GENERATION ENERATION ADEQUACY ASSESSMENT OF POWER SYSTEM WITH WIND ENERGY SOURCE

Dissertation

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CERTIFICATE

I, here by, certify that the Thesis entitled **"Generation Adequacy Assessment of Power System with Wind Energy Source"** in the partial fulfillment of the requirement for the degree of Master of Engineering in Power Systems submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala is an authentic work carried out under the guidance of **Ms.Manbir Kaur**, Associat Professor, EIED, Thapar University.

The work presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is certifying that the above statement made by the student is correct and true to the best of my knowledge and belief.

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Abstract

In long term planning of power system, sustainable energy resources are considered to play a significant role in generation adequacy. Wind power is a resource with continuous increase in its penetration level in conventional power system, has led to reduce its dependence on fossil fuels, reduced greenhouse emissions and supports the reduction in energy production costs. The power output from conventional units is deterministic whereas wind power output is intermittent due to its stochastic nature of wind speed. Wind unit is represented as a multistate model in contrast to a two state model of conventional unit for reliability evaluation. In this dissertation work, generation adequacy assessment is carried out in a power system comprising hydro, thermal and wind units using multistep model for wind unit and two step model for conventional units. The solution methodology is implemented in two parts. In first part, a probabilistic characteristic wind speed model is developed. In second part, reliability of system is assessed through estimation of loss of load expectation (LOLE) parameter. The validity of the model is carried out on a RBTS test system comprising four thermal, seven hydro and wind units with historical data obtained for three different geographic locations.

TABLES OF CONTENTS

Contents **Page No**

LIST OF FIGURE

LIST OF TABLE

LIST OF ABBREVIATIONS

A	Availability
ARMA	Auto regressive and moving average
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
Fi	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
Li	Forecast peak load on day i
LOEP	Loss of Energy Probability
LOLD	Loss of Load Duration
LOLE	Loss of Load Expectation
	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
Pi	Probability of the ith capacity state
PLC	Probability of Load Curtailment
PDFs	probability distribution function
RTS	Reliability Test System
RPS	Renewable portfolio standard
U	Unavailability
WTG	wind turbine generator
WECS	wind energy conversion system
σ	standard deviation

Chapter 1

Introduction

1.1 Overview

In present current scenario (wind power is established and cost-effective, particularly on a large scale) and one of the fastest growing energy sources, and is regarded as an important alternative to traditional power generating sources. Enhanced public awareness of the environment has led to rapid wind power growth throughout the world to reduce greenhouse gas emissions associated with conventional energy generation. An energy policy known as the renewable portfolio standard (RPS) is being widely accepted around the world. Acceptance of the RPS is a commitment to produce a specified percentage of the total power generation from renewable sources within a certain time period many counties. renewable energy resources by 2014–2019. Most of this renewable energy will come from wind as other renewable sources are not suitable for bulk power generation.[1]

1.2 Literature Review

Wind power source is not continuous available resource therefore. The development of comprehensive reliability and cost evaluation techniques becomes more important as wind power penetration levels in traditional power systems continue to increase in the near future. Both Monte Carlo simulation and analytical methods have been utilized in adequacy assessment of generation systems containing wind power. Simulation methods can recognize the chronology of wind variation and its impact on a power system.
Xifan Wang *et al.* [4] has proposed the modeling of the reliability characteristics in both probability and frequency of large electric utility application wind turbine generators together with their associated utility interface equipment. A computationally efficient algorithm is developed and applied to a wind farm with a special AC/DC/AC interface currently under design. The effects of various wind turbine/interface system component forced outage rates on the expected annual energy output of the farm have been examined.
P.K. Vohra *et al.* [5] has proposed the effects of terminal stations in composite system reliability evaluation by using the IEEE Reliability Test System the paper also provides a valuable extension of the original RWS by including switching configurations at each bus.

R. Ramakumar *et al.* [6] has proposed an algorithm to simulate the hourly wind speed using a time-series auto regressive and moving average (ARMA) model. The method requires actual hourly wind speed data collected over a long period of time for the particular geographic location to construct a wind speed simulation model for the specific site. This model can reflect the true probabilistic characteristics of wind speed for the wind site.

R.Billinton *et al.* [7] have presented .the development of a common wind speed model that can generate wind speed probability distributions for multiple wind farm sites if their annual mean wind speed and standard deviation are known.. The wind speed distribution obtained from the common wind speed model has been used in an analytical method for reliability evaluation of power systems containing wind farms

R. Karki *et al.* [8] have presented. a wind turbine generator (WTG) is modeled as a multistate unit in reliability evaluation using an analytical method

J. G. Slootweg *et al.* [9] have presented the multistate model represents a WTG by a number of derated power output states using the wind speed model for the wind farm location and the power curve of the WTG. The model appropriately reflects the fluctuating characteristics of the site specific wind. Reliability studies using the Roy Billiton Test System (RBTS) *et al.*

R. Karki *et al.* [10] have determined the appropriate number of states in the multistate WTG model, and developed a simplified model applicable to any wind farm connected to a power system. The development of a simplified 6-step common wind speed model that can be applied to any wind farm in power system reliability evaluation

Amir Mehrtash *et al.* [11] have presented. an Equivalent Multi-state Generation provider (EMGP) model to represent a wind farm connected to the generation system. In this procedure, only the parameters of EMGPs and their impacts on the reliability indices change

G. Bai *et al.* [12] have presented a methodology for capacity adequacy evaluation of power systems including wind energy. The results and discussions on two representative systems containing both conventional generation units and wind energy conversion systems (WECS) are presented. A Monte Carlo simulation approach is used to conduct the analysis. The hourly wind speeds are simulated using an autoregressive moving average time-series model. A wide range of studies were conducted on two different sized reliability test systems.

Francois Vallee *et al.* [13] have presented wind equivalent capacities are calculated using a Non Sequential Monte Carlo Simulation. Moreover, in order to evaluate the importance of the wind correlation level between parks located in the same geographical region

R. N. Allan *et al.* [14] have presented a probabilistic approach based on the convolution technique to assess the performance of utility-interactive wind electric conversion systems supplying loads

R. Billinton *et al* [15] have presented some of the basic factors and procedures that need to be considered when conducting wind integrated system adequacy assessment. Focus is placed on possible wind speed data models, wind energy conversion system models and their application in generation and bulk system adequacy evaluation

Amir Mehrtash *et al.* [16] have presents given a methodology for maintenance scheduling that combination 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 behavior of the system. Some 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)

[17] Wind speed data collection

Jadhav H. T. *et al.* [18] have presented the economic load dispatch (ELD) to meet the system load demand in an optimal manner considering wind power in power system using plant growth simulation algorithm (PGSA). Uncertain nature of wind power was included in study by using Weibull probability distribution function. The errors in wind forecasting are taken in to account by adding costs such as over estimation cost and under estimation cost.

1.3 Research Objectives

The main objectives of the present work to

1) Collect the data of wind sources
2) Development of generation models for wind
3) To study and investigate the probabilistic model of wind generating units
4) To propose an evaluation method to be used for generation capacity adequacy planning for consumer demand in future by estimating LOLE

1.4 Organization of work

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

Chapter 2 It deliberates on model of wind system, and Weibull probability distribution function

Chapter 3 highlights the probabilistic approach for reliability calculation, gives the basic concepts of generation reliability by state-space representation, analytical methods, system reliability parameters and indices used to evaluate generation reliability

Chapter 4 it presents the algorithm, problem formulation and results by analytical method for reliability evaluation of LOLE with wind and without wind

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

Chapter 2

Reliability Evaluation of Generation System

2.1 Introduction

An electric power system serves the basic function of supplying customers, both large and small, with electrical energy as economically and as reliably as possible. The reliability associated with a power system is a measure of its ability to provide an adequate supply of electrical energy for the period of time intended under the operating conditions encountered.

Modern society, because of its pattern of social and working habits, has come to expect the Electrical power supply to be continuously available on demand - this, however, is not physically possible in reality due to random system failures which are generally outside the control of power system engineers, operators and planners.

The probability of customers being disconnected can be reduced by increased investment during the planning phase, operating phase, or both. Over-investment can lead to excessive operating costs which must be reflected in the tariff structure. Consequently, the economic constraints can be violated even though the system may be highly reliable.

On the other hand, under-investment can lead to the opposite situation. It is evident therefore that the economic and reliability constraints can be quite competitive, and this can lead to extremely difficult managerial decisions at both the planning and operating phases.

The criteria and techniques first used in practical applications were basically deterministic (rule-of-thumb) ones, for instance

- **Planning generating capacity** - installed capacity equals the expected maximum plus deman a fixed percentage of the expected maximum demand;
- **Operating capacity** - spinning capacity equals the expected load demand plus a reserve equal to one or more largest units;
- **Planning network capacity** - construct a minimum number of circuits to a load group, the minimum number being dependent on the maximum demand of the group.
- Although the above-mentioned three and other criteria have been developed to account for randomly occurring failures, they are inherently deterministic. The essential weakness of these methods is that they do not account for the probabilistic/stochastic nature of system behavior, customer load demands and/or of component failures. Such aspects can be considered only through probabilistic criteria.

2.2 Typical probabilistic aspects are as follows

- Forced outage rate of generating units is known to be a function of unit size and therefore a fixed percentage reserve cannot ensure a consistent risk;

- Failure rates of overhead lines are functions of their lengths, design aspects, locations and environment, etc. - therefore a consistent risk of supply interruption cannot be ensured by constructing a minimum number of circuits;
- All planning and operating decisions are based on load forecasting techniques which cannot predict future loads precisely, i.e., uncertainties will always exist in the forecasts. This imposes statistical factors which should be assessed probabilistically.
- It is important to conjecture at this point on what can be done regarding reliability assessment and why it is necessary. Failures of components, plant, and systems occur randomly; the frequency, duration and impact of failures vary from one year to the next. Generally all utilities record details of the events as they occur, and produce a set of performance measures, such as:
    - system availability
    - estimated unsupplied energy
    - number of incidents
    - number of hours of interruption
    - excursions beyond set voltage (and frequency) limits
    - These performance measures are valuable since:
    - they identify weak areas needing reinforcements and modifications
    - they establish chronological trends in reliability performance
    - they establish existing indices which serve as a guide for acceptable values if future reliability assessments
    - they enable previous predictions to be compared with actual operating experience
    - they monitor the response to system design changes
    - The important thing to note is that the above measures are statistical indices - they are not deterministic values.

2.3 Adequacy and Security:

The concept of power system reliability, i.e., the overall ability of the system to satisfy the customer load requirements economically and reliably, is extremely broad. For the sake of simplicity, power system reliability can be divided into the two basic aspects of

- system adequacy
- System security.

Adequacy relates to the existence of sufficient facilities within the system to satisfy customer load demands. These include the facilities to generate power, and the associated transmission and distribution facilities required to transport the generated energy to the load points. Adequacy, therefore, relates to static system conditions.

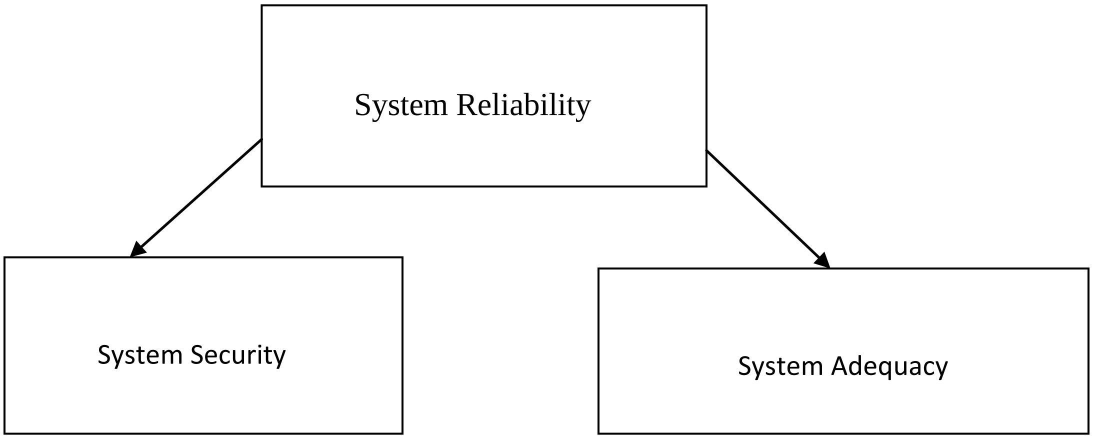

Figure 2.1 Subdivision of system reliability

- Security pertains to the response of the system to the perturbations/disturbances it is subjected to. These may include conditions associated with local and widespread disturbances and loss of major generation/transmission
- Most of the techniques presently available are in the domain of adequacy assessment

2.4 Study of Generation Reliability

The Generation of reliability study is to derive the more suitable measures of successful performance on the basis of components 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 best 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 availability and unit size, and they are most useful when comparing the relative reliability of different generation configurations. The system demand 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 clarify 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 neigh bouring 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.

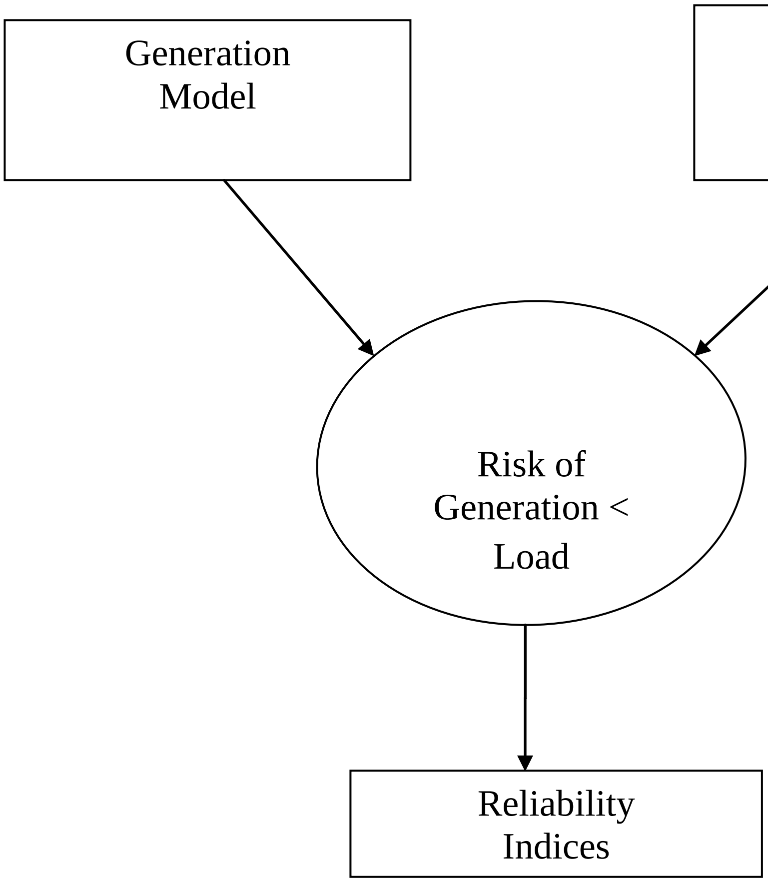

Figure 2.2 Elements of generation reliability evaluation.

2.4.1 Generation System Model

2.4.1.1 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

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

r = mean time to repair (MTTR)

$T = 1/\lambda + 1/\mu$ = mean time between failures (MTBF)

$f = 1/T$ = state frequency

$q = f / \mu$ = forced outage rate (FOR)

2.4.1.2 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 $P(X = x_i) = \left\{ \begin{matrix} 1-q & x_i = c \\ q & x_i = o \end{matrix} \right\}$ (2.1)

The cumulative state probability is

$$P(X \le x_i) = \left\{ \begin{matrix} 0 & x_i < 0 \\ q & 0 \le x_i < c \\ 1 & c \le x_i \end{matrix} \right\} \tag{2.2}$$

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

$P(X = x_i) = p(x_i)$ i=0,1,2,3… (2.3)

The cumulative state probability is

$$P(x_k) = p(X \ge x) = \sum_{i \ge k} p(x_i) \tag{2.4}$$

Or, equivalently, $P(x_k) = P(x_k) - P(x_{k+1})$ (2.5)

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,

$$f_i = f_{ij} = p_i \lambda_{ij} = (1-q)\lambda \tag{2.6}$$

$$f_i = f_{ij} = p_i \lambda_{ij} = q\mu \tag{2.7}$$

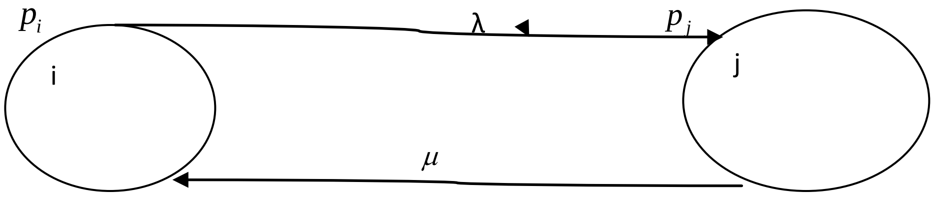

Figure 2.3 Frequency Transition Diagram

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

$$f^* = f_{ij} - f_{ji} = 0 \tag{2.8}$$

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

$$f_i = p_i \sum_{i=j} \lambda_{ij} \qquad (2.9)$$

This equation can also be written as

$$f_i = p_i(\lambda_i{}' + \lambda_i^{''}) \qquad (2.10)$$

In equation (2.9) λi and λ_j” are respectively the upward (increasing capacity) and downward (decreasing capacity) state transition states. From equation(2.10) and using the mathematical inductive method, a recurrence formula can be obtained for calculating the cumulative state frequency:

$$f^* = f^*{}_{k-1} + p_i(\lambda'{}_j - \lambda_i^{''}) \qquad (2.11)$$

The inconvenience caused in calculating the cumulative frequency using Equation (2.11) led to the introduction of the concept of frequency increment, which is defined

$$f(x_i) = p_i(\lambda'{}_j - \lambda_i^{''}) \qquad (2.12)$$

The cumulative frequency is then a direct sum of

$$F(x) = f(X \geq x) = \sum_{i \geq k} f(x_i) \qquad (2.13)$$

2.4.1.3 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 10 MW, four 30 MW and six 70 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

$$P(X_i) = {}^nC_i q^i (1-q)^{n-i} \qquad (2.14)$$

The cumulative probability is

$$P(X_i) = \sum_{k \leq i} P(X_i) \qquad (2.15)$$

The cumulatively frequency is

$$F(X_k) = P(X_i) K \mu \qquad (2.16)$$

2.4.2 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. 2.3, 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. (2.17).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

$$Unavailability U = \frac{\sum\left[down\,time\right]}{\sum\left[down\,time\right] \; + \; \sum\left[up\,time\right]} \qquad . \qquad (2.17)$$

The unit unavailability can be expressed in terms of unit’s failure rates and repair rates, as indicated in eq. (2.18).

$$U = \frac{\lambda}{\lambda \; + \; \mu} = \frac{r}{m \; + \; r} \qquad (2.18)$$

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 = μU = λA

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

$$availability, A = \frac{\sum\left[up\,time\right]}{\sum\left[down\,time\right] \; + \; \sum\left[up\,time\right]} \qquad (2.19)$$

$$A = \frac{\mu}{\lambda \; + \; \mu} = \frac{m}{m \; + \; r}$$

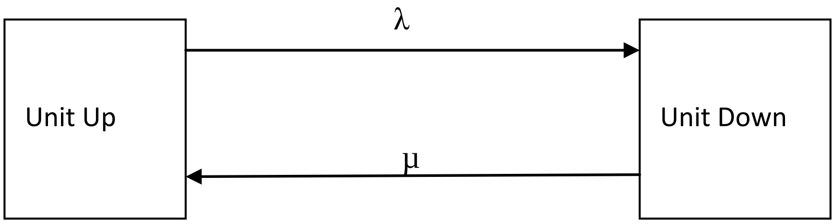

Figure 2.4 two-state model

$$LOLP = \sum_j \frac{E_j P_j}{E_o} \approx \sum_j \frac{(L_o - C_j).P(C_j)}{L_o} \text{ for } L_o > C_j \qquad (2.20)$$

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 (3.18).. 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

$$FOR = \frac{forced \quad outage \quad hours}{in \quad service \quad hours \quad + \quad forced \quad outage \quad hours} \tag{2.21}$$

2.4.3 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 Gi 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… 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.

2.4.4 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 modeling is one of the more difficult problems in power systems. 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 2.5.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.

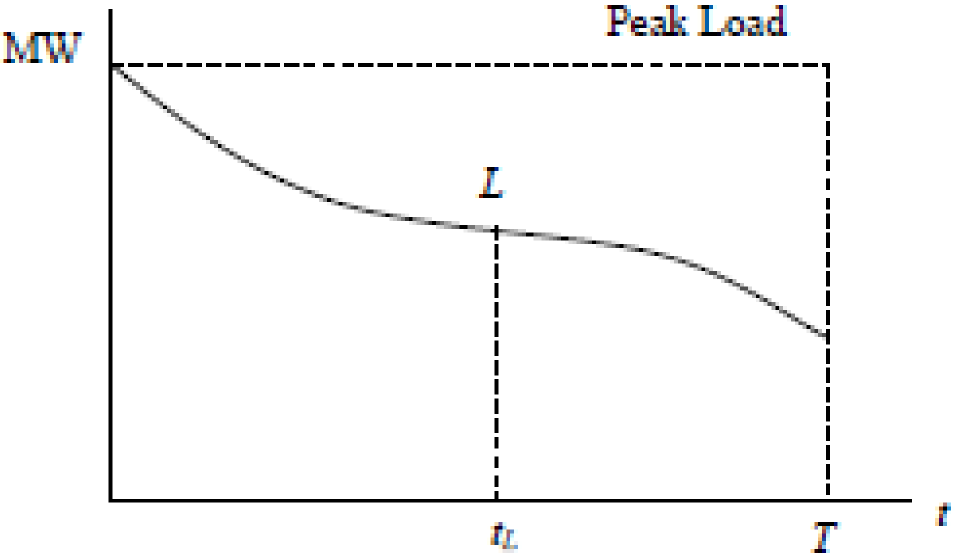

Figure 2.5 Cumulative Load Curve

If L isthe 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[$C_A \le L$][1]

2.5 Generation Reliability Indices

According to Amir Mehrtash[16] 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 faultysystems.

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) are briefly discussed here

2.5.1 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 a, the LOLP is:

$$LOLP = \sum_{j} P[L_o > C_j] \qquad (2.22)$$

Equation (3.22) is equal to the cumulative probability of $L_o > C_j$ 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 2.6 with a daily peak load curve. O_k is the magnitude of the k-th outage in the system, pk 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.

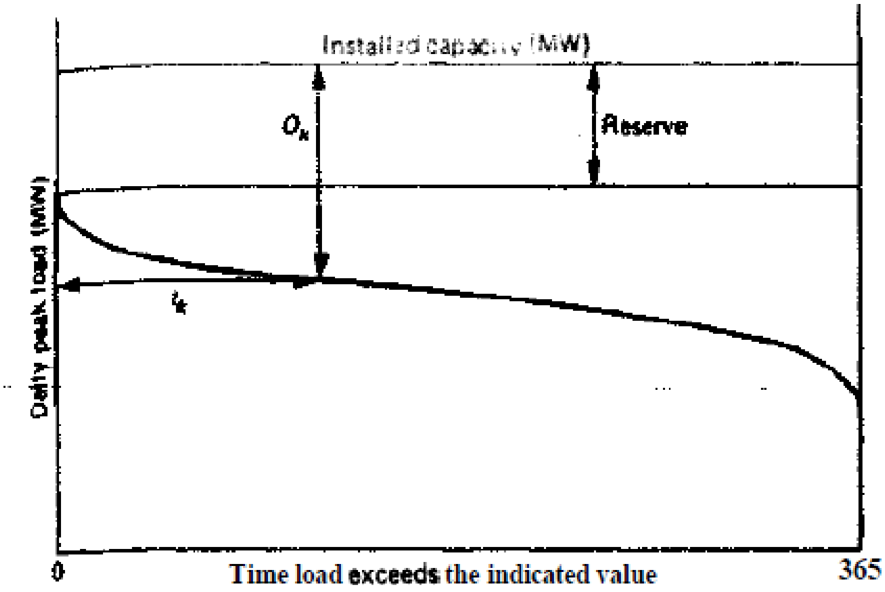

Figure 2.6: LOLP calculation

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 $p_k t_k$ The system LOLP for the period is

$$LOLP = \sum_k P_k t_k \tag{2.23}$$

Equation (3.23) 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

$$LOLE = \sum_{i=1}^{n} P_i (C_i - L_i) Days / period \tag{2.24}$$

Where C_i = available capacity on day i,

L_i = forecast peak load on day i, and

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

2.5.2 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 Helper in 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:

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

4. The average state duration *Tj* 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:

$$f = A\lambda \tag{2.25}$$

The frequency of encountering state 0 in figure 2.3 is the probability of being in the state multiplied by the rate of departure from the state.

2.5.3 Fast sorting technique

A fast sorting technique (FST) has been developed [2], 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 if the component is in the up state at time t = 0, the associate time dependent probabilities are

$$[p(t), q(t)] = \left[\frac{\mu}{\mu+\lambda} + \frac{\lambda}{\mu+\lambda} e^{-(\lambda+\mu)t}, \frac{\lambda}{\mu+\lambda} + \frac{\mu}{\mu+\lambda} e^{-(\lambda+\mu)t} \right] \tag{2.26}$$

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 (2.26) by letting

Where $t \to \infty$

$$[\overline{p}, q] = [p(\infty), q(\infty)] = \left[\frac{\mu}{\mu+\lambda}, \frac{\lambda}{\mu+\lambda} \right] \tag{2.27}$$

where p and q are steady-state (or limiting state) probabilities for the up and the downstate’s, 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

$$[p(t), q(t)] = \left[\frac{\mu}{\mu+\lambda} - \frac{\lambda}{\mu+\lambda} e^{-(\lambda+\mu)t}, \frac{\lambda}{\mu+\lambda} + \frac{\mu}{\mu+\lambda} e^{-(\lambda+\mu)t} \right] \tag{2.28}$$

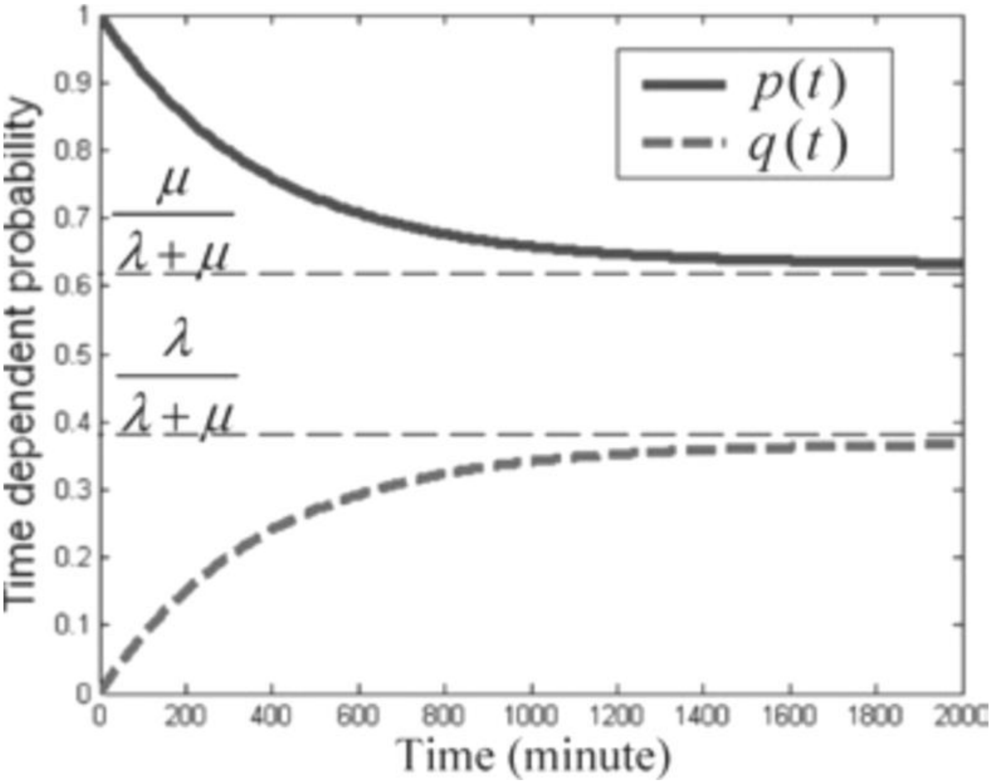

Figure 2.7 Time –dependent probability (initial state is up state)

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

$$[\overline{p}, \overline{q}] = [p(\infty), q(\infty)] = \left[\frac{\mu}{\mu+\lambda}, \frac{\lambda}{\mu+\lambda}\right] \tag{2.29}$$

Figures 2.7 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

Chapter 3
Development of a Wind Generation model

3.1Introduction

Utilization of renewable energy, like as that provided by the wind, for electrical power generation is being given serious thought around the world due to the global environmental concerns associated with conventional energy sources.

The wind source is associate intermittent and diffuse energy supply as wind speed is highly variable and site specific. Wind behavior is kind of completely different from that associated with conventional energy sources. analysis of the contribution to generating capability adequacy as a result to standard due to a wind energy conversion system (WECS), therefore, involves special modeling and data considerations. The capability profit that may be appointed to a WECS is highly dependent on the wind regime at the site location. A WECS is inherently less reliably than a conventional generating unit and, therefore, plays a different role in electric utility energy supply. This development is illustrated by scrutiny the performance of WECS which of of conventional units from a system reliability point of view. [5]

3.2 Sources of Energy

Energy development is a field of endeavor focused on making available sufficient primary energy sources and secondary energy forms to meet the needs of society. Primarily the sources of the energy was taken from the nature itself like kinetic energy of water fall, energy taken from the sun as solar energy, thermal energy from coal fire etc. Due to the advancement of technology now we have plenty of other sources which can be classified as follows.

- Conventional Sources of energy.
- Non- conventional Sources of energy.

3.2.1 Conventional Sources of Energy

Energy that has been used from ancient times is known as conventional energy. oil, natural gas, Coal, and firewood are examples of conventional energy sources. (or usual) sources of energy (electricity) are oil, coal, wood, peat, uranium.

3.2.2 Non-Conventional Sources of Energy

Non-conventional sources of energy include:

- Solar power.
- Hydro-electric power (dams in rivers).
- Wind power.
- Tidal power.
- Ocean wave power.
- Geothermal power (heat from deep under the ground).
- Ocean thermal power (the difference in heat between shallow and deep water).
- Biomass (burning of vegetation to stop it producing methane).
- Biofuel (producing ethanol (petroleum) from plants.

Wind energy is one of the safest energy technologies among innovative energy technologies. wind industry has an outstanding health & safety record; in over 20 years of generation with more than

50,000 machines installed worldwide, no member of the public has ever been injured during the normal operation of a wind farm. Apart from generating electricity without causing injury wind energy has numerous other advantages. Wind energy Bio fuel (producing ethanol (petroleum) from plants..[3]

3.2.3 Wind Energy

The origin for wind energy is Sun. When sun ray falls on the earth, its surface gets heated up and as a consequence unevenly winds are formed. Kinetic energy in the wind can be used to run wind turbines but the output power depends upon the wind speed. Turbines generally require a wind in the range of 20km/hr.[3]

- The conversion of wind energy into electricity using wind turbines (land and offshore).
- Wind energy is ample, widely, renewable, distributed, and clean.
- Large scale wind farms for national electrical grids as well as small turbines for grid-isolated or rural residences locations.
- Wind power is intermittent.

3.2.4 Advantages of Wind Energy

With the increase in fuel prices, environmental concerns, and reduction in wind-turbine generating system cost, the integration of wind power generation in the power system having conventional power generators is increasing. Due to intermittency and unpredictable nature of wind, the wind power generation is not reliable and also it creates difficulty in the control of frequency and scheduling of generation. Some of the advantages of wind energy given below:

- Reducing dependence on fossil resources.
- Reducing greenhouse gas emissions and environmental protection.
- After the initial land and capital costs, there is essentially no cost involved in the production of power from wind energy conversion systems. Hence reducing the energy production cost

3.3 Wind Speed and Probability Function

Scientific literature related to renewable energies that propose the use of a variety of probability distribution function (PDFs) to describe wind speed frequency distributions. The flexibility and usefulness of the PDFs is dependent upon the description of different wind regimes like high frequencies of null winds, uni modal, bimodal, bitangential regimes, etc.

3.3.1 Types of Distribution

There are many probability distributions that are applicable in many areas of study but we describe here some continuous frequency distribution function. These functions are relating to each other. Due to their close relationship with each other by changing the values of a parameter or keeping single parameter as a constant variable, we converts the whole distribution into another one. Some distribution functions are follows as:[3]

- Normal Distribution
- Rayleigh Distribution
- Chi-square Distribution
- Weibull Distribution

3.3.1.1Normal Distribution

The normal distribution is the most reliable and best distribution to see any data whether it is normally distributed or not. With a certain condition the normal distribution is a subset of the Weibull distribution. If we put k=3.2 the Weibull distribution gives the shape of standard normal distribution

$$f(v) = \frac{1}{\sigma\sqrt{2}} \exp\left[-\frac{1}{2} \left(\frac{v_i - \mu}{\sigma} \right)^2 \right] \tag{3.1}$$

Where,

μ is the mean speed and is expand by equation 3.2

$$\mu = \sum_{i=1}^{N} \frac{v_i}{N-1} \tag{3.2}$$

σ is standard deviation and is expend by equation 3.3

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (v_i - \mu)^2} \tag{3.3}$$

v_i is variable speed and can have the range[$-\infty$,$+\infty$] . But it is physically impossible for wind speed to be negative.

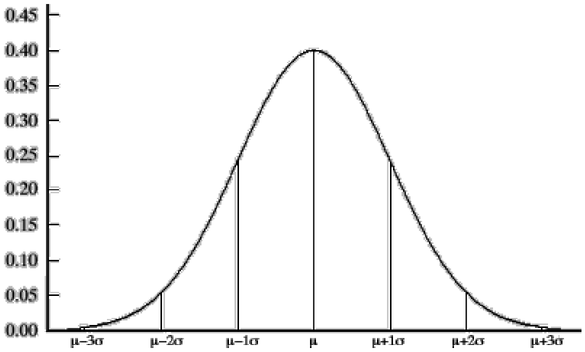

Figure 3.1 Normal distribution curve

3.3.1.2 Rayleigh Distribution

Normal distribution is also a subset of Weibull distribution. Weibull distribution with shape factor k=2 gives the same shape of Rayleigh distribution. The Rayleigh probability density function is given in equation 3.4

$$f(v) = \frac{\pi v_i}{2\mu^2} \exp\left[-\frac{\pi}{4} \left(\frac{v_i}{\mu} \right)^2 \right] \tag{3.4}$$

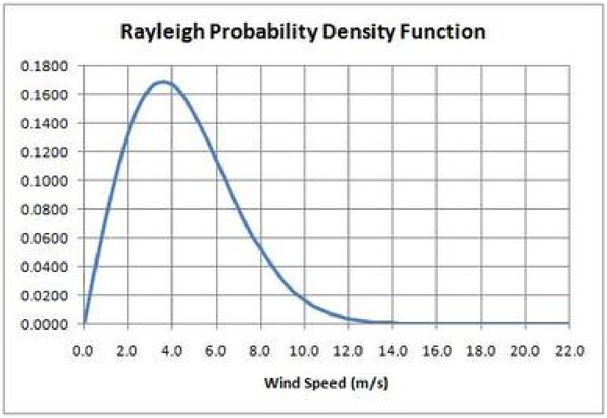

Figure 3.2 Rayleigh distribution curve

2.3.1.3 Chi-square Distribution

Some relationship exist between normal, Rayleigh, and Weibull distributions. In case of normal distribution, when N (0, 1) the normal distribution becomes the chi-square distribution. The probability density function for chi-square random variable is

$$f(v) = \frac{\pi v_i}{2m^2}\exp\left[-\frac{\pi}{4}\left(\frac{v_i}{m}\right)^2\right] \tag{3.5}$$

where,

v_i is the wind speed of the ith unit

m is average wind speed

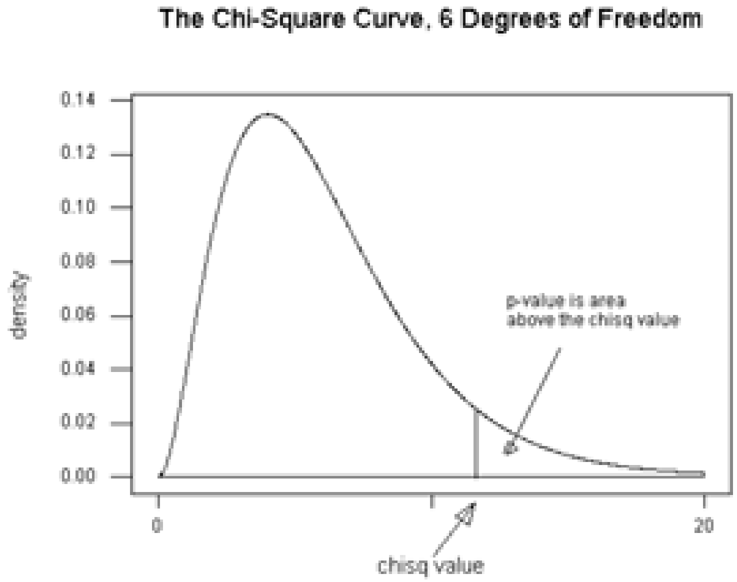

Figure 3.3 Chi-square distribution curve

2.3.1.4 Weibull Distribution

Weibull distribution is important, common and well known continuous distribution when estimating the wind power and energy, all over the world due to its versatility. This is only continuous distribution which is not derived from any other distribution. The wind speed variations for a particular place can be best described by the Weibull pdf, with two parameters, the scale parameter (c) and the shape parameter (k).The probability of wind speed during any time interval is given by,

$$f_V(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} (e)^{-(vc)^k}, 0 < v < \infty \tag{3.6}$$

where

v : wind speed;

c : scale factor at a given location (units of wind speed);

k : shape factor at a given location (dimensionless);

The shape parameter k vary between 1.0 to 3.0 and the scale parameter ranged from 5 to 20

In the probability distribution chart, f is plotted against v over a chosen time period, where

$$f = \frac{fraction\ \ of\ \ time\ \ wind\ \ speed\ \ in\ \ between\ \ v\ \ and\ \ (v+\Delta v)}{\Delta v} \tag{3.7}$$

By definition of the probability function, probability that the wind speed will be between zero and infinity during that period is unity, i.e.:

$$\int_0^\infty f.dv = 1 \tag{3.8}$$

Figure 3.1 depicts the variation of probability function versus wind speed v for three different values of k. By keeping shape parameter k=1,2 and 3.6, the Weibull distribution becomes exponential, Rayleigh, and normal distribution, respectively

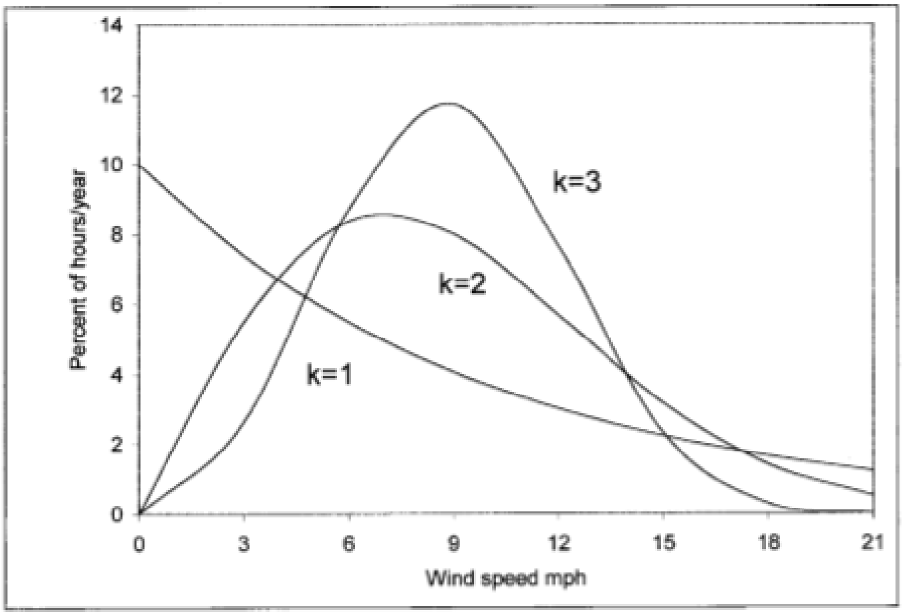

Figure 3.4 Weibull Probability Distribution Function with Scale Parameter c=10 and Shape Parameters k = 1, 2and 3.

The curve on the left with k = 1 has a heavy bias to the left, where most days are wind less(v=0). The curve on the right with k = 3 looks more like a normal bell shape distribution, where some days have high wind and equal number of days have low wind. The curve in the middle with k = 2 is a typical wind distribution found at most sites. In this distribution, more days have lower than the mean speed, while few days have high wind. The value of determines the shape of the curve, hence is called the 'shape parameter'. The Weibull distribution with k = 1 is called the exponential distribution which is generally used in the reliability studies. For k>3, it approaches the normal distribution, often called the Gaussian or the bell-shape distribution.

k =1 makes it the exponential distribution, $f = \lambda.e^{-\lambda v}$ where λ=1/c

k = 2 makes it the Rayleigh distribution, $f = 2\lambda^2.V.e^{-(\lambda v)^2}$, and

k> 3 makes it approach a normal bell-shape distribution.

Figure 3.2 shows the distribution curves corresponding to k = 2 with different values of changing from 8 to 16 mph (1 mph = 0.446 m/s). For greater values of c, the curves shift right to the higher wind speeds. That is, the higher the c, the more number of days has high winds. Since this shifts the distribution of hours at a higher speed scale, the c is called the scale parameter [2]

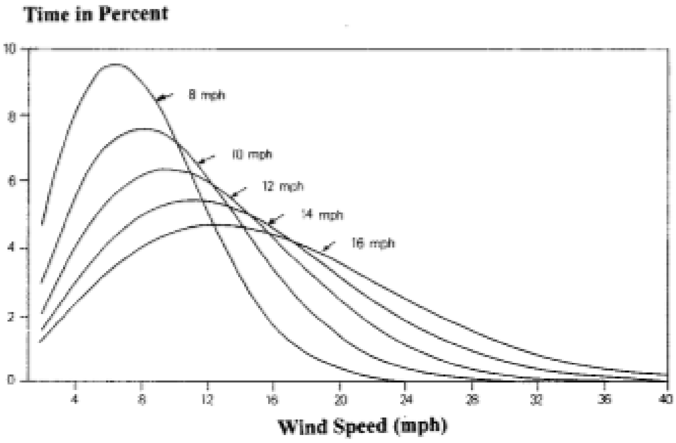

Figure 3.5 Weibull Probability Distribution with Shape Parameter k = 2 and the Scale Parameters Ranging from8 to 16 miles per hour (mph).

For later use in conjunction with the wind power probability function, the Weibull PDF is given by:

$$F_V(v) = \int_0^v f_V(\tau)d\tau = 1 - e^{-(v/c)^k} \qquad (3.9)$$

The Weibull distribution function with a shape factor of 2 is also known as the Rayleigh distribution. The advantages of the Weibull distribution are as follows:

- It is a two- parameter distribution, which is more general than the single- parameter
- Rayleigh distribution, but less complicated than the five-parameter vicariate normal distribution;
- It provides a good fit to observed wind speed data;
- If the k and c parameters are known at one height, a methodology exists to find the corresponding parameters at another height. The characteristics of the wind depend on various factors like geography, topography, etc., and can be estimated by the observed frequency of wind speed in the target region.

2.4 Mathematical Model of Wind Energy unit

The power generated by wind turbine expressed as a function of undisturbed wind velocity is given as in equation (3.10)

$$P = \rho A V^3 C_p \qquad (3.10)$$

where,

ρ: is the air density in kilograms per cubic meters (kg/m^3);

A: is the swept rotor area in square meters (m^2);

V: is the wind speed in meter per second (m/s);

C_p: is the power coefficient of the turbine, defined as power output from turbine / Energy available in the wind;

For a given wind speed input, the output of the wind power generator is expanded by equation (3.11)

$$
\begin{aligned}
&P_i=0 && V>V_{ci} \text{ and } V<V_{co} \\
&P_i=P_r\,(A+B.V+C.V^2) && V_{ci}<V<V_r \\
&P_i=P_r && V_r<V<V_{ci}
\end{aligned}
\qquad (3.11)
$$

Where A, B and C are constant are can be determined [ ] by equation (3.12)

$$
\begin{aligned}
A&=\frac{1}{(V_{ci}-V_r)^2}\left[V_{ci}(V_{ci}+V_r)-4V_{ci}V_r\left(\frac{V_{ci}+V_r}{2V_r}\right)^3\right] \\
B&=\frac{1}{(V_{ci}-V_r)^2}\left[4(V_{ci}+V_r)\left(\frac{V_{ci}+V_r}{2V_r}\right)^3-(3V_{ci}+V_r)\right] \\
C&=\frac{1}{(V_{ci}-V_r)^2}\left[2-4\left(\frac{V_{ci}+V_r}{2V_r}\right)^3\right]
\end{aligned}
\qquad (3.12)
$$

where,

V_{ci}, V_{co}, V_r: are cut-in, cut out and rated wind velocity for wind turbine system respectively;

P_i,: is the power output from wind-powered generator;

P_r,: is the rated power of wind-powered generator;

Thus, WECS wind energy has:

1) No power output up to cut-in wind speed(V_{ci}) ;

2) A linear power output relationship between cut-in(V_{co}) and rated wind speed(V_r) ;

3) A constant rated power output between the rated wind speed (V_r) and cut-out wind speed(V_{co}) ;

4) Once again has no power output with wind speeds(V) greater than the cut-out wind speed(V_{co});

The WECS power output is a mixed random variable, which is continuous between values of zero and rated power, and is discrete as well values of zero and rated power output It is assumed that the wind speed has Weibull distribution. The necessary transformation to simulate a wind model that convert the distribution to a wind power distribution is expanded in equation 3.13

$$P=T(V)=aV+b \qquad (3.13)$$

$$f(P_i)=f[T^{-1}(P_i)]\left[\frac{dT^{-1}(P_i)}{dPi}\right]=f\left(\frac{p-b}{a}\right)\left|\frac{1}{a}\right| \qquad (3.14)$$

T: a transformation ;
P: wind power random variable;
V: wind speed random variable;
P_i: wind power (a realization of the wind power random variable);
v: wind speed (a realization of the wind speed random variable).
a and b are cost coefficients;
The probability of wind power being zero, rated or in between zero and rated at the available wind speeds can be expressed respectively as in equations 3.15 and 3.16
$\Pr(P_i=0)=F(V_{ci})+\{1-F(V_{co})\}$

$$=1-exp\left(-\left(\frac{V_{ci}}{c}\right)^{k}\right)+exp\left(-\left(\frac{V_{co}}{c}\right)^{k}\right) \quad (3.15)$$

Pr(P_i=P_r)= F(V_{co}) -F(V_r)

$$= exp\left(-\left(\frac{V_r}{c}\right)^{k}\right)- exp\left(-\left(\frac{V_{co}}{c}\right)^{k}\right) \quad (3.16)$$

To make the transformation from the wind speed random variable to the WECS power output owing the simplicity of the model ,the linear portion of the curve is extracted and the wind power [2]and wind speed ratios are defined as :

$$\rho = \frac{Pi}{P_r}$$

is the ratio of wind power output(P_i) to rated wind power (P_r)

$$l = \frac{Vr-V_{ci}}{V_{ci}}$$

is the ratio of liner range of wind speed to cut –in wind speed

Arranging the equation 3.14 by incorporating the defined ratios as

$$f(P_i) = \frac{klVci}{c}\left(\frac{(1+\rho l)Vci}{c}\right)^{k-1} exp\left(-\left(\frac{(1+\rho l)V_{ci}}{c}\right)^{k}\right) \quad (3.17)$$

It is assumed that the wind farm containing same type of wind turbines experience the same wind speeds hence the same power output.

2.5 Common Wind Speed Model for Multiple Sites

For multiple sites, the wind speeds at different geographical locations is different. The common wind speed model can be used to obtain the wind speed probability distribution for any geographic location with wind speed characteristics close to selected sites. The block diagram of obtaining the wind-turbine-generator (WTG) model for wind units at different geographical locations is shown in Fig. 4.6.

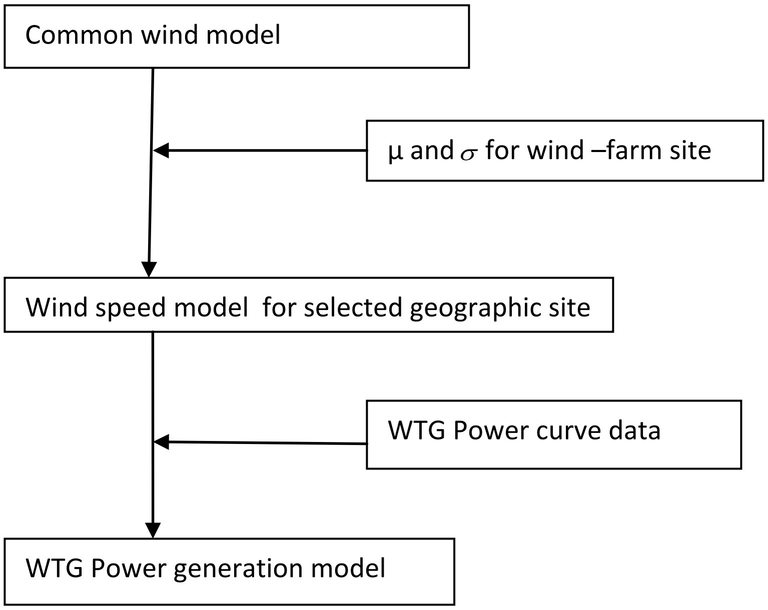

Figure 4.6 Development of a WTG model

2.6 For common wind speed model

If three consecutive standard deviation are σ_1, σ_2 and σ_3 the average value of standard deviation is expended in equation 3.18

$$\sigma_{ave} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{3.18}$$

If three consecutive mean value are μ_1, μ_2 and μ_3 the average value of mean value is expended in equation 3.19

$$\mu_{ave} = \frac{\mu_1 + \mu_2 + \mu_3}{3} \tag{3.19}$$

Chapter 4

Problem Formulation and Results

4.1 Introduction

Wind resource at a geographic location is highly variable. Power generated from WTG depends on the wind speed, which fluctuates randomly with time. Wind power studies, therefore, require accurate models to forecast wind speed variation for wind farm locations of interest. Wind speed distributions are often characterized by Weibull distributions. Historical hourly data for the wind farm site collected over significant time are normally required to obtain the shaping parameters

Historical wind data was obtained for three different locations in Canada: Swift Current, North Battleford, and Toronto. Swift Current lies in the southern part of the Saskatchewan province and is home to one of the largest wind farms in Canada. North Battleford lies to the north in the same province, but does not have a good wind resource. Toronto lies at the great lakes and has a coastal wind regime. These three locations have diverse wind variation patterns and are therefore selected in the study .Historical data on hourly wind speeds for three years (from January 1, 2011 to December 31, 2013)[17].

4.2 Algorithm for wind speed model for multiple sites

Procedure to determine the probability distribution curve for a given wind speed at a location is described as;

Step-1. Read hourly wind speed data of various sites r=1,2.3……N_r for the consecutive year y=1,2,3 … y_r

Step-2. Compute the mean wind speed μ and standard deviation σ of each site using equation equations 3.2 and 3.3

Step-3 Computed value of mean and standard deviation for three wind sites are tabulated in table 4.1

Table-4.1 Actual Wind Speed Data parameters

Wind sites	Mean value (μ) km/hour	Standard deviation (σ) km/hour
Site1	15.8582	9.0985
Site2	21.4608	9.9786
Site3	17.0577	9.7817

Step-4 Plot the probability distribution curve of wind speed at all the location under normal probability distribution for the computed values of mean and standard deviation of all sites as depicted in figure 4.1

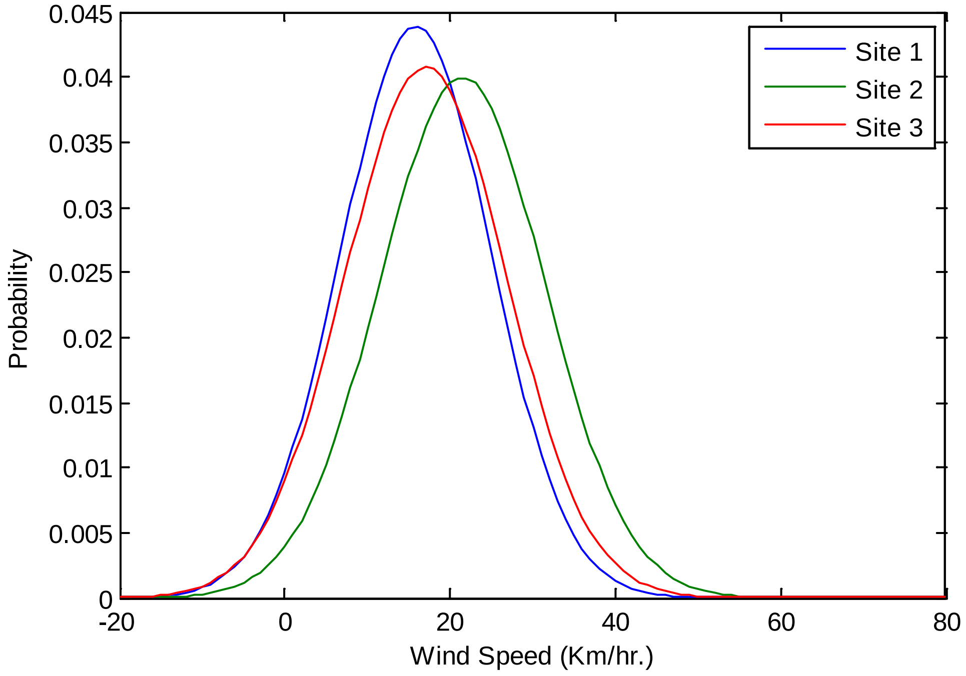

Figure 4.1 Normal Probability distributions of wind speed data

Step 5 Read the value of μ and σ for each wind site and compute the common mean and common standard deviation using equation 3.18 and 3.19

Step 6 Plot the probability distribution curve of common model for wind sites as shown in figure 4.2

4.3 Computation of Power Output

The procedure to calculate the power output from three different sites is as follows:

Step 1: Divide the probability distribution curve as depicted in figure 4.2 into N number of intervals. The range is selected for speed is the 10 times of the standard deviation of the curve at a location. [8]

Step 2: Each step has a length of $10\sigma/N$ and identify the mid-point of each interval as $\mu-4.9\sigma$, $\mu-4.8\sigma$,…. $\mu-.1\sigma$, μ,$\mu+0.1\sigma$,$\mu+0.2\sigma$,…..$\mu+4.9\sigma$,

Step 3: Determine the wind speed V(i=1…….,N) values of these step by equation 4.1

$$V=\mu+(10\sigma/N).(i-0.5N) \quad \text{for even N and} \tag{4.1}$$

$$= \mu+(10\sigma/N).\{i-0.5N.(N+1)\} \quad \text{for odd N}$$

Step 4: Determine the value of power output P_i using equation 3.11 for calculated values of speed in step 3.

Step 5: The calculated value of wind speed V and power output P_i are tabulated in table 4.2 (with reference to cut-in and rated speed)and is depicted in fig 4.3

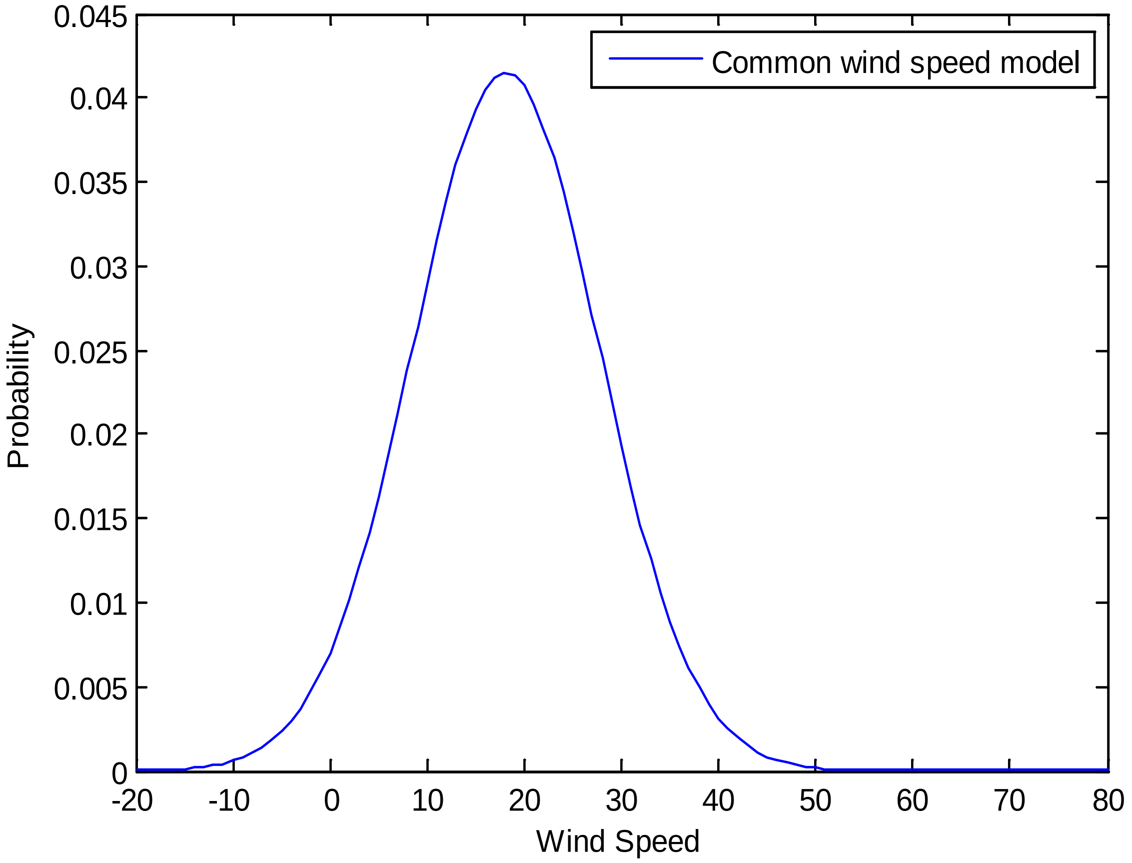

Figure 4.2 Probability distribution for common wind speed model

TABLE 4.2 Output power generation for common wind model

Wind speed (km/h)	Power output(MW)
0.8103	0
2.7342	0
4.6581	0
6.5820	0
8.5060	0
10.4299	0
12.3538	0
14.2777	0

16.2016	0.0177
18.1256	0.0463
20.0495	0.0850
21.9734	0.1338
23.8973	0.1926
25.8212	0.2616
27.7452	0.3406
29.6691	0.4297
31.5930	0.5289
33.5169	0.6382
35.4408	0.7575
37.3648	0.8869
39.2887	1.0265
41.2126	1.1760
43.1365	1.3357
45.0604	1.5000
46.9844	1.5000
48.9083	1.5000
50.8322	1.5000
52.7561	1.5000
54.6800	1.5000
56.6040	1.5000
58.5279	1.5000
60.4518	1.5000
62.3757	1.5000
64.2996	1.5000
66.2236	1.5000

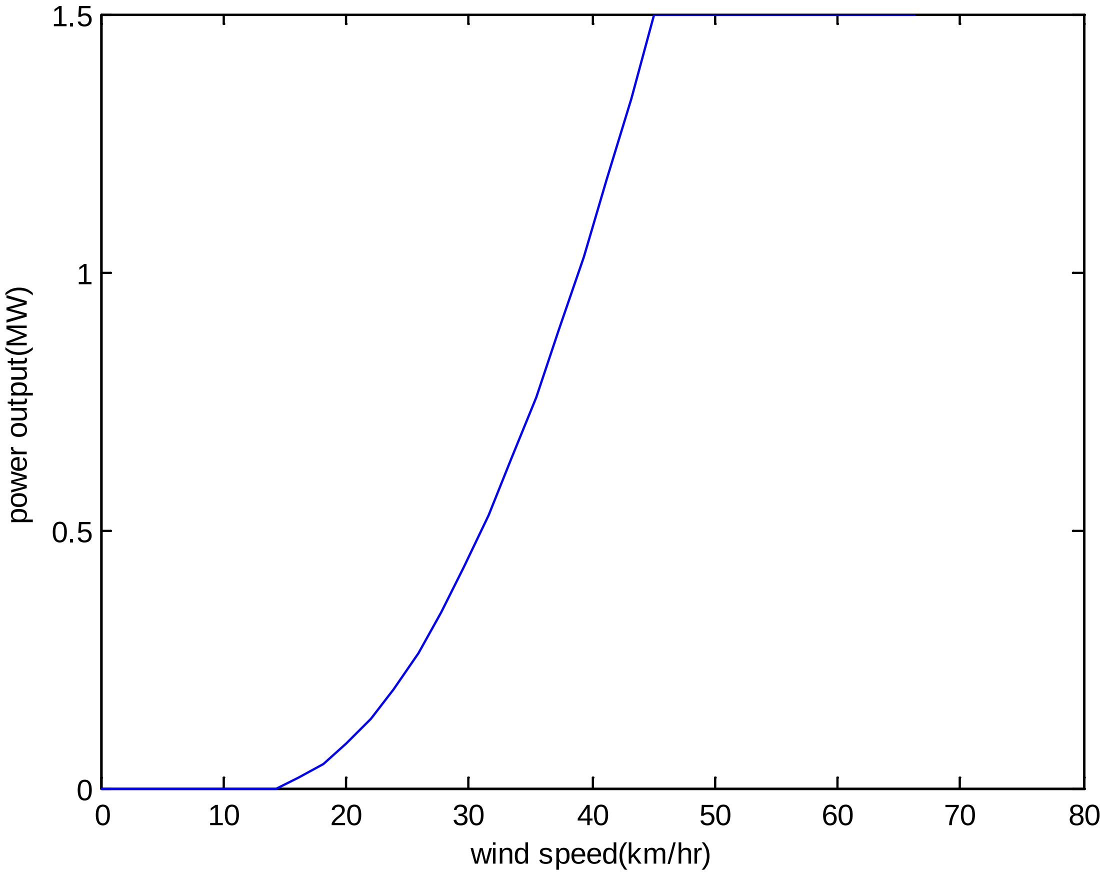

Figure.4.3 Power output model of WTG

For IEEE basic reliability test system data table shows in appended in appendix 1 The results for reliability evaluation of generation system by basic probability method and Frequency and Duration (FAD) method are appended in this chapter

4.4 Reliability Indices of Generation Adequacy

4.4.1 Algorithm for Loss of load expectation

Step 1 Input N , μ , λ and capacity of unit C_i for i=1 to N

Step 2 Calculate capacity outage probability table (COPT).

Step 3 Calculate the value of L_i = forecast peak load on day i, for different C_i = available capacity on day i

Step 4 Calculate the performance index LOLE using equation 2.24

4.4.2 Capacity Outage Probability Table (COPT)

Capacity outage probability table (COPT) shows the state probability and state frequency for corresponding system power available and unavailable Power system is considered for the generation system evaluation. For this, COPT for each system is required for calculating the LOLE of generation systems

4.4.3 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 for i = 1, 2, …, N.

Step 2 : For N units, calculate number of states and calculate Unavailability, U and Availability , A from Equation (3.18) and (3.19).

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 using equation 2.14 when first unit goes an outage.

Step 6 : j = j + Ci.

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

4.4.4 Loss of load expectation (LOLE) for without wind

4.4.4.1 Test Problem 1 Capacity outage probability table without wind

For IEEE basic reliability test system [8] System peak load is 185 MW and number of conventional units is N =11 are tabulated in table 4.3

Number of possible operating states $2^N = 2^{11}$ = 2056 states, which include repeated state value for same power available.

The repeated values corresponding to common states are merged and form a reduced COPT with total 49 states. The state probability curve of capacity available for the calculated values of COPT are plotted as shown in fig 4.5

Table -4.3 Generating unit reliability data (RBTS) without Wind

no	Unit size (MW)	Type	No of units	Forced Outage rate
1	5	hydro	2	.01
2	10	thermal	1	.02
3	20	hydro	4	.015
4	20	thermal	1	.025
5	40	hydro	1	.020
6	40	thermal	2	.030

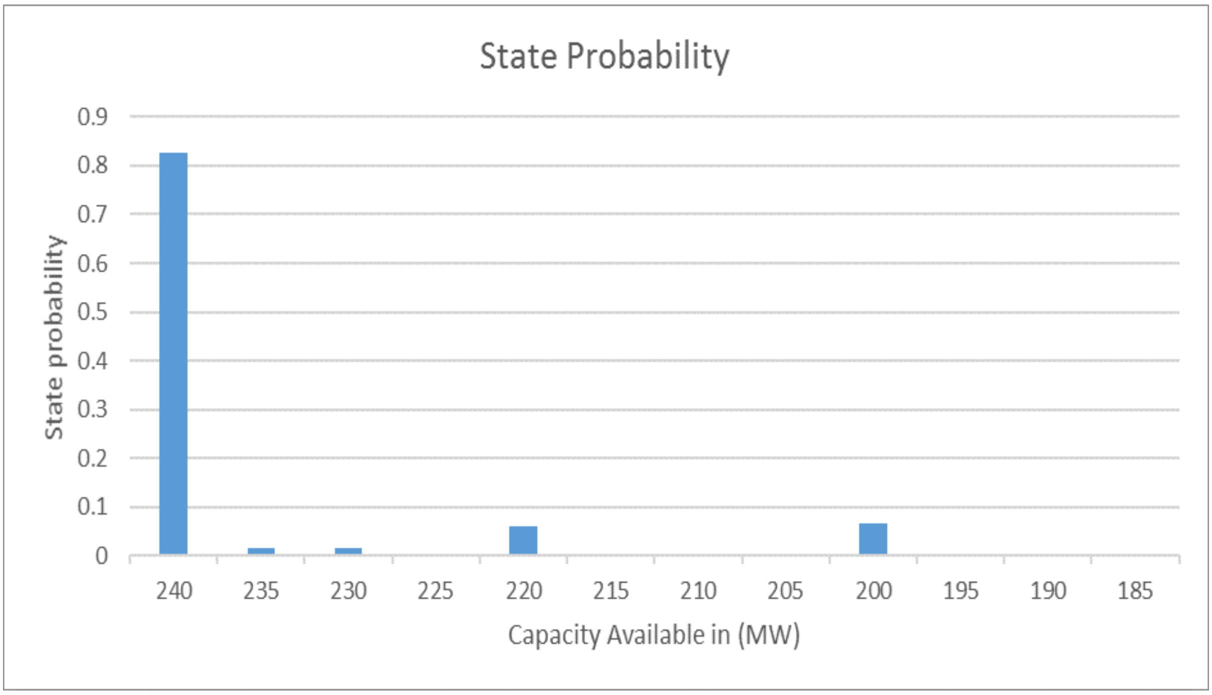

Figure 4.4 State probability vs Capacity Available (without wind)

4.4.4.2 Test Problem 1 Loss of load expectation (LOLE) for without wind

In test problem 1 only conventional units are considered.

LOLE is computed for test system 1 using equation (2.24). The variations of the LOLE with capacity available are shown in figure 4.5

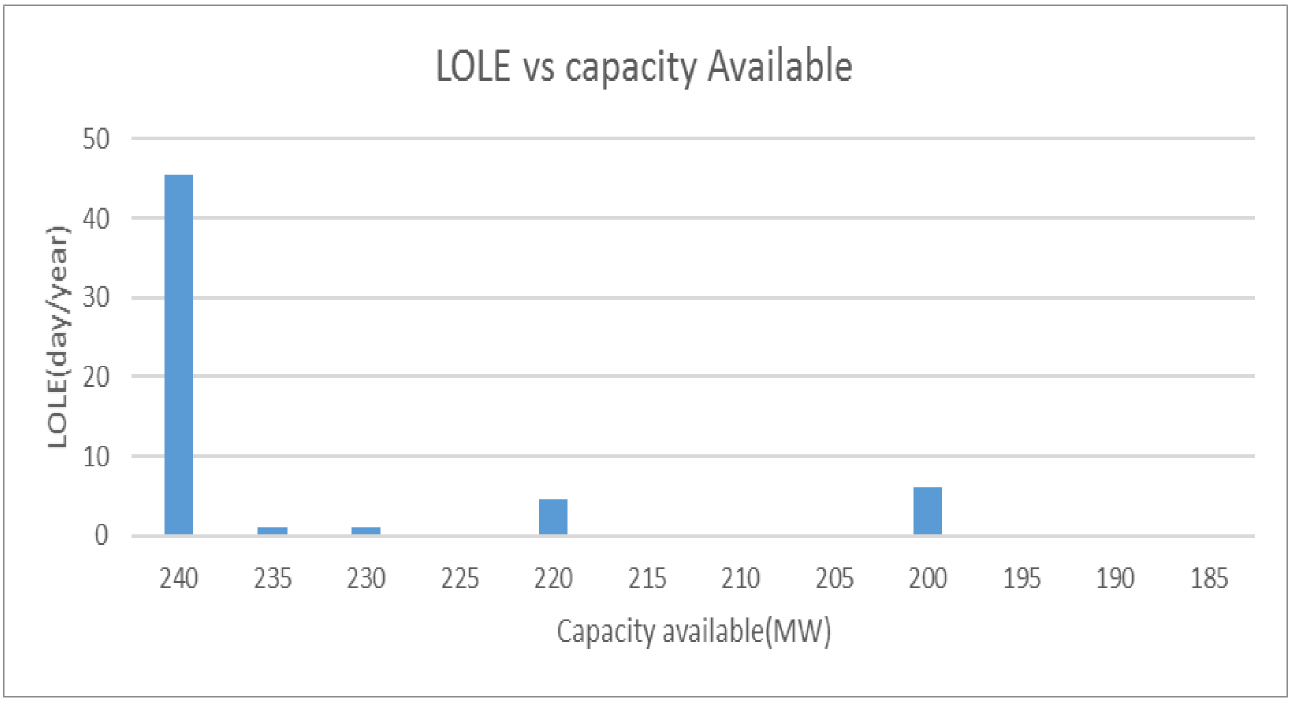

Figure4.5 LOLE vs capacity available

4.4.5 Loss of load expectation (LOLE) for Variable Wind Speed

4.4.5.1 Loss of load expectation (LOLE) for Site -1

For IEEE basic reliability test system and the system load is 185MW [8] There are 12 units i.e. N = 12, hence there should be 2^N = 2^{12} = 4112 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 24 states and the calculated value of LOLE with the help of equation 3.11 are tabulated in Table 4.4 and fig 4.6. depicts that the LOLE curve of variable Wind Power

Table 4.4 Loss of load Expectation (LOLE) for Site -1

Wind Speed	Wind Power	LOLE(day/year)
15.8582	0.0136	58.9393
17.6779	0.0387	58.9637
19.4976	0.0729	58.9970
21.3173	0.1160	59.0389
23.1370	0.1682	59.0898
24.9567	0.2294	59.1493
26.7764	0.2996	59.2176
28.5961	0.3788	59.2947
30.4158	0.4670	59.3806
32.2355	0.5643	59.4753
34.0552	0.6705	59.5786
35.8749	0.7858	59.6908
37.6946	0.9101	59.8118
39.5143	1.0435	59.9417
41.3340	1.1858	60.0802
43.1537	1.3372	60.2275
44.9734	1.4976	60.3836
46.7931	1.5000	60.3860

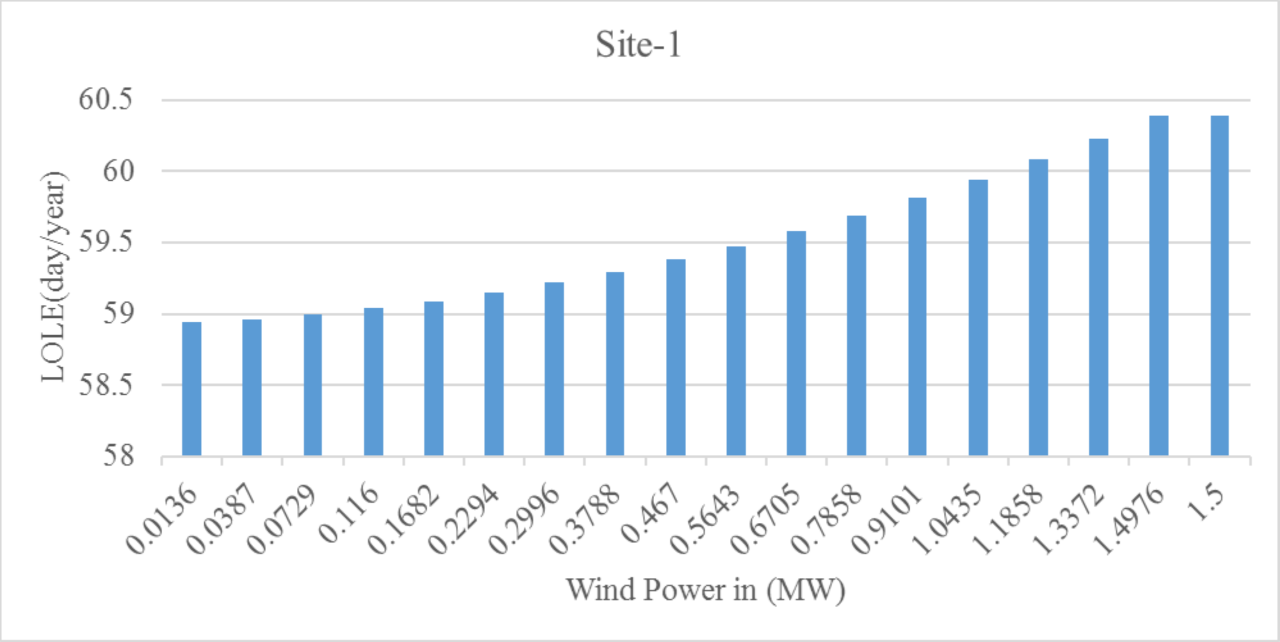

Figure 4.6 LOLE vs variable Wind Power(Site-1)

4.4.5.2 Loss of load Expectation (LOLE) for Site -2

For IEEE basic reliability test system and the system load is 185MW [8] there are 12 units i.e. N = 12, hence there should be $2^N = 2^{12} = 4112$ states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 24 states and the calculated value of LOLE with the help of equation 3.11 are tabulated in Table 4.5 and fig 4.7 depicts that the LOLE curve of variable Wind Power

Table 4.5 Loss of load Expectation (LOLE) for Site -2

Wind Speed(Km/h)	Wind Power (MW)	LOLE(day/year)
15.4736	0.0095	58.9353
17.4694	0.0354	58.9605
19.4651	0.0722	58.9963
21.4608	0.1198	59.0426
23.4565	0.1783	59.0996
25.4522	0.2476	59.1670
27.4480	0.3277	59.2450
29.4437	0.4188	59.3337
31.4394	0.5206	59.4327
33.4351	0.6333	59.5424
35.4308	0.7569	59.6627

37.4266	0.8913	59.7935
39.4223	1.0365	59.9348
41.4180	1.1926	60.0868
43.4137	1.3595	60.2492
45.4094	1.5000	60.3860

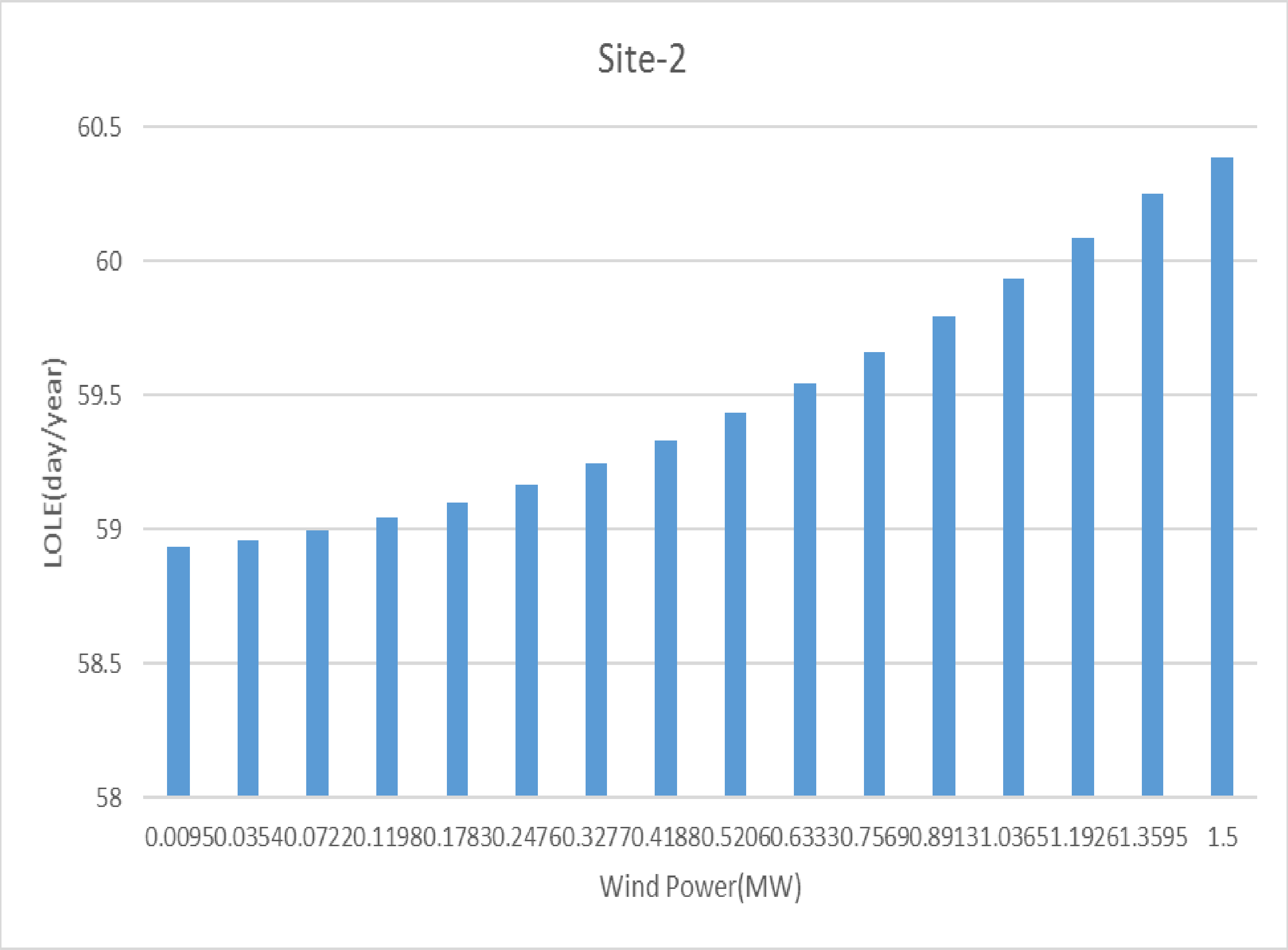

Figure 4.7 LOLE vs variable Wind Power(Site-2)

4.4.5.3 Loss of load expectation (LOLE) for Site -3

For IEEE basic reliability test system and the system load is 185MW [8] there are 12 units i.e. N = 12, hence there should be $2^N = 2^{12}$ = 4112 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 24 states and the calculated value of LOLE with the help of equation 3.11 are tabulated in Table 4.6 and fig 4.8 depict that the LOLE curve of variable Wind Power

Table. 4.6 Loss of load Expectation (LOLE) for Site -3

Wind Speed (Km/h)	Wind Power(MW)	LOLE(day/year)
15.1014	0.0058	58.9317
17.0577	0.0292	58.9545
19.0140	0.0629	58.9873
20.9704	0.1071	59.0303
22.9267	0.1617	59.0834
24.8831	0.2267	59.1467
26.8394	0.3022	59.2202
28.7957	0.3880	59.3037
30.7521	0.4843	59.3974
32.7084	0.5910	59.5013
34.6648	0.7082	59.6153
36.6211	0.8357	59.7394
38.5774	0.9737	59.8737
40.5338	1.1221	60.0182
42.4901	1.2809	60.1727
44.4465	1.4502	60.3375
46.4028	1.5000	60.3860

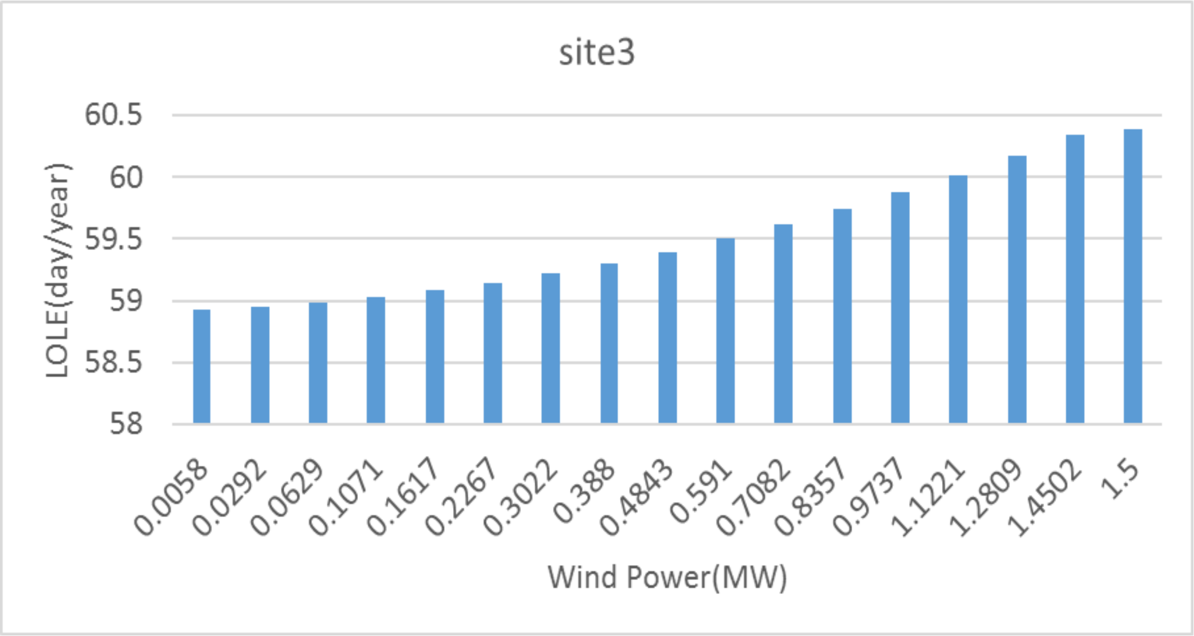

Figure 4.8 LOLE vs variable Wind Power(Site-3)

4.4.5.4 Loss of load expectation (LOLE) for common wind speed Model with variable wind speed

For IEEE basic reliability test system and the system load is 185MW [8] there are 12 units i.e. N = 12, hence there should be 2^N = 2^{12} = 4112 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 24 states and the calculated value of LOLE with the help of equation 3.11 are tabulated in Table 4.7 and fig 4.9 depict that the LOLE curve of variable Wind Power

Table 4.7 Loss of load Expectation (LOLE) for common wind speed Model

Wind speed(Km/h)	Wind power(MW)	LOLE(day/year)
16.2016	0.0177	58.9433
18.1256	0.0463	58.9711
20.0495	0.0850	59.0088
21.9734	0.1338	59.0563
23.8973	0.1926	59.1135
25.8212	0.2616	59.1807
27.7452	0.3406	59.2575
29.6691	0.4297	59.3443
31.5930	0.5289	59.4408
33.5169	0.6382	59.5472
35.4408	0.7575	59.6633
37.3648	0.8869	59.7892
39.2887	1.0265	59.9251
41.2126	1.1760	60.0706
43.1365	1.3357	60.2260
45.0604	1.5000	60.3860

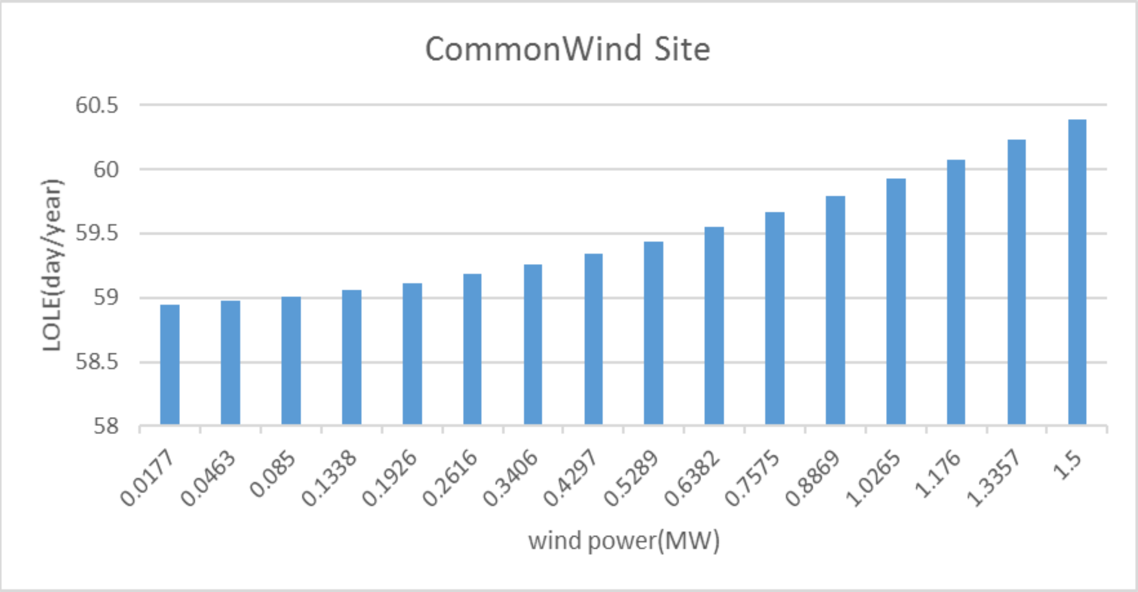

Figure 4.9 LOLE vs variable Wind Power (Common Wind Model)

4.4.6 Loss of Load Expectation (LOLE) for Constant Wind Speed

A wind farm with 18 WTG units is added in IEEE basic reliability system. Each WTG is rated at 1.5 MW, The added wind capacity is 27 MW. The contribution of wind units is considered by merging units in different ways randomly. However the system peak load is assumed to be 185 MW [8] in all cases

4.4.6.1 Test Problem 2 Case-1 Capacity Outage probability Table with wind

For IEEE basic reliability test system when 6(1.5MW) wind units merge in 1(9MW) units are tabulated in table 4.4, there are 14 units i.e. N = 14, hence there should be 2^N = 2^{14}= 16448 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 196 states the calculation value of COPT are depicted in fig 4.10 that is the state probability curve of capacity available

Table -4.8 Generating unit reliability data with wind(RBTS)(case1)

no	Unit Size(MW)	type	No of units	FOR
1	5	hydro	2	.01
2	10	thermal	1	.02
3	20	hydro	4	.015
4	20	thermal	1	.025
5	40	hydro	1	.020
6	40	thermal	2	.030
7	9	wind	3	.02

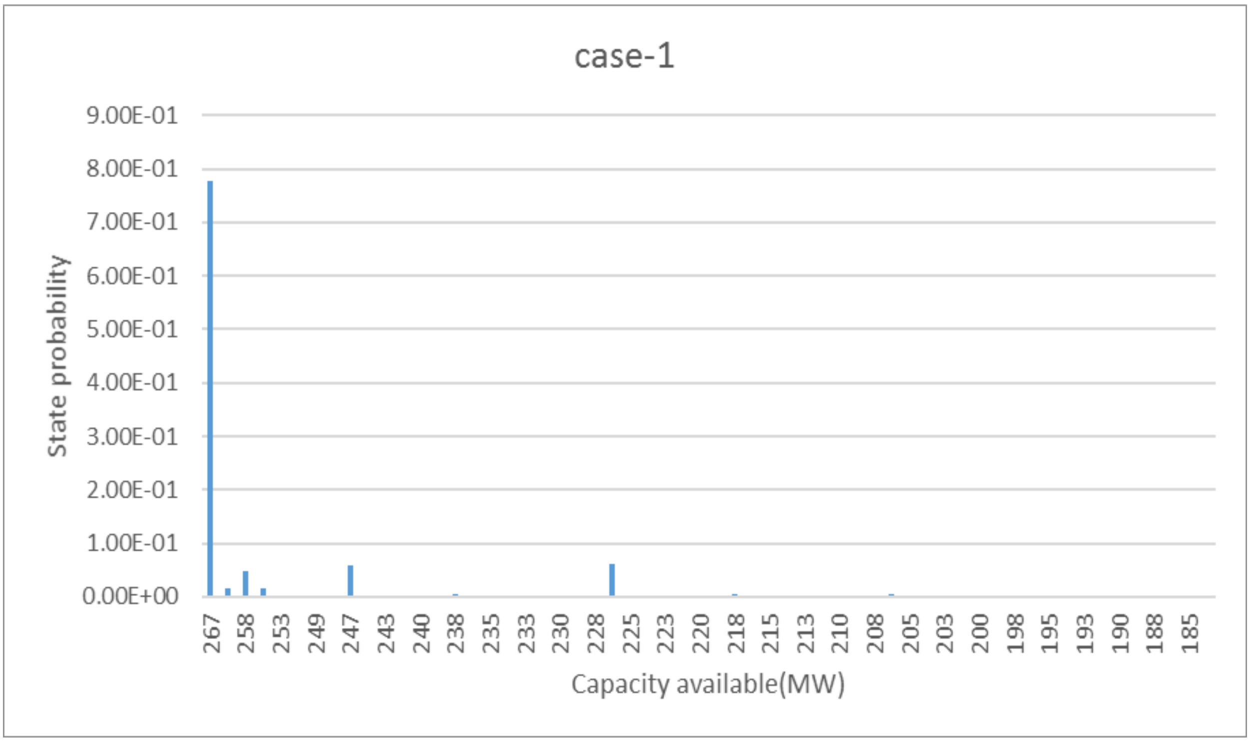

Figure4.10 case-1 State probability Vs Capacity available(with wind)

4.4.6.2 Test Problem 2 Case-1 Capacity Outage Probability Table (COPT) for LOLE with Wind

LOLE is computed by given equation (2.24). The variations of the LOLE with capacity available are shown in figure 4.11.

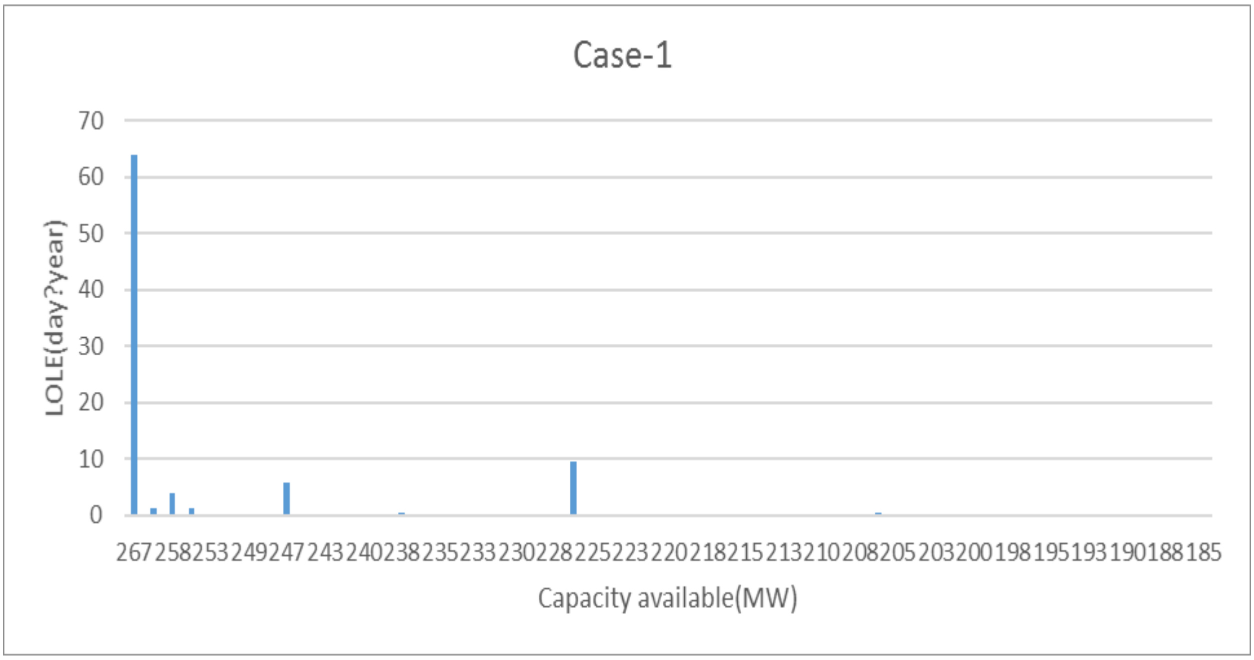

Figure 4.11 Case-1 LOLE Vs Capacity available(with wind)

4.4.6.3. case 2 Capacity Outage probability Table with wind

For IEEE basic reliability test system , when 4(1.5MW) wind units merge in 1(6MW) unit and 2(1.5MW) wind units merge in 1(3MW) unit given in Appendix 1.There are 16 units i.e. N = 16, hence there should be 2^N = 2^{16}= 65792 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 260 states the calculation value of COPT are depicted in fig 4.12 that is the state probability curve of capacity available

Table -4.9 Generating unit reliability data with wind(RBTS)(case2)

No	UnitSize(MW)	type	No of units	FOR
1	5	hydro	2	.01
2	10	thermal	1	.02
3	20	hydro	4	.015
4	20	thermal	1	.025
5	40	hydro	1	.020
6	40	thermal	2	.030
7	6	wind	4	.02
8	3	wind	1	.02

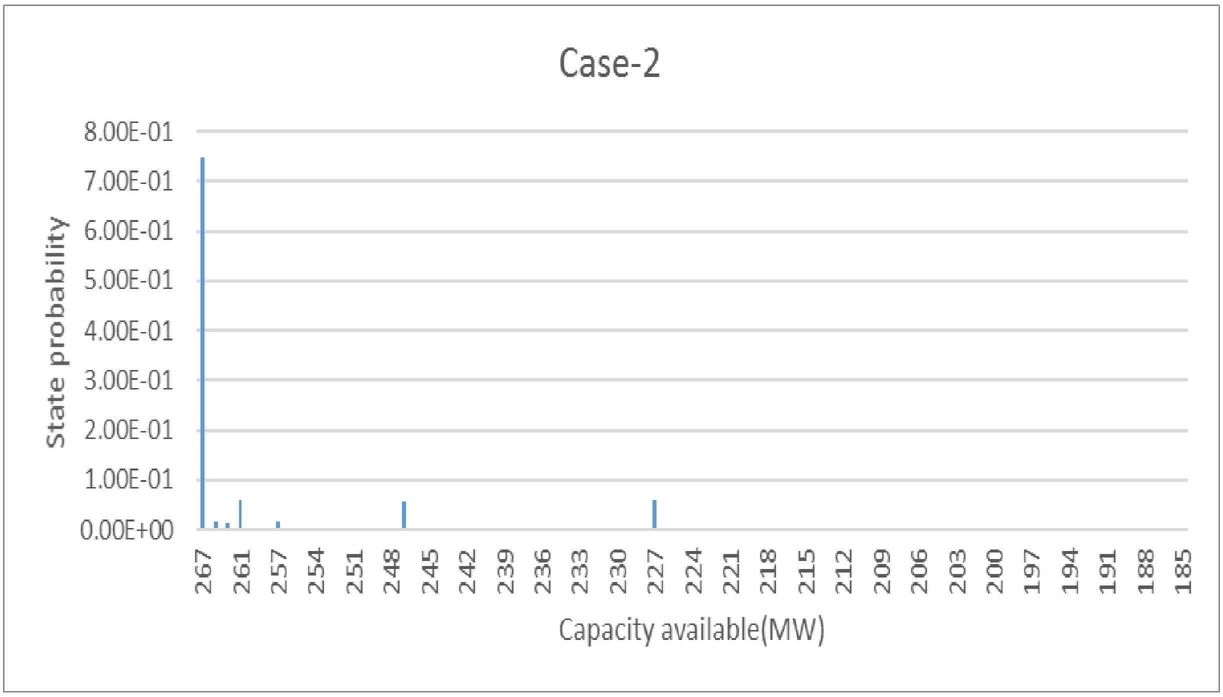

Figure 4.12 Case-2 State probability Vs Capacity available (with wind)

4.4.6.4Test Problem 2 case2 Capacity Outage Probability Table (COPT) for LOLE with Wind

LOLE is computed by given equation (2.24). The variations of the LOLE with capacity available are shown in figure 4.13.

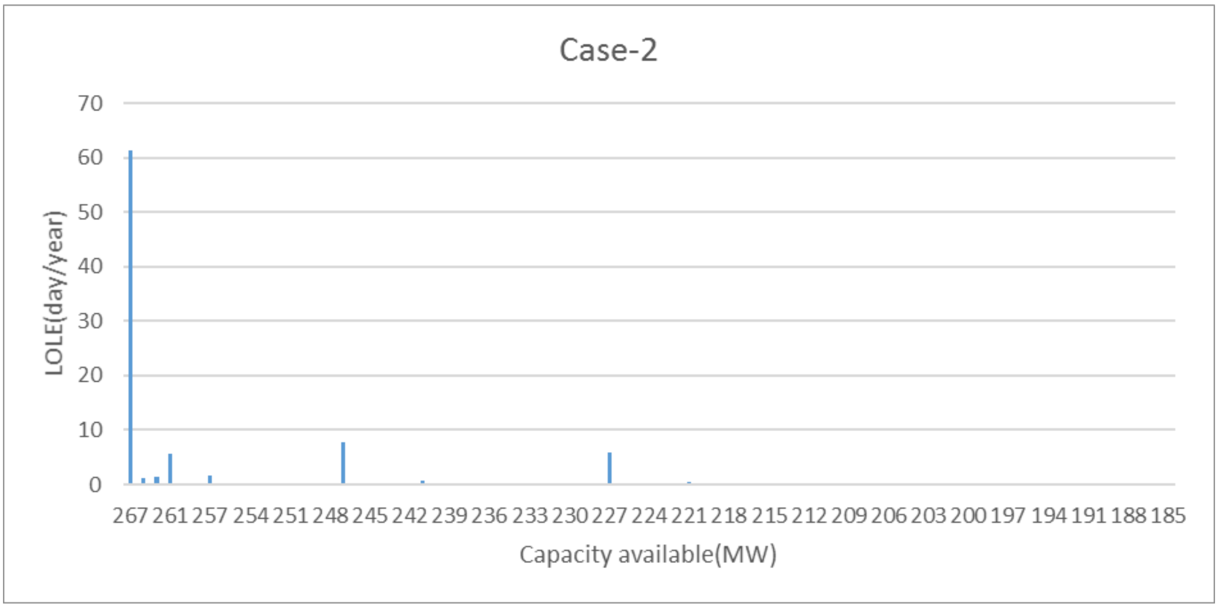

Figure4.13 Case-2 LOLE Vs Capacity available(with Wind)

4.4.6.5 Test Problem 2 case -3Capacity Outage probability Table with wind

For IEEE basic reliability test system , When 3(1.5MW) wind units merge in 1(4.5MW) unit given in Appendix 1 there are 17 units i.e. N = 17, hence there should be 2^N = 2^{17}= 131584 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 343 states the calculation value of COPT are depicted in fig 4.14 that is the state probability curve of capacity available

Table -4.10 Generating unit reliability data with wind(RBTS)(case3)

no	Unit Size(MW)	type	No of units	FOR
1	5	hydro	2	.01
2	10	thermal	1	.02
3	20	hydro	4	.015
4	20	thermal	1	.025
5	40	hydro	1	.020
6	40	thermal	2	.030
7	4.5	wind	6	.02

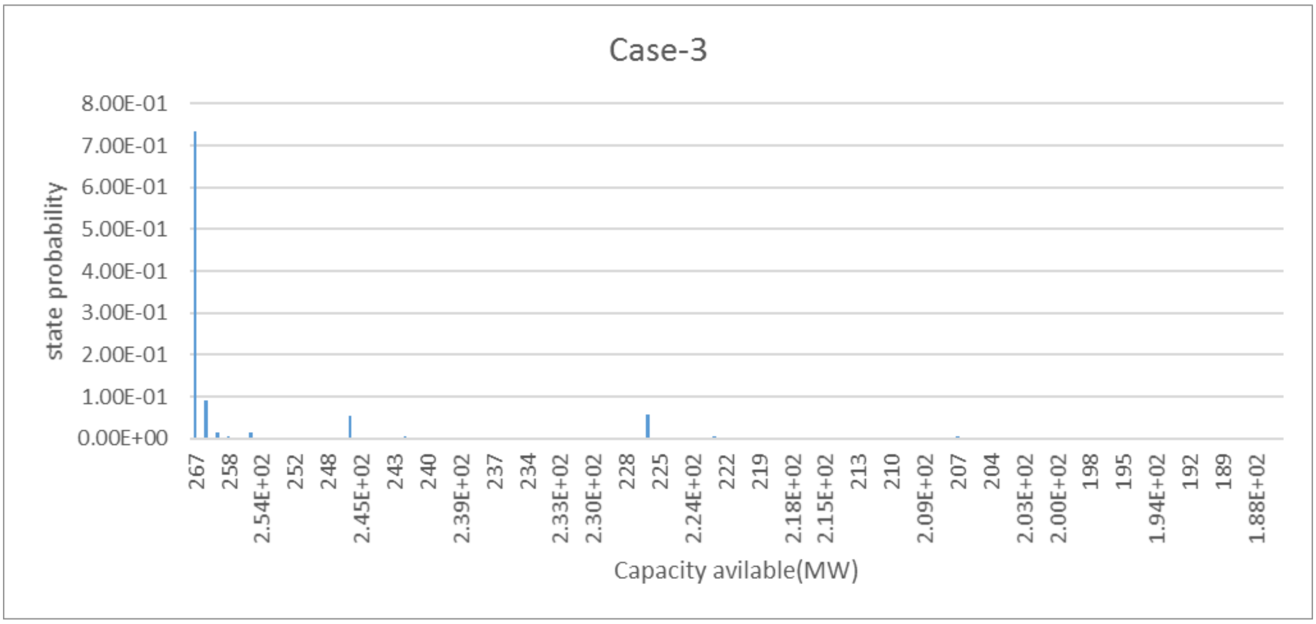

Figure 4.14 Case-3 State probability Vs Capacity available(with wind)

4.4.6.6 Test Problem 2 Case-3 Capacity Outage Probability Table (COPT) for LOLE with Wind

LOLE is computed by given equation (2.24). The variations of the LOLE with capacity available are shown in figure 4.15.

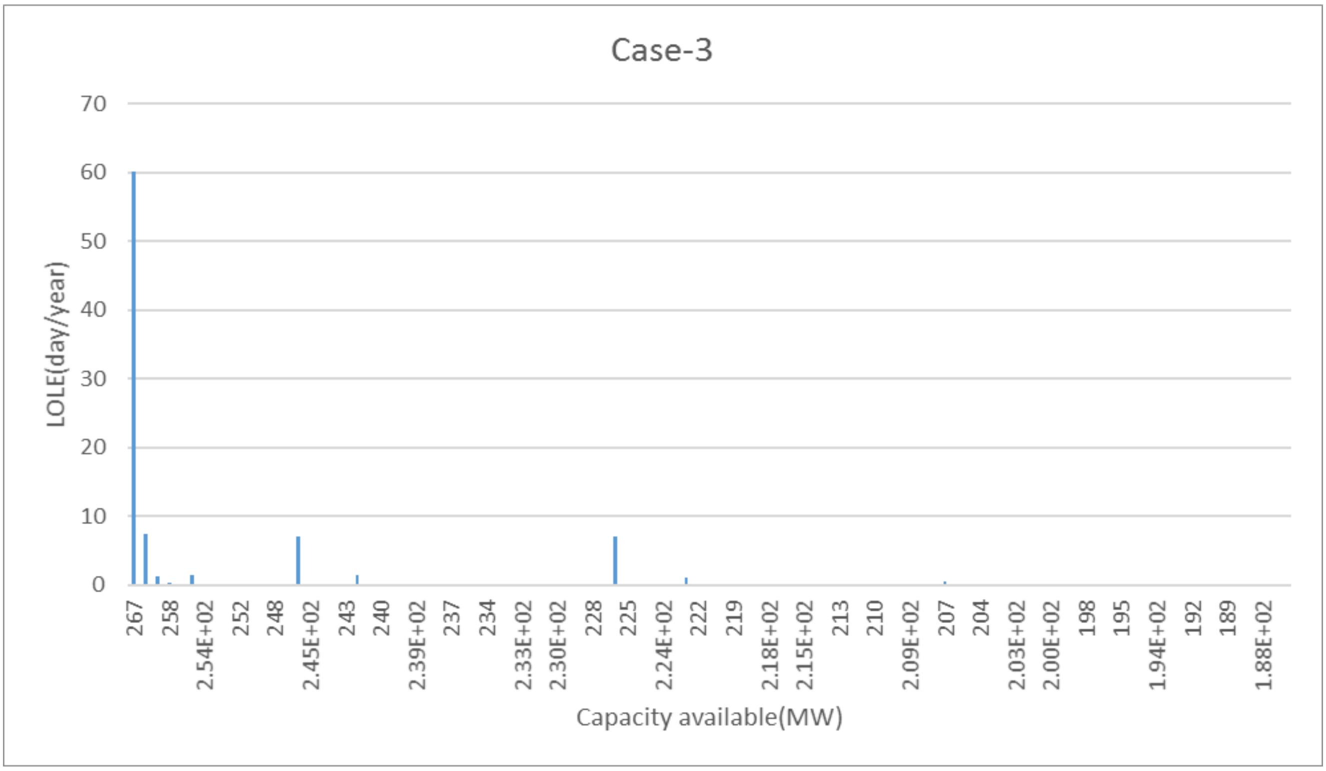

Figure 4.15 Case-3 LOLE Vs Capacity available(with Wind)

4.4.6.7 Test Problem 2 Case-4 Capacity Outage probability Table with wind

For IEEE basic reliability test system , When 2(1.5MW) wind units merge in 1(3MW)unit given in Appendix 1 there are 20 units i.e. N = 20, hence there should be 2^N $=2^{20}=$ 1052672 states, which include repeated state value for same power available. These repeated values merge and form a reduced COPT with total 259 states the calculation value of COPT are depicted in fig 4.16 that is the state probability curve of capacity available

Table-4.11 Generating unit reliability data with wind(RBTS)(case4)

no	Unit Size(MW)	type	No of units	FOR
1	5	hydro	2	.01
2	10	thermal	1	.02
3	20	hydro	4	.015
4	20	thermal	1	.025
5	40	hydro	1	.020
6	40	thermal	2	.030
7	3	wind	9	.02

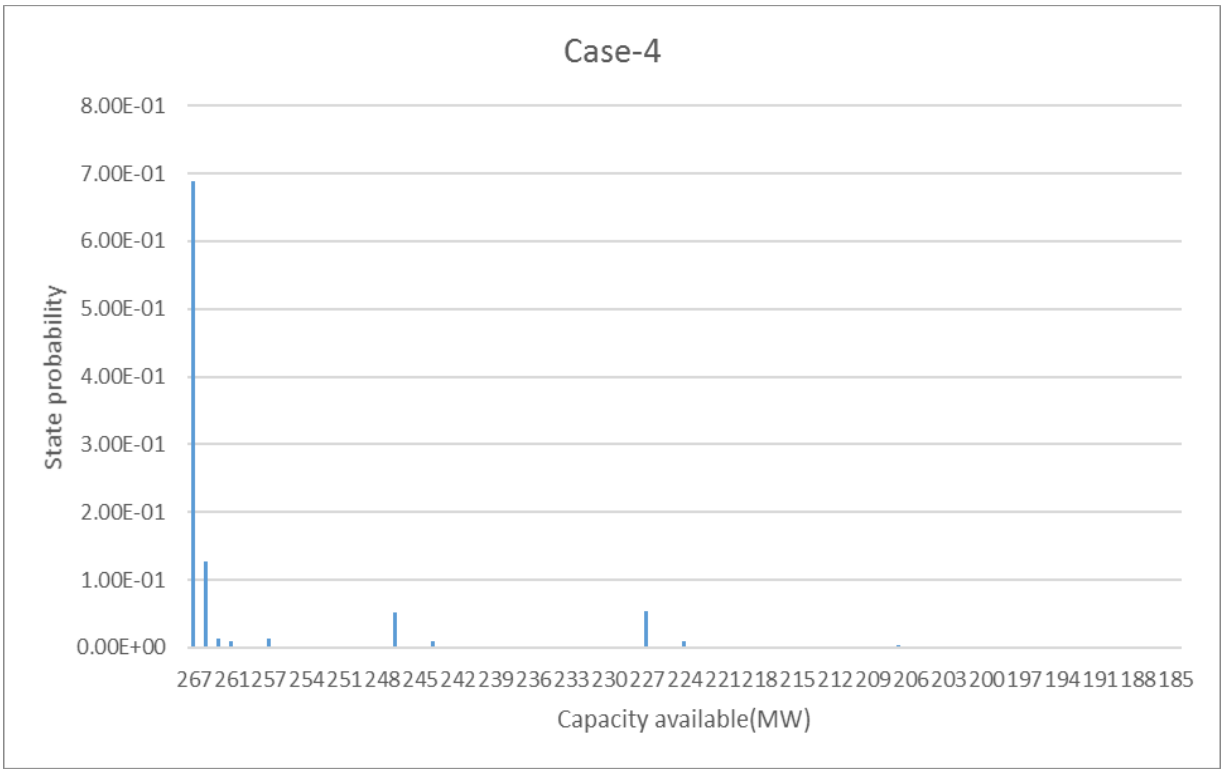

Figure4.16 Case-4State probability Vs Capacity available(with wind)

4.4.6.8 Test Problem 2 Case-4 Capacity Outage Probability Table (COPT) for LOLE with Wind

LOLE is computed by given equation (2.24). The variations of the LOLE with capacity available are shown in figure 4.17.

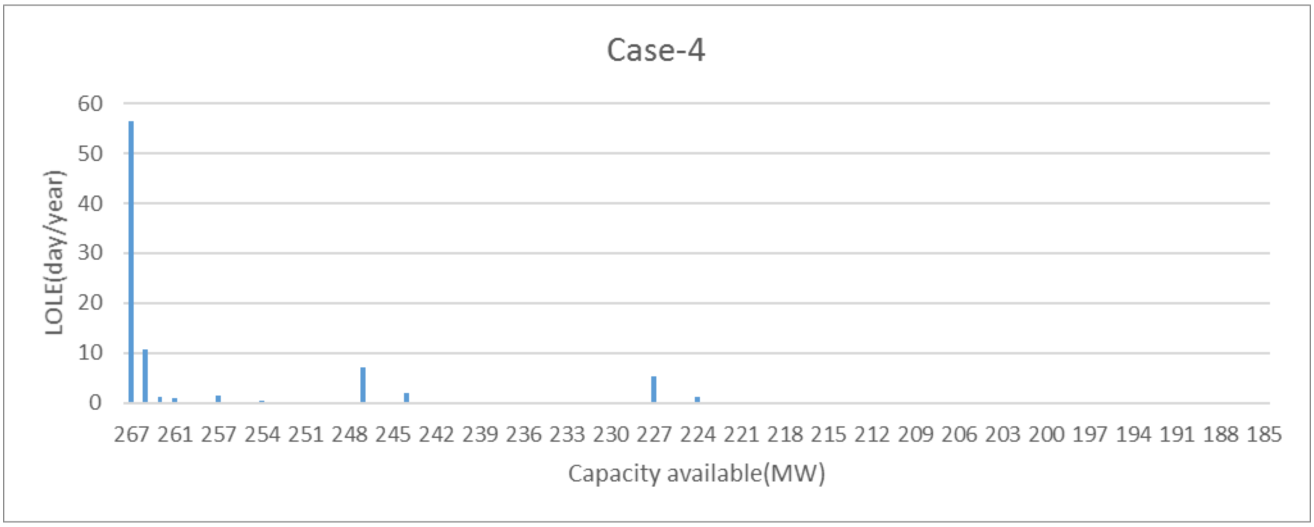

Figure 4.17 Case-4 LOLE Vs Capacity available (with wind)

4.5 LOLE for all test problem

Table -4.12 Different case study in IEEE basic Reliability test system

Different case study in IEEE basic reliability test system	**LOLE(day/year)**
Test Problem 1 without wind	59.3909
Test Problem 2 with wind case-1	87.8878
Test Problem 2 with wind case-2	87.9876
Test Problem 2 with wind case-3	88.9774
Test Problem 2 with wind case-4	88.2147

Chapter 5
Conclusion and Future Scope of Work

5.1 Conclusion

It becomes increasingly important to develop realistic reliability evaluation techniques that are practically useful for electric power industries that are expected to include a rapidly growing proportion of wind generation in the coming years. The benefits from wind sources are largely dependent upon the wind speed at the wind farm site. It is, therefore, very important to obtain suitable wind speed simulation models and appropriate techniques to develop power generation model for WTG in reliability evaluation.

It requires a significant amount of historical data and effort to develop a realistic wind speed model for a geographic site. Historical data from three Canadian sites with diverse wind regimes were used to obtain a common wind speed model in this dissertation. The common wind speed model can be applied to obtain a wind farm power generation model for any geographic location if the mean wind speed and standard deviation, and the WTG power curve parameters are known. In this dissertation work , generation adequacy is estimated using loss of load expectation index for a system with and without wind units. Due to variable speed of wind, the wind units are considered in partial available states. It is concluded from the results obtained that as the penetration of wind units is increasing with certain definite mount of power, the generation adequacy increases.

5.2 Future Scope-

1. The results show that the simplified method can be used in the reliability evaluation of a generating system including wind power with reasonable accuracy. This approach will be very useful for wind farm locations lacking adequate historical data. The presented simplified method can be easily used for practical applications.

2. Development of wind speed model also applicable for solar and other renewable sources

APPENDIX

Table-A 1 100 points load data for the RBTS

Peak load(p.u)	Study period (p.u)
1.0000	0.0000
0.9733	0.0006
0.9466	0.0024
0.9199	0.0076
0.8931	0.0160
0.8664	0.0333
0.8397	0.0614
0.8130	0.1004
0.7863	0.1452
0.7596	0.1918
0.7329	0.2339
0.7061	0.2773
0.6794	0.3300
0.6527	0.3934
0.6260	0.4591
0.5993	0.5242
0.5726	0.5742
0.5459	0.6265
0.5191	0.6881
0.1924	0.7603
0.4657	0.8302
0.4390	0.8880
0.4123	0.9420
0.3856	0.9783
0.3588	0.9949
0.9933	0.0002

0.9666	0.0008
0.9399	0.0034
0.9132	0.0081
0.8865	0.0189
0.8597	0.0401
0.8330	0.0718
0.8063	0.1122
0.7796	0.1574
0.7529	0.2005
0.7262	0.2436
0.6995	0.2909
0.6727	0.3448
0.6460	0.4094
0.6193	0.4771
0.5926	0.5390
0.5659	0.5869
0.5692	0.6415
0.5125	0.7043
0.4857	0.7810
0.4590	0.8473
0.4323	0.9029
0.4056	0.9549
0.3789	0.9827
0.3522	0.9977
0.9866	0.0003
0.9599	0.0010
0.9332	0.0040
0.9065	0.0100
0.8798	0.0239

0.8531	0.0464
0.8264	0.0823
0.7996	0.1254
0.7729	0.1704
0.7462	0.2114
0.7195	0.2561
0.6928	0.3030
0.6661	0.3616
0.6394	0.4260
0.6126	0.4932
0.5859	0.5501
0.5592	0.5592
0.5325	0.6544
0.5058	0.7218
0.4791	0.7992
0.4523	0.8599
0.4256	0.9159
0.3989	0.9347
0.3722	0.9867
0.3455	0.9991
0.9800	0.0004
0.9532	0.0015
0.9265	0.0058
0.8998	0.0137
0.8731	0.0290
0.8464	0.0517
0.8197	0.0906
0.7960	0.1353
0.7662	0.1823

0.7395	0.2232
0.7128	0.2670
0.6861	0.3163
0.6594	0.3769
0.6327	0.4420
0.6060	0.5089
0.5792	0.5625
0.5525	0.6134
0.5259	0.6706
0.4991	0.7410
0.4724	0.8158
0.4457	0.8758
0.4190	0.9293
0.3922	0.9721
0.3655	0.9905
0.3388	1.0000

Table A 2 Bus load data

Bus	Load(MW)	Bus load in & of system load
2	20	10.81
3	85	45.95
4	40	21.62
5	20	10.81
6	20	10.81
	Total=185	total=100

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