FUZZY RELIABILITY ANALYSIS OF DISTRIBUTION SYSTEMS

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in System Engineering and Operations Research)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation entitled **FUZZY RELIABILITY ANALYSIS OF DISTRIBUTION SYSTEMS** in the partial fulfilment of the requirements for the award of the degree of **Master of Technology in Electrical Engineering** with specialization in **System Engineering and Operations Research**, submitted in the **Department of Electrical Engineering**, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from November 2006 to June 2007 under the supervision of **Dr. Surendra Kumar**, Assistant Professor, Electrical Engineering Department, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Distribution system Reliability is one of the most important topics in the electric power industry due to its high impact on the cost of electricity and its high correlation with customer satisfaction. Distribution reliability primarily relates to equipment outages and customer interruptions. The distribution system reliability can be evaluated with analytical and simulation methods. The analytical methods for the reliability evaluation are highly developed. These methods use the data such as the failure rate, repair rate switching rate etc which is obtained from the historical data. These are not accurate and contain a lot of uncertainty in them. Fuzzy set theory is an excellent tool for modeling such kind of uncertainty associated with vagueness, imprecision and/ or with lack of information regarding a particular component or system. This thesis describes about the Markov Modeling and Event Tree Analysis for the Distribution System Reliability Assessment

Markov Modeling is a powerful method based on system states and transition between the states. When a fault occurs on the distribution system network the system transitions form the successful state to failure state and once the repair is done it again transitions into success or operating state. The Markov modeling analysis is done by finding the probability of system or component in each state. The data used for the Markov Model in this thesis has been taken from the from the reliability test system proposed by Dr. Roy Billinton.

Event tree analysis can be used to recognize the sequential logic of the system. The Event Tree Analysis gives the sequence of operations of the protective devices after the fault has been initiated.

This thesis describes the application of fuzzy set theory in the evaluation of reliability of power distribution networks using fuzzy Markov modeling and fuzzy event tree analysis to reduce the uncertainty.

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(M. Chandra Sekhar)

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CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 Electric Power System

The function of an electric power system is to generate electrical energy as economically as possible and to transfer this energy over transmission line and distribution networks with maximum efficiency for delivery to consumers at acceptable voltages, frequency and reliability. An electric power system consists of three principal segments: the generating stations, the transmission system, and the distribution systems. Generating plants produce electrical energy from other forms of energy such as fossil fuels, nuclear fuels or water flow. Generation substations connect generating plants to transmission lines through step-up transformers that increase the generation voltage to transmission levels. Transmission systems transport electricity over long distances from generating facilities to transmission or distribution substations. Most transmission lines are overhead but there is a growing trend towards the use of underground transmission cables. Distribution systems deliver power from bulk power systems to retail customers. Distribution substations receive power from the transmission system and step down the transmission voltages using power transformers to supply the primary distribution systems.

1.2 Power System Reliability

Power systems have evolved over decades. Their primary emphasis has been on providing a reliable and economic supply of electrical energy to their customers. Overinvestment can lead to excessive operating costs, which impact the tariff structure and lead to high customer costs. Underinvestment results in decreases in the reliability of customer service. The resulting economic and reliability impacts can lead to difficult managerial decisions in both the planning and operating phases. Many designs, planning and operating criteria and techniques have been developed to resolve and satisfy the dilemma between the economic and reliability constraints. The criteria and techniques used in early practical applications were all deterministically based System behavior, however, is stochastic in nature and deterministic techniques can not respond to this condition. Probabilistic technique have been developed which recognize not only the severity of an event but also the likelihood or probability of its occurrence. Enhancements in computing facilities and improvements in evaluation techniques have resulted in the development of a wide range of probabilistic methodologies for power system reliability evaluation. Power system reliability evaluation, both deterministic and probabilistic, can be divided into the two aspects of system adequacy and system security. This relationship is shown in figure 1.1.

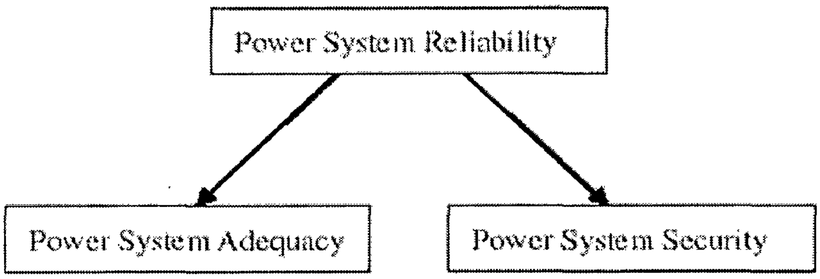

Figure 1.1 subdivision of system reliability [2]

System adequacy is generally considered to relate to the existence of sufficient facilities within the system to satisfy the consumer demand. These facilities include those necessary to generate sufficient electrical energy and the associated transmission and distribution networks required to transport the energy to the actual consumer load points. System security is related to the ability of the system to respond to disturbances arising within the system without causing widespread cascading events. Security is therefore associated with the response of the system to whatever disturbances the system is subjected to. These disturbances are considered to include conditions causing local and widespread effects and the loss of major generation and transmission facilities. Considerable effort has been devoted to reliability assessment of power systems.

1.3 Power System Functional Zones and Hierarchical Levels

Power system reliability assessment can be conducted in the three basic functional zones of generation, transmission and distribution. Hierarchical levels (HL)[2] can be created by combining the three functional zones. This is illustrated in Figure 1.2

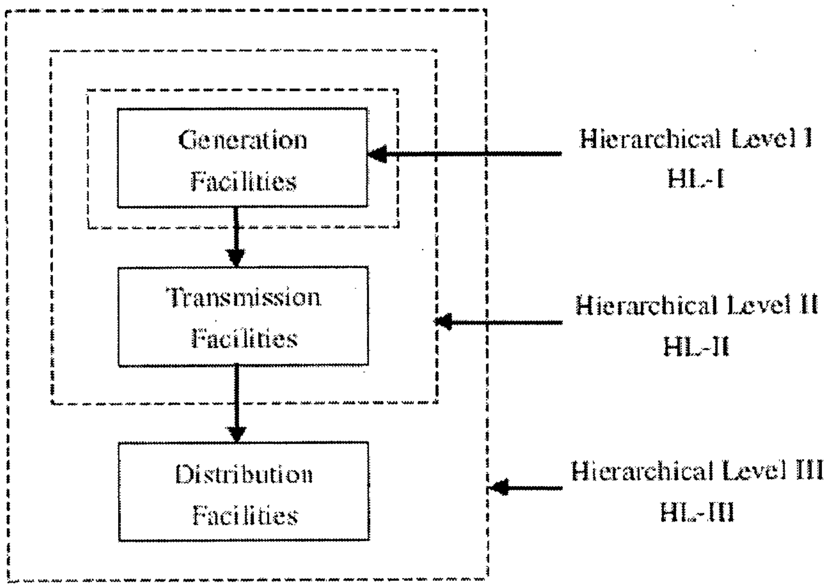

Figure 1.2 hierarchical levels in power systems [2]

Reliability assessment at hierarchical level I (HLI) deals with the generating system. In an HLI study, the system generation is examined to determine its ability to meet the total system load requirement, considering random failures and preventive maintenance of the generating units. The transmission network and the distribution facilities are not included in assessments at this level.

Both the generation and transmission facilities are included in a hierarchical level II (HLII) study. Reliability assessment at HLII is concerned with the ability of the system to deliver energy to the bulk supply points. HLII analysis is more complicated than that at HLI and includes overload effects, redispatch of generation, and consideration of independent, dependent and common-cause outages.

Hierarchical level III (HLIII) assessment refers to the complete system including distribution and the overall system ability to satisfy the capacity and energy demands of individual consumers. Although HLI and HLII analyses are regular performed, HLIII studies are usually impractical because actual power systems are very large and complex and it is very difficult to evaluate the entire system using a single and direct technique such of those applied at HLI or HLII. Distribution systems are usually assessed separately and combined with HLII parameters if necessary.

1.4 Distribution System Reliability

Distribution system reliability is one of the most important topics in the electric power industry due to its high impact on cost of electricity and its high correlation with customer satisfaction. Since distribution systems account for up to 90% of the customer reliability problems, improving distribution reliability is the key to improving customer reliability. Historically, distribution systems have received less attention regarding reliability modeling and evaluation than that devoted to generating systems. A distribution system has a relatively low cost and distribution outages have much more localized effects than events on generating systems, where inadequacy could have widespread economic consequences for the society.

Analysis of customer statistics failure shows that distribution systems make the greatest individual contribution to unavailability of customer supply. A customer connected to an unreliable distribution system could receive poor energy supply even though generation and transmission system are highly reliable. This fact clearly illustrates the importance and necessity in conducting the reliability evaluation in the area of distribution systems.

1.5 Objective of the Thesis

The reliability of a power system can be evaluated with the help of failure rates, repair rates and switching rates of the component or system. All these parameters are not accurate and are obtained only from the historical data. These contain a lot of uncertainty in them and may not produce accurate results

The main objective of the thesis is to apply fuzzy logic methods to the reliability assessment models to reduce the uncertainty in them. In this thesis two methods 1)The Markov Modeling Technique and 2) The Event Tree Analysis have been discussed and fuzzy logic is applied there after to a test system and the fuzzy probability values are calculated.

1.6 Outline of the Report

The main objective of this dissertation is to apply fuzzy logic to the power distribution system reliability analysis methods. The dissertation report is organized in the following way

Chapter 2 gives us an idea of distribution systems and its importance in the entire power system. The other concepts in the chapter include distribution system reliability, factors affecting distribution system reliability, distribution system reliability indices and different analytical and simulation methods for the analysis of distribution system reliability are also discussed.

Chapter 3 gives us an introduction fuzzy logic, the difference between fuzzy theory and probability theory and the fuzzy logic tools used in the dissertation report.

Chapter 4 gives us the Markov Modeling technique and fuzzy Markov modeling technique, use of this technique in the reliability evaluation studies. Different types of Classical Markov Modeling technique (continuous and discrete) are discussed with example in the chapter. The fuzzy Markov Modeling technique is applied to a Reliability Test System proposed by Dr. Roy Billinton and the fuzzy probabilities of different states have been calculated.

Chapter 5 gives us the Event Tree analysis technique and also the fuzzy implementation of the event tree analysis and the procedure of calculating the fuzzy probabilities of different sequences of operations and the level of consequence of each sequence of operation.

Chapter 6 concludes the report and future research that can be done in the area of the Markov Modeling technique and the Event Tree analysis technique and the consequences of work already done.

CHAPTER 2

ELECTRIC DISTRIBUTION SYSTEMS

2.1 Introduction

A power distribution system is the segment of the overall power system that links the bulk electricity system to the consumer service points. It contains: sub-transmission circuits, distribution substations, primary feeder circuits, distribution transformers, secondary circuits and service lines. Figure 2.1 shows a simplified drawing of a distribution system in an overall electric power system. Distribution substations convert energy to lower primary system voltages for local distribution and usually provide facilities for voltage regulation of the primary voltage

2.2 Distribution Substations

Distribution systems begin at distribution substations. The source of power to the substation is a single overhead head line which terminates on a take off structure. High voltage components are connected to the primary side of the substation. The medium side of the transformer is connected to the secondary breaker. If a transformer fault occurs, the breakers on both primary and secondary side will open to isolate the substation. The substation secondary components supply power to the primary distribution systems. Many distribution substations are designed with redundancy allowing a portion of feeders to remain energized if any major component fails or taken out for maintenance.

2.3 Primary Distribution Systems

2.3.1 Radial distribution systems:

A radial system is connected to only one source of supply and is exposed to many interruption possibilities. The most important of which are those due to overhead line or underground cable failures or transformer failures. Each event may be accompanied by a long interruption. Radial feeders tend to have lower reliability than feeders with alternate supply capability. Feeders and transformers have finite failure

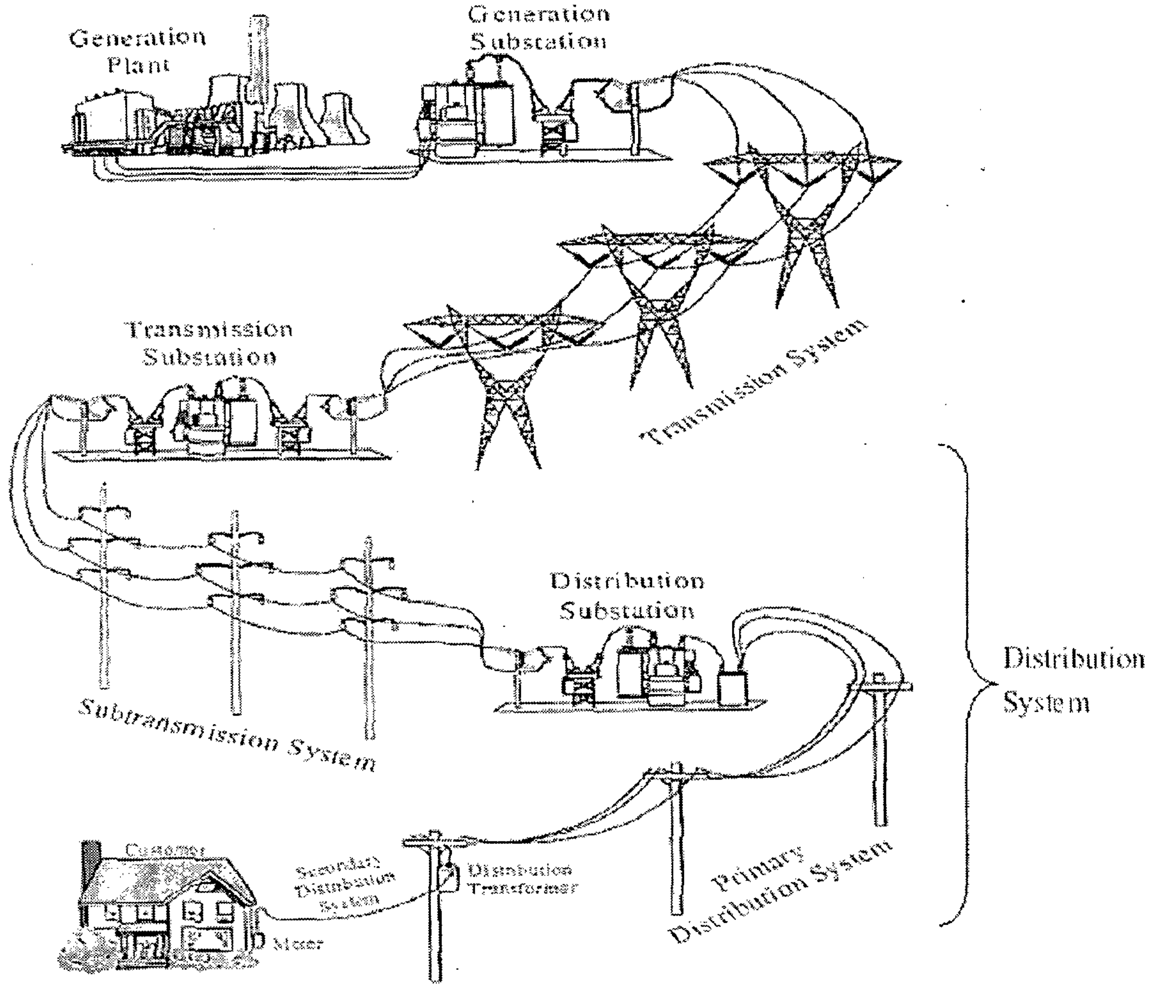

figure 2.1 An overall power system and its subsystems [1]

rates and interruptions are expected and statistically predictable. Feeder breaker reclosing action or temporary faults are likely to affect sensitive loads. Purely radial feeders with no alternate supply capability are usually used for small loads or rural systems. Figure 2.2 shows an example of a small radial feeder.

2.3.2 Primary loop distribution systems

A big improvement over radial system is obtained by providing a primary loop, which can provide power from two sources. This is also called an open ring system. A simple example of an open ring system is shown in figure 2.3. Normal power flow to the consumer is by way of a single path at any one time from either side of a loop. The loop is normally operated with the sectionalizer switch open. Any section of the feeder can be isolated and switching action performed to restore service. Sensitive loads can be affected by reclosing under temporary fault conditions.

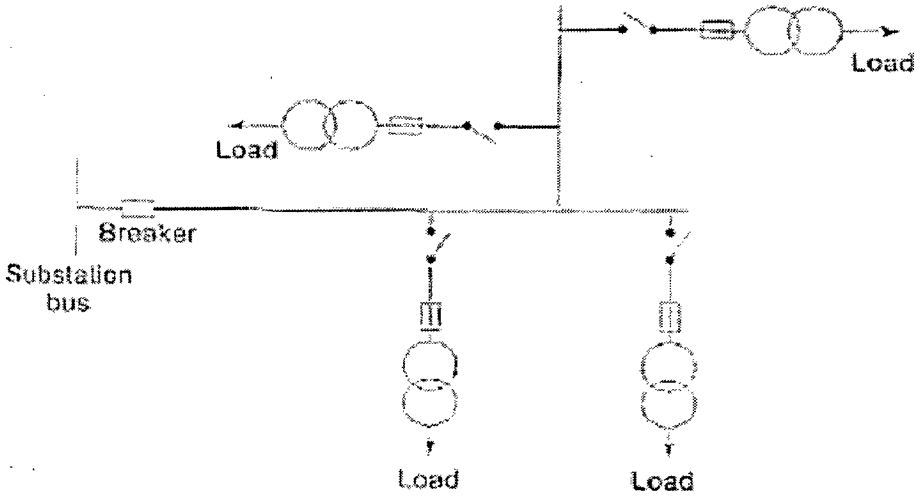

figure 2.2 A radial distribution system [1]

2.4 Secondary Distribution Systems.

Secondary systems connect distribution transformers to customer service entrances.

Secondary mains and service drops: customers are connected to the distribution systems via service drops. Customers close to a distribution transformer are connected directly to the transformer secondary connections. Other customers are reached by routing a secondary main for service drop connections.

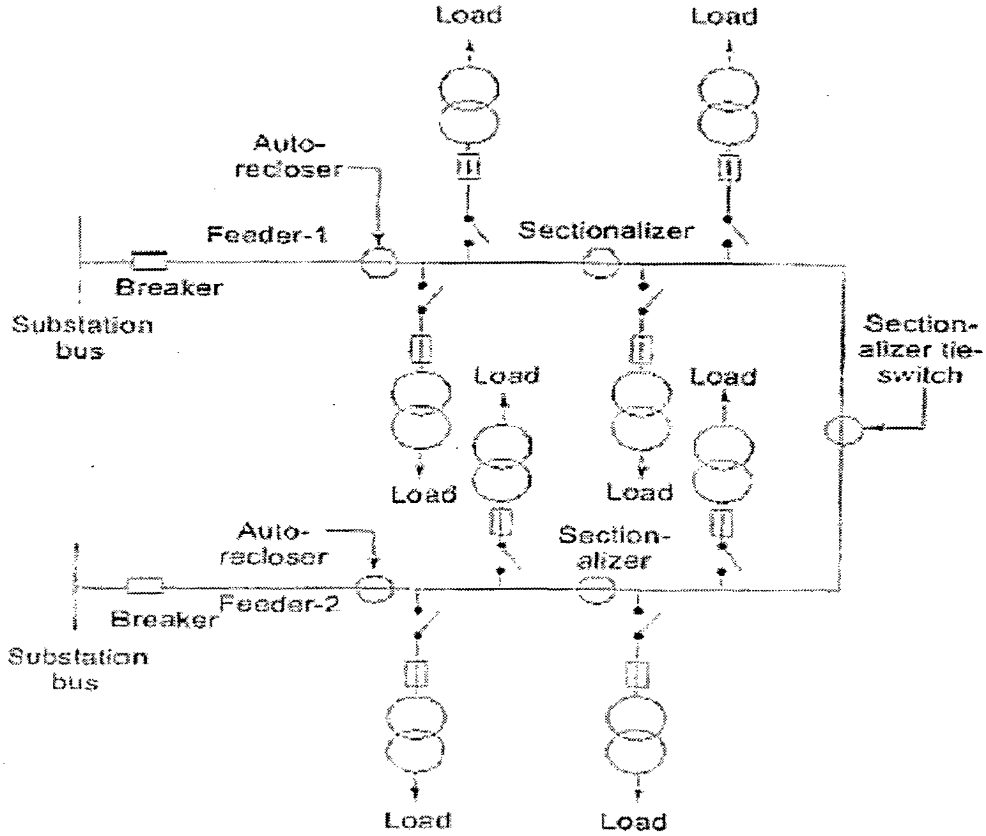

figure 2.3 primary loop distribution system. [1]

2.5 Distribution System Reliability

Distribution reliability primarily relates to equipment outages and customer interruptions. In normal operation conditions all equipment s energized and all customers are energized. Scheduled and unscheduled events disrupt normal operating conditions and can lead to outages and interruptions. Several key terms relating to distribution reliability include

1) contingency
2) open circuit
3) fault
4) outage
5) momentary interruption
6) momentary interruption event
7) sustained interruption

2.6 Factors Effecting Distribution System Reliability.

Customer interruptions are caused by a wide range of phenomena including equipment failure, animals, trees, severe weather conditions and human errors. These causes are at the root of distribution reliability.

Equipment failures: These include failure of transformers, underground cables, overhead lines, circuit breakers, surge arresters, insulators and bushings etc.

Animals: Animals such as squirrels, mice, rats, birds, snakes, fire ants and some large animals are some of the causes of customer interruptions.

Severe weather conditions: Wind storms, lighting, icing, extreme heat and earth quakes are some of the conditions which affect the distribution reliability.

Human factors: Human errors, vehicular accidents, dig in's, mischief and vandalism are some of the causes of interruptions.

Trees: Trees are one of the causes of customer interruptions

2.7 Distribution System Reliability Indices

Reliability indices are statistical aggregations of reliability data for a well defined set of loads, components or customers. Most reliability indices are average values of a particular reliability characteristic for an entire system, operating region, substation service territory or feeder.

The reliability of a distribution system can be described using two sets of reliability parameters. These are the individual load point reliability indices and the overall system reliability indices.

2.7.1 Load Point Indices

There are three basic load point reliability indices used to characterize the continuity of power supply to an individual load point. They are the load point failure rate (λ), the average outage time (r) and the annual unavailability or the average annual outage time (U). The load point failure rate indicates the number of failures that a load point experiences during a period of time, usually a year. The average outage time is the average outage duration at a load point due to a load point failure. The average annual outage time at a load point can be estimated from the product of the failure rate and average outage time. This is the total duration in a year that power supply to the load points is unavailable. The three annual predictive indices are expected values and not deterministic parameters. They are therefore long run average values and have underlying probability distributions.

2.7.2 System Reliability Indices or Customer Based Reliability Indices

The three primary load point indices introduced above are very important from a customer standpoint. The system performance can also be assessed on an overall system basis. These indices reflect the adequacy of overall system supply and indicate the system behavior and response. The system basic indices are defined as follows:

(1) System Average Interruption Frequency Index (SAIFI)

This index is defined as the average number of interruptions per customer serviced per year.

$$SAIFI = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} = \frac{\sum(\lambda_i . N_i)}{\sum N_i} \quad (2.1)$$

Where, λ_i is the failure rate and N_i is the number of customers at load points i.

(2) System Average Interruption Duration Index (SAIDI)

This index is defined as the average interruption duration per customer served per year.

$$SAIDI = \frac{\text{Sum of Customer Interruption Durations}}{\text{Total Number of Customers}} = \frac{\sum(U_i . N_i)}{\sum N_i} \quad (2.2)$$

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

(3) Customer Average Interruption Duration Index (CAIDI)

This index is defined as the average interruption duration for customer interrupted during a year.

$$CAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customer\ Interruptions} = \frac{\sum(U_i.N_i)}{\sum(\lambda_i.N_i)} \tag{2.3}$$

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

(4) Index of Reliability (IOR) or Average Service Available Index(ASAI)

$$IOR = ASAI = \frac{8760Hours/year - SAIDI}{8760Hours/year} \tag{2.4}$$

(5) Average service unavailability index (ASUI):

$$ASUI = 1 - ASAI = \frac{SAIDI}{8760Hours/year} \tag{2.5}$$

(6) Expected energy not supplied index (EENS):

$$EENS = \sum L_i.U_i \tag{2.6}$$

Where L_i and U_i respectively are the average connected load and the average annual outage time at load point i.

(7) Average energy not supplied index (AENS):

$$AENS = \frac{\text{Total Energy not Supplied}}{\text{Total Number of Customers Served}} = \frac{\sum L_i.U_i}{\sum N_i} \tag{2.7}$$

Where N_i, L_i and U_i are defined as above.

The first five indices are customer-oriented indices and the last two are load and energy-oriented indices. These indices can be used not only to assess the past performance of a distribution system but also to predict the future system performance. The other customer based indices include

Customer average interruption frequency index (CAIFI)
Customer total average interruption duration index (CTAIDI)
Momentary average interruption frequency index (MAIFI)
Momentary event average interruption frequency index (MAIFI)

The load point indices and the system reliability indices are determined on an annual basis. Because of the stochastic nature of power system, the indices for a particular year are random values and are functions of component failure rates, repair times and restoration times with in the year. A complete restoration of these indices involves the knowledge of the underlying probability distributions. It is relatively easy to compute the average values as the associated analytical techniques are highly developed for both radial and meshed distribution systems.

2.7.3 Power Quality Indices

Reliability is a subset of power quality, and many reliability decisions affect other areas of power quality. Because of this, familiarity with basic power quality indices is desirable.

1) system average RMS frequency index (SARFI)
2) system instantaneous average RMS variation frequency index (SIARFI)
3) system momentary average RMS variation frequency index (SMARFI)
4) system temporary average RMS variation frequency index (STARFI)

2.8 Reliability Assessment Techniques

The predictive reliability assessment techniques in power distribution systems can be divided into the two basic approaches of analytical methods and simulation techniques. The following is a brief introduction to these methods.

2.8.1 Analytical Methods

Analytical methods represent a distribution system by mathematical models to obtain the expected load point values Analytical techniques for distribution system reliability evaluation is highly developed. Analytical models can become quite complicated, however, when the system has complex configurations and complicated operating procedures. Simulation techniques can prove advantageous in these cases. The reliability indices obtained using a basic analytical technique are average or expected values and contain no information in the distribution of the indices.

Some of the analytical methods used for the assessment of reliability in distribution systems are

1) Direct methods
2) Network reduction method
3) Failure modes and effects analysis method
4) State space diagrams
5) Fault tree analysis method
6) Event tree analysis

Direct Method

A direct analytical approach can be used to obtain the average reliability indices at the different load points and for the overall distribution system. The three basic load point reliability indices i.e. the failure rate, the average outage time and the average annual outage time can be obtained as follows.

$$\lambda_i = \sum_j \lambda_j \tag{2.8}$$

$$U_i = \sum_j \lambda_j . r_j \tag{2.9}$$

$$r_i = \frac{U_i}{\lambda_i} \tag{2.10}$$

Where λj, rj are the failure rate, repair time of event j respectively and *Ui is* the annual outage time at load point i.

Network Reduction Method:

The network reduction method creates a sequence of equivalent components obtained by gradually combining series and parallel components.

The load point indices for a series and parallel connected system are given below

Series connected system

The failure rate, repair rate and unavailability rate for a series connected systems are:

$$\lambda = \lambda_1 + \lambda_2 \tag{2.11}$$

$$U = \lambda_1 r_1 + \lambda_2 r_2 \tag{2.12}$$

$$r = U / \lambda \tag{2.13}$$

Parallel connected system

The equations of failure rate, repair rate and unavailability rate of a parallel connected system are:

$$\lambda = \lambda_1 \lambda_2 (r1+r2) \tag{2.14}$$

$$U = \lambda_1 \lambda_2 r_1 r_2 \tag{2.15}$$

$$r = 1 / (1/r_1 + 1/r_2) \tag{2.16}$$

The three main disadvantages of this method are:

1) It cannot be used to analyze the system in which the components are not simply in series or parallel.
2) Critical or unreliable areas and components become absorbed into equivalent components and their effect becomes increasingly impossible to identify as the amount of reduction increases. Essential attributes of a properly structured reliability analysis are to identify the events causing a system to fail and the contribution made by each event in addition to the overall values of load point indices.
3) The technique is not amenable for further development in order to include different modes of failure, maintenance and weather effects, etc.

Despite these disadvantages, the network reduction method can be useful in practice, particularly in case of simple hand calculations when extra analytical refinements are not desired.

Failure Mode and Effect Analysis (FMEA)

It is an inductive technique that seeks to identify all possible equipment failure modes and their associated impact on system reliability. The failure modes are directly related to the minimal cut sets of the system and therefore the latter is used for the identification of failure modes.

For each component the following information is required

- list of failure modes
- possible causes for each failure modes
- possible system effect of each failure mode
- probability of each failure mode occurring
- Possible actions to reduce the failure rate or effect of each failure mode.

State Space Diagrams

One method that can be used to evaluate the reliability of continuously operated distribution systems is based on the construction of state space diagrams. Although, this method is accurate it becomes infeasible in large distribution networks. However, it has an important role to play in the power system reliability evaluation. Firstly, it can be used as the primary reliability evaluation method in certain applications. Secondly, it is frequently used as a means of deducing approximate evaluation techniques. Thirdly, it is extremely useful as standard evaluation method against which accuracy of approximate methods can be compared.

Fault Tree Analysis

It is a top-down approach to failure analysis starting with an undesirable event called top event, such as a failure or malfunction and then determining all the ways it can happen. The analysis proceeds by determining how these top events can be caused by individual or combined lower level failures or events. Fault-trees have been widely used to investigate the reliability and safety of complex and large systems for diagnostic applications. The main reason for the widespread use of fault-tree analysis is if there is critical failure mode, then all possible ways that mode could occur must be discovered. it was first used by Bell Telephone Laboratories in connection with the safety analysis of the Minuteman missile launch control system in 1962.

Event Tree Analysis

Event trees are useful for system reliability analysis and risk quantification since they illustrate the logic of combination of probabilities and consequences of event sequences. Event trees have been fond to be most popular choice in terms of building an analytical model of the system. It provides a compact representation of the system and is easily understood by the humans.

2.8.2 Simulation Methods

The reliability indices obtained using analytical methods are average values. These indices are very important but have limitations regarding the uncertainty of the system behavior. Simulation method can be used to overcome this deficiency. Probability distributions provide a practical vehicle to describe the variation of reliability measures about their means. Monte Carlo simulation can provide information related to the probability distributions of the reliability indices in addition to their average values.

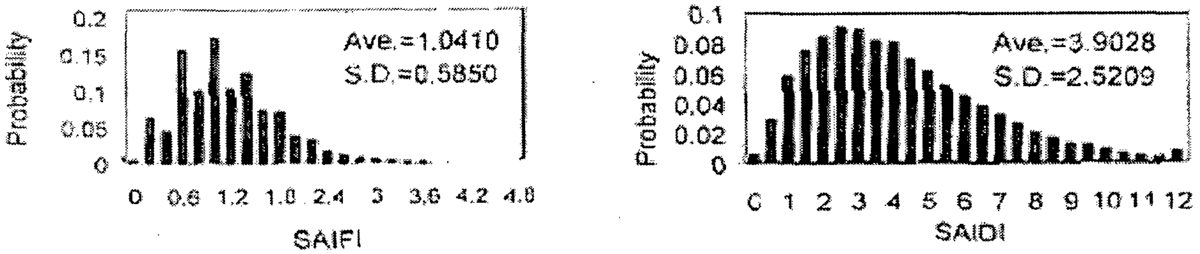

Figure 2.4 probability distributions for Monte Carlo simulation [15]

Figure 2.4 shows the average value of each reliability index and also the likelihood that certain values occur in the future. Probability distributions obtained using a simulation method can provide considerable additional information and prove useful in assessing future risks. Simulation methods use a random number generator and the probability distributions of the component failure and restoration processes to generate a history of component up and down times. The system reliability indices and their distributions are obtained from the generated system history. The index probability distributions reflect the future reliability performance of the system.

After the system has been constructed and placed in operation, it begins to form its actual reliability based on real life conditions encountered over time. The system reliability may be quite different from that predicted in the planning stage. Most utilities collect system reliability data such as customer interruptions, annual outage times and calculate the SAIFI and SAIDI on an annual basis. These actual yearly data can be used to create index distributions and compared with those produced using the simulation method. The amount of collected data is far less than that generated in a simulation method. The distributions created from actual historical data reflect the actual existing system performance and therefore are very valuable.

Studies examining the distributions associated with the basic reliability indices indicate that the load point failure rate is approximately Poisson distributed. The failure rate probabilities can be readily obtained using the mean load point failure rate, since the Poisson distribution is a single-parameter function.

CHAPTER 3

INTRODUCTION TO FUZZY SET THEORY

3.1 INTRODUCTION

Fuzzy logic has been described and advanced since its development in 1960's by Lofti Zadeh. However, only recently it has achieved acclaim in technical literature and its application to power systems. The obvious advantages of the applications of fuzzy logic to complex systems are,

1) The ability to model complex systems with simple mathematics,
2) Its flexibility to fit to various areas of application,
3) The ability to handle imprecise data,
4) Its basis on natural language,

Fuzzy logic begins with the concept of fuzzy set. Fuzzy sets consist of elements with partial degrees of membership. A fuzzy set is a generalization of an ordinary set in that it allows the degree of membership for each element to range over the unit interval [0, 1]. One major difference between crisp set and fuzzy set is that crisp set always has unique membership functions, where as a fuzzy set has infinite number of membership functions that may represent it. Linguistic variables are used to represent the members in the set and natural language is used to express the meaning of the members in the set.

3.2 Fuzzy Logic and Possibility

The fuzzy set theory introduced by Zadeh is an intuitive and powerful mathematical tool. It is an extension of standard set theory in which partial membership in a set is possible. A standard, or crisp, set A defined over X can be represented by a characteristic function $\mu(x)$ such that $\mu(x) = 1$ iff $x \in A$ and $\mu(x) = 0$ iff $x \notin A$. In a fuzzy set, the characteristic function is replaced with a membership function that can have any value between zero and one. This number represents our `belief' or `the degree of truth' of the statement $x \in A$. The obvious advantage of this is that we are no longer limited to only true and false, but have access to all the shades of grey in between. There is tremendous representational power in this simple idea, An example would be the set of things that are hot. A crisp representation of `hot' might have $\mu(x) = 1$ iff $x > 40C$. A fuzzy set for hot might be

$$\mu(x) = \begin{cases} 0 : x < 30C \\ (x-30)/40 : 30C < x < 70C \\ 1 : x > 70C \end{cases}$$

Note how the fuzzy set offers a more flexible and accurate description of the linguistic adjective `hot' than is possible with a crisp set. It takes into account that some temperatures are definitely or definitely not hot, and that there is a `fuzzy' region in between these where the temperature can be described as hot with varying degrees of truth. Fuzzy sets have found many applications interpreting between human language and numerical values for this reason.

The standard set operations that are used on crisp sets are also used with fuzzy sets. The intersection operation is usually represented by the minimum of the two membership functions. It is obvious that this reduces to the crisp intersection if the sets are both crisp. Similarly, the union operator is commonly the maximum of the two functions, and the complement operation is often one minus the membership function.

Crisp Operation	Equivalent Fuzzy Operation
Union	$\max(\mu_a(x), \mu_b(x))$
Intersection	$\min(\mu_a(x), \mu_b(x))$
Complement	$1 - \mu_a(x)$

Table 3.1 Standard Fuzzy Operations

A `fuzzy number' is a useful way to represent uncertainty or noise in data. A common way to define a fuzzy number is a triangular membership function with a peak at the titular value and a base width and position appropriate to the uncertainty involved. For large amounts of uncertainty, trapezoidal membership functions are often appropriate. This thesis uses trapezoidal membership functions to represent the failure rates and repair rates of the distribution system. The failure rates of such components can only be guessed very roughly before a model of the complete system is built for testing.

Let [al; ah] and [bl; bh] be equivalent alpha-cuts for fuzzy sets A and B. Table 2.1 lists the results of several different fuzzy arithmetic operations formed on these cuts . Note that it is assumed that all variables are on the interval [0, 1], as this is the usual case in reliability. Without this assumption, some of these formulas are slightly more complicated.

Operation	Equation to find α-cut
$A+B$	$[a_l+b_l, a_h+b_h]$
$A-B$	$[a_l-b_h, a_h-b_l]$
$A\times B$	$[a_l\times b_l, a_h\times b_h]$
$A\div B$	$[a_l\div b_h, a_h\div b_l]$
A^B	$[a_l^{b_h}, a_h^{b_l}]$
$\exp(A)$	$[\exp(a_l), \exp(a_h)]$
$\exp(-A)$	$[\exp(-a_h), \exp(-a_l)]$

Table 3.2 fuzzy α-cut operations on the interval [0, 1]

3.3 Fuzziness and Probability

Fuzziness is often confused to probability. Fuzzy set theory provides a mean for representing uncertainties whereas probability theory is used as the primary tool for representing uncertainty in mathematical models.

Basic statistical analysis is founded on probability theory or stationary random processes, where as most experimental results contain both random and non random processes. The random processes or stationary random processes exhibit the following three characteristics:

1) The sample space on which the processes are defined cannot change from one experiment to another, that is, the outcome space cannot change.

2) The frequency of occurrence, or probability, of an event within that sample space is constant and cannot change from trial to trial or experiment to experiment.

3) The outcomes must be repeatable from experiment to experiment. The outcome of one trial does not influence the outcome of a previous or future trial.

However, in the case of fuzzy sets, the outcomes of any particular realization of a random process are strictly a matter of chance; a prediction of a sequence of events is not possible. For a random process it is only possible given a precise description of its long-run averages.

Not all uncertainty is random. Some forms of uncertainty are nonrandom and hence not suited to treatment or modeling by probability theory. In fact, one can argue that the predominant amount of uncertainty associated with complex systems is nonrandom in nature. Fuzzy set theory is an excellent tool for modeling the kind of uncertainty associated with vagueness, with imprecision, and/or with a lack of information regarding a particular element of the problem at hand.

The fundamental difference between fuzziness and probability is that fuzziness deals with deterministic plausibility, while probability concerns the likelihood of nondeterministic, stochastic events. Fuzziness is one aspect of uncertainty. It is the ambiguity (vagueness) found in the definition of a concept or the meaning of a term such as *comfortable temperature* or *well cooked.* However, the uncertainty of probability generally relates to the occurrence of phenomena, as symbolized by the concept of randomness. In other words, a statement is probabilistic if it expresses some kind of likelihood or degree of certainty or if it is the outcome of clearly defined but randomly occurring events.

Hence, fuzziness and randomness differ in nature; that is, they are different aspects of uncertainty. The former conveys "subjective" human thinking, feelings, or language and the latter indicates an "objective" statistic in the natural sciences.

3.4 The Fuzzy Inference System

Fuzzy inference system is also known as fuzzy knowledge based systems. These can be applied to various engineering disciplines. These can be applied to decision processes and they can map the inputs of a system to the output based on the knowledge of a system. These knowledge based systems consist of the three concepts as previously stated: membership functions, if – then rules, and logic operators. The basic process of building a fuzzy inference system consists of the four operational steps described in the following sections.

Fuzzy Inference System Process:

- Step 1: Fuzzification interface
- Step 2: Knowledge Base
- Step 3: Fuzzy Inference Machine
- Step 4: Defuzzification interface

The block diagram of the fuzzy inference system is given in figure.

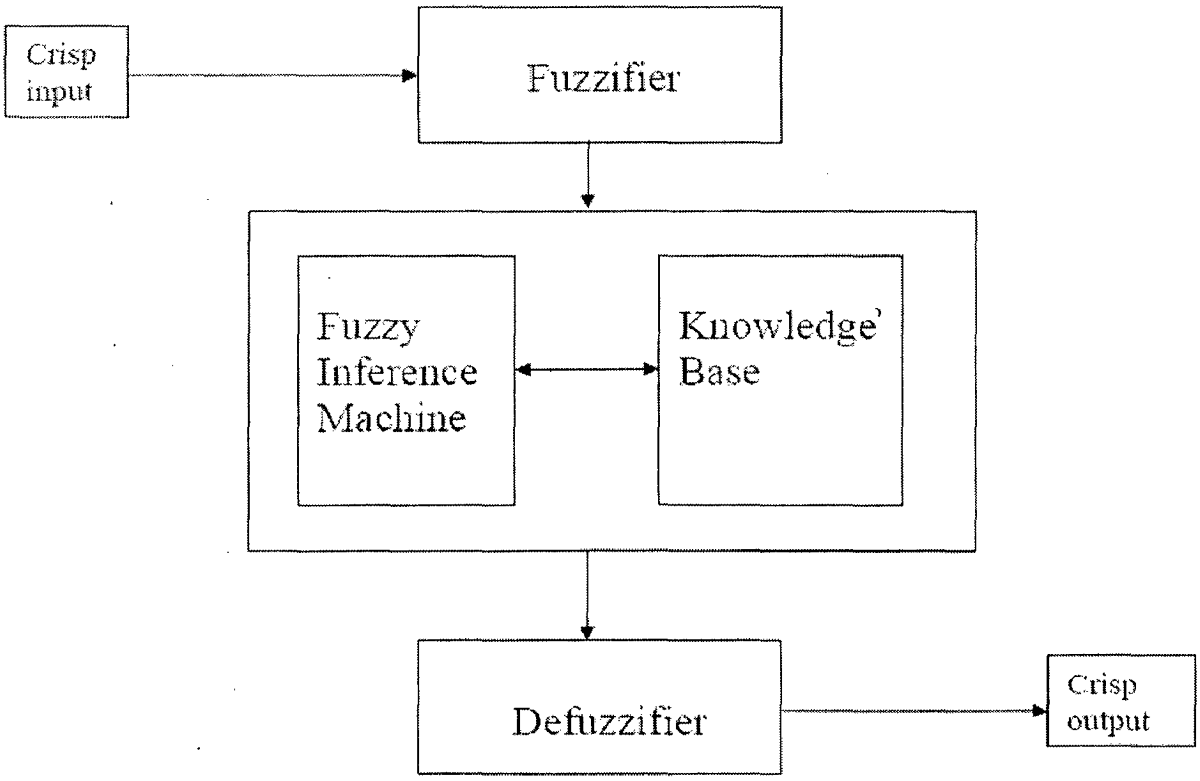

Figure 3.1 Fuzzy Inference System

3.4.1 Fuzzification Interface

Fuzzification process takes the inputs and determines their degree of membership in the appropriate fuzzy sets using the membership functions. Before the inputs are evaluated, they must be fuzzified against the linguistic fuzzy sets. For a crisp input the membership function can be found by evaluating the linguistic set for the input set.

3.4.2 Knowledge Base

The knowledge base contains the information about the boundaries, possible transformations of the domains, and the fuzzy sets with their corresponding linguistic terms. This information represents the data base. In addition, the knowledge base contains a rule base consisting of linguistic control rules

3.4.3 Decision Logic

The decision logic represents the processing unit. It determines the corresponding output value from the measured input according to the knowledge base.

3.4.4 Defuzzification Interface

The defuzzification interface has the task of determining a crisp output value taking the information about the control variable provided by the decision logic into account. Finally, if necessary, it carries out a transformation of the output value into the appropriate domain. The different methods for defuzzification are:

1) Centroid method.
2) Mean of Maximum method.
3) Maximum Membership Function method.
4) Weighted Average method.

3.5 Basic Fuzzy Reliability Concepts

The reliability studies depend on the analysis of system behavior, taking the failures of the equipments into account. Classical reliability studies are based on two assumptions: the probabilistic assumption, which state that the system behavior can be fully defined and understood through probabilistic theory, and the binary state assumption, which requires that the state of equipment, of failure or functioning, be completely defined.

The consideration of fuzzy concepts to reliability leads to the following reliability models [4]:

- PROBIST model: assuming the probabilistic assumption and the binary state assumption
- PROFUST model: keeping the probabilistic assumption but introducing fuzzy state assumption.
- PROBIST model: introducing a possibilistic assumption as to the description of events and the laws governing their repetition, together with the binary state assumption.
- POSFUST model: combining the possibilistic assumption and the fuzzy state assumption.

The fuzzy reliability methods presented in this thesis are based on the PROFUST model. Two interpretations are given to the meaning of fuzzy state assumption. The first interpretation of a fuzzy state assumption is that one cannot precisely define the state of a component, namely the meaning of system failure, as if the borders of the functioning state and failure state were not precise, leading to the definition of a fuzzy success state and fuzzy failure state. The second interpretation shows that one can define exactly the operating and the failure states, but cannot define precisely how the transition occurs, that is how often the transition occurs.

CHAPTER 4

FUZZY MARKOV MODELLING

4.1 Introduction

Markov modeling is a powerful method based on system states and transition between the states. Markov modeling techniques can be applied to a variety of modeling problems and many areas related to the reliability analysis. But the only drawback of the Markov modeling is that this method is computationally intensive as the number of states increases.

Markov models make two assumptions regarding the system behavior. The first assumption is that the system does not require any memory i.e., the system is memory less. The future probability of events is solely a function of the existing state of the system and not what has occurred before the system entered into the present state. The second assumption is that the system is a stationary system and the transition probabilities between the states do not vary with time.

Markov models can be either discrete or continuous [3]. Discrete Markov models have state transitions that occur at discrete time intervals where as for continuous Markov models have constant state transitions. Most of the reliability applications utilize continuous Markov models for finding the probability of being in certain state.

4.2 Continuous Markov Modeling

Continuous Markov modeling is generally used in the assessment of reliability of distribution systems. Like a Markov chain, the Markov process is described by a set of states and transition characteristics between the states but the state transitions occur continuously rather than at discrete time intervals.

Markov processes are easily applied to distribution system reliability models. Here the failure rate of the system or component is equivalent to the state transition rate. As long as the equipment failures are assumed to be exponentially distributed the failures are constant and the Markov models can be applied. Along with the failure rates, repair rate and switching rate can also be used as transition rates. Assuming exponential distributions to the switching rate and repair rate, switching rate is equal to reciprocal of mean time to switch and repair rate is equal to mean time to repair.

λ ; failure rate (4.1)

$\sigma = 1/MTTS$; switching rate (4.2)

$\mu = 1/MTTR$; repair rate (4.3)

Though the failure rate is assumed as exponentially distributed, the switching rate and the repair rate are not generally exponentially distributed and therefore cannot accurately described by constant state transition rates. But the switching rates and the repair rates can be modeled as constant values will small sacrifice in the accuracy.

States in Markov models are characterized by transitions into the state (represented by positive values) and transitions out f the state (represented by negative values).

Example to Illustrate Continuous Markov Modeling for Distribution Systems.

Let us consider a simple distribution system as shown in Figure 4.1a. The system consists of two substations SS1 and SS2, a circuit breaker CB1, two line sections LS1 and LS2, a normally closed switch SW1 and a normally open switch SW2. The system is normally in state 0. If the line LS1 fails, circuit breaker CB1 opens and the system transitions into state 1a. To restore supply to the customers, switch SW1 will be opened and SW2 will be closed. Now the system transitions into state 1b. When the line LS1 is repaired switches are positioned in the normal way transitioning the system into state 0 again. A similar sequence of events will occur when the line LS2 fails. The Markov model representing the distribution system is shown in Figure 4.1b, with λ_1, σ_1, μ_1 corresponding to LS1 and λ_2, σ_2, μ_2 corresponding to LS2.

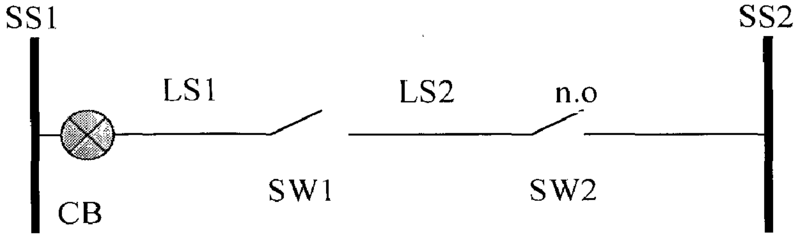

Figure 4.1a. A simple distribution system.[1]

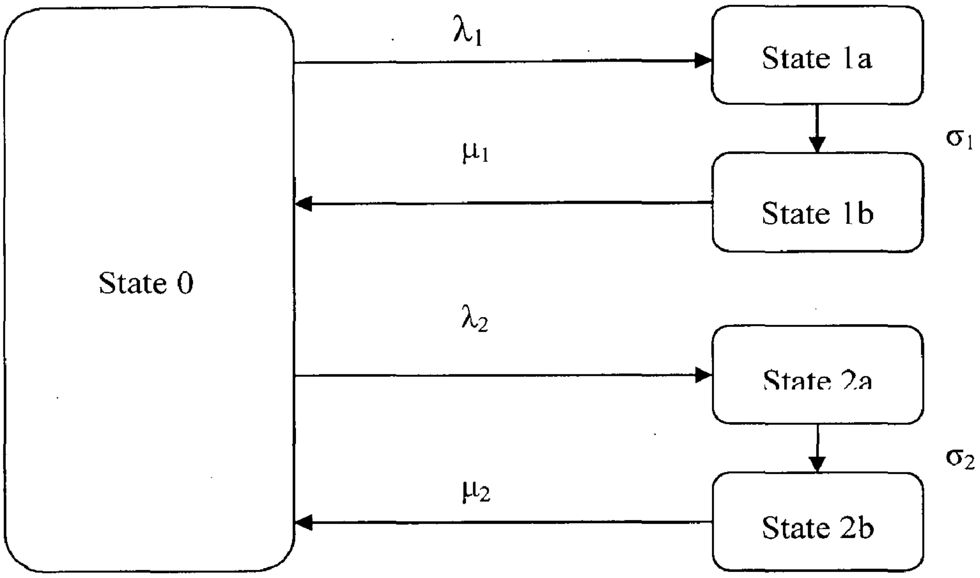

Figure 4.1b Markov model for the distribution system in 4.1a

Markov models are solved in the manner similar to the Markov chains except that differential equations rather than difference equations are utilized. The transition rate into each state is equal to the sum of the probability of transferring in from external states minus the probability of transferring out from the considered state. The set of equations for the above Markov model are shown below.

$$\begin{bmatrix} dp_o/dt \\ dp_{1a}/dt \\ dp_{1b}/dt \\ dp_{2a}/dt \\ dp_{2b}/dt \end{bmatrix} = \begin{bmatrix} -(\lambda_1+\lambda_2) & 0 & \mu_1 & 0 & \mu_2 \\ \lambda_1 & -\sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_1 & -\mu_1 & 0 & 0 \\ \lambda_2 & 0 & 0 & -\sigma_2 & 0 \\ 0 & 0 & 0 & \sigma_2 & -\mu_2 \end{bmatrix} \begin{bmatrix} P_0(t) \\ P_{1a}(t) \\ P_{1b}(t) \\ P_{2a}(t) \\ P_{2b}(t) \end{bmatrix} \tag{4.4}$$

The above equation can be used for simulation of the probabilities. Similar to Markov chain, the probability of being in state 0 initially is 100% and the probability of the future states is computed by linearized changes in the probabilities associated with small time steps. State probabilities asymptotically converge as time approaches infinity, indicating an ergodic system.

Steady state solutions for Markov process are computed by setting all state transition derivatives equal to zero. Since the set of equations is undetermined, one of the rows must be replaced with an equation indicating that the sum of all state probabilities must be equal to unity. So the above state transition matrix at steady state becomes

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ \lambda_1 & -\sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_1 & -\mu_1 & 0 & 0 \\ \lambda_2 & 0 & 0 & -\sigma_2 & 0 \\ 0 & 0 & 0 & \sigma_2 & -\mu_2 \end{bmatrix} \begin{bmatrix} P_0(t) \\ P_{1a}(t) \\ P_{1b}(t) \\ P_{2a}(t) \\ P_{2b}(t) \end{bmatrix} \tag{4.5}$$

Solving the above set of equations the probability of system being in certain state i.e., P_0, P_{1a}, P_{1b}, P_{2a}, P_{2b} can be obtained.

For example

For the above Markov model let system parameters are given as:

For line LS1:

λ_1=0.5/yr (0.0000571/yr)

σ_1= 1/hr (MTTS = 1hr)

μ_1=0.25/hr (MTTR= 4hr)

For line LS2:

λ_2= 0.2/yr (0.0000228/hr)

σ_2= 1/hr (MTTS = 1hr)

μ_2= 0.125/hr (MTTR = 8hr)

Solving the above set of equations by substituting the parameters listed above the state probabilities converge to:

$$P_0 = 0.999511$$
$$P_{1a} = 0.000057$$
$$P_{1b} = 0.000228$$
$$P_{2a} = 0.000023$$
$$P_{2b} = 0.000181$$

Before a Markov model reliability assessment is complete, state probabilities must be converted into standard reliability measures. To do this, the reliability implications associated with each customer must be computed for each state (e.g. interrupted or not interrupted). Once complete the unavailability of a customer's service can be computed by adding up the probabilities of all states associated with the customer being interrupted. Computing the customer interruption frequencies is a bit more complicated, but can be achieved by examining the probability of transitioning between states where customer is not interrupted to states where customer is interrupted. For the above example, the customers associated with line LS1 are interrupted in state 1a, 1b and 2a and have an unavailability of $P_{1a} + P_{1b} + P_{2a}$. Interruption frequencies are associated with transition between state 0 and either state 1a or state 2a, and have a corresponding frequency of P0 ($\lambda 1 + \lambda 2$).

4.3 Fuzzy Markov Modeling

From the distribution system point of view, Markov models are very important, because they form the basis of many simplified models used in practice. In the sense of the PROFUST fuzzy reliability model, it is possible to define Markovian models for the behavior of the component or system, with the following characteristics.

(a) The state space is completely defined and crisp i.e., the failure state or the success state.

(b) The transitions between the states are assumed as obeying the general probabilistic laws; i.e., a Markov model with no memory is characterized by exponential distributions with constant rate.

(c) The definition of transitions themselves between the states is fuzzy; one is uncertain about the actual value of the transition rates and therefore describes then as fuzzy numbers.

Let us analyze a two state Markov model of a component with a failure *f* and success *s* state and a fuzzy failure rate λ and a fuzzy repair rate μ. The objective is to try to assess the value of the steady state probabilities P_s and P_f of finding the component in either state. Since the raw data used for finding the probabilities is fuzzy the probability values will also be fuzzy.

The state diagram for a two state Markov model is given below:

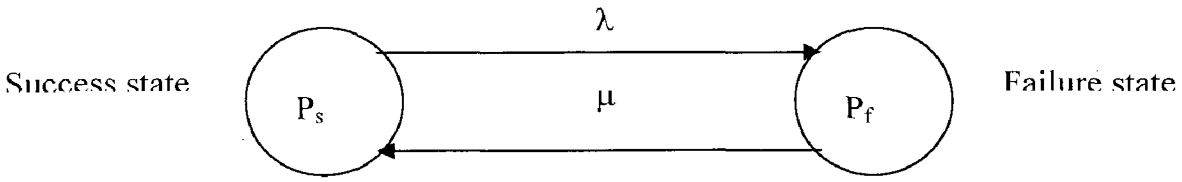

Figure 4.2 Two state Markov model

The steady state transition matrix for a continuous time Markov model is given by:

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -\lambda & \mu \\ \lambda & -\mu \end{bmatrix} \begin{bmatrix} P_s \\ P_f \end{bmatrix} \tag{4.6}$$

By solving the above set of equations the probabilities of success and failure states are obtained as

$$P_s = \frac{\mu}{\lambda + \mu} \tag{4.7}$$

$$P_f = \frac{\lambda}{\lambda + \mu} \qquad (4.8)$$

These expressions can be taken as basis for fuzzy model. However, it would be wrong to just replace in them the crisp rates λ and μ by fuzzy definitions. The result would give a much larger uncertainty than necessary, because one would be using more than once the same fuzzy variable in the calculations. The correct form of the expressions for fuzzy values of P_s and P_f are obtained by dividing the numerator and denominator of the expression with the numerator.

$$P_s = \frac{1}{1 + \left({}^{1}\!/_{\mu} \right) \lambda} \qquad (4.9)$$

$$P_f = \frac{1}{1 + (1/\lambda)\,\mu} \qquad (4.10)$$

Using the above set of equations the fuzzy probability of success and fuzzy probability of failure can be found.

If we consider a Markov model with three states, a success state, a failure state and a derated state, the transition matrix is given as:

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ -\lambda & 0 & \mu \\ \lambda & -\sigma & 0 \\ 0 & \sigma & -\mu \end{bmatrix} \begin{bmatrix} P_S \\ P_D \\ P_F \end{bmatrix} \qquad (4.11)$$

Where

λ= fuzzy failure rate of the component or system

μ= fuzzy repair rate of the component or system

σ= fuzzy switching rate of the component or system.

By solving the above set of equations the probabilities of the success, derated and the failure states can be obtained as

$$P_S = \frac{1}{1+\lambda\left(1/\sigma+1/\mu\right)} \qquad (4.12)$$

$$P_D = \frac{1}{1+\sigma\left(1/\mu+1/\lambda\right)} \qquad (4.13)$$

$$P_F = \frac{1}{1+\mu\left(1/\sigma+1/\lambda\right)} \qquad (4.14)$$

4.4 Fuzzification of Transition Parameters

Let us consider a failure rate value λ relative to a component or system. In order to make the failure rate a fuzzy value, level of confidence is assumed for the failure rate. The designation of level of confidence does not relate to any classical statistical concepts but to the discourse of the fuzzy set theory. An interval of confidence α corresponds to the cutset at level α defined in relation to the membership function of a fuzzy set.

A fuzzy number can be represented as nested intervals of confidence. Therefore for a trapezoidal membership function the failure rate λ can be represented as

$$\lambda_\alpha = \left[(\lambda - l) - k(1-\alpha), \quad (\lambda + l) + k(1-\alpha)\right] \qquad (4.15)$$

Where λ is the failure rate of the component or system, α is the level of confidence and 2K is the interval of confidence and λ_α is the interval of confidence at the confidence level α.

For example: for a λ= 0.01and K=0.02,and l=0.03 the fuzzy failure rate is represented as shown in Fig. 4.3

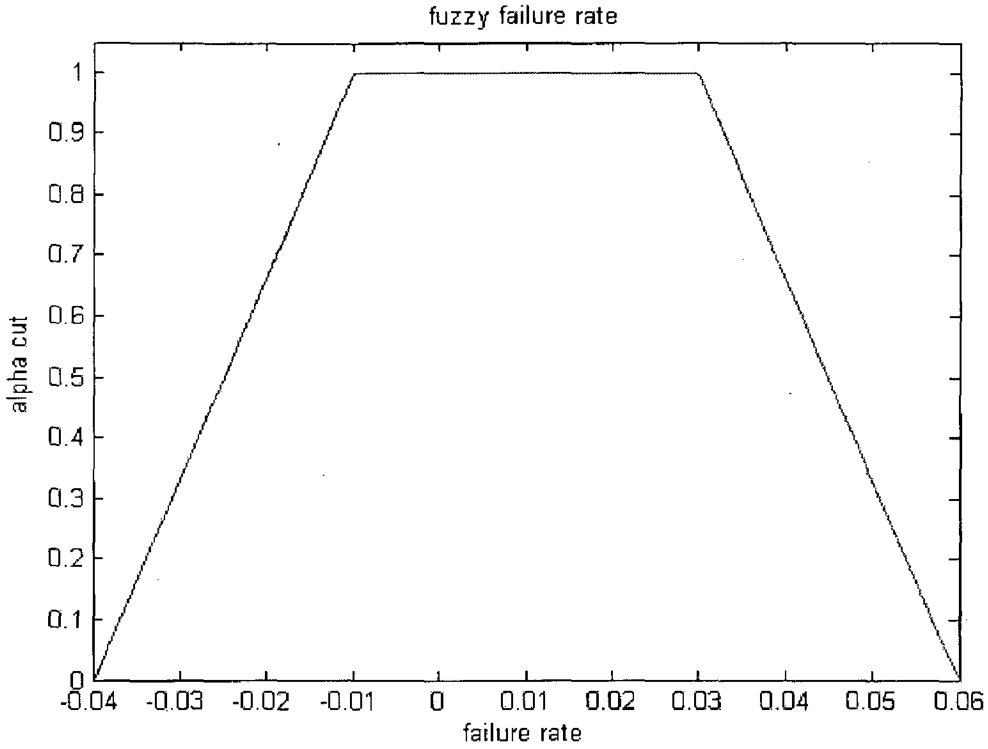

Figure 4.3 Trapezoidal Fuzzy failure rate

Similarly the repair rate and the switching rate can also be fuzzified using the above procedure. The expressions are given below:

$$\mu_\alpha = \left[(\mu - l) - k(1-\alpha),\ \ (\mu + l) + k(1-\alpha)\right] \qquad (4.16)$$

$$\sigma_\alpha = \left[(\sigma - l) - k(1-\alpha),\ \ (\sigma + l) + k(1-\alpha)\right] \qquad (4.17)$$

4.5 Application of Fuzzy Markov Modeling to Test System

Let us consider the feeder 3 of bus 6 of the reliability test system proposed buy R.Billinton for the application of fuzzy Markov modeling. The network is shown below

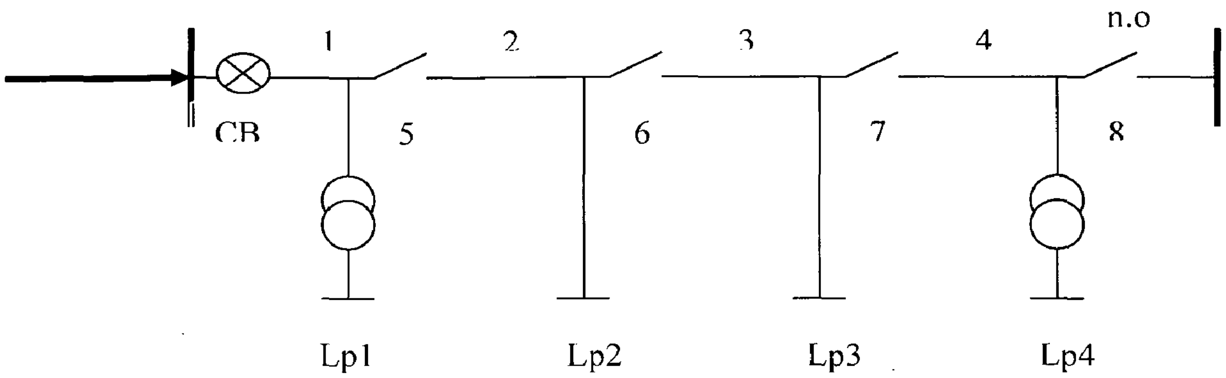

Figure 4.4 distribution network at feeder 3 at bus 6 of RBTS[15]

The parameters for the network shown in the figure are given in table:

Table 4.1a main section data for the feeder in Fig.4.4[15]

$\lambda = 0.065$ f/km.yr

Main section	Length km	λ f/yr	r hr	s hr
1	0.75	0.04875	5	1
2	0.80	0.05200	5	1
3	0.60	0.03900	5	1
4	0.75	0.04875	5	1

Table 4.1b lateral section data for the feeder in Fig.4.4[15]

Lateral section	Length Km	λ f/yr	r hr	s hr
5	0.60	0.03900	5	1
6	0.75	0.04875	5	1
7	0.80	0.05200	5	1
8	0.60	0.03900	5	1

The Markov model for the distribution system network shown in figure is given below:

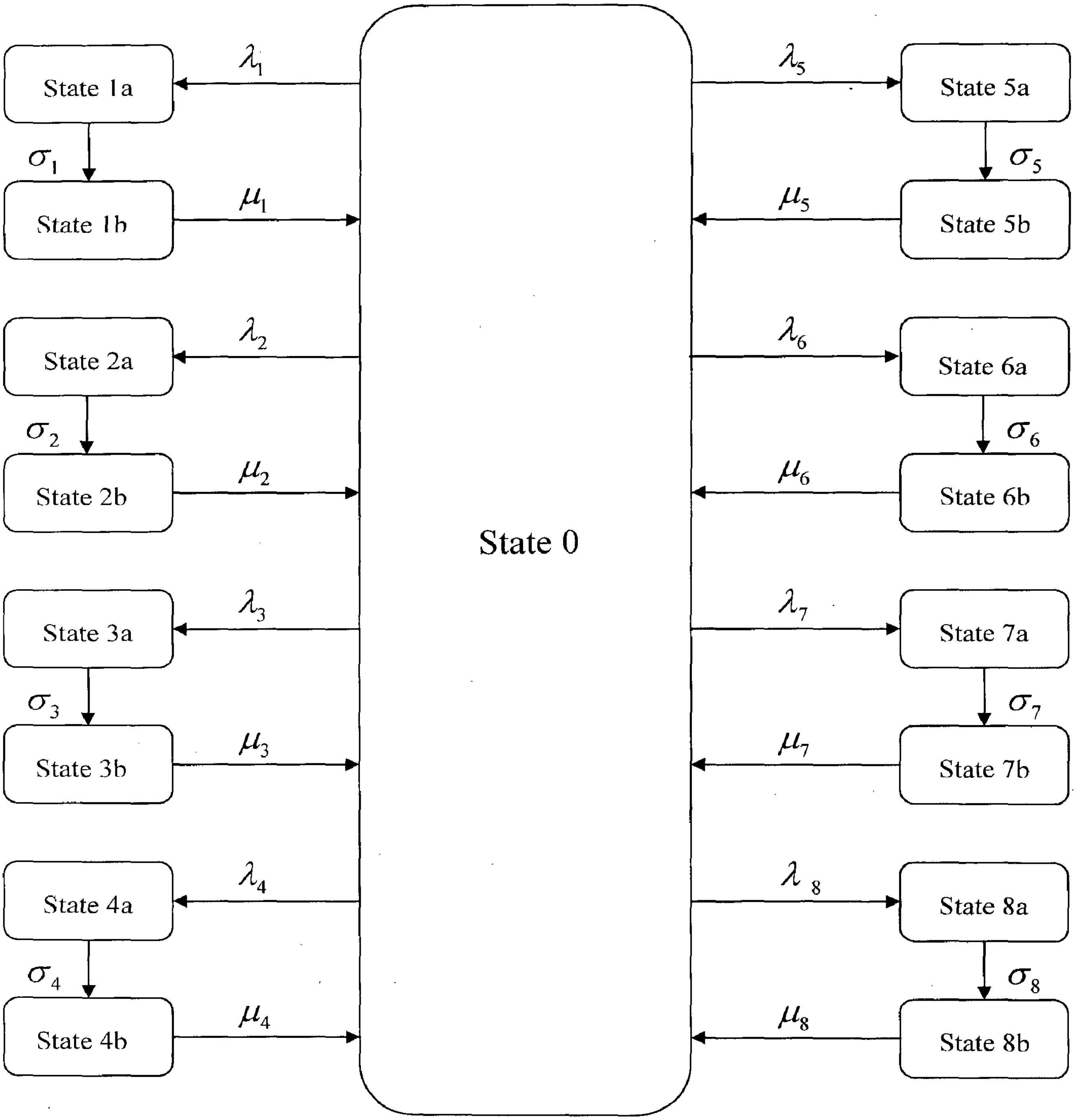

Figure 4.5 Markov model for the distribution test system

The steady state transition matrix for the Markov model shown in figure is given by:

$$A=\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\lambda & -\sigma_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \sigma_1 & -\mu_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_2 & 0 & 0 & -\sigma_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \sigma_2 & -\mu_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_3 & 0 & 0 & 0 & 0 & -\sigma_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \sigma_3 & -\mu_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_4 & 0 & 0 & 0 & 0 & 0 & 0 & -\sigma_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_4 & -\mu_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sigma_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_5 & -\mu_5 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sigma_6 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_6 & -\mu_6 & 0 & 0 & 0 & 0 \\
\lambda_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sigma_7 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_7 & -\mu_7 & 0 & 0 \\
\lambda_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sigma_8 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma_8 & -\mu_8
\end{bmatrix}$$

The equation becomes

$$B= A.P \tag{4.18}$$

Where A= transition matrix

$B= [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$

P= probability matrix and is given by

$[P_o\ P_{1a}\ P_{1b}\ P_{2a}\ P_{2b}\ P_{3a}\ P_{3c}\ P_{4a}\ P_{4b}\ P_{5a}\ P_{5b}\ P_{6a}\ P_{6b}\ P_{7a}\ P_{7b}\ P_{8a}\ P_{8b}]^T$

By solving the equation, we get

$$P_0=\frac{1}{\left(1+\sum_{i=1}^{8}\left(\frac{\lambda_i}{\sigma_i}+\frac{\lambda_i}{\mu_i}\right)\right)} \tag{4.19}$$

$$P_{ia} = \frac{\lambda_i}{\sigma_i} P_0 \tag{4.20}$$

$$P_{ib} = \frac{\lambda_i}{\mu_i} P_0 \tag{4.21}$$

Where i= 1, 2, 3, …., 8.

Fuzzification of the transition parameters:

Let us assume triangular membership function for the Fuzzification process. By using the equations we get

For λ= 0.04875f/yr = .5565e-5f/hr let k=0.004 then for different α-cuts we get:

Table 4.2 Fuzzy failure rate at different α-cuts

α-value	λ -ve(f/hr) 1.0e-005 *	λ +ve(f/hr) 1.0e-005 *
0	0.4965	0.6165
0.1	0.5005	0.6125
0.2	0.5045	0.6085
0.3	0.5085	0.6045
0.4	0.5125	0.6005
0.5	0.5165	0.5965
0.6	0.5205	0.5925
0.7	0.5245	0.5885
0.8	0.5285	0.5845
0.9	0.5325	0.5805
1.0	0.5365	0.5765

This can be represented as [0.4965 e-5 0.5365e-5 0.5765e-5 0.6165e-5]

Similarly the failure rates of other sections of the network can be fuzzified.

Table 4.3a Fuzzification of different failure rates

Failure rate	Fuzzy failure rate
0.03900f/yr (0.4452e-5f/hr)	[0.3852e-5 0.4252e-5 0.4652e-5 0.5052e-5]
0.04875f/yr (0.5565e-5f/hr)	[0.4965 e-5 0.5365e-5 0.5765e-5 0.6165e-5]
0.05200f/yr (0.5936e-5f/hr)	[0.5536e-5 0.5736e-5 0.6136e-5 0.6536e-5]

Table 4.3b Fuzzification of repair rate

Repair rate	Fuzzy repair rate
0.2/hr	[0.17 0.19 0.21 0.23]

Table 4.3c Fuzzification of switching rate

Switching rate	Fuzzy switching rate
1/hr	[0.97 0.99 1.01 1.03]

By substituting the values of failure rate, repair rate and switching rate at different alpha cuts in the equations 4.19, 4.20 and 4.21 fuzzy values of probability of different states at different α-cuts can be found.

4.6 Results

4.6.1 Fuzzy Probability of States

The fuzzy probability value of state 0 obtained can be shown as:

α-value	P0-ve	P0+ve
0	0.9997434	0.9997515
0.2	0.9997442	0.9997512
0.4	0.9997450	0.9997508
0.6	0.9997457	0.9997505
0.8	0.9997464	0.9997501
1.0	0.9997471	0.9997497

Table 4.4 fuzzy probability of state 0 at different α-cuts

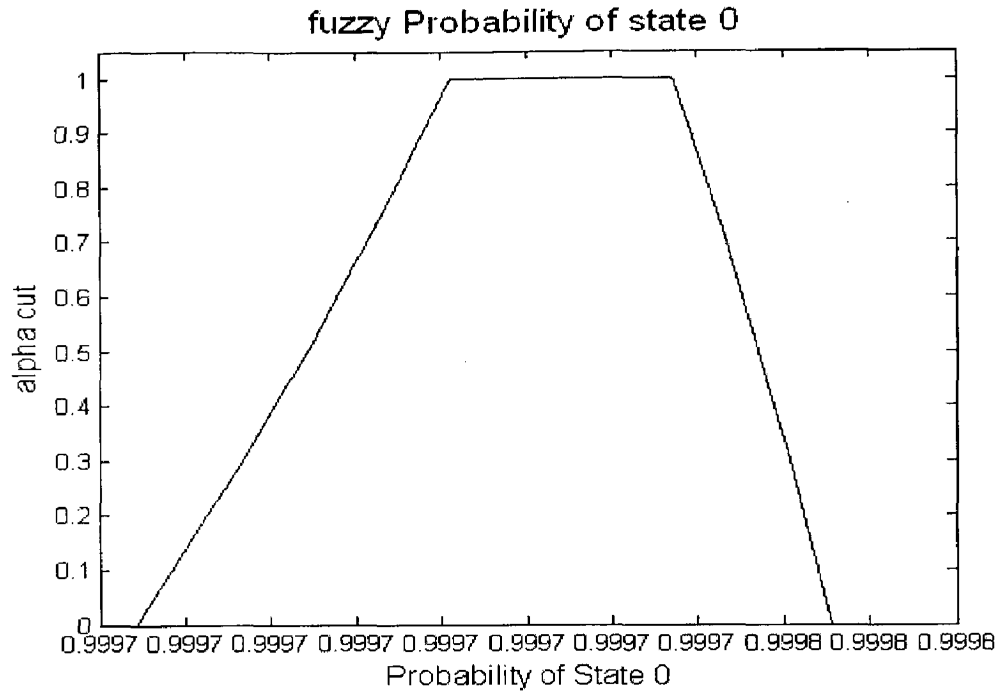

Figure 4.6 fuzzy P0 vs. α-cut

The plot for the fuzzy value of P0 is not perfectly a triangular membership function but it is assumed to be a triangular membership function.

The fuzzy probability of state 1a is given by:

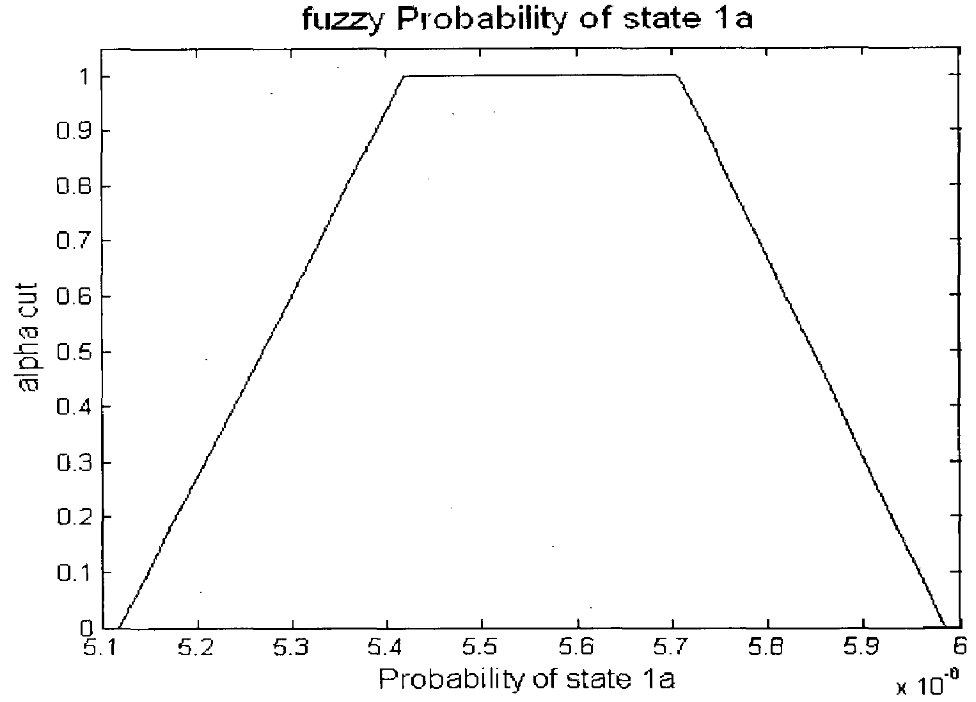

Figure 4.7 fuzzy P1a vs. α-cut

α-value	P1a-ve 1.0e-005*	P1a+ve 1.0e-005*
0	0.5117	0.5984
0.1	0.5148	0.5957
0.2	0.5178	0.5929
0.3	0.5209	0.5902
0.4	0.5239	0.5874
0.5	0.5269	0.5847
0.6	0.5299	0.5819
0.7	0.5329	0.5791
0.8	0.5359	0.5763
0.9	0.5388	0.5765
1.0	0.5418	0.5707

Table 4.5 fuzzy probability of state 1a at different α-cuts

The fuzzy probability value of state P1b is obtained as:

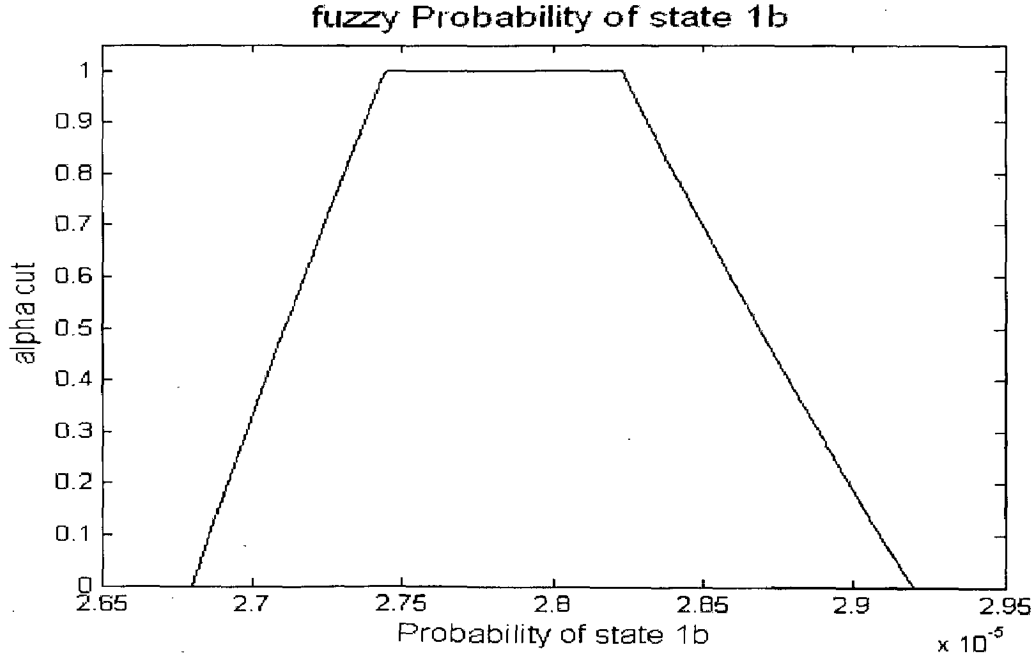

Figure 4.8 fuzzy P1b vs. α-cuts

α-value	P1b-ve 1.0e-004*	P1b+ve 1.0e-004*
0	0.2920	0.2680
0.1	0.2909	0.2686
0.2	0.2899	0.2692
0.3	0.2889	0.2698
0.4	0.2879	0.2704
0.5	0.2869	0.2711
0.6	0.2859	0.2717
0.7	0.2850	0.2724
0.8	0.2841	0.2731
0.9	0.2832	0.2738
1.0	0.2823	0.2745

Table 4.6 fuzzy probability of state 1b at different α-cuts

The fuzzy probability values of other states are also found in the same process.

4.6.2 Fuzzy Probability of Unavailability ay Load Points

The fuzzy probability unavailability of the customers being interrupted at each load point can be calculated by adding up all the probabilities of all the states associated with customer interruption.

Therefore for load point 1, the states causing interruption to the customers' service are P1a, P1b, P2a, P3a, P4a, P5a, P5b. The probability of unavailability is calculated by adding all these states:

Probability of unavailability at Load Point 1= P1a+ P1b+P2a+ P3a+ P4a+ P5a+ P5b

= [7.2413e-5 7.4798e-5 7.7297e-5 7.9958e-5]

Probability of unavailability of Load Point 2= P1a+ P2a+ P3a+ P4a+ P2b+ P6b

= [8.002e-5 8.2993e-5 8.6209e-5 8.9769e-5]

Probability of unavailability of Load Point 3= P1a+ P2a+ P3a+ P4a+ P3b+ P7b
= [8.2022e-5 8.5136e-5 8.8525e-5 9.2319e-5]

Probability of unavailability of Load Point 4= P1a+ P2a+ P3a+ P4a+ P4b+ P8b
= [7.2413-5 7.4798e-5 7.7297e-5 7.9958e-5]

4.6.3 Variation of Reliability with Time

The reliability of component 1 is discussed here. The failure rate of component 1 is given by 0.04875failures/year. Since the failure rate is constant in this case the exponential probability distribution function is assumed for the plotting the reliability curve. To get the fuzzy reliability curve the failure rate of the component has to be fuzzified

For λ=0.04875f/yr the fuzzy value is given by [0.04475 0.04875 0.5275]

The fuzzy reliability function is given by

$$R(t) = \left[e^{-\lambda_\alpha^{-ve} t} \quad e^{+\lambda_\alpha^{+ve} t} \right] \tag{4.22}$$

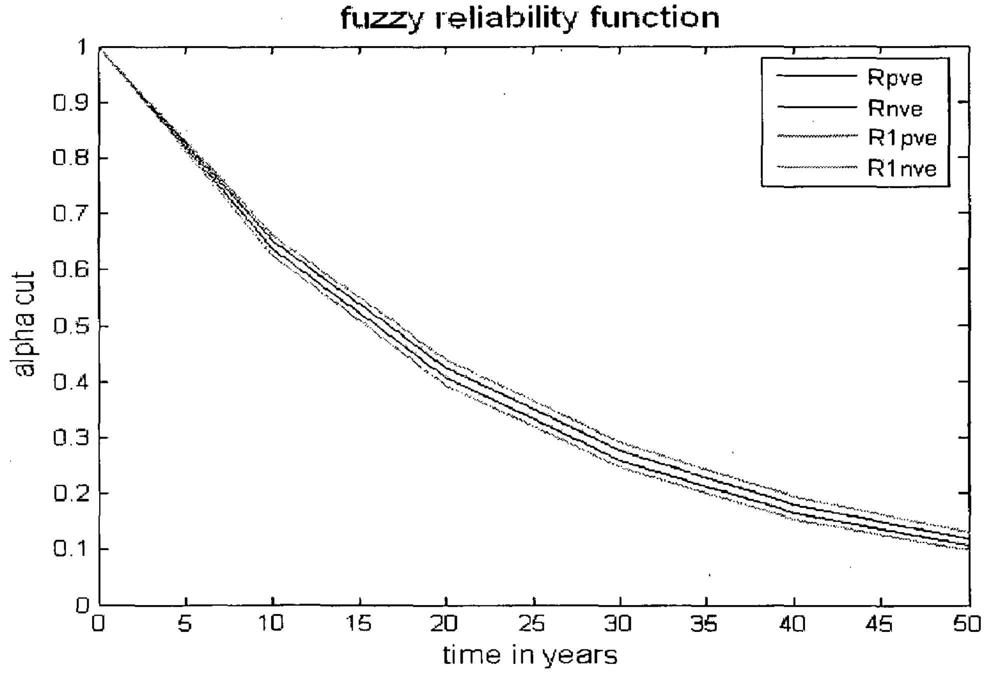

Figure 4.9 fuzzy reliability curve of component 1

Time in years	R-ve at $\alpha=0$	R-ve at $\alpha=1$	R+ve at $\alpha=1$	R+ve at $\alpha=0$
0	1.0000	1.0000	1.0000	1.0000
20.0000	0.4253	0.3926	0.4404	0.4066
40.0000	0.1809	0.1541	0.1940	0.1653
50.0000	0.1179	0.0966	0.1287	0.1054
80.0000	0.0327	0.0238	0.0376	0.0273
100.0000	0.0139	0.0093	0.0166	0.0111
120.0000	0.0059	0.0037	0.0073	0.0045
140.0000	0.0025	0.0014	0.0032	0.0018
160.0000	0.0011	0.0006	0.0014	0.0007
180.0000	0.0005	0.0002	0.0006	0.0003
200.0000	0.0002	0.0001	0.0003	0.0001

Table 4.7 fuzzy reliability of component 1 w.r.t years

Table.4.7 shows the variation of reliability of a component with time. For the component considered the reliability becomes zero after 200 years. The plot for the fuzzy reliability function is shown in the figure 4.9

4.7 Limitations of Markov Modeling.

The main draw back of the Markov Modeling is that as the number of components in the system increases, the number of states in the state model increases. As a result of this the computational complexity of the model increases. This method becomes very time consuming in case of complex distribution systems.

CHAPTER 5

FUZZY EVENT TREE ANALYSIS

5.1 Event Tree Analysis

Event trees are useful for system reliability analysis and risk quantification since they illustrate the logic of combination of probabilities and consequences of event sequences. Event trees have been fond to be most popular choice in terms of building an analytical model of the system. It provides a compact representation of the system and is easily understood by the humans.

5.2 Event Tree Analysis Requirements

The following requirements are necessary before the Event tree analysis on a system is done:

1) Thorough knowledge of how the system works.
2) Knowledge of the logic relationships in the system (operation of protection devices, interlocks, control interfaces, power supply feeds etc.).

5.3 Procedure for Event Tree Analysis

The following procedure is used for the event tree analysis:

1) Each event that the system can sense, for example, is considered in turn.
2) The full consequences of the event are followed through logically.
3) For each event, "forward reasoning" is involved.
4) The resulting states are analyzed, and these may include both safe and hazardous states.

For example, consider a particular component that is protected by two breakers B1 and B2. Assume that both breakers are operated by the same fault detector (FD), relay(R) and trip signal device (TS). This is clearly an unrealistic operating procedure since considerably more redundancy, diversity and independence will generally be included in a practical system. This example however is intended to illustrate the modeling procedure, the basic evaluation method and the effect of common components. The event tree for this system, given an active failure on the component, is shown in Figure 5.1. This illustrates the sequence of events together with the outcomes of each event path, only one of which in this case leads to both breakers operating successfully and four of, which lead simultaneously to both breakers not operating.

This event tree assumes that each component can reside in one of only two states; these being the operable state, i.e. it can respond to a system fault when-one occurs, and the inoperable state, i.e.-it is failed and cannot respond to a system fault. A further state-exists in practice which represents an inadvertent operation and causes the breaker to trip. This state however is generally associated with a revealed fault of the protection system or breaker. The event tree for this example is shown in Figure 5.1

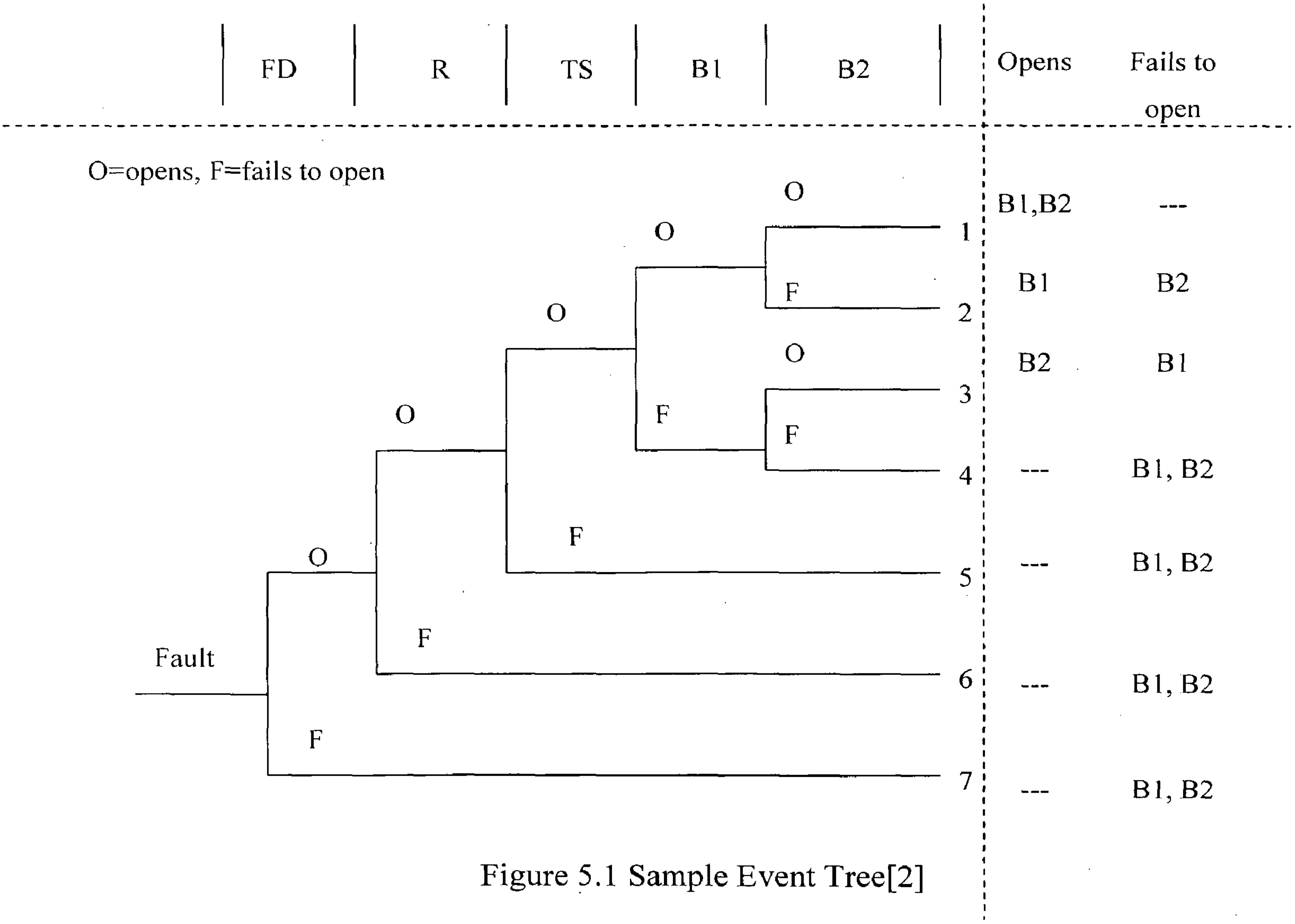

Figure 5.1 Sample Event Tree[2]

The traditional method of event tree generation is much more time consuming and requires manually identifying all initiating events and all the system responses associated with these events. The results of the event tree analysis are the probabilities of all the system outcomes associated with the initiating events. These results can be translated into a reliability analysis by determining the system impact of each outcome and weighing this impact by the probability of the associated outcome occurring.

5.4 Fuzzy Event Tree Analysis

Event trees are useful for system reliability studies and risk quantification since they illustrate the logical combination of probabilities and consequences of event sequences. For many systems, estimation of single number for probabilities and consequences is difficult due to uncertainty and imprecision of data, and hence a range of values has to be used in the analysis. Fuzzy probability can handle imprecision since a range of values is used to describe a level of consequence. The fuzzy event tree logic allows:

1) uncertainty in the probability of failure and
2) Verbal statements for the probabilities and consequences such as low, moderate, and high for the impact of certain sequences of events.

5.5 Application of Fuzzy event Tree Analysis to Distribution Systems:

Let us consider the electric power distribution network shown in Figure 5.2. Each of the transformers is protected by a differential scheme, i.e. both circuit breakers protecting each of the transformers are operated by the same fault detector, FD, and a combined relay/trip signal device, RTS. Generally electric power protection systems involve the sequential operation of the set of components and devices. Fault trees are particularly useful because they recognize the sequential operation logic of a system. The fuzzy event tree for the network in Figure 5.2 is shown in Figure5.3

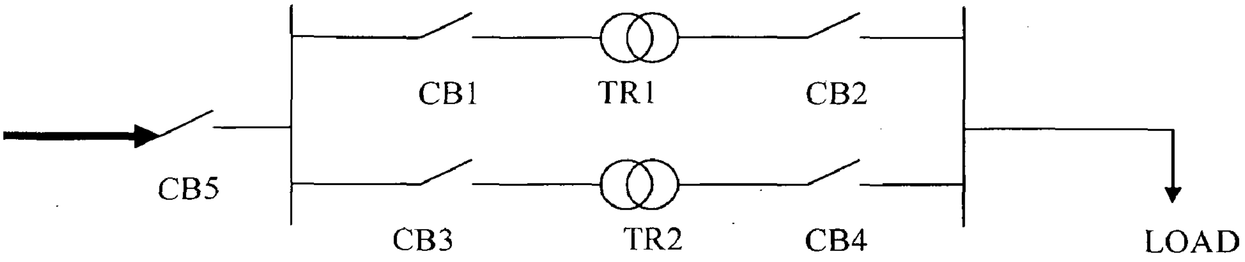

figure 5.2 A Dual transformer distribution feeder[2]

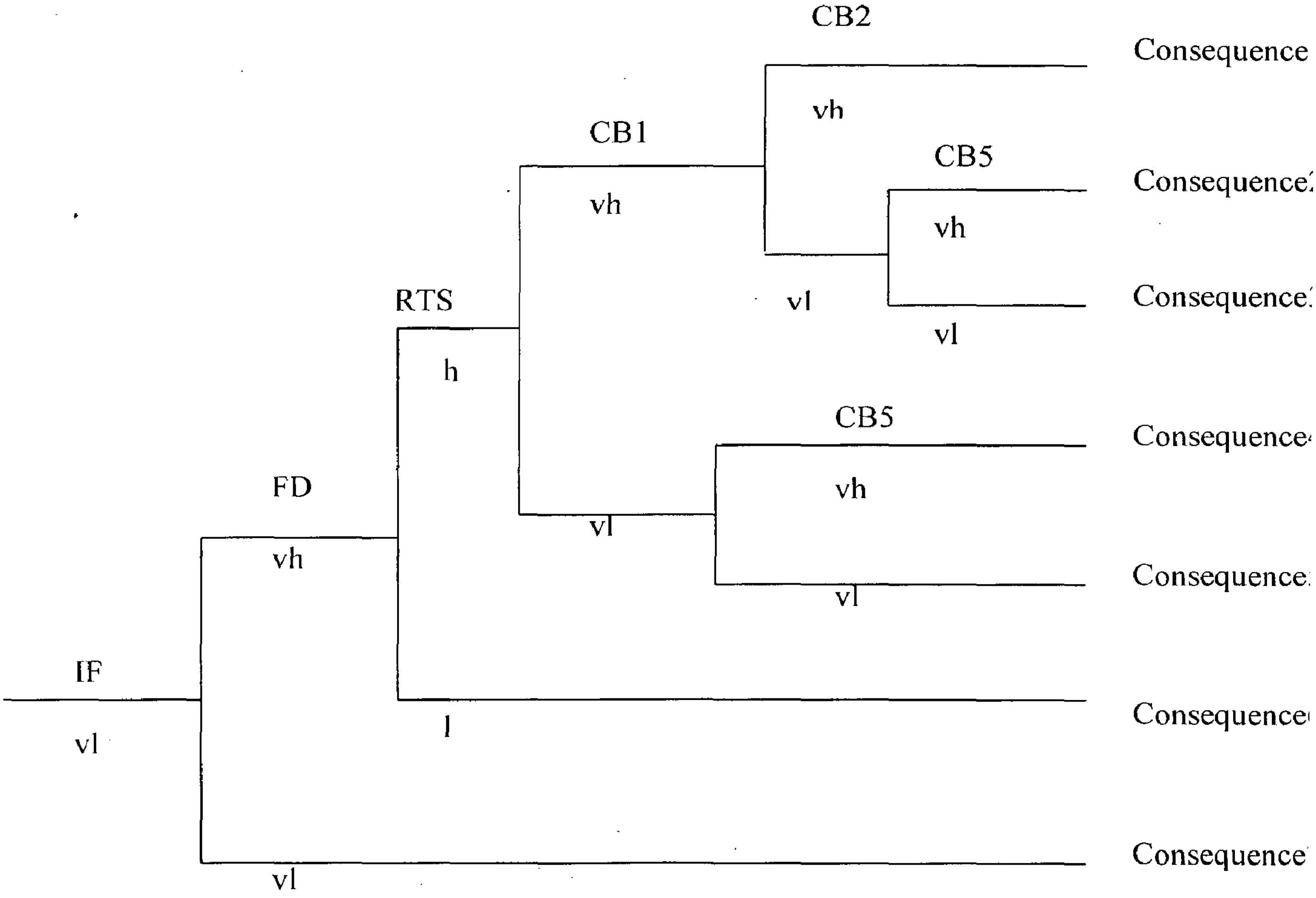

Figure 5.3 Fuzzy event Tree for Fault on Transformer 1.

Where vl=very low,

vh= very high,

l= low,

h= high

IF= Initiating Fault
FD= Fault Detector
RTS= Relay/Trip Signal
CB= Circuit Breaker

Here the fault on transformer TR1 is considered for the analysis and the series of system responses associated with the fault.

1) Very low probability is considered for the fault on transformer because they are rigid systems with no moving parts and thus generally the failure rate of transformers is very low.
2) The fault detecting system consists of current transformers and high impedance relays. These are also highly reliable systems except in the case of faults with high currents. Thus the probability of successful operation is considered to be very high.
3) The relay/trip signal device consists of a relay, a trip coil and pneumatic systems along with moving parts, thus high probability is assumed for its successful operation.
4) Circuit breakers are very highly reliable systems because of using highly developed technologies its design and manufacturing process. Thus the probability of successful operation of circuit breakers is considered to be very high

Form the fuzzy fault tree shown in Figure 5.3, seven consequences can be derived for this scheme.

Consequence 1: All the protective devices operate successfully.

In this consequence all the components related to the protection scheme operate successfully in the event of fault on transformer TR1. Then the lower transformer TR2 will supply power to the load under the condition that the capacity of line and transformer are not exceeded. This consequence is rated as Very Low Consequence.

Consequence 2: CB2 failed and CB5 is operating successfully.

In this mode the generating system is saved due to the successful operation of CB5, but the supply to the load is disconnected for few minutes until the manual operation is done. Therefore this consequence is considered as a Low Consequence.

Consequence 3: CB2 and CB5 both failed.

In this mode there is damage to the transformer as well as to the generator along with the instability in the power system. Thus this consequence is rated as Moderate Consequence.

Consequence 4: CB1 failed and CB5 operating.

This consequence is same as consequence 2 and therefore rated as Low Consequence.

Consequence 5:CB1and CB5 both failed.

This consequence is same as consequence 3 and therefore rated as Moderate Consequence.

Consequence 6: RTS is in failure state.

Here the relay trip signal is in failure state due to the circuit breaker tripping system. This can damage the generating system and therefore rated as High Consequence.

Consequence 7: Fault detection system fails.

In this mode the fault detection system fails due to the saturation of current transformer because of high fault currents. This may result in loss of supply to the load and also damage to the generating system and transformers. Therefore this is rated as Very High Consequence.

5.5.1 Calculation of Fuzzy Probability Values

The fuzzy probability of an event can be put into following subcategories based on the range of probability:

1) Very high probability :$P_{vh} > 0.75$
2) High probability :$0.5 < P_h < 1$
3) Moderate probability :$0.25 < P_m < 0.75$
4) Low probability :$0 < P_l < 0.5$
5) Very low probability :$P_{vl} < 0.25$

The above probabilities can be represented in the form of fuzzy sets by using triangular membership functions as:

1) $P_{vh} = \{(.75, 0), (0.999, 0.995), (1,1)\}$
2) $P_h = \{(0.5,0), (0.75,1), (1,0)\}$
3) $P_m = \{(0.25,0), (0.5,1), (0.75,0)\}$
4) $P_l = \{(0.01,0), (0.25,1), (0.5,0)\}$
5) $P_{vl} = \{(0.001,1), (0.999,0.995), (0.25,0)\}$

The outcomes of various sequences obtained from the event tree shown in Fig 5.3 are:

$$P_1 = P_{vl}.P_{vh}.P_h.P_{vh}.P_{vh} \tag{5.1}$$

$$P_2 = P_{vl}.P_{vh}.P_h.P_{vh}.P_{vl}.P_{vh} \tag{5.2}$$

$$P_3 = P_{vl}.P_{vh}.P_h.P_{vh}.P_{vl}.P_{vl} \tag{5.3}$$

$$P_4 = P_{vl}.P_{vh}.P_h.P_{vl}.P_{vh} \tag{5.4}$$

$$P_5 = P_{vl}.P_{vh}.P_h.P_{vl}.P_{vl} \tag{5.5}$$

$$P_6 = P_{vl}.P_{vh}.P_l \tag{5.6}$$

$$P_7 = P_{vl}.P_{vl} \tag{5.7}$$

By substituting the fuzzy probability values in equations 5.1 to 5.7 the following fuzzy probabilities are obtained:

- $P_1=\{(2.109e-4,0), (7.5e-3,.1), (0.25,0)\}$
- $P_2=\{(2.109e-7,0), (7.5e-5,1), (0.0625,0)\}$
- $P_3=\{(2.8125e-10,0), (7.5e-7,1), (0.0156,0)\}$
- $P_4=\{(2.8125e-7,0), (7.5e-5,1), (0.0625,0)\}$
- $P_5=\{(3.75e-10,0), (7.5e-7,1), (0.0156,0)\}$

- $P_6=\{(7.5e\text{-}6,0), (2.5e\text{-}3,1), (0.125,0)\}$
- $P_7=\{(1e\text{-}6,0), (1e\text{-}4,0.995), (0.0625,0)\}$

5.5.2 Estimating the Level of Consequence Using Fuzzy Inference System

The event tree analysis uses the probability values of different protective devices used in the system for estimation of the level of consequence of the fault. The fuzzy inference system for finding the level of consequence is given below:

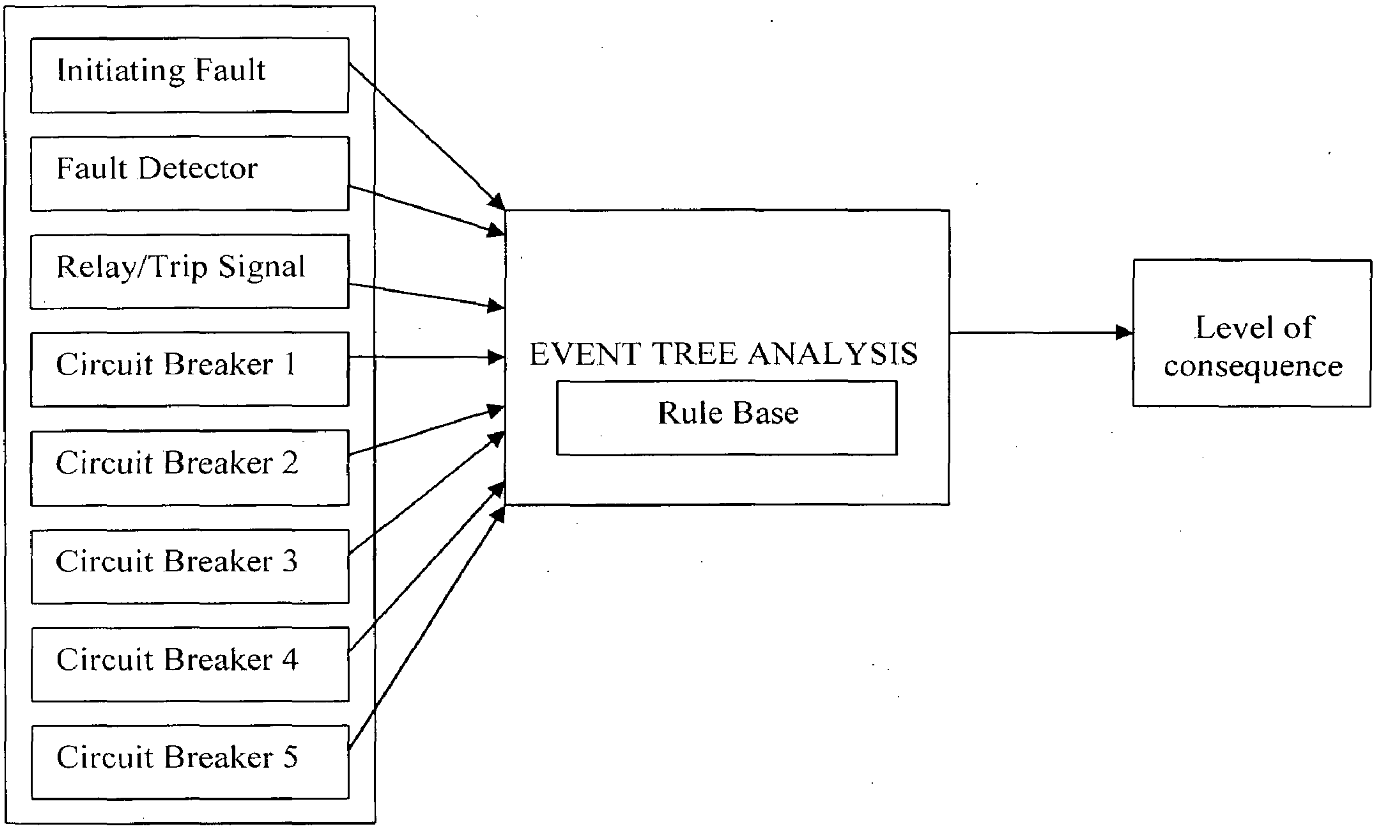

Figure 5.4 Fuzzy Inference System to find Level of Consequence

<u>Knowledge Base</u>

The knowledge base of the fuzzy inference system consists of the necessary information for the proper function of the fuzzification procedure. The information in the knowledge base includes:

- Fuzzy membership functions representing the linguistic values of input and output variables.

- The physical domains (universe of discourse) for each input and output variables.

The variables used in this analysis are the probability of fault, probability of operation of the fault detector, relay/trip signal, and circuit breakers. The triangular function is used for the input and output linguistic variable to aid the speed of computation and defuzzification calculation.

The universe of discourse for the probability of operation is [0, 1]. The linguistic variable set for the probability of operation is given by

[Very low, Low, Moderate, High, Very high]

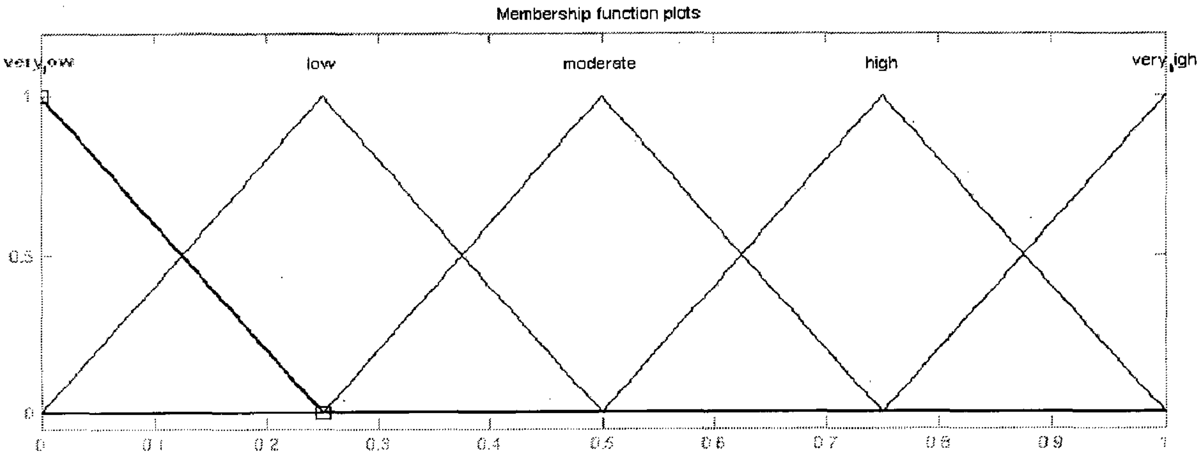

Figure 5.5 Fuzzy Probability Distribution

Rule Base

The derivation of the rules is accomplished by examining the experience based knowledge in linguistic variable terms. Consequent tuning of the membership functions and the rules by weighting the effect of each variable on the output is the necessary next step. The compound rules developed for the system relating inputs to the output consequence are:

Rule 1: If the initiating fault is low and the successful operation of fault detector is very high, and the successful operation of the relay/trip signal is high and the successful operation of the circuit breakers is very high then the consequence is very low.

Rule 2: If the fault is very low, and the successful operation of fault detector is very high, and the probability of successful operation of the RTS is high and the successful operation of the circuit breaker 1 and 5 is very high and the successful operation of circuit breaker 2 is very low then the consequence is low.

Rule 3: If the fault is very low, and the successful operation of fault detector is very high, and the probability of successful operation of the RTS is high and the successful operation of the circuit breaker 1 is very high and the successful operation of circuit breaker 2 and 5 is very low then the consequence is moderate.

Rule 4: If the fault is very low, and the successful operation of fault detector is very high, and the probability of successful operation of the RTS is high and the successful operation of the circuit breaker 5 is very high and the successful operation of circuit breaker 1 is very low then the consequence is low.

Rule 5: If the fault is very low, and the successful operation of fault detector is very high, and the probability of successful operation of the RTS is high and the successful operation of the circuit breaker 1 and 5 is very low then the consequence is moderate.

Rule 6: If the fault is very low, and the successful operation of fault detector is very high, and the probability of successful operation of the RTS is low then the consequence is high.

Rule 7: If the fault is very low, and the successful operation of fault detector is very low, then the consequence is very high.

Level of Consequence

The level of consequence of the fault on the systems for different event tree paths can be obtained by defuzzifying the fuzzy output obtained. The level of consequence shows the impact of the fault on the distribution system. If we know the probability of operation of different protective devices the level of consequence of the fault on the system can be obtained and the maintenance can be done in advance. The level of consequence for different event tree paths is shown in the table below 5.1

consequence	Level of consequence
Consequence 1	0.08
Consequence 2	0.25
Consequence 3	0.5
Consequence 4	0.25
Consequence 5	0.5
Consequence 6	0.75
Consequence 7	0.92

Table.5.1level of consequence.

From the Table .5.1 it can be observed that the consequence 1 has the very less impact on the system.

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

A Fuzzy Markov Model and Fuzzy Fault Tree Analysis for the reliability evaluation of electric distribution network components to include uncertainty in the data have been presented.

The input to Markov Model reliability analysis is parameters that are obtained from Reliability Test System proposed by Dr. Roy Billinton. There is a significant uncertainty in the values used in the calculations. This can lead to obtain reliability results that are far from representing system functionality.

In order to reduce uncertainty, fuzzy arithmetic has been used, considering fuzzy number for the transition rates between different component states. But if we make a direct translation of equations with crisp numbers to equations with fuzzy numbers by simply substitute crisp variables by fuzzy variables, we can widen the influence of data uncertainty in the results, being necessary to arrange reliability expressions, making them suitable for fuzzy calculations.

But, as the components involved in the network increases the Markov model states also increases and the number of transition parameters increases there by increasing the computational complexity. For large complex distribution systems this method proved to be very time consuming.

The fuzzy Event Tree Analysis gives the sequence of operations of the protective devices after the fault has been initiated considering the linguistic terms for the probability of different protective devices. A method to find the level of each consequence was also discussed with the help of fuzzy inference system. This method is proved to be useful in a network consisting of different protective devices and their sequence of operations when a fault has occurred.

6.2 Future Scope

Future work in the area of fuzzy Markov modeling is likely to focus on following areas. The first and most obvious of these is reduction of the computational complexity of the model. Similarly, further methods of simplification of the model should be considered. Additionally, Markov modeling is a very broad area, and this thesis only considers fuzzification of the most basic of Markov models. During the Fuzzification process of the transition parameters the value of interval of confidence was assumed for modeling. The optimal value of interval of confidence may be found by formulating an optimization problem and its constraints and solving for the optimum value so that we may get more accurate results.

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