Reliability Evaluation of WTG's based on Reliability Indices

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***Abstract*: Wind power generation is the most promising renewable energy and it is increasingly attractive to power industry and the whole society. Wind energy is available everywhere in abundance, tapping this energy and utilizing it optimally is the need of the day. Hence the optimal utilization requires some process. In this paper reliability evaluation of wind power generation system is carried. 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 Harapanahalli near Davanagere of Karnataka state.**

***Keywords*–WTG, Reliability evaluation, Probabilistic model, 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.

1.1Generation 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.

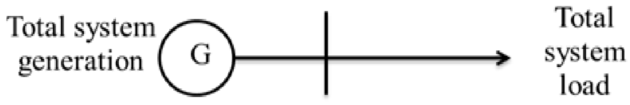

Figure1: Generation system reliability model

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 Ck, the energy not supplied Ek is given numerically by summing all positive values of (Li - Ck) .where Li is the i-th load level and i=1 to n. The expected energy not supplied is given in the equation 1.

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

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.

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

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. Collection of data
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 **Collection of Data**

For the evaluation process the data is obtained from Harapanahalli wind farm site. 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^o. 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

"Excel data analysis tool" is used for the data analysis. 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, andthe 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[2]:

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 ui. 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 ui will be defined as mi. The mean is then given by the equation 3.

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

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 (ui – 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.

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

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

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

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.

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

2.4 WTG Power Curve Data:

This is the data obtained from the turbine manufacturers[3] 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 probabilityP of the discrete wind speed ui being observed as,

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

Where, P is probability, ui is measured wind speed at the interval i, mi is the hours in which ui is observed, n is the total number of hours. The cumulative distribution function F(ui) as the probability that a measured wind speed will be less than or equal to ui is given in the equation 6b.

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

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.

$$P_g = \frac{power\ \ output\ \ from\ \ discrete\ \ wind\ \ speed}{total\ \ estimated\ \ energy\ \ output\ \ through\ year} \qquad (7)$$

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.

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

Where, Cp is the capacity factor given by the turbine manufacturer
ρ is air density at the wind site kg/m3
A is area swept by the turbine in m2 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 Up1, State Up2 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.

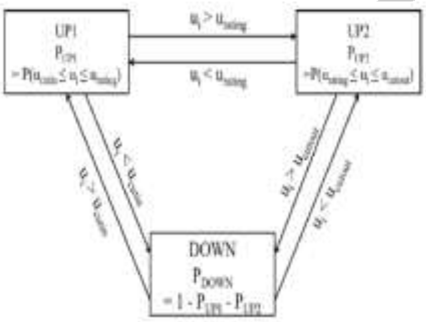

Figure 2: Three state model of WTG

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 UP1 is,

$$P_{UP1} = P(u_{cutin} \le u_i \le u_{rating}) \qquad (9)$$

Probability of WTG in state UP2 is,

$$P_{UP2} = P(u_{rating} \le u_i \le u_{cutout}) \qquad (10)$$

Probability of WTG in state DOWN is

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

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

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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 thetheoretical 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,

$$\%\,Plant\ Factor = \frac{Actual\ power\ generated\ in\ simulated\ time}{Rated\ power\ generated\ in\ simulated\ time} X\ 100 \qquad (12)$$

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.

$$Plant\ availability = \frac{Plant\ available\ for\ generation\ in\ hours}{total\ hours\ in\ the\ simulated\ data} X\ 100 \qquad (13)$$

$$Unavailability = 1 - Plant\ availability \qquad (14)$$

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.

$$LOLE = \frac{1}{N}\sum P_i T_i \ldots\ldots\ldots hours/year \qquad (15)$$

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 Harapanahalli, Davanageredistrict of Karnataka state. This site consists of 24 numbers of Vestas® made 1.650MW rated WTG. The elevation of the wind site 2 is 2076ft from the sea level. The data obtained is from 01/01/2014 01:00 AM to 28/12/2014 00:00 PM. Air density at the wind site 1 is 1.119 kg/m^3.

3.2 Features of WTG

Rating – 1.650MW

Blades – 3 numbers

Rotor diameter – 82 meter

Hub height – 82 meter

Cut in wind speed – 3.5 m/sec

Cutout wind speed – 25 m/sec

Rated wind speed – 16 m/sec

Conversion factor – 1Mph = 0.44704 m/sec

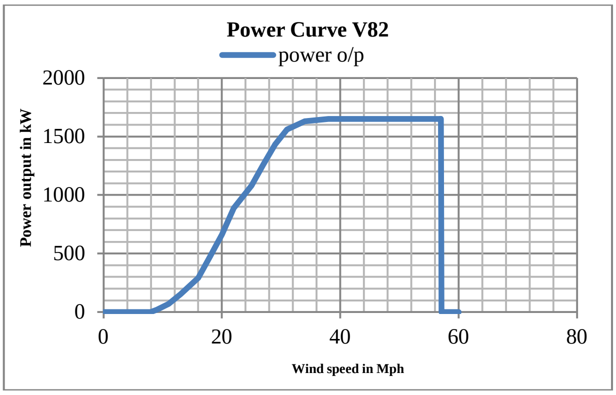

Figure 3: WTG power curve

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 sped 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 7.02 m/sec is estimated as 3751750 kWh and annual production is 3751750 kWh/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 8m/sec is given by,

$$P_g(8) = \frac{1272.20kWh}{3751750kWh} = 0.00033995$$

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:

$P_{UP1} = P(3.5\leq u_i\leq 12)$

Total number of hours in which wind speed is between cut in and rated = 6837hrs

Total number of hours in the data = 8676hrs

Therefore $P_{UP1} = P(3.5\leq u_i\leq 12) = \frac{6837}{8676} = 0.7880$

Probability of wind speed between cut in and rated or probability of state UP1 is 78.80%

State UP2:

$P_{UP2} = P(12\leq u_i\leq 22)$

Total number of hours in which wind speed is between rated and cutout = 859hrs

Total number of hours in the data = 8676hrs

Therefore $P_{UP2} = P(12\leq u_i\leq 22) = \frac{859}{8676} = 0.0990$

Probability of wind speed between rated and cutout or probability of state UP2 is 9.90%

State DOWN:

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

$P_{DOWN} = 1 - 0.7880 - 0.0990 = 0.1129$

Probability of state DOWN is 11.29%

The plant factor is calculated by the relation12 and it is given by,

$$\%\ Plant\ Factor = \frac{3751749kWh}{1650kW\ \times 8676hrs}\ X\ 100$$

$$\%\ Plant\ Factor = 0.2620\ \times 100$$

$$\%\ Plant\ Factor = 26.20$$

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.

$$Plant\ availability = \frac{6837hrs + 589hrs}{8676hrs}\ X\ 100$$

$$Plant\ availability = 0.8870\ \times 100$$

$$Plant\ availability = 88.70\ \%$$

$$Unavailability\ = 1 - \ 0.8870$$

$$Unavailability\ = \ 0.1129\ \times 100$$

$$Unavailability\ = \ 11.29\ \%$$

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 equation15. And the value of LOLE for wind site is found LOLE=2324.0hrs/year. Second reliability index is EENS and it is calculated by using equation 1 and the calculated value EENS=1012.40kWh. 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,

$$EIR = 1 - \frac{1012.40kWh}{1650kW\ \times\ 8676hrs}$$

$$EIR = 0.99992927$$

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

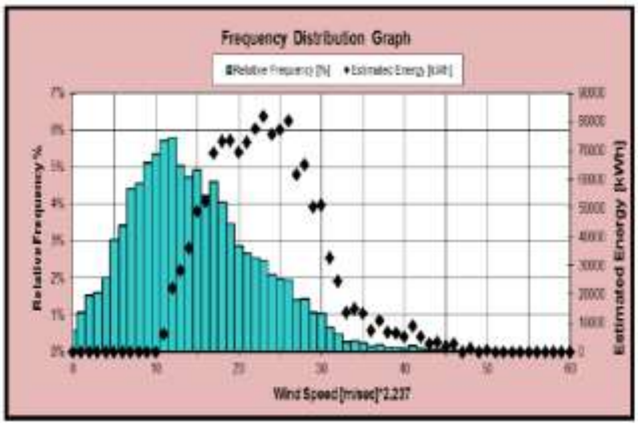

Figure 4: Frequency distribution of wind speeds and estimated energy

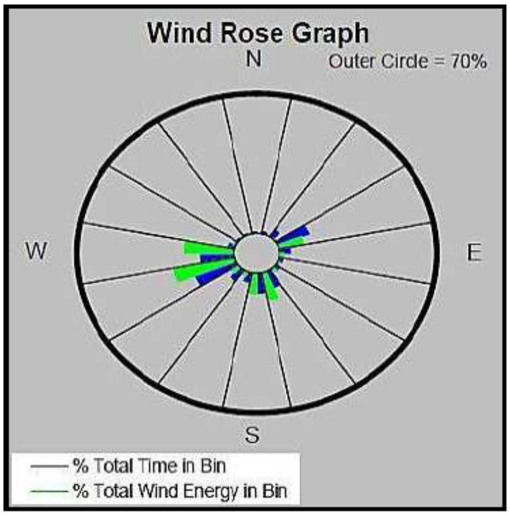

Figure 5: Wind rose graph for wind site indicating direction of wind

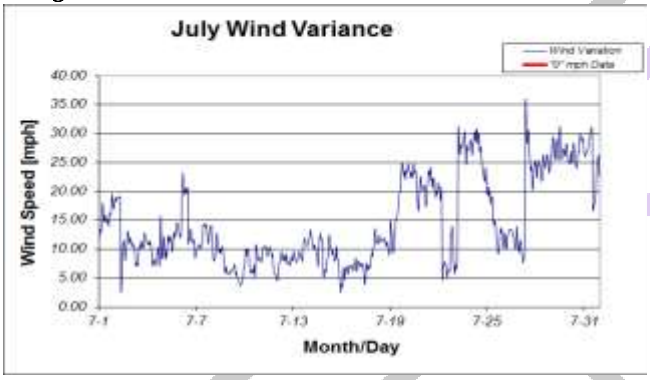

Figure 6: Julywind variance at the wind site

Conclusion

Probabilistic reliability evaluation technique isuseful 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 WTGin reliability evaluation. In this work the plant factor is found to be 26.20% 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 88.70%. Reliability indices LOLE, EENS and EIR are found to be 2324.0hrs/year, 1012.40kWh and 0.99992927respectively. 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.

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