INVESTIGATIONS OF SHORT TERM AND LONG TERM RELIABILITY ASSESSMENT FOR GENERATION ADEQUACY IN POWER SYSTEM

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in

POWER SYSTEMS & ELECTRIC DRIVES

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CERTIFICATE

I hereby certify that the work which is being presented in dissertation entitled, "Investigations of Short term and Long term Reliability Assessment for Generation Adequacy in Power system", in partial fulfillment of the requirement for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in *Electrical and Instrumentation Engineering Departmen*t of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of ***Ms. Manbir Kaur*** and refers other researcher's work which are duly listed in the reference section. The matter embodies in this dissertation has not been submitted for the award of any other degree to any other university, except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

The main and foremost important function of electrical power utility is to deliver economical, reliable and quality power to its consumer. The reliability evaluation of generation system is an important aspect in the operational and planning purposes for future system expansion in case of consumer satisfaction with electricity. This dissertation will particularly focus on evaluating the generation system adequacy reliability indices by analytical probabilistic assessment. Two case studies have been carried out for evaluation of long term and short term reliability on IEEE 30-bus system and Delhi Power System and to examine the normal and abnormal contingency states for each system with analytical method i.e., loss of load (LOLE) method and frequency and duration (FAD) method. Network violations in a contingency state are alleviated through real power load shedding. The two-state model with up and down states is used for all system components of system. The outage states with the large probability at a future time are selected using the proposed Fast Sorting Technique that selects the required number of states in descending order of probability. For the short term reliability assessment, time varying system operating conditions i.e. time dependent state probabilities of components have been considered and steady state probability of each component has considered for the long term reliability assessment.

Dedicated to My Parents, Karunya and Komal.

TABLE OF CONTENTS

List of Figures

List of Tables

List of Symbols and Abbreviations

A	Availability
C_i	Available capacity on day *i*
COPT	Capacity Outage Probability Table
EDLC	Expected Duration of Load Curtailment
EENS	Expected Energy Not Supplied
E_k	Non-served energy
ELC	Expected Load Curtailed
f	State frequency
FAD	Frequency and Duration
F_i	Frequency of state available
FOR	Forced Outage Rate
FST	Fast Sorting Technique
$F_x(x)$	Cumulative distribution function (c.d.f.)
$f_x(y)$	Probability density function (p.d.f.)
HL	Hierarchical Levels
IEEE	Institute of Electrical and Electronics Engineers
λ	Unit Failure Rate
L_i	Forecast peak load on day *i*
LOEP	Loss of Energy Probability
LOLD	Loss of Load Duration
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MTTF, *m*	Mean Time to Failure
MTTR , *r*	Mean Time to Repair
μ	Expected Repair Rate
MW	Mega -Watt
MWh	Mega Watt hour
P_i	Probability of the i^{th} capacity state
PLC	Probability of Load Curtailment
RTS	Reliability Test System
σ^2	Variance
U	Unavailability
X	Continuous random variable

Chapter 1
Introduction

1.1 Overview

The function of an electrical power system is to convert the energy available from natural sources into the electrical form, then transmit and distribute this electrical power to the different customers taking into account the demand forecast and the service level of the different components in the system. The configuration of a power system is composed of a few subsystems as generating stations, transmission networks and distribution networks. The overall function of an electric power system should be performed efficiently, reliably and at the least cost. The observance of these performance requirements involves a great deal of effort to model, monitor and control the system and its performance, Reliability analysis is an important aspect of the study of power systems, as it provides needed measures of the quality of the performance of the power system [1].

The failure of power has significant economic impact on utility and its customers although failure in power system is random, sometimes outside of the controls. The electrical power network is very complex and a failure may result in loss of power to a large number of customers or sometimes catastrophic events such as blackouts. Therefore reliable power system operation and design is very important. The probability of customers being disconnected can be reduced by increased investment during the planning phase, operating phase or both. It is evident therefore that the economic and reliability constraints can conflict, and this can lead to difficult managerial decisions at both the planning and operating phases.

Design, planning and operating criteria and techniques have been developed in an attempt to resolve and satisfy the dilemma between the economic and reliability constraints. The essential weakness of deterministic criteria is that they do not respond to nor reflect the probabilistic or stochastic nature of system behaviour, of customer demands or of component failures. The need for probabilistic evaluation of system behaviour has been recognised since 1930s. Unit sizes, high voltage transmission and interconnections between utilities have been rapidly expanded to take advantage of the economies of scale. The timing of unit construction and the development of quantitative methods for determining the correct amount of spare capacity in both single and highly interconnected systems became more important. The main reasons were lack of data, limitations of computational resources, lack of realistic reliability techniques, aversion to the use of probabilistic techniques and a misunderstanding of the significance and mean of probabilistic criteria and risk indices. None of these reasons need be valid today as most utilities have reliability databases, computing facilities are greatly enhanced, reliability evaluation techniques are highly developed.

1.2 Literature Review

Reliability evaluation techniques were well developed and various papers, articles and books are published [2-4]. Deterministic and probabilistic techniques are in use for the reliability evaluation. The most common deterministic indices are the reserve margin and the largest set in the system. An important shortcoming of these methods is that they do not account for the stochastic nature of system behaviour [5]. In general, reliability can be defined as the probability of a device performing its intended function adequately over the period of time intended under the operation conditions encountered [6]. Power system reliability assessment, both deterministic and probabilistic, can be divided into the two basic aspects of system adequacy and system security [5-7]. System adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. It therefore relates to static system conditions. On the other hand, system security relates to the ability of the system to respond to disturbances arising within that system. Security is therefore associated with the response of the system to perturbations. Most of the probabilistic techniques presently available for power system reliability evaluation are in the domain of adequacy assessment.

Probabilistic methods those can provide more meaningful information to be used in design and resource in planning and allocation. There are two approaches that use probabilistic evaluation: Analytical Methods and Monte Carlo Simulation. The analytical methods represent the system by mathematical models and use direct analytical solutions to evaluate reliability indices from the model. In the past decades, publications have been documented in comprehensive bibliographies [8-15]. These publications extended the frequency and duration approach by developing a recursive technique for model building which have presented recursive algorithms for capacity model building and load model combination which facilitated digital computer application. In case of short reliability evaluation [16-23], Singh and Billinton [24] have presented a frequency and duration approach which has defined the concepts of interval frequency and fractional duration, and numerical techniques for their calculation have been developed. For interconnected system, Wee and Billinton [25] have presented a practical technique for performing interconnected system reliability evaluation using frequency and duration concepts. In 1975, Aggarwal *et. al.* [26] has presented a easy and computational economic algorithm to obtain a simplified reliability expression for a general network with all the success paths of the network. Also, Xie *et al.* [27] have presented an efficient practical reliability evaluation algorithm for large-scale radial electrical distribution networks (EDN) using a section technique which account the construction features of the EDN. In 2003, Billinton and Abdulwhab [28] have given a methodology for maintenance scheduling that combines a probabilistic approach and an acceptable deterministic criterion into a single framework. For the Monte Carlo simulation, reliability indices are estimated by simulating the actual random behaviour of the system. So of the commonly used probabilistic reliability indices are Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE), Expected Energy Not Served (EENS), and Loss of Load Duration (LOLD) [29]. Most of these indices are basically expected values of a random variable. Expectation indices provide valid adequacy indicators which reflect various factors such as system component availability and capacity, load characteristics and uncertainty, system configurations and operational conditions.

System adequacy studies can be conducted individually in each of three zones of power system. Billinton *et.al* [30] has discussed the reliability indices which can be calculated at the three hierarchical and discussed on the contribution to the actual customer reliability made by the generation, transmission and distribution functional zones. In previous method for the reliability evaluation for adequacy assessment techniques which considered only the active power capability constraints. Goel and Billinton [32] have presented a paper which considered the influence of element outages in all parts of an electric power system and the relative contributions to the system indices of composite generation and transmission failures and distribution zone failures were also assessed.

For modern power system planning purpose, planner also considered the cost factor for generation at economic levels with the reliability issues. Ding and Wang [33] have presented the techniques to evaluate both reliabilities and prices for the pool and bilateral customers in a hybrid power market. In 1979, Reliability Test System (RTS) Task Force of the Application of Probability Methods Subcommittee [34] has prepared a report which described a load model, generation system, and transmission network which can be used to test or compare methods for reliability analysis of power systems. Allan *et. al.* [35] has presented a paper which extended the RTS by including more factors and system conditions which may be included in the reliability evaluation of generating systems. These indices have been evaluated without any approximations in the evaluation process and therefore provided a set of exact indices against which the results from alternative and approximate methods can be compared. Further in 1996, similar report [36] has described an enhanced test system (RTS-96) for use in bulk power system reliability evaluation studies. The test system was developed by modifying and updating the original IEEE RTS to reflect changes in evaluation methodologies and to overcome perceived deficiencies. Liu *et. al.* [37] have presented on online short-term reliability of a power system at real-time system which considering both speed and accuracy requirements..

1.3 Research Objectives

The main aim of this dissertation is to analyse the capacity distribution of 30-bus System and Delhi Power System for different operational states and the impact that has on system reliability. Besides, it is hoped that the methodology developed can be useful for future study in planning for capacity expansion of the existing power system.

1. To focus on the analytical approach through the estimated probability distribution of loss of load and frequency and duration approach on generation system of IEEE 30-bus System and Delhi Power System.
2. To establish a generation system reliability calculation tool for IEEE 30-bus system and Delhi Power System to evaluate conventional generation systems reliability based on the analytical method by probabilistic assessment approach.
3. To propose an evaluation method to be used for generation capacity adequacy planning for consumer demand in future.
4. To obtain the state sequence for IEEE 30-bus System and Delhi Power System by using fast sorting technique (FST).
5. To evaluate the short-term and long-term reliability indices for IEEE 30-bus System and Delhi Power System by applying a fast sorting technique (FST) for credible state selection.

1.4 Organisation of work

The dissertation is organized into five chapters. The organization of chapters is as follows:

Chapter-1 summarized the overview, brief background and literature review, scope of the work research objectives and organization of the dissertation.

Chapter-2 highlights the probabilistic approach for reliability calculation, measures and methods of probabilistic assessment, brief system analysis and reliability concept.

Chapter-3 gives the basic concepts of generation reliability by state-space representation, analytical methods, system reliability parameters and indices used to evaluate generation reliability. It also includes the state selection method by fast sorting technique (FST) and short-term and long-term reliability indices.

Chapter-4 presents the algorithm, problem formulation and results by analytical methods for reliability evaluation of the IEEE 30-bus system and Delhi Power System.

Chapter-5 presents the conclusions and the scope of the future work followed by the reference section.

Chapter 2
Probabilistic Assessment

2.1 Introduction

System behaviour is stochastic in nature, and therefore it is logical to consider that the assessment of such systems should be based on techniques that respond to this behaviour i.e., probabilistic techniques. All planning and operational criteria (both deterministic and probabilistic) were intended to minimize such interruptions within economic limits. For effective application of mandatory reliability in the deregulated probabilistic data such as outage frequencies, duration, availability, LOLP and EENS can be used to measure reliability compliances related to system design, operations, maintenance, etc. It is well recognized that probabilistic methods are suitable for project ranking, least cost resource planning and operations. So this chapter gives the brief introduction about probabilistic assessment of power system for reliability evaluation, methods of assessments and the concepts of adequacy and security.

2.2 Probabilistic Measures for Reliability Assessment

It is important to find the probabilistic measures for reliability assessment because failures of components, plant, and systems occur randomly; the frequency, duration, and impact of failures vary from one year to the next. The assumption can be made that failures which occur randomly in the past will also occur randomly in the future and therefore the system behaves probabilistically, or more precisely, stochastically. Predicted measures that can be compared with past performance measures or indices can also be extremely beneficial in comparing the past history with the predicted future.

2.2.1 Methods of Probabilistic Assessment

The two main approaches for probability assessment are analytical and simulation. The vast majority of techniques have been analytically based and simulation techniques have taken a minor role in specialized applications due to simulation generally requires large amounts of computing time, and analytical models and techniques have been sufficient to provide planners and designers with the results needed to make objective decisions.

- **Analytical technique**

  It represents the system by a mathematical model and evaluates the reliability indices from this model using direct numerical solutions. They generally provide expectation indices in a relatively short computing time. Unfortunately, assumptions are frequently required in order to simplify the problem and produce an analytical model of the system.

- **Simulation methods**

  It estimates the reliability indices by simulating the actual process and random behaviour of the system. These random events include such as outages and repairs of elements represented by general probability distributions, dependent events and component behaviour, queuing of failed components, load variations, variation of energy input such as that occurring in hydro-generation, as well as all different types of operating policies.

The simulation process can follow one of two approaches. First, random which examines basic intervals of time in the simulated period after choosing these intervals in a random manner. Second, sequential which examines each basic interval of time of the simulated period in chronological order.

2.2.2 Concepts of adequacy and security

Power system reliability invariably involves a consideration of system states and whether they are adequate, secure, and can be ascribed an alert, emergency, or some other designated status. The system reliability involves the two subdivisions as shown below in the figure 2.1.

The concept of adequacy is generally considered to be the existence of sufficient facilities within the system to satisfy the consumer demand. These facilities include those necessary to generate sufficient energy and the associated transmission and distribution networks required to transport the energy to the actual consumer load points. Adequacy is therefore considered to be associated with static conditions which do not include system disturbances.

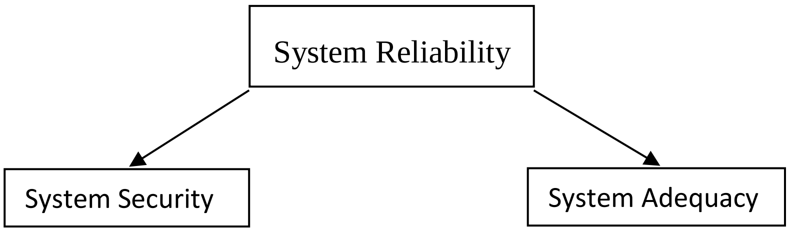

Figure 2.1 Subdivision of system reliability

Security is considered to relate to the ability of the system to respond to disturbances arising within that system. Security is therefore associated with the response of the system to whatever disturbances they are subjected. These are considered to include conditions causing local and widespread effects and the loss of major generation and transmission facilities. Power system engineers tend to relate security to the dynamic process that occurs when the system transits between one state and another state. Both of these states may themselves be acceptable if viewed only from adequacy; i.e., they are both able to satisfy all system demands and all system constraints. However, this ignores the dynamic and transient behaviour of the system in which it may not be possible for the system to reside in one of these states in a steady-state condition.

2.3 System Analysis

Large computer installations are not powerful enough to analyze in a completely realistic and exhaustive manner all of a power system as a single entity. However, this is not a problem because the system can be divided into appropriate subsystems which can be analyzed separately. The most convenient approach for dividing the system is to use its main functional zones [5]. These are: generation systems, composite generation and transmission systems, and distribution systems.

2.3.1 Functional zones

The basic techniques for adequacy assessment can be categorised in terms of their application to segments of a complete power system. These segments are shown in figure 2.2 and are defined as functional zones: generation, transmission and distribution. This division is the most appropriate as most utilities are either divided into these zones for purposes of organisation, planning, operation and/or analysis or are solely responsible for one of these functions. Adequacy studies are, conducted individually in these three functional zones.

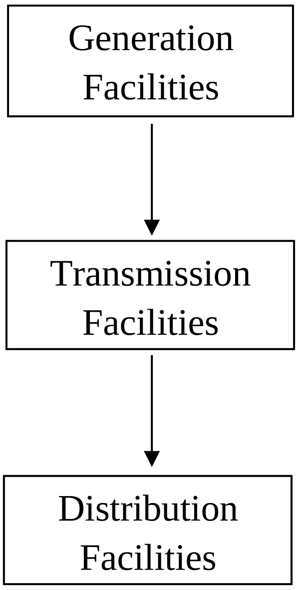

Figure 2.2 Functional zones

2.3.2 Hierarchical levels

The concept of hierarchical levels (HL) has been developed in order to establish a consistent means of identifying and grouping these functional zones. These are illustrated in Figure 2.3, in which the first level (HLI) refers to generation facilities and their ability on a pooled basis to satisfy the pooled system demand.

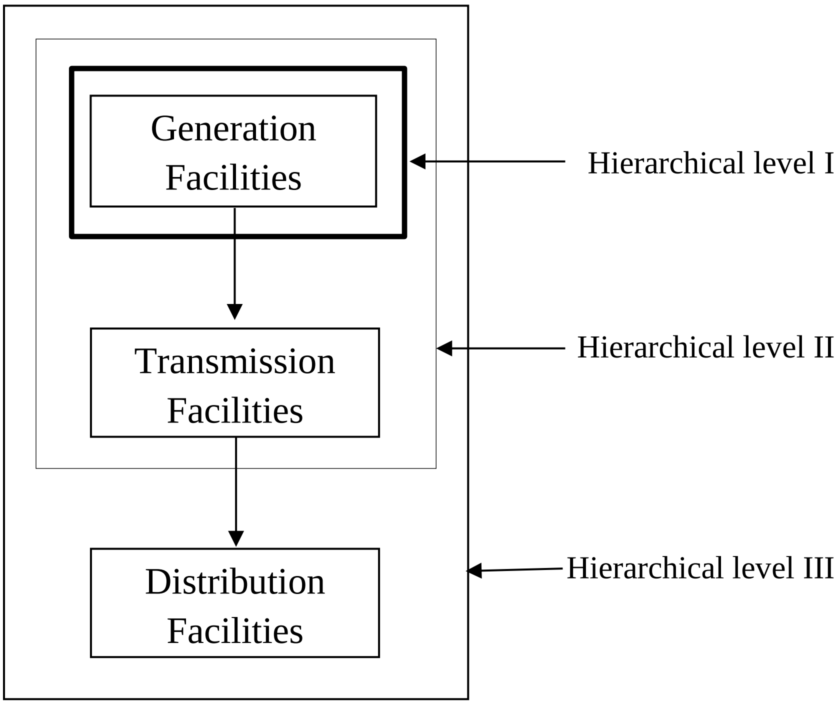

Figure 2.3 Hierarchical Levels

The second level (HLII) refers to the composite generation and transmission (bulk power) system and its ability to deliver energy to the bulk supply points, and the third level (HLIII) refers to the complete system including distribution and its ability to satisfy the capacity and energy demands of individual consumers. The functional zones shown in Figure 2.2 can be combined to give the hierarchical levels shown in Figure 2.3. Hierarchical level I (HLI) is concerned only with the generation facilities. Hierarchical level II (HLII) includes both generation and transmission facilities and HLIII includes all three functional zones in an assessment of consumer load point adequacy. HLIII studies are not usually done directly due to the enormity of the problem in a practical system. Instead, the analysis is usually performed only in the distribution functional zone, in which the input points may or may not be considered fully reliable.

Based on the above concepts and system structure, the following main subsystems are generating stations, Generating capacity, interconnected systems, composite generation/transmission, distribution networks, protection systems, substations and switching stations. The techniques described in forthcoming chapter focus on the analytical approach of LOLE method and Frequency and Duration (FAD) Method.

2.4 Mathematical Basics for Probabilistic Assessment

2.4.1 Continuous Random Variables

A continuous random variable is one that is measured on a continuous scale. Examples are measurements of time, distance and other phenomena that can be determined with arbitrary accuracy [38]. This section reviews the general concepts of probability density functions and presents a variety of named distributions often used to model continuous random variables.

- **Probability Distributions**

The probability density function (p.d.f.) is a function, $f_x(y)$, which defines the probability density for each value of a continuous random variable. Integrating the probability density function between any two values gives the probability that the random variable falls in the range of integration.

$$P(a < X < b) = \int_a^b f_x(y)dy \tag{2.1}$$

The meaning of p.d.f. is different for discrete and continuous random variables. For discrete variables p.d.f. is the probability distribution function and it provides the actual probabilities of the values associated with the discrete random variable. For continuous variables, p.d.f. is the probability density function, and probabilities are determined by integrating this function. The probability of any specific value of the random variable is zero.

- **Cumulative Distribution Function**

The cumulative distribution function (c.d.f.), $F_x(x)$, of the random variable is the probability that the random variable is less than the argument x. The p.d.f. is the derivative of the c.d.f. We drop the subscript on both f_x and F_x when there is no loss of clarity. The c.d.f. has the same meaning for discrete and continuous random variables; however values of the probability distribution function are summed for the discrete case while integration of the density function is required for the continuous case.

$$F_x(x) = P(X < x) = \int_{-\infty}^{x} f_x(y)dy \qquad (2.2)$$

$$f_x(x) = \frac{dF_x(x)}{dx} \qquad (2.3)$$

As *x* goes to infinity, $F_x(x)$ must go to 1. The area under an acceptable p.d.f. must, therefore, equal 1. Since negative probabilities are impossible, the p.d.f. must remain nonnegative for all *x*.

2.4.2 Numerical Attributes of Random Variables

In many practical problems, the characteristics of random variables can be described by the average and the degree of scatter of their possible values.

a) Mathematical expectation (the mean)

Suppose a discrete random variable can have values $x_1, x_2, ...,$ and their corresponding probabilities are

$$P(X = x_i) = p_i \qquad i = 1, 2, 3\ldots \qquad (2.4)$$

The mathematical expectation *E(X)* of the random variable is defined as

$$E(X) = \sum_{i=1}^{\infty} x_i p_i \qquad (2.5)$$

For continuous random variable *X* which has a density function *f(x)*, the expectation is given by

$$E(X) = \int_{-\infty}^{\infty} xf(x)dx \qquad (2.6)$$

For the mathematical expectation of a group of random variables X_i (*i* =1, 2, 3… n), we have the following equation:

$$E\left(\sum_{i=1}^{n} X_i\right) = \sum_{i=1}^{n} E(X_i) \qquad (2.7)$$

b) Variance

The variance of a discrete random variable, denoted by σ^2, is defined as

$$\sigma^2 = \sum_{i=1}^{\infty} (x_i - m)^2 \qquad (2.8)$$

In which $m = E(x_i)$ is the mean value. Obviously σ^2 is a measure of the degree of scatter of all the possible values around the mean *m*.

For a continuous random variable X, we have

$$\sigma^2 = \int_{-\infty}^{\infty} (x - m)^2 f(x)dx \qquad (2.9)$$

Chapter 3

Reliability Evaluation of Generation System

3.1 Introduction

The reliability of supply in a power system can be improved by increasing the investment in installed capacity and by incurring the operating costs of keeping reserves in service. This chapter reviews different methods employed to evaluate the reliability of system-wide generation. A stochastic model to evaluate the risk of supply shortages, next, common reliability measures used to assess said risk, and finally, we compare different reliability indices, looking at their physical relevance and usefulness are reviewed.

3.2 Risk of Supply Shortages

A model of bulk generation must consider the size of generation units and the two main processes involved in their operation, namely the failure and the restoration processes. A failure in a generating unit results in the unit being removed from service in order to be repaired or replaced; this event is known as an *outage*. Such outages can compromise the ability of the system to supply the load and affect system reliability. An outage may or may not cause an interruption of service depending on the margins of generation provided. Outages also occur when the unit undergoes maintenance or other scheduled work necessary to keep it operating in good condition.

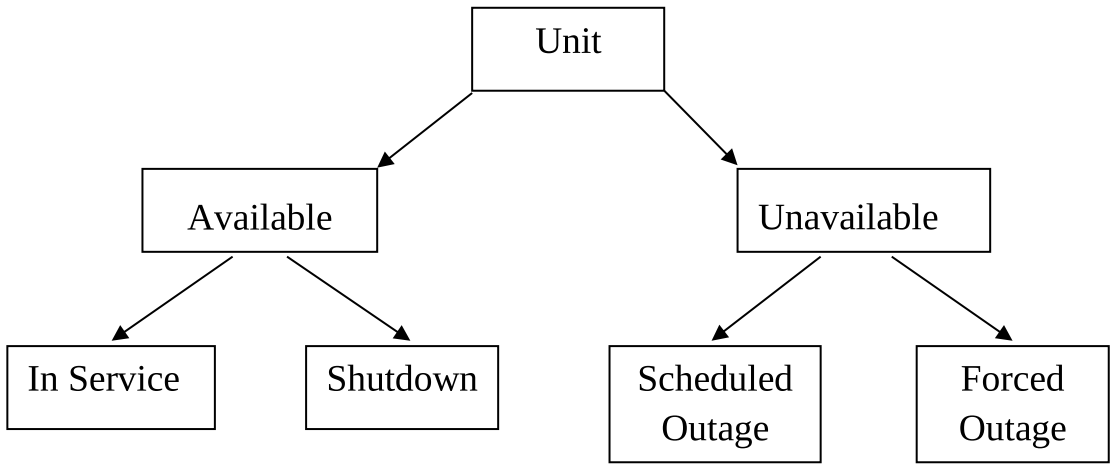

Figure 3.1: Generating unit states

- A forced outage is an outage that results from emergency conditions, requiring that the component be taken out of service immediately.

- A scheduled outage is an outage that results when a component is deliberately taken out of service, usually for purposes of preventive maintenance or repair.

The status of a generating unit is conveniently described as residing in one of several possible states. A hierarchical representation of states is shown in Fig. 2.3. The basic generating parameter used in static capacity evaluation is the probability of finding the unit on forced outage. This probability is nothing but the unavailability of the generator in the system on account of failure or planned maintenance. To investigate the effect of a unit on system generation reliability, it is sufficient to know its capacity and the probability of residing in each state.

3.3 Generation Reliability

The object of a reliability study is to derive suitable measures of successful performance on the basis of component failure information and system configuration. For generation reliability studies the components of interest are the generating units and system configuration refers to the specific units scheduled to serve the load. The indices used to measure generation reliability are probabilistic estimates of the ability of a particular generation configuration to supply the load demand. These indices are better understood as estimates of system-wide generation adequacy and not as absolute measures of system reliability. The indices are sensitive to basic factors like unit size and unit availability, and they are most useful when comparing the relative reliability of different generation configurations. The system is deemed to operate successfully as long as there is sufficient generation capacity to supply the load. First, mathematical representations of generation and load are combined to model the risk of supply shortages in the system. Secondly, probabilistic estimates of shortage risk are used as indices of bulk power reliability for the considered configuration.

Generating capacity reliability is defined in terms of the adequacy of the installed generating capacity to meet the system load demand. Outages of generating units and/or load in excess of the estimates could result in “loss of load”, i.e., the available capacity (installed capacity - capacity on outage) being inadequate to supply the load. In general, this condition requires emergency assistance from neighbouring systems and emergency operating measures such as system voltage reduction and voluntary load curtailment. Depending on the shortage of the available capacity, load shedding may be initiated as the final measure after the emergency actions. The conventional definition of “loss of load” includes all events resulting in negative capacity margin or the available capacity being less than the load.

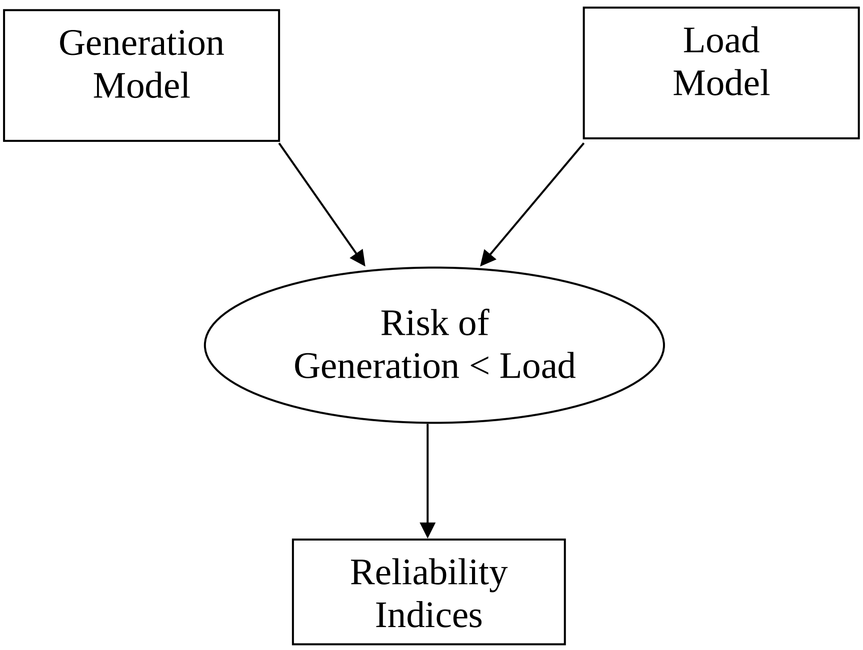

Figure 3.2: Elements of generation reliability evaluation.

The basic methodology for evaluating generating system reliability is to develop probability models for capacity on outage and for load demand, and calculate the probability of loss of load by a convolution of the two models. This calculation can be repeated for all the periods in a year considering the changes in the load demand, planned outages of units, and any unit additions or retirements, etc. The reliability of supply in a power system can be improved by increasing the investment in installed capacity and by incurring the operating costs of keeping reserves in service.

3.3.1 Generation Model

3.3.1.1 Generating Unit Reliability Data

In power system reliability analysis, boilers, steam or water turbines and generators are often treated as an entity, called the generating unit. The reliability data include:

c = generating unit's effective capacity

λ = generating unit's failure rate (downward transition rate), per year

μ = 1/r = generating unit's repair rate (upward transition rate), per year

r = mean time to repair (MTTR)

T = 1/λ + 1/μ = mean time between failures (MTBF)

f = 1/T = state frequency

q = *f* / μ = forced outage rate (FOR)

3.3.1.2 One or single-generating unit model

The system loses generation capacity *c* with a certain probability when the generating unit has to be forced to stop due to random failures. Therefore, the capacity or the outage capacity is considered to be a random variable in power system reliability analysis. The unit model is the probability and frequency table of a generator unit's capacity state.

a) Probability Model

The dual-state model assumes that a generator unit only has two states: operation and failure or repair. The individual state probability is

$$P(X = x_i) = \begin{cases} 1-q & x_i = c \\ q & x_i = 0 \end{cases} \tag{3.1}$$

The cumulative state probability is

$$P(X \le x) = \begin{cases} 0 & x_i < 0 \\ q & 0 \le x_i < c \\ 1 & x_i \ge c \end{cases} \tag{3.2}$$

The model gives way to a multi-state model when the generating unit is forced to operate at a capacity lower than the nominal capacity. There is a forced outage rate for every capacity. The individual state probability is

$$P(X = x_i) = p(x_i) \qquad i = 0,1,2,... \tag{3.3}$$

The cumulative state probability is

$$P(x_k) = P(X \geq x) = \sum_{i \geq k} p(x_i) \tag{3.4}$$

Or, equivalently,

$$p(x_k) = P(x_k) - P(x_{k+1}) \tag{3.5}$$

b) Frequency Model

Suppose $p_i = P(X = x_i)$ the individual probability of i state (capacity), f_i is the state frequency and f_{ij} is the transition frequency from state i to state j. For the dual-state model, the frequency transition diagram is shown Figure 3.3.

According to the definition of state frequency,

$$f_i = f_{ij} = p_i \lambda_{ij} = (1 - q)\lambda \tag{3.6}$$

$$f_j = f_{ji} = p_j \lambda_{ji} = q\mu \tag{3.7}$$

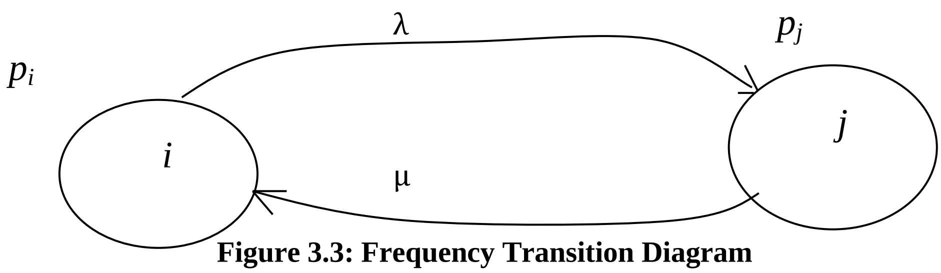

Figure 3.3: Frequency Transition Diagram

The above means that the state frequency equals the state probability multiplied by the departure rate. It will be proved in the forthcoming discussion that the cumulative state frequency is

$$f^* = f_{ij} - f_{ji} = 0 \tag{3.8}$$

In the case of the multi-state model, the state frequency is

$$f_i = p_i \sum_{i \neq j} \lambda_{ij} \tag{3.9}$$

This equation can also be written as

$$f_i = p_i(\lambda_i' + \lambda_i'') \tag{3.10}$$

In equation (A2.36), λ_i' and λ_i" are respectively the upward (increasing capacity) and downward (decreasing capacity) state transition states. From equation (A2.36) and using the mathematical inductive method, a recurrence formula can be obtained for calculating the cumulative state frequency:

$$f^* = f_{k-1}^* + p_i(\lambda_j' - \lambda_i'') \tag{3.11}$$

The inconvenience caused in calculating the cumulative frequency using Equation (3.11) led to the introduction of the concept of frequency increment, which is defined as

$$f(x_i) = p_i(\lambda_i' - \lambda_i'') \tag{3.12}$$

The cumulative frequency is then a direct sum of $f(x_i)$

$$F(x) = f(X \geq x) = \sum_{i \geq k} f(x_i) \tag{3.13}$$

Now we can write down the capacity model for a single generating unit in Table A2.1.

Table 3.1 Probability and frequency model for a single generating unit

Available capacity, MW	Outage capacity, MW	Exact probability, p_i	Accumulative probability, P_i	Exact frequency, f_i	Accumulative frequency, F
C	0	1 – q	1	(1 – q)λ	0
0	C	Q	Q	qμ	Qμ

Similarly for two-generating unit model, we can write down the capacity model for a two-generating unit in Table 3.2.

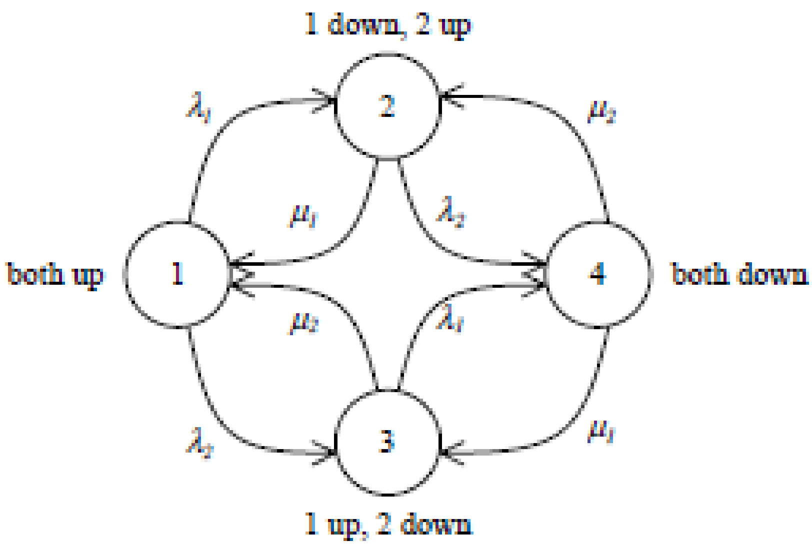

Figure 3.4: Two-generating unit model

The cumulative state frequency can be calculated using the formula (3.11)

$$\begin{aligned} f_1^* &= p_{00}(\mu_1 + \mu_2) \\ f_2^* &= p_{00}\mu_1 + p_{01}\mu_2 \\ f_3^* &= p_{10}\mu_2 + p_{01}\mu_1 \\ f_4^* &= 0 \end{aligned} \tag{3.14}$$

Table 3.2 Probability and frequency model for a two-generating unit

Available capacity, MW	Outage capacity, MW	Exact probability, p_i	Accumulative probability, P_i	Exact frequency, f_i	Accumulative frequency, F
C_1+C_2	0	p_1 p_2	1	f_{11}	0
C_1	C_2	p_1 q_2	P_3	f_{10}	f_3*
C_2	C_1	q_1 q_2	P_2	f_{01}	f_2*
0	C_1+C_2	q_1 q_2	P_1	f_{00}	f_1*

3.3.1.3 Fast recursive algorithm for calculating COPT

A power system usually consists of some components with the same capacity and reliability indices. For example, there are five 12 MW, four 20 MW and six 50 MW identical generating units among the 32 generating units in the reliability test system. Suppose there are *n* identical generating units with capacity equal to *c*, *FOR* equal to *q* and repair rate μ.

For binominal distribution, the individual probability when *i* generating units outage due to failure is

$$p(X_i) = \binom{n}{i} q^i (1-q)^{n-i} \tag{3.15}$$

The cumulative probability is

$$P(X_i) = \sum_{i \geq k} p(X_i) \tag{3.16}$$

The cumulatively frequency is

$$F(X_k) = p(X_i) K\mu \tag{3.17}$$

3.3.2 State Space Representation of Generating Units

The operating life of a generation unit can be represented by a simple two-state model in a "service-repair" process as shown in Fig. 3.3, where λ and μ are the unit failure rate and repair rate respectively. The long-run failure probability, known as the unavailability of a unit, *U*, is defined by Equation. (3.18).

The basic generating parameter used in static capacity evaluation is the probability of finding the unit on forced outage. This probability is nothing but the unavailability of the generator in the system on account of failure or planned maintenance. In power system applications this is known as forced outage rate (FOR) as

$$\text{Unavailability } U = \frac{\sum[down \quad time]}{\sum[down \quad time] + \sum[up \quad time]} \tag{3.18}$$

The unit unavailability can be expressed in terms of unit's failure rates and repair rates, as indicated in eq. (3.19).

$$U = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \tag{3.19}$$

Where λ = unit failure rate, μ = expected repair rate

m = mean time to failure, MTTF =1/ λ,

r = mean time to repair, MTTR = 1/ μ

$t = m + r$ = mean cycle time,

$f = 1/T$ = cycle frequency = $\mu U = \lambda A$

The parameter U is a good approximation of a unit failure probability even when preventive maintenance is considered, provided that maintenance is scheduled during low demand periods. The unavailability is then an adequate estimator of the probability of finding a unit out of service at some point in the future.

$$\text{Availability, } A = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \tag{3.20}$$

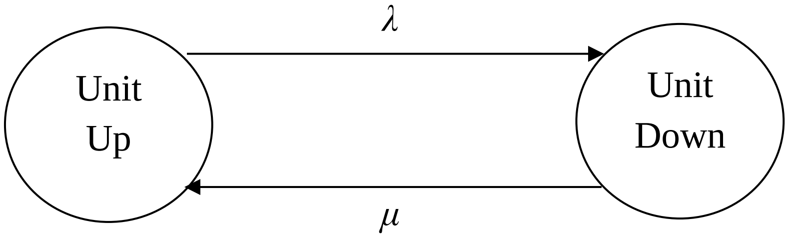

Figure 3.5: Two-state Model

$$LOEP = \sum_j \frac{E_j . p_j}{E_o} \approx \sum_j \frac{(L_o - C_j).p(C_j)}{L_o}, \quad for \quad L_0 > C_j \tag{3.21}$$

The unit unavailability is commonly referred to as the 'forced outage rate', *FOR*, which in fact is not a rate but the ratio of Equation (3.22).. Models with multiple states can be used to represent partial outages as de-rated states. Multistate models are also useful to accommodate intermittent operation and start-up failure rates. Of course, the level of detail of the model depends on the degree of accuracy sought. In most reserve studies the two-state representation is sufficient.

$$FOR = \frac{forced \quad outage \quad hours}{in \quad service \quad hours + forced \quad outage \quad hours} \tag{3.22}$$

3.3.3 Capacity Outage Distribution

To build a generation model, is to combine the capacity and availability of the individual units to estimate available generation in the system. The result is a capacity model, in which each generating unit is represented by its nominal capacity G_i and its unavailability index U_i or forced outage rate. For each of the N generators in the system, the available capacity G_i, $I = 1 \ldots N$, is a random variable that can take the value 0 with probability U_i and the value G_i with probability $A_i = 1 - U_i$.

There are 2^N possible different capacity states. In practice, several states have the same capacity so they can be grouped in a single state with the same capacity and probability equal to the sum of the single probabilities. Finally, the model is reduced to a series of capacity states and probabilities. This capacity probability distribution is usually tabulated and referred to as the capacity outage probability table.

The generation model required in the loss of load approach is sometimes known as a capacity outage probability table. If all units in the system are identical in capacity, binomial distribution can be used to obtain the capacity outage table. Generators can be multi states; besides up and down, generators can have de-rated states which are between up and down. In this particular evaluation we are just considering two-state generator model. Units are added together using probability concepts to form capacity outage table.

3.3.4 Generation Shortages

The applicable capacity outage distribution needs to be combined with an appropriate system load representation to derive a measure of generation shortage risk. However, realistic load modelling is one of the more difficult problems in power systems.

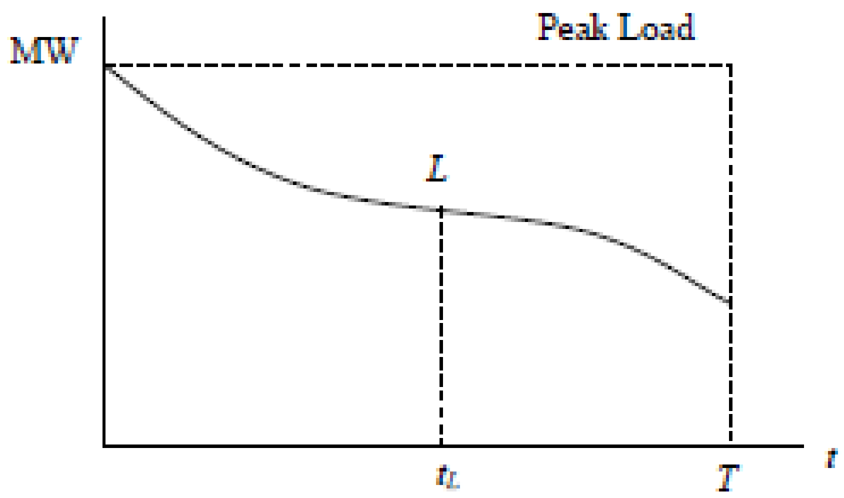

Figure 3.6: Cumulative Load Curve

A simple static, constant power, approach represents the aggregate load in the system using either demand duration histograms, in which the number of hours the load exceeds any given level is plotted, or historical load curves for typical days, weeks and seasons. The simplest load duration model is one in which each day is represented by its daily peak load. The individual peak loads are arranged in descending order to form a cumulative load model known as the daily peak load variation curve as shown in figure 3.6.

Another method uses hourly load values in a given period and organizes them in descending order to produce the load duration curve. A supply shortage will occur whenever the system load exceeds the generating capacity remaining in service. If L is the system load, the probability of having power shortages will be the probability of all the outage events for which C_A is less than L, or $P[C_A \leq L]$.

3.4 Generation Reliability Indices

According to Wang and McDonald [38] the evaluation of power system reliability starts by creating a mathematical model of a system or a subsystem and then proceeding with a numerical solution just as in the calculation of load flows, short circuit current, etc. The creation of component reliability models, which is the preparation for creating the reliability model for the whole system. The process is summarized in the following general steps:

1. Define the boundary of the system and list all the components included.
2. Provide reliability data such as failure rate, repair rate, repair time, scheduled maintenance time, etc., for every component.
3. Establish reliability models for every component.
4. Define the mode of system failure, or define the criterion for normal and faulty systems.
5. Establish a mathematical model for the system reliability and its basic assumptions.
6. Select an algorithm to calculate the system reliability indices.

The application of probability models to the evaluation of generation reliability allows the integration of different unit sizes and types, the effects of maintenance, the capacity of interconnections and other factors. The analytical methods commonly employed are the “loss of load” and the “frequency and duration” approaches. The generation reliability indices such as loss of load probability (LOLP), loss of energy probability (LOEP) and expected energy not supplied (EENS) are briefly discussed here.

3.4.1 Loss of Load Indices

Loss of load occurs when the system load exceeds the generating capacity available for use. Loss of Load Probability (LOLP) is a projected value of how much time, in the long run, the load on a power system is expected to be greater than the capacity of the available generating resources. It is defined as the probability of the system load exceeding the available generating capacity under the assumption that the peak load of each day lasts all day. LOLP is based on combining the probability of generation capacity states with the daily peak probability so as to assess the number of days during the year in which the generation system may be unable to meet the daily peak

The overall probability that the load demand will not be met is called the Loss-of-Load Probability or LOLP. For an expected load L and available generation capacity C_A, the LOLP is:

$$LOLP = \sum_j P[L_o > C_j] \tag{3.23}$$

Equation (3.23) is equal to the cumulative probability of $C_j < L_o$. Therefore, the LOLP can be read directly from the capacity outage table for a given dispatch. The assumption of a constant load is sufficient for evaluating short-run generation adequacy, for instance in systems where the dispatch is determined hourly.

The LOLP can be used to measure loss-of-load risk hour by hour or just consider the expected peak load during the dispatch period. For long-run and installed capacity evaluation, a cumulative load curve is used. The LOLP calculation is illustrated in Figure 3.7 with a daily peak load curve. O_k is the magnitude of the k-th outage in the system, p_k is the probability of a capacity outage of magnitude O_k, and t_k is the number of days that an outage of magnitude O_k would cause a loss of load in the system.

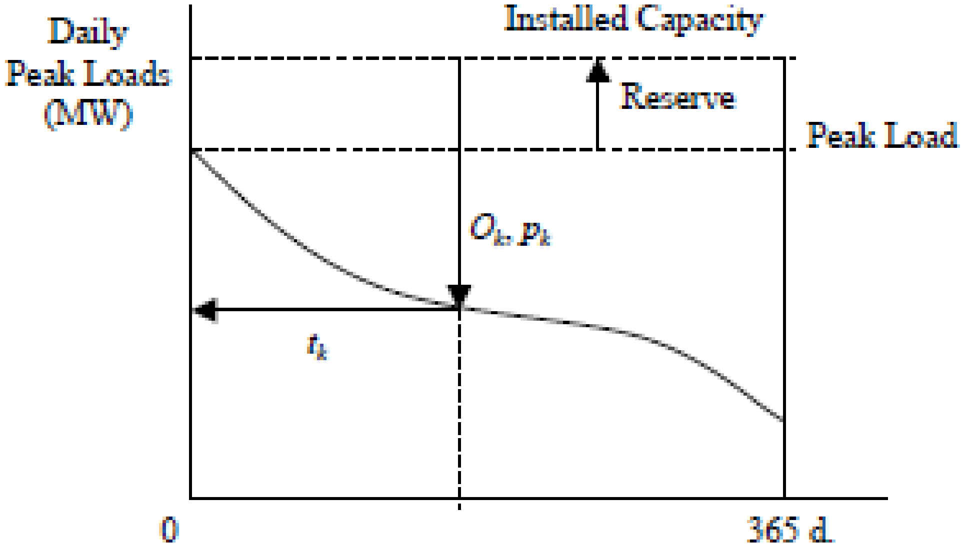

Figure 3.7: LOLP calculation

Capacity outages less than the reserve will not contribute to loss-of-load risk. A particular capacity outage greater than the reserve will contribute to the overall risk by the amount $p_k \times t_k$.

The system LOLP for the period is

$$LOLP = \sum_k p_k . t_k \tag{3.24}$$

Equation (3.24) is an expected value instead of a probability, and it is also known as the loss of load expectation LOLE. When the daily peak load curve is used, the value of LOLE is in days for the period of study, usually days per year. A widely accepted LOLE risk criterion is the "one day in ten years" or 0.1 days/year standard.

$$LOLE = \sum_{i=1}^{n} P_i (C_i - L_i) \qquad \text{Days/period} \tag{3.25}$$

Where C_i = available capacity on day i,

L_i = forecast peak load on day i, and

$P_i\ (C_i - L_i)$ = probabilities of loss of load on day i, which can be obtained directly from the capacity outage probability table.

3.4.2 Loss of Energy Indices

Loss-of-energy method is another measure for generation reliability assessment. The measure of interest in this case is the ratio of the expected energy not served (EENS) during some long period of observation to the total energy demand during the same period.

3.4.2.1 Evaluation of Energy Indices

The loss-of-energy method is a variation of the loss-of-load method. Here the measure of interest is the ratio of expected non-served energy to total energy demand over a period of time. If E_k is the energy not supplied due to a capacity outage O_k, and E is the total energy demand during the period of study, the Loss-of-Energy Probability, LOEP is given by the following ratio

$$LOEP = \sum_k \frac{E_k . p_k}{E} \tag{3.26}$$

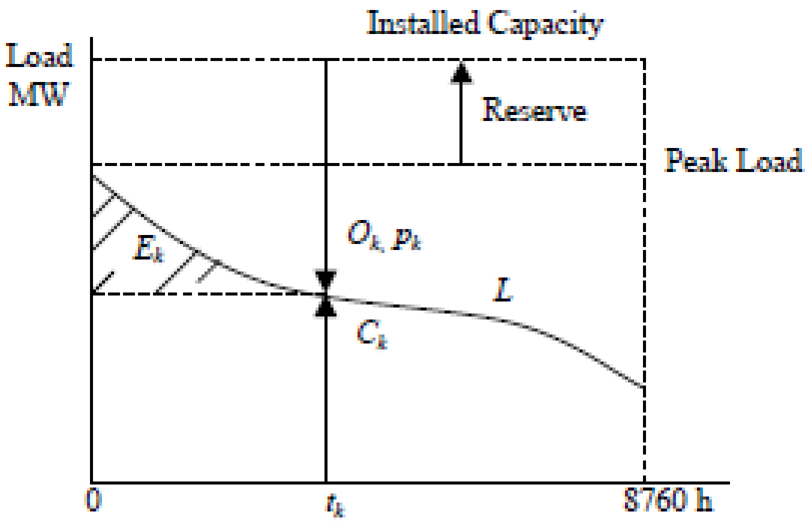

Figure 3.8: LOEP calculation

Equation (3.26) is also known as the Loss-of-Energy Expectation LOEE. Again, the simplest case is when the load is constant and known. If L_o is the expected load during say 1h, the energy demanded is $E_o = L_o \times$ 1h (MWh), and the system loss-of energy probability during the hour will be:

$$LOEP = \sum_j \frac{E_j . p_j}{E_o} \approx \sum_j \frac{(L_o - C_j).p(C_j)}{L_o}, \quad for \quad L_0 > C_j \tag{3.27}$$

For longer periods and installed capacity evaluation the load duration curve is used. Any capacity outage exceeding the reserve will result in load interruption and energy curtailment. The non-served energy is the shaded area in Figure 3.8. The system LOEP is given by eq. (3.26), where:

$$E_k = \int_0^{t_k} (L - C_k) dt \quad and \quad E = \int_0^{8760} (L - C_k) dt \tag{3.28}$$

3.4.2.2 Expected energy not supplied (EENS)

Expected energy not supplied is an index which calculates the actual MWh of load curtailment because of total system outages which result in loss of load.

$$EENS = \sum_{i=1}^{N} E_i \times P_i \tag{3.29}$$

Where N = total number of capacity states in the current system capacity -probability table.

E_i = area under load duration curve above a load equal to the capacity of the i^{th} capacity state.

P_i = probability of the i^{th} capacity state

The expected energy not supplied (EENS), is the expectation of energy curtailment, which is the product of probability of that particular outage state.

3.4.3 Frequency and Duration (FAD) Method

The basic indices are the expected number of days (or hours) in a given period that the load exceeded the available capacity and the expected energy not supplied in the period due to insufficient installed capacity. These are useful indices which can be used to compare the adequacy of alternative configurations and expansions. They do not give any indication of the frequency of occurrence of an insufficient capacity condition, nor the duration for which it is likely to exist. A frequency and duration approach to capacity evaluation was first introduced by Halperin and Adler in 1958.

The LOLP and LOEP indices do not give indications about the frequency of occurrence or likely duration of a generation deficit. The frequency and duration FAD method measures these figures and is helpful to evaluate customer point reliability.

The FAD method utilizes the transition rate parameters λ and μ of generation units. This technique applies the state-space approach to the set of units present in the system. In short, each possible combination of units in up (in service) and down (forced outage) states defines a capacity state of the system. The resulting states are characterized by their available capacity, the associated state probabilities and the transition rates. The steps of a frequency and duration (FAD) analysis are as follows:

- The capacities C_j and the probabilities p_j of each state are calculated for the system capacity outage distribution.
- The frequency of encountering a state j, f_j, is the expected number of stays in (or arrivals into, or departures from) j per unit time, computed over a long period.
- The frequency of state j is $fj = pj.(\lambda_{j+} + \lambda_{j-})$, where λ_{j+} is the transition rate from state j to higher capacity states and λ_{j-} the transition rate to lower capacity states.
- The average state duration T_j is defined by the relation $p_j = f_j.T_j$.

This representation is combined with a load model to identify marginal states, that is, states where a transition to a lower capacity state results in a generation deficit ($Cj < L$). Next, cumulative probabilities and frequencies are computed for the marginal states and suitable indices are derived as:

$$f = A\lambda \tag{3.30}$$

The frequency of encountering state 0 in figure 3.3 is the probability of being in the state multiplied by the rate of departure from the state.

3.4.3.1 State Selection

The state selection process [1] is illustrated by considering first and second order generating unit outages in the system and using the probability of failure and occurrence of failure from generation model. In the system there are 3 elements which represent a total of 8 states. It becomes necessary therefore to limit the number of states by selecting the contingencies which will be included. For large unit system like IEEE 30-bus System with seven units and Delhi Power System with eight units, the state selection is more necessary to limit the number of states. In the IEEE 30-bus system with seven units which represent a total of states 2^7 = 128 and in the Delhi Power System with eight units which represent a total of states 2^8 = 256.

For state selection, first is to simply specify the contingency level, i.e. first order, second order etc. This can be modified by neglecting those contingencies which have a probability of occurrence less than a certain minimum value. A useful approach is to consider those outage conditions which result from independent events and have a probability exceeding some minimum value and, in addition, to consider those outage conditions resulting from outage dependence such as common mode or station related events again having the same probability constraint. In this dissertation, cascading failure of line outages are considered for IEEE 30-bus System and in case of Delhi Power System Network, the maximum load shedding [40] for 2012 is considered as the most sever contingency levels as shown in appendix Table A.5.

3.4.3.2 System Reliability Parameters and Indices

For a power system with independent components, the state probability, the departure rate, the frequency, and the total system available real power capacity for state with failed components can be determined using the following equations:

The state probability is given as

$$p_i = \prod_{j=M+1}^{N} A_j \prod_{j=1}^{M} U_j \tag{3.32}$$

The departure rate as

$$\lambda_i = \sum_{j=M+1}^{N} \lambda_i + \sum_{j=1}^{M} \mu_j \tag{3.33}$$

The frequency of state available is given as

$$F_i = p_i \lambda_i \tag{3.34}$$

The total system available real power capacity for state with failed components

$$P_i = \sum_{k=1}^{N_{gi}} P_k \tag{3.35}$$

where A_j, U_j, λi, and μj are the availability, the unavailability, the failure rate, the repair rate of component, respectively, P_k is the real power capacity of generator k, and N_{gi} is the number of available generators in the system for state i. It should be noted that the state probability have to be adjusted for a common cause failure.

Expected load curtailed,

$$ELC = \sum_{i=1}^{NC} LC_i \times F_i \tag{3.36}$$

Expected energy not supplied,

$$EENS = \sum_{i=1}^{NC} LC_i \times p_i \times 8760 \tag{3.37}$$

Expected duration of load curtailment,

$$EDLC = \sum_{i=1}^{NC} p_i \times 8760 \tag{3.38}$$

where NC is the total number of considered contingencies,

LC_i is the real load curtailments due to real power shortage for state i.

3.4.4 Short-term and Long-term Reliability Evaluation

As discussed above in Section 3.4.2 and 3.4.3, the conventional reliability evaluation techniques had been developed based on the steady-state probability of a component and had been used for power system planning for many years. Reliability indices based on the steady-state probability of a component represent long-term system reliability. However, the steady-state probability of a component cannot reflect the system's real-time reliability, which varies with operating conditions. The short-term and long-term reliability evaluation has been performed in IEEE 30 bus System and Delhi Power System. This technique predicts the short-term and long-term reliability associated with the current operating state using the time-dependent state probability of a component.

3.4.4.1 Fast sorting technique

A fast sorting technique (FST) has been developed [37], which can select credible system states. The FST can quickly select the required number of system states in descending order probability. In the evaluation algorithm, the relative accuracy of a reliability index is defined as the stopping rule that terminates state selection and evaluation; only a small number of system states are required to achieve high accuracy. This technique predicts the short-term and long-term reliability associated with the current operating state using the time-dependent state probability of a component.

The basic equation to determine the time-dependent probabilities for different initial states [37]: if the component is in the up state at time t = 0, the associate time-dependent probabilities are

$$[p(t),q(t)]=\left[\frac{\mu}{\lambda+\mu}+\frac{\lambda}{\lambda+\mu}e^{-(\lambda+\mu)t},\frac{\lambda}{\lambda+\mu}-\frac{\lambda}{\lambda+\mu}e^{-(\lambda+\mu)t}\right] \tag{3.39}$$

where *p(t)* and *q(t)* are the time-dependent probabilities of the component in up and down states, respectively, λ and μ are the failure rate and the repair rate of the component, respectively.

The limiting state (steady-state) probabilities can be obtained from (3.40) by letting $t\rightarrow\infty$

$$[\overline{p},q]=[p(\infty),q(\infty)]=\left[\frac{\mu}{\lambda+\mu},\frac{\lambda}{\lambda+\mu}\right] \tag{3.40}$$

where p and q are steady-state (or limiting state) probabilities for the up and the down states, respectively. The steady-state probabilities are basic parameters used in conventional long-term reliability evaluation.

Similarly, if the component is in the down state at time t = 0, the associate time-dependent probabilities are

$$[p(t),q(t)]=\left[\frac{\mu}{\lambda+\mu}-\frac{\mu}{\lambda+\mu}e^{-(\lambda+\mu)t},\frac{\lambda}{\lambda+\mu}+\frac{\mu}{\lambda+\mu}e^{-(\lambda+\mu)t}\right] \tag{3.41}$$

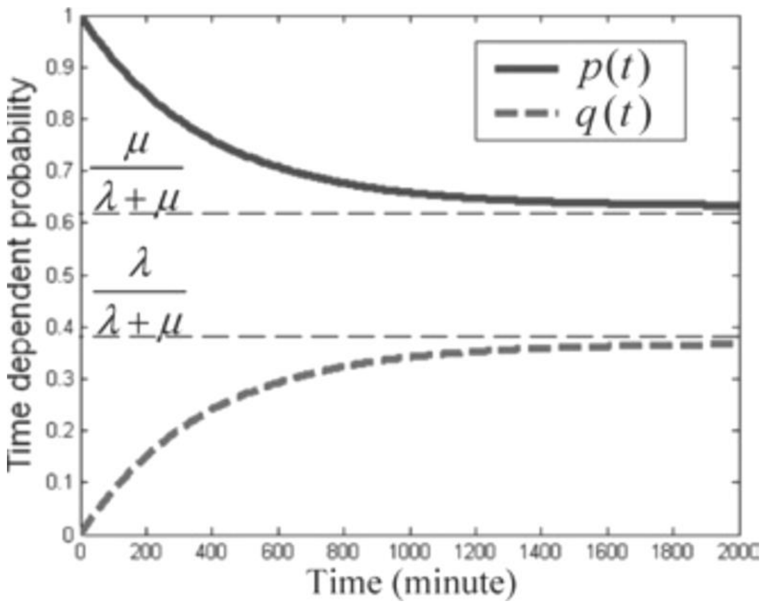

Figure 3.9: Time-dependent probability (initial state is up state)

As $t \to \infty$, the steady-state probabilities are

$$[\overline{p}, \overline{q}] = [p(\infty), q(\infty)] = \left[\frac{\mu}{\lambda+\mu}, \frac{\lambda}{\lambda+\mu}\right] \tag{3.42}$$

Figures 3.9 show that the steady-state probabilities of a component vary with time and approach the steady-state probabilities when time tends to infinity. The time-dependent state probabilities of components will cause the time-dependent probabilities of system states and time-dependent reliability indices.

3.4.4.2 Relative accuracy of a reliability index

It is impossible to obtain the exact reliability indices in this evaluation that requires investigating all possible contingency states. However, the lower and upper bounds of a reliability index can be defined to estimate the accuracy of the evaluation. The lower bound $I(t)_{Low}$ and upper bound $I(t)_{Up}$ of an index $I(t)$ are, respectively, defined in Equation (3.43) and (3.44)

$$I(t)_{Low} = \sum_{k=1}^{n} F_{S_k} P_{S_k}(t) + F_{Low}\left(1 - \sum_{k=1}^{n} P_{S_k}(t)\right) \tag{3.43}$$

$$I(t)_{Up} = \sum_{k=1}^{n} F_{S_k} P_{S_k}(t) + F_{Up}\left(1 - \sum_{k=1}^{n} P_{S_k}(t)\right) \tag{3.44}$$

where S_k is the k^{th} system state, F_{S_k} the value of the index for state S_k, $P_{S_k}(t)$ the time-dependent state probability of S_k, 'n' the number of system states selected and F_{Low} and F_{Up} are the lower and upper bounds of the index value for the remaining system states, respectively.

For the PLC index, F_{S_k} = 1 if there is load curtailment for S_k; and

F_{S_k} = 0 otherwise.

Since the PLC is a probability, F_{Low} = 0 and F_{Up} = 1. The lower and upper bounds of the PLC can be obtained as

$$PLC(t)_{Low} = \sum_{k=1}^{n} F_{S_k} P_{S_k}(t) \tag{3.45}$$

$$PLC(t)_{Up} = PLC_{Low} + \left(1 - \sum_{k=1}^{n} P_{S_k}(t)\right) \tag{3.46}$$

The relative accuracy of the index *I(t)** is defined on the basis of the lower and upper bounds of an index as

$$I(t)^* = \frac{I(t)_{Low}}{I(t)_{Up}} \tag{3.47}$$

The relative accuracies of PLC, ENLC, EENS and EDLC are, respectively

$$PLC(t)^* = \frac{PLC(t)_{Low}}{PLC(t)_{Up}}\ , \tag{3.48}$$

$$ENLC(t)^* = \frac{ENLC(t)_{Low}}{ENLC(t)_{Up}}\ , \tag{3.49}$$

$$EENS(t)^* = \frac{EENS(t)_{Low}}{EENS(t)_{Up}}\ , \text{ and} \tag{3.50}$$

$$EDLC(t)^* = \frac{EDLC(t)_{Low}}{EDLC(t)_{Up}} \tag{3.51}$$

Equations (3.43) and (3.44) indicate that the difference between the upper and lower bounds decreases and both bounds approach the exact index as the number of system states considered increases. The relative accuracy of an index can be used as a stopping rule in the evaluation.

Chapter 4
Problem Formulation and Results

4.1 Introduction

The data for test problems IEEE 30-bus system and Delhi Power System is appended in appendix A. The results for reliability evaluation of generation system by basic probability method and Frequency and Duration (FAD) method are appended in this chapter,

4.2 Capacity Outage Probability Table (COPT)

Capacity outage probability table (COPT) shows the state probability and state frequency for corresponding system power available and unavailable. IEEE 30-bus system and Delhi Power system is considered for the generation system evaluation. For this, COPT for each system is required for calculating the reliability indices of both generation systems.

4.2.1 Algorithm for COPT

The following steps present the method of calculating Capacity Outage Probability Table (COPT) for evaluating reliability of generation system with the help of Frequency and Duration (FAD) method:

Step1: Input number of units, 'N', transition rates, 'λ *and* μ', and capacity of units C_i for $i = 1, 2, \ldots, N$.

Step 2: For N units, calculate number of states and calculate Unavailability, U and Availability, A from Equation (3.2) and (3.3).

Step 3: Set $i = 0$, calculate probability when no generating unit is on outage.

Step 4: Set $j = 0$.

Step 5: Set $i = i + 1$, calculate probability when first unit goes an outage.

Step 6: $j = j + C_i$.

Step 7: Repeat Step 5 and 6 for $j \leq N + 1$, otherwise go to Step 8.

Step 8: Print capacity outage probability table, COPT

4.2.2 COPT for IEEE 30-bus System

For IEEE 30-bus system, there are seven units i.e. $N = 7$, hence there should be $2^N = 2^7 = 128$ states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 16 states as shown in Table 4.1 and this distribution for seven units of IEEE 30-bus system is shown in Figure 4.1.

Table 4.1 Capacity outage probability table for 30-bus System

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
360	0	0.8332322579	31.2462096703
320	40	0.0513636323	12.9436353484
300	60	0.1027255057	23.2334276176
280	80	0.0010554171	0.4923520784
260	100	0.0063323942	2.7904961456
240	120	0.0047564432	1.9750869373
220	140	0.0001301177	0.0852492061
200	160	0.0002927598	0.1842454441
180	180	0.0000984761	0.0596685426
160	200	0.0000060156	0.0050762141
140	220	0.0000060155	0.0049207466
120	240	0.0000007931	0.0006392671
100	260	0.0000001236	0.0001276248
80	280	0.0000000464	0.0000466612
60	300	0.0000000008	0.0000010557
40	320	0.0000000010	0.0000011631
0	360	≅0.0000000000	0.0000000094

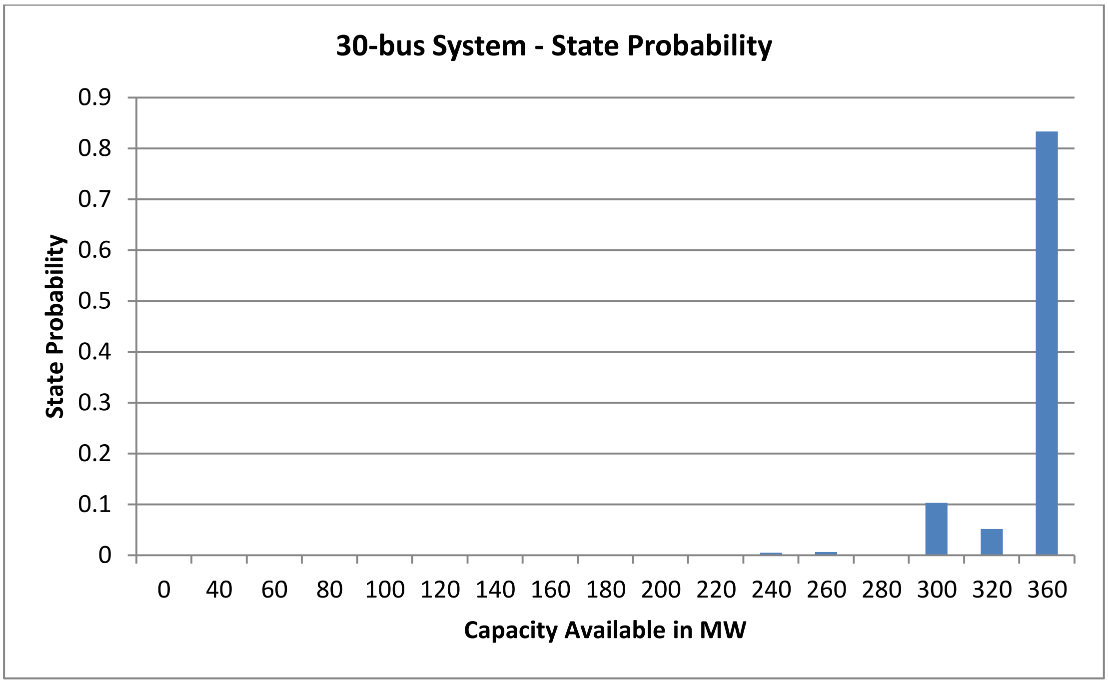

Figure 4.1: Capacity Probability Distribution for Seven-unit IEEE 30-bus system

4.2.3 COPT for Delhi Power System

In case of Delhi Power System, there are eight units, $N = 8$, hence there should be $2^N = 2^8 = 256$ states, which include repeated state value for same power available. The system consists of four generating stations with 135 MW Rajghat Power Station (1 unit), 270 MW Gas Turbine Power station (2 units), 330 MW Pragati Power Station (2 units) and 705 MW Badarpur Thermal Power Station (3 units). These repeated values merge and form a reduced COPT with total 150 states as shown in Table 4.2 and this distribution for seven units of IEEE 30-bus system is shown in Figure 4.2.

Table 4.2 Capacity outage probability table for Delhi Bus System

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
1440	0	0.290371188	19.74524076
1350	90	0.090543397	8.148905705
1318	122	0.026213186	4.167896599
1305	135	0.087322865	6.549214874
1260	180	0.090543397	8.148905705
1232	208	0.026213186	4.167896599
1230	210	0.052150362	8.303380562
1228	212	0.008173782	1.479454621
1215	225	0.027228972	2.64121024
1183	257	0.00788305	1.308586257
1170	270	0.028233196	3.162117965
1155	285	0.026075181	4.151690281
1142	298	0.008173782	1.479454621
1140	300	0.016261499	2.946908908
1138	302	0.008173782	1.479454621
1125	315	0.027228972	2.64121024
1110	330	0.002366389	0.591597202
1108	332	0.004707861	1.178000932
1097	343	0.00788305	1.308586257
1095	345	0.015683095	2.606844083
1093	347	0.002458089	0.462120653
1065	375	0.00813075	1.473454454
1052	388	0.008173782	1.479454621
1050	390	0.016261499	2.946908908

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
1048	392	0.002548745	0.517395174
1035	405	0.008490524	1.01037237
1033	407	0.00235393	0.589000466
1022	418	0.004707861	1.178000932
1020	420	0.010920971	2.090541752
1018	422	0.001468003	0.399619715
1007	433	0.002458089	0.462120653
1005	435	0.004890295	0.920451288
1003	437	0.002458089	0.462120653
975	465	0.00884239	1.656346021
973	467	0.001415788	0.364168857
962	478	0.002548745	0.517395174
960	480	0.005070653	1.030457998
947	493	0.00235393	0.589000466
945	495	0.004683075	1.172829349
943	497	0.000734001	0.199809858
932	508	0.001468003	0.399619715
930	510	0.003913171	0.859849222
928	512	0.001468003	0.399619715
917	523	0.002458089	0.462120653
915	525	0.004890295	0.920451288
913	527	0.00076648	0.160960787
900	540	0.000425001	0.145018826
898	542	0.000919276	0.254258603
887	553	0.001415788	0.364168857
885	555	0.003461396	0.758420748
883	557	0.00044147	0.123267292
857	583	0.000734001	0.199809858
855	585	0.001460274	0.397837085
853	587	0.000734001	0.199809858
842	598	0.001468003	0.399619715
840	600	0.003405372	0.726789849
838	602	0.000457752	0.134679759

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
827	613	0.00076648	0.160960787
825	615	0.00173739	0.393071631
823	617	0.000422763	0.144348348
812	628	0.000919276	0.254258603
810	630	0.001540857	0.410696655
808	632	0.000286648	0.085589045
797	643	0.00044147	0.123267292
795	645	0.000441476	0.123268496
793	647	0.00044147	0.123267292
767	673	0.000734001	0.199809858
765	675	0.001588084	0.442343034
763	677	0.000292444	0.089489683
752	688	0.000457752	0.134679759
750	690	0.000990116	0.22731655
737	703	0.000422763	0.144348348
735	705	0.000276531	0.095908063
733	707	0.000131826	0.047910798
722	718	0.000286648	0.085589045
720	720	0.00057167	0.17085015
718	722	0.000286648	0.085589045
707	733	0.00044147	0.123267292
705	735	0.000288767	0.082184796
703	737	0.000137659	0.041465642
690	750	8.29874E-05	0.030504982
688	752	0.000127137	0.044299608
677	763	0.000292444	0.089489683
675	765	0.000495196	0.148825483
673	767	1.98219E-05	0.007342822
647	793	0.000131826	0.047910798
645	795	0.000131828	0.047911313
643	797	0.000131826	0.047910798
632	808	0.000286648	0.085589045
630	810	0.000480469	0.138633549

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
628	812	8.93824E-05	0.028654746
617	823	0.000137659	0.041465642
615	825	0.000106632	0.037142745
613	827	0.000018982	0.008212738
602	838	0.000127137	0.044299608
600	840	8.91109E-05	0.032128446
598	842	3.96438E-05	0.014685645
587	853	1.98219E-05	0.007342822
585	855	3.98536E-05	0.014754602
583	857	1.98219E-05	0.007342822
557	883	0.000131826	0.047910798
555	885	9.19663E-05	0.034324795
553	887	4.11059E-05	0.01584385
542	898	8.93824E-05	0.028654746
540	900	0.000136934	0.041277462
527	913	0.000018982	0.008212738
525	915	1.19005E-05	0.005408085
523	917	5.9189E-06	0.002691109
512	928	3.96438E-05	0.014685645
510	930	4.55946E-05	0.017389846
508	932	3.96438E-05	0.014685645
497	943	1.98219E-05	0.007342822
495	945	1.24271E-05	0.004874169
493	947	6.1809E-06	0.002425614
480	960	1.14773E-05	0.005043567
478	962	5.7084E-06	0.002509763
467	973	4.11059E-05	0.01584385
465	975	2.22342E-05	0.008710425
437	1003	5.9189E-06	0.002691109
435	1005	1.19005E-05	0.005408085
433	1007	5.9189E-06	0.002691109
422	1018	3.96438E-05	0.014685645
420	1020	2.77865E-05	0.010629579

Capacity in (MW)	Capacity out (MW)	State Probability	State Frequency
418	1022	1.23617E-05	0.004851228
407	1033	6.1809E-06	0.002425614
405	1035	1.7136E-06	0.00089734
392	1048	5.7084E-06	0.002509763
390	1050	3.5788E-06	0.001651417
388	1052	0.00000178	0.000821753
375	1065	1.7894E-06	0.000825708
347	1093	5.9189E-06	0.002691109
345	1095	3.7108E-06	0.001767985
343	1097	1.8456E-06	0.000879744
332	1108	1.23617E-05	0.004851228
330	1110	6.1483E-06	0.002414196
315	1125	5.343E-07	0.000291563
302	1138	0.00000178	0.000821753
300	1140	3.5788E-06	0.001651417
298	1142	0.00000178	0.000821753
285	1155	0.000000558	0.000269747
270	1170	5.153E-07	0.000273463
257	1183	1.8456E-06	0.000879744
225	1215	5.343E-07	0.000291563
212	1228	0.00000178	0.000821753
210	1230	1.1159E-06	0.000539495
208	1232	0.000000555	0.000268449
180	1260	1.607E-07	8.88062E-05
135	1305	1.666E-07	9.45807E-05
122	1318	0.000000555	0.000268449
90	1350	1.607E-07	8.88062E-05
0	1440	5.01E-08	2.87938E-05

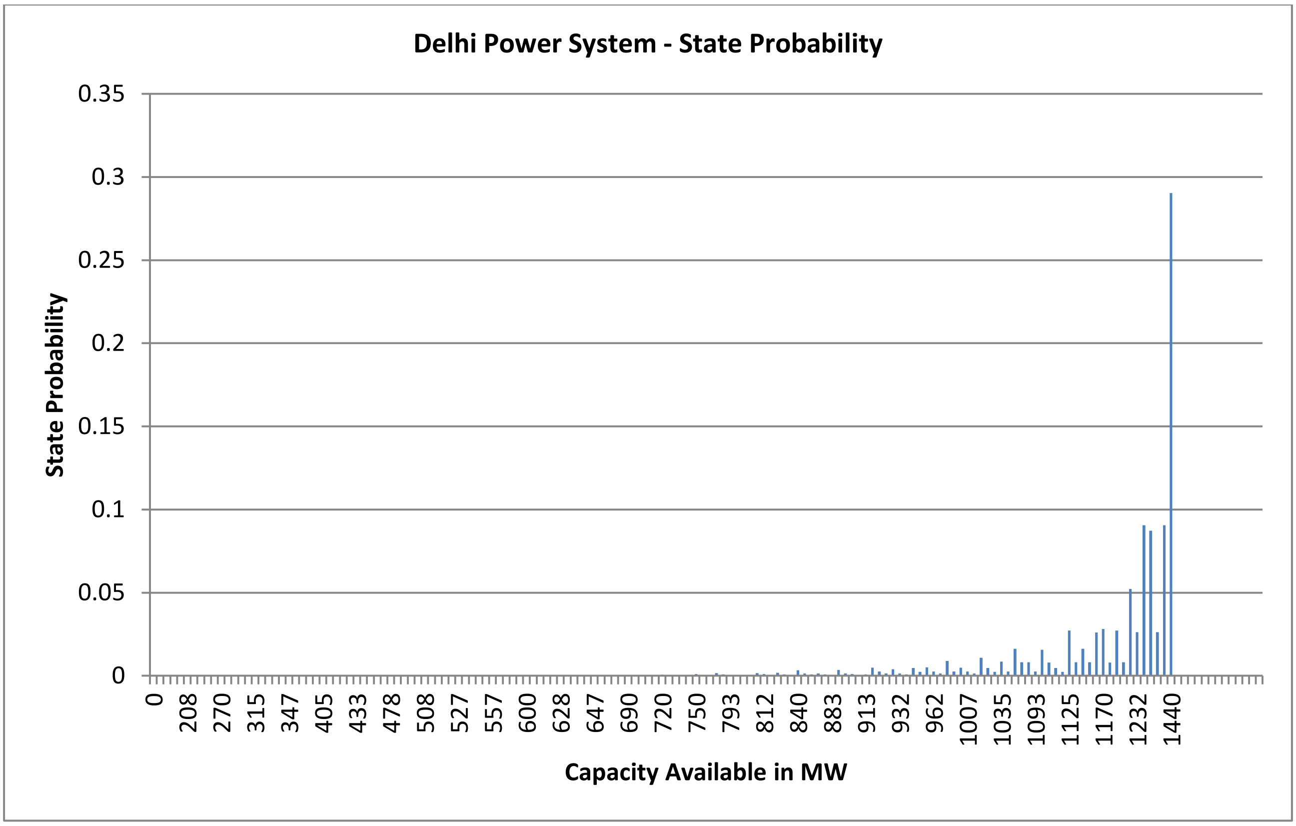

Figure 4.2: Capacity Probability Distribution for Eight-unit Delhi Power system

4.3 Calculation of reliability indices

The evaluation of power system reliability starts by creating a mathematical model of a system or a subsystem and then proceeding with a numerical solution just as in the calculation of load flows, short circuit current, etc. The creation of component reliability models, which is the preparation for creating the reliability model for the whole system. The power system under consideration is a single nodal system in which all the generating units and system loads are connected to a single bus-bar. The application of probability models to the evaluation of generation reliability allows the integration of different unit sizes and types, the effects of maintenance, the capacity of interconnections and other factors. In addition, economic aspects can be better accommodated. The analytical methods commonly employed are the "loss of load" and the "frequency and duration" approaches. General calculation procedure for reliability indices calculation is stated as:

1 Compile the generating unit's reliability data table with number of units, transition rates, unit capacity.

2 Create the generator unit's outage capacity model – probability and frequency tables as shown in section 3.2.2 with the help of algorithm stated in section 4.2.1.

3. Compile the load curtailed data table.

4. Calculate the generation by the system for each cases of load curtailment i.e. for normal and abnormal contingency states. For IEEE 30-bus System, normal state and abnormal state contingencies are referred from paper [35] .

5. Select the appropriate state for fulfil the supply demand by state selection for the maximum probability and maximum frequency state from the 2^N states. The state selection process is used for this purpose is briefly given in section 3.4.3.2.

6. Calculate the reliability indices by Equation (3.19), (3.20) and (3.21).

EENS can be calculated using the following equation:

$$EENS = \sum_{M_k<0} M_k p_k \times 8760 \qquad MWh / year \tag{4.1}$$

Hence the margin $M_k = C_j - L_i$.

4.3.1 Loss of Energy Indices

It measures the expected fraction of system energy not served due to capacity outage events. The loss-of-energy approach has much greater physical relevance than the other approaches and takes into account the magnitude of the different outage event.

Case-I IEEE 30-bus System

The modified IEEE 30-bus system as shown in Figure A.1 was analyzed to illustrate the frequency and duration method. The system has five *PV* buses and 24 *PQ* buses. The total system active and reactive power peak loads for the normal state are 283.4 MW and 126.2 MVar, respectively. It is assumed that 4 × 60 MW units are connected at Bus 1 and 3 × 40 MW units at Bus 2 in order to consider generator reliability in the evaluation.

From appendix, Table A.1 shows the weekly peak loads in percent of the annual peak. This seasonal load profile can be used to adapt to any system peaking season one desires to model. For example, if week number 1 is assumed to be the first week of the calendar year, then Table 4.1 shows a winter peaking system with the peak occurring in the week prior to Christmas. If week number one is assumed to be the first week of August, then table 2 shows a summer peaking system with an assumed peak occurring in the month of July.

The load duration curve for weekly peak load against peak load in MW verses time percentage is shown in Figure 4.4. The expected energy not supplied for 30 bus system is shown in the Table 4.3.

As discussed earlier in Section 3.4.1, LOLE can be calculated by given formula in Equation (3.7). Hence, LOLE for given load system in A.2 is

$$LOLE = 7.488 \times 10^{-5} \qquad \text{days/year}$$

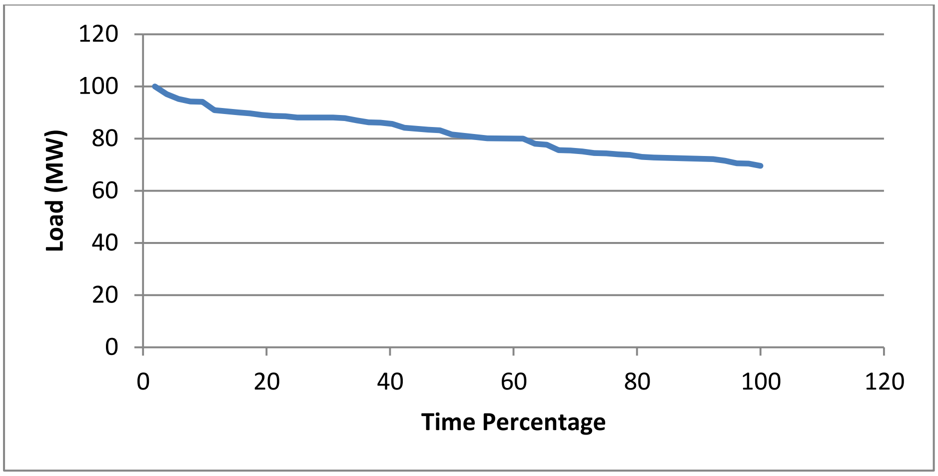

Figure 4.3 Load duration curve for weekly peak load

Table 4.3 Expected Energy Not Supplied for 30 bus system

Capacity In(MW)	Capacity Out(MW)	Probability	Energy Curtailed(MWh)	Expectation (MWh)
360	0	0.8332322579	-	-
320	40	0.0513636323	-	-
300	60	0.1027255057	-	-
280	80	0.0010554171	-	-
260	100	0.0063323942	-	-
240	120	0.0047564432	-	-
220	140	0.0001301177	-	-
200	160	0.0002927598	-	-
180	180	0.0000984761	-	-
160	200	0.0000060156	-	-
140	220	0.0000060155	-	-
120	240	0.0000007931	-	-
100	260	0.0000001236	-	-
80	280	0.0000000464	17.01923	0.000000789692
60	300	0.0000000008	2140.000	0.000001712
40	320	0.0000000010	4101.538	0.00000410154
0	360	0.000000000007	8024.615	0.0000000561723
			Total EENS	0.0000066594

The total expected energy not supplied (EENS) is 6.6594×10^{-6} MWh/year. The basic requirement for calculating EENS is to develop a sequential capacity outage probability table for the generating system.

Case-II Delhi Power System

The Delhi Power system is used for the evaluation of reliability by analytical approaches. The system consists of four generating stations with 135 MW Rajghat Power Station, 270 MW Gas Turbine Power station, 330 MW Pragati Power Station and 705 MW Badarpur Thermal Power Station. Load duration curve for April 2012 is given in Delhi Transco Limited - State Load Dispatch Centre, Progress Report. The analytical method for calculation of expected energy not supplied (EENS) described early in section 3.4.2 in which load duration curve required for particular time period like daily, weekly, monthly or annually. The load duration curve for Delhi in April 2012 is shown in Figure 4.4.

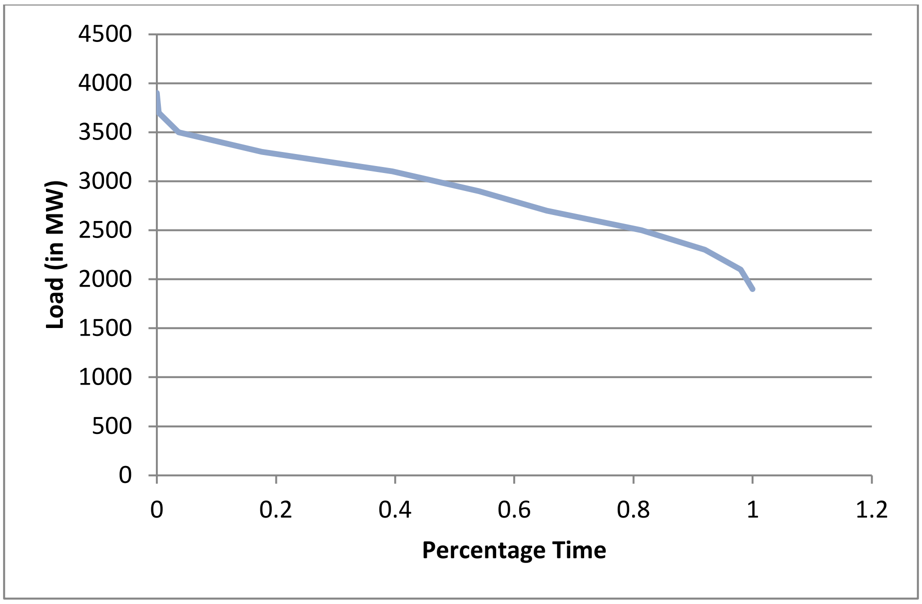

Figure 4.4: Load Duration Curve for Delhi in April 2012

Using Load Duration Curve for Delhi in April, 2012, the energy curtailed is calculated under the load duration curve and above the capacity in the graph is the energy supplied to the system for fulfil the consumer demand.

From Section 3.4.1, LOLE is given by Equation (3.7) and hence, LOLE for Delhi Power System is 8.8994×10^{-2} Days/year.

Table 4.4: Expected Energy Not Supplied (EENS) for Delhi in April 2012

Capacity In(MW)	Capacity Out(MW)	Probability	Energy Curtailed(MWh)	Expectation (MWh)
1440	0	0.29037119	1246.88	362.0580294
1350	90	0.0905434	2354.88	213.2188418
1318	122	0.02621319	1368.88	35.88271153
1305	135	0.08732286	1381.88	120.6697138
1260	180	0.0905434	1426.88	129.1945666
1232	208	0.02621319	1454.88	38.13704587
1230	210	0.05215036	1456.88	75.97681648
1228	212	0.00817378	1458.88	11.92456417
1215	225	0.02722897	1471.88	40.07777636
1183	257	0.00788305	1503.88	11.85516123
1170	270	0.0282332	1516.88	42.82637642
1155	285	0.02607518	1531.88	39.94404674
1142	298	0.00817378	1544.88	12.62750925
1140	300	0.0162615	1546.88	25.15458912
1138	302	0.00817378	1548.88	12.66020437
1125	315	0.02722897	1561.88	42.52838366

1110	330	0.00236639	1576.88	3.731513063
1108	332	0.00470786	1578.88	7.433145997
1097	343	0.00788305	1589.88	12.53310353
1095	345	0.0156831	1591.88	24.96561323
1093	347	0.00245809	1593.88	3.917900489
1065	375	0.00813075	1621.88	13.18710081
1052	388	0.00817378	1634.88	13.36314945
1050	390	0.0162615	1636.88	26.61812412
1048	392	0.00254874	1638.88	4.177079011
1035	405	0.00849052	1651.88	14.02532018
1033	407	0.00235393	1653.88	3.893117748
1022	418	0.00470786	1664.88	7.838021957
1020	420	0.01092097	1666.88	18.20394647
1018	422	0.001468	1668.88	2.44991584
1007	433	0.00245809	1679.88	4.129296229
1005	435	0.00489029	1681.88	8.224880945
1003	437	0.00245809	1683.88	4.139128589
975	465	0.00884239	1711.88	15.13711059
973	467	0.00141579	1713.88	2.426494165
962	478	0.00254874	1724.88	4.396270651
960	480	0.00507065	1726.88	8.756404072
947	493	0.00235393	1739.88	4.095555728
945	495	0.00468308	1741.88	8.15736339
943	497	0.000734	1743.88	1.28000792
932	508	0.001468	1754.88	2.57616384
930	510	0.00391317	1756.88	6.87497011
928	512	0.001468	1758.88	2.58203584
917	523	0.00245809	1769.88	4.350524329
915	525	0.00489029	1771.88	8.665007045
913	527	0.00076648	1773.88	1.359643542
900	540	0.000425	1786.88	0.759424
898	542	0.00091928	1788.88	1.644481606
887	553	0.00141579	1799.88	2.548252105
885	555	0.0034614	1801.88	6.237027432
883	557	0.00044147	1803.88	0.796358904
857	583	0.000734	1829.88	1.34313192
855	585	0.00146027	1831.88	2.675039408
853	587	0.000734	1833.88	1.34606792
842	598	0.001468	1844.88	2.70828384
840	600	0.00340537	1846.88	6.289309746
838	602	0.00045775	1848.88	0.84632482
827	613	0.00076648	1859.88	1.425560822
825	615	0.00173739	1861.88	3.234811693
823	617	0.00042276	1863.88	0.787973909

812	628	0.00091928	1874.88	1.723539686
810	630	0.00154086	1876.88	2.892009317
808	632	0.00028665	1878.88	0.538580952
797	643	0.00044147	1889.88	0.834325324
795	645	0.00044148	1891.88	0.835227182
793	647	0.00044147	1893.88	0.836091204
767	673	0.000734	1921.88	1.41065992
765	675	0.00158808	1891.88	3.00445679
763	677	0.00029244	1923.88	0.562619467
752	688	0.00045775	1904.88	0.87195882
750	690	0.00099012	1906.88	1.888040026
737	703	0.00042276	1949.88	0.824331269
735	705	0.00027653	1951.88	0.539753376
733	707	0.00013183	1953.88	0.25758
722	718	0.00028665	1964.88	0.563232852
720	720	0.00057167	1966.88	1.12440629
718	722	0.00028665	1968.88	0.564379452
707	733	0.00044147	1979.88	0.874057624
705	735	0.00028877	1981.88	0.572307488
703	737	0.00013766	1991.88	0.274202201
690	750	0.00008299	1996.88	0.165721071
688	752	0.00012714	1998.88	0.254137603
677	763	0.00029244	2009.88	0.587769307
675	765	0.0004952	2011.88	0.996282976
673	767	0.00001982	2013.88	0.039915102
647	793	0.00013183	2039.88	0.26891738
645	795	0.00013183	2041.88	0.26918104
643	797	0.00013183	2043.88	0.2694447
632	808	0.00028665	2054.88	0.589031352
630	810	0.00048047	2056.88	0.988269134
628	812	0.00008938	2058.88	0.184022694
617	823	0.00013766	2069.88	0.284939681
615	825	0.00010663	2071.88	0.220924564
613	827	0.00001898	2073.88	0.039362242
602	838	0.00012714	2084.88	0.265071643
600	840	0.00008911	2086.88	0.185961877
598	842	0.00003964	2088.88	0.082803203
587	853	0.00001982	2099.88	0.041619622
585	855	0.00003985	2101.88	0.083759918
583	857	0.00001982	2103.88	0.041698902
557	883	0.00013183	2129.88	0.28078208
555	885	0.00009197	2131.88	0.196069004
553	887	0.00004111	2133.88	0.087723807
542	898	0.00008938	2144.88	0.191709374

540	900	0.00013693	2146.88	0.293972278
527	913	0.00001898	2159.88	0.040994522
525	915	0.0000119	2161.88	0.025726372
523	917	0.00000592	2163.88	0.01281017
512	928	0.00003964	2174.88	0.086212243
510	930	0.00004559	2176.88	0.099243959
508	932	0.00003964	2178.88	0.086370803
497	943	0.00001982	2189.88	0.043403422
495	945	0.00001243	2191.88	0.027245068
493	947	0.00000618	2193.88	0.013558178
480	960	0.00001148	2206.88	0.025334982
478	962	0.00000571	2208.88	0.012612705
467	973	0.00004111	2219.88	0.091259267
465	975	0.00002223	2221.88	0.049392392
437	1003	0.00000592	2249.88	0.01331929
435	1005	0.0000119	2251.88	0.026797372
433	1007	0.00000592	2253.88	0.01334297
422	1018	0.00003964	2264.88	0.089779843
420	1020	0.00002779	2266.88	0.062996595
418	1022	0.00001236	2268.88	0.028043357
407	1033	0.00000618	2279.88	0.014089658
405	1035	0.00000171	2281.88	0.003902015
392	1048	0.00000571	2294.88	0.013103765
390	1050	0.00000358	2296.88	0.00822283
388	1052	0.00000178	2298.88	0.004092006
375	1065	0.00000179	2311.88	0.004138265
347	1093	0.00000592	2339.88	0.01385209
345	1095	0.00000371	2341.88	0.008688375
343	1097	0.00000185	2343.88	0.004336178
332	1108	0.00001236	2354.88	0.029106317
330	1110	0.00000615	2356.88	0.014494812
315	1125	0.00000053	2371.88	0.001257096
302	1138	0.00000178	2384.88	0.004245086
300	1140	0.00000358	2386.88	0.00854503
298	1142	0.00000178	2388.88	0.004252206
285	1155	0.00000056	2401.88	0.001345053
270	1170	0.00000052	2416.88	0.001256778
257	1183	0.00000185	2429.88	0.004495278
225	1215	0.00000053	2461.88	0.001304796
212	1228	0.00000178	2474.88	0.004405286
210	1230	0.00000112	2476.88	0.002774106
208	1232	0.00000056	2478.88	0.001388173
180	1260	0.00000016	2506.88	0.000401101
135	1305	0.00000017	2551.88	0.00043382

122	1318	0.00000056	2564.88	0.001436333
90	1350	0.00000016	2596.88	0.000415501
0	1440	0.00000005	2686.88	0.000134344
			Total EENS	1519.771703

The total expected energy not supplied in April 2012 is 1519.771703 MWh/month.

4.3.2 Frequency and Duration (FAD) Method

The frequency of system failure measures the average number of failure occurrences per unit time. The corresponding duration indicates the average residence time on the failure states.

Case-I IEEE 30-bus System

The modified IEEE 30-bus system as shown in Fig. 2 was analyzed to illustrate the frequency and duration method. The system has five *PV* buses and 24 *PQ* buses. The total system active and reactive power peak loads for the normal state are 283.4 MW and 126.2 MVar, respectively. It is assumed that 4 × 60 MW units are connected at Bus 1 and 3 × 40 MW units at Bus 2 in order to consider generator reliability in the evaluation.

Table 4.5 Results for normal and abnormal states for IEEE 30-Bus system

States	Load Curtailed	State Probability	State Frequency	ELC (MW)	EENS (MWh)	EDLC (hours)
Normal	76.6	0.025681	5.808357	444.9201	17232.61	224.9689
Outage line 6,7,5,15,19,21	251.45	7.52E-07	0.000596	0.149779	1.656268	0.006587
Outage line 6,7,18,15,19,21	82.34	0.025681	5.808357	478.2601	18523.94	224.9689
Outage line 6,7,1,15,19,21	32.12	0.833232	31.24621	1003.628	234447.6	7299.115

Case-II Delhi Power System

The Delhi Power system is used for the evaluation of reliability by analytical approaches. The system consists of four generating stations with 135 MW Rajghat Power Station, 270 MW Gas Turbine Power station, 330 MW Pragati Power Station and 705 MW Badarpur Thermal Power Station. Load duration curve for April 2012 is given in Delhi Transco Limited - State Load Dispatch Centre, Progress Report. The capacity outage probability table (COPT) is shown in the Table 4.2, have total 151 states with corresponding state probabilities and state frequencies.

Table 4.6 Results for maximum load curtailed state in Delhi, 2012

Month	Load Curtailed (MW)	State Probability	State Frequency	ELC (MW)	EENS (MWh)	EDLC (hours)
January	556	0.000766	0.160961	89.4942	306.8372	0.551866
February	201	0.087323	6.549215	1316.392	12637.37	62.87246
March	225	0.027229	2.64121	594.2723	4411.093	19.60486
April	621	0.000766	0.160961	99.95665	342.7085	0.551866
May	916	6.92E-05	0.020827	19.07783	45.63468	0.04982
June	406	0.008491	1.010372	410.2112	2481.95	6.113177
July	499	0.008491	1.010372	504.1758	3050.476	6.113177
August	417	0.008491	1.010372	421.3253	2549.195	6.113177
September	355	0.027229	2.64121	937.6296	6959.725	19.60486
October	334	0.027229	2.64121	882.1642	6548.023	19.60486
November	380	0.027229	2.64121	1003.66	7449.847	19.60486
December	508	0.008491	1.010372	513.2692	3105.494	6.113177
Total				6791.628	49888.348	166.898

Hence, for 2012

Total ELC = 6791.628 MW

Total EENS = 49888.348 MWh

Total EDLC = 166.898 hrs

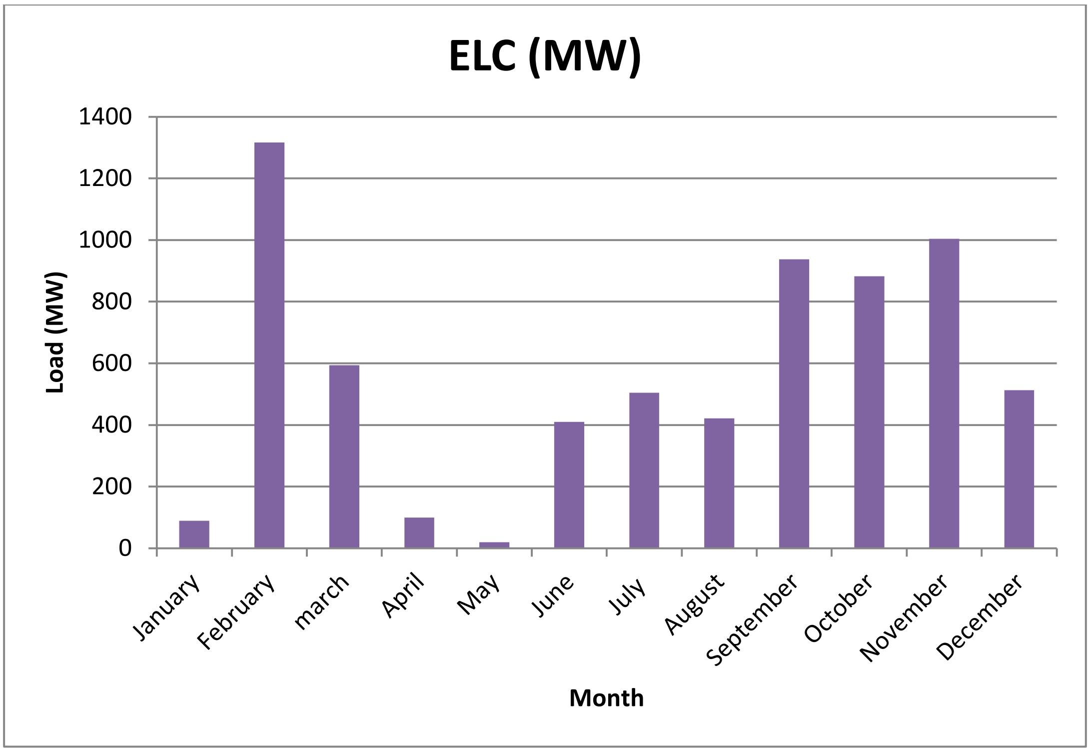

Figure 4.5(a) Expected Load Curtailment (MW) for Delhi-2012

The results for Delhi Power System in 2012 are shown as in Figure 4.5. Expected Load Curtailed (ELD) in MW is shown in Figure 4.5(a), Expected Energy Not Supplied (EENS) in MWh is shown in Figure 4.5(b) and Expected Duration of Load Curtailment (EDLC) in hours is shown in Figure 4.5(c).

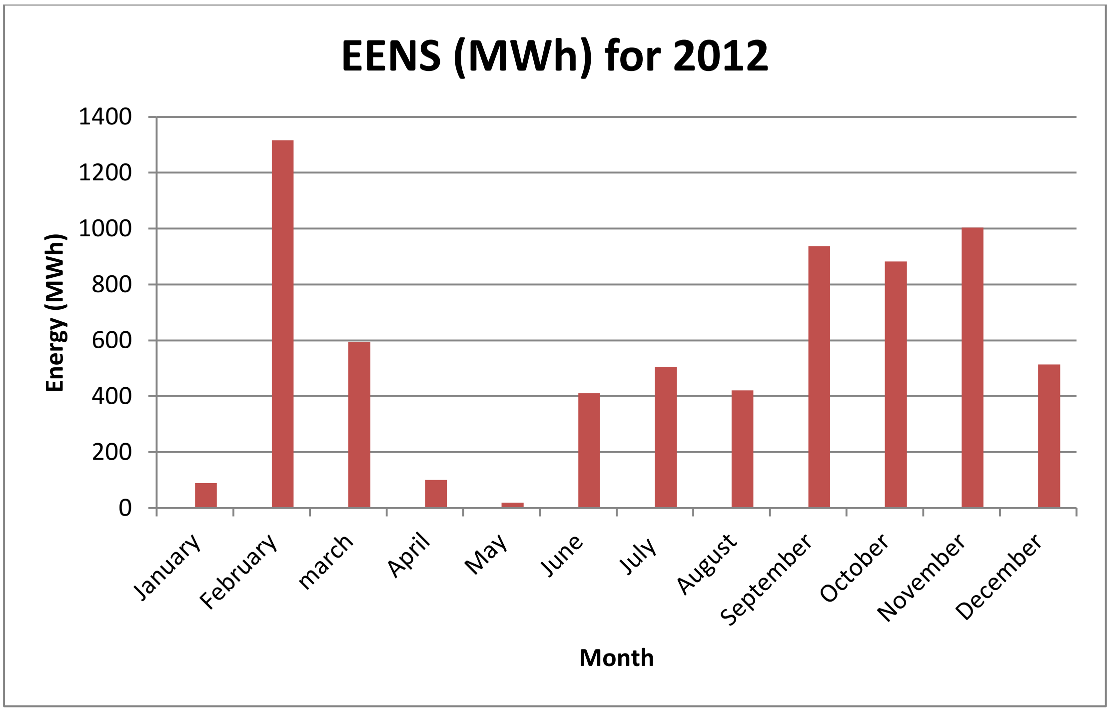

Figure 4.5(b) Expected Energy Not Supplied (MW) for Delhi-2012

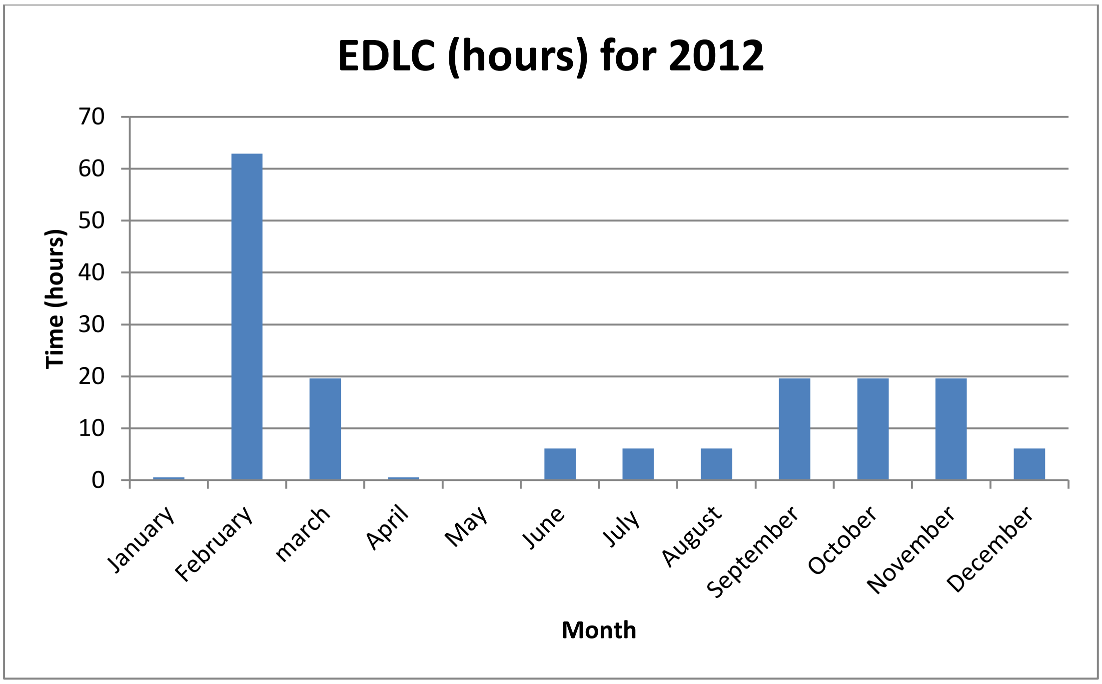

Figure 4.5(c) Expected Duration of Load Curtailment (hours) for Delhi-2012

4.3.3 Short-term and Long-term Reliability Evaluation

Long term reliability analysis is based on steady state probability values of the component. Load conditions in the system change continuously and may be considered on hourly basis for calculations. The time-dependent state probability of a component should be used to evaluate the real-time reliability of power system. The value of the time-dependent state probability of a component in a short-term reliability study depends on time in which the system operating condition changes from one level to another. Short-term probability associated with the current operating state using the time-dependent state probability of a component is implemented on IEEE 30-bus System and Delhi Power System. To achieve high accuracy and to save computation time, number of credible states are required to evaluate short time reliability. The fast sorting technique is used to select the required number of system states in descending order probability with a minimum number of computations and comparisons

4.3.3.1 Algorithm for Fast Sorting Technique (FST)

The fast sorting technique (FST) is implemented to arrange the possible system states based on their probabilities. The objective is to determine the first *k* system states S_1, S_2..., S_k in descending order of probability from all levels without searching all system states. The procedure for sorting all-level states [37] is as follows:

Step 1 Let k = 1, determine the first system state $S_1 = S_{0,1}$.

Step 2 Given $S_k = S_{i_k,m_k}$, determine S_{i_k,m_k+1} applying level-i_k state sorting algorithm if required.

Step 3 Determine $S_{i_k+1,1}$, applying level-(i_k + 1) state sorting algorithm if required.

Step 4 Determine neighbourhood D_k using Equation (4.1)

$$D_k = \begin{cases} \{S_{1,1}\}, k = 1 \\ D_{k-1} \cup \{S_{i_k, m_k+1}\} - \{S_{i_k, m_k}\}, k > 1, and \quad m_k \neq 2 \\ D_{k-1} \cup \{S_{i_k, m_k+1}\} \cup \{S_{i_k+1,1}\} - \{S_{i_k, m_k}\}, k > 1, m_k <_n C_{i_k} \quad and \quad m_k \neq 2 \\ D_{k-1} - \{S_{i_k, m_k}\}, k > 1, and \quad m_k =_n C_{i_k} \end{cases} \quad (4.1)$$

Step 5 Determine S_{k+1}, which is the state with the largest probability in neighbourhood D_k.

Step 6 Let $k = k + 1$ and go to step 2 if k is smaller than the required number. Stop otherwise.

where S_{i_k, m_k} is the m_k states for level i_k,

D_k is the neighbouring states, and

S_{k+1} is the state with the largest probability in neighbourhood D_k.

Case-I: FST on IEEE 30-bus System

Table 4.7 All-level state sorting procedure using FST for IEEE 30-bus System

State Sequence	State Level,	Probability
S_1	$S_{0,1}$	8.3323E-01
S_2 = S(4)	$S_{1,1}$	2.5681E-02
S_3 = S(3)	$S_{1,2}$	2.5681E-02
S_4 = S(2)	$S_{1,3}$	2.5681E-02
S_5 = S(1)	$S_{1,4}$	2.5681E-02
S_6 = S(7)	$S_{1,5}$	1.7121E-02
S_7 = S(6)	$S_{1,6}$	1.7121E-02
S_8 = S(5)	$S_{1,7}$	1.7121E-02
S_9 = S(3,4)	$S_{2,1}$	7.9154E-04
S_{10} = S(2,4)	$S_{2,2}$	7.9154E-04
S_{11} = S(2,3)	$S_{2,3}$	7.9154E-04
S_{12} = S(1,4)	$S_{2,4}$	7.9154E-04
S_{13} = S(1,3)	$S_{2,5}$	7.9154E-04
S_{14} = S(1,2)	$S_{2,6}$	7.9154E-04
S_{15} = S(4,7)	$S_{2,7}$	5.2770E-04
S_{16} = S(4,6)	$S_{2,8}$	5.2770E-04
S_{17} = S(4,5)	$S_{2,9}$	5.2770E-04
S_{18} = S(3,7)	$S_{2,10}$	5.2770E-04
S_{19} = S(3,6)	$S_{2,11}$	5.2770E-04
S_{20} = S(3,5)	$S_{2,12}$	5.2770E-04
S_{21} = S(2,7)	$S_{2,13}$	5.2770E-04
S_{22} = S(2,6)	$S_{2,14}$	5.2770E-04
S_{23}= S(2,5)	$S_{2,15}$	5.2770E-04
S_{24} = S(1,7)	$S_{2,16}$	5.2770E-04
S_{25} = S(1,6)	$S_{2,17}$	5.2770E-04
S_{26} = S(1,5)	$S_{2,18}$	5.2770E-04
S_{27} = S(6,7)	$S_{2,19}$	3.5181E-04
S_{28} = S(5,7)	$S_{2,20}$	3.5181E-04

$S_{29} = S(5,6)$	$S_{2,21}$	3.5181E-04
$S_{30} = S(2,3,4)$	$S_{3,1}$	2.4396E-05
$S_{31} = S(1,3,4)$	$S_{3,2}$	2.4396E-05
$S_{32} = S(1,2,4)$	$S_{3,3}$	2.4396E-05
$S_{33} = S(1,2,3)$	$S_{3,4}$	2.4396E-05
$S_{34} = S(3,4,7)$	$S_{3,5}$	1.6264E-05
$S_{35} = S(3,4,6)$	$S_{3,6}$	1.6264E-05
$S_{36} = S(3,4,5)$	$S_{3,7}$	1.6264E-05
$S_{37} = S(2,4,7)$	$S_{3,8}$	1.6264E-05
$S_{38} = S(2,4,6)$	$S_{3,9}$	1.6264E-05
$S_{39} = S(2,4,5)$	$S_{3,10}$	1.6264E-05
$S_{40} = S(2,3,7)$	$S_{3,11}$	1.6264E-05
$S_{41} = S(2,3,6)$	$S_{3,12}$	1.6264E-05
$S_{42} = S(2,3,5)$	$S_{3,13}$	1.6264E-05
$S_{43} = S(1,4,7)$	$S_{3,14}$	1.6264E-05
$S_{44} = S(1,4,6)$	$S_{3,15}$	1.6264E-05
$S_{45} = S(1,4,5)$	$S_{3,16}$	1.6264E-05
$S_{46} = S(1,3,7)$	$S_{3,17}$	1.6264E-05
$S_{47} = S(1,3,6)$	$S_{3,18}$	1.6264E-05
$S_{48} = S(1,3,5)$	$S_{3,19}$	1.6264E-05
$S_{49} = S(1,2,7)$	$S_{3,20}$	1.6264E-05
$S_{50} = S(1,2,6)$	$S_{3,21}$	1.6264E-05
$S_{51} = S(1,2,5)$	$S_{3,2}$	1.6264E-05
$S_{52} = S(4,6,7)$	$S_{3,23}$	1.0843E-05
$S_{53} = S(4,5,7)$	$S_{3,24}$	1.0843E-05
$S_{54} = S(4,5,6)$	$S_{3,25}$	1.0843E-05
$S_{55} = S(3,6,7)$	$S_{3,26}$	1.0843E-05
$S_{56} = S(3,5,7)$	$S_{3,27}$	1.0843E-05
$S_{57} = S(3,5,6)$	$S_{3,28}$	1.0843E-05
$S_{58} = S(2,6,7)$	$S_{3,29}$	1.0843E-05
$S_{59} = S(2,5,7)$	$S_{3,30}$	1.0843E-05
$S_{60} = S(2,5,6)$	$S_{3,31}$	1.0843E-05
$S_{61} = S(1,6,7)$	$S_{3,32}$	1.0843E-05
$S_{62} = S(1,5,7)$	$S_{3,33}$	1.0843E-05
$S_{63} = S(1,5,6)$	$S_{3,34}$	1.0843E-05
$S_{64} = S(5,6,7)$	$S_{3,35}$	7.2289E-06
$S_{65} = S(1,2,3,4)$	$S_{4,1}$	7.5193E-07
$S_{66} = S(2,3,4,7)$	$S_{4,2}$	5.0129E-07
$S_{67} = S(2,3,4,6)$	$S_{4,3}$	5.0129E-07
$S_{68} = S(2,3,4,5)$	$S_{4,4}$	5.0129E-07
$S_{69} = S(1,3,4,7)$	$S_{4,5}$	5.0129E-07
$S_{70} = S(1,3,4,6)$	$S_{4,6}$	5.0129E-07
$S_{71} = S(1,3,4,5)$	$S_{4,7}$	5.0129E-07
$S_{72} = S(1,2,4,7)$	$S_{4,8}$	5.0129E-07

S_{73} = S(1,2,4,6)	$S_{4,9}$	5.0129E-07
S_{74} = S(1,2,4,5)	$S_{4,10}$	5.0129E-07
S_{75} = S(1,2,3,7)	$S_{4,11}$	5.0129E-07
S_{76} = S(1,2,3,6)	$S_{4,12}$	5.0129E-07
S_{77} = S(1,2,3,5)	$S_{4,13}$	5.0129E-07
S_{78} = S(3,4,6,7)	$S_{4,14}$	3.3420E-07
S_{79} = S(3,4,5,7)	$S_{4,15}$	3.3420E-07
S_{80} = S(3,4,5,6)	$S_{4,16}$	3.3420E-07
S_{81} = S(2,4,6,7)	$S_{4,17}$	3.3420E-07
S_{82} = S(2,4,5,7)	$S_{4,18}$	3.3420E-07
S_{83} = S(2,4,5,6)	$S_{4,19}$	3.3420E-07
S_{84} = S(2,4,6,7)	$S_{4,20}$	3.3420E-07
S_{85} = S(2,4,5,7)	$S_{4,21}$	3.3420E-07
S_{86} = S(2,4,5,6)	$S_{4,22}$	3.3420E-07
S_{87} = S(1,4,6,7)	$S_{4,23}$	3.3420E-07
S_{88} = S(1,4,5,7)	$S_{4,24}$	3.3420E-07
S_{89} = S(1,4,5,6)	$S_{4,25}$	3.3420E-07
S_{90} = S(1,3,6,7)	$S_{4,26}$	3.3420E-07
S_{91} = S(1,3,5,7)	$S_{4,27}$	3.3420E-07
S_{92} = S(1,3,5,6)	$S_{4,28}$	3.3420E-07
S_{93} = S(1,2,6,7)	$S_{4,29}$	3.3420E-07
S_{94} = S(1,2,5,7)	$S_{4,30}$	3.3420E-07
S_{95} = S(1,2,5,6)	$S_{4,31}$	3.3420E-07
S_{96} = S(4,5,6,7)	$S_{4,32}$	2.2280E-07
S_{97} = S(3,5,6,7)	$S_{4,33}$	2.2280E-07
S_{98} = S(2,5,6,7)	$S_{4,34}$	2.2280E-07
S_{99} = S(1,5,6,7)	$S_{4,35}$	2.2280E-07
S_{100} = S(1,2,3,4,7)	$S_{5,1}$	1.5451E-08
S_{101} = S(1,2,3,4,6)	$S_{5,2}$	1.5451E-08
S_{102} = S(1,2,3,4,5)	$S_{5,3}$	1.5451E-08
S_{103} = S(2,3,4,6,7)	$S_{5,4}$	1.0301E-08
S_{104} = S(2,3,4,5,7)	$S_{5,5}$	1.0301E-08
S_{105} = S(2,3,4,5,6)	$S_{5,6}$	1.0301E-08
S_{106} = S(1,3,4,6,7)	$S_{5,7}$	1.0301E-08
S_{107} = S(1,3,4,5,7)	$S_{5,8}$	1.0301E-08
S_{108} = S(1,3,4,5,6)	$S_{5,9}$	1.0301E-08
S_{109} = S(1,2,4,6,7)	$S_{5,10}$	1.0301E-08
S_{110} = S(1,2,4,5,7)	$S_{5,11}$	1.0301E-08
S_{111} = S(1,2,4,5,6)	$S_{5,12}$	1.0301E-08
S_{112} = S(1,2,3,6,7)	$S_{5,13}$	1.0301E-08
S_{113} = S(1,2,3,5,7)	$S_{5,14}$	1.0301E-08
S_{114} = S(1,2,3,5,6)	$S_{5,15}$	1.0301E-08
S_{115} = S(3,4,5,6,7)	$S_{5,16}$	6.8671E-09
S_{116} = S(2,4,5,6,7)	$S_{5,17}$	6.8671E-09

S_{117} = S(2,3,5,6,7)	$S_{5,18}$	6.8671E-09
S_{118} = S(1,4,5,6,7)	$S_{5,19}$	6.8671E-09
S_{119} = S(1,3,5,6,7)	$S_{5,20}$	6.8671E-09
S_{120} = S(1,2,5,6,7)	$S_{5,21}$	6.8671E-09
S_{121} = S(1,2,3,4,6,7)	$S_{6,1}$	3.1748E-10
S_{122} = S(1,2,3,4,5,7)	$S_{6,2}$	3.1748E-10
S_{123} = S(1,2,3,4,5,6)	$S_{6,3}$	3.1748E-10
S_{124} = S(2,3,4,5,6,7)	$S_{6,4}$	2.1165E-10
S_{125} = S(1,3,4,5,6,7)	$S_{6,5}$	2.1165E-10
S_{126} = S(1,2,4,5,6,7)	$S_{6,6}$	2.1165E-10
S_{127} = S(1,2,3,5,6,7)	$S_{6,7}$	2.1165E-10
S_{128} = S(1,2,3,4,5,6,7)	$S_{7,1}$	6.5235E-12

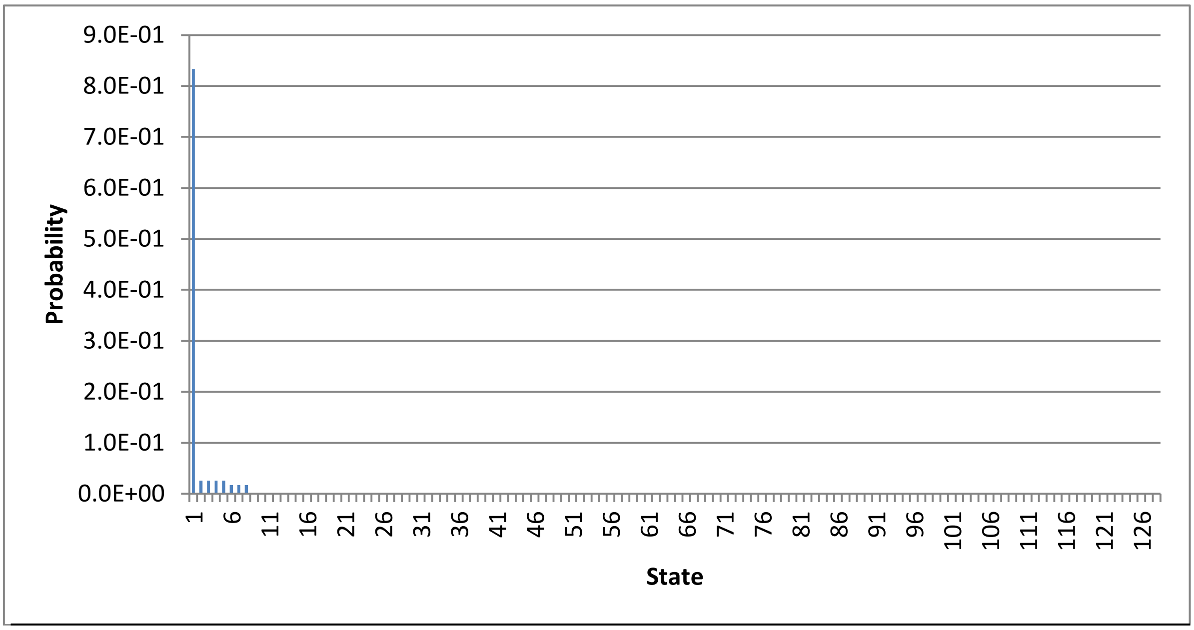

Figure 4.6: State Probability Distribution - IEEE 30 bus System

Case-II: FST on Delhi Power System

Table 4.8: All-level state sorting procedure using FST for Delhi Power System

State Sequence	Capacity Available (MW)	Probability
$S_0 = S_{0,1}$	1440	2.9037E-01
S_1 = S(3)	1350	9.0543E-02
S_2 = S(2)	1260	9.0543E-02
S_3 = S(1)	1305	8.7323E-02
S_4 = S(2,3)	1170	2.8233E-02
S_5 = S(1,3)	1215	2.7229E-02
S_6 = S(1,2)	1125	2.7229E-02
S_7 = S(5)	1318	2.6213E-02
S_8 = S(4)	1232	2.6213E-02
S_9 = S(8)	1230	2.6075E-02
S_{10} = S(7)	1230	2.6075E-02

S_{11} = S(6)	1155	2.6075E-02
S_{12} = S(1,2,3)	1035	8.4905E-03
S_{13} = S(3,5)	1228	8.1738E-03
S_{14} = S(3,4)	1142	8.1738E-03
S_{15} = S(2,5)	1138	8.1738E-03
S_{16} = S(2,4)	1052	8.1738E-03
S_{17} = S(3,8)	1140	8.1308E-03
S_{18} = S(3,7)	1140	8.1308E-03
S_{19} = S(3,6)	1065	8.1308E-03
S_{20} = S(2,8)	1050	8.1308E-03
S_{21} = S(2,7)	1050	8.1308E-03
S_{22} = S(2,6)	975	8.1308E-03
S_{23} = S(1,5)	1183	7.8831E-03
S_{24} = S(1,4)	1097	7.8831E-03
S_{25} = S(1,8)	1095	7.8415E-03
S_{26} = S(1,7)	1095	7.8415E-03
S_{27} = S(1,6)	1020	7.8415E-03
S_{28} = S(2,3,5)	1048	2.5487E-03
S_{29} = S(2,3,4)	962	2.5487E-03
S_{30} = S(2,3,8)	960	2.5353E-03
S_{31} = S(2,3,7)	960	2.5353E-03
S_{32} = S(2,3,6)	885	2.5353E-03
S_{33} = S(1,3,5)	1093	2.4581E-03
S_{34} = S(1,3,4)	1007	2.4581E-03
S_{35} = S(1,2,5)	1003	2.4581E-03
S_{36} = S(1,2,4)	917	2.4581E-03
S_{37} = S(1,3,5)	1005	2.4451E-03
S_{38} = S(1,3,7)	1005	2.4451E-03
S_{39} = S(1,3,6)	930	2.4451E-03
S_{40} = S(1,2,8)	915	2.4451E-03
S_{41} = S(1,2,7)	915	2.4451E-03
S_{42} = S(1,2,6)	840	2.4451E-03
S_{43} = S(4,5)	1110	2.3664E-03
S_{44} = S(5,8)	1108	2.3539E-03
S_{45} = S(5,7)	1108	2.3539E-03
S_{46} = S(5,6)	1033	2.3539E-03
S_{47} = S(4,8)	1022	2.3539E-03
S_{48} = S(4,7)	1022	2.3539E-03
S_{49} = S(4,6)	947	2.3539E-03
S_{50} = S(7,8)	1020	2.3415E-03
S_{51} = S(6,8)	945	2.3415E-03
S_{52} = S(6,7)	945	2.3415E-03
S_{53} = S(1,2,3,5)	913	7.6648E-04
S_{54} = S(1,2,3,4)	827	7.6648E-04

S_{55} = S(1,2,3,8)	825	7.6244E-04
S_{56} = S(1,2,3,7)	825	7.6244E-04
S_{57} = S(1,2,3,6)	750	7.6244E-04
S_{58} = S(3,4,5)	1020	7.3789E-04
S_{59} = S(2,4,5)	930	7.3789E-04
S_{60} = S(3,5,8)	1018	7.3400E-04
S_{61} = S(3,5,7)	1018	7.3400E-04
S_{62} = S(3,5,6)	943	7.3400E-04
S_{63} = S(3,4,8)	932	7.3400E-04
S_{64} = S(3,4,7)	932	7.3400E-04
S_{65} = S(3,4,6)	857	7.3400E-04
S_{66} = S(2,5,8)	928	7.3400E-04
S_{67} = S(2,5,7)	928	7.3400E-04
S_{68} = S(2,5,6)	853	7.3400E-04
S_{69} = S(2,4,8)	842	7.3400E-04
S_{70} = S(2,4,7)	842	7.3400E-04
S_{71} = S(2,4,6)	767	7.3400E-04
S_{72} = S(3,7,8)	930	7.3014E-04
S_{73} = S(3,6,8)	855	7.3014E-04
S_{74} = S(3,6,7)	855	7.3014E-04
S_{75} = S(2,7,8)	840	7.3014E-04
S_{76} = S(2,6,8)	765	7.3014E-04
S_{77} = S(2,6,7)	765	7.3014E-04
S_{78} = S(1,4,5)	975	7.1164E-04
S_{79} = S(1,5,8)	973	7.0789E-04
S_{80} = S(1,5,7)	973	7.0789E-04
S_{81} = S(1,5,6)	898	7.0789E-04
S_{82} = S(1,4,8)	887	7.0789E-04
S_{83} = S(1,4,7)	887	7.0789E-04
S_{84} = S(1,4,6)	812	7.0789E-04
S_{85} = S(1,7,8)	885	7.0417E-04
S_{86} = S(1,6,8)	810	7.0417E-04
S_{87} = S(1,6,7)	810	7.0417E-04
S_{88} = S(2,3,4,5)	840	2.3009E-04
S_{89} = S(2,3,5,8)	838	2.2888E-04
S_{90} = S(2,3,5,7)	838	2.2888E-04
S_{91} = S(2,3,5,6)	763	2.2888E-04
S_{92} = S(2,3,4,8)	752	2.2888E-04
S_{93} = S(2,3,4,7)	752	2.2888E-04
S_{94} = S(2,3,4,6)	677	2.2888E-04
S_{95} = S(2,3,7,8)	750	2.2767E-04
S_{96} = S(2,3,6,8)	675	2.2767E-04
S_{97} = S(2,3,6,7)	675	2.2767E-04
S_{98} = S(1,3,4,5)	885	2.2190E-04

S_{99} = S(1,2,4,5)	795	2.2190E-04
S_{100} = S(1,3,5,8)	883	2.2074E-04
S_{101} = S(1,3,5,7)	883	2.2074E-04
S_{102} = S(1,3,5,6)	808	2.2074E-04
S_{103} = S(1,3,4,8)	797	2.2074E-04
S_{104} = S(1,3,4,7)	797	2.2074E-04
S_{105} = S(1,3,4,6)	722	2.2074E-04
S_{106} = S(1,2,5,8)	793	2.2074E-04
S_{107} = S(1,2,5,7)	793	2.2074E-04
S_{108} = S(1,2,5,6)	718	2.2074E-04
S_{109} = S(1,2,4,8)	707	2.2074E-04
S_{110} = S(1,2,4,7)	707	2.2074E-04
S_{111} = S(1,2,4,6)	632	2.2074E-04
S_{112} = S(1,3,7,8)	795	2.1957E-04
S_{113} = S(1,3,6,8)	720	2.1957E-04
S_{114} = S(1,3,6,7)	720	2.1957E-04
S_{115} = S(1,2,7,8)	705	2.1957E-04
S_{116} = S(1,2,6,8)	630	2.1957E-04
S_{117} = S(1,2,6,7)	630	2.1957E-04
S_{118} = S(4,5,8)	900	2.1250E-04
S_{119} = S(4,5,7)	900	2.1250E-04
S_{120} = S(4,5,6)	825	2.1250E-04
S_{121} = S(5,7,8)	898	2.1138E-04
S_{120} = S(5,6,8)	823	2.1138E-04
S_{121} = S(5,6,7)	823	2.1138E-04
S_{122} = S(4,7,8)	812	2.1138E-04
S_{123}= S(4,6,8)	737	2.1138E-04
S_{124} = S(4,6,7)	737	2.1138E-04
S_{125} = S(6,7,8)	735	2.1027E-04
S_{126} = S(1,2,3,4,5)	705	6.9194E-05
S_{127} = S(1,2,3,5,8)	703	6.8830E-05
S_{128} = S(1,2,3,5,7)	703	6.8830E-05
S_{129} = S(1,2,3,5,6)	628	6.8830E-05
S_{130} = S(1,2,3,4,8)	617	6.8830E-05
S_{131} = S(1,2,3,4,7)	617	6.8830E-05
S_{132} = S(1,2,3,4,6)	542	6.8830E-05
S_{133} = S(1,2,3,7,8)	615	6.8467E-05
S_{134} = S(1,2,3,6,8)	540	6.8467E-05
S_{135} = S(1,2,3,7,8)	540	6.8467E-05
S_{136} = S(3,4,5,8)	810	6.6262E-05
S_{137} = S(3,4,5,7)	810	6.6262E-05
S_{138} = S(3,4,5,6)	735	6.6262E-05
S_{139} = S(2,4,5,8)	720	6.6262E-05
S_{140} = S(2,4,5,7)	720	6.6262E-05

S_{141} = S(2,4,5,6)	645	6.6262E-05
S_{142} = S(3,5,7,8)	808	6.5913E-05
S_{143} = S(3,5,6,8)	733	6.5913E-05
S_{144} = S(3,5,6,7)	733	6.5913E-05
S_{145} = S(3,4,7,8)	722	6.5913E-05
S_{146} = S(3,4,6,8)	647	6.5913E-05
S_{147} = S(3,4,6,7)	647	6.5913E-05
S_{148} = S(2,5,7,8)	718	6.5913E-05
S_{149} = S(2,5,6,8)	643	6.5913E-05
S_{150} = S(2,5,6,7)	643	6.5913E-05
S_{151} = S(2,4,7,8)	632	6.5913E-05
S_{152} = S(2,4,6,8)	557	6.5913E-05
S_{153} = S(2,4,6,7)	557	6.5913E-05
S_{154} = S(3,6,7,8)	645	6.5566E-05
S_{155} = S(2,6,7,8)	555	6.5566E-05
S_{156} = S(1,4,5,8)	765	6.3905E-05
S_{157} = S(1,4,5,7)	765	6.3905E-05
S_{158} = S(1,4,5,6)	690	6.3905E-05
S_{159} = S(1,5,7,8)	763	6.3568E-05
S_{160} = S(1,5,6,8)	688	6.3568E-05
S_{163} = S(1,5,6,7)	688	6.3568E-05
S_{164} = S(1,4,7,8)	677	6.3568E-05
S_{165} = S(1,4,6,8)	602	6.3568E-05
S_{166} = S(1,4,6,7)	602	6.3568E-05
S_{167} = S(1,6,7,8)	600	6.3234E-05
S_{168} = S(2,3,4,5,8)	630	2.0662E-05
S_{169} = S(2,3,4,5,7)	630	2.0662E-05
S_{170} = S(2,3,4,5,6)	555	2.0662E-05
S_{171} = S(2,3,5,7,8)	628	2.0553E-05
S_{172} = S(2,3,5,6,8)	553	2.0553E-05
S_{173} = S(2,3,5,6,7)	553	2.0553E-05
S_{174} = S(2,3,4,7,8)	542	2.0553E-05
S_{175} = S(2,3,4,6,8)	467	2.0553E-05
S_{176} = S(2,3,4,6,7)	467	2.0553E-05
S_{177} = S(2,3,6,7,8)	465	2.0445E-05
S_{178} = S(1,3,4,5,8)	675	1.9927E-05
S_{179} = S(1,3,4,5,7)	675	1.9927E-05
S_{180} = S(1,3,4,5,6)	600	1.9927E-05
S_{181} = S(1,2,4,5,8)	585	1.9927E-05
S_{182} = S(1,2,4,5,7)	585	1.9927E-05
S_{183} = S(1,2,4,5,6)	510	1.9927E-05
S_{184} = S(1,3,5,7,8)	673	1.9822E-05
S_{185} = S(1,3,5,6,8)	598	1.9822E-05
S_{186} = S(1,3,5,6,7)	598	1.9822E-05

S_{187} = S(1,3,4,7,8)	587	1.9822E-05
S_{188} = S(1,3,4,6,8)	512	1.9822E-05
S_{189} = S(1,3,4,6,7)	512	1.9822E-05
S_{190} = S(1,2,5,7,8)	583	1.9822E-05
S_{191} = S(1,2,5,6,8)	508	1.9822E-05
S_{192} = S(1,2,5,6,7)	508	1.9822E-05
S_{193} = S(1,2,4,7,8)	497	1.9822E-05
S_{194} = S(1,2,4,6,8)	422	1.9822E-05
S_{195} = S(1,2,4,6,7)	422	1.9822E-05
S_{196} = S(1,3,6,7,8)	510	1.9718E-05
S_{197} = S(1,2,6,7,8)	420	1.9718E-05
S_{198} = S(4,5,7,8)	690	1.9082E-05
S_{199} = S(4,5,6,8)	615	1.9082E-05
S_{200} = S(4,5,6,7)	615	1.9082E-05
S_{201} = S(5,6,7,8)	613	1.8982E-05
S_{202} = S(4,6,7,8)	527	1.8982E-05
S_{203} = S(1,2,3,4,5,8)	495	6.2136E-06
S_{204} = S(1,2,3,4,5,7)	495	6.2136E-06
S_{205} = S(1,2,3,4,5,6)	420	6.2136E-06
S_{206} = S(1,2,3,5,7,8)	493	6.1809E-06
S_{207} = S(1,2,3,5,6,8)	418	6.1809E-06
S_{208} = S(1,2,3,5,6,7)	418	6.1809E-06
S_{209} = S(1,2,3,4,7,8)	407	6.1809E-06
S_{210} = S(1,2,3,4,6,8)	332	6.1809E-06
S_{211} = S(1,2,3,4,6,7)	332	6.1809E-06
S_{212} = S(1,2,3,6,7,8)	330	6.1483E-06
S_{213} = S(3,4,5,7,8)	600	5.9503E-06
S_{214} = S(3,4,5,6,8)	525	5.9503E-06
S_{215} = S(3,4,5,6,7)	525	5.9503E-06
S_{216} = S(2,4,5,7,8)	510	5.9503E-06
S_{217} = S(2,4,5,6,8)	435	5.9503E-06
S_{218} = S(2,4,5,6,7)	435	5.9503E-06
S_{219} = S(3,5,6,7,8)	523	5.9189E-06
S_{220} = S(3,4,6,7,8)	437	5.9189E-06
S_{221} = S(2,5,6,7,8)	433	5.9189E-06
S_{222} = S(2,4,6,7,8)	347	5.9189E-06
S_{223} = S(1,4,5,7,8)	555	5.7386E-06
S_{224} = S(1,4,5,6,8)	480	5.7386E-06
S_{225} = S(1,4,5,6,7)	480	5.7386E-06
S_{226} = S(1,5,6,7,8)	478	5.7084E-06
S_{227} = S(1,4,6,7,8)	392	5.7084E-06
S_{228} = S(2,3,4,5,7,8)	420	1.8554E-06
S_{229} = S(2,3,4,5,6,8)	345	1.8554E-06
S_{230} = S(2,3,4,5,6,7)	345	1.8554E-06

S_{231} = S(2,3,5,6,7,8)	343	1.8456E-06
S_{232} = S(2,3,4,6,7,8)	257	1.8456E-06
S_{233} = S(1,3,4,5,7,8)	465	1.7894E-06
S_{234} = S(1,3,4,5,6,8)	390	1.7894E-06
S_{235} = S(1,3,4,5,6,7)	390	1.7894E-06
S_{236} = S(1,2,4,5,7,8)	375	1.7894E-06
S_{237} = S(1,2,4,5,6,8)	300	1.7894E-06
S_{238} = S(1,2,4,5,6,7)	300	1.7894E-06
S_{239} = S(1,3,5,6,7,8)	388	1.7800E-06
S_{240} = S(1,3,4,6,7,8)	302	1.7800E-06
S_{241} = S(1,2,5,6,7,8)	298	1.7800E-06
S_{242} = S(1,2,4,6,7,8)	212	1.7800E-06
S_{243} = S(4,5,6,7,8)	405	1.7136E-06
S_{244} = S(1,2,3,4,5,7,8)	285	5.5797E-07
S_{245} = S(1,2,3,4,5,6,8)	210	5.5797E-07
S_{246} = S(1,2,3,4,5,6,7)	210	5.5797E-07
S_{247} = S(1,2,3,5,6,7,8)	208	5.5504E-07
S_{248} = S(1,2,3,4,6,7,8)	122	5.5504E-07
S_{249} = S(3,4,5,6,7,8)	315	5.3433E-07
S_{250} = S(2,4,5,6,7,8)	225	5.3433E-07
S_{251} = S(1,4,5,6,7,8)	270	5.1533E-07
S_{252} = S(2,3,4,5,6,7,8)	135	1.6662E-07
S_{253} = S(1,3,4,5,6,7,8)	180	1.6069E-07
S_{254} = S(1,2,4,5,6,7,8)	90	1.6069E-07
S_{255} = S(1,2,3,4,5,6,7,8)	0	5.0106E-08

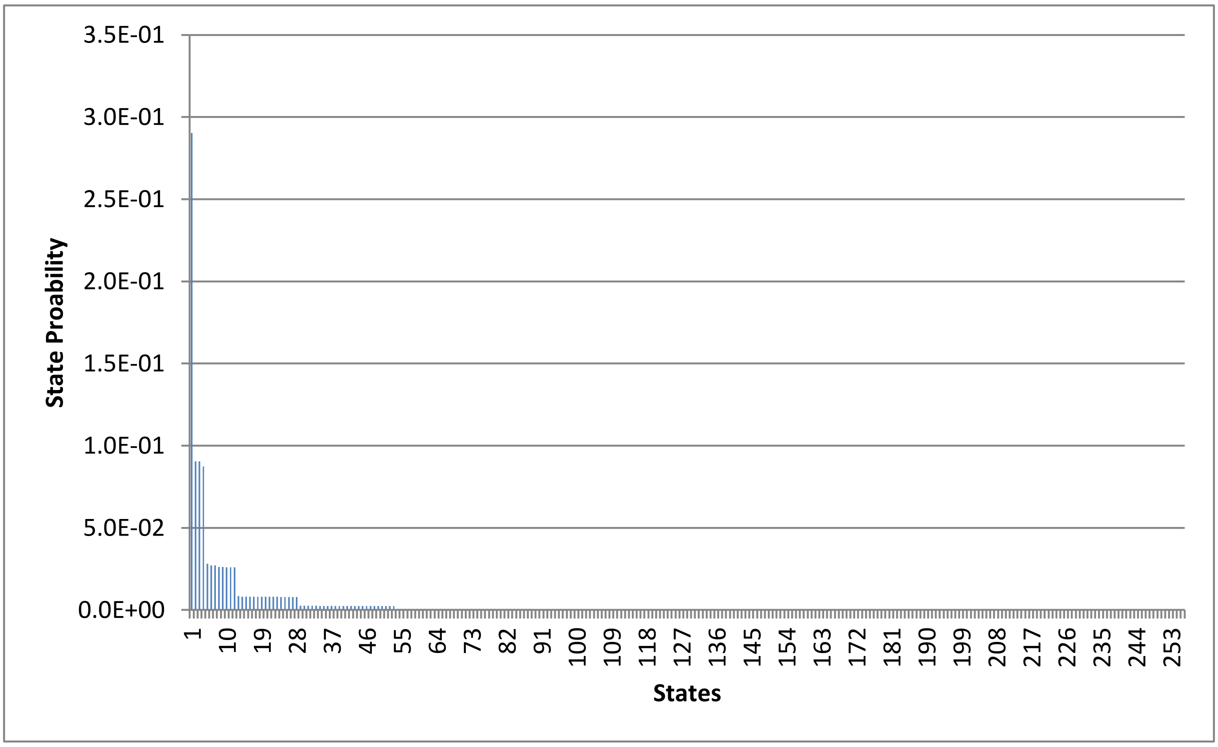

Figure 4.7: Probability Distribution of States - Delhi Power System

4.3.3.2 Comparison between Conventional method and FST for state selection

In conventional method for state selection, first calculate the all states probability then state selection procedure is taken out from the all state. By this procedure, the computational time is more than FST. In case of FST, calculation can be carried out on the bases of the levels, in which the levels are determined from the number of system failure. By knowing the generation capacity outage, we can calculate the level of the failure because the number capacity outage is equal to the level of the failure. In FST, calculation can be done for only that particular level rather than to calculate the all state level by conventional method. So, for calculating the states for that particular level will reduce the computational time by applying FST in place of conventional method.

Table 4.9: Selected State for Level-3system failure for IEEE 30-bus system

State Sequence	State Level, $S_{i,m}$	Probability
S_1 = S(2,3,4)	$S_{3,1}$	2.4396E-05
S_2 = S(1,3,4)	$S_{3,2}$	2.4396E-05
S_3 = S(1,2,4)	$S_{3,3}$	2.4396E-05
S_4 = S(1,2,3)	$S_{3,4}$	2.4396E-05
S_5 = S(3,4,7)	$S_{3,5}$	1.6264E-05
S_6 = S(3,4,6)	$S_{3,6}$	1.6264E-05
S_7 = S(3,4,5)	$S_{3,7}$	1.6264E-05
S_8 = S(2,4,7)	$S_{3,8}$	1.6264E-05
S_9 = S(2,4,6)	$S_{3,9}$	1.6264E-05
S_{10} = S(2,4,5)	$S_{3,10}$	1.6264E-05
S_{11} = S(2,3,7)	$S_{3,11}$	1.6264E-05
S_{12} = S(2,3,6)	$S_{3,12}$	1.6264E-05
S_{13} = S(2,3,5)	$S_{3,13}$	1.6264E-05
S_{14} = S(1,4,7)	$S_{3,14}$	1.6264E-05
S_{15} = S(1,4,6)	$S_{3,15}$	1.6264E-05
S_{16} = S(1,4,5)	$S_{3,16}$	1.6264E-05
S_{17} = S(1,3,7)	$S_{3,17}$	1.6264E-05
S_{18} = S(1,3,6)	$S_{3,18}$	1.6264E-05
S_{19} = S(1,3,5)	$S_{3,19}$	1.6264E-05
S_{20} = S(1,2,7)	$S_{3,20}$	1.6264E-05
S_{21} = S(1,2,6)	$S_{3,21}$	1.6264E-05
S_{22} = S(1,2,5)	$S_{3,2}$	1.6264E-05
S_{23} = S(4,6,7)	$S_{3,23}$	1.0843E-05
S_{24} = S(4,5,7)	$S_{3,24}$	1.0843E-05
S_{25} = S(4,5,6)	$S_{3,25}$	1.0843E-05
S_{26} = S(3,6,7)	$S_{3,26}$	1.0843E-05
S_{27} = S(3,5,7)	$S_{3,27}$	1.0843E-05
S_{28} = S(3,5,6)	$S_{3,28}$	1.0843E-05
S_{29} = S(2,6,7)	$S_{3,29}$	1.0843E-05

S_{30} = S(2,5,7)	$S_{3,30}$	1.0843E-05
S_{31} = S(2,5,6)	$S_{3,31}$	1.0843E-05
S_{32} = S(1,6,7)	$S_{3,32}$	1.0843E-05
S_{33} = S(1,5,7)	$S_{3,33}$	1.0843E-05
S_{34} = S(1,5,6)	$S_{3,34}$	1.0843E-05
S_{35} = S(5,6,7)	$S_{3,35}$	7.2289E-06

In IEEE 30-bus System, for any level of system failure, states calculated by conventional method are 2^7 = 128 whereas states calculated by FST for 3-level system failure is 35 as shown in Table 4.9.

Table 4.10: Selected State for Level-3 system failure for Delhi Power system

State Sequence	State Level, $S_{i,m}$	Probability
S_1 = S(1,2,3)	$S_{3,1}$	8.4905E-03
S_2 = S(2,3,5)	$S_{3,2}$	7.8415E-03
S_3 = S(2,3,4)	$S_{3,3}$	2.5487E-03
S_4 = S(2,3,8)	$S_{3,4}$	2.5353E-03
S_5 = S(2,3,7)	$S_{3,5}$	2.5353E-03
S_{56} = S(2,3,6)	$S_{3,6}$	2.5353E-03
S_7 = S(1,3,5)	$S_{3,7}$	2.4581E-03
S_8 = S(1,3,4)	$S_{3,8}$	2.4581E-03
S_9 = S(1,2,5)	$S_{3,9}$	2.4581E-03
S_{10} = S(1,2,4)	$S_{3,10}$	2.4581E-03
S_{11} = S(1,3,5)	$S_{3,11}$	2.4451E-03
S_{12} = S(1,3,7)	$S_{3,12}$	2.4451E-03
S_{13} = S(1,3,6)	$S_{3,13}$	2.4451E-03
S_{14} = S(1,2,8)	$S_{3,14}$	2.4451E-03
S_{15} = S(1,2,7)	$S_{3,15}$	2.4451E-03
S_{16} = S(1,2,6)	$S_{3,16}$	2.4451E-03
S_{17} = S(3,4,5)	$S_{3,17}$	7.3789E-04
S_{18} = S(2,4,5)	$S_{3,18}$	7.3789E-04
S_{19} = S(3,5,8)	$S_{3,19}$	7.3400E-04
S_{20} = S(3,5,7)	$S_{3,20}$	7.3400E-04
S_{21} = S(3,5,6)	$S_{3,21}$	7.3400E-04
S_{22} = S(3,4,8)	$S_{3,2}$	7.3400E-04
S_{23} = S(3,4,7)	$S_{3,23}$	7.3400E-04
S_{24} = S(3,4,6)	$S_{3,24}$	7.3400E-04
S_{25} = S(2,5,8)	$S_{3,25}$	7.3400E-04
S_{26} = S(2,5,7)	$S_{3,26}$	7.3400E-04
S_{27} = S(2,5,6)	$S_{3,27}$	7.3400E-04
S_{28} = S(2,4,8)	$S_{3,28}$	7.3400E-04
S_{29} = S(2,4,7)	$S_{3,29}$	7.3400E-04
S_{30} = S(2,4,6)	$S_{3,30}$	7.3400E-04
S_{31} = S(3,7,8)	$S_{3,31}$	7.3014E-04

S_{32} = S(3,6,8)	$S_{3,32}$	7.3014E-04
S_{33} = S(3,6,7)	$S_{3,33}$	7.3014E-04
S_{34} = S(2,7,8)	$S_{3,34}$	7.3014E-04
S_{35} = S(2,6,8)	$S_{3,35}$	7.3014E-04
S_{36} = S(2,6,7)	$S_{3,36}$	7.3014E-04
S_{37} = S(1,4,5)	$S_{3,37}$	7.1164E-04
S_{38} = S(1,5,8)	$S_{3,38}$	7.0789E-04
S_{39} = S(1,5,7)	$S_{3,39}$	7.0789E-04
S_{40} = S(1,5,6)	$S_{3,40}$	7.0789E-04
S_{41} = S(1,4,8)	$S_{3,41}$	7.0789E-04
S_{42} = S(1,4,7)	$S_{3,42}$	7.0789E-04
S_{43} = S(1,4,6)	$S_{3,43}$	7.0789E-04
S_{44} = S(1,7,8)	$S_{3,44}$	7.0417E-04
S_{45} = S(1,6,8)	$S_{3,45}$	7.0417E-04
S_{46} = S(1,6,7)	$S_{3,46}$	7.0417E-04
S_{47} = S(4,5,8)	$S_{3,47}$	2.1250E-04
S_{48} = S(4,5,7)	$S_{3,48}$	2.1250E-04
S_{49} = S(4,5,6)	$S_{3,49}$	2.1250E-04
S_{50} = S(5,7,8)	$S_{3,50}$	2.1138E-04
S_{51} = S(5,6,8)	$S_{3,51}$	2.1138E-04
S_{52} = S(5,6,7)	$S_{3,52}$	2.1138E-04
S_{53} = S(4,7,8)	$S_{3,53}$	2.1138E-04
S_{54}= S(4,6,8)	$S_{3,54}$	2.1138E-04
S_{55} = S(4,6,7)	$S_{3,55}$	2.1138E-04
S_{56} = S(6,7,8)	$S_{3,56}$	2.1027E-04

In Delhi Power System, for any level of system failure, states calculated by conventional method are 2^8 = 256 whereas states calculated by FST for 3-level system failure is 55 as shown in Table 4.10.

Table 4.11: Comparison between Conventional Method and FST

Level of System failure	IEEE 30-bus System		Delhi Power System	
	Conventional Method	FST	Conventional Method	FST
0	128	1	256	1
1	128	7	256	8
2	128	21	256	28
3	128	35	256	56
4	128	35	256	70
5	128	21	256	56
6	128	7	256	28
7	128	1	256	8
8	-	-	256	1

Table 4.11 shows the number of the states calculated for each level of system failure by Conventional Method and FST of state selection in IEEE 30-bus System and Delhi Power System. FST has a significantly lower number of states calculated at each level of system failure as compare to the conventional method. For the lower number of states calculation leads to less computational time. Hence, FST is more efficient than old conventional method of state selection.

4.3.3.3 Algorithm for relative accuracy of a Reliability Index

The relative accuracies of PLC, ENLC, EENS and EDLC are calculated using Equation (3.27), (3.27), (3.27) and (3.30) respectively. The evaluation procedure for short-term reliability evaluation using FST is summarised in the following steps:

Step 1: Input reliability and operation data of components and system.

Step 2: Find the real power for the current operating state.

Step 3: Calculate the time-dependent state probabilities of components at time *t*. If *t* is much shorter than the component repair time, the repair process is normally neglected. The repair process should be considered, as *t* is not relatively short.

Step 4: Determine the system state with the largest probability in the remaining states using the FST.

Step 5: Check the network conditions for the selected system state considering spinning reserve units, rapid start units and hot reserve units.

Step 6: Calculate short-term reliability indices.

Step 7: Update the number, total probability of all selected states and relative accuracy of the index.

Step 8: If the stopping rules are reached, output the reliability indices. Otherwise proceed to Step 4.

Case-I: IEEE 30-bus System

Table 4.12, 4.13, 4.14 and 4.15 show the lower and upper bounds of PLC, ENLC, EENS and EDLC, respectively. Table 4.16 shows the short-term reliability indices at different times obtained by using the proposed algorithm.

Table 4.12: Lower and upper bounds of PLC

Duration	$PLC(t)_{Low}$	$PLC(t)_{Up}$	PLC*(t)
15 min	7.22890E-06	0.029627	2.44E-04
1 hr	5.27690E-04	0.066628	7.92E-03
2 hr	3.51800E-04	0.066629	5.28E-03
1 day	2.56814E-02	7.295844	3.52E-03
2 days	1.71212E-02	0.100124	1.71E-01
1 week	9.41174E-02	0.366215	2.57E-01

Table 4.13: Lower and upper bounds of ENLC

Duration	$ENLC(t)_{Low}$	$ENLC(t)_{Up}$	ENLC*(t)	ENLC*(t) (1E+1)
15 min	0.004923	25.40626	1.938E-04	1.938E-05
1 hr	0.007104	1.443081	4.923E-03	4.923E-04
2 hr	0.016412	0.070576	2.325E-01	2.325E-02
1 day	0.431455	2.628939	1.641E-01	1.641E-02
2 days	0.580836	0.134623	4.315	4.315E-01
1 week	3.164117	0.544753	5.808	5.808E-01

Table 4.14: Lower and upper bounds of EENS

Duration	$EENS(t)_{Low}$	$EENS(t)_{Up}$	EENS*(t)	EENS*(t) (1E+2 MWh)
15 min	0.02548542	0.0323871	0.7869	0.007869
1 hr	0.07469852	0.037972	1.9672	0.019672
2 hr	0.14265365	0.0362571	3.9345	0.039345
1 day	1.83659856	0.0389006	47.2126	0.472126
2 days	32.153656	0.3405195	94.4253	0.944253
1 week	143.566695	0.4344075	330.4885	3.304885

Table 4.15: Lower and upper bounds of EDLC

Duration	$EDLC(t)_{Low}$	$EDLC(t)_{Up}$	EDLC*(t) (hours)
15 min	0.000172289	0.0167271	0.0103
1 hr	0.000545277	0.021217	0.0257
2 hr	0.00123518	0.0240307	0.0514
1 day	0.005256814	0.0085283	0.6164
2 days	0.016581211	0.0134511	1.2327
1 week	0.941173595	0.218142	4.3145

Figure 4.8 shows that there are significant differences between the short-term and long-term reliability indices. The real-time reliability evaluation should therefore be based on the time-dependent state probability of a component.

Table 4.16: Relative Accuracies of PLC, ENLC, EENS and EDLC

Duration	PLC*(t)	ENLC*(t) (1E+1)	EENS*(t) (1E+2 MWh)	EDLC*(t) (hours)
15 min	2.44E-04	1.93766E-05	0.007869	0.0103
1 hour	7.92E-03	0.000492287	0.019672	0.0257
2 hours	5.28E-03	0.023254135	0.039345	0.0514
1 day	3.52E-03	0.016411736	0.472126	0.6164
2 days	1.71E-01	0.431454512	0.944253	1.2327
1 week	2.57E-01	0.58083569	3.304885	4.3145

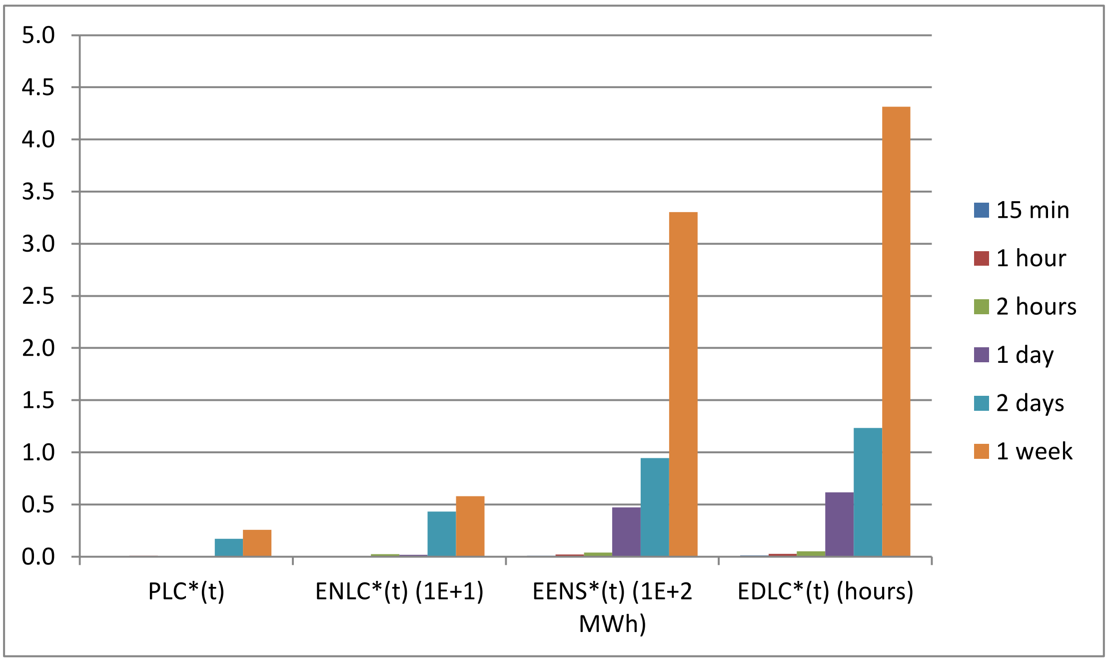

Figure 4.8: Short-term and Long-term Reliability Indices for IEEE-30 bus System

Case-II: Delhi Power System

Table 4.17, 4.18, 4.19 and 4.20 show the lower and upper bounds of PLC, ENLC, EENS and EDLC, respectively. Table 4.21 shows the short-term reliability indices at different times obtained by using the proposed algorithm.

Table 4.17: Lower and upper bounds of PLC

Duration	PLC(t)low	PLC(t)up	PLC*(t)	PLC*(t)(1E-1)
15min	5.95E-06	0.066571	8.94E-05	0.000894
1hr	2.10E-04	0.274332	7.66E-04	0.007665
2hr	6.59E-05	0.500000	1.32E-04	0.001318
1day	2.34E-03	1.595024	1.47E-03	0.01468
2days	8.49E-02	3.118186	2.72E-02	0.27229
7days	2.90E-01	3.206970	9.05E-02	0.905434

Table 4.18: Lower and upper bounds of ENLC

Duration	$ENLC(t)_{Low}$	$ENLC(t)_{Up}$	ENLC*(t)	ENLC*(t) (1E+1)
15min	0.004874	1.701E-01	2.865E-02	0.002865
1hr	0.014686	3.065E-01	4.791E-02	0.004791
2hr	0.138634	8.611E-01	1.610E-01	0.0161
1day	1.656346	4.145E+00	3.996E-01	0.039962
2days	2.946909	1.116E+00	2.641E+00	0.264121
7days	6.549215	8.037E-01	8.149E+00	0.814891

Table 4.19: Lower and upper bounds of EENS

Duration	EENS(t)Low	EENS(t)Up	EENS*(t) (MWh)	EENS*(t) (1E+2 MWh)
15min	0.012568	0.1066893	0.1178	0.001178
1hr	0.08523689	0.1773552	0.4806	0.004806
2hr	0.2563651	0.264185	0.9704	0.009704
1day	4.35656245	0.3392935	12.8401	0.128401
2days	13.32569566	0.5496197	24.2453	0.242453
7days	135.2659325	1.5006538	90.138	0.90138

Table 4.20: Lower and upper bounds of EDLC

Duration	$EDLC(t)_{Low}$	$EDLC(t)_{Up}$	EDLC (hours)
15min	2.36353E-05	1.23E-01	1.92E-04
1hr	8.32659E-05	1.09E-01	7.66E-04
2hr	0.000836563	5.58E-01	1.50E-03
1day	0.035324589	1.92E+00	1.84E-02
2days	0.08562456	2.33E+00	3.68E-02
7days	2.934562472	2.28E+01	1.29E-01

Figure 4.9 shows that there are significant differences between the short-term and long-term reliability indices. The real-time reliability evaluation should therefore be based on the time-dependent state probability of a component.

As short-term reliability indices are for the operational purpose which last from few minutes to few days, hence the short-term reliability indices are calculated at different time say 15 min., 1hr, 2hr, 1 day or 2 days and the long-term reliability indices, for the planning purpose, are calculated at 1 week, for the both IEEE 30-bus System and Delhi Power System by time-dependent state probability.

Table 4.21: Relative Accuracies of PLC, ENLC, EENS and EDLC

Duration	PLC*(t) (1E-1)	ENLC*(t) (1E+1)	EENS*(t) (1E+2 MWh)	EDLC*(t) (hours)
15min	8.94E-04	0.002865	0.001178	1.92E-04
1hr	7.66E-03	0.004791	0.004806	7.66E-04
2hr	1.32E-03	0.0161	0.009704	1.50E-03
1day	1.47E-02	0.039962	0.128401	1.84E-02
2days	2.72E-01	0.264121	0.242453	3.68E-02
7days	9.05E-01	0.814891	0.90138	1.29E-01

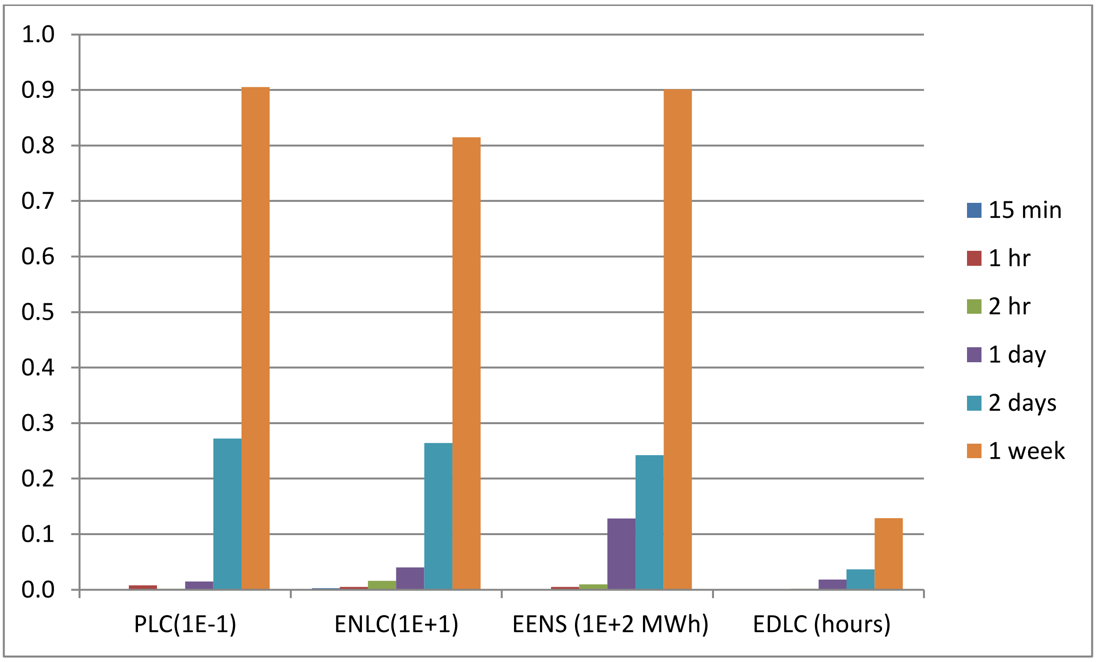

Figure 4.9: Short-term and Long-term Reliability Indices for Delhi Power System

Figures 4.8 and 4.9 show the short-term reliability indices (PLC, ENLC, EENS, and EDLC) are quite low as compared to the long-term reliability indices. Hence, there are significant differences between the short-term and long-term reliability indices.

Chapter 5
Conclusion and Future Scope of Work

5.1 Conclusion

In this dissertation work, the analytical approach through the estimated probability distribution of LOLE and frequency and duration (FAD) approach on generation system of IEEE 30-bus System and Delhi Power System has carried out. From system studies, it can be concluded that:

1. It has established a generation system reliability calculation tool to evaluate conventional generation systems reliability based on the analytical method by probabilistic assessment approach and has proposed an evaluation method to be used for generation capacity adequacy planning for consumer demand in future.

2. LOLE technique and FAD approach have developed based on the steady-state probability of a component and have used for power system planning for many years.

3. The short-term reliability evaluation has performed on IEEE 30-bus System and Delhi Power System and a fast sorting technique (FST) has been developed to reduce the computational time for state selection.

4. The short-term reliability indices at different times obtained by using the FST based algorithm which indicates that the short-term indices increase with time and approach their limiting values, that is, long-term indices obtained by using the steady-state probability of each component.

5.2 Future Scope

This dissertation was started with the intention of providing a means to evaluate the reliability parameters and indices for IEEE 30-bus System and then the Delhi Power System has also been incorporated. Nevertheless, this work has provided a foundation and starting point to the initial idea about the reliability evaluation by analytical approach on any number unit system. Hence, the presented work can be extended in the following area:

1. Development of reliability models for wind, solar and other renewable sources can be integrated into the existing system reliability evaluation methodology has given in this dissertation.
2. As reactive power plays a significant role in power system operation, then reactive power considerations in reliability analysis of a system can be down in future.

Annexure 1

Reliability Models

A1.1 Structure Function

A device or system is described as a collection of parts or components. The system operates successfully if all its components operate successfully, but it may also operate if a subset of components has failed. The structure function is a model that determines the status of the system given the status of its components. We use the structure function to compute the system reliability. The system is a collection of *n* identifiable components performing some function. We define two operating states that relate to the system's ability to perform its function.

a) Success: The system performs its function satisfactorily for a given period of time, where the criterion for success is clearly defined.

b) Failure: The system fails to perform its function satisfactorily.

The system reliability is the probability that a system performs its function satisfactorily (i.e., the probability of success).

To provide a mathematical model of system reliability, we first consider the components. Like the system we also allow two possible states for each component. The success indicator for component *i* is the binary random variable X_i that indicates the status of component *i*

$X_i = 1$ implies component *i* is working

$= 0$ implies component *i* is failed

The status vector is the vector of component status indicators.

$$X = (X_1, X_2, \ldots, X_n) \quad \text{(A1.1)}$$

There are 2^n possible realizations of this vector. The structure function is a binary function that indicates the status of the system (success or failure) given the status of each component.

$$\Phi(X_1, X_2, \ldots, X_n) \text{ or } \phi(X) \quad \text{(A1.2)}$$

is the structure function, which has a value of 1 or 0 for each of the 2*n* possible vectors **X**. The structure function is a complete model of the failure and success characteristics of the system.

Given the structure function of the system, one can compute its reliability. The component reliability, p_i, is the probability that component *i* is operating correctly. The component failure probability, q_i, is the probability that a component has failed. In terms of the success indicators,

$$p_i = P\{X_i = 1\} \quad \text{(A1.3)}$$

$$q_i = P\{X_i = 0\} = 1 - p_i \quad \text{(A1.4)}$$

When the probability of success or failure of a component does not depend on the status of some other component, the components are said to be independent. The assumption of this chapter is that all components are independent.

The probability that the system is operating correctly is the system reliability, R. It is the probability that the structure function is 1.

$$R = P\{(X) = 1\} = E[(X)] \tag{A1.5}$$

A1.2 State Space Approach for Reliability Calculations

Power system components are divided into two main parts, namely, the generating equipment and the transmission equipment. A prediction of reliability is an important element in the process of selecting equipment for use by power system. A system component such as a generator, a transmission line, or a reactive power compensator can be represented using the two-state reliability model. The performance of a component is either represented by a state space model or by a life history diagram representing the different operation and failure duration the component went through. A life history diagram is shown in Figure A1.1 where the successive operation and failure duration are shown.

Often the reliability of a component is given as functions of time. For example, a common assumption is that components have an exponential distribution for time to failure. In this case the component reliability is

$$p(t) = 1 - P(\text{failure time} \;\square\square\; t) = e^{-\lambda t} \tag{A1.6}$$

The parameter is called the failure rate of the component and is given in units of failures per unit time. This distribution for failure time implies that the probability that the component fails in the next small interval of time is independent of how long the component has been working.

One of the advantages of the constant failure rate assumption is obtained with a series system. In this case, the system reliability is

$$\begin{aligned} R(t) &= p_1 p_2 \ldots\ldots p_n = (e^{-\lambda_1 t})(e^{-\lambda_2 t})\ldots\ldots(e^{-\lambda_n t}) \\ &= \exp\left(-\sum_{i=1}^{n} \lambda_i t\right) \end{aligned} \tag{A1.7}$$

The system failure rate is the sum of the component failure rates. Other failure probability distributions are appropriate for other classes of components. In common use is the Weibull distribution that models increasing failure rates with age.

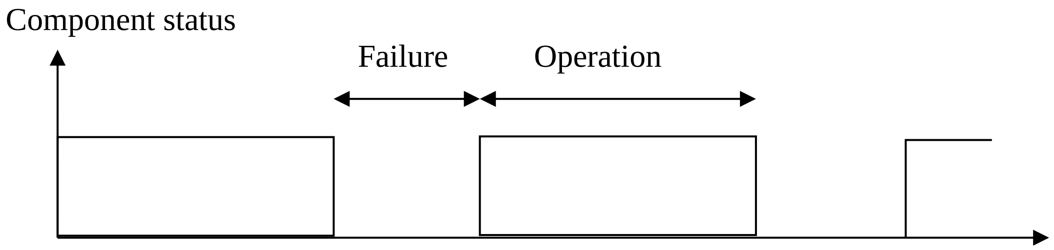

Figure A1.1 Performance chain of a component

The state space representation of a component consists of two or more states. Two states represent operation and failure condition extra states may be included to represent partial operation, queuing for repair etc. A two state model for repairable component is shown in Figure A1.2. The transformation of a component from one state to another is represented by a transition rate indicating, for example, rates of failure or rates of repair.

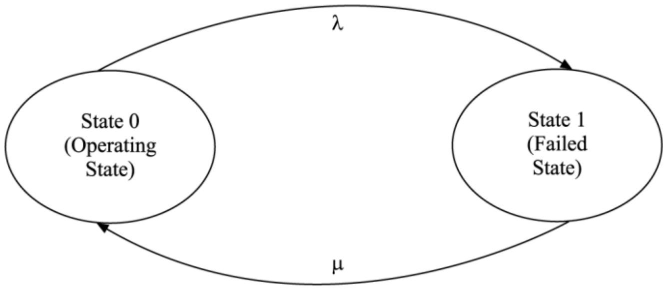

Figure A1.2 A Two-State Space Model of a Component Performance

A1.2.1 Component Failure

Various causes can result in a component suddenly breaking down and entering a forced outage. Therefore, the continuous working time T of a component is a random variable, the probability characteristics of which can be described by the distribution function:

$$F(t) = P(T \le t) \qquad t \ge 0 \qquad \text{(A1.8)}$$

F (t) is called the failure function of a component, while

$$R(t) = P(T > t) \qquad t \ge 0 \qquad \text{(A1.9)}$$

R(t) is the probability that a component still operates after a designated time *t*, and is called the reliability function of a component or the reliability. Obviously

$$R(t)+F(t) = 1 \qquad \text{(A1.10)}$$

$$\frac{dR(t)}{dt} = -\frac{dF(t)}{dt} = -f(t) \qquad \text{(A1.11)}$$

In which *f (t)* is the failure probability density function and is defined by failure rate function.

a) Failure rate function $\lambda(t)$

The conditional probability that a component is working before the time instant *t* and develops a fault in the unit time Δt after the time instant *t*,

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(t < T \le t + \Delta t \,|\, T > t) \qquad \text{(A1.12)}$$

$\lambda(t)$ is called the failure rate function of a component.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{-1}{R(t)} \frac{dR(t)}{dt} \qquad \text{(A1.13)}$$

After integration

$$R(t) = \exp\left(-\int_0^t \lambda(t) dt \right) \qquad \text{(A1.14)}$$

$$F(t) = 1 - \exp\left(-\int_0^t \lambda(t)dt\right) \tag{A1.15}$$

$$f(t) = \lambda(t)\exp\left(-\int_0^t \lambda(t)dt\right) \tag{A1.16}$$

Here the failure rate function *λ(t)* is arbitrary. Presently it is believed that the failure rate function of power equipment has a 'bath-tub' shape and can be divided into three stage: early failure, useful life and wear-out failure.

In occasional phase or during the service lifetime, the failure rate is constant, *λ(t) = λ*. Therefore, it is believed that a component's continuous working time follows an exponential distribution.

$$R(t) = \exp\left(-\int_0^t \lambda dt\right) = e^{-\lambda t} \tag{A1.17}$$

$$F(t) = 1 - e^{-\lambda t} \tag{A1.18}$$

$$f(t) = \lambda e^{-\lambda t} \tag{A1.19}$$

Mean time between failures (*MTBF*)

The mean of the random variable T is called a component's mean time between failures (MTBF), which is another index to evaluate a component's reliability. If the failure density function *f(t)* is known, then

$$MTBF = E(t) = \int_0^\infty tf(t)dt = \int_0^\infty R(t)dt \tag{A1.20}$$

If an exponential distribution is obeyed, then

$$MTBF = \frac{1}{\lambda} \tag{A1.21}$$

b) Repair Rate Function $\mu(t)$

The repair process is very complicated after a fault has occurred in a component. Because of many influential factors such as the cause of the failure, the failure location, the degree of damage and repair facilities, the repair time T_D is also a random variable. The repair rate can be defined in a form similar to that for the failure rate:

$$\mu(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(t < T_D \leq t + \Delta t | T_D > t) \tag{A1.22}$$

There is still no consensus on an acceptable distribution of a component's repair time: that is to say, *μ* is a constant. Then

$$F_D(t) = P(T_D \leq t) = 1 - e^{-\mu t} \tag{A1.23}$$

$$f_d(t) = \frac{dF_D(t)}{dt} = \mu e^{-\mu t} \tag{A1.24}$$

Mean time to repair (MTTR)

The mean of a component's repair time T_D or the mean repair time can be written as

$$MTTR = E(T_D) = \int_0^\infty t \frac{dF_D(t)}{dt} dt = \int_0^\infty t dF_D(t) \qquad \text{(A1.25)}$$

For an exponential distribution,

$$MTTR = \frac{1}{\mu} \qquad \text{(A1.26)}$$

Appendix

A.1 IEEE 30-bus System Data

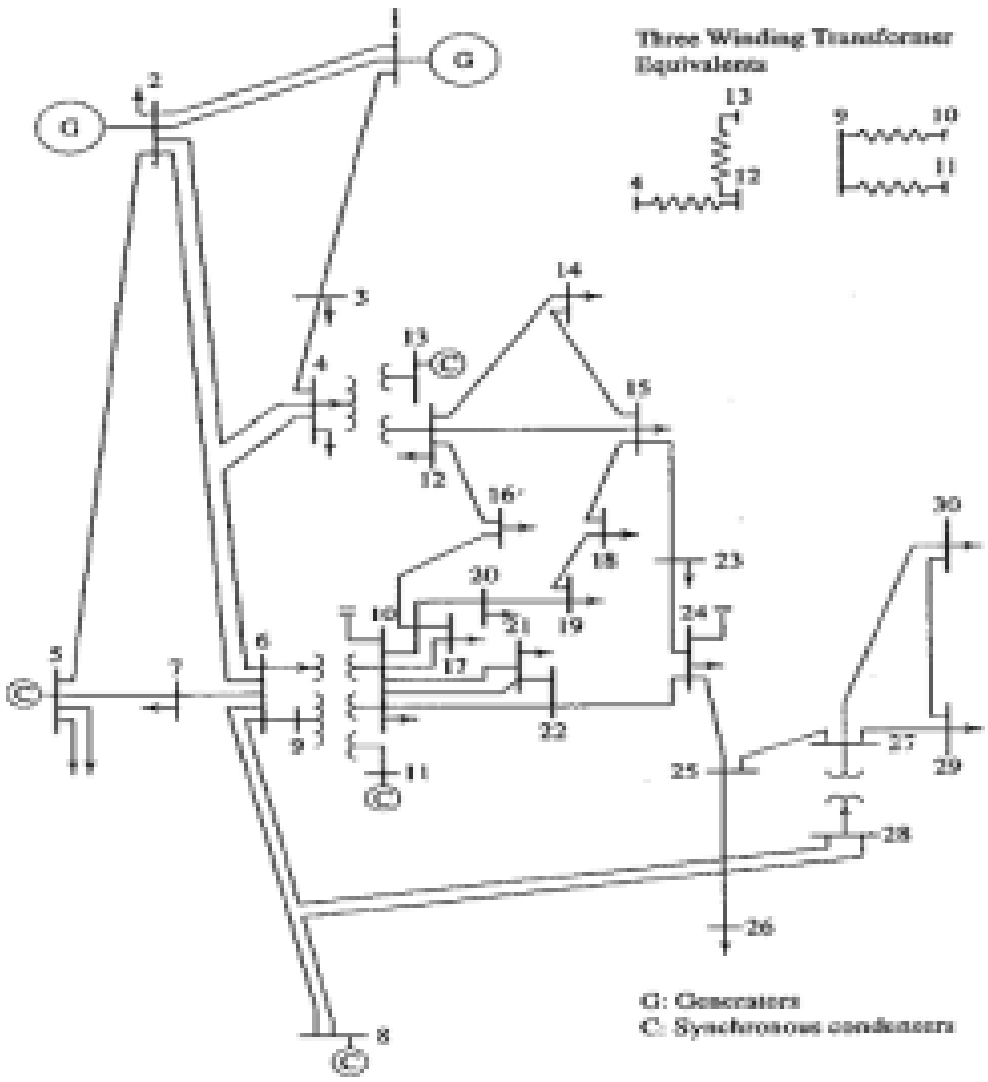

Figure A.1 Single line diagram of IEEE 30-bus system

Table A.1 IEEE 30-bus system reliability data

Unit	Capacity (MW)	Failure Rate (λ)	Repair Rate (μ)
1	60	6	194.67
2	60	6	194.67
3	60	6	194.67
4	60	6	194.67

5	40	4.5	219
6	40	4.5	219
7	40	4.5	219

Table A.2 Weekly Peak Load in Percent of Annual Peak for IEEE 30-bus system [32]

Week	Peak Load	Week	Peak Load
1	86.2	27	75.5
2	90.0	28	81.6
3	87.8	29	80.1
4	83.4	30	88.0
5	88.0	31	72.2
6	84.1	32	77.6
7	83.2	33	80.0
8	80.6	34	72.9
9	74.0	35	72.6
10	73.7	36	70.5
11	71.5	37	78.0
12	72.7	38	69.5
13	70.4	39	72.4
14	75.0	40	72.4
15	72.1	41	74.3
16	80.0	42	74.4
17	75.4	43	80.0
18	83.7	44	88.1
19	87.0	45	88.5
20	88.0	46	90.9
21	85.6	47	94.0
22	81.1	48	89.0
23	90.0	49	94.2
24	88.7	50	97.0
25	89.6	51	100
26	86.1	52	95.2

Table A.3 Load Curtailed Data [35]

States	Load Curtailed
Normal state	76.6
Outage line 6,7,5,15,19,21	251.45
Outage line 6,7,18,15,19,21	82.34
Outage line 6,7,1,15,19,21	32.12

A.2 Delhi Power System Data

Table A.4: Delhi Power System Reliability Data [3]

Station	Unit	Capacity (MW)	Availability (A)	Unavailability (U)
Rajghat Power	1	135	0.7688	0.2312
Gas Turbine	2	180	0.7623	0.2377
Gas Turbine	3	90	0.7623	0.2377
Pragati Power Plant	4	208	0.9172	0.0828
Pragati Power Plant	5	122	0.9172	0.0828
Badarpur Thermal Power Station	6	285	0.9176	0.0824
Badarpur Thermal Power Station	7	210	0.9176	0.0824
Badarpur Thermal Power Station	8	210	0.9176	0.0824

Table A.5: Load Curtailed Month wise for 2012 [36]

Month	Load Curtailed (MW)
January	556
February	201
March	225
April	621
May	916
June	406
July	499
August	417
September	355
October	334
November	380
December	508

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