COMPARISON BETWEEN ANALYTICAL AND NON-SEQUENTIAL MONTE CARLO TECHNIQUES FOR GENERATION ADEQUACY ASSESSMENT OF BANGLADESH POWER SYSTEM

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A Thesis submitted to the Department of Electrical and Electronic Engineering Of BRAC University, in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering

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December, 2019

Declaration

We hereby declare that

1. The thesis submitted is our own original work while completing degree at BRAC University.

2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.

3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.

4. We have acknowledged all main sources of help.

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Abstract

Generation system adequacy is employed to estimate the ability of the power system generation unit to fulfil the total system load. The assessment is conducted by calculating a common reliability index 'Loss of Load Expectation (LOLE)'. The LOLE is a statistical measure of the the expected amount of energy not supplied due to a shortage of generation capacity under a probabilistic based scenario and is generally expressed in the number of hours or days.

The main objective of the research work presented in this thesis is to apply the commonly used probabilistic techniques in LOLE estimation of Bangladesh power generating units. This work calculates and compares the LOLE estimation using two different techniques: analytical technique and non-sequential Monte Carlo simulation techniques. Both techniques have been tested on the Bangladesh power system consisting of sixty-one generation units. The models, methodologies, results and discussion presented in this thesis provide helpful information for power system planners for assessing the adequacy of electric power generation systems.

Acknowledgement

We would like to extend our sincere gratitude to our supervisor Dr. A. S. Nazmul Huda, Assistant Professor, Department of Electrical and Electronics Engineering, Brac University for his guidance, continuous support, crucial opinion and suggestions during the entire process of research which helped us in completing this thesis. We are grateful to Brac University for providing us with all the necessary materials required for the successful completion of the thesis.

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List of Abbreviations

HL1	Hierarchical Level-I
LOLP	Loss of Load Probability
LOLE	Loss of Load Expectation
COPT	Capacity Outage Probability Table
MCS	Monte Carlo simulation
PDF	Probability distribution function
MTTF	Mean time to failure
MTBF	Mean time between failures
MTTR	Mean time to repair
FOR	Forced outage rate
LOEE	Loss of Energy Expectation
LOLF	Loss of Load Frequency
EDPI	Expected duration per interruption
ENSPI	Energy not supplied per interruption
DNSPI	Demand not supplied per interruption

Chapter 1

Introduction

1.1 Power System Reliability Evaluation

Electric power systems are quite complicated and are particularly integrated in order to provide power to end users. One of its fundamental purposes is to provide power according to load demand while taking into consideration of the quality and continuity that end users receive. It is also important to consider the cost involved in supplying power of better quality. Securing an uninterrupted power supply is crucial for any advanced economy to function economically, socially and politically [1].

Power system reliability is defined as a measure of the ability of the system to meet the customer load demand in a cost-effective way. The area of reliability is generally divided into the two aspects of system such as adequacy and system security [2], as shown in Figure 1.1.

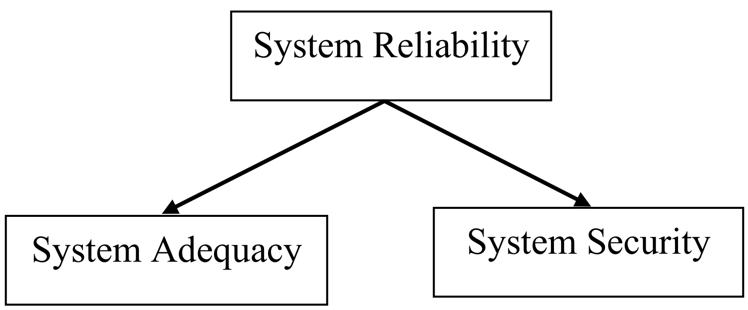


Figure 1.1: Subdivision of power system reliability

System adequacy determines whether the system has enough resources to supply electric energy to the end users within component ratings and voltage limits and according to load demand while keeping into account the scheduled/ unscheduled outages [2].

On the other hand, system security involves how the system counters the random and sudden disturbances that arise within the system from faults or equipment outages. It includes the transient responses along with cascading sequences after any fault or outage. Transient response includes variation in system frequency and bus voltage. If voltage or frequency fluctuations go beyond certain operating limits, cascading sequences occur and may continue until the system collapses. This is a concern of security rather than adequacy [2]. This thesis is concerned to adequacy assessment of power systems.

An electric power system is generally subdivided into three functional zones as follows which are responsible for generating, transmitting and distributing electrical energy to consumers:

- Generation system
- Transmission system and
- Distribution system

These three zones are combined into different hierarchical levels as shown in Figure 1.2 for conducting power system reliability assessment [3]. Hierarchical Level-I (HL1) is only about the analysis of the generation system and its adequacy. Generation as well as transmission system are comprised within Hierarchical Level-II (HL2) which is also regarded as the assessment of reliability of bulk power system or the composite power system. Hierarchical Level–III (HL3) includes the entire power system and its segments. This research work conducted in this thesis will focus on HL1.

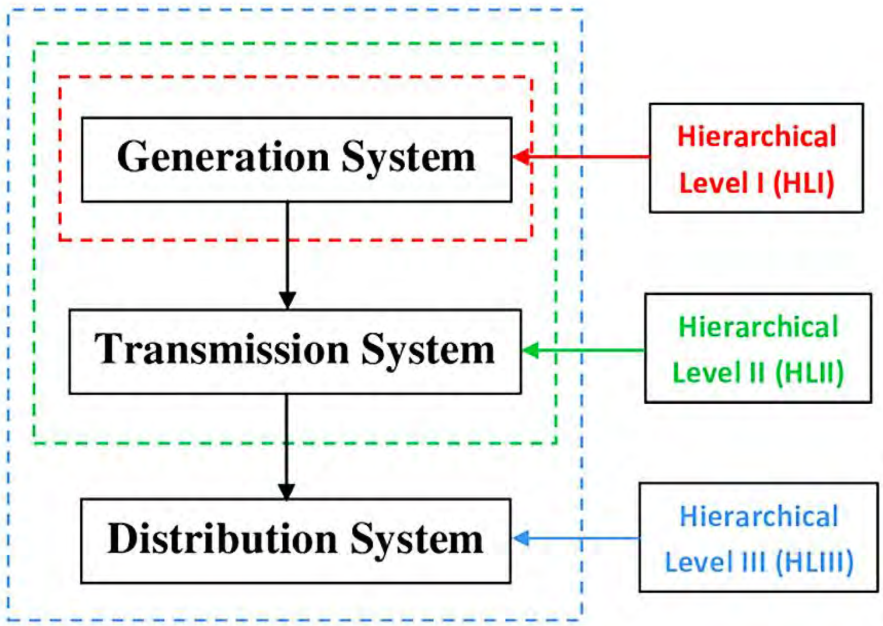


Figure 1.2: Hierarchical levels in power system

Reliability of a power system is usually analyzed either on deterministic or probabilistic basis [3]. Deterministic technique does not take uncertainties or errors that occur within reliability. This involves simpler calculations and less number of data is required. On the other hand, probabilistic techniques consider the stochastic uncertain nature of system behavior, customer demands or component failures. Uncertainty includes the probability of failure and the frequency of failure. The probability of failure defines the chances that a component will fail and is difficult to predict. Frequency of failure defines the number of failures of a system or component within a specified time; this could be predicted from previous data and expressed in per hour or day or year [4].

Power system reliability is usually expressed in terms of some indices. These indices reflect the system capability and the service supplied to the customers such as Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE) [5].

For the evaluation of reliability are of two basic methods are utilized - Analytical and simulation approaches [6]. Capacity Outage Probability Table (COPT) based analytical method for generation adequacy assessment. Simulation approaches are based on Monte Carlo simulation (MCS) where sampling of system states are carried out either randomly (non-sequential MCS approach) or in chronological order (sequential MCS approach).

1.2 Importance of Reliability Evaluation

Several developing countries including Bangladesh face a lot of power outages. The amount of power outage might be small in cities but are huge in various rural areas. Power outage has adequate amount of effect on the country's economy as well as the social lifestyle of the general public. The demand for electric power is increasing at a higher rate. The demand for power in Bangladesh is expected to reach 34,000 megawatts (MW) by the year 2030 [7]. About 54.35% of electricity is generated from private sectors in Bangladesh, while 45.65% generated by the state-owned power plants [8]. It is crucial for the government of Bangladesh to produce electrical energy beyond expected demand in order to aid the growing population as well as to expand the economy.

One of the key reasons for which countries face power failure is the inefficiency of the electrical components involved in generation, transmission and distribution of power which includes transformers and generators which are required to operate beyond their voltage limits, faults occurring within the components, overloading the equipment etc. Reliability analysis therefore helps to detect error or faults present in generators and transformers, find any system losses, expand the existing generating and distribution facilities predict the overall effectiveness and efficiency as well as solve any disturbance before they emerge.

Reliability analysis includes determining both adequacy and security. With system adequacy assessment, it can be determined whether the capacity of the existing generating units capacity is enough to provide power according to various demands which alter with time. This would eventually prevent overloading the generators. On the other hand, via security assessment we could determine the risk involved in using components, the possibility of their failures and how they would respond to any unpredictable faults.

1.3 Research Gaps and Objectives

In an earlier study, an analytical method based on recursive algorithm was discussed for adequacy evaluation (Loss of Load Probability) of Bangladesh power system [9]. In this thesis, the main objective is set to apply the two probabilistic techniques (e.g., analytical and non-sequential MCS simulation techniques) in the Bangladesh power generation system adequacy assessment.

The main objectives of the study are as follows.

- Evaluate the adequacy (Loss of Load Expectation) of the power generating units of Bangladesh by examining the data related to its installed capacity and load demand.

- With respect to the evaluation of the adequacy of the generation capacity for the designated system, compare the results obtained using two probabilistic techniques: analytical and non-sequential MCS.
- Examine the effect of probability distribution function and load variations on the system adequacy represented by the generation capacity index.

1.4 Thesis Outlines

This thesis consists of five chapters organized as follows:

- **Chapter 1** presents an introduction of power system reliability evaluation and necessity of reliability evaluation, followed by the objectives and outline of the thesis.
- In **Chapter 2**, a comprehensive literature review on generating capacity adequacy assessment, techniques of adequacy assessment, adequacy indices have been discussed.
- In **Chapter 3**, the methodologies of the two different techniques based on analytical and simulation techniques have been described.
- In **Chapter 4**, results of the adequacy assessment techniques are presented. A comparison between 'analytical technique based on Capacity Outage Probability Table' and 'simulation technique based on non-sequential Monte Carlo simulation' is presented. The results of sensitivity analysis by varying probability distribution function and load demand are also presented.
- In **Chapter 5**, conclusions and summary of this research are highlighted. Some future work is also suggested here.

Chapter 2

Generating Adequacy Assessment

2.1 Introduction

The purpose of generating adequacy assessment is to measure the ability of the installed generating capacity to meet the requirements of a specified load demand. In adequacy evaluation, generating unit model and load model are two main components of a generating system. Both the generating unit and the load models are then combined to form the risk model [3] as Figure 2.1. This chapter starts with the definition of some basic terminologies which are used for modeling generation and load. The basic differences of two algorithms studied in this research are also presented in this chapter.

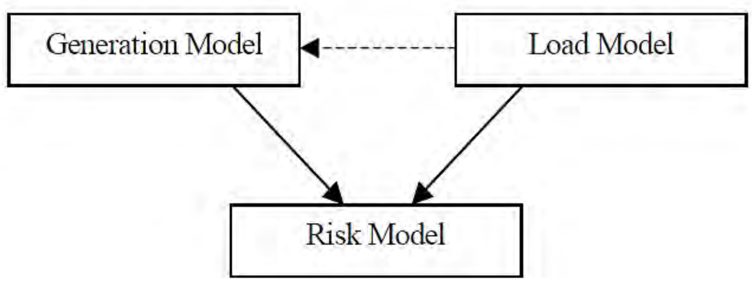
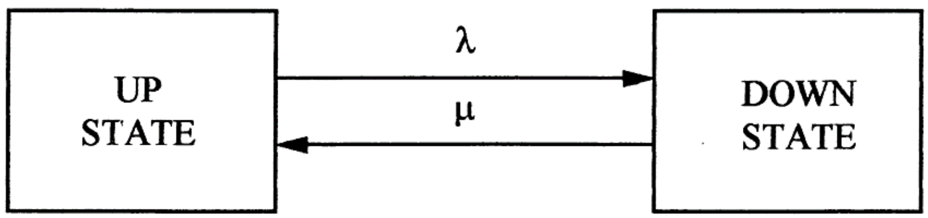


Figure 2.1: Conceptual tasks for HL-I assessment

2.2 Some Basic Terminology

2.2.1 Up-down State

In an HL-I generation model, a generating unit is represented by either a two-state model (fully rated state or failed state) [3] as shown in Figure 2.2. In the up state, generating unit is in operating condition. On the other hand, in down-state, generating unit is not in operating condition. In this thesis, assumption is made that each generating unit is in either up state or down state at their full capacities rather than different percentages of their full capacity. Generating units are either in groups or individual. Further examples will be shown in the calculations of COPT. Here it can be observed that in each group, the generating units are either on or off (up or down). Generators being grouped, all might be up or down.



where λ = expected failure rate (failures/yr),

μ = expected repair rate (repairs/yr).

Figure 2.2: Two-state model of a generating unit

2.2.2 Failure Rate

Failure rate is the number of expected failures of a component or generating unit in a specified time period. Bathtub curve [3] as shown in Figure 2.3 can be used to describe the failure rate of deteriorating equipment.

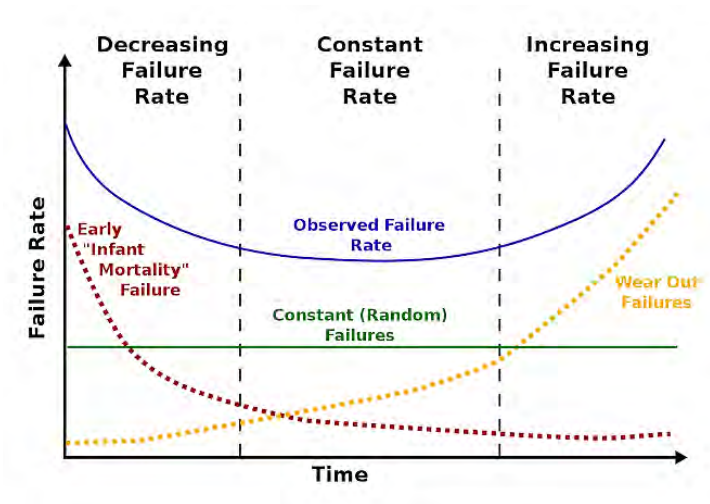


Figure 2.3 Reliability Bathtub curve

The bathtub curve shows the lifespan of equipment. It is composed of three main detectable periods. At the very beginning, it is the infant mortality phase, also known as the debugging phase, where the failure rate decreases with time exponentially then reaches to a constant value. The failures are the initial problems being identified while testing.

It then reaches the normal or useful period where the failure rate remains constant. Here failures occur randomly and independently. During this time the equipment is in full capacity operating condition.

Beyond this period is the wear out period where the failure begins to increase exponentially with time. This is the termination of the useful life as the parts begin to age or wear out. Mathematically, the failure rate of a component or generating unit can be expressed as follows:

$$Failure\ rate = \frac{number\ of\ failures}{total\ operating\ time\ of\ units} \tag{2.1}$$

The failure rate of similar component is assumed equal. The reliability can be expressed as a function of failure rate as follows:

$$R(t) = 1 - F(t) \tag{2.2}$$

where $R(t)$ is the reliability function.

$F(t)$ is the probability that a failure happens before time t. Here it is assumed that the probability of a failure is exponentially distributed. The pdf of the exponential distribution is expressed by

$$f(t) = \lambda e^{-\lambda t} \tag{2.3}$$

Based on the previous definition of the reliability function, it is a relatively easy matter to derive the reliability function for the exponential distribution:

$$R(t) = 1 - \int_0^t \lambda e^{-\lambda t}\, dt$$

$$R(t) = 1 - [1 - e^{-\lambda t}]$$

$$R(t) = e^{-\lambda t} \tag{2.4}$$

where λ is the failure rate of the generating unit. Mean time to failure (MTTF) is the reciprocal of failure rate.

$$MTTF = 1/\lambda \tag{2.5}$$

$$MTBF = MTTF = 1/\lambda$$

MTBF is the mean time between failures. The difference between MTTF and MTBF is that MTBF is used when the equipment is repairable. There is significant repair or replacement time upon failure of product.

2.2.3 Repair Rate

The repair rate is demonstrated by the number of repair activities executed per unit time. It is a basic measure of power system reliability and its symbol is μ. Mathematically it can be expressed as follows [3]:

$$\mu = \frac{Total\ restoration\ time}{Number\ of\ repairs} \tag{2.6}$$

Mean time to repair (MTTR) is the reciprocal of the repair rate. It is the time taken for a faulty generating unit to be fixed. This repair time is inclusive of the time taken to figure out the fault with the unit repair or replace the part of the component which has the fault and then assess the entire electrical system to check if it is restored properly. This can be a short or long process depending on the magnitude of the fault types in the component.

2.2.4 Forced Outage Rate

In the outage state, power system is unable to carry out its functions. Outage rate is the probability that a power system will be unavailable when it is required to execute its functions. In other words, the outage rate is the number of hours a system is out of service over the total number of hours the power system is in service and the number of hours it is out of service. Outages mostly occur due to failure of components or generating units.

Forced outage rate is the probability that a power system will be unavailable when it is required to execute its functions due to forced outages. Forced outages are unlike scheduled outages where entire electrical systems are deliberately taken out of service due to maintenance or other emergencies. The probabilities of forced outage rate of power generation systems are quite significant in generation capacity expansion projects.

The forced outage rate (FOR) of the generating unit is defined as the probability that the unit will not be in service when required [10]. It is generally estimated based on the historical operating data of the unit. FOR can also be expressed as the unit unavailability, U as follows:

$$FOR = \frac{\lambda}{\lambda+\mu} \tag{2.7}$$

2.3 Generating Unit Model

Generating unit model can be defined as the capacity available to system with respect to the number of possible states or time. Generating units can exist in two states as mentioned in Section 2.2.1 or in or multiple states. For example, it can exist in the fully up state which means operating at 100 percent capacity. In the fully down state, the generating unit operates at 0 percent capacity. In the derated state, the generating unit can be in any percentage capacity between 0 to 100 percent. Derated state can exist due to changes in load demand such as when the demand for power is not excessive such as due to off peak hours and seasonal variations, the generators are operated at lower capacities. A representation of a generating unit with the three existing states is shown in Figure 2.4.

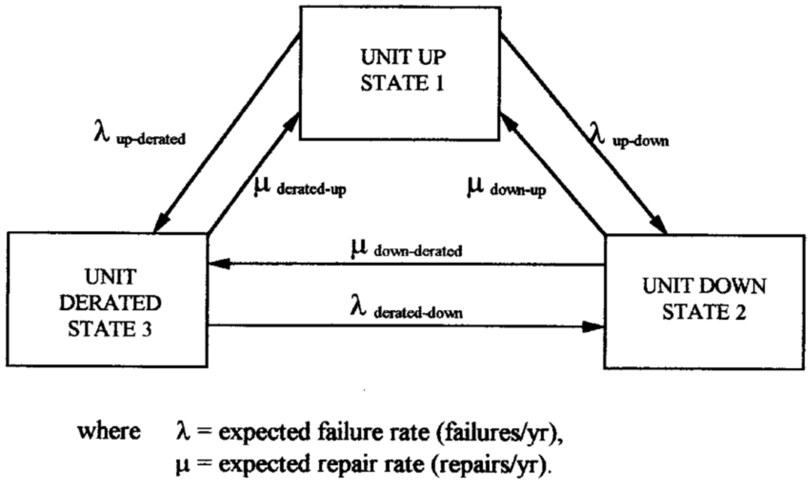


Figure: 2.4: Three state model of generating unit

The availability, A and unavailability, U of a generating unit can be expressed as follows using the up (T_{up}) and down time (T_{down}) histories [10].

$$A = \frac{\mu}{\lambda+\mu} = \frac{MTTF}{MTTF+MTTR} = \frac{\sum T_{up}}{\sum T_{up}+\sum T_{down}} \tag{2.8}$$

$$U = \frac{\lambda}{\lambda+\mu} = \frac{MTTR}{MTTF+MTTR} = \frac{\sum T_{down}}{\sum T_{up}+\sum T_{down}} \tag{2.9}$$

The Capacity Outage Probability Table is usually employed to represent the generation model. The COPT can be constructed using a recursive technique [3]. This technique is very powerful and can be used to add both two-state and multi-state generating units.

2.3.1 Recursive Algorithm

A recursive algorithm for adding two state generating units is given in Equation (2.10). This equation shows the cumulative probability of a certain capacity outage state of X MW calculated after a unit of capacity C MW, with a forced outage rate U, is added.

$$P(X) = (1-U)P'(X) + (U)P'(X-C) \tag{2.10}$$

Here $P'(\mathrm{X})$ and $P'(X-C)$ are cumulative probabilities of a capacity outage level of X MW before and after the unit of capacity C is added respectively. Equation (2.10) is initialized by setting $P'(X) = 1.0$ for X < 0 otherwise $P'(X) = 0$.

Equation (2.10) is modified as shown in Equation (2.11) for generating units with derated states.

$$P(X) = \sum_{i=1}^{n} P_i \, P'(X - C_i) \tag{2.10}$$

where n=the number of unit states,

C_i=capacity outage state i for the unit being added,

P_i= probability of existence of the unit state i.

The capacity outage probability table is complete after all the generating units are added.

2.4 Load Model

Demand of power is expressed through the load model. The load model can be two types, fixed or variable. The fixed load model has a fixed value of load and the variable load model is represented with the help of a load curve. The load curve represents the demand for power with respect to time. The time duration for the load curve can vary between hourly, daily, weekly, monthly or yearly time frame. The most common load curves that are used for calculation are Daily Peak Load Variation Curve (DPLVC) and load variation curve (LDC) [3]. The simplest load model is based on consideration of a peak load of the system as a fixed load for the entire period of study. The LDC and DPLVC are used in the analytical technique and the non-sequential MCS technique [3]. The chronological load model, recognized also as the time series load model, is often used in sequential MCS techniques [3].

2.5 General Assessment Techniques

The deterministic approach and probabilistic approach are the two main approaches developed to address the adequacy of generation capacity issue. Probabilistic method is popular than deterministic method due to advantages which will be described later in this section. Probabilistic methods can be usually classified as analytical and simulation techniques. This section also provides a brief description of analytical methods and simulation methods which are based on non-sequential and sequential Monte Carlo simulation techniques.

2.5.1 Deterministic Approach

The deterministic approach is a very simple method. The approach helps to assess power system reliability according to previous records of power system. The most common deterministic techniques [3, 11] are as follows:

I. Percent Margin: A required reserve margin should be equal to a fixed percentage value of either the total installed capacity or the predicted demand. So, the appropriate percentage value is determined based primarily on past experience.

II. Loss of the Largest Unit: A required reserve margin should be equal to the capacity of the largest generator unit connected to the system.

III. Loss of the Largest Unit and Percent Margin: A required reserve margin should be equal to the capacity of the largest generator unit plus a fixed percentage value of either the total installed capacity or the predicted demand.

However, the problem is that the deterministic approach cannot be used to assess modern day electrical power systems. The reason behind is this approach does not take into consideration the unpredictability and stochastic random nature of the power system. Moreover, the deterministic approach cannot be trusted to make proper estimations which can lead to wrong financial investments and solutions. Therefore, in these modern times the probabilistic approach is preferred over the deterministic approach in many cases.

2.5.2 The Probabilistic Approach

The unpredictability related to electrical power systems is taken into account by the probabilistic approach. This makes the probabilistic approach the most suitable method for power system reliability assessment. The states of weather, component, hydrological resource and the state of load are the standard unreliability in electrical power systems. These uncertainties are included in the probabilistic approach.

This approach allows the reference to the Markov Model. The Markov Model is used to model randomly changing systems. In this model, exponential distribution is used to show the period of events of the system. This causes constant transition rates between states i.e. the future states are based only on the current state. This is known as the homogenous Markov model. The probability of the state is determined from the transition rates between the states [3]. Some period of events may not follow exponential distributions. Therefore, special methods like that of

Weibull distributions in the homogeneous Markov models are used for periods of events that follow non-exponential distributions [3].

Table 2.1 shows some of the features of deterministic and probabilistic techniques [12].

Table 2.1: Features of deterministic and probabilistic techniques

Deterministic approach • Based on past experience • Most common approaches: (Percent reserve, Capacity of the largest unit, or both) • Straightforward and easy to understand and implement • Uncertainties associated with component failures or customer demands are not included • Lead to either under or over reliability estimation
Probabilistic approach • Incorporate the inherent stochastic in component failures and load variations • Lead to accurate risk reliability estimation • The generation and the load models are combined to form the risk model • Categorized as analytical and simulation methods

Probabilistic approaches can be classified into two techniques as analytical and simulation techniques. The analytical technique is used to assess power system reliability by performing numerical computation of mean value of the power system reliability indices. This technique is used for simple systems as it provides unreliable results for much more complex systems. The simulation technique on the other hand, determines reliability indices by irregular sampling of events. The simulation technique is capable of handling more complex power systems than the analytical method.

2.5.2.1 Analytical Techniques

In most analytical techniques, the generation model is normally in the form of an array of capacity levels and their associated probabilities. This representation is known as a COPT [3]. For large power systems, the Capacity Outage Probability table can be shortened by cutting out unnecessary data such as probability values which are lower than the standard probabilities of the generation unit in question. This allows a much simple and powerful assessment of the system. The COPT can be constructed using a recursive technique as described earlier.

2.5.2.2 Simulation Techniques

Analytical methods are more familiar as these methods are conventional and hold similarities to mathematical solutions. However, the simulation methods are more adaptable and capable as these consider the random fault occurrences and also it allows the variation of different indices. Simulation techniques are basically based on Monte Carlo simulation (MCS). MCS provides additional information that relates the probability distribution of the reliability indices along with the average solutions.

MCS uses random sampling and statistical modelling to estimate mathematical functions and tries to replicate the process of complicated systems. The method converts a random set of numbers into a different set of numbers but retaining the same distribution of the variables that are being considered. The result for each iteration is saved and after all the iterations are complete, the result sequence is converted into a frequency distribution that allows descriptive statistics of calculus, for example standard deviation, mean and variance.

MCS provides results that are coherent with results obtained from the Analytical methods. Additionally, the method provides information about the existence of failures, the duration of failure, load affect at point of failure, probability distribution of system indices and the variation of those indices. It helps to calculate more variations with the indices, which is not possible with the conventional analytical approach. Therefore, MCS method is the more practical approach to calculating power system reliability indices which help predict future outcome by taking into account of the randomness of the occurrence of failures.

Monte Carlo simulation techniques are classified as two types. They are:

(I) Sequential MCS technique

(II) Non-sequential MCS technique

Sequential MCS technique: The method is used to generate a random number as a probability of the failure or repair of the operational unit to generate an up-down sequence for its state. From previous data, the distributions and reliability indices are obtained. With the help of probability distribution, information about future reliability performance of the power system can predicted [13].

Non-sequential MCS technique: Non-Sequential Monte Carlo Simulation technique is the other method of Monte Carlo Simulation [14]. This method approaches the states of the system in a random manner over the duration of its life time and does not take the concept of time in account. The key being it is chosen randomly. In the case of Non-Sequential Monte Carlo Simulation, the effect of time is not taken into account like that of Sequential Monte Carlo. The approach does not include the sampling of up-down cycles. Neither does it requite to retain the information of the current state while the transition of state takes place. It is a time saving, less CPU memory consuming method that does not have the ability to provide the results in frequency and duration indices. Since the method does not require the generation of the up-down cycle it is considered to be less cumbersome but fairly accurate. However, the duration of the service of is also taken of a large value to obtain accurate average results for this approach as well.

The advantages and disadvantages of different techniques are presented in Table 2.2.

Table 2.2: Advantages and disadvantages of different techniques [12]

Analytical Technique	Non-sequential MCS Technique	Sequential MCS Technique
Advantages 1) Short computational time 2) Very efficient technique for small systems and for two state units 3) Very good method for indices (LOLE, LOEE)	**Advantages** 1) Practical for a large system that contains a large number of elements 2) Easily incorporates multi-state components without increase in complexity or	**Advantages** 1) The chronological nature of the generation model and load model are considered. 2) Very efficient method for a system that contains variable energy resources, such as

Disadvantages 1) Relatively complicated for large systems and for multi-state units. 2) The chronological nature of generation and load models is not considered. 3) Time-based indices cannot be easily and accurately calculated	computing time 3) Requires less computing time and effort than does the time sequential MCS method **Disadvantages** 1) The chronological nature of generation and load models are not considered 2) Time-based indices cannot be easily and accurately calculated	wind and solar. 3) Provides a wider range of indices (i.e., expected indices, time-based indices, and index probability distributions) **Disadvantages** 1) Requires greater computing time and effort, as well as more complex procedures

2.6 Risk Model/Adequacy Indices

Power system reliability is usually reflected by indices that measure the reliability and adequacy of the system. The indices most widely accepted and used for the assessment of generating capacity adequacy are as follows [3]:

1. **Loss of load probability (LOLP) (dimensionless):** This is defined as the expected annual probability during which the load will exceed the available generation.

2. **Loss of load expectation (LOLE) (hours/year):** This denotes the expected annual average number of hours/days during which the existing generating capacity fails to meet the demand.

3. **Loss of energy expectation (LOEE) (MWh/year):** This represents the expected annual amount of energy not supplied due to a shortage of generation capacity.

There is also a set of indices that have additional physical meaning and can provide the system planners with sensitive and useful information. Although these indices are well established and documented in the literature, they are not widely used due to the additional data and complexity that they need. Some of these indices are as follows [3]:

1. **Loss of load frequency (LOLF) (occurrences/year):** This signifies the expected annual frequency of encountering a generation deficiency in supplying the required load.

2. Expected duration per interruption (EDPI) (hours/interruption): This indicates the average duration of each occurrence when the load exceeds the available generation.

3. Energy not supplied per interruption (ENSPI) (MWh/ interruption): This denotes the average amount of energy not supplied for each occurrence in which the available generation cannot supply the demand.

4. **Demand not supplied per interruption (DNSPI) (MW/interruption):** This indicates the expected demand capacity not supplied for each occurrence in which the load is not supplied.

Chapter 3

Methodology

In this chapter, first the test generating units with their respective capacity and FOR is included. The models of generating unit and load will also be included here. The procedures of analytical and non-sequential simulation methods used in this thesis will be discussed here the calculate the Loss of Load Expectation (LOLE).

3.1 Generating Units

In this study, sixty-one generators having a total installed capacity of 5275 MW of Bangladesh power system are considered. Table 3.1 presents the individual capacity and FOR of the generators.

Table 3.1: Capacity and FOR of Bangladesh power system [15]

Gen No.	Capacity (MW)	FOR	Gen No.	Capacity (MW)	FOR
1	40	1.4×10^{-6}	32	15	0.15
2	40	1.4×10^{-6}	33	15	0.15
3	50	1.4×10^{-6}	34	15	0.15
4	50	1.4×10^{-6}	35	15	0.15
5	50	1.4×10^{-6}	36	35	0.1
6	210	0.16	37	35	0.1
7	50	0.113	38	21	0.122
8	109	0.07	39	120	0.04
9	55	0.185	40	77	0.101
10	55	0.185	41	100	0.04
11	210	0.095	42	125	0.1
12	210	0.019	43	125	0.1
13	210	0.08	44	110	0.301

14	210	0.08	45	60	0.402
15	64	0.116	46	28	0.5
16	64	0.116	47	28	0.5
17	150	0.013	48	20	0.045
18	150	0.014	49	20	0.2
19	150	0.014	50	20	0.2
20	56	0.321	51	20	0.119
21	56	0.321	52	60	0.50
22	30	0.15	53	8	0.30
23	100	0.30	54	450	0.07
24	210	0.197	55	235	0.07
25	210	0.197	56	125	0.07
26	60	0.117	57	142	0.07
27	28	0.6	58	45	0.07
28	28	0.6	59	45	0.07
29	12	0.15	60	110	0.11
30	12	0.15	61	110	0.07
31	12	0.15			

3.2 Generation Model

For our analysis, only two states are considered- up and down state of the generating units. In this paper, the possibility of generator being in a derated or partially active state is not considered for simplicity. The generation model is combined with the load model to obtain the risk model. The parameters that are required to build the generation model are FOR, installed capacity, MTTR and MTTF. FOR is calculated from previous functioning data of generating units such as MTTR and MTTF. The two state model for a generating unit is shown in the Figure 2.1.

By considering the two state model, two types of probabilistic approach model are developed using Analytical and non-sequential MCS methods. The analytical method is conducted in two different ways using Binomial distribution and Poisson distribution.

3.3 Load Model

The simplest load model is based on consideration of a peak load of the system as a fixed load for the entire period of study. In this research, fixed peak load of each generating unit is being assumed. Due to the data constraint, the actual load demand of the generating unit couldn't found. However, a sensitivity analysis by varying load demand has been conducted to show the impact of peak load variation.

3.4 Loss of Load Expectation (LOLE)

LOLE denotes the expected annual average number of days during which the existing generating capacity fails to meet the demand (i.e. the peak load exceeds the available capacity). The general formula for which can be written as:

$$LOLE = \sum_{i=1}^{n} P_i(C_i - L_i) \quad \text{day/period} \tag{3.1}$$

where C_i = capacity available on that day i, L_i = load demand on day I,

$P_i\ (C_i - L_i)$ = probability of loss of load on day i

Figure 3.1 shows a typical load-capacity relationship.

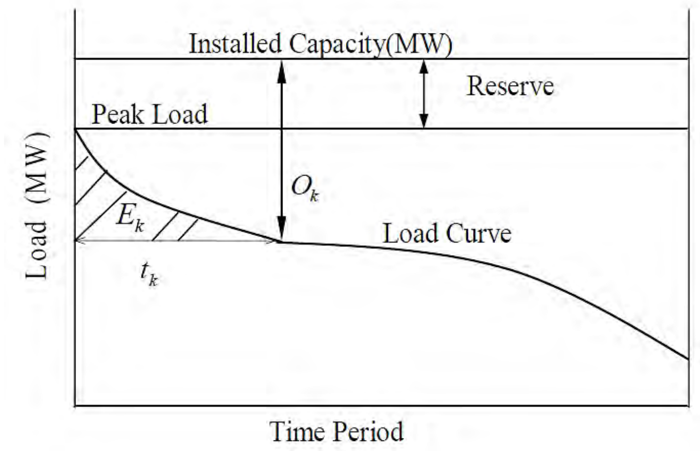


Figure 3.1: Relationship between capacity, load and reserve [3]

A capacity outage O_k, which exceeds the reserve t_k, causes a load loss for a time shown in Figure 3.1. Each such outage state contributes to the system LOLE by an amount equal to the product of the probability p_k and the corresponding time unit t_k. The summation of all such products gives the system LOLE in a specified period as expressed in Equation (3.2) [12]. A capacity outage less than the reserve does not contribute to the system LOLE.

$$LOLE = \sum_{k=1}^{n} p_k \times t_k = \sum_{k=1}^{n} P_k \times (t_k - t_{k-1}) \qquad (3.2)$$

where n= the number of capacity outage state in excess of the reserve.

p_k= probability of the capacity outage

t_k= the time for which load loss will occur.

P_k= the cumulative outage probability for capacity outage.

3.5 Analytical Method

In Analytical method, the loss of load approach requires a generation model. This generation model is often referred to as Capacity Outage Probability Table (COPT). COPT is a table which contains the capacity levels and the corresponding probability of occurrence of that particular capacity. If the generator capacity and the FOR of that generating unit match, then a group can be formed. This group can be used to form a particular COPT. This COPT can be used to calculate LOLE by applying two different probability distribution functions, which are Binomial distribution and Poisson distribution.

In Equation 3.2, if the probability follows Binomial distribution, then it can be written as [3]

$$P(x) = nC_x p^x (1-p)^{n-x} \tag{3.3}$$

where n = number of generating units

x = number of units out

p = unavailability(FOR)

After adjustments, an easier to use formula was obtained

$$(a+b)^n = \sum_{k=0}^{n} nC_k \, a^{n-k} b^k \tag{3.4}$$

where a = availability

b = unavailability (FOR)

n = number of generating units

For Poisson distribution, the probability function can be written as [3]

$$P(x) = \frac{\mu^x e^{-\mu}}{x!} \tag{3.5}$$

where μ = unavailability(FOR) and x = number of units out

3.6 Non sequential MCS

The simulation steps of non-sequential MCS can be described as follows:

Step 1) Initialization of D and N by setting both D and N as 0. where D represents the number of days on which loss of load is encountered and N is the number of sample years.

Step 2) Set the random number U in the interval 0 to 1. If the value for U is less than the value of FOR then the state of generating unit is considered in the down state with zero capacity being fulfilled. If the value for U is more than the value of FOR, then the state generating unit is considered to be available with full capacity.

Step 3) After all the capacities of the units have been defined. The total capacity is calculated by adding up all the individual unit capacities that have been obtained.

Step 4) The total capacity is then compared with the load. If the total capacity is less than the load, the value of D is increased. If the situation is otherwise, then the value for D remains the same.

Step 5) With this process the iteration for a sample of 1 year is completed and the value of N is increased.

Step 6) The Loss of Load Probability (LOLP) is calculated by diving D by N. LOLE for the respective sample year is calculated by multiplying the corresponding LOLP value with 365. Hence, the value of LOLE for the sample year is obtained in days/year.

Step 7) In this way the system is sampled for a total of 100,000 sample years by running the above steps in a loop and calculating for 100,000 iterations.

Step 8) Finally, a graph of LOLE Vs sample years is plotted and an average value of LOLE for 100,000 sample years is calculated.

Chapter 4

Results and Analysis

In this chapter, the results of LOLE index calculation using both analytical and non-sequential MCS techniques are presented. The results obtained using each technique were then compared. Two sensitivity analysis results by varying load and distribution function are also presented.

4.1 Results Based on Analytical Method

Table 4.1 presents the results for all generating unit groups obtained using analytical method based on COPT where binomial distribution is used. Generating units with same capacities and same FORs have been grouped together. The lowest and highest LOLE vales have been found 0.0365 and 182.5 days/year, respectively for generating units are 1, 2 (grouped) and 52, respectively. Based on the analysis, the values of LOLE can be reduced by the expansion of generating units or suitable load modeling.

Table 4.1 Results of calculated LOLE using binomial distribution

Generator no.	**Capacity (MW)**	**FOR**	**Load (MW)**	**LOLE(days/year)**
1,2	40×2	1.4×10^{-6}	50	0.0365
3,4,5	50×3	1.4×10^{-6}	60	0.108
6	210	0.16	50	58.4
7	50	0.113	30	41.25
8	109	0.07	50	25.55
9,10	55×2	0.185	50	12.41
11	210	0.095	50	34.68
12	210	0.019	50	6.94
13,14	210×2	0.08	220	56.06

15,16	64×2	0.116	60	5.475
17	150	0.013	50	4.75
18,19	150×2	0.014	200	10.95
20,21	56×2	0.321	50	37.595
22	30	0.15	10	54.75
23	100	0.30	40	109.5
24,25	210×2	0.197	200	14.235
26	60	0.117	20	42.705
27,28	28×2	0.60	25	131.4
29,30,31	12×3	0.15	15	22.192
32,33,34,35	15×4	0.15	20	4.38
36,37	35×2	0.10	30	3.65
38	21	0.122	10	44.53
39	120	0.04	50	14.6
40	77	0.101	25	36.865
41	100	0.04	80	3.2
42,43	125×2	0.10	120	3.65
44	110	0.301	100	109.87
45	60	0.402	55	146.73
46,47	28×2	0.50	20	91.25
48	20	0.045	18	16.425
49,50	20×2	0.20	15	14.6
51	20	0.119	10	43.435
52	60	0.50	50	182.5

53	8	0.30	5	109.5
54	450	0.07	250	25.55
55	235	0.07	100	25.55
56	125	0.07	50	25.55
57	142	0.07	80	25.55
58,59	45×2	0.07	65	49.312
60	110	0.11	50	40.15
61	110	0.07	50	25.55

Table 4.2 shows the COPT for generators no 32, 33, 34 and 35. Each generator has capacity of 15 MW and FOR of 0.15. The load was assumed to be 20 MW.

Since, Unavailability = 0.15.

Therefore, Availability = 1- 0.15 = 0.85.

Table 4.2 COPT for generating units 32, 33, 34 and 35.

Units out	Capacity out (MW)	Capacity in (MW)	Probability	Cumulative Probability	Load loss (MW)
0	0	60	0.5220	1	0
1	15	45	0.3685	0.4780	0
2	30	30	0.0975	0.1095	0
3	45	15	0.0115	**0.0120**	5
4	60	0	5.0625×10^{-4}	5×10^{-4}	20

From the above Table 4.2, LOLP is found as 0.012

Therefore, LOLE=LOLP×365 = 0.0120×365= 4.38 days/year

4.2 Results Based on Non-sequential MCS

Figure 4.1 shows the variation of LOLE with the number of samples using a non-sequential method for generating units 32, 33, 34 and 35. Average value of LOLE from non-sequential MCS after 100,000 samples is 4.1414 days/year. From the above analysis, the value of LOLE using non-sequential MCS method was found to be 4.1414 days/year. Therefore, it can be concluded that the differences of LOLE values obtained using the different techniques are relatively small.

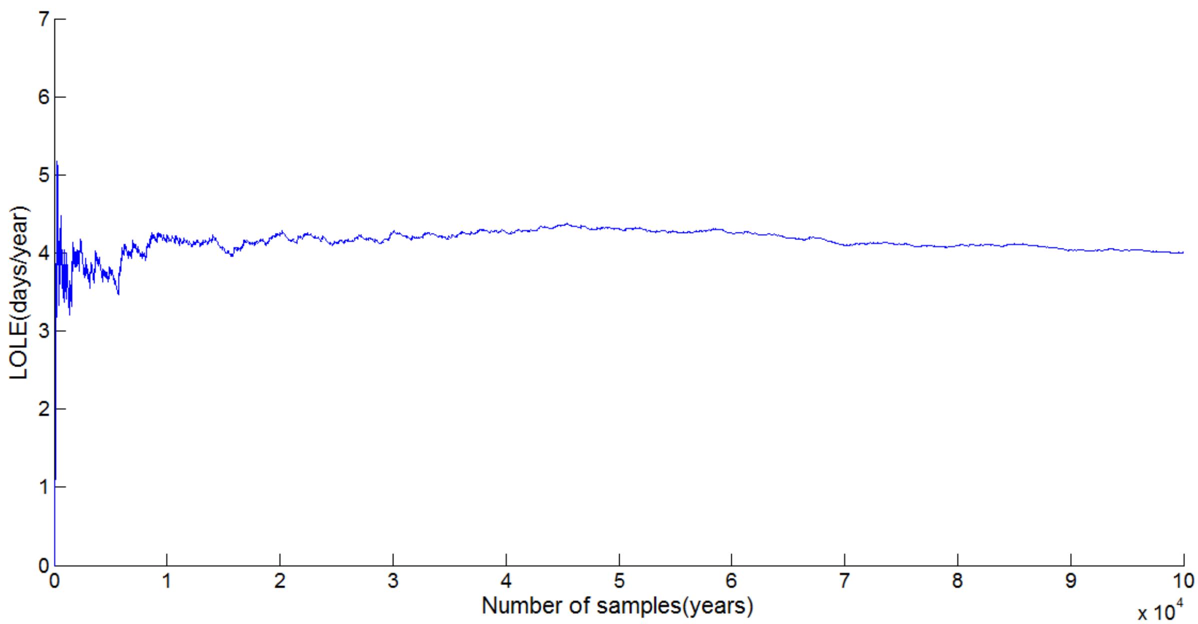


Figure 4.1: LOLE(days/year) using non-sequential MCS

4.3 Sensitivity Analysis

To further enhance the dynamic of the research two sensitivity analysis are carried out by varying the loads in the system keeping the same capacity and varying of the probability distribution function. This helps to give a different perspective on the analysis and helps to gain a new understanding. By comparing these different results, we are able to get a better understanding of how well the system would behave to these changes in the parameters.

4.3.1 Varying Probability Distribution Function

Table 7.3 presents the LOLE results obtained using Binomial and Poisson distribution functions. The value of LOLE for generators no 32,33,34,35 using Poisson distribution is 0.183 days/year. It is seen that there is a considerable amount of differences using two different probability functions.

Table 4.3 LOLE results obtained using Binomial and Poisson distribution functions

Probability distribution function	**LOLE(days/year)**
Binomial distribution	4.38
Poisson distribution	0.183

4.3.2 Varying Load Value

Figures 4.2 and 4.3 show the variation of LOLE using analytical methods based on Binomial and Poisson distribution respectively. The load was varied from 0-70 MW. The generation capacity was considered to be fixed and no additional expansion was considered. The results suggested that LOLE values increase with the increase of load and maintaining the reliability is very important for this case.

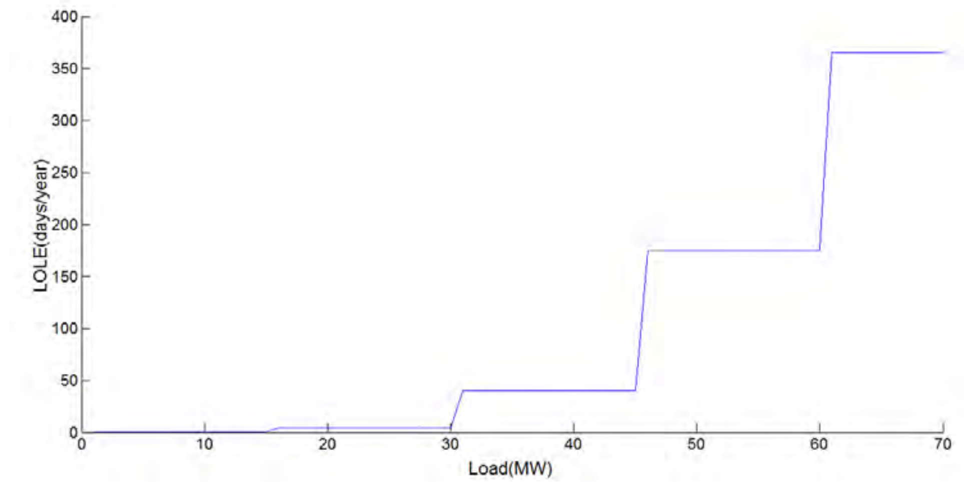


Figure 4.2: Sensitivity analysis using analytical method based on Binomial distribution

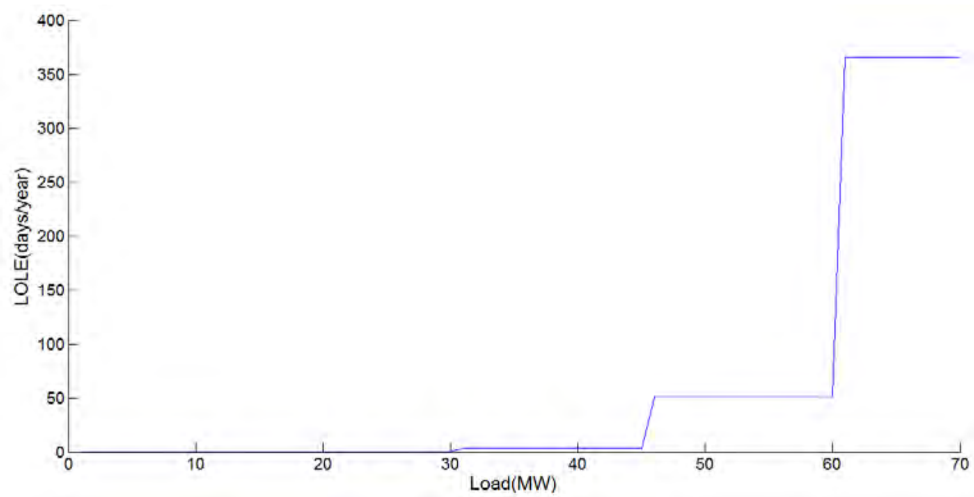


Figure 4.3 Sensitivity analysis using analytical method based on Poisson distribution

Chapter 5

Conclusions and Future Work

5.1 Summary

The purpose of this thesis was to compare values of LOLE using different techniques. LOLE was calculated by using analytical and MCS techniques. The value of LOLE using analytical technique based on Binomial distribution was found to be as 4.38 days/year. On the other hand, the value of LOLE using non-sequential MCS method was found to be 4.1414 days/year. Both these values are very close and hence this confirms the accuracy of the methods.

Two different types of probability distributions were used for the sensitivity analysis. The value of LOLE was calculated by using Binomial and Poisson distributions. Further sensitivity analysis was done by varying the load. This showed how LOLE changed with change in probability function and load. All the calculations have been done by creating computer programs in MATLAB. Thus models were created to calculate LOLE using the analytical and non-sequential MCS techniques. These models can be used for different datasets to evaluate the reliability of different systems.

5.2 Future Work

In future, the value of LOLE in hours/year can be computed using sequential MCS techniques or other computationally efficient methods. The integration of renewable energy units can also be considered for further analysis to find the impacts of renewable energy generating units.

For further research, a software or mobile application can be developed with the help of different coding languages with the help of which all the analysis can be programmed to be shown by allowing the user to input the desired values. This would be highly beneficial, as all the information about the comparison and analysis would be available from the palm of the evaluator's hands.

References

[1] M. Schmidthaler and R. Johannes, “Assessing the socio-economic effects of power outages ad hoc.” *Computer Science-Research and Development*, vol. 31, no. 3, pp. 157-161, 2016.

[2] W. Li and J. Zhou, “Probabilistic reliability assessment of power system operations,” *Electric Power Components and Systems,* vol. 36, pp. 1102-1114, 2008.

[3] R. Billinton and R. Allan, *Reliability evaluation of power systems*, 2nd Edition, Plenum Press, New York, 1996.

[4] W. Li, *Reliability Assessment of Electrical Power Systems using Monte Carlo Methods*, Springer, 1994.

[5] R. Allan and R. Billinton, “Probabilistic assessment of power systems,” *Proc IEEE,* vol. 88, pp. 140-162, 2000.

[6] R. Billinton and L. Gan, “Use of Monte Carlo simulation in teaching generating capacity adequacy assessment,” *IEEE Transactions on Power Systems,* vol. 6, pp. 1571-1577, 1991.

[7] Bangladesh Power and Energy, https://www.export.gov/article?id=Bangladesh-Power-and-energy. Retrieved December 19, 2019.

[8] Private sector dominates power generation with 54.35% contribution. https://www.dhakatribune.com/bangladesh/power-energy/2018/12/01/private-sector-dominates-power-generation-with-54-35-contribution. Retrieved December 19, 2019.

[9] N. A. Masood, M. N. Sahadat, S. R. Deeba, S. Ahmad, G. A. K. Biswas, A. U. Elahi & N. M. Zakaria, “Reliability evaluation of Bangladesh Power System using cumulant method,” *3rd International Conference on Electronics Computer Technology*, Kanyakumari, 2011, pp. 127-131.

[10] R. Billinton and G. Bai, “Generating capacity adequacy associated with wind energy”, *IEEE Transactions on Energy Conversion*, vol. 19, No. 3, September 2004, pp.641-646.

[11] R. Billinton, “Criteria used by Canadian utilities in the planning and operation of generating capacity,” *IEEE Transactions on Power Systems,* vol. 3, pp. 1488-1493, 1988.

[12] A. almutairi, *Evaluating wind power generating capacity adequacy using MCMC time series model*, MSc thesis, University of Waterloo, 2014.

[13] R. Billinton, H. Chen and R. Ghajar, “A sequential simulation technique for adequacy evaluation of generating systems including wind energy”, *IEEE Transactions on Energy Conversion*, Vol.11, No.4, 1996.

[14] A. A. Kadhem, N. I. A. Wahab, I. Aris, J. Jasni, and A. N. Abdalla, “Computational techniques for assessing the reliability and sustainability of electrical power systems: A review”, Renewable and Sustainable Energy Reviews, 80, pp.1175-1186, 2017.

[15] F. Yasmin, S. M. I. Samad, and M. S. S. Haque, *Reliability analysis of Bangladesh power system*, BSc thesis, Brac University, 2012.