

Probabilistic Reliability Evaluation of Wind Power Generators

Bindhu L.

P.G scholar,

Dept. of Electrical and Electronics Engineering, AIT.
Chikkamagaluru, Karnataka, India.

Prof. K R Mohan.

Dept. of Electrical and Electronics Engineering, AIT.
Chikkamagaluru, Karnataka, India.

Prof. B Kanthraj.

Dept. of Electrical and Electronics Engineering, AIT.
Chikkamagaluru, Karnataka, India.

Abstract

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. The 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 system reliability shows the availability and the power generation model. In this work the basic system reliability indices are calculated. Historical data collected over one year is used for the evaluation. For the data analysis excel data analysis tool is used and probability distribution of the wind speeds are calculated. This work presents the reliability evaluation procedure for wind power generation system. This study shows the system availability for the generation of power from wind turbine generators installed at the Chithradurga district of Karnataka state.

Keywords – Probabilistic model, Reliability evaluation, WTG, wind energy.

Introduction

The basic function of a power system is to supply the customer demands in both small and large within the economic limits in an acceptable reliability and quality^[1]. To satisfy this, power system should also remain in the operational conditions. In the modern living status energy should be continuously supplied to the consumers. Particularly in Indian electricity sector there is a huge gap between power supply and demand. To overcome this crisis Indian government released some energy policies regarding electricity supply to all. And also released rural electrification policy 2006, this policy aims at providing electricity to all households. To meet this criterion the probabilistic evaluation of the system has to be carried. In other words reliability evaluation has to be carried on the system availability and the amount in which the power is generated. In this work reliability evaluation of wind power generation system is carried to obtain the availability of the system to generate power form variable wind speed.

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. The system model in generation is shown in the figure 1.

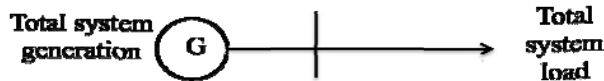


Figure1: Generation system reliability model

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. The energy not supplied can be found using the technique in which each state of the 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 the equation 1.

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

Where, P_k is probability of capacity state C_k
 n is the total capacity states.
 Also the EIR is given in the equation 2.

$$EIR = 1 - \frac{EENS}{\text{energy demand}} \quad (2)$$

Wind Power Generation System

Renewable energy sources, particularly WTGs, are considered as important power generation alternative 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. Reliability evaluation of wind turbine generating systems is a composite process. It needs an accurate wind speed predicting method for the wind site. The method involves 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 actual site. The estimation process should also exactly model the irregular nature of power output from the wind farm. In the evaluation process, there are many steps involved. This work includes nine steps for evaluation process which 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 Capacity factor and Availability
9. Calculation of reliability indices

2.1 Data Collection

For the evaluation process the data is obtained from Chithradurga wind farm site ^[2]. 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 0o. Wind data is available in hourly basis through the year measured by the anemometers installed at the site location. these data are obtained directly from the wind site through the anemometer. The wind site data and turbine data are obtained from the installed turbine manufacturers. Those data are available in the turbine manufacturer web site. Wind site data contains geographic information about the wind site, turbine power curve, swept area, capacity of the installed turbine.

2.2 Data Analysis

For the data analysis “Excel data analysis tool” is used. The purpose of this tool is to analyze the wind data to prove a wind resource exists at a specific location. The spreadsheet is a program to create a Wind Rose graph, and also a folder containing power curves for various wind turbine generators. The data provided by wind farm are used as an input to the tool. Some important parameters calculated by the spreadsheet are the average wind speed, estimated annual production, and the capacity factor. A report sheet is also included, which summarizes results and displays graphs.

2.3 Wind Speed Model for Selected Geographic Location

This is the estimation of wind speed model for the specific geographic location. 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^[3]:

The speed of the wind is continuously changing with the time, making it required to define 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.

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 equation 3.

$$\bar{u} = \frac{1}{n} \sum_{i=1}^w m_i u_i \quad (3)$$

Where, w is the number of different values of wind speed observed and 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 $(u_i - \bar{u})$ is zero, which does not indicate much. Therefore to get all positive quantities square each deviation. The variance of the data is then given by the equation 4.

$$\sigma^2 = \frac{1}{n-1} \left[\sum_{i=1}^w m_i u_i^2 - \frac{1}{n} (\sum_{i=1}^w m_i u_i)^2 \right] \quad (4)$$

Where, w is the number of different values of wind speed observed and n is the total number of observations. Standard deviation is given in the equation 5

$$\text{standard deviation} = \sqrt{\text{variance } \sigma} \quad (5)$$

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 6.

$$\text{frequency}(u_i) = \frac{\text{number of hours in which } u_i \text{ is occurred}}{\text{total number of hours in data}} \times 100 \quad (6)$$

2.4 WTG Power Curve Data:

This is the data obtained from the turbine manufacturers^[4] 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.

2.5 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 2.3 and 2.4 subsections.

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

$$P(u_i) = \frac{m_i}{n} \quad (6a)$$

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 6b.

$$F(u_i) = \sum_{j=1}^i P(u_j) \quad (6b)$$

2.6 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 7.

$$P_y = \frac{\text{power output from discrete wind speed}}{\text{total estimated energy output through h year}} \quad (7)$$

The power generated can be calculated using the power formula given in equation 8. A detailed explanation is given in reference [4] to obtain the power equation for the wind turbine. It can also be calculated by WTG power curve.

$$P_m = C_p \left(\frac{1}{2} \rho A u^3 \right) \dots \dots \dots \text{watts} \quad (8)$$

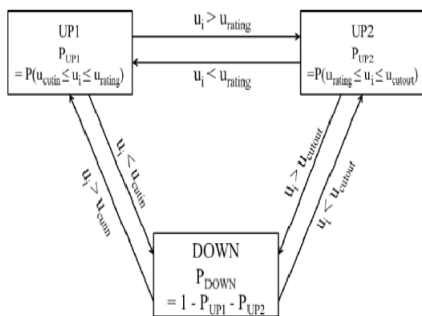
Where, C_p is the capacity factor given by the turbine manufacturer

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

2.7 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. State U_{p1} , State U_{p2} and State Down are three states, which represent variable, constant and no outputs, respectively, in terms of wind speed variation. The WTG three-state model is shown in Figure 2. 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

Probability of WTG in state U_{P1} is,

$$P_{UP1} = P(u_{\text{cutin}} \leq u_i \leq u_{\text{rating}}) \quad (9)$$

Probability of WTG in state U_{P2} is,

$$P_{UP2} = P(u_{\text{rating}} \leq u_i \leq u_{\text{cutout}}) \quad (10)$$

Probability of WTG in state DOWN is

$$P_{\text{DOWN}} = 1 - P_{UP1} - P_{UP2} \quad (11)$$

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

2.8 Calculation of Plant Factor and Plant Availability

Since wind speed is not constant and continuous, a wind farm's annual power production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. Plant factor is the theoretical maximum ratio of actual productivity in a year. Typical Plant factors [4] 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 equation 12 and it is given by,

% Plant Factor

$$= \frac{\text{Actual power generated in simulated time}}{\text{Rated power generated in simulated time}} \times 100 \quad (12)$$

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 equation 13.

Plant availability

$$= \frac{\text{Plant available for generation in hours}}{\text{total hours in the simulated data}} \times 100 \quad (13)$$

$$\text{Unavailability} = 1 - \text{Plant availability} \quad (14)$$

2.9 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 15.

$$\text{LOLE} = \frac{1}{N} \sum P_i T_i \dots \dots \text{hours/year} \quad (15)$$

In addition to this basic reliability index some more indices are used those are described in the equation 1 and 2 respectively in the subsection 1.2.

Case Study

3.1 Wind Site Description

This site is located in Chitradurga district of Karnataka state. This site consists of 11 numbers of Siemens® made 600kW rated WTG with internal electrical lines connecting the project with local evacuation facility. The elevation of the wind site is 2742.78ft from the sea level. The data obtained is from 01/01/2011 01:00 to 28/12/2011 00:00. Air density at the wind site is 1.119 kg/m³.

3.2 Features of WTG

Rating – 600kW

Blades – 3 numbers Rotor diameter – 40 meter Hub height – 50 meter (made up of steel tubular tower) Cut in wind speed – 5 m/sec Cutout wind speed – 25 m/sec Rated wind speed – 16 m/sec

Conversion factor – 1Mph = 0.44704 m/sec Average wind speed: This is calculated from the equation 3 and it is found $u = 14.81 \text{ Mph} = 6.6207 \text{ m/sec}$ Standard deviation: It is calculated from the equation 4. And it is found $\sigma = 7.7406 \text{ Mp} \sigma = 3.4603 \text{ m/sec}$

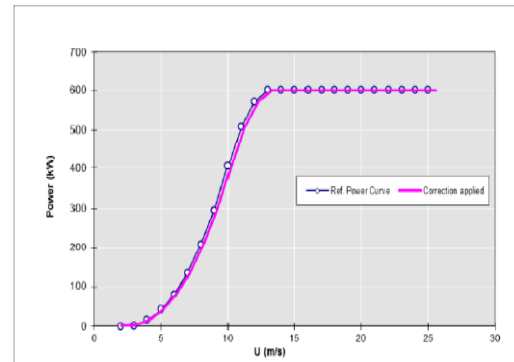


Figure 3: WTG power curve

Figure 3 shows the wind turbine power curve to calculate the power output from the WTG at different wind speeds. The power generation model is obtained by combining this power curve and the wind speed distribution. The distribution of the discrete wind speed plot is shown in the data analysis report in figure 4 It shows the distribution of different wind speeds through the year and gives the 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 6.62 m/sec is estimated as 133086 kWh and annual production is 1353795kWh/year.

3.3 Probabilistic Evaluation of Power Generated

With the power output formula the power generated by the Wind turbine generator is calculated

and the probability of generated power at different wind speed is calculated by using the equation 7. 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. From equation 7, probability of generated power at wind speed 5m/sec is given by,

$$P_g(5) = \frac{6012.86812kWh}{1333086kWh} = 0.00451$$

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

3.4 Three State Model for WTG System

State UP1:

$$P_{UP1} = P(5 \leq u_i \leq 16)$$

$$P_{UP1} = P(5 \leq u_i \leq 16) = \frac{5734}{8626} = 0.664734524$$

State UP2:

$$P_{UP2} = P(16 \leq u_i \leq 25)$$

$$P_{UP2} = P(16 \leq u_i \leq 25) = \frac{129}{8626} = 0.014954787$$

State DOWN:

$$P_{DOWN} = 1 - P_{UP1} - P_{UP2}$$

$$P_{DOWN} = 1 - 0.664734524 - 0.014954787$$

$$= 0.320310688$$

The plant factor is calculated by the relation 12 and it is given by,

$$\% \text{ Plant Factor} = \frac{1353795kWh}{600kW \times 8626hrs} \times 100$$

$$\% \text{ Plant Factor} = 26.16$$

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

13.

$$\text{Plant availability} = \frac{5841hrs}{8626hrs} \times 100 \text{Plant availability} = 67.72 \%$$

$$\text{Unavailability} = 1 - 0.677138882$$

$$\text{Unavailability} = 32.29 \%$$

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 calculated by using equation 15. And the value of LOLE for wind site is found LOLE=221.7051783hrs/year. Second reliability index is EENS and it is calculated by using equation 1 and the calculated value EENS=59987.28932kWh. It is the energy which is not supplied by the WTG due to lack of wind speed. Third reliability index is the Energy index of reliability (EIR). For the wind turbine generator installed at the wind site EIR is calculated by the equation 2 and it is given by,

$$EIR = 1 - \frac{59987.28932kWh}{600kW \times 8626hrs}$$

$$EIR = 0.988409597$$

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

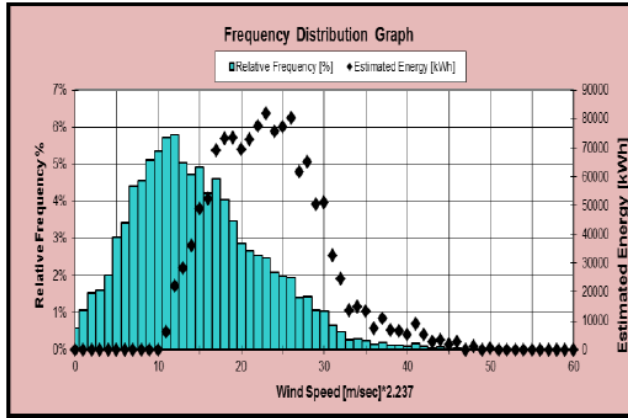


Figure 4: Frequency distribution of wind speeds and estimated energy

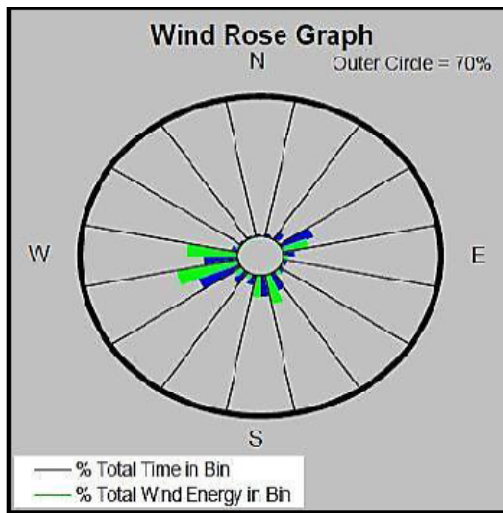


Figure 5: Wind rose graph for wind site indicating direction of wind

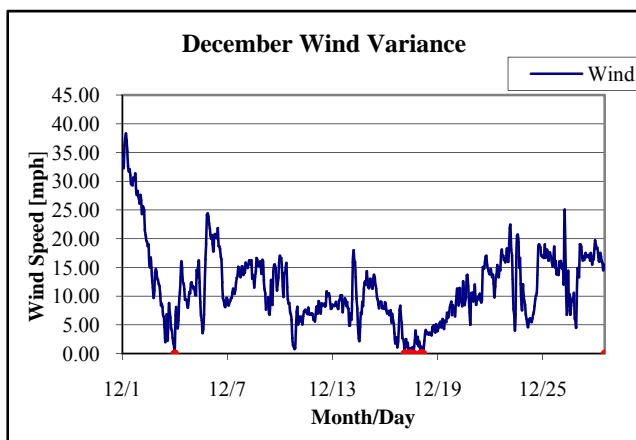


Figure 6: December wind variance at the wind site

Conclusion

Probabilistic reliability evaluation technique is useful for electric power industries. which are expected to include power form wind. The benefits from wind sources are largely said by the wind organization at the wind farm site. It is, therefore, very important to obtain suitable wind speed simulation models and appropriate techniques to develop power generation model for WTG in reliability evaluation. In this work the plant factor is found to be 26.16% and it is very useful to generate power from the wind in that wind site. And the plant available for generation is found to be 67.72%. Reliability indices LOLE, EENS and EIR are found to be 221.70hrs/year, 59987.28932kWh and 0.9885 respectively. These indices show that the plant installed at the taken site works satisfactorily. This work becomes more valuable, when we consider wind turbine generator and turbine outage models.

References

- [1]. Roy Billinton and Ronald N. Allan, “Reliability Assessment of Large Electric Power Systems”, The Kluwer international series in engineering and computer science, Boston, USA, ISBN: 0-89838-266-1
- [2]. Sheela K. Ramasesha and Arindam Chakraborty. “ Power generation using wind energy in northwest

Karnataka, India” Current Science, 104, (6), 25
MAR 2013.

[3] Dr. Gary L. Johnson “*Wind Energy Systems*”,

Halsted Press, New York, October 10, 2006.

[4]<http://www.powergeneration.siemens.com/en/windpower/index.cfm> accessed on 16 Feb 2014.