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Reliability Evaluation of Wind Farms

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Abstract: The Renewable energy sources, especially wind turbine generators, are considered as important generation alternatives in electric power systems due to their non-exhausted nature and benign environmental effects [1]. The fact that wind power penetration continues to increase has motivated a need to develop more widely applicable methodologies for evaluating the actual benefits of adding wind turbines to conventional generating systems. In this paper reliability evaluation of wind power generation system is carried. Reliability evaluation of generating systems with wind energy sources is a complex process. It requires an accurate wind speed forecasting technique for the wind farm site. The method requires historical wind speed data collected over many years for the wind farm location to determine the necessary parameters of the wind speed models for the particular site [3]. The evaluation process should also accurately model the intermittent nature of power output from the wind farm. For the data analysis excel data analysis tool is used and probability distribution of wind speeds are calculated [10]. This study shows the system availability for the generation of power from wind turbine generators installed at the Hanamasagar, a village near Gajendragada of Karnataka State.

Keyword: WTG, Reliability evaluation, wind energy, probabilistic model and excel data analysis.

I. INTRODUCTION

The worldwide of the concern about the environmental pollution and a possible energy crisis, there has been a rapid increase in renewable energy sources worldwide in the past decade. Among various renewable sources, wind power is the most rapidly growing one. The wind is a free, clean, and inexhaustible energy source[4]. The kinetic energy of the wind can be changed into other forms of energy, mechanical work in the water pumps and wind mills and electrical power in modern wind power plants. It is predicted that nearly 10% of the world energy needs could be met by the wind energy by the year 2020.

Wind power generation is one of the most important renewable energy technologies. The most common type of wind turbine used to generate electrical power is the fixed-speed wind turbine with the induction generator connected directly to the grid [4]. This system although is the most simple does not allow to perform grid control level and is very sensitive to wind fluctuations. Due to intermittent wind speed, the output power fluctuations lead to not only voltage fluctuations, but also other serious problems [6]. When variable-speed wind turbines are used the dynamic behaviour of the wind turbine, power quality and power compensations are improved. Electrical power generation from the wind is established in India in the 1990s, and has significantly increased in the last few years. Although a relative newcomer to the wind industry compared with Denmark or the United States, India has the fifth largest installed wind power capacity in the world. In 2009-10 India's growth rate was highest among the other top four countries. India emerged as the second leading wind power market in Asia.

As of 31 March 2014 the installed capacity of wind power in India was 21136.3 MW, mainly spread across Tamil Nadu (7154 MW), Gujarat (3,093 MW), Maharashtra (2976 MW), Karnataka (2113 MW), Rajasthan (2355 MW), Madhya Pradesh (386 MW), Andhra Pradesh (435 MW), Kerala (35.1 MW), Orissa (2MW), West Bengal (1.1 MW) and other states (3.20 MW). It is estimated that 6,000 MW of additional wind power capacity will be installed in India by 2014. Wind power accounts for 8.5% of India's total installed power capacity, and it generates 1.6% of the country's power.

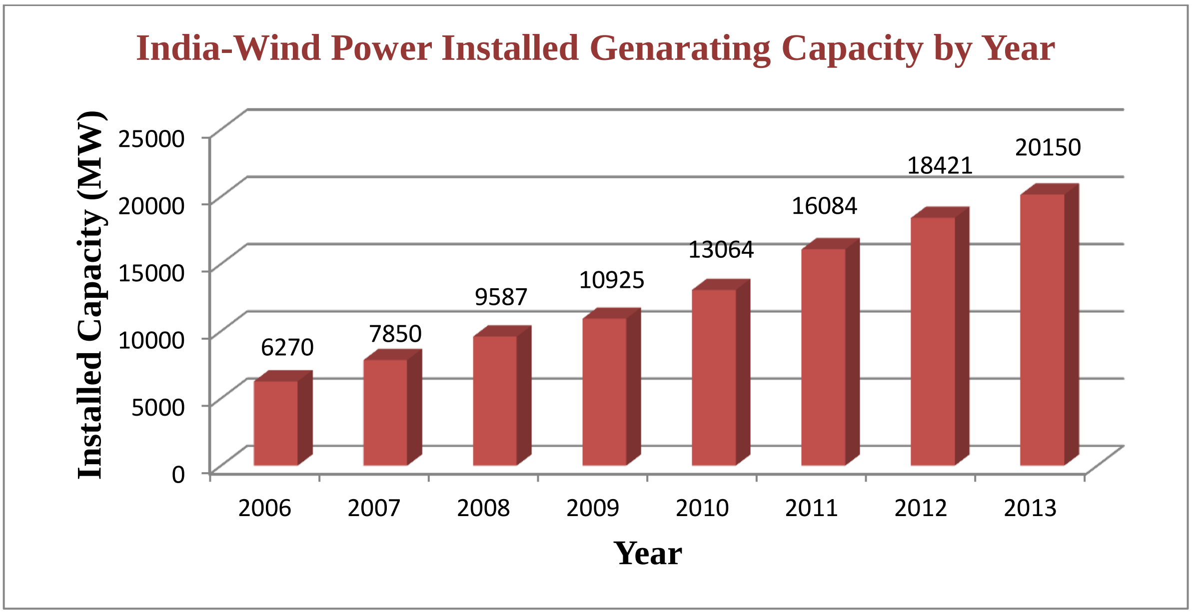

Fig. 1: Progress in India's installed wind power generating capacity since 2006

1.1 Generation System Reliability Studies

In the generation system the total system generation is evaluated to find the system adequacy to meet the total system load demand [7]. The system is model in generation is shown in below figure 2.

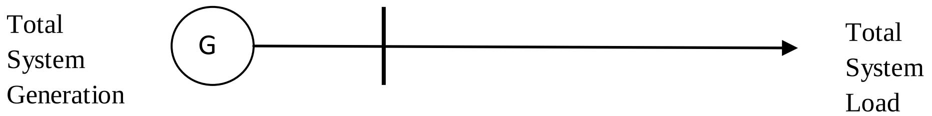

Fig. 2: Generation system reliability model

1.2 Reliability indices

The most popular generation reliability index [1] is the loss of load expectation (LOLE). In addition to this index expected energy not supplied (EENS) and energy index of reliability (EIR) are used [1]. The energy not supplied can be found using the technique each state of capacity model C_k, the energy not supplied E_k is given numerically by summing all positive values of $(L_i$-$C_k)$ where L_i is the i-th load level and i = 1 to n. The expected energy not supplied is given in equation (1.1).

$$EENS = \sum_{k=1}^{n} E_k P_k \quad \ldots\ldots\ldots\ldots kWh \qquad (1.1)$$

Where, P_k is the probability of capacity state C_k

n is the total capacity states.

The EIR given by the equation (1.2)

$$EIR = 1 - \frac{EENS}{Energy\ Demand} \qquad (1.2)$$

II. METHODOLOGY

2.1 Wind power generation system

Renewable energy sources, particularly wind turbine generators, are considered as important generation alternatives in electric power systems due to their unexhausted nature and being environmental friendly. The fact that wind power contribution continues to increase has motivated a need to develop more widely applicable methodologies for evaluating the actual benefits of wind turbine generating systems [9]. Reliability evaluation of wind turbine generating systems is a complex process. It requires an accurate wind speed forecasting technique for the wind farm site. The method requires historical wind speed data collected over many years for the wind farm location to determine the necessary parameters of the wind speed models for the particular site. The evaluation process should also accurately model the intermittent nature of power output from the wind farm [10].

In this process there are many steps are involved, for my work I have considered nine steps those are listed below.

1. Data collection
2. Data analysis
3. Wind speed model for selected geographic location
4. WTG power curve data
5. WTG power generation model
6. Probabilistic evaluation of power generated
7. Three state model for WTG system
8. Evaluation of Cp and Availability
9. Calculation of reliability indices

2.1.1 Data collection

For the evaluation process the data used is obtained from National Renewable Energy Laboratory (NREL). It consists of hourly basis average wind speed, standard deviation and wind rose data. Wind rose data is the data consists of wind direction with respect to north and it is considered as 0^0.

Wind data is available in hourly basis through the year measured by the anemometers installed at the site location. These measured data are available in the NREL web site; these data are called secondary data. Primary data are the data obtained directly from the wind site through the anemometer. For my work I have used secondary data that is data which is recorded in a system, which is provided by NREL.

Turbine data and the wind site data are obtained from the installed turbine manufacturers. Those data are available in the turbine manufacturer web site. These data contains geographic information about the wind site, turbine power curve, dimension, capacity.

2.1.2 Data analysis

In the data analysis “Excel wind analysis tool” is used. The raw data obtained from NREL is used as an input to the Excel wind analysis tool. The purpose of this tool is to analyze wind data to prove a wind resource exists at a specific location. The spreadsheet is a program to create a Wind Rose graph, as well as a folder containing power curves for various wind turbines. Some important items calculated by the spreadsheet are the average wind speed, capacity factor, and estimated annual energy production. A report sheet is also included, formatted for printing, which summarizes results and displays graphs.

2.1.3 Wind speed model for selected geographic location

This is the estimation of wind speed model for the specific geographic location. In this work two geographic locations are considered. In this step the wind speed model is developed by calculating the average and standard deviation of the discrete wind speeds. With this model frequency of occurrence and probability of the wind speed in that specific site can be obtained. This model also gives the probability distribution of the discrete wind speeds.

Wind speed statistics

The speed of the wind is continuously changing, making it desirable to describe the wind by statistical methods. One statistical quantity which is the average is calculated by a set of measured wind speeds u_i. Standard deviation is calculated by the variance [12].

Average wind speed

The measured wind speeds are in integer values, so that each integer value is observed many times during a year of observations. The numbers of observations of a specific wind speed u_i will be defined as m_i. The mean is then given by the relation 2.1.

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{w} m_i\, u_i \qquad (2.1)$$

Where, w is the number of different values of wind speed observed
n is the total number of observations.

Standard deviation:

To find the deviation of each number from the mean and then find some sort of average of these deviations. The mean of the deviations (ui – u) is zero, which does not indicate much. Therefore square each deviation to get all positive quantities. The variance of the data is then given by the equation 2.2.

$$\sigma^2 = \frac{1}{n-1}\left[\sum_{i=1}^{w} m_i\, u_i^2 \; - \frac{1}{n}\left(\sum_{i=1}^{w} m_i u_i\right)^2\right] \qquad (2.2)$$

Where, w is the number of different values of wind speed observed
n is the total number of observations.
Standard deviation is given by the equation 2.3

$$Standard\ deviation = \sqrt{variance\ \sigma} \qquad (2.3)$$

Frequency of occurrence:

This is the determination of the number of times in which the recorded wind speed occurred through the measured time. The percent value is given by the equation 2.4.

$$frequency\ (u_i) = \frac{number\ of\ hours\ in\ which\ u_i\ is\ occured}{total\ numberb\ of\ hours\ in\ data} \times 100 \quad (2.4)$$

2.1.4 WTG power curve data

This is the data obtained from the turbine manufacturers installed at the wind site. This data contains the power output of the wind turbine generator at different wind speed and the rated wind speed for the rated power output, cut-in wind speed, cut-out wind speed of the wind turbine. This can be represented in the graphical form by plotting wind speed on x-axis and power output on y-axis.

These power curve data is combined with the wind speed model obtained for specific wind site to obtain power generated at different wind speeds distributed through the year.

2.1.5 WTG power generation model

Wind turbine power generation model is obtained by combining the wind speed distribution and wind turbine generator power curve data. This model includes the total annual power generated; power generated at different wind speeds through the year. This is calculated by combination of subsection 2.1.3 and 2.1.4.

The probability P of the discrete wind speed u_i being observed as,

$$P(u_i) = \frac{m_i}{n} \quad (2.5)$$

Where, P is probability, u_i is measured wind speed at the interval I, m_i is the hours in which u_i is observed, n is the total number of hours.

The cumulative distribution function F (u_i) as the probability that a measured wind speed will be less than or equal to u_i is given in the equation 2.6

$$F(u_i) = \sum_{j=1}^{i} P(u_j) \quad (2.6)$$

2.1.6 Probabilistic evaluation of power generated

This includes the probabilistic evaluation of the generated power at different wind speeds through the year. This is calculated by combining distribution of discrete wind speeds. This can be calculated by estimated energy output by the discrete wind speed and total energy estimated through the year. This is described in the equation 2.7.

$$P_g = \frac{power\ output\ from\ descrete\ wind\ speed}{total\ estimated\ energy\ output\ through\ year} \quad (2.7)$$

The power generated can be calculated using the power formula given in equation 2.8.

$$P_m = C_p \left(\frac{1}{2}\rho A u^3\right) \quad (2.8)$$

Where, C_p is the capacity factor given by the turbine manufacturer

ρ is air density at the wind site kg/m^3

A is area swept by the turbine in m^2

u is the wind speed in m/sec

2.1.7 Three state model for WTG system

The output of a wind turbine generator (WTG) is a function of the wind speed. In this work the WTG is represented by a three-state model. Up1, Up2 and Down are three states, which represent variable, constant and zero outputs, respectively, in terms of wind speeds. A WTG can also suffer a forced outage, which can be represented by Up and Down states. The WTG three-state model is shown in

Fig.2.1. A wind farm usually consists of many units and therefore the specified wind velocity is assumed to be the same for all the units in the farm. The power output of a wind farm is the summation of the output of all the available units.

The probability of turbine being in three different states is calculated according to the state representation and it is described by the relation as shown below.

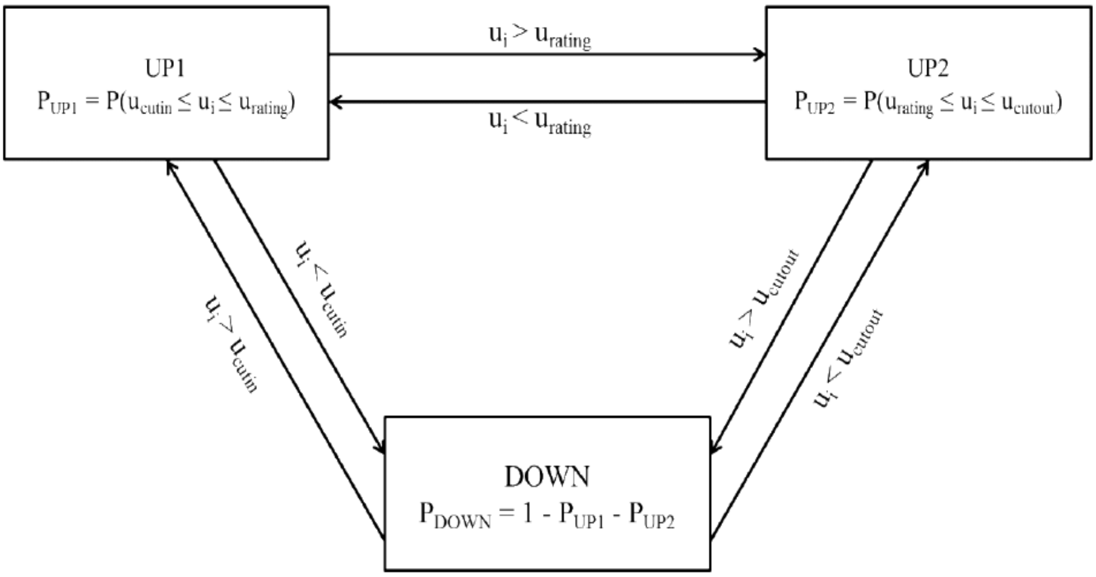

Fig. 2.1: Three state model of WTG

Probability of WTG in state UP1 is,

$$P_{UP1} = P\,(u_{cutin} \leq u_i \leq u_{rating}) \qquad (2.9)$$

Probability of WTG in state UP2 is,

$$P_{UP2} = P\,(u_{rating} \leq u_i \leq u_{cutout}) \qquad (2.10)$$

Probability of WTG in state DOWN is

$$P_{DOWN} = 1 - P_{UP1} - P_{UP2} \qquad (2.11)$$

Where, u_i is the measured wind speed at the interval i.

2.1.8 Calculation of Plant factor and Plant availability

Since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the Plant factor. Typical Plant factors [12] are 15–50%; values at the upper end of the range are achieved in favorable sites and are due to wind turbine design improvements.

The plant factor is calculated by the relation 2.12 and it is given by,

$$Plant\ factor = \frac{Actual\ power\ generated\ in\ simulated\ time}{Rated\ power\ generated\ in\ simulated\ time} \times 100 \qquad (2.12)$$

The value of Plant factor between 15 to 50% is good for wind power generation. And if the wind is continuous the Plant factor will be more except for planned and forced outage.

Plant availability is the wind turbine generator which is available to generate power. This is obtained from the relation that is given in equation 2.13.

$$Plant\ avialability = \frac{Plant\ available\ for\ generation\ \ in\ hours}{Total\ hours\ in\ the\ simulated\ data} \times 100 \qquad (2.13)$$

$$Plant\ unavialability = 1 - \ Plant\ avialability \qquad (2.14)$$

2.1.9 Calculation of reliability indices

The basic reliability index used in this work is Loss of load expectation; it is the average number of hours for which the load is expected to exceed the available generating capacity. And it is given in the equation 2.15.

$$LOLE = \frac{1}{N}\sum P_i\,T_i \ \ldots\ldots\ldots\ldots\ldots\ldots\ hours/year \qquad (2.15)$$

III. CASE STUDY

3.1 Wind Site Description

This site is located in Gadag district of Karnataka state. This site consists of 20 numbers of Vestas made 1.8MW rated WTG with internal electrical lines connecting the project with local evaluation facility. The elevation of the wind site is 2863.38ft from the sea level. The data obtained is from 01/01/2013 01:00 to 28/12/2013 12:00. Air density at the wind site is 1.114 kg/m^2.

3.2 Features of WTG

Rating- 1.8MW
Blades- 3Numbers
Hub Height- 60 meter (made up of steel tubular tower)
Cut in wind speed- 4 m/sec
Cutout wind speed- 25 m/sec
Rated wind speed- 15 m/sec
Conversion factor- 1Mph = 0.44704m/sec
Average wind speed: This is calculated from the equation 2.1 and it is found ū = 13.88 Mph = 6.2049 m/sec
Standard deviation: It is calculated from the equation 2.2. And it is found σ = 8.1276 Mph = 3.6334 m/sec

The power curve is calculated at air density 1.114 kg/m^3

Cut-In Wind Speed: 4 m/sec

Wind speed (m/sec)	Power (kW)
3	0
4	38
5	155
6	329
7	534
8	769
9	1024
10	1305
11	1494
12	1624
13	1739
14	1794
15	1800
16	1800
17	1800
18	1800
19	1800
20	1800
21	1800
22	1800
23	1800
24	1800
25	1800
>25	0

Power curve for V80

1800 kW

1.114 kg/m^3

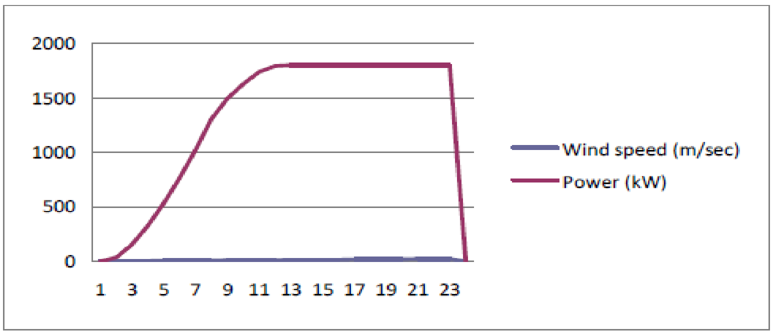

Fig.3.1 WTG Power curve

Fig. 3.1 shows the turbine power curve to calculate the power output from the WTG at different wind speeds. The power generation model is obtained by combing this power curve and the wind speed distribution. The distribution of the discrete wind speed plot is shown data analysis report in fig.3.2, it shows the distribution of different wind speed through the year and gives probability of wind speeds. From the equation 8 the power generated by WTG is calculated and with the necessary data described in section 3.2 the WTG power output obtained by the average wind speed of 6.2049 m/sec is estimated as 4767266 kWh and annual production is 4813422 kWh/year.

3.3 Probabilistic Evaluation of Power Generated

With the power output formula the power generated by the WTG is calculated and the probability of generated power at different wind speed is calculated by equation 2.7. This includes the probabilistic evaluation of the generated power at different wind speeds through the year. This is calculated by combing distribution discrete wind speeds.
From equation 2.7, probability of generated power at wind speed 4 m/sec is given by

$$P_g(4) = \frac{20745.849}{4813422} = 0.00431$$

The probability of generated power from WTG at different wind speed is calculated in same way.

3.4 Three State Model for WTG System

State UP1:
$P_{UP1} = P(4 \leq u_i \leq 15)$
$P_{UP1} = P(4 \leq u_i \leq 15) = \frac{5787}{8676} = 0.667012$
State UP2:
$P_{UP2} = P(15 \leq u_i \leq 25)$
$P_{UP2} = P(15 \leq u_i \leq 25) = \frac{127}{8676} = 0.014638$
State DOWN:
$P_{DOWN} = 1 - P_{UP1} - P_{UP2}$
$P_{DOWN} = 1 - 0.667012 - 0.014638 = 0.31835$

The plant factor is calculated by the equation 2.12 and is given by

$$\%\, Plant\ Factor = \frac{4887055\ kWh}{1800 \times 8676} \times 100 = 31.29$$

Plant availability is the wind turbine generator which is available to generate power this is obtained from the relation that is given in equation 2.13

$$Plant\ avialability = \frac{6355\ hours}{8676\ \ hours} \times 100\ = 73.24\ \%$$

$$Plant\ unavialability = (1 -\ 0.7324) \times 100 = 26.76\%$$

The basic reliability index used in this work is loss of load expectation; it is the average no of hours for which the load is expected to exceed the available generating capacity and it is calculated by using equation 2.15. The value of LOLE for wind site is found LOLE = 237.27035 hrs/year and reliability index is EENS = 115992.2 kWh. It is the energy which is not supplied by the WTG due to lack of wind speed. Third reliability index is energy index of reliability which is given by

$$EIR = 1 - \frac{115992.2}{1800 \times 8676} \quad = 0.992572$$

These reliability indices are calculated by considering all operating states of WTG.

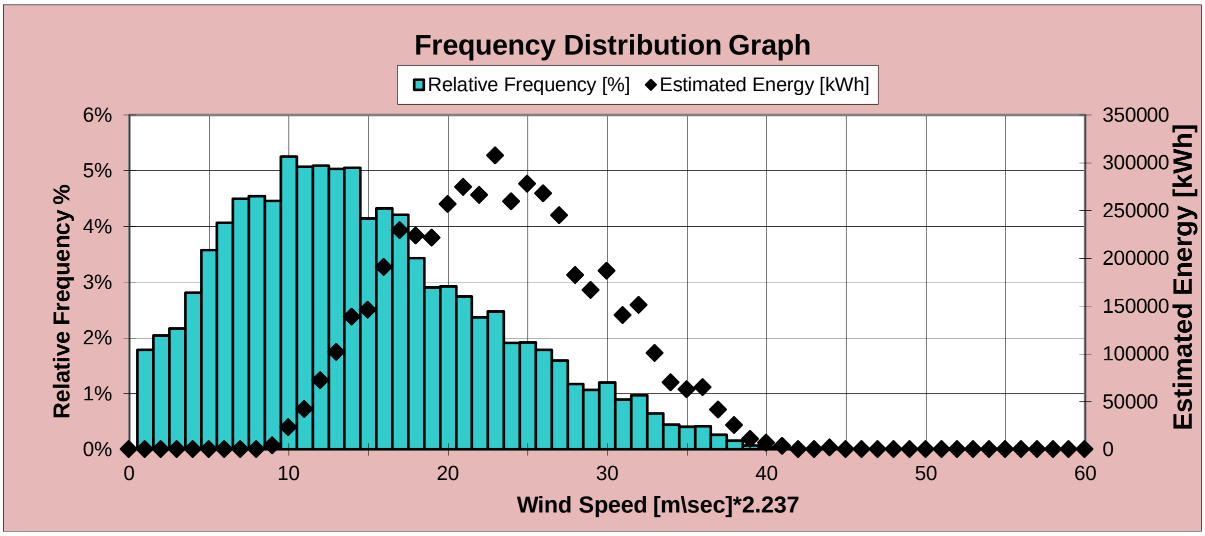

Fig.4 Frequency distribution of wind speed and estimated energy

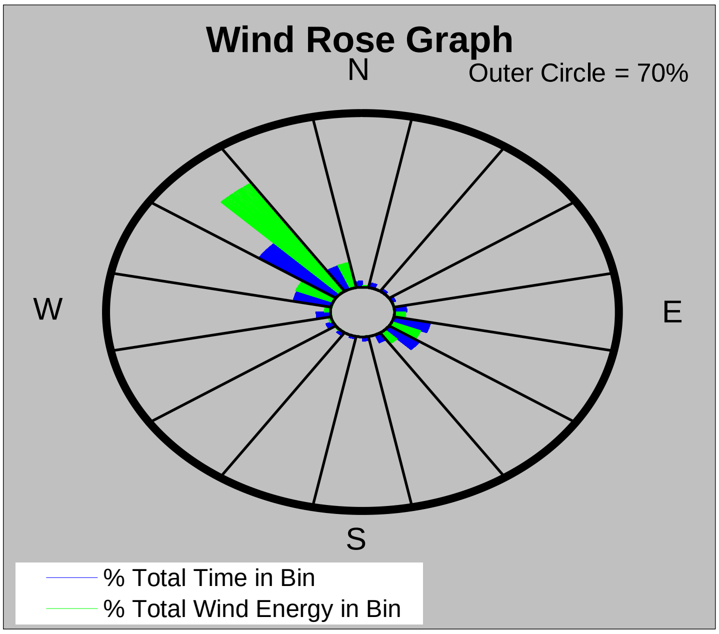

Fig.5 Wind rose graph for wind site indicating direction of wind

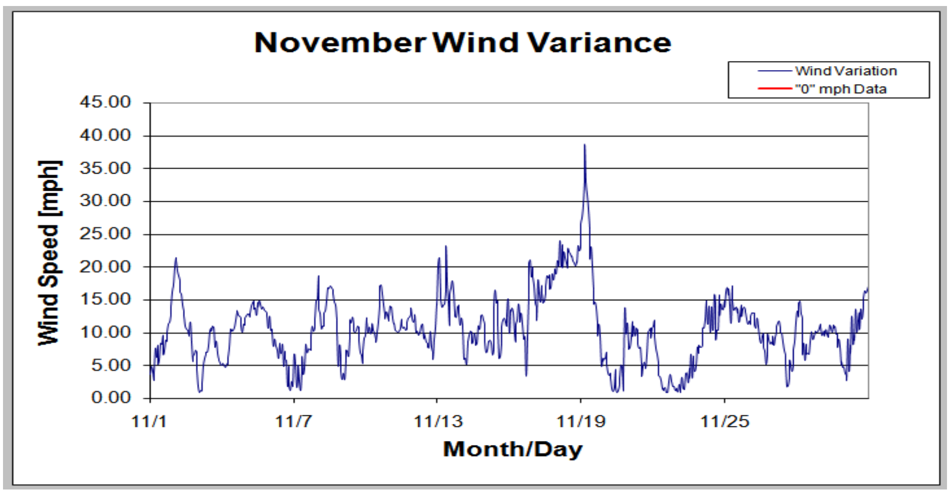

Fig.6 November wind variance at the wind site

IV. CONCLUSION

It is very important to develop probabilistic reliability evaluation technique useful for electric power industries which are expected to power from wind. It is therefore very important to obtain suitable wind speed simulation models and appropriate techniques to develop power generation model for WTG in reliability evaluation. In this work The Plant Factor is found 31.29 % and is very useful to generate power from the wind in that site. The plant available for generation is found 73.24%. Reliability indices LOLE, EENS and EIR are found to be 237.27035 hrs/year, 115992.2 kWh and 0.992572 respectively. These indices show that the plant installed at the said site work satisfactorily. This work will comes more valuable, when we consider wind turbine generator and turbine outage models

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