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Applications of minimal path set and dual fault tree approach for piecewise reliability evaluation of large-scale electrical power systems.

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Applications of Minimal Path Set and Dual Fault Tree Approach for Piecewise Reliability Evaluation of Large-scale Electrical Power Systems

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Abstract--Reliability assessment techniques and programs handling is an important issue for both power systems planning and testing in existing power system configurations. The Assessment techniques are suitable for detecting weak points in the reliability assessment. The reliability study of bulk power systems indicates the ability of the composite generation and transmission system to satisfy the load demand at major load points. The major burden of the developed methods used is the computation time required to solve a large number of credible contingencies or outage states. This paper presents a novel approach capable of the reliability evaluation for real large-size networks using normal size computers. It calculates the reliability indices at individual load buses and reliability of the whole system. The effect of the loading factor between loads on reliability is also investigated. The proposed approach is expanded to calculate the reliability of composite generation and transmission system taking the following constraints into consideration: amount of reliability of system generation, amount of reliability of transmission lines, maximum system generation capacity, maximum transmission lines capacity and maximum connected load at each bus. The approach is based on the minimal path set and dual fault tree techniques. A new concept of "constant reliability region", which is utilized in the field of optimum operation of power networks, is introduced. A special program is developed for the proposed technique. The comparison between the proposed and the previous techniques confirms that the proposed method is more accurate and precise.

KEYWORDS: Bulk Power Systems, Reliability, Minimal path set, and Dual fault tree.

I. INTRODUCTION

Customers expect the electric power supply to be continuously available on demand. Because random failures are generally beyond the control of system engineers, reliability is always one of the major factors in planning, design, operation and maintenance of power systems [1]. Reliability study in any network detects the weak points at which probability of customer being disconnected is high. It also calculates the cost of interruption to add it to the project total annual operating and capital costs to form a total cost index. It is also necessary to show the sensitivity of the whole network reliability to the individual reliabilities of the system elements. The development of mathematical tools that handle high dimension system probabilistic models is one of the most pressing problems in large-scale systems analysis [2]. The large memory and the long computation time needed for the complex, highly integrated modern power systems, introduced the dividing of the power system into sub-systems which can be analysed separately [3].

Several criteria may be employed to measure the quality of supply. One of the main criteria is to quantify the event of system failure based on: loss of continuity of supply [4], ability to meet the required load [5], presence of unacceptable voltage, frequency fluctuations and component overloads. Based on such criteria, the reliability indices may evaluate a measure to one or more of the following [6]: frequency of occurrence of system failure, the mean duration of failure or between failures, expectations such as expected number of days in a year when a system failure occurrence is evaluated.

Due to the complexity, most of reliability studies of power systems fall into three broad categories (hierarchical levels): level 1 concerned only with generating facilities, level 2 includes both generation and transmission, while level 3 includes generation, transmission and distribution. Reliability of a bulk system is a measure of the ability to deliver power to all utilization points within acceptable standards and desired amount. Reliability criteria for bulk systems fall into two categories [7]:

1. Index or variable, probabilistic criteria.
2. Attribute or performance, deterministic criteria.

Where: Indices are numerical parameters which provide measure of reliability or unreliability. Attribute criteria takes the form of sets of contingencies the bulk power system must be capable of withstanding.

The reliability of the power system is expressed by a number of indices that fit into: probability, frequency, duration and expectation of system failure. Several other indices are also engaged such as: loss of load probability index (L.O.L.P) which is probability of loads exceeding generation, probability of not meeting the annual peak load index, load interruption index, customer interruption frequency index and customer interruption duration index. These groups of indices are usually derived for every load point in the system and for the entire system, thus the power system indices can be classified into two major groups; namely: individual load point indices and overall system indices.

The measurement of reliability of bulk systems requires means of identification of success and failure states. Some reliability evaluation techniques take the "continuity of supply criterion" as the success state while others take "meeting the required load levels criterion" as success state [8].

This paper suggests a new technique to calculate the L.O.L.P for the whole network and another technique to calculate the

L.O.L.P at individual load points. The evaluation of these indices is based on minimal path set and dual fault tree techniques. Implementation of the proposed technique is given. Different networks will be investigated to examine the power and merits of the suggested method. A computer application of the suggested approaches for different diversity factors at all points is given.

II. NOVEL APPROACH TO ELECTRICAL NETWORK RELIABILITY EVALUATION BASED ON DUAL FAULT TREE

Reliability indices have been proposed for both total network reliability [14] and individual buses. The dual fault tree approach is used for the evaluation of LOLP which measures the probability of not supplying the load connected to a certain bus and for measuring the probability of not supplying all connected loads considering all network buses. Previously this method was used to evaluate the reliability of individual buses, but this is not sufficient, the reliability of individual buses may be high although reliability of the buses together at the same time may give unacceptable overall system reliability. In the proposed approach, an algorithm that evaluate the reliability of the whole network taking into account the effect of diversity factors among load buses is given. The reliability for each individual bus is also evaluated using the well known old methods [3, 9] and compared to the whole system reliability. This shows that the proposed algorithm gives better indication of network reliability; moreover it will point out at which diversity factor the network is more reliable. A special program is designed to evaluate the whole network reliability at full load with different diversity factors among loads as well as the reliability of each bus individually. The algorithm allows the study of the effect of outage of generators and loads on the whole network reliability. The proposed approach uses the minimal path set technique [13] implementing dual fault tree analysis [6], which depends upon the type of distribution system.

A. FAULT TREE ANALYSIS

It is a systematic analysis of the system failure events and the subsystem and component failure events that can cause them. A logic tree is a tree with directed edges where a single edge originates from every node except one denoted the root of the tree. A fault tree is a logic tree where the edge represents failure events at the system, subsystem or component levels at their inputs and outputs. It is formed of a signal event at the root of the tree which is called the top event and many branches connected to each other by logic operation to reach the top event. The most common logic operations (logic gates) are the 'AND', 'OR' and 'NOT'. The fault tree analysis advantages are: documenting the cause effect relationship between failures at various subsystem levels, identifying the most important failures and the weakest points in the system. Its limitations are: system components must be two states and dependent components.

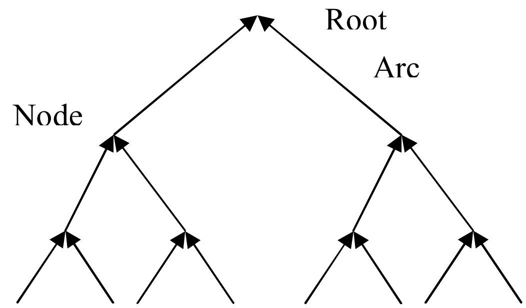


Figure 1 A Logic tree

B. TYPES OF DISTRIBUTION SYSTEMS

1. Radial System: no closed loop, direct path of power flow to load.
2. Network System: at least one closed loop, more than one path of power flow to load.

The Choice of different distribution systems that can be used depends considerably on the quality of service required. Quality of Service is divided into:

1. Reliability of service, which is obviously the lowest in a complete radial system.
2. Voltage regulation and dip limits, which is 'cost-sensitive'. Automatic regulation provided by regulating devices must be carefully sized and located to ensure economic system design.

C. USEFUL DEFINITIONS

1. Stochastic Network: all system buses are represented by nodes, all generators represented by arcs originating from a single node (source node) and directed towards nodes they are supplying. Arcs represent the elements of the system and their direction is the direction of power flow obtained from a load flow study.
2. A minimal path: is the string of directed arcs that ends with the load node.
3. Minimal path set: set of all minimal paths.
4. The Element-Node Incidence matrix: For a network of 'e' branches and 'n' nodes, it is e × n matrix whose elements a_{ij} = 1 if element i is incident to the node j, and = 0 otherwise. Since every element is incident on only two nodes, each row of matrix has two ones.
5. Capacity matrix: is a square matrix n × n where n is the total number of nodes in a stochastic network including the source node given by 0. C_{ij} is the capacity of the element leaving node i and entering node j. Thus column representing node j include only capacity of elements entering that node, while the row representing node i will include only the capacity of elements leaving that node, all other matrix elements including the diagonal are zero.
6. Capacity-Load matrix: is the capacity matrix obtained by pairing each capacity in any column with the load at the node that is represented by that column.
7. A broken element in any minimal path: Any element whose capacity is less than the sum of loads connected to

the nodes following that element within the path considered.
8. A reliable path: a minimal path which doesn't include any broken element.
9. Loading factor**:** is defined here as the ratio between actual total diversified load and the algebraic sum of all loads.

III. Proposed Algorithm

This includes two novel algorithms for evaluating the reliability of any load bus and the total reliability of the whole network.

1. Algorithm for individual buses:

Steps of solution are:

1. Determine the minimal paths for each load bus. This can be divided into reliable and unreliable paths.
2. Unreliable paths are then grouped together in pairs, triples ... etc. to form, if possible, reliable complex paths according to the following rules:
    - Unreliable paths that have at least one common broken element cannot be combined together to form one reliable complex path.
    - Any unreliable minimal path in which the broken element, j enters node i not common to any other unreliable minimal path and for which the condition $C_j < L_i$ is satisfied, where L_i is the load at bus i, can be discarded out right.
    - Unreliable paths which have no common broken element can be combined in pairs to form reliable complex path, if the following condition is satisfied:

      $$F_m + F_m' \geq \sum_{i=1}^{n} L_i$$

      Where;
      i: meeting node of the two paths.
      F_m: electrical power flow through element m entering node i in the first path.
      F_m': electrical power flow through element m entering node i in the second path.

      $$F_m = C_m \quad \text{if } F_{m-1} - L_{i-1} \geq C_m$$
      $$= F_{m-1} - L_{i-1} \quad \text{if } F_{m-1} - L_{i-1} < C_m$$

      L_1.......L_n: loads connected from node i to node n which is the last node in either path.
    - Unreliable paths can be paralleled to form complex reliable paths consisting of 3 or more unreliable paths provided that no such complex path includes complex reliable paths of lower order.
3. The dual fault tree, fig. 2, can now be constructed as follows: The constituents of any complex reliable path must feed into an 'AND' gate since they all must be healthy for the complex path to become reliable. All reliable paths (simple or complex) will feed into an 'OR' gate since supplying the load at any node will be successful if one or more reliable path is healthy.

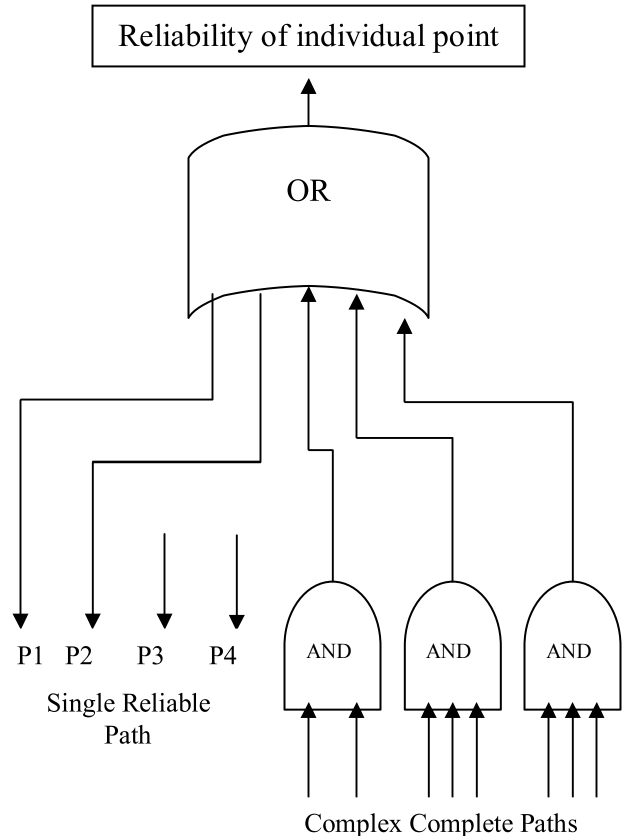


Figure 2 Dual fault tree representation of individual point

2. Algorithm for the Whole network:

Steps of solutions are:

1. Determine all paths in all directions in stochastic network.
2. Neglect any unreliable minimal path that has broken element.
3. Classify the paths into two groups; the first as complete path and the second incomplete path, where:
    - Complete path is the path which feeds all buses in the network.
    - Incomplete path is the path which feeds some of the buses in the network.
4. Incomplete paths can be combined in pairs to form complex complete paths.
5. Following the same rules in previous algorithm, incomplete paths can be paralleled to form complex complete paths consisting of 3 or more incomplete paths.
6. Calculate the union path (AND) probability of each incomplete path to determine reliability of complex path.
7. Calculate the intersection (OR) probability of all complete paths and complex complete paths to produce the total probability of the network. The dual fault tree of the whole network is schematically represented as shown in fig. 3.

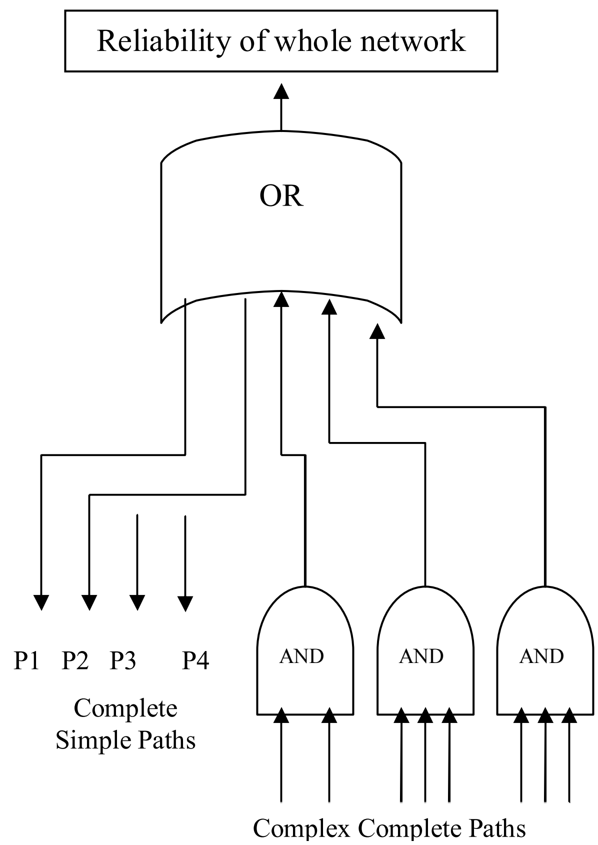


Figure 3 Dual fault tree representation of the whole network

Advantages of proposed algorithm:

1. The steps of solution do not include any complex calculations.
2. The algorithm does not include any load flow iterations that consume a lot of time and is subjected to divergence in some contingencies.
3. The operation time for any program based on this algorithm is very small if compared to other algorithms.

These advantages were verified by the implementation of the algorithm in the coming section.

IV. Implementation Of The Algorithm

The previously proposed algorithm was applied to different distribution system models. Different networks (simple radial, simple loop, and network systems up to 14-bus system) were investigated in order to examine the power and merits of the suggested method. The role of the loading factor in reliability assessment was taken into consideration to investigate its effect on the results obtained. For the illustration of the algorithm in this paper, an example of a simple loop system consisting of three load buses and two generators, given by fig. 4, is used. Numeric operating data are given in tables 1 and 2 consequently. The stochastic network is shown in fig. 5 with the orientations of the power flow study for loading conditions.

TABLE 1: OPERATING DATA OF LOADS

Node	Load
1	1
2	3
3	4

TABLE 2: DATA OF LINES

Line	From	To	Capacity of line (p.u)	Reliability of line (R)
1	0	1	6	0.85
2	0	2	4	0.85
3	1	2	5	0.84
4	1	3	4	0.83
5	2	3	3	0.82

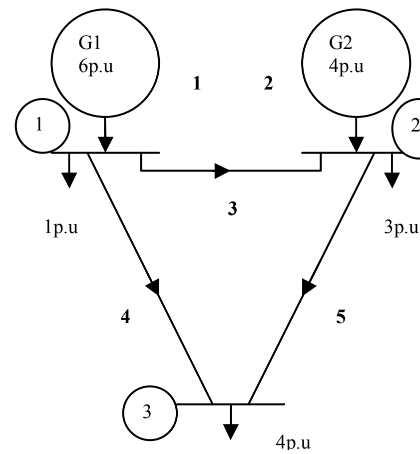


Figure 4 the 3-bus system

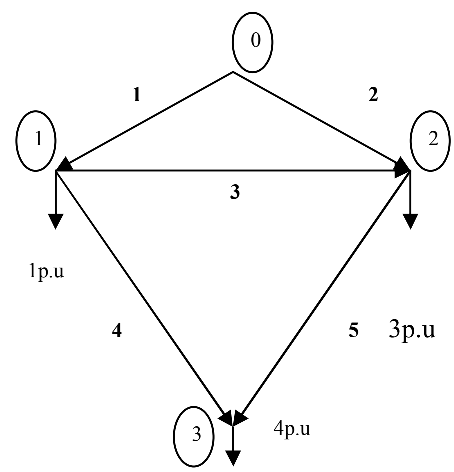


Figure 5 Stochastic network of the three bus system

Reliability of individual buses:

We start with evaluating the loss of load probability (LOLP) for the individual buses:

Bus1:

The only minimal path set is (1)

Simple reliable path is (1) because the load at bus 1 equals 1p.u and path (1) has a maximum capacity of 6p.u.

Reliability of bus 1 = R_1 = 0.85

LOLP = 1-0.85 = 0.15

Bus 2:

Minimal paths are (2) and (1, 3),

Simple reliable paths are (2) and (1, 3), because the load at bus 2 is 3p.u and path (2) has a maximum capacity of 4p.u while paths (1, 3) has a maximum capacity of 5p.u.

Reliability of bus 2=R [path (2) OR path (1, 3)]

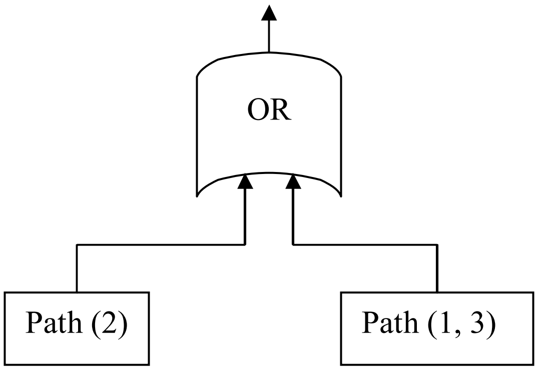
$=R_2 + R_1R_3 - R_2 \cup R_1 R_3$

$=R_2 + R_1R_3 - R_2 R_1 R_3$

=0.85 + (0.85*0.84) – (0.85*0.85*0.84)

=0.9571

LOLP = 1 – 0.9571= 0.0429



Bus 3:

Minimal paths are (1, 4), (2, 5) and (1, 3, 5). Unreliable paths are (2, 5) and (1, 3, 5), as these paths have a broken element (line 5) as it has a maximum capacity of 3p.u which is lass than the feeding load of 4p.u.

Simple reliable path is (1, 4) as it has a maximum capacity of 4p.u which is equal to the load at bus 3.

Reliability of bus 3 = R [path (1, 4)]

$= R_1R_4$

= 0.85 * 0.83 = 0.7055

LOLP = 1 – 0.7055 = 0.2945

Reliability of the whole Network:

The next step is the study of the loss of load probability (LOLP) for the whole network at different values of loading factors among load buses.

- At loading factor = 1

This means that all buses operate at their full load at the same time. There is no simple reliable paths but there is complex reliable paths, which are [(1, 4) and (2)].

Reliability of the whole network =R [path (1, 4) AND path (2)] = $R_1 R_4 R_2$ = 0.85*0.83*0.85 = 0.599675

LOLP = 1 – 0.599675 = 0.400325

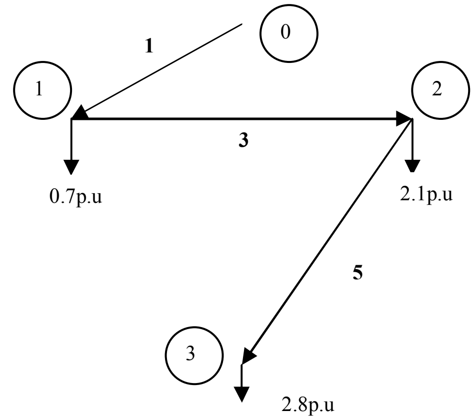
- At diversity factor = 0.7

Now the loads at the buses becomes as shown in table 3.

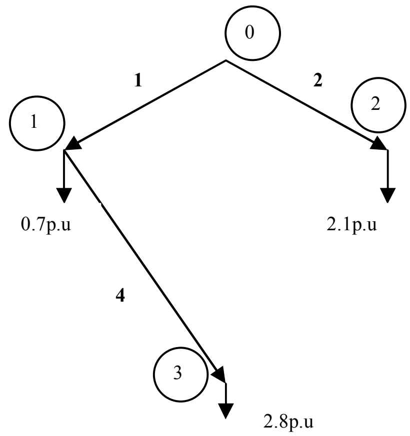
TABLE 3: LOADS AT DIVERSITY FACTOR = 0.7

Node	Load (p.u)
1	0.7
2	2.1
3	2.8

The simple reliable path is (1, 3, 5) as shown in the next figure.



The complex reliable path is [path (1, 4) AND path (2)] as shown:



∴ The reliability of the whole network =

R[path(1, 3, 5)] OR R[path(2) AND path(1,4)]

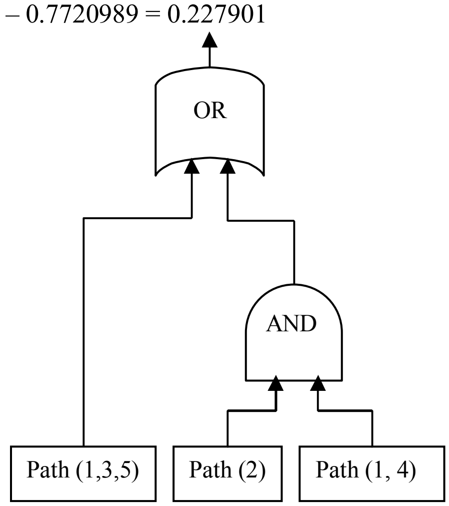
$= (R_1 R_3 R_5)$ OR $(R_2 R_1 R_4)$

$= R_1 R_3 R_5 + R_2 R_1 R_4 - R_1R_2 R_3R_4R_5$

=0.85*0.84*0.82+0.85*0.85*0.83– 0.85*0.85*0.84*0.83*0.82

= 0.7720989

LOLP = 1 – 0.7720989 = 0.227901



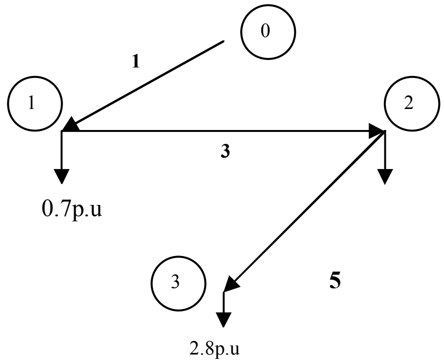
- At diversity factor = 0.5

The loads at buses are given in table 4.

TABLE 4: LOADS AT DIVERSITY FACTOR = 0.5

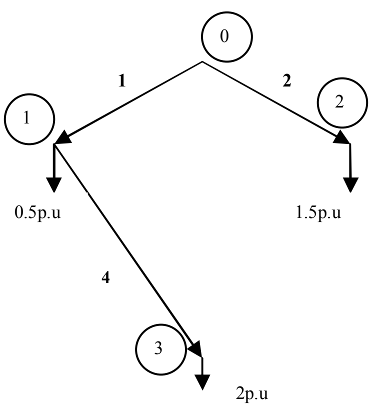
Node	Load (p.u)
1	0.5
2	1.5
3	2

The simple reliable path is (1, 3, 5) as shown:

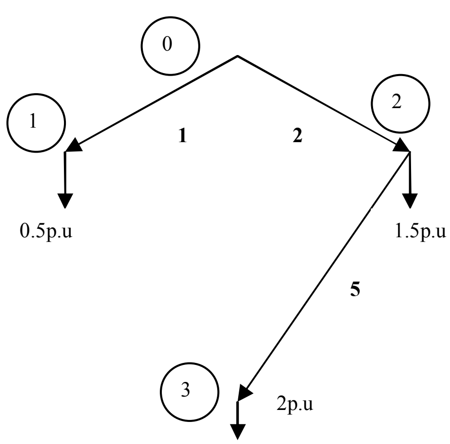


And the complex reliable paths are:

1. Path (1, 4) AND path (2) as shown:



2. Path (2, 5) AND path (1) as shown:



∴ The reliability of the whole network = R[path(1,3,5)] OR R[path (1) AND path(2,5)] OR R[path(2) AND path (1, 4)]

= (R_1 R_3 R_5) OR ($R_1 R_2$ R_5) OR (R_2 R_1 R_4)

= $R_1 R_3 R_5 + R_1 R_2 R_5 + R_2 R_1 R_4 - R_1 R_2 R_3 R_5 - R_1 R_2 R_3 R_4 R_5 - R_1 R_2 R_4 R_5 + R_1 R_2 R_3 R_4 R_5$

= 0.7882135

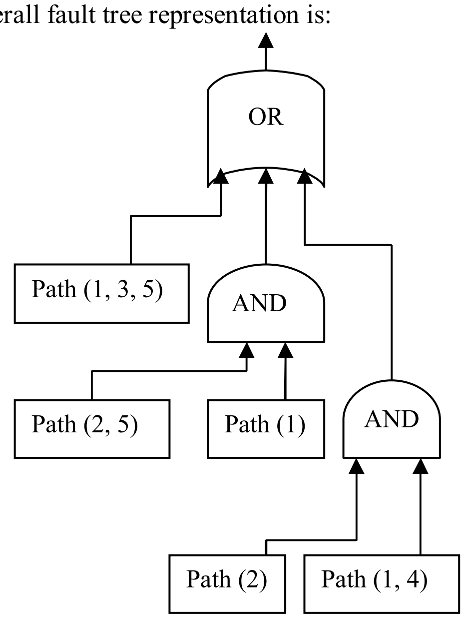
LOLP = 1- 0.7882135 = 0.2117865

From the calculations' results obtained we can find that:

Diversity factor between load buses	1	0.7	0.5
Network Reliability	0.599675	0.772098	0.788213

Calculation results indicate that the maximum reliability of the whole network at permissible loading among the loads is 0.7882135. Hence the optimal operating condition of the system is at 0.5 loading factor.

The overall fault tree representation is:



Notice that all minimal paths for the whole network are:

(1, 3, 5), or

(1, 4) AND (2), or

(2, 5) AND (1)

The criterion of success taken here is "meeting the required load – levels criterion".

The proposed approach provides an easy, small number of operations with reduced time and memory size, method which can judge the reliability of every node as well as that of the whole network. It can help in problems of system planning, contingency analysis and comparing various system configurations as it allows examining of the effect of change in the network configuration on node and whole network reliability.

In order to enhance the algorithm; a computer program was designed and applied to the same simple radial, simple loop, and network systems up to 14-bus system. Program results were then compared to those obtained before to confirm accuracy of program. Computer results obtained for the loop system given here in figure 4 are shown in tables 5 and 6.

TABLE 5: RELIABILITY OF INDIVIDUAL BUSES

Bus	Reliability	LOLP
1	0.8500	0.1500
2	0.9571	0.04290
3	0.7055	0.2945

TABLE 6: RELIABILITY OF WHOLE NETWORK

Loading factor	Whole network reliability	Whole network LOLP
1	0.599675	0.400325
0.9	0.599675	0.400325
0.8	0.599675	0.400325
0.7	0.772099	0.227901
0.6	0.772099	0.227901
0.5	0.788213	0.211787
0.4	0.788213	0.211787
0.3	0.788213	0.211787
0.2	0.788213	0.211787
0.1	0.788213	0.211787

We notice in this network that there are three regions of reliability. First region lays from loading factor (1) to (0.8), second from (0.7) to (0.6) and third from (0.5) to (0.1). The maximum reliability is 0.788213 and the highest load at this reliability will be at loading factor (0.5). In a loop system the reliability of the whole network is usually less than the least reliability of any point at full load because the whole reliability of this system depends on "meeting of load level" criterion for all network points. Therefore the reliability of the whole network is inversely proportional to loading factor of loads. Thus we will introduce a new criterion to define the whole system reliability known as "Constant reliability region", which is important in network design, since the reliability will be almost constant over a wide range of fluctuation of load. Any network is divided into few regions of reliability according to loading factor of load; we must select the widest region as it stands for the bigger changes of loads in network during any time of service.

V. CONCLUSION

The main achievement of this paper is introducing a new simple approach, based on dual fault tree method, for dealing with large power system reliability problems. The proposed approach evaluates the whole electric power network reliability where meeting the required load levels is taken as a success criterion. The proposed approach has been validated by several test networks, where one of these has been illustrated here in this paper. The proposed approach offers several practical advantages over existing reliability evaluation methods such as:

1. It can be applied to any network
2. Less computing time which doesn't increase fast with the size of network.
3. It indicates whether the whole network is reliable or unreliable at full load, and if unreliable it specifies the maximum load level at which the network is reliable.
4. It can determine the load level at which the network reliability is maximum.
5. It introduces the "constant reliability region" criterion to define system reliability; which is important in system design.
6. It enables examining the effects of: removing any load, increasing load at new areas or any generator out of service on the whole network reliability.
7. It can easily study the effect of removing one or more link from the network on the reliability of both the network nodes and the whole network.
8. It facilitates examining the effect of improving the reliability of any element on the rest of network nodes.
9. Optimal network operation can be achieved through combination between this method and daily load curve by taking some generator units out of service at light loading conditions and returning them on peak times.

This new approach can also be applied to several practical problems, some of these are:

1. Predicting the best values of loads for a certain network configuration. It may also help in finding the best configuration for the whole network.
2. Offering an easy way of determination of the importance of every link in the network, for the purpose of reliability improvement.
3. Designing of a network by adding a new set of lines to achieve optimum conditions.

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