average duration of a load level greater than x (hours)</td>
<td></td>
</tr>
<tr>
<td>16 - 25</td>
<td>F 10.3</td>
<td>probability of occurrence of a load level greater than x</td>
<td></td>
</tr>
</tbody>
</table>

This set of cards must end with a blank card after all load levels have been specified.

(iv) **Subsystem Data** *(one group of cards for each subsystem)*

a) **Control Data** *(obligatory) - 1 card*

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>Subsystem number</td>
<td>0 (program error)</td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>total number of components in the subsystem including &quot;equivalent components&quot;</td>
<td>0</td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>total number of &quot;equivalent components&quot; off the busbars in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>total number of branches in the subsystem including &quot;equivalent branches&quot; (program error)</td>
<td>.0</td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>number of unidirectional branches in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>number of components on which an active failure is to be simulated</td>
<td>0</td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>number of sources in the subsystem</td>
<td>0</td>
</tr>
<tr>
<td>36 - 40</td>
<td>I 5</td>
<td>number of busbars at which the reliability indices are to be calculated (program error)</td>
<td>0</td>
</tr>
<tr>
<td>41 - 45</td>
<td>I 5</td>
<td>number of normally open breakers in the subsystem</td>
<td>0</td>
</tr>
</tbody>
</table>

b) Data to consider "loss of quality" (obligatory if in data set (iii)- card 1, the option under (note b) is = 1) - as many cards as required

b-1) loss of busbars

Card 1

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>number of busbars in the subsystem</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>maximum load level that the system can withstand after an outage of the above busbar</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>--------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>....... sequentially until all busbars have been included or the card is completed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Card 2 and following</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>maximum load level that the system can withstand after an outage of the above busbar</td>
<td></td>
</tr>
<tr>
<td>....... sequentially until all busbars have been included or the card is completed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-2) loss of branches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>branch number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>maximum load level that the system can withstand after an outage of the above branch</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>branch number</td>
<td></td>
</tr>
<tr>
<td>....... sequentially until all branch outages have been included. Use as many cards as required.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: in its present form the program does not consider double branch outages to evaluate the effects of "loss of quality". It is suggested that when the user requires the incorporation of "loss of quality" in the reliability analysis the maximum number of overlapping outages chosen in (iii) - card 1, columns 51-55 should be 2.

c) Source data (obligatory) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>source number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>source number</td>
<td></td>
</tr>
<tr>
<td>....... sequentially until all source numbers are included</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
d) **Load point busbar data (obligatory) - 1 card**

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 3</td>
<td>I 3</td>
<td>busbar number at which the reliability indices are to be evaluated</td>
<td></td>
</tr>
<tr>
<td>4 - 6</td>
<td>I 3</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

...... sequentially until all load point busbars are included

e) **Network topology data (obligatory) - 1 card for each branch in the subsystem including "equivalent branches"**

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>branch number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>sending end number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see note a)</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>receiving end number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(see notes a and b)</td>
<td></td>
</tr>
<tr>
<td>16 -20</td>
<td>I 5</td>
<td>branch component number</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>nearest sending end</td>
<td></td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>next branch component number</td>
<td></td>
</tr>
</tbody>
</table>

...... sequentially until all branch components are included

(note a) for bidirectional branches, the sending end and the receiving end are chosen arbitrarily; for unidirectional branches, the sending and receiving ends define the direction of power flow

(note b) if a branch has only one of its ends in the subsystem being considered, the receiving end number is punched as zero (0) or left blank

f) **Normally open component data (obligatory if normally components exist) - 1 card**
<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>normally open component number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all normally open components are included

g) **Active failure and protection data** (obligatory if active failures are to be considered) - 1 card for each actively failed component

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number where active failure is to be simulated</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>breaker number that protects the actively failed component</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all relevant breakers are included

h) **Component reliability data** (obligatory if reliability indices are to be evaluated) - 2 cards for each component but not including "equivalent branches" off the busbars.

---

**Card 1**

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Defaults</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number</td>
<td></td>
</tr>
<tr>
<td>6 - 15</td>
<td>F 10.3</td>
<td>total failure rate under normal weather (f/yr of normal weather)</td>
<td></td>
</tr>
<tr>
<td>16 - 25</td>
<td>F 10.3</td>
<td>total failure rate under adverse weather (f/yr of adverse weather)</td>
<td></td>
</tr>
<tr>
<td>26 - 35</td>
<td>F 10.3</td>
<td>active failure rate under normal weather (f/yr of normal weather)</td>
<td></td>
</tr>
<tr>
<td>36 - 45</td>
<td>F 10.3</td>
<td>active failure rate under adverse weather (f/yr of adverse weather)</td>
<td></td>
</tr>
<tr>
<td>46 - 55</td>
<td>F 10.3</td>
<td>temporary failure rate under normal weather (f/yr of normal weather)</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>56 - 65</td>
<td>F 10.3</td>
<td>temporary failure rate under adverse weather (f/yr of adverse weather)</td>
<td></td>
</tr>
<tr>
<td>66 - 75</td>
<td>F 10.3</td>
<td>maintenance rate in outages/year</td>
<td></td>
</tr>
</tbody>
</table>

**Card 2**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>Component number (the same as in card 1; if not the program prints out a error massage; check reliability data cards)</td>
<td></td>
</tr>
<tr>
<td>6 - 15</td>
<td>F 10.3</td>
<td>minimum average component repair time (hrs)</td>
<td></td>
</tr>
<tr>
<td>16 - 25</td>
<td>F 10.3</td>
<td>medium average component repair time (hrs)</td>
<td></td>
</tr>
<tr>
<td>26 - 35</td>
<td>F 10.3</td>
<td>maximum average component repair time (hrs)</td>
<td></td>
</tr>
<tr>
<td>36 - 45</td>
<td>F 10.3</td>
<td>component switching time (hrs)</td>
<td></td>
</tr>
<tr>
<td>46 - 55</td>
<td>F 10.3</td>
<td>component reclosure time (minutes)</td>
<td></td>
</tr>
<tr>
<td>56 - 65</td>
<td>F 10.3</td>
<td>average maintenance time (hrs)</td>
<td></td>
</tr>
<tr>
<td>66 - 75</td>
<td>F 10.3</td>
<td>component stuck probability</td>
<td></td>
</tr>
<tr>
<td>75 - 80</td>
<td>I 5</td>
<td>N (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The integer N indicates that the next N cards define components having the same reliability indices as those just read. In the next N cards, columns 6-80 may be left blank and card 2 must not be included, which reduces data preparation for identical components. If new data is to be inputted then N is punches zero or left blank.

1)"Equivalent components" reliability data (obligatory if components off the busbars are to be evaluated as "equivalent components") — 1 card for each equivalent component
<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>component number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>number of real components that the &quot;equivalent component&quot; represents</td>
<td></td>
</tr>
<tr>
<td>11 - 20</td>
<td>F 10.3</td>
<td>Active failure rate under normal weather (f/yr of normal weather)</td>
<td></td>
</tr>
<tr>
<td>21 - 30</td>
<td>F 10.3</td>
<td>active failure rate under adverse weather (f/yr of adverse weather)</td>
<td></td>
</tr>
<tr>
<td>31 - 40</td>
<td>F 10.3</td>
<td>temporary failure rate under normal weather (f/yr of normal weather)</td>
<td></td>
</tr>
<tr>
<td>41 - 50</td>
<td>F 10.3</td>
<td>temporary failure rate under adverse weather (f/yr of adverse weather)</td>
<td></td>
</tr>
<tr>
<td>51 - 55</td>
<td>F 5.2</td>
<td>switching time (hrs)</td>
<td></td>
</tr>
<tr>
<td>56 - 60</td>
<td>F 5.2</td>
<td>reclosure time (minutes)</td>
<td></td>
</tr>
<tr>
<td>61 - 70</td>
<td>F 10.3</td>
<td>stuck probability</td>
<td></td>
</tr>
<tr>
<td>71 - 75</td>
<td>I 5</td>
<td>(M)) (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The integer \(M\) indicates that the next \(M\) cards define "equivalent components" having the same reliability indices as that just read. In the next \(M\) cards, columns 11-80 may be left blank. If new data is to be inputted then \(M\) is punched zero or left blank.

(v) Interconnector data (obligatory if the system has more than one subsystem)

a) Interconnector branch data (obligatory) - 1 card for each interconnector

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>Interconnector number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>Subsystem number in which one end of the interconnector belongs</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>busbar number to which this end of the interconnector is connected</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>I 5</td>
<td>subsystem number in which the other end of the interconnector belongs</td>
<td></td>
</tr>
<tr>
<td>21 - 25</td>
<td>I 5</td>
<td>busbar number to which this end of the interconnector is connected</td>
<td></td>
</tr>
<tr>
<td>26 - 30</td>
<td>I 5</td>
<td>component number of the interconnector nearest end defined in columns 6-10</td>
<td></td>
</tr>
<tr>
<td>31 - 35</td>
<td>I 5</td>
<td>next component number</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all components of the interconnector are included

b) Normally open component data (obligatory if normally open components exist in the interconnector system) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>normally open component number</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>ditto</td>
<td></td>
</tr>
</tbody>
</table>

..... sequentially until all normally open components are included

c) Component reliability data (obligatory) - 2 cards for each component, data format as for data set (IV g)

d) Data to consider "loss of quality" (obligatory if in data set (iii), card 1 the option under (note b) is = 1) - 1 card for each interconnector

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>Interconnector number</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td>Default</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>maximum load level that sub-system 1 can withstand after an outage of the interconnector</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>as above but for subsystem 2</td>
<td></td>
</tr>
<tr>
<td>....... sequentially until all subsystems have been included</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(vi) - Subsystem objective data (obligatory if overall indices are to be evaluated) - 1 card

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>F 10.2</td>
<td>number that quantifies the &quot;objective&quot; of subsystem 1</td>
<td></td>
</tr>
<tr>
<td>11 - 20</td>
<td>F 10.2</td>
<td>number that quantifies the objective of subsystem 2</td>
<td></td>
</tr>
<tr>
<td>....... sequentially until all subsystems have been included</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(vii) - Reduction of subsystem objective data (obligatory if overall indices are to be evaluated) - 1 group of cards for each subsystem

Note: order of insertion of each group of cards

- if a restricted number of subsystems to be analysed have been specified in data set (iii b), the order of insertion must be as specified in data set (iii b)

- if all subsystems are to be analysed and data set (iii b) is blank, the order of insertion must be subsystem 1, subsystem 2, etc., i.e. in ascending order of subsystem number

a) Single busbar outages - as many cards as required

<table>
<thead>
<tr>
<th>Columns</th>
<th>Format</th>
<th>Meaning</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Format</td>
<td>Meaning</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>6 - 10</td>
<td>F 5.2</td>
<td>reduction of the subsystem objective expressed as a percentage of the number that quantifies the objective of the subsystem</td>
<td></td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>busbar number</td>
<td></td>
</tr>
<tr>
<td>16 - 20</td>
<td>F 5.2</td>
<td>reduction of the subsystem objective in %</td>
<td></td>
</tr>
</tbody>
</table>

... sequentially until all single busbar outages have been included

b) Combination of 2 busbars outages - as many cards as required

**Card 1**

<table>
<thead>
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<tbody>
<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>number of combinations of two busbars (each causing an x% reduction) to be considered</td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>busbar number</td>
</tr>
<tr>
<td>11 - 15</td>
<td>I 5</td>
<td>busbar number</td>
</tr>
<tr>
<td>16 - 20</td>
<td>F 5.2</td>
<td>reduction of the subsystem objective expressed as a percentage of the number that quantifies the objective of the subsystem caused by the combined outage of the two above busbars</td>
</tr>
</tbody>
</table>

... sequentially until all combinations have been included or the card is completed

**Card 2 and following**

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<th>Meaning</th>
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<tr>
<td>1 - 5</td>
<td>I 5</td>
<td>busbar number</td>
</tr>
<tr>
<td>6 - 10</td>
<td>I 5</td>
<td>busbar number</td>
</tr>
<tr>
<td>11 - 15</td>
<td>F 5.2</td>
<td>reduction of subsystem objective</td>
</tr>
</tbody>
</table>
... sequentially until all combinations have been included or column 75 has been reached.

c) - Change of busbar consequences - unavailability data (obligatory)
- 1 card

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<tr>
<td>1 - 10</td>
<td>F 10.3</td>
<td>rate of occurrence of event 1 in occurrences/year</td>
<td></td>
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<tr>
<td>11 - 20</td>
<td>F 10.3</td>
<td>average duration of event 1 in hours</td>
<td></td>
</tr>
<tr>
<td>21 - 30</td>
<td>F 10.3</td>
<td>rate of occurrence of event 2 in occurrences/year</td>
<td></td>
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<tr>
<td>31 - 40</td>
<td>F 10.3</td>
<td>average duration of event 2 in hours</td>
<td></td>
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This card defines the two events which, when happen, cause a change in the impact of some busbars. If this change is not to be considered, a blank card must be inserted.

d) New busbar consequences (obligatory if above card if not blank)
data format as data sets (vii a and b)

(viii) Continuation or termination card (obligatory) - 1 card
If further systems to be analysed punch *CONTINUE in columns 1-9.
If no further systems to be analysed punch *END OF RUN in columns 1-11.
FIG. 2 - Flowchart showing data preparation
APPENDIX VII

DETAILED ANALYSIS OF THE FAILURE EVENTS
ASSOCIATED WITH BUSBAR 7 IN FIG. 9.1

This appendix gives a detailed analysis of the failure events and reliability indices associated with busbar 7 in fig. 9.1. These results are shown as obtained using the computer program developed to incorporate the reliability model described in chapter VIII (program RELNET 2) assuming that the normally open paths do not fail when required to operate. The corresponding input data is given and discussed in sections 9.2 and 9.3.
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<td>COMPONENT 10 ACT: FAILED &amp; STUCK</td>
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RELIABILITY INDICES FOR NODE 7

Forced Failure Rate: 1.5917E+02 (Outages per year)
Forced Outage Average Duration: 1.9879E+01 (Hours)
Forced Outage Time per Year: 2.9253E+02 (Hours per year)

Failure Rate Due to Maintenance: 0. (Outages per year)
Outage Average Duration Due to Maint: 0. (Hours)
Total Outage Time per Year Due to Maint: 0. (Hours per year)

Total Failure Rate: 1.5917E+02 (Outages per year)
Average Outage Time: 1.9879E+01 (Hours)
Total Outage Time per Year: 2.9253E+02 (Hours per year)

Contribution to the above indices (using the same dimensions)

<table>
<thead>
<tr>
<th>Due to Cuts Eliminated by A Working Action</th>
<th>Due to Cuts That May Be Eliminated by Switching</th>
<th>Due to Temporary Failures (Reclosure Action)</th>
<th>Due to Overloads (Load Scheduling)</th>
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<tr>
<td>FFR = 431064E+01</td>
<td>FFR = 16516E+00</td>
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<td>FOAD = 00000E+01</td>
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