RELIABILITY ASSESSMENT OF LARGE WIND FARMS USING ARIMA MODELING AND AVAILABILITY ENHANCEMENT BY RELIABILITY ALLOCATION

A THESIS

Submitted by

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CERTIFICATE

This is to certify that the work presented in this thesis entitled "**RELIABILITY ASSESSMENT OF LARGE WIND FARMS USING ARIMA MODELING AND AVAILABILITY ENHANCEMENT BY RELIABILITY ALLOCATION**" is based on the authentic record of research done by **RAJEEVAN.A.K** under my guidance towards the partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** of the Cochin University of Science and Technology and has not been included in any other thesis submitted for the award of any degree.

I further certify that all the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral Committee have been incorporated in the thesis.

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DECLARATION

I hereby declare that the work presented in this thesis entitled "**RELIABILITY ASSESSMENT OF LARGE WIND FARMS USING ARIMA MODELING AND AVAILABILITY ENHANCEMENT BY RELIABILITY ALLOCATION**" is based on the original research work carried out by me under the supervision and guidance of **Dr. Usha Nair**, Professor, Division of Electrical Engineering, School of Engineering, Cochin University of Science and Technology, Kochi-22 and has not been included in any other thesis submitted previously for the award of any degree.

Kochi
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ABSTRACT

The wind power generation will play a vital role in the future power needs in view of the increasing demand of electrical energy and depletion of fossil fuel with its environmental impact. The main constraint of wind power generation is the uncertainty associated with wind speed and the low reliability of generated power. Suitable wind speed forecasting methodologies and wind turbine availability enhancement techniques will overcome these issues to some extent.

In a power generation system, reliability estimation of generated power will help to assess whether load demand is met by number of units generated. Also generation reliability is an important aspect of planning for the future development of power system. This work is directed to quantify generation reliability of Wind Energy System (WES) and discusses methods to improve the reliability.

First part of the thesis is concerned with the modeling of wind speed by Autoregressive Integrated Moving Average (ARIMA) method. Accuracy of the wind speed model is a crucial factor in determining the exact value of WES generation reliability. ARIMA model can accommodate long range correlations. Also in this model the nonstationary wind speed time series is converted into an associated stationary time series without changing basic statistical characteristics. These unique properties provide the ARIMA model an upper hand over conventional time series modeling. WES reliability estimation is accomplished by convolving generation model with load model. In generation model, to improve the accuracy an eleven state capacity outage probability table is developed using Wind Turbine (WT) power curve

and the developed ARIMA model. Load model is the load duration curve of the grid. The estimated reliability values are compared with bench mark values.

The power generation reliability not only depends on the speed of incoming wind but also on the turbine availability. Second stage of the work is concerned with turbine availability enhancement methods. A Markov model of the WT with condition monitoring is developed using failure and repair rate values. This model accommodates failure and repair values of all components of turbine which enhances the accuracy of the model. Using this model, different sensitivity analyzes are performed on the WT data, to learn the characteristics of turbine components that are likely to have an impact on system availability the most. Finally reliability allocation is performed on major WT components to enhance the availability to the benchmark level. The results are presented.

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LIST OF ABBREVIATIONS

ACF - Auto Correlation Function
ANNs - Artificial Neural Networks
AR - Auto Regressive
ARIMA - Auto Regressive Integrated Moving Average
ARMA - Auto Regressive Moving Average
CBM - Condition Based Maintenance
CF - Capacity Factor
CM - Condition monitoring
CMS - Condition Monitoring System
CMSs - Condition monitoring Systems
COE - Cost of Energy
COPT - Capacity Outage Probability Table
DPLVC - Daily Peak Load Variation Curve
FOR - Forced Outage Rate
GFS - Global Forecasting System
HAWT - Horizontal Axis Wind Turbine
HL - Hierarchical Level
HPP - Homogeneous Poisson Process
LDC - Load Duration Curve
LLU - Loss of Largest Unit
LOEE - Loss of Energy Expectation
LOLE - Loss of Load Expectation
LOLP - Loss of Load Probability
MA - Moving Average
MCS - Monte Carlo Simulation
MDP - Markov Decision Process
MDT - Mean Down Time
MDT$_S$ - Mean Down Times
MTBF - Mean Time Between Failures
MTTF - Mean Time To Failures
MTTR - Mean Time To Repair
NWP - Numerical Weather Prediction
O&M - Operation and Maintenance
PACF - Partial Auto Correlation Function
PLP - Power Law Process
RM - Reserve Margin
SCADA - Supervisory Control and Data Acquisition System
SVM - Support Vector Machine
VAWT - Vertical Axis Wind Turbine
WES - Wind Energy Systems

WF	-	Wind Farm
WRF	-	Weather Research and Forecasting
WT	-	Wind Turbine
WTG	-	Wind Turbine Generator
WTs	-	Wind Turbines

LIST OF NOMENCLATURE

Symbols	
A	Rotor swept area in m^2
A_s	Turbine availability
A_1	Gear box availability
A_2	Generator availability
A_3	Electronics and other parts availability
A_4	Blades/ pitches availability
E_k	Energy not supplied due to capacity outage O_k
g_i	Nominal capacity index
$\widetilde{G_A}$	Total generating capacity
G_j	Capacity of the jth state
N	Total number of generators in the system
n	Number of Wind turbine components
O_k	Magnitude of the k^{-th} outage in the system
P	Wind power generated in watts
p_k	Probability of a capacity outage of magnitude O_k
P_r	Rated power of the turbine
$R_{(t)}$	system reliability
sw_t	Simulated wind speed
t_k	Number of outage hours of magnitude O_k
u_i	Unavailability index
V	Wind speed in m/s
V_{ci}	Cut in wind speed
V_{co}	Cut out wind speed
V_r	Rated wind speed
θ	Mean time between failure

$\theta_q(B)$	Moving average operator of order *q*
λ	Failure rate
λ_i	Deterioration rate of the *i*th deterioration stage
${\lambda_1}^i$	Transition rate from up state to de-rated state of sub-component *i*, *i*=1, 2, 4
${\lambda_2}^i$	Transition rate from de-rated state to down state of sub-component *i*, *i*=1, 2, 4
$\lambda^{\mathbf{3}}$	Transition rate from up state to down state of sub-component 3
λ_{eq}	Equivalent failure rate
$\lambda_s.$	Predicted system failure rate
${\lambda_s}^*$	Specified system failure rate
μ	Repair rate
μ_{eq}	Equivalent repair rate
ρ	Density of dry air in kg/m^3
$\hat{\rho}_k$	Sample autocorrelation
$\phi_p(B)$	Autoregressive operator of order *p*
ϕ_{kk}	Partial autocorrelation
$\hat{\phi}_{kk}$	Sample partial autocorrelation

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Power generation and its utilization is one of the most significant performance indicators of total development of any country and the per capita energy consumption is increasing day by day. Currently, major portion of world’s energy demand is met by fossil fuel operated power generating plants, which leads to global warming and emission of unwanted gases. Statistics by International Energy Agency indicates that in the next two decades the global energy demands will shoot up by 90% from the current demand. Thermal power plants constitute 63% of the worlds installed capacity of power generation as on 2016 and this quota is expected to reduce progressively in the near future as more and more renewable energy sources penetrate into the existing energy market [1].

India raises the utilization of renewable energy sources by following strict emission standard and regulatory frameworks. Deteriorating availability of fossil fuel also increases the popularity of renewable energy sources. India’s reliance on coal as a source of energy is normal for a developing economy, but the need to balance the economic growth with environmental concerns are more significant and this points towards the use of renewable energy sources like wind, solar, biomass, small hydel etc. Societies, as they progress, tend to take more initiative to reduce the carbon footprint and replace it by renewable sources.

To address the issues of global warming and green house gas effects, world is looking forward to green energy sources like wind and solar which are abundant, cleaner, environmentally friendly and inexhaustible. The Indian government has strongly committed to its targets of reducing emissions by 33% by 2030, as set out during the COP21 summit in Paris, and towards this it has initiated a strong push to a green energy based economy and has also invested heavily in renewable energy [2]. But getting renewable to market too soon may mean costly and inefficient subsidies for technology that is irrelevant. So renewable energy must be introduced at the right time with suitable advances in technology. Among the different green energy technologies, Wind Energy System (WES) is the most accomplished and matured technology which can efficiently minimize environmental pollution, abolish fuel price variations and economically beneficial. Wind power plays a vital role for the development and establishment of sustainable electric power supply system.

Currently power generation from Wind Farms (WFs) using mega watt class Wind Turbines (WTs) is economic than any other green energy generation and it can effectively compete with conventional coal based power generation at the present cost. According to the Global Wind Energy Council (GWEC) report 2016, global wind energy capacity has reached 487GW by the end of December 2016 and the global wind power share is close to 5% of world’s total electricity demand [3]. Presently, almost 110 countries are benefited by wind energy on commercial basis. As per World Wind Energy Association (WWEA), by the year 2020, the world is expecting an installed wind generation capacity of more than 700GW and the contribution of India is expected to be 75GW by 2022. Wind power constantly keeps growing in India and in the rest of the world as Fig.1.1.

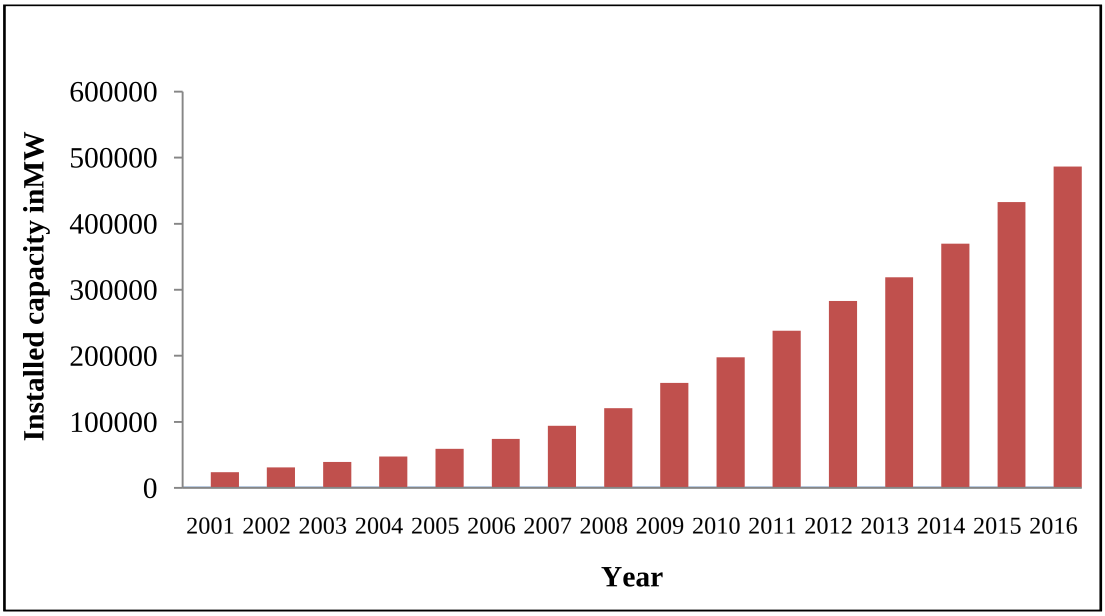

Fig.1.1 Global Cumulative Installed Wind Capacity 2001 to 2016

But the uncertainty linked with wind velocity is a matter of question which should be taken into consideration for wind power generation to be successfully integrated into an existing power system. The uncertainty can be managed to a great extend by the use of accurate wind forecasting techniques.

Electric system behaviour is stochastic in nature, and therefore it is relevant to consider that the assessment of such systems should be based on probabilistic techniques. The power system reliability theory based probabilistic techniques is capable of quantitatively estimating the risks associated with planning and operation of the system. The uncertainty of the wind power integrated to the main grid can be quantitatively estimated with this theory which is well-developed in the recent decades.

The first and the foremost step in reliability assessment is the accurate mathematical modelling of the stochastic quantity.Commonly used stochastic based method of wind speed modeling is Auto Regressive Moving Average (ARMA) [4]. In ARMA modeling, non stationary wind speed time series is assumed to be stationary, which introduces error in the wind power modeling as well as reliability analysis. Thus a better and more accurate wind speed model is highly essential for achieving exact reliability indices which results in the accurate generation planning and scheduling of the system. These facts lead to the search for a suitable wind speed model for the reliability evaluation of WES. The Autoregressive Integrated Moving Average time series model is capable of accommodating the nonstationary nature of wind speed. This works also give suggestions to improve generation availability by identifying the most sensitive components using Markov model. Moreover, reliability allocation is performed on Wind Turbine (WT) components to enhance returns from Wind Farm (WF).

The objective of the work and organisation of the thesis are given below.

1.2 OBJECTIVE OF THE WORK

Even though WES is presented as a way to minimize green house gas emission, its variability increases uncertainty and risk in expected generation. The aim of the research is to estimate the annual reliability of the WF using suitable wind speed model and suggest a method to improve the generation reliability. The work also aims to identify the most sensitive WT component to generation availability and to do reliability allocation. The major objectives can be summarized as follows:

- To develop a mathematical model Auto Regressive Integrated Moving Average (ARIMA) for wind speed of the site.
- To conduct generation reliability evaluation of the WF.
- To develop Markov model for the WT.
- To perform WT sensitivity analysis with Condition Monitoring.
- To conduct WT reliability allocation.

1.3 ORGANIZATION OF THESIS

Chapter 1 gives an overview of the work and organization of the thesis.

Chapter 2 describes the reliability evaluation and enhancement methods. The significance of accurate wind speed modeling and its challenges are also presented in this chapter. It discusses published works in the proposed area. Various reliability evaluation methods and WES availability improvement techniques are also mentioned.

Chapter 3 presents the time series modeling of real time wind speed data. The wind speed data for time series analysis is collected from a WF in the southern region of India with an installed capacity of 99MW having 60 WTs each with a capacity of 1.65MW. The ARIMA time series model is developed for this data and the analysis is carried out for adequacy check of this model.

Chapter 4 describes conventional generation system reliability indices and evaluation approaches. The basic system model and flow chart for reliability evaluation are explained. Using the wind speeds generated by the ARIMA model, wind power generation model in the form of Capacity Outage Probability Table is (COPT) for the system under study is formulated. Using the hourly load values collected from the substation, a load model for the grid is developed which is combined with the generation model for the reliability evaluation of the WF. Based on this various reliability indices are derived, using which reliability level of the WF is assessed. Different annual reliability indices are evaluated and conclusions on the reliability of the considered WF are arrived upon.

Chapter 5 presents a Markov model of the WES, for an accurate modeling with majority of components demanding 3- transition states. The mathematical formulation of the proposed Markov model incorporating the failure and repair values of all the components is explained in detail. Using this model, sensitivity analysis of the WT is performed considering all the constraints applicable to the system. Using the failure and repair data, reliability allocation is also carried out for the availability enhancement to the benchmark level.

Chapter 6 The major contributions and conclusions of the present work are consolidated in this chapter. The future scope of the work is also presented at the end of the chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The commercial use of electricity began in the late 1870s in North America, when arc lamps were used for street lighting and lighthouse illumination purpose. The first complete electric power system (dc system) was built by Thomas Alva Edison – the famous pearl street station in New York which began operation in September 1882 [5]. In India electricity was first introduced by the British people by lighting bulbs on the streets of Calcutta city. Afterwards, the authorities framed Electricity Act of India in the year 1910 regarding the supply and use of electrical energy [6]. At the time of independence, India was having power generation of about 1360 MW, that too in a highly decentralized manner in and around the urban areas [7]. It followed decades of development in power sector. Net result visible in this context has been formulation of state power grids, then regional grids, and now stepping towards evolution of national grid with transmission voltage increasing gradually from 132 kV to 765 kV class with intermediate voltages as 220 kV and 400 kV in AC system, while 500 kV and 800 kV in DC system [7-9]. Power Grid Corporation of India Limited (PGCIL) along with Central Power Research Institute (CPRI) developed ultra - high voltage AC (UHVAC) technology and 1200kV national test station for UHVAC in India at Bina. Two test transmission lines i) 1200kV single circuit and ii) 1200kV double circuit are successfully charged along with one 400/1200kV bay in 2015 [9].

In India, per capita energy consumption for the year 2014- 2015 is 1010 kWh, which is almost 62 times more than the per capita consumption in 1947 [10]. The world wide average per capita energy consumption in 2014 is 3144.377kWh which is too high compared to India's per capita consumption [11], [12]. Almost all the regions in India are facing energy crisis with national average energy shortage of about 2.1 % for the financial year 2015-16 [13]. To overcome this energy shortage, the government is promoting distributed generation and co- generation. It resulted in an increase of 215% for renewable energy generation compared to 34.6% for conventional thermal power generation in 11th plan. This will carry on with the 12th plan period also in view of the new policies of government to encourage nonconventional energy for meeting the increasing demand [14], [15]. Among the renewables, wind and solar occupy the major portions, and it is estimated that potential of grid connected wind power is 49130MW and solar power is 20MW to 30MW per sqkm in India [16]. The contribution of nonconventional energy generation towards total demand is around 17.4% as on 23/05/2017 in India, and the total demand for electricity of the nation is expected to cross 950 GW by 2030 [13], [17]. Green energy plays a significant role to supply this increasing demand and because of the matured technology, among the different renewables wind power has a vital role. The intermittency of wind power generation can be accounted for power system planning and operation by the application of power system reliability theory with appropriate wind speed modeling. Apart from that, generation availability of WES can be improved by the proper mathematical modeling and analysis of WT components. The above said facts are the essence of this thesis. This chapter reviews the published works related to these areas.

2.2 WIND ENERGY SYSTEM

The basic working principle of WES comprises of two energy conversion processes. The Wind Turbine (WT) rotor extracts kinetic energy from wind velocity and converts it into mechanical energy at the rotor shaft which is connected to the generator. For a grid interactive system, electrical power generated is delivered to the grid system to share the total load. The diagrammatic representation of the general working of WES is shown in Fig. 2.1

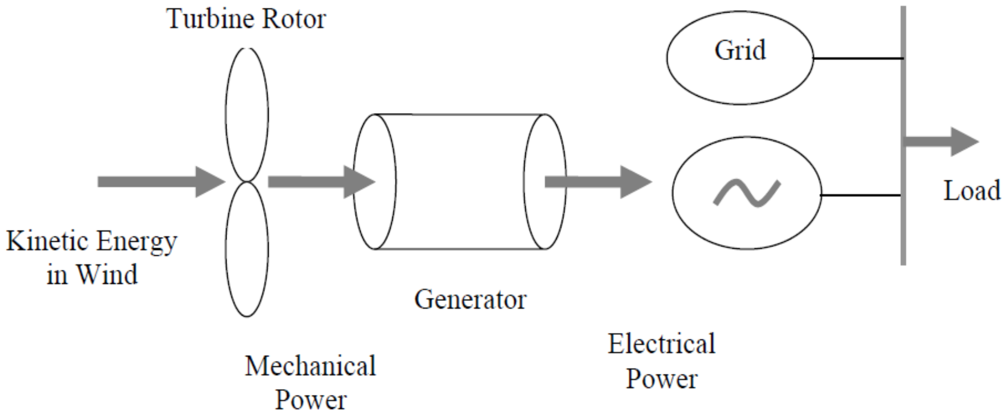

Fig. 2.1 General working principle of WES

The power produced by a WES is proportional to the cube of the wind velocity, and according to the axes of rotation by this wind, WTs are widely classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). HAWT have their axis of rotation almost parallel to the wind stream and horizontal to the ground. HAWT generally have high power coefficient and low cut in wind speed and easy furling. But, since the gear box and generator of these WTs are to be kept over the tower, its design is more complex and is much expensive. A tail or yaw drive arrangement orients the turbine towards the wind. According to the number of blades used, HAWT are further grouped as single bladed, double bladed and multi bladed [18], [19].

The axis of rotation of VAWT is almost perpendicular to the wind direction and is vertical to the ground. The complicated yaw devices can be eliminated in VAWT as it can receive wind from any direction. Generally, in VAWT the gear box and the generator are housed at the ground level. For this system, pitch control is not required when used for synchronous applications. Their main disadvantage is that, they are not self starting. Once it is stopped, additional mechanisms may be needed to push or start the turbine. As the rotor complete a rotation the blades have to pass through aerodynamically dead zones which will result in lowering the system efficiency. Because of these drawbacks most of the present commercial WTs used for power generation are three bladed HAWT [20-22].

2.2.1 Components of a Wind Energy System

A representative structure of modern WTs which are presently being deployed around the world is shown in Fig.2.2. These are horizontal axis geared WT with three composite blades, which have aeroplane propeller like structure. These blades are joined to rotor hub to drive the system by collecting energy from the incoming wind. This rotor drives a gear box and a generator coupling couples the gear box to the generator. A main shaft, which carries the main thrust of the rotor, is supported on suitable bearings and the rotor thrust is completely absorbed by the main bearing [23]. Gearing and generator are usually at the top of the tower in a nacelle and the gear box converts low speed of the rotor blades to the rated rpm of the generator. A safety brake arrangement is also placed between generator and gear box. A generator cooling system, controlling unit and the hydraulic system are also there in the nacelle. With the help of yaw bearing, the complete system which is covered by the nacelle frame is placed on the top of the tower. The wind sensors on the nacelle give signal to the yaw controller, to position the turbine and nacelle towards the direction of the wind to harvest maximum energy.

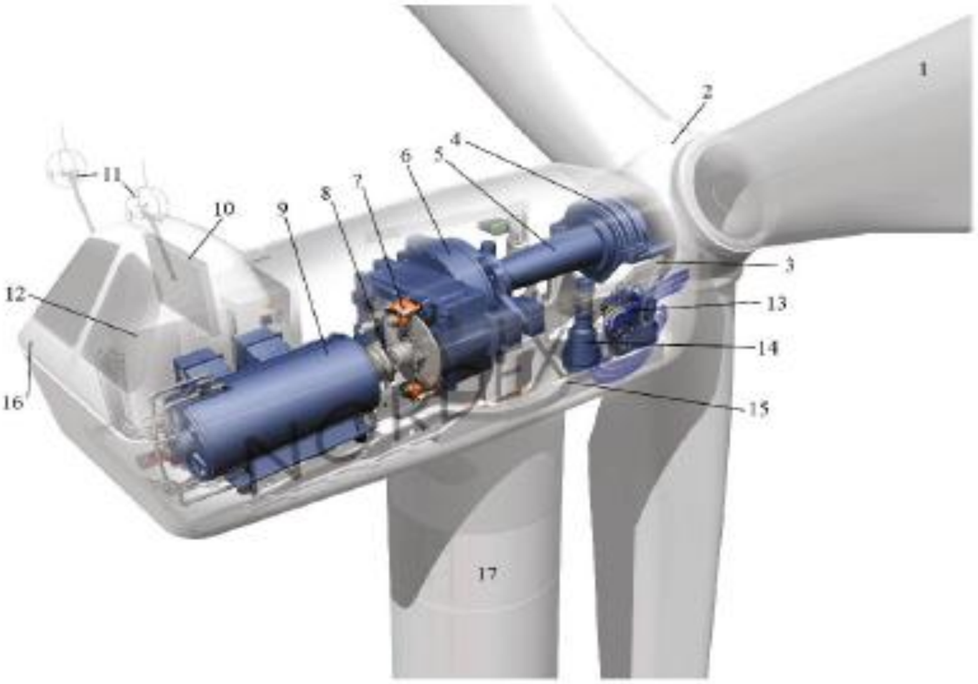

Fig. 2.2 Nacelle of a state of the art wind turbine

1. Rotor blade
2. Rotor hub
3. Nacelle firame
4. Main bearing
5. Rotor shaft
6. Gearbox
7. Safety brake
8. Generator coupling
9. Induction generator
10. Generator and gearbox cooler
11. Wind sensors
12. Nacelle control
13. Hydraulic system
14. Yaw drive
15. Yaw bearing
16. Nacelle cover
17. Tower

2.2.2 Power of a Wind Turbine Generator

Wind power generation from a particular site varies with the Wind Turbine Generator (WTG) characteristics and thus power generated depends on proper selection and design of the generator and the turbine system.

$$P = \frac{1}{2} \rho A V^3 \tag{2.1}$$

Where, P = Power Output from wind

ρ = Density of dry air in kg/m^3

A = Rotor swept area in m^2

V = Wind speed in m/s

It is observed from Equation 2.1 that power generated is directly proportional to the rotor area and the density of air [24]. Hence, it is equally important to choose suitable WTG design parameters to match a specific wind site. As power generation by wind is proportional to the cube of the wind speed, precise wind speed modeling is crucial for studying wind power effect on system reliability.

2.3 WIND SPEED MODELING

The reliability evaluation of wind integrated power system can be divided into three steps – wind speed modeling, WES output power evaluation, and system risk modeling [25].Wind speed modeling involves the prediction of energy that can be extracted from the time varying wind speed and for that, the historical wind speed data for the specific site is required [26]. In 1980’s, the wind speed models developed for reliability analysis of WES was in analytical domain and it has the drawback that chronological characteristics of wind speed and its impact on wind power output cannot be incorporated in the model. Thus, later on to overcome this drawback, sequential Monte Carlo simulation to simulate hourly wind speed for reliability analysis of WES was introduced [27-30]. Different probability distribution like Weibull, Rayleigh and Exponential distributions are also suitable to model wind speed. Generally Weibull distribution has been used to assess the potential of wind power in many works. The historical data of the wind farm (WF) is collected to evaluate the shape factor and scale factor of the Weibull distribution [31], [32].

In order to improve the evaluation accuracy of reliability indices of a wind integrated power system, a multi state Markov model is proposed in 1996 [33] and this model is suffering from the computation overhead during reliability evaluation. In addition to Markov model, other useful tool, which is applicable for reliability modeling for chronological wind power fluctuation is ARMA model, which is first developed by R. Billinton [34]. This method is applied for cost effective evaluation of wind energy, to study the correlation of wind speed among different stations and system well being analysis [35-38].

Black box method and gray box methods are the commonly referred methods in wind speed modeling and forecasting [39]. The world wide accepted traditional method is statistical method, which comes under black box method. This method gives good results in most of the cases like estimation of mean monthly, quarterly or annual wind speed. On the other hand in learning approaches or artificial intelligence like methods comes under gray box methods give good results in short term horizons like mean daily or hourly wind speed forecast [39].

The statistical methods commonly used to model and forecast wind speed are Auto Regressive (AR), Moving Average (MA), Auto Regressive Moving Average (ARMA), Box- Jenkins method and use of Kalman filter [40]. A number of studies concerning ARMA wind speed modeling and reliability analysis have been reported in the literature [26], [34], [41-45]. It has been shown that randomness wind velocity can be approximated by an ARMA model of order (n, n-1) and describes method for fitting wind speed models [34]. The wind speed is presented using ARMA method and the effect of replacing the conventional generating system with WES on reliability indices are examined on Roy Billionton Test System (RBTS) and IEEE-RTS [42]. The results show that to sustain a reliability criterion, the WES capacity should be higher than the conventional generating units. Also the system reliability can be improved by locating WTG units at multiple independent sites. In addition to this, energy storage in connection with WES can enhance the continuity of wind energy and hence can improve the reliability contribution [41], [44]. Wind speed simulation using ARMA model generates both positive and negative values and all negative values are set to zero during reliability evaluation [43]. This may lead error in further calculations, resulting analysis and future predictions.

References [46], [47] presented the use of ARIMA technique for load forecasting in power system with better accuracy. In [48] authors detailed how ARIMA technique can be utilized to predict electricity price in the electricity market of Spain and California with good results. A comprehensive fractional ARIMA model for forecasting hourly mean wind speeds is presented in [49] and the results show that by this method the forecasting accuracy is enhanced by an amount of 42 percentages in comparison with the persistence technique. A limited ARIMA model is used for wind power modeling relying on annual wind power measurement at Nysted offshore Wind Power Plant (WPP) in Denmark [50]. The LARIMA model is developed by introducing a limiter in ARIMA model to represent the upper and lower bounds of the wind power.

2.4 RELIABILITY EVALUATION

A power system provides reliable and economic supply of power to all its consumers. To make the continuously increasing demand of electric power, various nonconventional sources are being developed, of which WES also plays an important role. One of the major challenges in utilizing the potential of wind energy is that available wind speed is continuously varying, which makes the power output from a WTG uncertain and thus the probability of obtaining rated power very low. Hence power system reliability evaluation with WES is an important criterion in system planning and designing for ensuring healthy system operation [51 - 53].

Modern power systems are generally very complex and it is almost impossible to conduct various analyses on entire power systems. The system is usually broken into different functional zones of generation, transmission and distribution. System reliability can be examined separately at the three different hierarchical levels (HL) [54-57], as shown in Fig. 2.3.

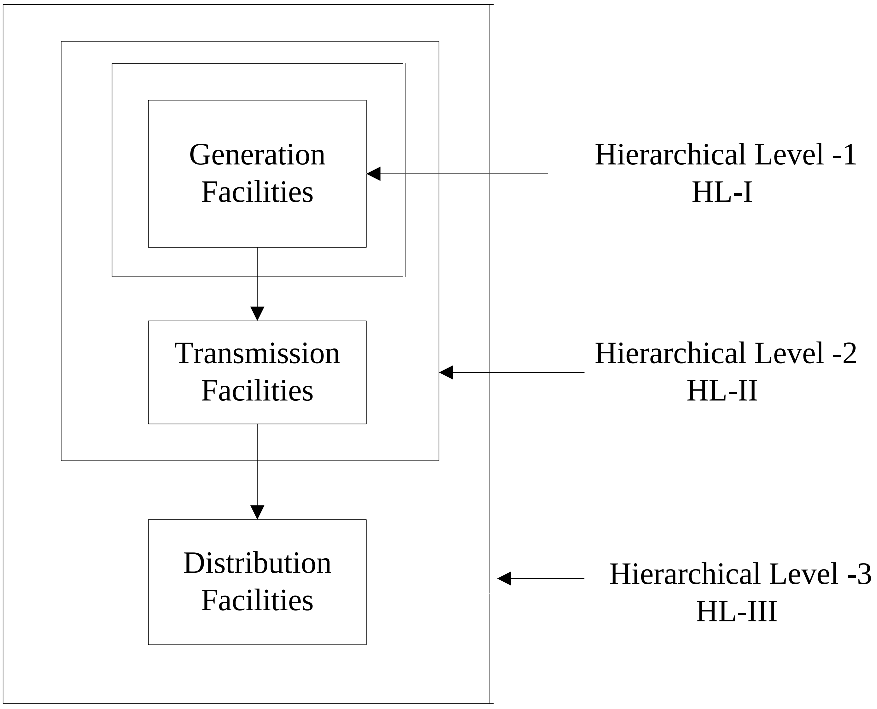

Fig.2.3: Power System – Hierarchical Levels

Different procedures have been used by power utilities for reliability assessment at the HL-I in generating system planning. Reliability evaluation methods are generally classified into deterministic and probabilistic methods which are discussed in next session.

2.4.1 Deterministic Techniques

Deterministic techniques were practiced in almost all utilities in the world in the past to determine adequate generating capacity to meet expected load demand in power system planning. The most commonly used criteria within this technique are described below.

1. Reserve Margin (RM) - In this criterion, the installed capacity is expected to be equal to the expected system peak load value plus a fixed percentage of the peak load. This method is also known as the percentage reserve margin. The RM criterion accounts for unexpected load growth in capacity planning [54], [58], [59].

   RM method was mainly used in early days for expansion planning of the small established systems. In this technique, the reserve margin depends on the expected peak load, that is, the adequacy is a function of peak load. So, based on the load demand or on the history of the load curve, usually 15% to 20% of the reserve is set to meet the peak demand. When the Reserve Margin goes below the expected level, plant addition is done. This technique is very easy to use and simple to understand in quantifying reliability and generation system adequacy [54].

2. Loss of the Largest Unit (LLU): In this method, to ensure the reliability of operation, the planning engineer, ensures that, the system will be capable of satisfying the peak load with the loss of largest generation unit. Under this criterion, the reserve capacity should be equal to or greater than the capacity of the largest unit in the system. The LLU criterion helps in avoiding load curtailment due to an outage of single unit in the system [54], [60], [61].

3. Combination of RM and LLU: The capacity reserve required in this case is equal to the capacity of the largest unit in the system plus a fixed percentage of either the installed capacity or the expected maximum demand. This

method ensures system reliability by anticipating an outage of any single generating unit and the uncertainty in the maximum demand [61].

Electric utilities in island nation, isolated systems and the developing world still make use of the conventional deterministic methods in generation planning. However, the deterministic method is not capable of identifying stochastic behavior of a power system and cannot give consistent value for system risk evaluation. Nowadays, major power utilities have changed from using deterministic to probabilistic techniques in generation planning [54], [61-63].

2.4.2 Probabilistic Techniques

The behavior of power system is stochastic and it is rational to compute system reliability based on methods that respond to the random system behavior in various scenarios. Probabilistic methods have been formulated to overcome such limitations of deterministic techniques and to give quantitative measure of system reliability [54], [64-67].

Many utilities around the world have used probabilistic techniques for system risk assessment at the HL-I. LOLE index is the most commonly used index for system reliability evaluation at the HL-I. The North American Electric Reliability Council (NERC) has indicated LOLE index of 0.1day/year as a benchmark for system planning at the HL-I. This criterion requires that the generation system be planned such that the system load does not go beyond the total generation for a long-term average value of 0.1 days in a year. Almost all utilities in the world use this LOLE criterion in generation planning. On the other hand few utilities use the energy-based index such as Expected Unused Energy (EUE) or Loss of Energy Expectation (LOEE) [68], [69].

Probabilistic techniques can be broadly divided into analytical and simulation techniques that can be used for getting different statistical system risk indices.

a) Analytical Technique: The majority of existing techniques are based on analytical methods, in which the system is represented by a mathematical model for the direct numerical solutions.

b) Simulation Technique: This method takes the problem as a series of real experiments and hence requires more computing time. The system reliability indices are calculated by simulating the actual process and random behavior of the system. Presently simulation methods are getting more attention with the continuous development of high-speed computers with their enormous memory storage [70], [71].

a) Analytical Techniques

Analytical techniques developed for HL-I reliability evaluation are commonly accepted and routinely applied by power utilities in generation planning. It is generally difficult to apply analytical techniques in composite system planning which needs system risk evaluation index at each and every load point in the power system [72], [73].

The basic HL-I system model is depicted in Fig. 2.4., where G denotes, the overall system generation which supplies power to the load and the basic approach to system reliability assessment at the HL-I is given by Fig. 2.5. The evaluation process is classified into three parts: as generation modeling, load modeling and risk modeling [74-76].

Fig. 2.4: Basic HL-I model

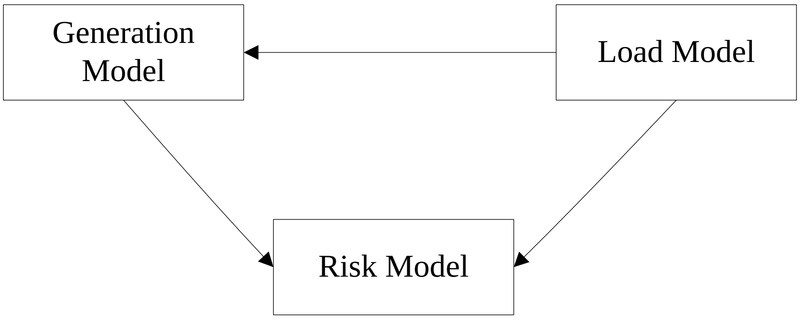

Fig. 2.5: HL-I reliability evaluation model.

In generation system modeling, the Forced Outage Rate (FOR) is an important parameter which is defined as the probability of finding the unit on forced outage at certain instant of time in the future. The FOR of a generating unit is computed as [54].

$$FOR = \frac{\sum(downtime)}{\sum(downtime) + \sum(uptime)} \tag{2.2}$$

Where

Uptime - from the moment component begins to operate to the moment it fails.

Downtime - from the instant the component fails to the instant it is returned to an operable condition.

The generating unit capacity ratings and the corresponding FOR are the useful data inputs that are used to create a Capacity Outage Probability Table (COPT). It is an array of generation capacity levels and the associated probabilities of existence.

A scheduled outage is also an outage that results when a generating unit is taken out of service, commonly for the intension of preventive maintenance. The ranking of a generating unit is generally reported as residing in one of the several feasible states [77] is represented in Fig. 2.6.

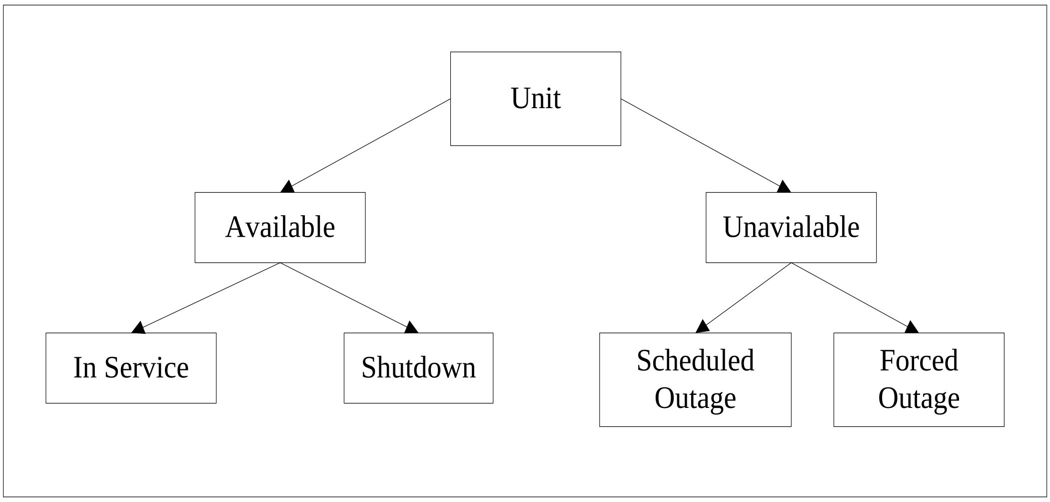

Fig. 2.6: Different states of generating unit

The load model gives the variation in the system load demand with time within a certain period. Usually in system planning and reliability study, the time period taken is 8760 hours ie, a calendar year. This is also presented in per unit of time. The system load can also be represented in per unit of the peak load [54]. The commonly used load models to calculate the risk indices are the Load Duration Curve (LDC) and the Daily Peak Load Variation Curve (DPLVC). The DPLVC is a model that gives the variation in the daily peak loads in the descending order. The net cumulative load model is known as the LDC when the individual hourly load values are used [54], [78].

Different risk or reliability indices are evaluated by convolving the generation model with load model. One of the most important risk indices is the Loss of Load Expectation

(LOLE), and is expressed as number of days in specific duration in which daily peak load runs over the available generation capacity [54],[79].

If the time is expressed in per unit of total time period, the index obtained is Loss of Load Probability (LOLP) in instead of the LOLE. The unit of LOLE is in days per year while using a DPLVC, and in hours per year while using a LDC load model [54], [80]. The area under the load duration curve represents the total energy demand in a year of the system. The energy based index Loss of Expected Energy (LOEE) also known as the Expected Unsupplied Energy (EUE), another useful index [80]. The probabilistic theory which deals with randomness of happenings is the appropriate method to model the stochastic nature of wind power generation.

b) Simulation Techniques

Simulation techniques are also probabilistic methods used in power system reliability evaluation. Unlike the analytical technique, this method simulates the actual system behavior on a computer to compute various risk indices. The recent advancement in computing technology has made simulation process faster [81]. The most commonly adopted simulation technique in reliability evaluation is Monte Carlo Simulation (MCS), which is based on random variable generator and it may give different numerical solution, every time the simulation is repeated. These techniques use chronological load variations for system risk evaluation [81], [82].

The MCS process can be either random or sequential. The random approach chooses intervals randomly to simulate the basic duration of the system lifetime, while sequential approaches do it chronologically. This approach is very critical to analyse the system for which one basic interval has remarkable effect on the next interval. Simulation methods are very useful in system risk evaluation at the HL-1 and HL-II. It suffers from difficulties that, it requires large computation time and memory space. Slightly different results are generally obtained when a simulation process is repeated. These techniques are generally not used when direct analytical techniques are available [81].

The simulation algorithms are more applicable for large-scale systems and can be categorized in to non-sequential and sequential simulations. Non- sequential simulations are concentrated on improving computation efficiency, and sequential simulations are concentrated on improving computation accuracy [71], [79].

2.5 WES GENERATION AVAILABILITY

Availability is a measure of reliability and is a significant figure in ensuring the success of a wind power plant. Poor availability is an indication of low reliability and it directly affects both the project's revenue stream through rising operation and maintenance (O&M) costs. Availability analysis is performed to verify that an item has a satisfactory probability of remaining operational so that it can achieve its intended objectives. The availability of a piece of element can be considered as a combination of its maintainability and reliability. Reliability can be considered as instantaneous availability when no maintenance or repair is performed [83]. By selecting proper O&M strategy, the availability can be improved to a higher value.

The historical data of failures and maintenance of components of WES is collected and analyzed statically, to evaluate the availability of the entire system [84]. A number of different methods have been adopted for modeling WTs and these methods vary depending on the purpose of the work. A suitable mathematical model for WES has to be selected to measure the availability of the system. In this work, Markov model is identified as a suitable mathematical model to conduct availability analysis which is detailed in the next session.

2.5.1 Two-State Markov Process

A Markov process is considered as a special type of stochastic process in which the state probabilities at a future instant do not depends on the states occupied in the past, but depends only on the present state of the process. A Markov process is memory less, and mathematically it can be briefed as, the probabilities of a random variable at t_{n+1} depends on the value of the random variable at t_n and not on the previous values. The process is illustrated with a two-state model [85], [86].

Consider a component that can only be in two states, either failed (down, $X=1$) or working (up, $X=0$). After failures, the component is repaired and restored to working state. The states and the possible transitions are shown in Fig. 2.7. The probability of being in one particular state at $t+\Delta t$ depend on the state the component is at time t and not on the previously assumed state.

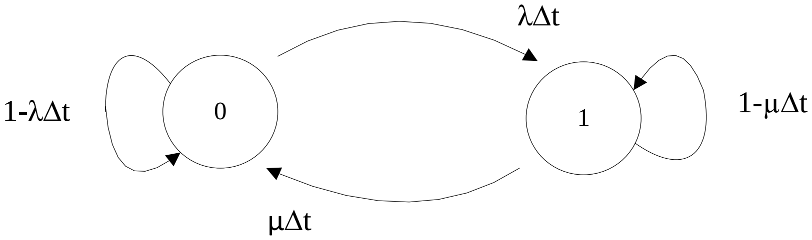

Fig. 2.7. Two State Markov Process

Let, T_0 be the component up time, T_1 be the component down time (distributed exponentially),

λ be the failure rate, μ be the repair rate

The transition probabilities p_{ij} from state i to j can be formulated as $p_{01} = \lambda\nabla\mathrm{t}$ and $p_{10} = \mu\nabla\mathrm{t}$ Also $p_{00} = 1 - \lambda\nabla\mathrm{t}$, and $p_{11} = 1 - \mu\nabla\mathrm{t}$.

- The state probabilities at $t + \nabla t$ are computed as:

$p_0(t + \Delta t) = p_0(t).(1 - \lambda\Delta\mathrm{t}) + p_1(t).\mu\Delta\mathrm{t}$, so $p_0(t + \Delta t) - p_0(t) = [-p_0(t).\lambda + p_1(t).\mu].\Delta\mathrm{t}$

$p_1(t + \Delta t) = p_0(t).\lambda\Delta\mathrm{t} + p_1(t).(1 - \mu\Delta\mathrm{t})$, so $p_1(t + \Delta t) - p_1(t) = [p_0(t).\lambda - p_1(t).\mu].\Delta\mathrm{t}$

- Dividing the above equations by $\Delta\mathrm{t}$ and letting $\Delta\mathrm{t} \rightarrow \infty$,

$p_{0(t)}^{\cdot} = -\lambda\mathrm{p}_{0(\mathrm{t})} + \mu p_1\,(t)$ and $p_{1(t)}^{\cdot} = \lambda\mathrm{p}_{0(\mathrm{t})} - \mu p_1\,(t)$

- Defining $P(t) = [p_0(t)\; p_1(t)]$, the equations can be written in matrix form:

$$\mathrm{P}^{\mathrm{l}}(\mathrm{t}) = \mathrm{p}(\mathrm{t}).\mathrm{A} \tag{2.3}$$

Where $\mathrm{A} = \begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix}$, which is termed as transition intensity matrix. On solving the above equation with initial conditions $(0) = [1 \quad 0]$, the equations for $p_0(t)$ and $p_1(t)$ are obtained, which are the solutions for the model.

2.5.2 Markov Process in WES

The main feature of the proposed Markov approach is that the deterioration and failure characteristics of a WT can be precisely captured by this method. The Markov model, which is also characterized as an intermediate state(s) model, has been used by a number of researchers in many application areas. Endrenyi et al and Anders et al. [87], [88] first applied the method to power systems equipment, enabling maintenance, deterioration and knowledge of the plant status to be modeled.

Billinton and Li [89] developed generation model for conventional plant including derated states and got a better solution than the conventional up/ down reliability model. In this paper, the intermediate states model (Markov process) is adopted for WT modeling, which helps in identifying the deterioration and failure characteristics of a WT. The other areas where Markov models utilizing intermediate states have been used are asset management applications; Oil filled Circuit Breakers in power system operations, water infrastructure [90] and road networks [91] in civil engineering.

2.6 AVAILABILITY ENHANCEMENT OF WTs

The total availability of a technical system depends on a number of aspects of its components, other than the parameters like failure frequencies, service demand of the system [92], [93]. The schematic representation of these aspects is depicted in Fig. 2.8. Even though the theoretical availability depends on failures per year, maintainability and serviceability the actual availability depends also on accessibility of the site and maintenance strategy.

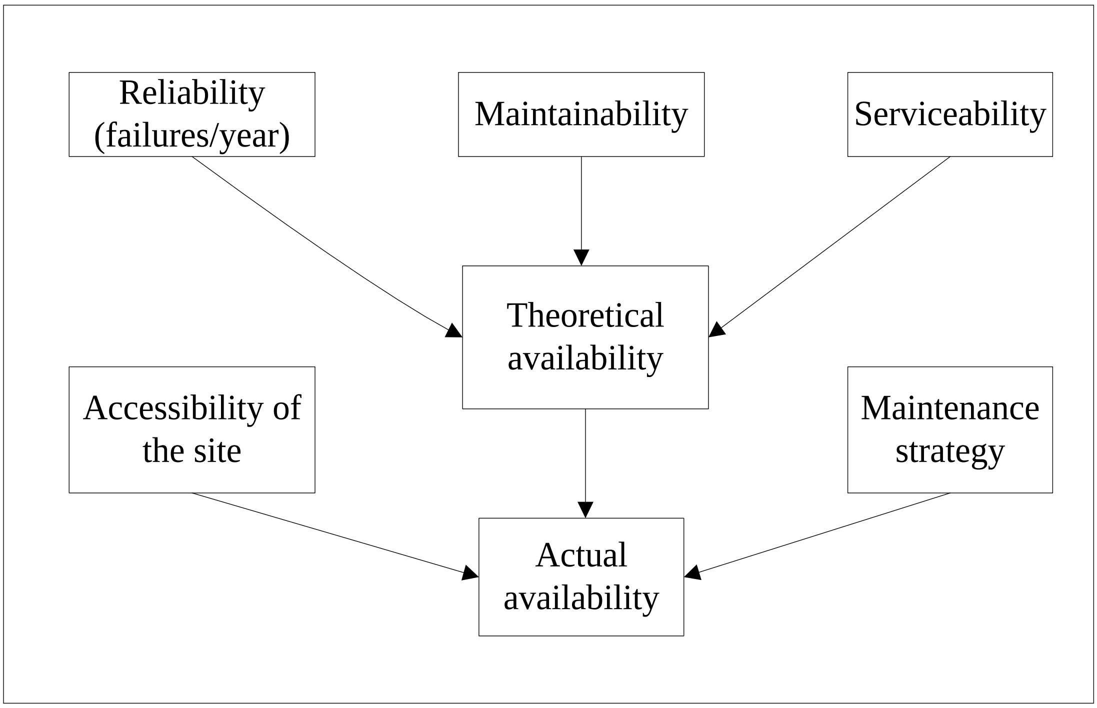

Fig. 2.8 Theoretical and actual availability

2.6.1 Component reliability

Reliability is defined as the ability of a system or component to perform its specified function for an intended period of time [55]. The failure frequency distribution per sub-systems for a population of WTs in Sweden is shown in Fig. 2.9. [94].

It is observed from Fig 2.9 that high rated wind turbines have higher frequencies of failures because of the sophisticated control system and electrical components [95],[96]. However, the electrical systems, pitch control systems and sensors in WTs have highest average failure rate. Usually a long down time is caused by failures of heavy and large components such as the generators, the gear box or the main shaft.

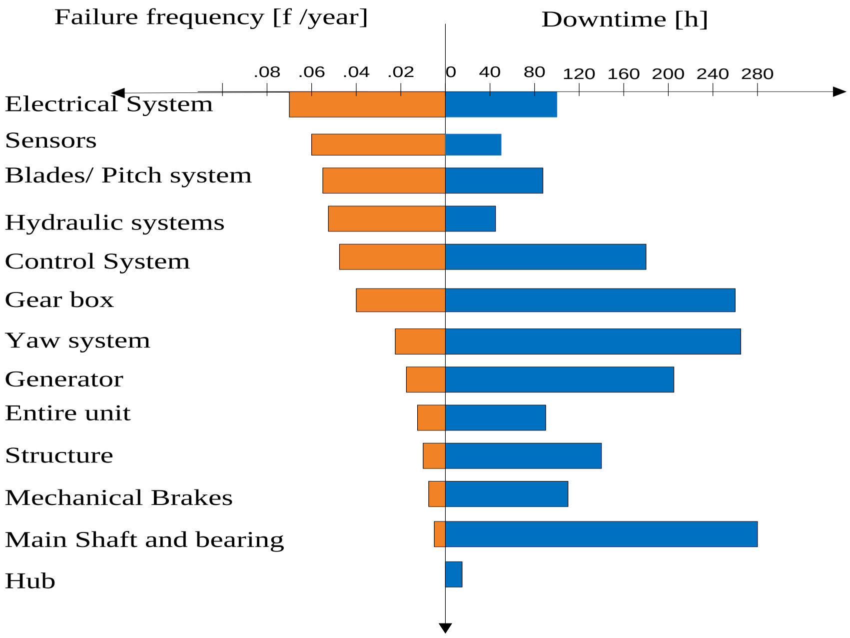

Fig. 2.9. Average occurance of failures and downtime per sub-system in WTs in Sweden in the period of 1997-2005

While the other components show low failure rates, high rate of failure coincide with considerable downtimes in the case of the gearbox, making this component especially crucial for the technical availability of the whole WT. A recent survey on failure rates of WTs reported that the average life times of the gearboxes are expected to a maximum of 6 to 8 years and they are having considerable failure rates.

2.6.2 Maintainability

In WES, generally maintenance or repair actions have to be taken at least two times a year, as could be deduced from the state-of-the-art failure characteristics. Generally a maintenance action is taken by a crew of two or three persons that drive to the failed WT with a service van. At the site they enter the WT and try to find out the cause of the failure and either start their maintenance action or come to the conclusion that additional equipment and/or spare parts are needed for the repair. The additional equipment can either be a crane for heavier lifting operations or "sky-work" utensils. The repair time can be anything between an hour to some days, when an exchange of a main component is essential for the operation [97-99].

2.6.3 Serviceability

The service demand of the currently manufactured WT in terms of man-hours is in the range of 40 to 85 hours and regular service visits is once in every 6 months [100]. Usually, once in every five years an intensive maintenance action has to be taken. During service shut down, certain major components are overhauled and the worn out parts can be replaced, that will take around 100 man-hours [101], [102].

2.6.4 Maintenance Strategy

A failure in a WT leads to direct costs for maintenance equipment, spare parts and maintenance staff required for rectifying the failures, as well as indirect cost due to energy production losses [103]. Maintenance strategies and organization of WT have to be clearly identified and implemented to reduce the high maintenance costs.

The maintenance strategies in the WT industry is widely classified into three main groups [104], 105]: as (1) Unscheduled (reactive or corrective) maintenance (2) time based (preventive maintenance) (3) condition based (predictive maintenance).

2.6.5 Unscheduled maintenance

A certain amount of unscheduled maintenance must be expected with any project. Commercial. WTs contain a variety of complex systems and each component should function correctly for the proper operation of the system [106]. Even the malfunction or failure of a minor component may frequently shut down the WT and need the attention of maintenance persons [106-109].

2.6.6 Preventive or Scheduled maintenance

Preventive maintenance is aim to replace components and refurbish systems that have defined useful lives, generally much shorter than the projected life period of the turbine [106], [107]. This work is normally termed as time based maintenance and this also include periodic inspections of the equipment, replacement of consumables such as brake pads and seals, adjustment of sensors and actuators, calibration, oil and filter changes, housekeeping and blade cleaning etc. Usually the maintenance manuals supplied by the turbine manufacturer explicitly defines the specific tasks and their frequency associated with planned maintenance. The costs associated with planned maintenance vary with the type and cost of consumables used, local labour costs, location and accessibility [106], [110-112].

2.6.7 Condition Based Maintenance (CBM)

Condition Based Maintenance (CBM) falls under preventive maintenance and is based on component behavior and parameter monitoring. [112]. CBM consists of all repair strategies such as inspections or permanently installed Condition Monitoring Systems

(CMS) to judge on the repair actions. The inspection involves monitoring techniques by the use of human senses (visual, noise etc.), or certain function tests [113].

After identifying the most sensitive elements to failures, select suitable criterion for monitoring of these components, then these criterions can be used to select sensors for collection of data using a data acquisition system and it can be used for monitoring. A particular unique attribute related to a particular component can be translated into a measurable parameter like current or voltage which may vary depending upon various operating conditions. This change will give information about operation conditions of various parts of the system [114], [115]. The appropriate maintenance strategy for the WES can be chosen after processing this data history and also either the faults can be predicted or detected for the continuous operation of the components for which they are designed to maintain the reliability [115].

A narration of models for CMSs can be found in [112-115] and this narration can be combined with concepts and definitions provided in [101, 116-120] which describes maintenance techniques and methods. The above references also depict the diagram relating technical concepts and the words used in the domain of WTCMS and the fault diagnosis. As shown in Fig. 2.10, CM is performed in three main steps:

1. Data acquisition with the help of sensors
2. Signal processing with the aid of modern data processing methods
3. Feature extraction through the retrieval of various parameters that will help in establishing the present status of the monitored equipment.

The fault of a system can be predicted or detected by using current information of the component via online monitoring and past status of the component which is obtained from the stored data. The corrective maintenance is carried out when a fault is detected. The two approaches of corrective maintenance are palliative maintenance and curative maintenance. Palliative maintenance consist of provisional solutions to failures while the other one for standing solutions to failures. The different preventive maintenance approach, which are taken when a fault is predicted are: current-state based or conditional maintenance, time-based or scheduled maintenance, status-based or proactive maintenance and parameter-projection-based or forecasting maintenance. [125], [126].

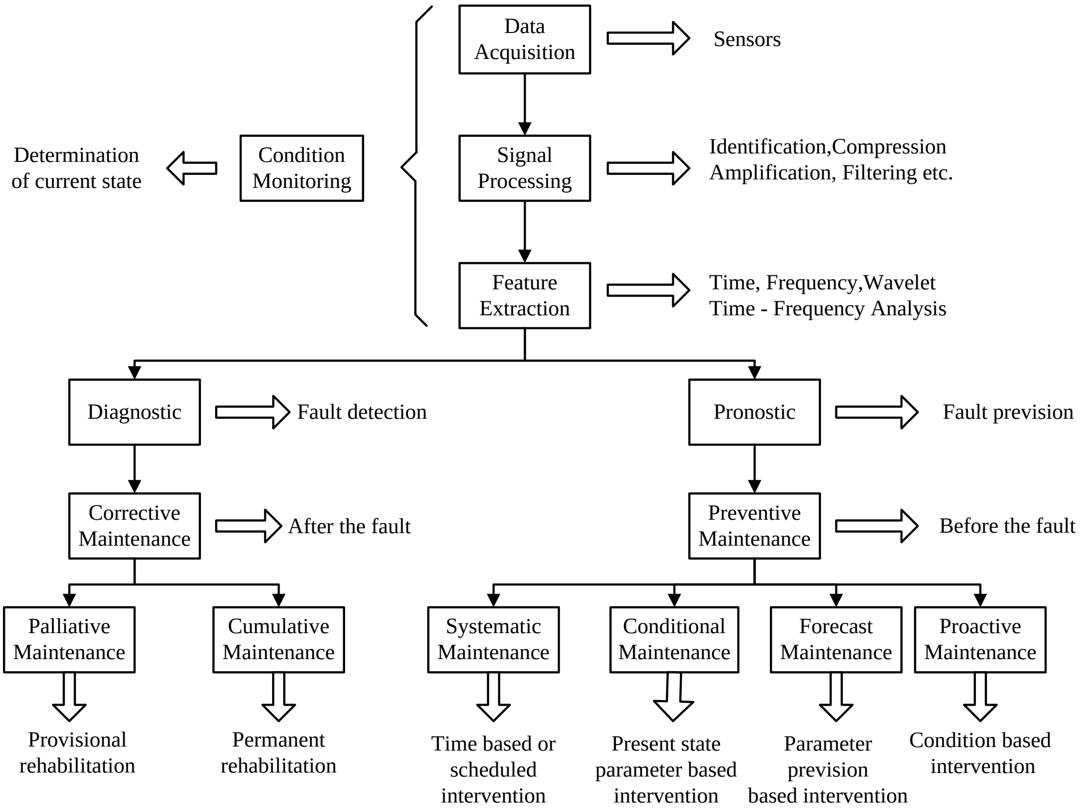

Fig. 2.10. Overview of condition-monitoring and maintenance processes for WTs

2.7 CONCLUSION

In this chapter an extensive literature survey is conducted in the area of reliability analysis of wind integrated power system. Power system reliability evaluation has been a hot topic of research and many methods are being continuously developed over the last five decades. Deterministic techniques were commonly used in power system planning and used by many utilities across the world. The nature of load variations in power systems or component failures cannot be recognized using these techniques. The development of probabilistic techniques, which are capable of accommodating the randomness, has attracted utilities to apply these methods in generation system planning. As the power developed by a WTG depends on the site-specific wind speed, reliability analysis in generation system planning requires accurate wind speed model to predict the fluctuating wind energy. Most of the wind speed modeling techniques, in reliability analysis is carried out using time series modeling techniques like AR, MA, and ARMA. Probabilistic techniques using analytical and simulation methods and the basic concepts behind analytical techniques for risk analysis are detailed. The most commonly used risk indices such as LOLE and LOEE are presented. Most of the utilities are also use these indices for generation system reliability evaluation. Availability is a measure of reliability and is a key factor in ensuring the success of a WES. Availability analysis is performed to verify that an item has a satisfactory probability of remaining operational so that it can achieve its intended objectives. By selecting proper O&M strategy, the availability can be improved to higher value.

CHAPTER 3

WIND SPEED ARIMA MODELING

3.1 INTRODUCTION

Power developed by a WT depends on the site-specific wind speed and hence the reliability analysis in the generation system planning requires an accurate wind speed model to predict the fluctuating wind energy. ARMA time series model is the mathematical tool used by most of the researchers in the field of reliability analysis of wind integrated power system. In this chapter, an accurate time series model ARIMA is introduced in which, Auto Correlation Function (ACF) and Partial Auto Correlation Function (PACF) of the observed and initially differenced hourly wind speed time series is plotted to check the stationarity. The best fitted ARIMA model for the stationary time series is then identified after conducting necessary adequacy checks. The work mentioned in this chapter has been published in the journal of Electrical Engineering Technology.

3.2 METHODOLOGY

3.2.1 Time Series Modeling Approach

Time series is an ordered sequence of observations. Commonly the ordering is through time, particularly in terms of equally spaced time intervals, it may also be taken through other dimensions such as space. Box and Jenkins introduced time series model for AR, MA or ARMA process [127], [40]. The importance of ARMA process is that a stationary time series can be modeled by it with a fewer parameters than a pure MA process or an AR process. Often the real world time series models are nonstationary in nature and therefore appropriate methods are to be adopted to convert the non stationary series to stationary series. To model a time series with the Box – Jenkins method, the observations have to be stationary. In practical terms, the series is stationary only if it tends to wander more or less uniformly around a fixed level. A series that exhibits a constant growth pattern, or overall trend, or a series that moves back and forth from one established level to another cannot be modeled before being converted to a stationary series. In statistical terms, a stationary process is assumed to be in a particular state of statistical equilibrium. If the properties of the process is unaffected by a change of time origin , the process is called strictly stationary, which indicates that the joint probability distribution of any 'm' observations made at times $t_{1,}\, t_2, \ldots \ldots t_m$ is the same as that associated with m' observations made at times $t_{1+k,}\, t_{2+k}, \ldots \ldots t_{m+k}$ [127].

As specified before, a non stationary time series has to be converted to a stationary series before being modeled by Box and Jenkins approach. This can be achieved by a computational process called "regular differencing" (RD), which is the process of computing the difference between every two successive values in a series and the resulting series of differences is called differenced series [127], [43]. The regular differencing is also called "a difference of order 1" as differences of higher order may also be used especially when dealing with seasonal time series. Differencing tends to remove the long term and short trends in a time series, and therefore is used to achieve stationarity. For most series it is unlikely that more than two regular differences would ever be needed to achieve stationarity. In the case of straight line trends a first order difference will produce stationarity [127], while for parabolic trends two first order differences will do so. In order to determine the correct amount of regular differencing, two more terms ACF and PACF are introduced. So the process of achieving stationarity could be an iterative process as shown in Fig. 3.1.

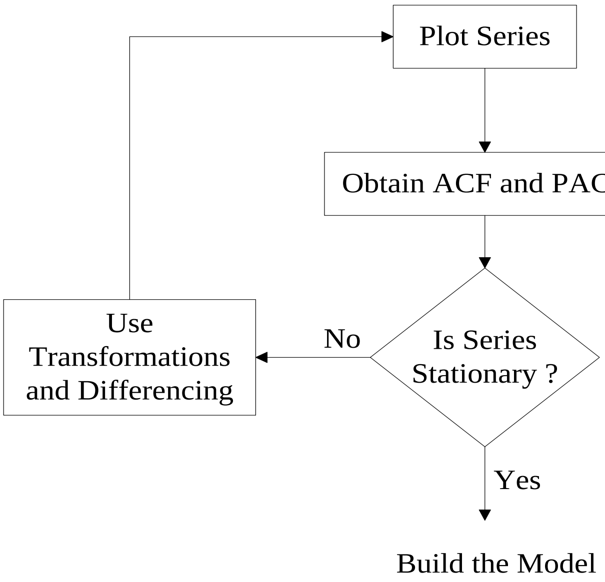

Fig.3.1 Process of achieving stationarity

3.2.2 ARIMA model

ARIMA time series forecasting technique has been developed by Box and Jenkins [127]. A general ARIMA (p,d,q) is given by,

$$\phi_p(B)\, w_t = \theta_q(B)\, e_t \tag{3.1}$$

where $\phi_p(B)$ is an autoregressive operator of order p, $\theta_q(B)$ is a moving average operator of order q and e_t is error series.

where $$w_t = \nabla^d \tilde{x}_t \tag{3.2}$$

B is the backward difference operator, d is the order of differencing and $\widetilde{x}_t$ - is the ARIMA model.

3.2.3 ARIMA model building algorithm

The general procedures of Box-Jenkins ARIMA involve:

- Identify appropriate differencing: Plot the time series observations and choose suitable transformations. The most widely adopted transformations are differencing operation and variance – stabilizing transformations. The first and most important step in forming an ARIMA model is the determination of the order of differencing needed to stationarize the series. Generally, the correct number of differencing is the lowest order of differencing that yields a time series which fluctuates about a well- defined mean value and whose ACF plot decays rapidly to zero, either from below or above. If the series still possess a long-term trend, or otherwise lacks a readiness to return to its mean value or if its autocorrelations are positive to a high number of lags, then it needs a higher order of differencing [34], [39], [127].

- Confirm stationarity : Compute and inspect the sample ACF and the sample PACF of the original time series to further affirm a necessary degree of differencing. Box –Jenkins forecasting models are tentatively identified by inspecting the behaviour of the sample autocorrelation function ρ_k and the sample partial autocorrelation function ϕ_{kk} . The ACF estimates the linear relationship between time series observations separated by a lag of k time units. That is, Autocorrelations are statistical measures that show how a time series is related itself over time. Autocorrelation coefficients are key statistical indicators in time series analysis; they are used to evaluate relationship among series values [34], [39], [127].The autocorrelation at lag1 indicates the correlation between the original series x_t and the same series moved forward by one period. It can be proven that ρ_k will always be between -1 and 1. A value of ρ_k , close to 1 shows that observations separated by a lag of k time units have a strong habit to move together in a linear fashion with a positive slope , while a value of ρ_k , close to -1 represents that observations separated a lag of k time units have a strong habit to move together in a linear manner with a negative slope.

The autocorrelation at lag k is defined by

$$\rho_k = \frac{E[(x_t - \mu)(x_{t+k} - \mu)]}{\sqrt{E[(x_t - \mu)^2]E[(x_{t+k} - \mu)^2]}} \qquad (3.3)$$

Where μ is the true mean of the stochastic process.

The autocorrelation of stationary data diminishes to zero comparatively quickly, while for a non stationary time series they are remarkably apart from zero for many time lags [127].

The sample autocorrelation at lag k is given by

$$\hat{\rho}_k = \frac{\sum_{i=b}^{n-k}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=b}^{n}(x_i - \bar{x})^2} \qquad (3.4)$$

where $\bar{x} = \frac{\sum_{i=b}^{n}(x_i)}{(n-b+1)}$ (3.5)

In addition to the auto correlation between x_t and x_{t+k}, it is needed to examine the correlation between x_t and x_{t+k} after their mutual linear dependency on the intervening variables $x_{t+1}, x_{t+2,\ldots}$ and x_{t+k-1} has been discarded is generally referred to as the partial autocorrelation in time series analysis [34], [127].

The partial autocorrelation between x_t and x_{t+k} is given by

$$\phi_{kk} = \frac{cov[(x_t - \hat{x}_t)(x_{t+k} - \hat{x}_{t+k})]}{\sqrt{var(x_t - \hat{x}_t)var(x_{t+k} - \hat{x}_{t+k})}} \tag{3.6}$$

Partial autocorrelations are another set of statistical indicators similar to autocorrelations that are used to examine the degree of association between x_t and x_{t+k} when the effects of other time lags *1,2,3….k-1* are removed [127]. In other words the partial autocorrelation is similar to an autocorrelation, except that when calculating it, the autocorrelations with all the elements within the lag are partialled out. If a lag of 1 is specified, then the partial autocorrelation is equivalent to autocorrelation.

Calculate and investigate the sample ACF and PACF of the properly differenced series to find the order of p and q. If the series possess positive autocorrelations out to a high number of lags, then it most likely needs a higher order of differencing. If the lag 1 autocorrelation is more negative than -0.5, this can be interpreted that the series has been over differenced. If the lag 1 autocorrelation is negative or zero, or the autocorrelations are patternless and all small, then the series does not need a further differencing [127].

- Identify suitable model: Box- Jenkins models are tentatively identified after confirming the satationarity using ACF and PACF. The time series ARIMA (p,d,q) is given by

$$y_t = \Phi_1 y_{t-1} + \Phi_2 y_{t-2} + \cdots + \Phi_p y_{t-p} + \alpha_t - \alpha_{t-1}\theta_1 - \alpha_{t-2}\theta_2 - \cdots - \alpha_{t-q}\theta_q \tag{3.7}$$

where Φ_i $(i = 1,2, \dots p)$ and θ_j $(j = 1,2, \dots q)$ are the AR and MA parameters of the model. α_t is a normal white noise process with a variance of σ_a^2 and zero mean [127].

- Check model adequacy: After confirming stationarity of the time series by proper differencing, the model parameters are estimated by assuming all possible combinational values of p and q. For each combination of p and q form the ARIMA model using the generated AR and MA values. Compare simulated wind speed statistical properties with those of observed wind speed and identify the optimum model.

3.2.4 ARIMA wind speed modeling and simulation

The wind speed data for time series analysis is collected from a WF in the southern region of India with an installed capacity of 99MW having 60 WTs each with a capacity of 1.65MW. The exact location of the WF, generator type, technical details, and data collection details are incorporated in appendix. The time interval of measurement is ten minutes with duration of one year (2011). The hourly average values of wind speed are computed by averaging six consecutive ten minute values of wind speed data [128]. This is represented in Fig.3.2. The sample ACF and sample PACF of the observed wind data is shown in Fig.3.3 and the ACF decays very slowly which indicates that the time series is nonstationary.

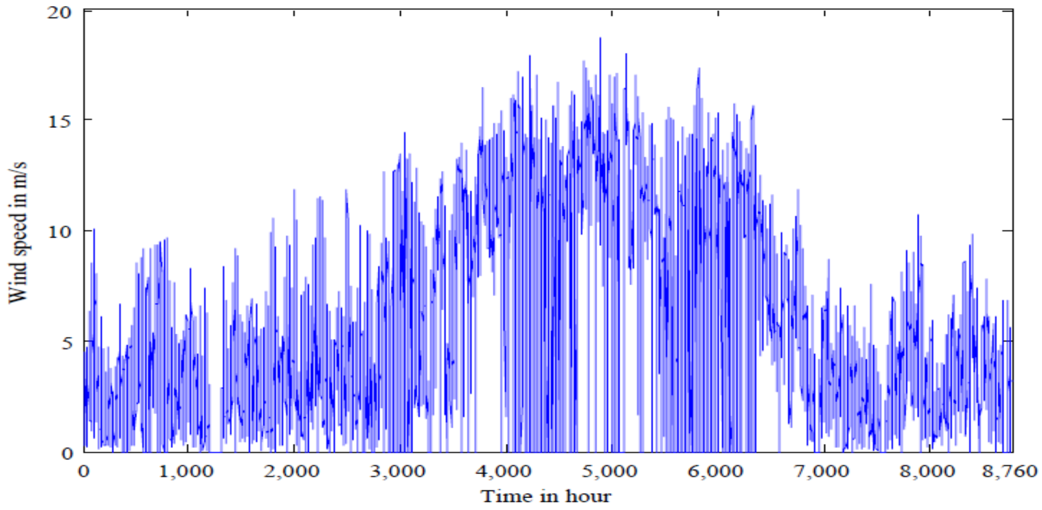

Fig.3.2 Wind speed time series

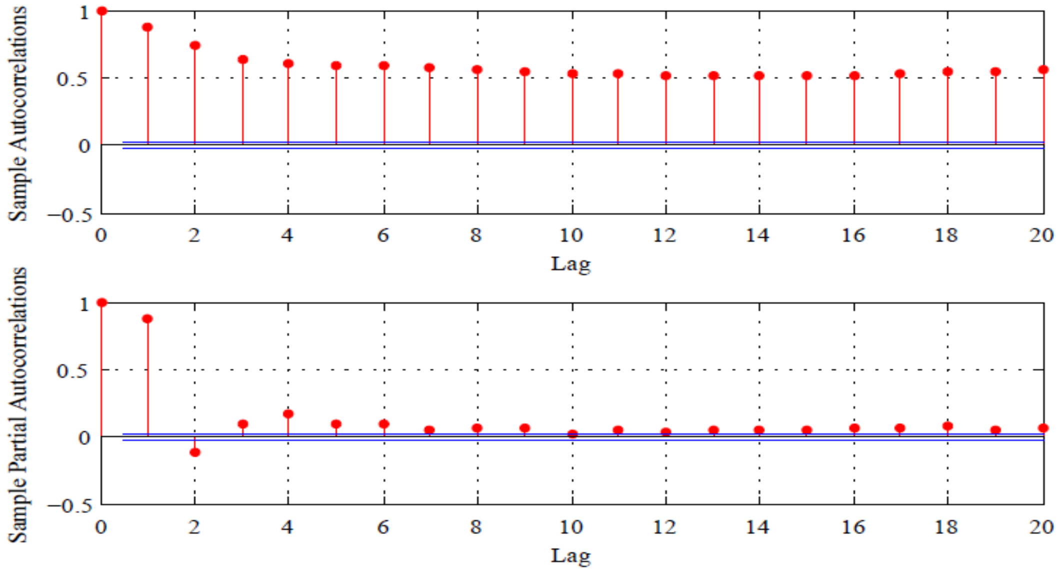

Fig.3.3 ACF and PACF of observed series

The non-stationary time series is converted to a stationary time series by taking first difference. The differencing tends to eliminate long and short term trends in a time series and is therefore used to achieve stationarity. The time series obtained after differencing is shown in Fig.3.4. The autocorrelation plot and partial autocorrelation plot of the first differenced time series are shown in Fig.3.5 and it can be seen that there is no clear pattern in the sample ACF and sample PACF where the time series seems to be stationary.

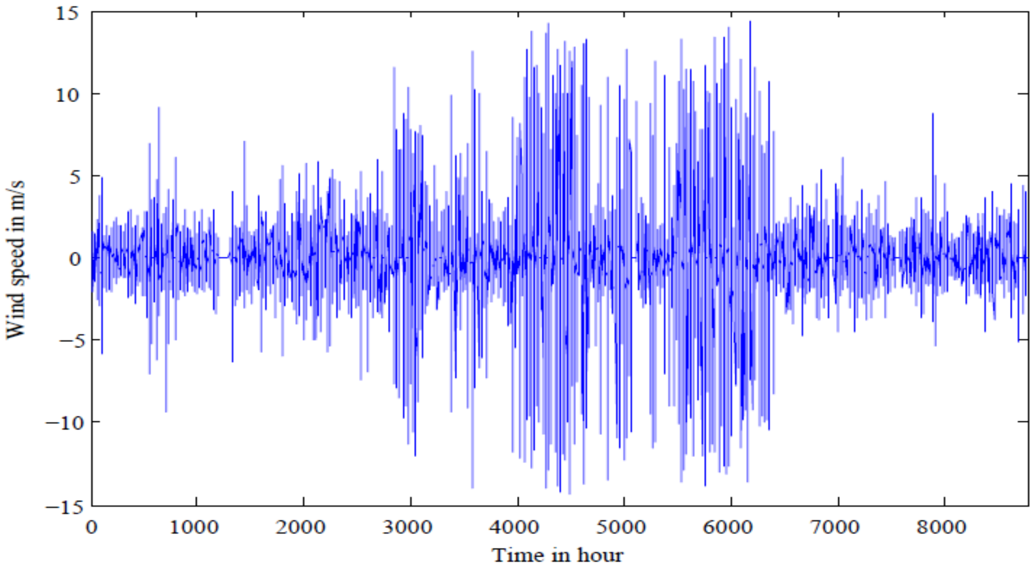

Fig.3.4 First difference time series of observed wind speed

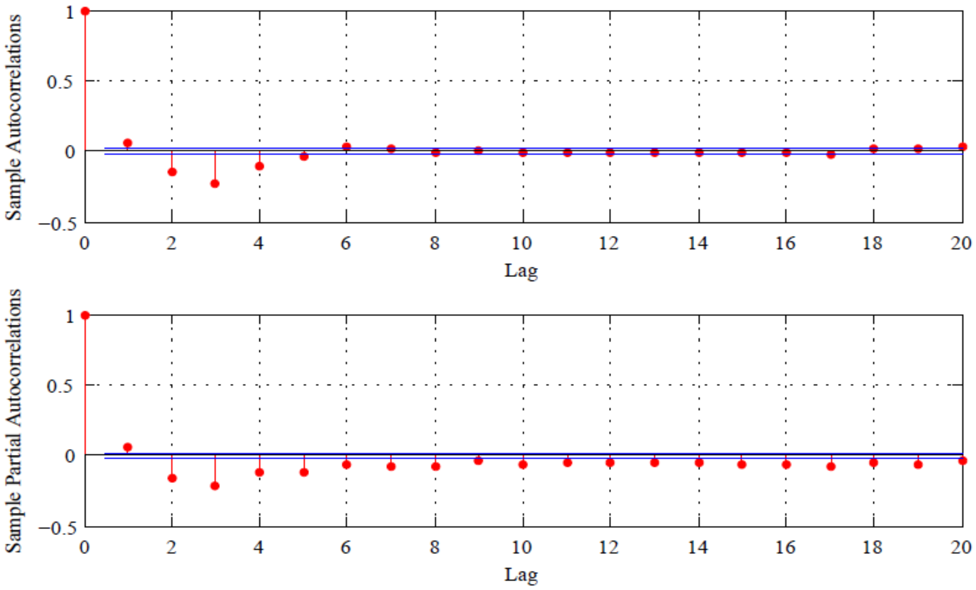

Fig.3.5 Autocorrelation functions of first difference series

Using the developed stationary time series, a family of ARIMA models are generated by varying p and q in the range of (0-3). The upper limit of value three for the model order was chosen keeping frugality in mind and practically within the limit model convergence will occur [127]. The possible ARIMA models after first difference are (1,1,1), (1,1,2), (1,1,3), (2,1,1), (2,1,2), (2,1,3), (3,1,1), (3,1,2), (3,1,3). For each of these models, the corresponding simulated wind speed sw_t at hour *t* can be estimated as follows

$$sw_t = \mu_t + \sigma_t \times y_t \tag{3.8}$$

where μ_t and σ_t are the mean and standard deviation of the measured wind speed time series [45]. y_t is the time series generated by the model for each combination of (p d q).

The aim of model adequacy check is to inspect how well the ARIMA (p, d, q) models follows the observed time series. This is done by comparing main statistical properties of simulated wind data with those of measured data and is shown in Table 3.1.

Table 3.1.Observed and simulated wind speed properties

Serial No	**ARIMA Models**	**Mean of Observed Wind Speed in m/s**	**Mean of Simulated Wind Speed in m/s**	**Standard Deviation of Observed Wind Speed**	**Standard Deviation of Simulated Wind Speed**
1	(1, 1, 1)	5.87	12.77	4.7	2.4
2	(1, 1, 2)		6.3		4.9
3	(1, 1, 3)		9.31		3.4
4	(2, 1, 1)		10.86		2.3
5	(2, 1 ,2)		15.12		2.8
6	(2 ,1, 3)		34.0		2.2
7	(3, 1 ,1)		9.32		2.3
8	(3, 1, 2)		26		2.6
9	(3,1, 3)		21.27		2.2

From the above table it is observed that ARIMA (1, 1, 2) model is the best fitted time series model for the wind site and the model is given by

$$y_t = -0.28002\, y_{t-1} - 0.64216\ e_{t-1} - 0.35784\ e_{t-2} \tag{3.9}$$

where $e_t \in N\ (0,\ 2.40097^2)$, represents a white noise whose variance is 2.40097^2 and mean is zero.

Fig. 3.6 describes the degree of matching of the measured and the simulated wind speed probability distributions using the ARIMA (1, 1, 2) model. It is also seen that two curves are following each other and the ARIMA (1, 1, 2) model is the optimum model of representing the observed wind speed.

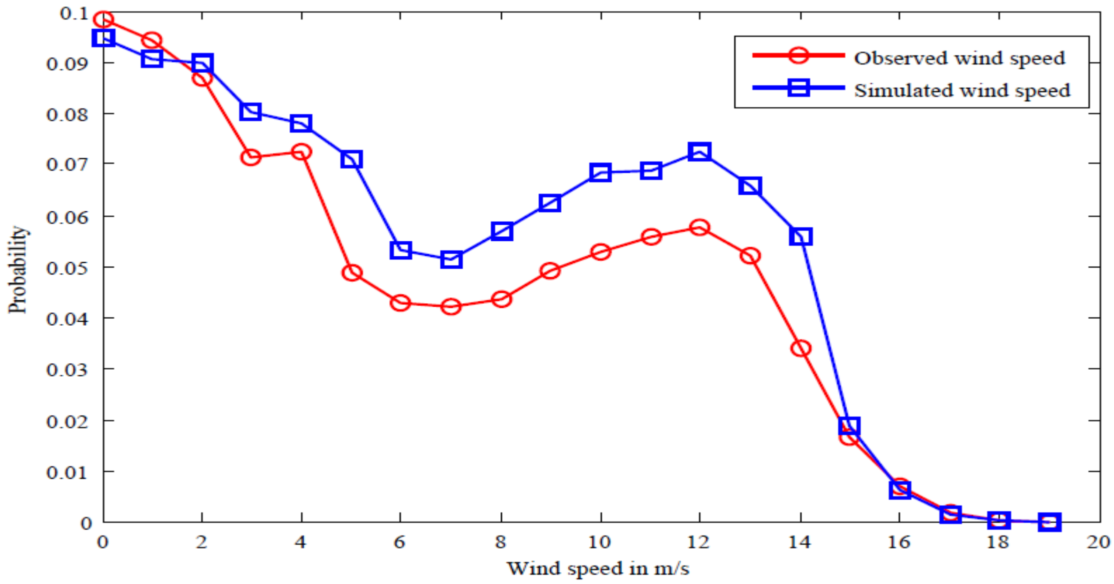

Fig. 3.6 Observed and simulated wind speed

3.3 CONCLUSION

In this Chapter, Box-Jenkins ARIMA time series model for wind speed is developed. Wind speed does not follow any specific pattern for any particular season and this necessicitates accurate modeling of wind speed like ARIMA for reliability evaluation. In ARIMA modeling, it is possible to convert the nonstationary wind speed series to an associated stationary time series without varying basic statistical properties. Also the

ARIMA model can accommodate long range correlations. These unique properties along with accuracy of the ARIMA model and its mathematical strength provide an upper hand over conventional ARMA modeling. The optimum model is identified as ARIMA (1,1,2). After developing ARIMA wind speed model for the site, an analytical probabilistic model for the evaluation of reliability of WES is presented in the next chapter.

CHAPTER 4

MODELING AND RELIABILITY ANALYSIS OF WIND POWER GENERATION SYSTEM

4.1 INTRODUCTION

The significance of wind power in meeting global energy needs has increased tremendously in recent years because of the growing environmental awareness and the emerging energy policies that encourage green energy. It was discussed earlier that wind speed fluctuates randomly with time, and is therefore significant to assess reliability of generation for effective integration and utilization of wind power in the grid. Reliability indices are used to quantify the reliability of the generation system, which plays a pivotal role in planning and operation. These probabilistic indices help to predict the reliability performance of the generation system in comparison with existing reliability standards. In this chapter, WF generation system reliability indices are evaluated by combining generation model with load model. Generation model is developed by making use of WT power curve and simulated wind power using ARIMA model. Load model used in this evaluation is annual load duration curve. The work mentioned in this chapter has been published in the journal of Electrical Engineering Technology.

4.2 GENERATION SYSTEM RELIABILITY

Reliability has always been one of the crucial factors in the design, planning, operation, and maintenance of a power system. The term reliability indicates the ability of a system to perform its assigned function, where past behavioural data of the system helps in estimating future performance [129]. Generation system reliability mainly address the reliability of generators in the power system, where electric power is generated from the conversion process of a primary energy to electricity before transmission. Generating system is the key part of the electricity supply chain and it is crucial that enough electricity is generated at every instant to meet the load demand. Generating units may occasionally fail to generate and the system operator has to assure that enough reserve is available to be operated when this happens [130-132]. This will enhance generation system reliability.

Reliability studies employed to a power system is classified into the two general categories of system adequacy and system security. The system adequacy describes the existence of sufficient generation, transmission and distribution facilities within the system to meet the customer load demand. The adequacy evaluation is therefore associated with system steady state conditions and is usually associated with system planning for both long and short terms, but is very important in system operation also. On the other hand, system security relates to the capability of the system to cope with disturbances and is consequently associated with transient system conditions. System security is concerned with both system planning and operation [130], [134]. System adequacy precedes system security. Satisfactory system security cannot be obtained without acceptable system adequacy.

Even though the most fundamental function of modern power systems is to fully satisfy the load demand under every possible circumstances, this function is always being challenged due to various inevitable and unpredictable stochastic factors. Typical types of uncertainties are as shown in Fig.4.1. The typical power system uncertainties are grouped into generation, transmission and load uncertainties. Generation uncertainties imply unit outages and stochastic power sources like wind, solar etc. The power system reliability theory focuses on identifying and estimating how power supplies are interrupted by such uncertainties [133].

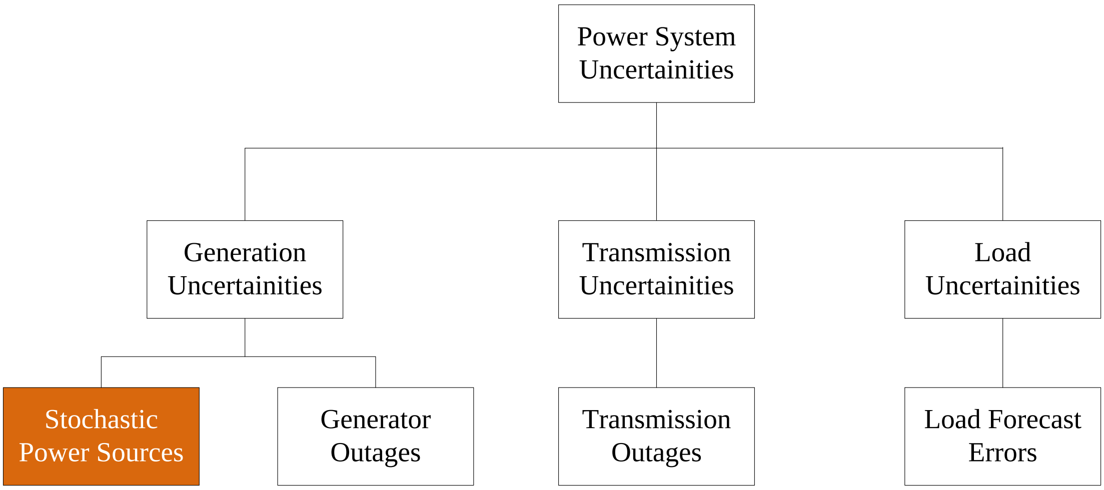

Fig. 4.1 Uncertainties in power system

The basic modeling method for the generation system reliability evaluation consists of three parts as depicted in Fig. 4.2. The generation model and the load model are combined to form an appropriate risk model [135], [136]. The condition where generation capacity is not adequate to meet the load demand is termed as 'risk' which is measured in terms of reliability indices.

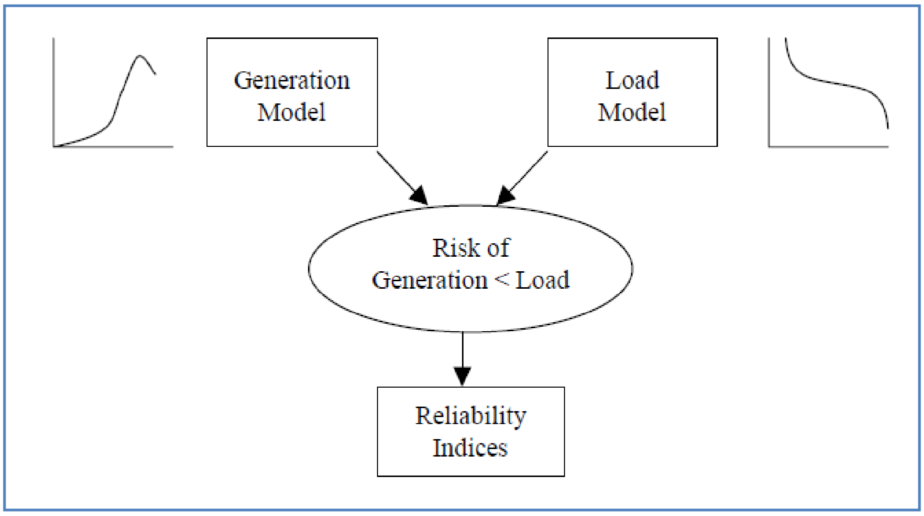

Fig. 4.2 Elements of generation reliability evaluation

4.2.1 Generation system reliability indices

The quantification of reliability is a significant aspect of generation system reliability evaluation. The assessment used to quantify reliability of a generation system is provided by various reliability indices. These reliability indices are used to check the reliability performance of a generation system, to compare alternative designs or to identify weak spots and determine ways for correction in the generation system.

Basically, system reliability assessment can be categorized into two, deterministic and probabilistic. The deterministic methods are simple and reliable to small generation systems. The most commonly used deterministic indices are the Reserve Margin (RM) and the largest set in the generation system. The main drawback of the deterministic method is that they do not take into account the random nature of system behavior [130], [136-138].

In generation system reliability assessment, probabilistic methods in particular analytical approach can provide more meaningful information. Analytical method is used in this thesis, where the system is represented by mathematical models and direct analytical solutions are used to calculate reliability indices from this model. The probabilistic reliability indices used in this work are LOLP, LOLE and LOEE, which are expected values of random variables.These indices are better understood as representatives of system-wide generation adequacy and not as absolute measures of system reliability. Furthermore, indices are sensitive to basic factors like size of the unit and its availability, and they are most significant when comparing the relative reliability of different generation configurations [130], [139].

4.3 GENERATION SYSTEM RELIABILITY EVALUATION APPROACH

The basic power system model with wind integration considered for evaluation is shown in Fig. 4.3. WF is connected to a power grid through a transmission line and has an installed capacity of 99 MW, which consist of 60 WTG units each rated at 1.65 MW and all are exposed to same wind regime.

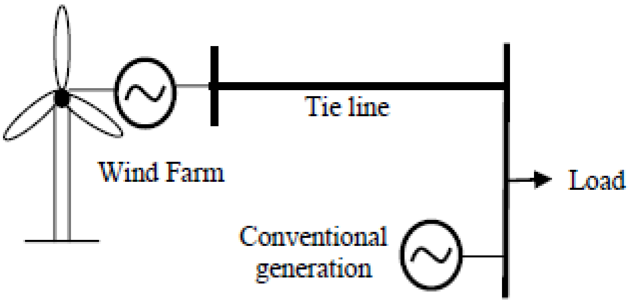

Fig.4.3 Basic system model with wind integration

The overall methodology of the reliability assessment of the system can be represented using a flow chart shown in Fig.4.4. The relevant reliability analysis is carried out as per the flow diagram and the corresponding reliability indices calculated from the process are LOLP, LOLE, and LOEE. The reliability evaluation is carried out by combining the generation model with the load model. The generation model is developed by a Capacity Outage Probability Table (COPT) and the load model is represented by annual load duration curve. The COPT is obtained from the simulated hourly wind speed using the developed ARIMA model from the hourly data collected.

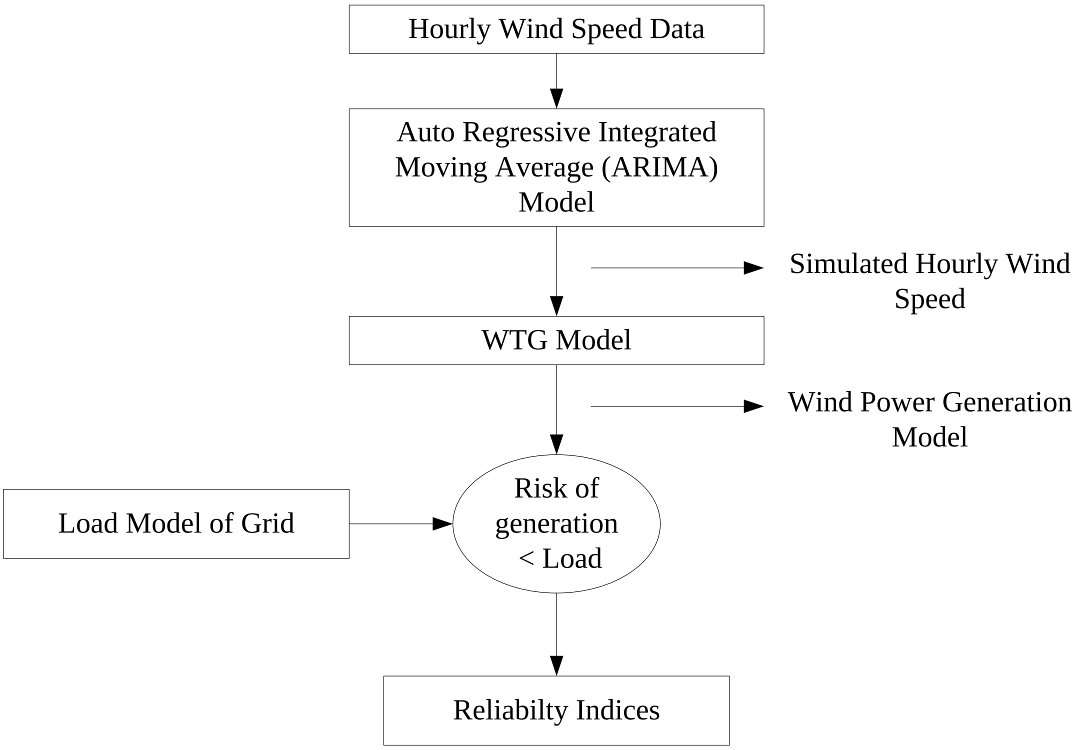

Fig. 4.4 Flow chart for reliability evaluation

The system is assumed to operate successfully as long as there is sufficient generation capacity to supply the load demand. The first step in reliability evaluation is to develop mathematical representations of generation and loads which are then 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 particular configuration under consideration. That is, the generation model and the load model are convolved to evaluate the probabilistic risk. The basic generation model is a COPT which contains the capacity outage states of the generating units together with their probability. The load model is represented by the annual load duration curve.

4. 3.1 Generation model

This section presents a detailed narration of the formation of the capacity outage distribution for multi-generating unit. The ultimate step in forming a generation model is to combine the rated capacity and availability level of the individual units to evaluate available generation in the power system. This results in the capacity model, in which each generating unit is denoted by its rated capacity g_i and its unavailability index u_i (or forced outage rate). If N is the total number of generators in the power system, then the available capacity can be represented asg_i , i =1…N, is a random variable whose value is zero with probability u_i and the value g_i with probability a_i =1-u_i [9],is given as.

$$\begin{tikzcd}
 & (g_i, a_i = 1 - u_i) \ \rightarrow (unit\ available) \\
\widetilde{g_i}\ (g_i, p_i) \arrow[ur] \arrow[dr] & \\
 & (0, a_i) \ \rightarrow (unit\ on\ outage)
\end{tikzcd}$$

The total generating capacity available in the system is $\widetilde{G_A} = \sum_{i=1}^{N} \widetilde{g_i}$. Here $\widetilde{G_A}$ is a random variable itself [140]. It is supposed that all units can fail and be repaired independently, that is, the availability of one unit is independent of repairs and failures of other units. In these circumstances, the probability distribution of G_A can be evaluated by combining the single probabilities of the different g_i. This results in a discrete capacity distribution $G_A = \{G_j, p_j\}$, j = 1…2^N, with a sample space of 2^N capacity states. Each capacity state indicates an outage event with one or several units out of service.

Let the capacity of the j^{th} state be G_j, and k be the available units, then N-k failed units is the sum of the capacities of the k available units, or

$$G_j = g_1 + g_2 + \cdots + g_k \tag{4.1}$$

The probability of finding the j^{th} state is equal to the product of the probabilities a_i of the k available units and the probabilities u_i of the N-k out-of-service units, or

$$P_i = a_1 a_2 \ldots a_k \,.\, u_1 u_2 \ldots \ldots . u_{n-k} \tag{4.2}$$

The probability distribution of $\widetilde{G_A}$ is given by the individual terms of the following binomial expansion [10]:

$$\prod_{i=1}^{N}(a_i + u_i) = a_1 a_2 \ldots a_N + a_1 a_2 \ldots a_{N-1} u_N + \cdots + a_1 a_2 \ldots a_{N-2} u_{N-1} u_N + \cdots \\ + u_1 u_2 \ldots u_N \tag{4.3}$$

Here, the possible different capacity states are 2^N. In practice, many states may have the same capacity so that they can be grouped in a single state with the same capacity and probability equal to the sum of the single probabilities [141], [142]. Finally, the model is reduced to a series of capacity states and associated probabilities stated as follows: The table which is usually tabulated with capacity and corresponding probability distribution is termed to as the (COPT). The capacity outage probability table formulated for the wind farm by making use of the wind turbine power curve and simulated wind power using ARIMA will be tabulated in the next session.

4.3.2 Load Models

The load in an electrical power system is seldom constant; means it varies from time to time. The graphical representation of variation of load with respect to time is termed as load curve or load duration curve. In its simplest form over a time period, the load is assumed to be constant[130].

Different risk indices can be deduced from various load models. In most of the works for adequacy evaluation of the power system, loads are taken to be constant over a period of one year at the annual peak load. The daily Peak Load Variation Curve that represents the variation in daily peak loads in the descending order and the Load Duration Curve are commonly used models in analytical evaluation [130].

A multi level load model for one year can represent the practical power system more accurately. The most accurate multilevel power system model is the annual hourly load variation curve in which 8760 levels indicates the annual hourly peaks. When the actual chronological hourly load variation is sorted in descending order, it is usually referred as hourly load duration curve which is used in this work.

4.4 RELIABILITY MODELING

As wind power sharing in conventional power system is increasing considerably now a days, formulation of a comprehensive reliability assessment draws more attention. Different probabilistic concepts which are used for the reliability evaluation in power system planning are LOLP, LOLE and LOEE. The main objective in generation capacity reliability evaluation is to check whether the load demand is met by number of units generated. Load data is essential to calculate the risk evaluation. Commonly used load models are load duration curve and daily peak load variation curve. In load duration curve approach, the individual hourly load data are used. An annual load duration curve is used in this analysis. The COPT shown in Table 4.2 is combined with system load characteristics to give an expected risk of load loss. This is discussed in next subsections.

4.4.1 Loss of Load Probability (LOLP)

LOLP is expressed as the probability that, load is more than the available generation. This is a probabilistic index. In long term generation capacity reliability evaluation, a load duration curve consists of daily peak loads arranged in descending order, can be used to measure LOLP with the assumption that the peak load of the day would last all day [143], [144]. The LOLP calculation is illustrated with a daily peak load curve in Fig.4.5, [54].

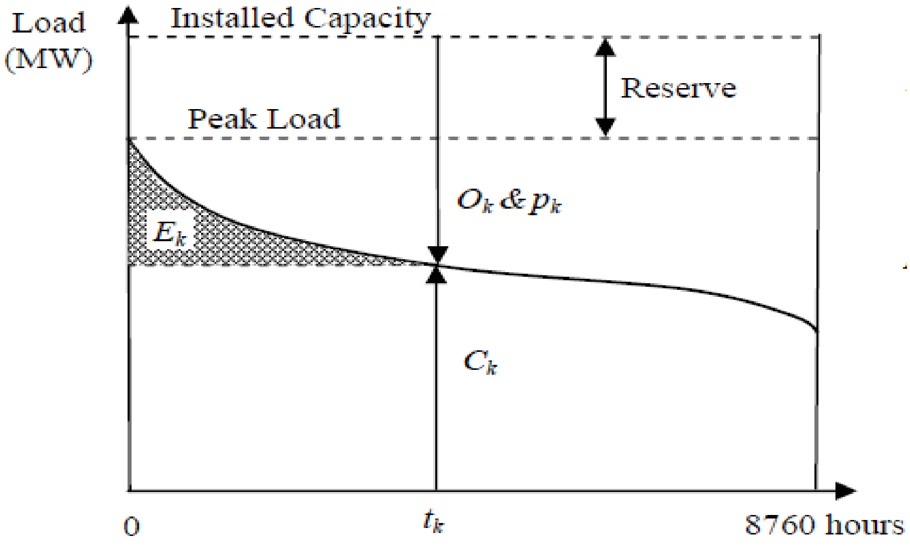

Fig.4.5 Load model and risk indices

where,

E_k is the energy not supplied due to capacity outage O_k

O_k is the magnitude of the k-th outage in the system

p_k is the probability of a capacity outage of magnitude O_k

t_k is the number of hours that an outage of magnitude O_k would cause loss of energy in the system.

Any capacity outage exceeding the reserve will result in the interruption of load and energy curtailment. The energy not served, E_k, is the shaded area shown under the load duration curve in Fig. 4.5

The mathematical formula for the calculation of LOLP is shown in Equation 4.4

$$LOLP = \sum_k \frac{p_k . t_k}{100} \tag{4.4}$$

Capacity outage less than the amount of reserves will not contribute to a loss of load. When a particular capacity outage is greater than the reserve, the risk in this case will be p_k x t_k.

The LOLP is like a rule of thumb to give an indication of the RM. But it provides a better indication or measure of reliability than the reserve margin index as it takes into account the system characteristics such as load unpredictability, individual generator reliability and unit de-rated states. The LOLP index has gained recognition and has become a widely used probabilistic index for generation reliability assessment. This is because it provides a probabilistic figure which can be relatively simple to calculate and employed in generation capacity planning. It also gives a simplified comparison of reliability.

4.4.2 LOLE index

LOLE is the most commonly used and accepted probabilistic method in risk analysis. It shows an average number of hours to which the given load is expected to overcome the available generation capacity. LOLE can be calculated as.

$$LOLE = \sum_{k=1}^{N} p_k \ t_k \tag{4.5}$$

Where N is the number of cases for which the generation outage is more than the reserve available [145].

The drawback of LOLP and LOLE index is that it cannot recognize the amount of energy shortage.

4.4.3 LOEE index

LOEE parameter is used to access the generation system reliability. It provides magnitude of expected energy shortage due to those occasions when the given load exceeds the generation. It is considered as more appealing index than LOLP and LOLE because it accounts the severity of energy deficiencies and their likely hood. Therefore it reflects system risk more truly. LOEE is given as

$$LOEE = \sum_{k=1}^{N} E_k \, p_k \tag{4.6}$$

E_k is the energy not supplied due to capacity outage O_k

p_k is the probability of a capacity outage of magnitude O_k

The total energy demand is calculated by computing the area under the load duration curve [145].

4.5 GENERATION SYSTEM RELIABILITY EVALUATION OF WES

WES reliability indices are evaluated by convolving the generation model with the load model. Generation model is developed by making use of WT power curve and the simulated wind power using ARIMA model.

4.5.1 Wind turbine power modeling

The WT power generation depends on three factors: wind pattern of the site, turbine availability and characteristics of the WT. The WTG with rated power (P_r) of 1.65MW manufactured by Vestas – V82 is used in this analysis [128]. The values of the operational parameters are shown in Table 4.1

Table 4.1 Operational parameters of Vestas – V82

Cut-in speed in m/s	**Rated speed in m/s**	**Cut-out speed in m/s**
3.5	13	20

The nonlinear relationship between the output power and the wind velocity of V82 – 1.65MW WT is depicted in Fig.4.6.The available output power of a WTG on hourly basis at any time point t can be computed using the following equation.

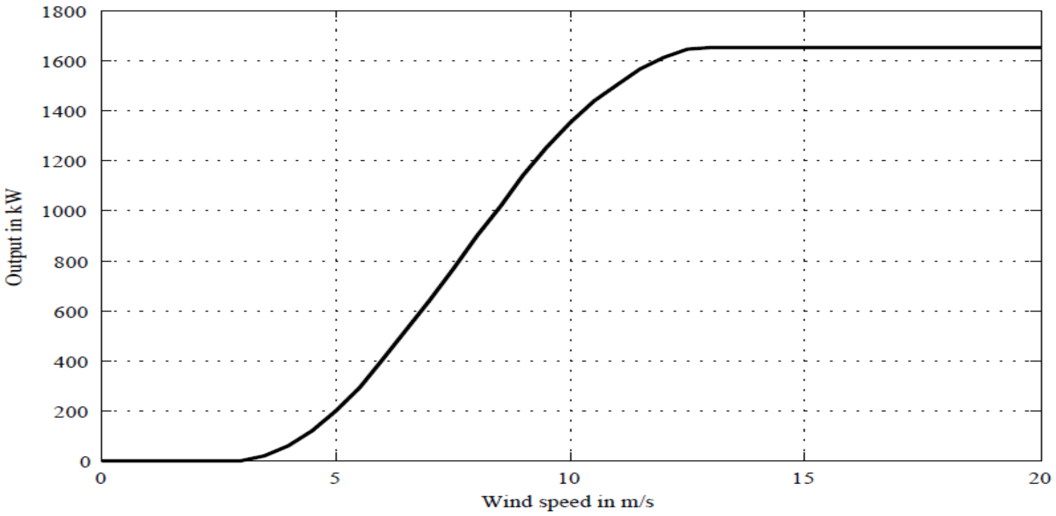

Fig.4.6 Power curve of V82-1.65MW turbine [24]

$$P(SW_t) = \begin{cases} 0 & 0 \le SW_t < V_{ci} \\ \left(A + B \times SW_t + C \times {SW_t}^2\right) \times P_r & V_{ci} \le SW_t < V_r \\ P_r & V_r \le SW_t < V_{co} \\ 0 & SW_t \ge V_{co} \end{cases} \tag{4.7}$$

where the constants A, B and C are presented in [26], values are tabulated in appendix.

SW_t is Simulated wind speed

V_{ci} is Cut-in speed in m/s

V_r is Rated speed in m/s

V_{co} is Cut-out speed in m/s

Even though time is not explicitly given in equation (4.7), the equation for simulated wind power for 8760 hours is a function of ARIMA wind speed modeling.

4.5.2 Capacity Outage Probability Table

A number of power generation models can be created by taking different number of partial states and the accuracy of the result increases with number of states. It is seen that a five state COPT is enough in capacity adequacy assessment of wind integrated power system [43]. In this work, hourly power outputs generated by the WF using the equation 4.4 is grouped into 11 states and their corresponding probabilities are tabulated. Table 4.2 indicates that probability of having full WTG output is comparatively low for this wind speed. Since reliability indices are not much changed by the Forced Outage Rates (FOR) of WES and hence not included in this calculation. WES reliability is mainly affected by the wind characteristics of the site and is considered for further analysis.

Table 4.2 Capacity outage probability table

Capacity out (MW)	**Capacity in (MW)**	**Probability**	**Capacity out (MW)**	**Capacity in (MW)**	**Probability**
0	99	0.30255	79	20	0.04218
5	94	0.07679	84	15	0.03467
21	78	0.05636	89	10	0.07019
49	50	0.07208	95	4	0.05226
69	30	0.04801	99	0	0.19361
74	25	0.0513			

4.5.3 Risk Evaluation

Installed capacity of the WF under consideration is 99MW. The hourly average power generation of the WF in year 2011 is 22MW. This quantity is too low in comparison with installed WF capacity and this is because of the uncertainty in wind speed and the wind turbines availability etc. For risk analysis, knowledge of load duration curve is essential. As WF provides power to the utility grid, it is better to apply the analysis to the load duration curve for the utility grid. To separate the contribution of WF from other sources, the load duration curve is scaled down in such a manner that the maximum demand of the grid is equal to hourly average power generation of the WF [144]. Here the hourly average power generation is 22MW which is taken as the peak load. Thus the newly deduced load duration curve for the analysis is of similar trends as that of the utility grid load curve, but with reduced magnitude and shown in Fig.4.7. Using this method, reliability evaluation of WF in real world circumstance is possible.

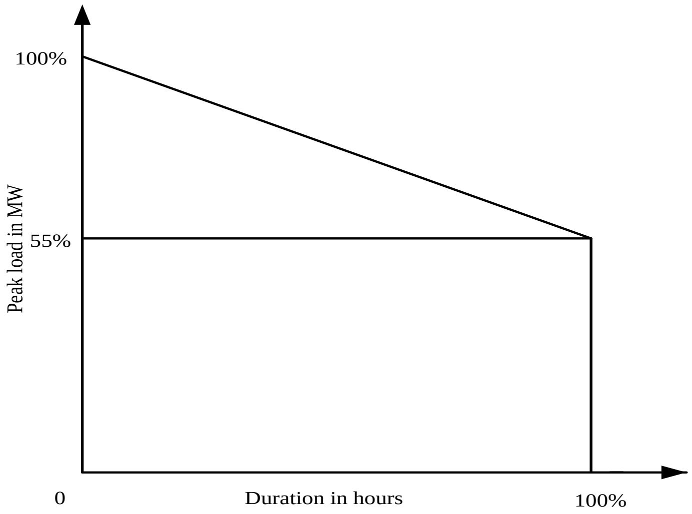

Fig.4.7 System load duration curve

4.6 RESULTS AND DISCUSSION

The different reliability indices of the WF under consideration are calculated and the significance of the values is presented in the next session.

4.6.1 WF Reliability Analysis

Hourly load variations are arranged in descending order and simplified to get the load duration curve which is depicted in Fig. 4.7. The study period taken for the analysis is one year and therefore 100 percentages on x- axis in Fig.4.7 corresponds to 8760 hours. Y-axis represents peak load in MW. The area under the system load pattern gives the energy required in that period. The annual reliability indices of WF are obtained by comparing the peak load demand of 22MW with corresponding annual load duration curve and the values are shown in Table 4.3. These values provide an insight into annual reliability of WF. Even though a number of indices are used for risk analysis in WES, the most significant index is LOLE; as it decides the future generation capacity [146], [147]. The risk index LOLE is calculated by convolving WF multistate equivalent generation model with load model.

Table 4.3 Annual reliability indices

LOLP	**LOLE**		**LOEE in MWh**
	in hours/year	**in days/year**	
0.3491	2178.322	90.76	457.213

The industry accepted reliability standard for LOLE criteria is 0.1day/year [147]. Annual LOLE value obtained in this analysis is much higher than of the standard value which indicates low reliability of the corresponding WF. Moreover LOLP value is 0.3491 and LOEE is 457.213 MWh which indicate the inefficiency of meeting the load demand and thus supports the result of LOLE. Wind speed is a weather operated phenomenon and this justifies the observed low reliability due to the partial availability of power generation. The annual reliability information obtained from the analysis is very useful in the power system planning point of view.

The general findings of the reliability and other aspects mentioned in the work are applicable for systems with any load duration [147].

4.7 CONCLUSION

In this chapter, an analytical probabilistic model for the evaluation of reliability of WES has been presented. The model accounts the stochastic nature of wind by incorporating ARIMA for wind speed modeling. The purpose of WF generation capacity reliability estimation is to check whether the load demand is met by number of units generated. Due to the time variability of wind, WF does not provide an equivalent amount of its installed capacity consistently. While operating a grid connected WF, it is worthwhile to know the magnitude of wind power and the time at which it was available to meet the load. Various probabilistic concepts which are used in this paper for generation capacity reliability estimation are LOLP, LOLE and LOEE. Moreover, reliability evaluation of WF in real world circumstance is done by omitting the effect of other generation systems from utility grid. The results show that LOLP = 0.3491, LOLE = 2178.3220 hours / year, LOEE = 457.2130 MWh and it is observed that the WF reliability is poor. The reliability indices provide an insight to the degree of matching of WF with existing load pattern in grid and such an evaluation is helpful to energy planners and power system operators in planning and decision-making.

After evaluating generation reliability of the WF, Markov modeling of the WT with CM is developed which is used for sensitivity analysis to identify more sensitive components to generation availability. Moreover, reliability allocation is performed on WT components to enhance the generation availability. This aspect is discussed in chapter 5.

CHAPTER 5

MARKOV MODELING AND RELIABILITY ALLOCATION IN WT FOR AVAILABILITY ENHANCEMENT

5.1 INTRODUCTION

Necessity has compelled man to improve upon the art of tapping wind energy for power generation: an appropriate reliever of strain exerted on the non-renewable fossil fuel. Even though wind power is the most accomplished green energy source, reliability and availability are still the primary issues for its successful generation. The components of the WES have different characteristics which influence the system reliability at different levels. Accurate modeling of WES is very essential to study about the possible failure probability which reflects in the availability and economics of operation. This chapter presents a suitable Markov model for a WES with Condition Monitoring (CM). Condition Monitoring Systems (CMS) are very useful tools to reduce the maintenance costs in WES. A sensitivity analysis is performed using the Markov model to learn the characteristics of turbine components that are likely to have an impact on system the reliability the most. The chapter also presents reliability allocation technique to improve the availability of WES. The work mentioned in this chapter has been published in the journal of Life Cycle Reliability and Safety Engineering.

5.2 WF OPERATIONAL AVAILABILITY AND MAINTENANCE

Unlike conventional power stations, WTs are almost unmanned and remote power plants. They are subjected to unpredictable and tough weather conditions, like breeze to storm, arctic cold to tropical heat, snow and lightning etc. Due to these extreme weather conditions, the loads and operational conditions of WTs are constantly changes which lead to high mechanical stress on the various parts of the WES. It is roughly estimated that the operational availability of WTs is 97% of the lifespan of a WT [148]. Meanwhile, 10 to 20% of the total Cost Of Energy (COE) is accounted for operation and maintenance (O&M) at the early stage of a wind power project, and to approximately 35% at the end of life span. The improvement of operational efficiency and reduction in the shutdown hours of the WT increases the revenue which is possible through a preventive-centered maintenance strategy of the WF based on parameter monitoring or performance of components [149-151]. In preventive maintenance strategy, accurate and reliable CM is a popular method to improve operational availability of the WF [152].

Failure analysis and monitoring of the operation of the components of a WES is very essential for the performance and design improvement. The total lifespan of a WES depends mainly on the design and operation of the WT. Several attempts like surveys and failure analysis have been conducted to sort out the critical components of a WES and based on the results, suggestions have been given to reduce the O& M cost. According to a recently conducted survey in Sweden about the failures of WES, gear box is identified as the most crucial component because of its higher down time per failure [153], while electrical system, converter and rotor are also identified as unreliable components because of their high frequency of failures [154]. A proper mathematical model with CM is necessary to identify the most sensitive components of the WES, which helps to analytically investigate about the reliability contribution of these components. Getting earlier warnings of failures or deterioration about these sensitive components helps in improving the reliability benefits for maintenance management as well as for improving the performance [155].

A new model for WES using Markov chain is detailed in this chapter to incorporate the characteristics of CMS and failure data of each component. The failure and deterioration states of a WT can effectively be captured by the application of Markov chain. Instead of reliability modeling of a few selected subassemblies, failure as well as repair characteristics of all subassemblies are included in the presented model, making WES reliability model more accurate. In addition to it, a novel method for generation availability enhancement, reliability allocation technique for WES is also presented in this chapter.

5.3 MARKOV MODEL

WT is a complex system consisting of a number of subassemblies with different reliability levels. Therefore proper selection and reliability modeling of components is a major task. In general, gear box, blades, generator and electronics parts are identified as the suitable components to represent the entire WES for reliability modeling [156-158]. Apart from failure frequency, another vital parameter is WT downtime which is also considered for the component selection. 75% of the downtime per annum is caused by only 15% of the WT failures [159].

Certain components may have low failure rate, but their down time will be high, thus can disturb the power generation at a higher rate than with a component having short down time with high failure rate. As an example, even though the gearbox system failure frequency is low, its down time and the repair cost are high. Thus the total percentage of production loss due to failure in the gear box system is the highest of all sub assemblies [160].

Inspite of selecting a few components for reliability modeling as in references [161] the failure and the repair characteristics of all WT components are included in the presented model. To minimize the complex nature of the proposed Markov model, all components having identical characteristics are grouped together. Depending upon the deterioration/failure and repair nature of each component, either a two state or a three state Markov model is adopted for reliability modeling and is explained in next subsection.

5.3.1 Two-State Markov Model

In this modeling technique a component having only up and down states is considered and is represented in Fig. 5.1. All components without CMS are represented by this two-state model. Because of simplicity, this model is commonly used in reliability analysis [157], [162].

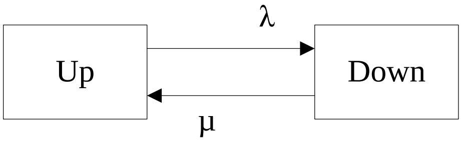

Fig. 5.1 Two-state Markov model

5.3.2 Intermediate State Model

This model is attractive for a component having up, derated and down states and is represented in Fig.5.2. The derated and failure states of a WES can effectively be captured by the application of Markov Chain and this property is used in this work to represent a component under condition monitoring.

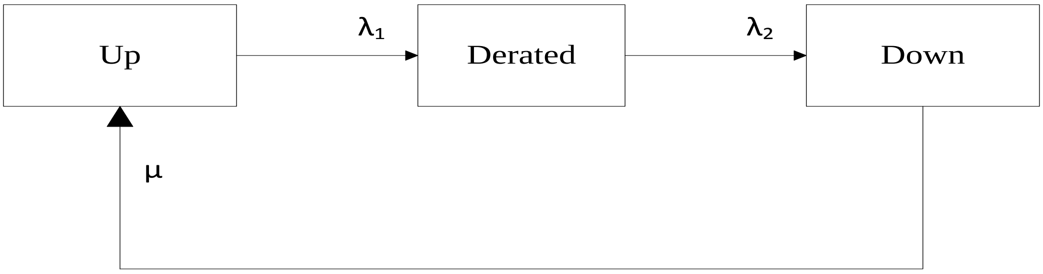

Fig. 5.2 Intermediate state model

The ability of a CMS to identify the deterioration state in time is related to the concept of its P-F curve [163]. A typical deterioration state of a component in time is represented in Fig. 5.3. Point P- in the curve represents the deterioration of the component that is detected the first time and F-represents the instant of failure and thus the curve P-F represents the progress of deterioration of the component. The CMSs uses the points in the P-F curve to diagnose the health of WES components which is described in the next subsection.

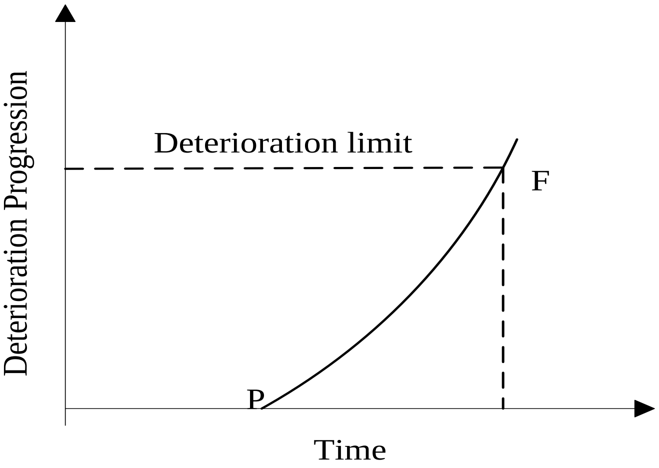

Fig.5.3. P-F curve concept

5.3.3 Condition Monitoring

WTs are frequently undergoing many types of unexpected environmental loads, which can be catastrophic in nature for the WF. Like any other industrial equipments WTs also need a monitoring system which is capable of predicting the up-coming faults of the critical components of the system to save it from a major breakdown [164]. The reliability of a WT is very crucial for the harvesting of maximum energy from the wind and this can be enhanced to a great extend by implementing an adequate CMSs [165].

Presently most WFs are incorporated with CMSs. Generator, blades and gearbox are the three main subassemblies with CM facilities in most WTs [161]. The continuous WT health states are examined using appropriate methods such as strain measurement, vibration analysis, oil analysis, acoustics and thermography [166].

Nowadays in the most modern WTs, Supervisory Control And Data Acquisition (SCADA) system are common. CM using this SCADA data analysis is cheap, since data collection and network of sensors are already implemented. Fig.5.4 shows the overview of WTCM based on SCADA data analysis. These systems are implemented for ensuring the operation of WTs conforming to power curve and running safely and efficiently.

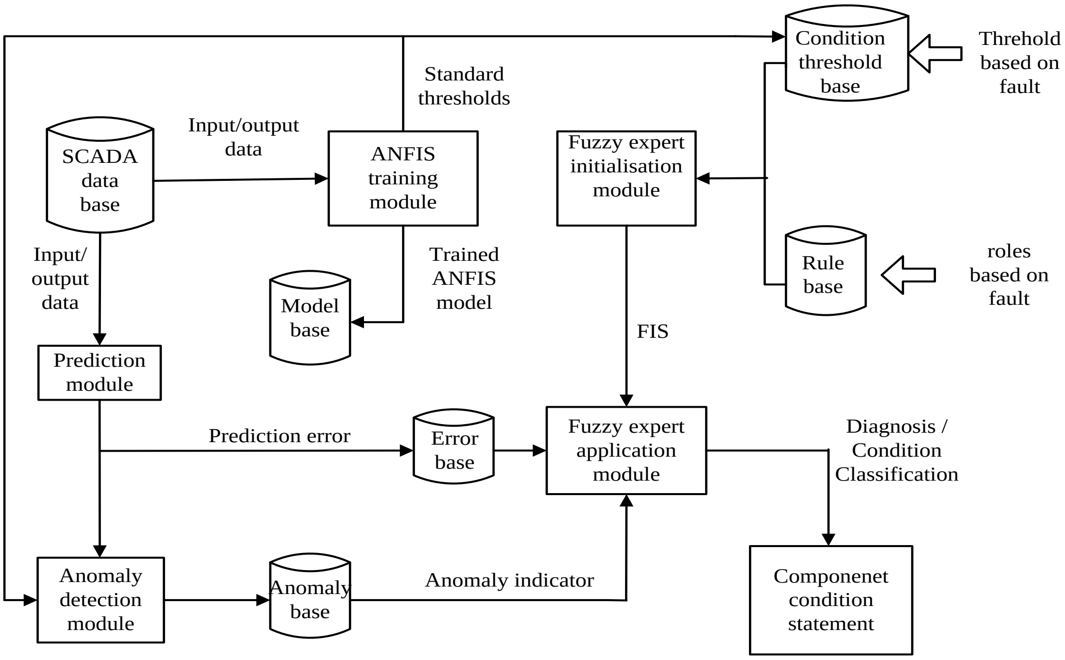

Fig. 5.4 Overview of WTCM -SCADA. FIS: fuzzy interference system

The SCADA system collects information from WT subassemblies using sensors, for wind speed, direction, temperature at different points, current flowing in the circuit, pressure exerted at different parts etc. The real time condition of a WES can be obtained by the analysis of SCADA data. The measurement parameters of SCADA also include [166].

- Active power output and standard deviation
- Power factor
- Reactive power
- Generator voltages and currents
- Anemometer measured wind speeds, and standard deviation
- Turbine and generator shaft speeds
- Gearbox bearing temperatures (for geared-drive turbines)

- Gearbox lubrication oil temperatures (for geared-drive turbines)
- Generator bearing temperatures
- Generator winding temperatures; and
- Average nacelle temperatures

Using the data processing and analyzes, a CMS can identify the health of a key subassembly so that fault can be predicted and suitable maintenance strategy can be selected [165].

5.4 THE PROPOSED MARKOV MODEL FOR WES

The complexity of the proposed model depends mainly on the number of components identified for reliability modeling. In this model, all WT subassemblies are categoried into four based on their importance, either in downtime period or failure frequency and also on the basics CMS to monitor these components (except from electronic components). The four component groups are:

1) *Gearbox:*
2) *Generator*
3) *Electronics and others:* The components which are not included in the other groups are represented here.

4) *Blades/pitch*

The component groups generator, gear box and blade/ pitches are presented by a three state model. The third state is the deterioration and in this state CMS detects faults. The component group 3 is represented by a two state model. After selecting the proper model for each of the groups, entire WES is modeled by combining the states of each group.

5.4.1 State Space Diagram

Theoretically, the number of system states developed in the Markov model for a WES is 54. In most of the reliability models the number of subsystem states is reduced to 28 by using the following simplifying assumptions.

1. Simultaneous degradation of components are insignificant
2. Simultaneous failures of two components are negligible.
3. System must transit to a failure state via a de-rated state before outright failure.
4. All the failure states are considered as absorbing states.

The resultant system state space after simplification is given in Fig.5.5 where each box indicates the overall operating condition of the WT, ie, the status of the 4-modeled component groups: down, derated and up.

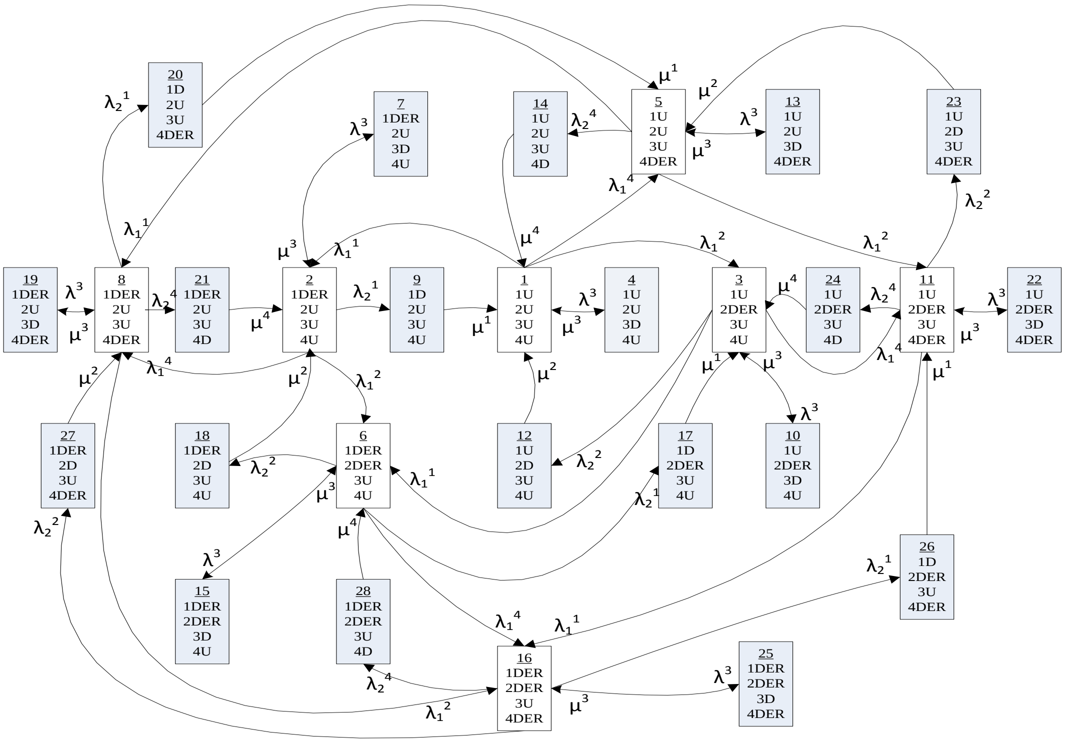

Fig.5.5. State space diagram of WES

5.4.2 State Transition Rate

For a single repairable component for which the failure and repair rate are constant, the transition rate is the rate at which the system transits from one state of the system to another [167]. Using this transition rate, the deterioration, failure and repair characteristics of every component group are incorporated in the developed system model and the model parameters of the WT are estimated from the historical data collected for a period of three years. In this work, the transitions are calculated from the average number of failures and average down time of the test system. The detailed method of calculation is given in section 5.4.3. λ_1^i represents the transition rate from up state to de-rated state, λ_2^i gives the transition rate from de-rated state to down state and the rate from down state to up state is given by μ^i for the component group i, where i= 1,2,4 respectively. As the third component group has only two states, λ^3 represents the transition rate from up state to down state of group 3.

5.4.3 Test System

The above mentioned Markov model is incorporated into a test system with both failure and repair rates collected from a 99MW WF in the southern region of India which is discussed in section 3.2.4 of chapter 3for wind speed modeling. Details of these data for a period of 3 years from 2012 to 2014 is shown in Table 5.1which is used for the calculation of equivalent values for the further evaluation of sensitivity parameters.

Operational statistics of WPPs are regularly collected by the control unit inside the WT. Most of the WTs are fitted with sophisticated equipments that make it possible to collect the operational data remotely via modem and internet. In this work, failure and repair rates of WT components are calculated using the raw data collected during the period of three years from 2012-2014. The repair time and number of failures of each component are calculated from this data and then the average repair time and value of failure rate per day are calculated.

Table 5.1. WT failure and repair rates

WT Components	**Failure Rate (λ)/day**	**Repair Rate (μ)/day**
Gear Box (1)	0.00027	0.0748
Generator (2)	0.00012	0.0983
Electronics and Other Parts (3)	0.00201	0.126
Blades and Pitches (4)	0.000235	0.2451

5.5 SENSITIVITY ANALYSIS

Since WES is a complex structure, in which certain components are considered as high risk items, because they are ‘weak points’ as they are expounded to be failure prone are inevitable for the operation of the turbine, or their repair time and energy lost is very high. Identifying such weak points is essential for the operation of the system to accomplish high availability and to minimize the maintenance cost. The main objective of a CMS is to give a reliable indication about the presence, severity and location of the fault so that maintenance scheduling can be well coordinated. To do CM in a cost effective way, identifying the most sensitive components to the availability of a WES is essential.

The reliability of a WES can be measured in terms of its availability and which is defined as, availability is the probability that a system or a component is capable of functioning at time t [167]. Which is given as

$$Availability = \frac{MTTF}{MTTF + MTTR} \tag{5.1}$$

where MTTF represent mean time to failure and MTTR is the mean time to recover

From the above equation of availability, it can be seen that availability value will be high for high MTTF or low MTTR or a combination of both. As availability is a function of both MTTR and MTTF, high downtime alone can never reduce the availability of a system. It does not depend directly on the frequency of failure. However, the availability analysis accounts all the failures, the down time of failures and the time taken to repair. As the availability of the WES depends on the performance of its components, it is essential to analytically diagnose critical components that affect the availability and this is done through the technique of sensitivity analysis. The result of sensitivity analysis also provides much meaningful information on the impacts of failure and repair rates of subassemblies to the total reliability of WES. Different sensitivity analyzes are performed on the test system to observe the effects of repair rates and failure rates of each subassembly on the reliability measures of the WES namely MTTR, MTTF, and system availability. After examining the degree of the sensitivity of each component to MTTR, MTTF and availability, the most sensitive component that affect the system availability can be identified.

5.5.1 Sensitivity of MTTF

The sensitivity of MTTF to failure rate is shown graphically in Fig.5.6. It can be inferred from the graph is that components which have high failure rates are the most sensitive elements to MTTF, and WES, these components are electronics and other parts. The other groups of subassemblies like generator, gearbox and blades/pitches having lower failure rate are least sensitive to MTTF. From the equation (5.2), it is seen that, by reducing the failure rate, MTTF can be increased and is revealed from the failure analysis of the components of WES.

$$MTTF = \frac{1}{\lambda_{eq}} \tag{5.2}$$

The equivalent failure rate of WT is given by equation (5.3)

$$\lambda_{eq} = \sum \lambda^{i} \tag{5.3}$$

Where λ^{i} represents failure rate of i^{th} component.

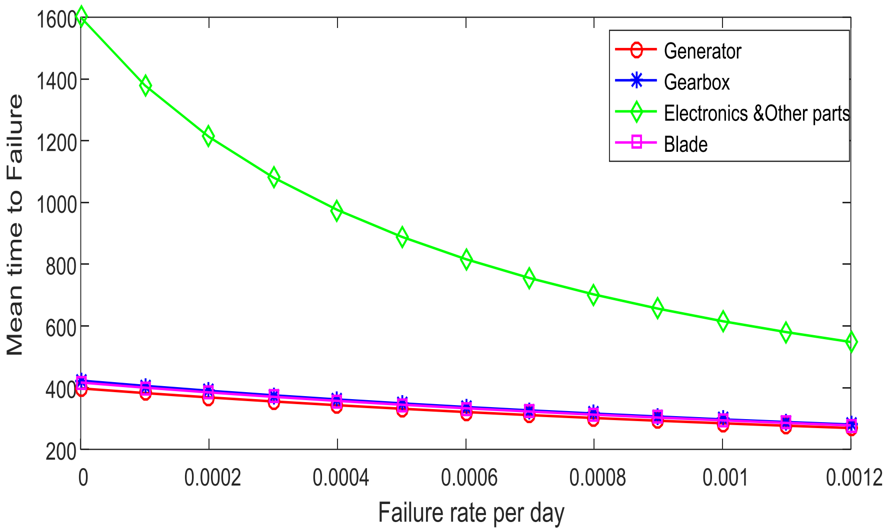

Fig.5.6. Variation of MTTF with failure rates

In a WES, it is assumed that all the components are connected in series, and according to reliability theory, for a series system MTTF is a function of failure rates of all components and is independent of repair rates. Therefore according to the sensitivity analysis MTTF does not vary with the changing repair rates.

5.5.2 Sensitivity of MTTR

Mean time to repair is sensitive to both repair rate and failure rates. The dependence of MTTR on repair rates, for each component group is given by the following equation.

$$MTTR_i = \frac{1}{\mu^i} \tag{5.4}$$

Where μ^i represents repair rate of i^th^ component and $MTTR_i$ shows mean time taken to repair component *i*.

$$MTTR_{eq} = \frac{\sum \lambda^i \times MTTR_i}{\sum \lambda^i} \tag{5.5}$$

Where $\mathrm{MTTR_{eq}}$ is the mean time taken to repair, ie. average down time of the WES. From equation (5.4) and (5.5),

$$MTTR_{eq} = \frac{\sum \lambda^i \times \frac{1}{\mu^i}}{\sum \lambda^i} \tag{5.6}$$

As per equation (5.6), MTTR of a WES is always a function of repair rate and failure rate of the system components. To analyze the trends, equation (5.6) is differentiated with respect to λ^i.

$$\frac{d\left(MTTR_{eq}\right)}{d\lambda^i} = \frac{\frac{\sum_{\forall k \neq i} \lambda^k}{\mu^i} - \sum_{\forall k \neq i} \frac{\lambda^k}{\mu^k}}{(\lambda^i + \sum_{\forall k \neq i} \lambda^k)^2} \tag{5.7}$$

The numerator of equation (5.7) can be rearranged as $\sum_{\forall k \neq i} \lambda^k \left(\frac{1}{\mu^i} - \frac{1}{\mu^k}\right)$. For a component with relatively smaller repair rate, the numerator term is positive and shows an increasing trend. But for components having higher repair rate, the numerator becomes negative and shows a decreasing trend.

The graphical representation of the variation of MTTR with respect to failure and repair rate proves the above theoretical results and is depicted in Fig.5.7 and 5.8. From the above figures it can be observed that, for subsystems like gear box and generator having high average down time, the value of MTTR increases with high failure rates. It can also be inferred that, for subsystems with low average down time, the value of MTTR decreases with increase in failure rate. Also, MTTR of the system is inversely proportional to the repair rate of its subsystems. The result of sensitivity analysis also shows that, for subsystems like electronics and generator having high failure rates the MTTR can be reduced by increasing the repair rate. Therefore, in general quick repairable failures are more attractive for a system than the failures that take a longer time to repair.

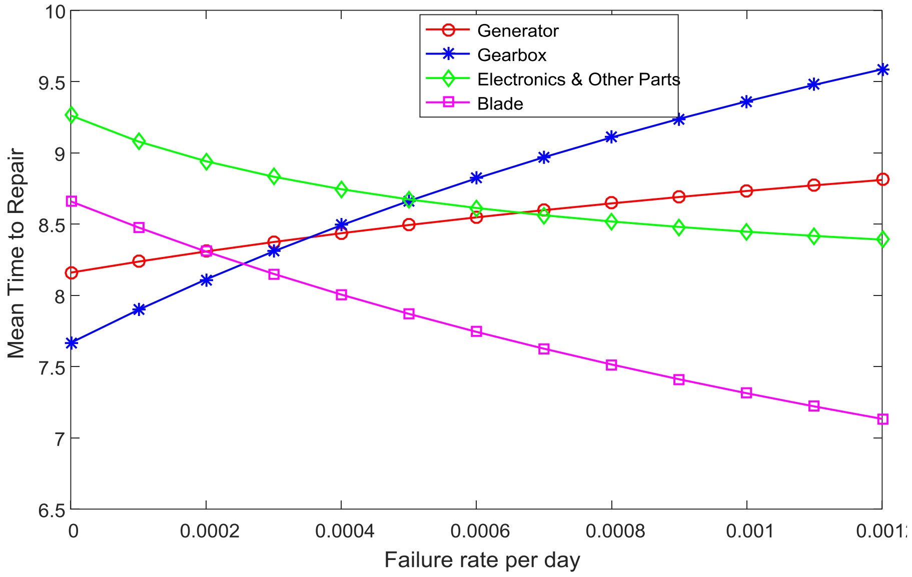

Fig.5.7.Variation of MTTR with failure rate

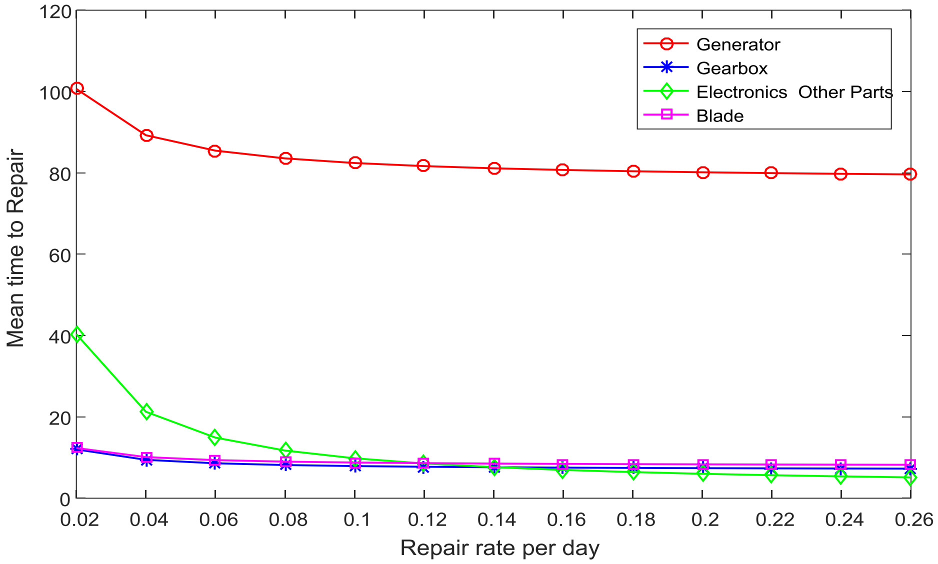

Fig.5.8 Variation of MTTR with repair rate

5.5.3 Sensitivity of Availability

The availability of the system is given by the expression, $A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$ which is sensitive to failure rate and repair rate of the subsystems as MTTF and MTTR are functions of λ and μ. The variation of availability with respect to the failure rate for each of the four groups is calculated according to the above equation and is depicted in Fig. 5.9. From the figure it can be observed that, the sensitivity of availability to the failure rates is highest for generator and gear box group and lowest for blades and pitches. Sensitivity of availability to repair rates for the above group is shown in Fig.5.10. From the figure it is clear that sensitivity of availability to repair rates increases with increase in the repair rate. In particular it is more sensitive to repair rate of electronics and other parts.

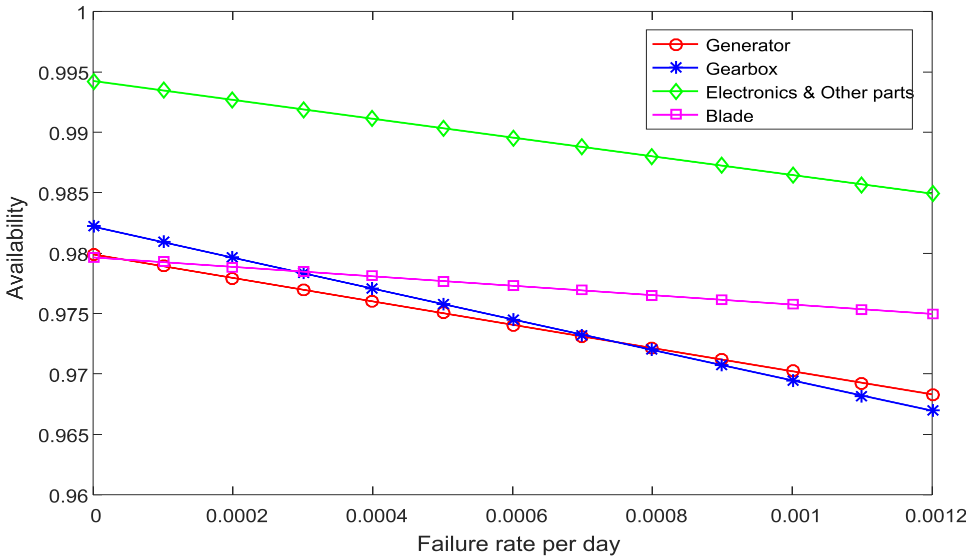

Fig. 5.9 Variation of availability with failure rate

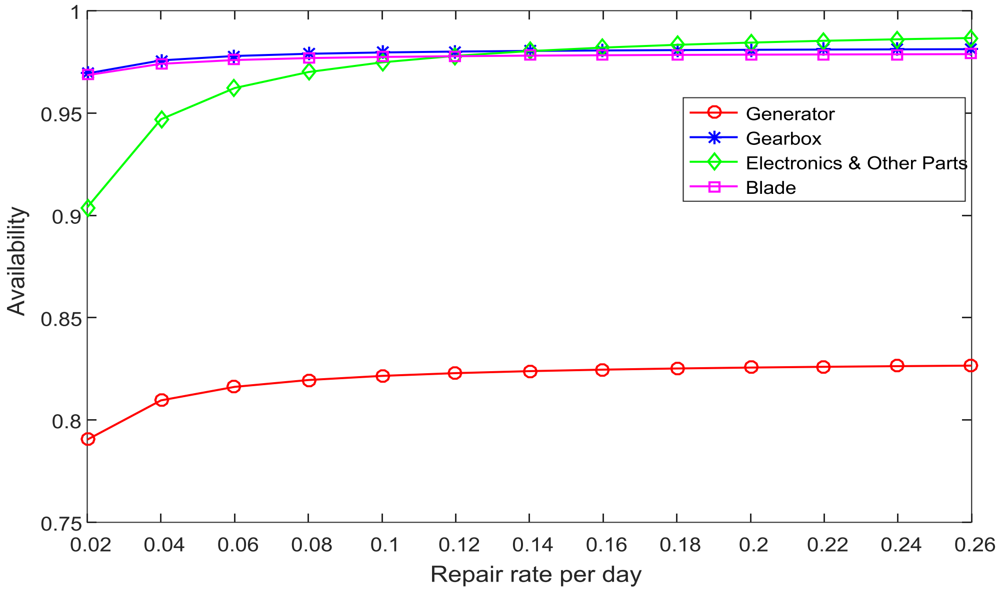

Fig. 5.10 Variation of availability with repair rate

The observations from sensitivity analysis highlight the significance of minimizing quick failures of the subassemblies with high mean down time such as generator and gear box. The results of the analysis also show that electronics and other components having higher failure rate can significantly improve MTTF of the WES by reducing the failure frequency of such components. The availability of the WES can be improved by reducing MTTR, which is achieved by lowering the failure frequency of components with high mean down time or by improving repair rates of components with comparatively higher failure frequency.

5.6 AVAILABILITY ENHANCEMENT

All WPPs have down time for scheduled as well as unscheduled maintenance. The percentage of time that a WPP is not down for maintenance and is available for operate is called its availability and it is a measure of reliability. As the wind is not always blowing, the percentage of time that the WT is actually producing electricity will be lower than this availability. Modern wind turbines have a guaranteed availability of 95% or more [96]. WES availability can be analyzed by the life cycle analysis of very components. The most important components are identified and reliability allocation technique is employed to enhance the availability which is detailed in the next session.

5.6.1 WT Life and Reliability

For reliability analysis of complex repairable systems, Power Law Process (PLP) is generally employed, which is a special case of Poisson process whose intensity function describes the failure rate λ in the following form [168], [169].

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \tag{5.8}$$

where β is shape parameter, θ is scale parameter,

Fig.5.11 depicts the complete life curve of the system described by the above equation and is commonly termed as the bathtub curve. The entire curve is divided into three regions namely:

$\beta < 1$; Early failure, $\beta = 1$; Constant failure; and $\beta > 1$; Deterioration.

If $\beta = 1$, then equation 5.1 represents Homogeneous Poisson Process (HPP) [168].

A WT is typically designed for a useful life period of 20 years. Time-based maintenance assures the failure behavior prediction of WT as which is comparable with mechanical systems.

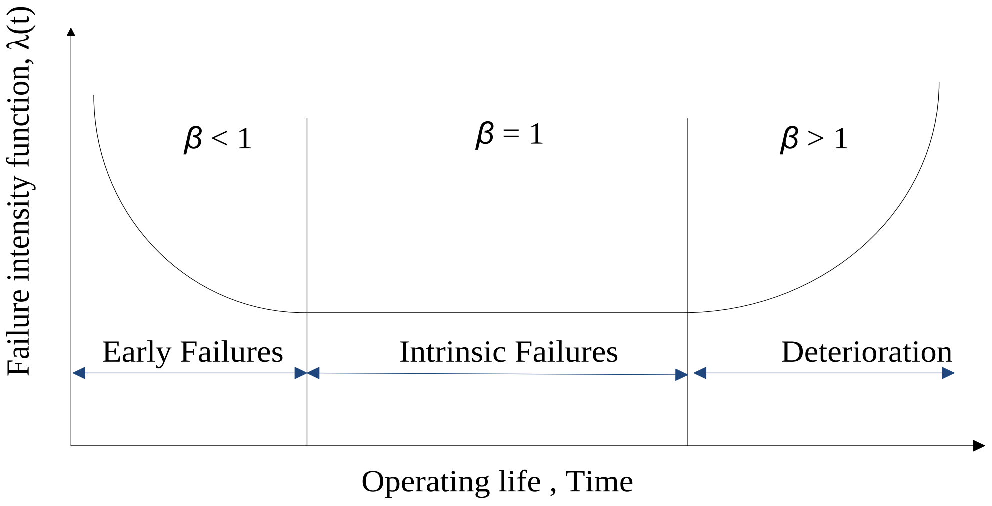

Fig. 5.11. Life curve of a system

5.6.2 WES Reliability Block Diagram

A WES consists of a group of key subassemblies and failure of any of these subassemblies, except the components meant for safety purposes, lead to the shutdown of system for repair of the component. During such periods the power output of the WES is zero. This assumption leads to the fact that the reliability block diagram of the WES can be framed as a series structure, where all the components are connected in series [170]. Even though the general reliability structure of a WES is rather complex, for analysis it is mainly divided into six major subsystems which are identified as rotor system, gear box system, generator system, tower system, other mechanical systems and other electrical systems. Thus reliability block diagram of a typical WES based on the above assumption is shown in Fig.5.12. In order to improve the reliability of a series connected system, reliability allocation technique is employed.

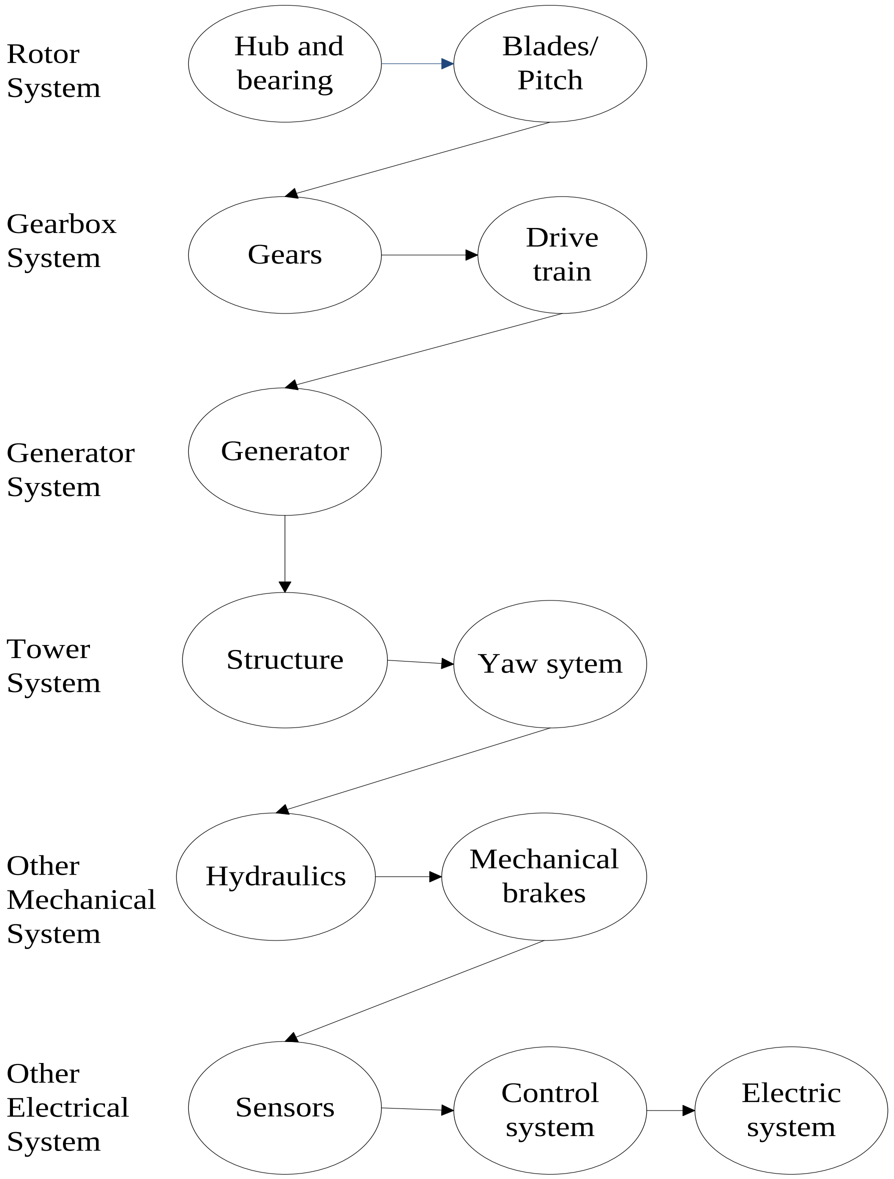

Fig.5.12. WES reliability block diagram

5.6.3 Reliability Allocation

Reliability allocation technique is classified into equal reliability allocation and weighted reliability allocation to single system components at a particular level. In equal allocation method the same reliability level is assigned to each system components at a specific level. On the other hand in weighted allocation a certain degree of importance is given to every component at a specific level and then a reliability level is assigned to the components. The basic principle of weighted reliability allocation technique at single system level is to determine how important and complex each component in that system structure. The equal reliability allocation technique is not very well applicable to WES because it does not reflect the design differences of various WES components. As WES is a complex structure, weighted reliability allocation method is the most appropriate technique to conduct reliability allocation which is used in this work [172].

Generally reliability value of a system is specified on the basis of overall mission requirements. When the system is composed of a number of subsystems and units, there should be a proper method to determine the reliability value for each of subsystems and units, so that when they are assembled to form a complete system, it should have the specified value. The reliability or the predicted failure probability of each subsystems and units is derived from its failure data analysis.

Reliability allocation is the process by which the failure allowance for a system is apportioned in some lucid manner among its subsystems and elements. The aim of reliability allocation is to set a reliability goal for each subsystem so that the operator or the manufacturer can have knowledge of the performance required of the system [171], [172].

Consider a system consisting of n components connected in series as shown in Fig.5.13 with individual reliability factors R_1, R_2 .....R_n. The system reliability $R_{(t)}$ is a function of these component reliabilities. Thus

$$R(t) = f(R_1, R_2, \ldots\ldots R_n) \tag{5.9}$$

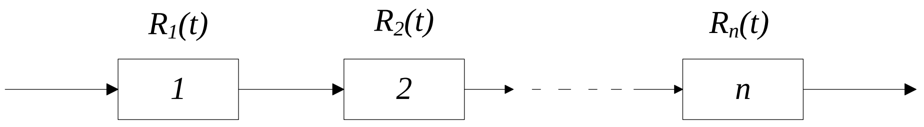

Fig. 5.13 A system representation

Assuming constant failure rates $\lambda_1 \ldots \lambda_n$ for each of the components, the above equation can be rewritten as

$$R(t) = \mathrm{e}^{(-\lambda_1 t)} \times \mathrm{e}^{(-\lambda_2 t)} \times \ldots \times e^{(-\lambda_n t)} \tag{5.10}$$

$$R(t) \quad = e^{[-(\lambda_1+\lambda_2+\cdots\ldots\lambda_n)t]} \tag{5.11}$$

$$R(t) \quad = \mathrm{e}^{(-\lambda_s t)} \tag{5.12}$$

λ_s is termed as predicted system failure rate [173].

To enhance the availability of the system the failure rate has to be brought down to a lower level, which is achieved by reducing the predicted system failure rate. Let $\lambda_s{}^*$ be the specified system failure rate which is assumed to be less than λ_s. Generally the specified system failure rate is subdivided in some equitable manner among the *n* components. Let $\lambda_1{}^*, \lambda_2{}^*$, ….. $\lambda_n{}^*$ be the new component failure rate, so that $\lambda_s{}^* = \lambda_1{}^* + \lambda_2{}^* +$ ….. $+\lambda_n{}^*$. To achieve this, the required failure rate $\lambda_s{}^*$ is apportioned according to the relative unit weight [171], [173].Thus

$$\lambda_1{}^* = \frac{\lambda_1}{\lambda_s}\lambda_s{}^* \tag{5.13}$$

$$\lambda_2{}^* = \frac{\lambda_2}{\lambda_s}\lambda_s{}^* \tag{5.14}$$

$$\lambda_n{}^* = \frac{\lambda_n}{\lambda_s}\lambda_s{}^* \tag{5.15}$$

Thus the new reliability goals for the n^{th} components can be written as

$$R_n{}^*(t) = e^{[-(\frac{\lambda_s{}^*}{\lambda_s})\,\lambda_n t]} \tag{5.16}$$

The expression λt - is small, so that

$$e^{-\lambda t} = 1 - \lambda t + \frac{(\lambda t)^2}{2} - \frac{(\lambda t)^3}{3 * 2} + \cdots \tag{5.17}$$

Neglecting the terms of higher orders,

$$R(t) = e^{-\lambda t} \cong 1 - \lambda t \tag{5.18}$$

5.6.4 Reliability allocation in WTs

WT is a complex system consisting of a number of subassemblies with different reliability levels, and generally it is impossible to directly quantify the reliability level of individual components and elements. To reduce the complexity gear box, blades, generator and electronics parts have been identified as the suitable components to represent the entire WES for reliability modeling and all the components are assumed to be connected in series [156], [158].

In this technique, the requirements put on the whole WT system will be apportioned to its four individual subsystems according to their relative unit weights and in such a manner as to meet the required reliability level of a system as a whole.

The entire block of WT is represented schematically in Fig.5.14 and A_1 to A_4 represent their corresponding availability values.

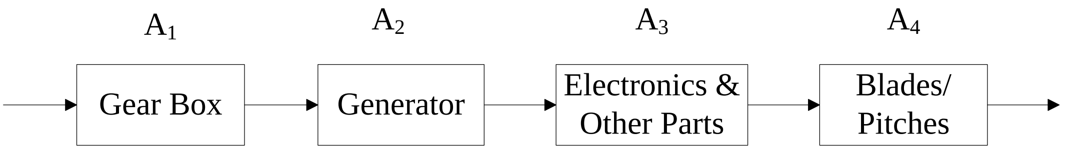

Fig. 5.14 WT representation

The observed and redefined (ie specified) failure rate of WT subsystems and corresponding availability values of the WF under consideration is given in Table no 5.2. From these values,

WT observed failure rate; $\lambda_s = 0.00027+0.00012+0.00201+0.000235 = 0.002635$

And present availability of WT, $A_s = A_1 \times A_2 \times A_3 \times A_4 = 97.86\ \%$

Generally the accepted bench mark value of WT availability is 98% [156]. To enhance the availability from observed level to the bench mark value, failure allowance allocation is performed on four major WT- subsystems keeping the repair rate constant.

Let λ_s^* be the redefined WT failure rate when availability is 98%, then the redefined failure rate of individual subsystems are obtained by iteration process and the values are given in Table 5.2. The value of λ^*_s for the total system obtained after iteration is 0.0024. Subsystems failure rate before and after reliability allocation is graphically represented in Fig.5.15. Corresponding to the redefined failure rate of each subsystem, its availability is tabulated in Table 5.2.

Table 5.2 WT subsystems failure rate and availability

WT Components	**Observed Values**		**Redefined Values**		**% change in λ**
	Failure rate (λ_s)	**Availability (A)**	**Failure rate (λ_s^*)**	**Availability (A^*)**	
Gear box	0.00027	0.9964	0.000245	0.9967	9.26
Generator	0.00012	0.9988	0.000109	0.9989	9.17
Electronics and Other parts	0.00201	0.9843	0.00183	0.9857	8.96
Blades and Pitches	0.000235	0.9991	0.000214	0.9992	8.94

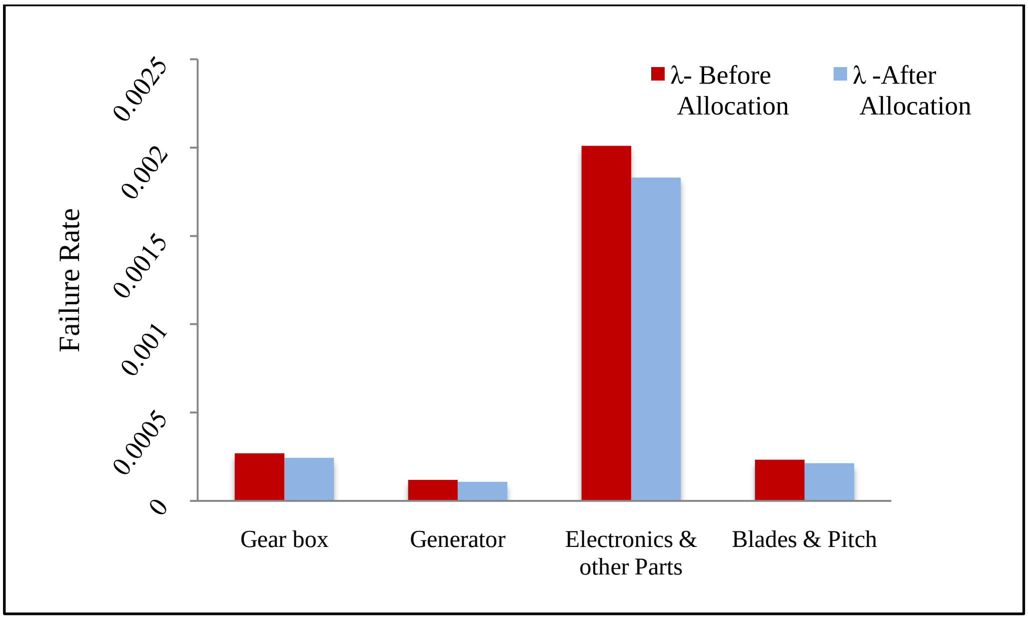

Fig. 5.15 WT subsystems failure allocation

5.7 RESULTS AND DISCUSSION

The points deduced from sensitivity analysis and the energy yield resulted due to reliability allocation of WES is described in this session.

5.7.1 WT Sensitivity Analysis

The sensitivity analysis investigates the impact of failure and repair rates of the main WT components like generator, gear box and blades/pitches with CM to the overall availability of a WES. The effect of remaining components like electronics and other parts without CM is also investigated. The availability of any system is a function of both MTTR and MTTF. The components of WES possess distinct characteristics even if they are combined together in the analysis. If the failure and repair rates of the components are known, generalized result to predict the sensitivity to the availability of a WES can be obtained.

The results of the analysis show that electronics and other components having higher failure rate can significantly improve MTTF of the WES by reducing the failure frequency of such components. The availability of the WES can be improved by reducing MTTR, which is achieved by lowering the failure frequency of components with high mean down time or by improving repair rates of components with comparatively higher failure frequency. Early fault detection using CM technique, minimizes the down time quickly because the components to be replaced can be ordered and delivered while the system is in the operating condition.

The observations from sensitivity analysis highlight the significance of minimizing quick failures of the subassemblies with high mean down time such as generator and gear box. The higher availability for WES with the most unreliable components like electronics and others without CM can be achieved by minimizing failures or replacing them with good quality reliable components. Another possible way is to improve repair rates of subassemblies that fail frequently.

5.7.2 WF Energy yield analysis

WT reliability allocation improves the WF generation availability to the bench mark level of 98% which in turn improves the energy yield [156].The annual energy yield of WF is as follows

$$\mathrm{MWh}_{\mathrm{year}} = \mathrm{Hrs}_{\mathrm{years}} \times \mathrm{Rating}_{\mathrm{MW}} \times \mathrm{CF} \times \mathrm{A} \qquad (5.19)$$

where

$\mathrm{Hrs}_{\mathrm{years}}$ – 8760
$\mathrm{Rating}_{\mathrm{MW}}$ – 1.65
A – Availability; 97.86% is observed value and 98% is benchmark value.

The capacity factor (CF) of WF is 0.2 [174], and the value is tabulated in appendix. Substituting values in the above equation.

- The observed energy yield of WF is 169736.213MWh.
- After reliability allocation the energy yield becomes 169979.04MWh.
- As a result additional energy generated is 242.83MWhr/year

Buyback power price is Rs 3.39/KWhr for 20 years [174].

- Additional income generated per year is 8.23lakh and in 20 years (WT life time) the value would be 1.65 crore, which is a significant figure because the additional investment is almost nil.

Payback period is the year in which net present value of all costs equals with the net present value of all benefits. It also indicates the minimum period over which the investment for the project is recovered. Payback period is a function of WT installation cost, annual maintenance cost, reference price received for the generated energy and turbine lifetime. For large WFs, about 65% of the costs account for WT themselves and installation and other costs account for the remaining 35% [96].

From Table 5.2 it is seen that around 9% reduction in failure rate leads the availability to the bench mark level and generally around 10% reduction in components failure from the observed level is attainable in WPP. Such a reduction in failure rate can be accomplished by the following practices.

- Gather information from sensitivity analysis
- Apply redundancy wherever possible
- Improve maintainability
- Thorough personal training

5.8 CONCLUSION

Even though wind power is a matured green energy source and turbine technology has significantly advanced in recent decades, the system faces expensive and extensive maintenance. WES reliability is one of the main factors in the success of a WPP and poor reliability causes increased O&M and reduced generation availability. So a better WT reliability model, analysis and availability enhancement techniques are very significant in WF operation. The first part of the chapter discusses reliability modeling and sensitivity analysis, and the latter part deals with reliability allocation technique. The major conclusions derived from the analysis are as follows.

- This chapter demonstrates the development of a new model for a WES using Markov chain with CM to incorporate repair rate and failure rate of all components. The model is then employed to identify more sensitive components of WES by conducting sensitivity analysis.

- With the presented model, the sensitivity analysis reveals that components with high failure frequencies or high MDTs can significantly influence the reliability of a WES. Although all components have been grouped into four to achieve reduced complexity, the results can also be generalized to understand the impact of any component with known failure and repair frequencies.

- Results also reveal that the failure rates of the turbine components with high MDT and repair and failure rates of the components having higher failure frequencies are equally important to the system availability.

- Reliability allocation is performed on WT components to enhance the availability from the present level of 97.86% to the benchmark level of 98%.

- By improving the availability to the benchmark level an additional energy yield of 242.83MWhr/year can be achieved, which can result in an additional income of 8.23lakhs/year.

CHAPTER 6

CONCLUSION, CONTRIBUTION AND SUGGESTIONS FOR FURTHER WORK

6.1 CONCLUSION

Wind power generation is one of the most successful technologies to increase the production of renewable energy. Because of its vast environmental and social benefits along with the policies implemented by the government authorities, wind power became the most encouraging and promising alternative source. In the last three decades, wind power generation has been enormous growth and is all set to increase in future. Technological advancement in the field of WT manufacturing has helped to reduce the cost of energy production from wind. Utilization of electrical energy in the modern society is exponentially increasing, with demand for power far exceeding its production. As bulk production of energy is highly appreciated in power sector, energy from wind became the most attractive one among renewable energy sources.

The power generation in a WF highly depends on site and wind speed which varies with season and time which in turn determine wind power modeling. It means that the development of an accurate wind speed model to predict the wind power fluctuations at a particular site is important. The stochastic nature associated with wind power is an issue which must be taken into consideration for wind power to be successfully integrated into an existing power system. This uncertainty can be managed by the application of suitable wind forecasting methodologies.

ARMA time series model is the mathematical tool used by most of the researchers in the field of reliability analysis of wind integrated power system. In this thesis, Box-Jenkins ARIMA modeling of wind speed, a novel technique for evaluating reliability indices of large WF is developed and is detailed in chapter 3. Even though wind speed is a nonstationary random process, while forecasting wind speed using ARMA, it is taken as stationary time series. In ARIMA modeling, it is possible to convert the nonstationary time series into an associated stationary time series by taking differences, without changing the basic statistical properties. Also the ARIMA model can accommodate long range correlations. These unique properties along with accuracy of the ARIMA model and its mathematical strength provide an upper hand over conventional ARMA modeling. A detailed ARIMA model building procedure of the WF under consideration is explained in chapter 3.In this work adequacy checks are performed on the developed ARIMA model which reveal that it well follows the observed wind speed time series and this approach is very useful for accurate wind speed and power forecasting.

A number of different evaluation methods are available for power system reliability analysis. These methods are classified into deterministic and probabilistic techniques. Both of these approaches are used in different aspects of power system planning. These techniques are narrated briefly in Chapter 2. Probabilistic methods can be mainly categorized into analytical and simulation methods. The simulation techniques are usually used when direct analytical techniques are not available. This research work is done using analytical techniques to obtain direct numerical solutions for system reliability assessment.

Power generation reliability is an important aspect of planning for the future development of the power system. The prominent system reliability indices such as LOLP, LOLE and LOEE are explained and this approach is very useful to quantify the reliability. System modeling and evaluation techniques developed for this research work are presented in Chapter 4. The overall modeling process is classified into three major tasks of wind speed modeling, wind system modeling and system reliability modeling. The basic system model and a flow chart for the reliability evaluation are presented. Generation model is developed by making use of WT power curve and simulated wind power using ARIMA model. Load model used in this evaluation is annual load duration curve of the utility grid. WF annual reliability values are calculated and then compared with industry accepted standard for LOLE criteria and found that WF reliability is low. This is because of the partial availability of power generation. The annual reliability information obtained from the analysis is very useful in the power system planning point of view.

The power generation reliability not only depends on the speed of incoming wind but also on the turbine availability. Sensitivity analysis and reliability allocation are detailed in this work to improve the availability.

A WES consists of a number of key subsystems with diverse characteristics which influence the system reliability at different levels. Accurate modeling of WES is very essential to study about the possible failure probability which reflects in the availability and economics of operation. A detailed Markov model building procedure with CM of the WF under consideration is explained in chapter 5. Even though failure rates of electronic components are high, it is not considered while developing

Markov model of WF in earlier works. In this work, the failure and repair rates of electronics and other such components are considered for model building which enhanced the accuracy of the model. The advantage of this model is its improved capability of accurately analyzing and assessing generation availability using analytical equations.

WES is a complex structure, in which certain components are considered as high risk items. Identifying such weak points is very much significant in the operation of the system to accomplish high availability and to minimize the maintenance cost. Using the developed Markov model, different sensitivity analyzes are performed on the WT data to observe the effects of repair rates and failure rates of each subassembly on the reliability measures of the WES viz. MTTR, MTTF, and system availability. Sensitivity analysis is described in chapter 5. The results indicate that the components with high failure rates and high mean down times are equally important to the availability of the system.

A reliability allocation method for WF generation availability enhancement, a novel technique is also detailed in chapter 5. In this technique, the reliability requirements put on the whole WT system is apportioned to its four major individual subsystems according to their relative unit weights. The subsystems selected in this topic are same as that of selected for Markov modeling. The reliability allocation results in improving WF availability to the benchmark level of 98%.

6.2 MAJOR RESEARCH CONTRIBUTIONS

- Reliable and accurate time series wind forecasting model is developed. In contrast to the reported works in this area, the developed ARIMA model can accommodate long range correlations. The non stationary stochastic nature of the wind speed is also taken into account for model building.

- Generation system reliability indices are quantified using the developed wind power model.

- Reliability improvement is achieved by enhancing turbine availability.

- Wind turbine reliability model is developed using the failure and repair characteristics of every turbine components.

- The developed model does not depend on the turbine model, make and type. This makes the system reliability model generalized in nature.

- More sensitive components to system reliability are identified by conducting sensitivity analysis using the developed mathematical models.

- Reliability allocation technique for turbine availability enhancement is investigated. Developed technique is independent of turbine model and make, which provides generalized nature of result.

The models and methods can provide more adaptive and cost effective maintenance policies to improve availability. These models may also aid wind farm operators to conduct maintenance activities effectively and efficiently. This indicates the practical significance of this research work.

6.3 SCOPE FOR FURTHER WORK

- An accurate wind power forecasting is essential to improve the share of wind energy in power system. A day-ahead wind power forecasting can be done by Numerical Weather Prediction (NWP) model and Artificial Neural Networks (ANNs). The NWP model can be constructed by coupling the Global Forecasting System (GFS) with the Weather Research and Forecasting (WRF) system together to predict meteorological parameters. In order to reduce the systematic errors in wind speed from WRF and enhance the forecasting accuracy Kalman filter can be integrated in this system.

- To guarantee the reliability of forecasting, WT power curves need to be analyzed at each wind speed. This can be done by using logistic regression method and Support Vector Machine (SVM) based on linear regression. Support vector machine is a type of supervised leaning and is used to analyze data and recognize patterns.

- A fitting approach of wind speed distribution based on maximum entropy principle can be proposed to assess the reliability of power systems. Then reliability indices like LOLP, LOLE can be evaluated on a general test system.

- Failure rate of each component has been considered independently in this paper, with the assumption that failure probability of each component is independent. However, as WES is an interconnected system, the failure probabilities of different components are interdependent leading to the term ‘secondary failures’. A WT modeling by making use of secondary failures give more accurate results than the present analysis.

- Develop CMS for WT electronic systems.

- Models developed by making use of real time online wind speed data have the capability to improve short term forecasting.

- It is important to develop new methods for wind speed forecasting in complex terrain.

APPENDIX

A1.1 Calculation of A, B and C Constants

The equation for power developed in a WES using simulated wind speed is given by

$$P(SW_t) \quad = \begin{cases} 0 & 0 \leq SW_t < V_{ci} \\ \left(A + B \times SW_t + C \times {SW_t}^2\right) \times P_r & V_{ci} \leq SW_t < V_r \\ P_r & V_r \leq SW_t < V_{co} \\ 0 & SW_t \geq V_{co} \end{cases} \qquad (A1.1)$$

In the above equation A, B and C are constants, whose values can be calculated using the equations.

$$A = \frac{1}{(v_{ci} - v_r)^2}\left[v_{ci}(v_{ci} + v_r\ ) - 4v_{ci}v_r\left[\frac{v_{ci} + v_r}{2v_r}\right]^3\right] \qquad (A1.2)$$

$$B = \frac{1}{(v_{ci} - v_r)^2}\left[4\ (v_{ci} + v_r)\left[\frac{v_{ci} + v_r}{2v_r}\right]^3 - (3\ v_{ci} + v_r)\right] \qquad (A1.3)$$

$$C = \ \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4\ \left[\frac{v_{ci} + v_r}{2v_r}\right]^3\right] \qquad (A1.4)$$

Giving the values v_{ci} =3.5 m/s, v_r =13 m/s, and v_{co} =20 m/s in the above equations

$A = 0.1245$, B = -0.0734847, C =0.0108329.

A1.2 Annual Capacity Factor

Wind speed statistical behaviour can be accurately depicted by Weibull probability density function, which is given by,

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (A1.5)$$

Where k and c are shape and scale parameters, which can be estimated from the statistical analysis of wind speed. The mean $\bar{v}$ and standard deviation σ of the wind speed at the selected site are calculated by the following expressions.

$$\bar{\mathrm{v}} = \left(\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{f_i v_i}^{\mathrm{n}}}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{f_i}}\right)^{\frac{1}{\mathrm{n}}} \qquad (\mathrm{A1.6})$$

and $\sigma = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{f_i}(\mathrm{v_i}-\bar{\mathrm{v}})^2}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{f_i}}}$ (A1.7)

And $k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086}$ $(A1.8)$

$$\mathrm{c} = \frac{\bar{\mathrm{v}}}{\Gamma\left(1+\frac{1}{\mathrm{k}}\right)} \qquad (\mathrm{A1.9})$$

n=3 for cubic mean cube root, the values are $k = 7.52$ and $c = 1.35$

The annual capacity factor of the WF is given by,

$$CF = \frac{e^{-\left(\frac{v_{ci}}{c}\right)^{k}} - e^{-\left(\frac{v_r}{c}\right)^{k}}}{\left(\frac{v_r}{c}\right)^{k} - \left(\frac{v_{ci}}{c}\right)^{k}} - e^{-\left(\frac{v_f}{c}\right)^{k}} \qquad (A1.9)$$

On substituting the values; $CF = 0.198$.

A1.3 Wind Farm Details

The 99MW wind farm described in the thesis is located at Andipetti thaluk, Theni district of Tamil Nadu, India. It uses 60 numbers of Vestas V82 geared wind turbines, each with a capacity of 1.65 MW, IEC Class IIB machine with a blade diameter of 82 m. The WTG is installed on a steel tower of 78 m hub height. The WPP sell 100% of the plant's power generation output to Tamil Nadu Electricity Board under the terms of a 20 year Power Purchase Agreement. The wind speed data used in this thesis is collected from WF anemometer records on a ten minute duration of one year (2011). Later hourly average values of the wind speed required for ARIMA modeling is calculated by averaging six consecutive values. Technical details of WF are given below.

A1.3.1 Rotor

Diameter: 82 m

Area swept: 5,281 m2

Nominal revolutions: 14.4 rpm

Number of blades: 3

Power regulation: Active-Stall

Air brake: Full blade pitch by three separate hydraulic pitch cylinders.

A1.3.2 Operational data

Cut- in wind speed: 3.5 m/s

Nominal wind speed: 13 m/s

Cut-out wind speed (10 minutes): 20 m/s

A1.3.3 Generator

Type: Asynchronous water cooled, DFIG

Nominal output: 1,650 kW

Operational data: 50/60 Hz 690/600V

A1.3.4 Gearbox

Type: Planetary/helical stages

A1.3.5 Control

Type: Microprocessor-based monitoring of all turbine functions with the option of remote monitoring. Output regulation and optimisation via Active-Stall.

A1.3.6 Weight

Nacelle: 52 t, Rotor: 43 t

Towers: 50Hz, 230V

Hub height: IEC IIA, 78 m 115 t

t = metric tonnes.

A1.3.7 Hourly Averaged Wind speed Data

0.7833
0.4667
1.3333
2.1833
2.3833
1.55
0.7333
0.2833
0.5167
0.85
1.0833
1.1
1.5667
1.6
1.8333
3.3167
4.5167
3.25
2.9
1.3167
1.9
3.5333
1.4833
2.05
2.7333
3.55
2.1167
2.4333
1.9833
1.0333
0.8
0.2333
0.2
0.85
0.9667
0.7667
1.6167
1.6
1.9833
3.4667
4.7
4.4
3.6
3.0167
2.0833

3.55
2.6
2.4833
4.2167
1.6333
1.65
1.7833
2.1833
2.6667
2.5167
2.0167
1.3833
3.3667
5.7167
6.3667
6.3
4.3667
3.2333
4.3
2.9833
1.3833
1.35
3.7833
3.2833
5.6
3.8
5.1333
7.2833
6.1833
4.05
2.6
3.5833
3.3167
1.8667
2.1667
0.9167
0.9833
3.05
4.7833
8.5333
6.55
3.6833
5.3333
4.4167
3.5333

8.3333
9.0167
10.1167
4.2333
1.2167
1.5833
1.05
2.3167
1.8167
1.9
1.8833
0.6667
1.95
1.2833
0.6167
1.35
3.2667
4.9667
6.1667
6.4833
6.6333
6.95
8.0833
7.3333
5.4667
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3.8833
3.9
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5.8833
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4.7667
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2.6667
2.85
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1.3
2.1333
2.6833
2.75
3.5
3.9833

4.6833
4.4833
4.2833
3.5167
4.3167
4.75
2.8833
1.3833
0.0833
0.3833
1.15
3.1
1.7167
1.7167
2.4167
0.35
0.2667
1.1667
0.7833
1
1.05
2.1333
2.85
2.7167
3.3667
4.0667
4.8
6.0833
4.7
3.8
1.8333
1.9667
0.75
0.55
0.4333
0.5333
0.2167
1.2833
1.5833
0.5
0.25
0.3833
0.5333
1.2333
1

1.45
1.3833
1.75
3.05
3.9333
4.6167
3.7167
2.4
2
2.0333
2.7667
0.6667
1.4167
3.25
2.3
3.8167
3.6
3.0333
1.4
0.2667
0.2833
0.5333
1.55
1.0667
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2.65
3.5333
3.6
2.85
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1.9
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2.4167
1.2333
1.5
1.0667
1.0667
3.2667
2.4
1.7333
1.0667
0.7833
0.4667
0.6333
0.3167

0.3
0.55
1.1667
1.3333
1.0833
1.6
4
4.3167
4.7167
3.8333
3.05
1.5167
1.6
1.3667
0.95
0.7167
1.3333
0.7333
1.9167
2.5333
1.75
0.5667
0.8167
0.6167
0.2
0.5667
1.1833
1.15
1.35
1.4
2.6667
3.2667
3.7333
3.6
2.6833
1.55
2.15
2.3333
1.6833
3.6167
3.1667
2.3833
1.7167
0.7667
0.8333

2.7167	1.35	0	2.7833	4.3833	7.6333
1.6333	0.5167	0	3.4333	4.15	7.25
1.1333	0.5833	0	0.6333	4.3167	6.3667
1.4667	0.4667	0	0	3.25	6.5833
0.7	0.3167	0	0.9333	3.4167	5.1167
0	0.2	1.0167	2.9333	1.9667	2.85
0	0.2833	3.95	2.2333	1.7333	3.8167
0	2.3667	1.65	1.5333	1.2333	3.0167
0	2.5	2.3	1.5167	0.5833	2.7667
0	2.35	2.1	1.1667	0.7	2.2333
0.9333	1.65	0.7333	0.5	1.05	3.0167
1.55	2.4833	1.1667	1.1167	1.0167	2.3167
1.1	3.5	0.8667	1.65	0.3833	2.0833
1.4167	4.15	1.9167	2.5833	0.3167	1.8333
1.0667	4.1167	4.3333	4.2167	0.7	2.1833
0.8833	4.0167	4.2167	4.1	0.8167	2.1167
0.3167	4.2667	3.8	4.1833	1.9667	2.1333
0.2333	3.9	3.7	4.3167	3.5	2.2167
0.4	4.55	4.2	2.7833	5.2667	5.0167
0.9667	4.8333	3.7667	3.5667	6.5	7.0167
1.2333	3.7167	3.7167	3.6833	6.4667	7.75
0.5333	1.3667	1.5167	5.1167	5.4333	8.0167
0.25	1.75	0	4.7167	4.7	7.1
0.4667	2.4667	0	3.65	4.9333	6.55
1.0167	3.8667	0	1.9667	4.5167	6.85
2.3833	6.65	0	1.3167	4.0167	6.8833
1.55	5.65	0	2.9833	2.8833	7.5
0.4667	3.25	0	1.2833	3.9333	5.9667
1.3833	0.9	0	1.35	1.6	6.1833
1.05	0.6333	0	1.2333	1.1167	7.2833
0.8333	2.7333	1.7833	0.95	1.4167	7.2667
1.6667	3.65	2.4	0.65	1.1833	3.5667
3.2167	2.5333	1.9833	0.3667	1.4	6.1
3.3833	2.3333	1.9667	0.0667	1.4667	5.6833
3.4	1.4	1.95	0.05	1.5	5.7167
3	2.2833	2.3167	0.35	0.7667	7.0167
3.6333	2.7833	2.5	0.7667	0.2833	4.9833
3.8667	3.1667	3.3667	2.1167	0.3667	3.2167
2.6333	4.0667	4.05	4.6333	0.9167	2.8167
1.6833	3.5333	3.9333	4.8333	1.9	1.5667
2.3	2.9333	4.8333	5.6833	3.6833	0.9167
2.65	1.6667	4.1333	5.5833	3.6167	1.15
1.7667	1.1667	3.9	4.6667	6.4	3.9333
1.6667	0	3.7333	3.9	8.5167	8.1167
2.55	0	3.3667	3.45	8.4833	8.0333

7.5167	4.8667	8.7667	2.3833	0	7.2833
7.35	6.6167	8.5667	3.2	0	4.8667
8.0167	6.35	8.2667	3.7667	0	5.1667
8.1833	6.4333	8.2833	3.8833	0	5.55
7.7333	6.35	8.2	4.4167	0	6.7833
6.6667	6.3833	7.6333	3.8833	1.8333	6.9667
6.9333	5.3	6.9833	4.05	1.2333	5.45
8.6667	5.0833	5.7833	3.5833	2.7667	4.9833
7.5833	5.2333	5.0667	4.2333	1.8167	3.15
7.5167	5.5333	4.95	6.9333	2.25	2.2167
1.9	4.0333	5.1333	9.3833	3.7667	1.85
8.8	5.45	5.4167	9.3833	5.4167	0.4
7.6	6.25	5	7.5	9.5167	0
8.4167	7.3833	4.9833	6.65	8.0167	0
1.4167	7.0333	3.6833	6.7167	6.5167	0
0	7.9333	2.7167	6.9333	7.9	0
2.4	7.5667	2.25	4.9	7.3	2.7833
4.8167	3.7167	2.1	5.2333	8.2	7.1667
5.2167	0	2.65	6.5	6.2333	8.1
2.7333	4.6833	2.15	5.9	4.6333	6.7833
2.6167	6.35	3.4167	7.6167	4.8333	9.65
6.0833	5.2333	4.6333	7.75	3.9833	8.35
9.15	7.5	4.1333	9.35	3.45	7.4667
7.5833	5.5333	3.15	0	2.8333	6.8167
7.4833	7.2833	5.2333	0	3.0667	5.9667
7.75	6.85	4.0667	0	3.9167	6.75
7	6.45	1.95	1.1	4.7167	6.1
6.5167	6.6833	2.0333	4.1833	3.8	1.0833
6.6667	7.3	3.4167	2.6167	3.65	7.1333
6.0667	7.55	3.9333	1.95	3.4	5.9
5.4833	7.3167	4.6833	4.1167	2.15	7.1667
4.9833	6.2833	4.2	4.55	0.6167	4.6167
4.7667	4.75	4.4167	4.8833	0.7167	3.55
4.75	5.7333	4.3	4.8333	1.35	1.75
5.8333	7	4.6833	6.3833	0.35	2.0333
0.65	7.5167	4.5833	6.5	0	3.2833
0	1.3	5.3833	8.0333	2.5333	5.35
0	5.3833	4.3167	7.7667	5.3833	5.4333
0	3.4833	2.65	7.8833	6.1	2.9333
0	0	2.5167	8.9333	9.5667	5.05
0	0	1.7333	6.2667	9.3833	5.1833
2.7333	0	1.9333	5.8167	8.8333	7.1833
6.4	0	4.05	7.1333	7.45	7.7667
3.7667	0	3.05	7.2333	7.85	5.8167
3.6167	9.1667	4.35	5.2	7.6167	6.3833

4.8167	7.5	4.75	0.6333	1.7167	0.5667
5.05	7.6167	4.9167	1.1667	2.6167	0.4667
4.45	6.6333	4.9	2.2167	3.1167	0.45
3.8667	6.05	3.2	3.1	3.7	0.9667
2.05	4.4	1.7667	4.3	4.5333	0.7333
2.7	2.4667	1.2167	4.4833	4.6833	0.2
2.15	2.2333	0.9833	4.3667	4.65	1.6833
1.8667	3.4667	2.7833	4.7833	5.2667	4.6167
0.9667	3.6833	2.6667	5.45	5.7333	3.5833
1.4667	4.5167	2.65	4.3833	5.5167	4.45
1.3	2.4333	1.9167	5.3167	5.5333	5.5833
0.6	2.9333	2.0333	4.25	5.4	5.4
0.4167	2.4	2.1667	3.4833	6.1	4.0833
0.1667	3.45	1.7	1.4667	6.25	4.9667
0.6	1.9667	1.1333	2.9833	6.7	5.05
1.1333	0.7667	2.1333	2.8333	6.8167	5.5167
1.1333	1.3167	1.9167	1.9667	8.3333	6.15
1.4167	1.2167	3.2	1.5167	6.7833	4.0833
1.4333	0.95	2.4167	1.2667	5.55	3.4167
1.4667	3.9167	1.5667	1.5167	6.4167	3.5833
2.0667	4.6833	1.15	1.15	4.7	2.3833
3.3667	4.2333	0.5167	0.9167	4.0167	2.2333
5	4.3	1.2167	1.5	2.1833	2.55
4.1167	5.2833	1.8667	0.6333	1.2833	1.0667
5.65	4.7667	2.7833	0.4167	0.7333	0.5833
4.8333	4.9833	3.75	1.3	0.75	0.7167
2.9333	5.1333	3.3167	4.1	0.7667	0.2333
1.0333	4.5667	4.6167	5.6833	2.95	0.9333
1.4	4.7833	5.1	5.0833	5.0167	0.5
1.5333	5.25	5.1	5.5833	6.45	0.25
2.15	4.8167	3.7	5.2333	6.15	1.8
0.6333	3.85	3.75	5.6167	6.7833	2.7
0.7333	1.5	3.05	6.2167	5.9	3.4667
1.3167	1.3833	4.7667	5.8833	5.5833	3.2333
0.4	2.7333	3.8333	5.1167	5.3333	3.3833
0.5	0.9833	3.2	4.4	5.8167	2.9833
0.4333	1.6167	3.4	3.5833	5.75	2.6167
1.2833	3.2667	2.7	3.85	4.6333	3.9
1.4167	3.2833	2.95	3.7667	4.4333	4.4
0.5	1.9667	3.25	3.5167	3.6167	4.4333
1.15	3.2667	3.3167	1.3	4.15	3.9833
2.5167	1.1833	3.45	1.6667	2.55	3.0167
4.4833	2.1833	1.7833	3.0833	2.4833	4.45
5.5167	3.5333	1.3	1.6167	0.5333	3.9167
6.8833	3.95	0.3	1.7667	0.9	4.4333

4	2.8833	5.4	0	0	0.2833
2.5667	3.15	5.6167	0	0	0.6667
1.9167	1.8	5.4333	0	0	1.8833
0.8	3.9667	6.3	0	0	1.85
1.4333	3.3	3.8333	0	0	2.2333
1.7167	2.1333	0.4333	0	0	2.8833
2.05	0.7667	0.4667	0	0	2.9
1.8333	0.05	1.0167	0	0	2.3667
1.25	0.4667	1.2833	0	0	3.9833
0.9167	0.9333	1.4167	0	0	2.8667
1.0333	1.6167	2.0833	0	0	1.4
0.9167	3.3333	1.1333	0	0	4.3333
0	1.45	1.3	0	0	8.4
0	1.3	1.95	0	0	2.1167
0	2.45	1.0667	0	0	1.4333
0.7667	2.65	1.05	0	0	0.6167
3.15	2.45	2.2667	0	0	1.3167
3.6833	2.6167	1.75	0	0	1.4167
5.3	3.5833	2.4167	0	0	1.45
5.3167	3.55	3.0333	0	0	1.8667
6.6	4.4667	2.2667	0	0	2.25
5.8333	4.4833	0	0	0	1.1333
4.7167	7.4167	0	0	0	1.0833
3.85	4.2167	0	0	0	1.4667
2.2833	2.8833	0	0	0	1.0667
3.3833	4.4333	0	0	0	0.85
2.7167	3.2	0	0	0	0.8667
2.0167	1.8	0	0	0	1.55
2.15	1.8333	0	0	0	1.6
0.3333	1.6	0	0	0	1.6167
0.1333	0.6667	0	0	0	2.9333
1.8333	0.6833	0	0	0	4.9167
2.4833	0.2333	0	0	0	5.65
0.5833	0.35	0	0	0	3.2
1.1167	0.05	0	0	0	4.9833
1.55	0.5167	0	0	0	6.8167
1.65	1.1833	0	0	0	3.85
1.7667	1.6833	0	0	0	2.6167
2.2833	2.0833	0	0	0	0.8167
2.0833	1.8667	0	0	0	0.9
3.3	2.4	0	0	0	0.8167
4.2833	2.4833	0	0	0	1.0167
4.3333	3.5833	0	0	0	1.8667
3.7833	3.8	0	0	0	1.7
2.8167	3.9667	0	0	0	2.1333

1.45	2.5333	5.3	2.95	5.2833	0
0.8167	3.1833	4.7333	3.9333	3.65	3.7167
0.8833	2.1667	4.8833	2	3.05	5.8833
0.4	0.7333	3.9	1.7	4.4833	6.8833
1.1167	1.4333	3.0167	1.1667	3.7333	5.5
1.7667	2.6333	3.5667	1.5	3.3833	2.5167
1.8667	3.5167	3.3333	1.7833	2.45	3.3833
1.55	4.1833	2.45	1.4	2.3	3.5
3.3667	4.9	2.1333	1.75	1.7	2.0667
4.2333	4.6333	4.35	0.6167	2.5833	1.1333
4.6333	6.15	4.7167	0.9167	2.3833	0.3333
4.2167	6.2667	7.9333	1.0667	2.05	0.4
2.6167	6.9	8.8667	2.4333	1.1	0.8667
3.2333	6.6	8.5	3.0167	1.2	0.4167
4.1667	7.6167	7.5833	4.2333	0.6833	1
1.6667	6.75	7.35	4.1	0.9833	1.2
2.8	7.6667	6.8667	5.15	2.2167	1.3667
2.5833	5.65	6.4833	5.7167	3.9167	0.85
3.4167	4.8667	6.2	5.8667	4.6333	0.7833
2.55	4.4333	5.5833	5.6333	5.1	3.55
3.0167	5.1	5.65	5.3667	4.6833	5.25
3.3333	3.4333	4.95	5.0833	5.1833	5.45
2.8833	2.8167	5.7833	4.5833	6.3333	5.6333
3.6333	2.2333	6.2167	5.1833	6.6	6.85
2.9	3.1667	4.2833	2.4167	5.9333	1.1333
2.9667	5.4	3.8833	1.8833	5.2333	3.7333
2.6667	4.9667	2.4667	1.7667	4.0167	5.6
1.2333	6.5	1.35	2.3167	2.0167	5.1167
1.6	5.5167	1.9833	0.6333	2.9167	5.0167
2.4667	5.2167	1.95	0.4333	2.6	2.6167
4	3.0667	0.7667	1.0167	1.7667	2.8833
4.15	0	0.4333	2.3167	2.3333	2.8
5.0833	0	1.4	2.1167	3.6	4.05
5.6333	0	2.05	2.1667	1.6167	3.3333
5.25	0	3.4167	2.8	1.5167	1.2167
5.7333	4.2	4.95	1.8167	0.9	0.5667
3.4833	1.35	5.2667	1.4667	0.8333	1.2667
5.35	8.3667	5.0667	2.4333	1.9667	1.4833
5.4167	9.15	5.7	4.0667	1.7167	1.9333
3.4333	8.55	5.1167	3.9167	2.0167	2.9167
2.5667	6.2333	6.2333	4.85	0.4167	3.9833
4.3333	6.4667	5.1833	5.35	0	4.45
3.2833	6.5167	6.0833	5.3167	0	1.9667
4.2	6.5167	5.9667	4.85	0	1.0667
3.15	5.7167	3.7667	4.75	0	2.9167

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7.3	0	0	2.45	0	10.1667
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8.3833	10.2333	0	0	0	0
7.9667	10.9333	0	0	0	0
6.1833	5.65	4.7	0	0	7.65
9.3	0	10	0	0	0
9.1167	0	9.45	4.0667	0	11.45
12.3667	6.0333	14.1667	7.3	0	12.7333
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12.4833	14.3667	13.0833	12.9667	0	13.6333
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12.1333	0	12.6167	13.0167	10.6167	15.1
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11.5833	10.5833	10.65	0	12.8667	14.1
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14.1667	12.4833	2.55	8.1667	0	10.0833
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11.0167	7.3167	0.3	2.9167	0	3.7833
9.2	8.6167	3.35	2.3667	0	5.4333
7.9	7.2833	3.25	3.0667	0	3.25
6.7167	9.0667	1.95	2.7333	0	2.0333
5.7333	7.35	0.8	1.3333	0	6.5333
4.6	6.9	3	2.8667	0	4.4167
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4.6167	6.3	1.6333	2.9833	0	4.5667
7.7	4.6333	1.2167	2.9833	0	3.8
8.5833	6.8333	1.1	0.75	0	3.2167
10.1667	7.5	1.8167	0.7	0	3.1667
10.1333	5.5833	1.6667	2.3833	0	2.95
8.55	1.8167	2.1333	1.2667	0	1.9167
9.9333	1.7833	4.4333	0.9333	0	1.3
10.25	2.85	3.7167	1.0667	0	2.9167
9.35	4.8	4.65	3.0667	0	3.3
9.05	6.6333	1.65	3.95	0	2.2667
8.6833	5.5167	1.7667	4.4333	0	2.2667
7.1333	2.2833	2.2	3.6	0	1.6333
8.1167	4.1833	1.3167	0	0.6	1.85
8.9167	2.55	1.15	0	2.9333	1.75
9.0833	3.85	1.25	0	1.85	2.0667
7.3	3.8167	0.5333	0	1.65	4.5833
7.0167	4.0167	0.95	0	2.0667	6.5667
6.95	5.9167	2.45	0	3.15	2.0833
6.1167	6.9	3.8	0	4.0333	6.1833
4.6333	6.4667	2.5667	0	4.2	6.35
3.9167	6.4	0.85	0	3.4333	6.45
3.9667	6.4667	1.25	0	1.2667	7.2333
3.0333	5.8833	0.8833	0	3.35	5.5
2.3167	3.45	0.9833	0	2.75	3.1667
4.6833	1.8667	0.75	0	2.8833	1.9667
9.2167	1.6333	0.7833	0	4.8667	2.8
6.6833	1.3	0.4833	0	4.8167	2.8
4.4167	1.2833	1.0333	0	2.5667	2.8333
7.1	6.6167	1.15	0	4.6	1.3667
3.5167	6.3	2.4	0	4.75	1.85
5.2	4.4833	3.5833	0	1.95	2.0667
6.95	3.55	7.0833	0	1.9167	2.0167
7.2833	3.9833	4.7333	0	1.8167	3.9167
8.1667	2.9667	2.4167	0	1.75	3.6833
7.6833	2.3333	1.65	0	0.6	2.4333
7.2667	0.95	1.2333	0	1.4667	1.2333
7.9	0.4	1.2	0	1.7833	0.8667

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2.9167	3.1667	2.6	2.0167	0.6833	0
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0.95	1.4333	0.7167	0.6833	2.4333	0
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4.6167	1.4667	0.5833	0.0167	0.8667	0

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3.1	2.9	1.4833	3.5667	2.3	2.9167
3.1667	2.8	0.7	3.9	5.0333	2.6
5.6167	3.7	1.0333	2.65	5.95	1.4667
7	4.55	0.6333	1.0333	3.9333	1.0167
9.0333	9.8833	1.2	0.3333	2.3167	0.8833
8.7167	10.6333	2.1167	0.3167	1.3	1.8833
7.5333	8.05	2.5	0.6	2.0667	2.25
5.7833	4.1167	2.3833	0.2167	2.6	2.85
6.4833	1.6	0.7167	0.2	1.3833	2.4
7.0167	10.3667	0.5	0.2	1.6	1.8167
6.1167	9.05	0.5167	0.8833	1	2.2833
4.4333	7.65	1.9667	1.4167	1.1333	3.1
5.2833	6.8667	1.0333	1.3667	0.1167	2.7833
5.75	9.4833	2.0167	1.65	0.1833	2.9
5.6	7.1333	2.5833	1.95	1	2.4
5.6167	8.0833	1.8667	3.0667	1.6333	1.7833
4.5667	2.7333	2.7667	3.6167	2.3833	1.45
3.55	0	2.7833	3.7667	2.4833	0.65
1.9833	0	2.4833	3.0167	2.3	1.3667
4.25	0	2.4167	4.75	2.05	1.9
4.2	0	1.75	4.0333	2.2667	1.5333
2.8833	0	2.45	2.0167	1.8333	1.15
2.45	0	1.3	0.8833	1.6333	1.2833
2.1833	4.9833	0.6167	0.65	2.55	1.15
2.45	8.35	0.7333	0.65	2.15	1.2833
2.75	8.3667	1.0667	5.0833	1.8833	1.85
3.1333	9.45	0.8	5.6333	2.2167	2.4
1.9833	9.7167	2.95	4.3167	2.1	1.0833
3.6833	9.7333	2.35	3.1833	2.7167	1.7
5.0667	9.7833	1.8833	2.1167	2.05	2.85
6.6667	8.9667	1.65	2.0667	1.8667	2.6833
5.9167	9.2667	3.8667	3.55	1.6333	2.0833
6.1	8.6833	4.2333	3.1	0.6	2.1167
5.5333	8.6667	2.5167	2.1833	0.4667	2.3167
4.75	6.7	1.9667	3.45	0.8333	0.9667
4.55	6.0833	2.5667	4.75	0.7833	1.9667
4.1833	8.45	2.75	5.1167	0.6333	0.5833
4.45	8.55	4.5	4.9667	1.35	0.4833
6.4833	8.4167	3.4833	3.2333	1.6667	1.3333
6.7	8.4333	2.4	2.7167	1.7833	0.55
8.3667	8.45	3.0667	2.65	2.0167	0.3
10.7333	7.1833	2.55	3.1667	2.5167	0.75
7.55	5.0833	0.4167	2.6	2.55	0.6833

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1.4667	3.8	1.2	0.3167	2.8667	3.8833
2.45	4.8333	0.6167	0.2833	3.2833	3.7
2.8667	4.8667	1.2	1.1333	2.9667	4.9667
3.6	4.4167	3.7167	0.9667	2.4333	5.5167
4.0333	4.4667	5.4167	0.45	1.4	5.3
2.6833	4.5167	6.05	2.5167	0.8667	5.05
2.7667	5.3167	5.2833	4.3833	1.7	4.1167
2.6667	4.2333	3.95	4.5333	2.3167	3.9
3.9333	3.95	4.9167	5.45	3.8667	3.9833
3.2167	4.35	4.75	4.7167	4.65	3.15
2.6667	3.6333	4.45	4.5833	4.6833	0.6667
3.35	3.1	3.6167	4.8	2.55	2.8833
3.0167	1.3833	4.6	4.1167	4.6667	4.55
2.15	0.9	7.05	4.05	2.4333	7.25
2.1167	0.9167	6.95	3.55	3.9833	5.9333
2.65	0.95	5.4667	2.8	4.85	5.8667
1.8667	0.9833	3.2167	2.2667	3.4167	6.5167
1.9833	1.15	1.6333	2.1	3.1333	6.55
1.9333	1.6833	2.2167	2.3333	2.8167	5
1.5	1.25	3.35	3.1833	2.5833	4.0833
2.3167	0.75	2.5	3.3333	2.8333	4.1
2.9667	0	2.7333	1.8167	2.1167	3.15
2.8833	0.15	3.1333	2.6	1.8333	2.8667
2.4333	1.4667	3.6	3.0333	3.1333	2.9667
3.1	2.5167	3.8833	2.55	4.25	4.05
3.75	4.5333	4.85	3.4333	4.1333	5.9667
3.45	4.7	4.7167	3.6833	5.6167	4.8833
3.75	5.4167	4.8333	2.1167	4.1333	3.4333
2.5833	5.8333	4.85	1.85	4.8667	2.3167
3.8	6.1667	4.1833	3.25	4.0333	1.9667
3.9667	5.9833	4.8667	4.7167	3.7333	3.25
3.2667	5.8833	3.5667	5.5333	3.2333	3.5333
2.8167	4.3833	3.9167	5.0167	5.9333	3.0833
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