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A Reliability Based Model for Wind Turbine Selection

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ABSTRACT: A wind turbine generator output at a specific site depends on many factors, particularly cut- in, rated and cut-out wind speed parameters. Hence power output varies from turbine to turbine. The objective of this paper is to develop a mathematical relationship between reliability and wind power generation. The analytical computation of monthly wind power is obtained from weibull statistical model using cubic mean cube root of wind speed. Reliability calculation is based on failure probability analysis. There are many different types of wind turbines commercially available in the market. From reliability point of view, to get optimum reliability in power generation, it is desirable to select a wind turbine generator which is best suited for a site. The mathematical relationship developed in this paper can be used for site-matching turbine selection in reliability point of view.

Keywords: reliability, weibull distribution, wind power, wind speed, wind turbine selection

1. Introduction

Increased awareness of environmental protection compels the governments and experts to reduce the dependence on conventional source of energy due to their pivotal role in the emission of green house gasses and their contributions to other types pollutions affecting the nature. This provided a major shift to non conventional sources of energy like solar, wind and biomass. Among them solar and wind power generation are considered to be greenest source of power. Several favorable factors make the wind power as the dominant energy technology for this decade. Technology advancement greatly helped to reduce the cost per unit energy for each new generation of wind turbines that have been available in the market from time to time. Consumption of energy in the modern society is increasing in a rapid pace, with demand for power far exceeding its production. Moreover, the spiraling hikes in the oil price and the expected depletion of oil reserves in the near future have given an added advantage for the competitiveness and selection of wind power (Hirsch *et al.* 2005; Meng & Bentley 2008; Bardi 2009). As bulk production is highly preferred in power sector, energy from wind becomes the most preferred one among non conventional energy sources.

The dependence of power generated from wind turbine on wind velocity is well established (Karki & Hu 2005). But the wind velocity variation with respect to time is random. Collection of wind speed data is significant in the study of wind speed model but the data may not be available from all potential sites.

A typical wind power curve is shown in Fig. 1. The functioning of a wind turbine generator can be explained in terms of cut-in speed V_{in} , rated speed V_r and cut-out speed V_{out}. Starting from zero, wind speed rises and when it is above the cut-in speed the generator begins to deliver power. The power increases with wind speed. When wind speed reaches rated speed V_r, the generator delivers rated power, and the power remains at this value with increase in wind speed. When wind speed is higher than cut- out speed V_{out}, the generator stops for protection (Manwell *et al.* 2002; Li & Niu 2008). Even though the rated wind speed of a wind turbine generator is about 13-14m/s the average wind speed in most wind farm is only in the range of 7-

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9m/s, which clearly indicates that generator could not reach the rated power always. Thus, lower load factor and the lower reliability of the power system in wind power could be attributed to the low utility of wind speed (Manwell *et al.* 2002; Li & Niu 2008).

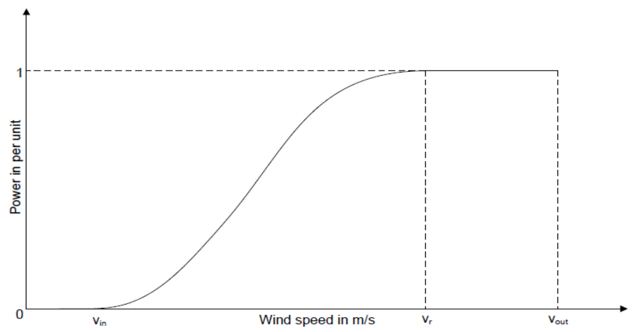

Fig. 1 A typical power- wind speed curve

Optimum wind utilization requires proper matching of wind turbine characteristics with installation site and wind data. A number of studies concerning the optimum turbine site matching have been reported in the literature (Salameh & Safari 1992; Abed & El-Mallah 1997; Jangamshetti & Rau 1999; Jangamshetti & Rau 2001a; Jangamshetti & Rau 2001b; Albadi & EI- Saadany 2010). The analysis is based on the assessment of wind potential of various sites and capacity factor models based on weibull probability density functions. Capacity factor of a turbine is an estimation of its average energy production, which can be used by manufactures and wind power project developers for optimum turbine site matching (Abed & El-Mallah 1997; Jangamshetti & Rau 1999; Jangamshetti & Rau 2001a; Jangamshetti & Rau 2001b; Albadi & EI- Saadany 2010).

Reliability can be defined as the probability that an item can perform a required function for a specified period of time under specified operating conditions (Charles 2000; Srinath 2005). A general model for reliability evaluation of power system containing grid connected wind hybrid system using time series ARMA model has been discussed in (A Survey of Canadian Utilities 1995; Billinton & Allan 1996; Karki & Billinton 2004; Karki & Hu 2005). Here analysis has been done by computing LOLE or LOEE, LLU and FOR. These power system reliability indices decreases with the number of wind turbine units added to the system, but tends to saturate when wind speed continue to increase. The simulation study is done by considering the wind data for five years from one or two sites.

This paper presents a mathematical relationship between reliability and wind power per unit swept area. To develop the proposed mathematical model, initially reliability and wind power per unit swept area are plotted against wind velocity. Then the relationship between reliability and wind power is identified by plotting a curve between them. The result of this analysis, if done in wind power planning helps to identify suitable site-matching wind turbine.

2. Problem Formulation

2.1 Wind Speed Statistical Modeling

The power from wind turbine generator depended mainly on wind speed. Significant variations in wind speed from season to season being common in most part of the world; the random variation of wind speed with time suggested a probability model for wind speed. The two parameter Weibull distribution is widely used for the modeling of wind speed due to its characteristics. The probability density function of Weibull distribution is given by:

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{(k-1)} e^{(-v)/c)^{k}} \qquad (k>0, v>0, c>1) \quad \textbf{(1)}$$

Where k is shape parameter and c is scale parameter. The shape factor k is related to the variance of the wind speed; therefore it is location specific.

The Weibull distribution provided accurate evaluation of energy production. The distribution parameters were obtained from the mean and standard deviation of wind speed at the chosen site. The monthly means and standard deviations of collected wind speed distributions were calculated using the following equations:

$$\bar{v}=\left(\frac{\sum_{i=1}^{N} f_i v_i^{\,n}}{\sum_{i=1}^{N} f_i}\right)^{1/n} \quad and \quad \sigma=\sqrt{\frac{\sum_{i=1}^{N} f_i\left(v_i-\bar{v}\right)^2}{\sum_{i=1}^{N} f_i}} \qquad \textbf{(2)}$$

where :

$(\bar{v})$ = mean wind velocity,
v = actual wind speed in m/s,
N = number of different values of wind speeds observed,
f_i = the numbers of observations of a specific wind speed v_i and
n = 1 for arithmetic mean,
n = 2 for root mean square,
n = 3 for cubic mean cube root.

The value of weibull parameters k and c are given by (Justus 1978; Jangamshetti & Rau 2001a;)

$$k=\left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \qquad \textbf{(3)}$$

and $$c=\frac{\bar{v}}{\Gamma\left(1+1/k\right)} \qquad \textbf{(4)}$$

Monthly wind power density per unit area of a region based on weibull probability density function is given by (Johnson & Gary 1985; Suchitra & Jangamshetti 2008);

$$P_D = \frac{1}{2}\rho c^3\left(1+\frac{3}{k}\right)\text{kw/sq.m} \quad \textbf{(5)}$$

where ρ is the air density in kg/m^3.

2.2 Turbine Output

The amount of energy produced by a wind turbine depends on a number of factors. The wind resource at the site is always the most important one. It is also depends on the size of the wind turbine, the rotor swept area, nominal power, the hub height and how efficient the turbine can convert the kinetic power of wind. Moreover, power generation of a wind electric system does not vary linearly with wind speed due to the nonlinear relationship between the wind turbine parameters and wind speed. The block diagram of wind electric system is shown in Fig. 2 (Jangamshetti & Rau 1999; Suchitra & Jangamshetti 2008).

Here P_w is the power in the wind, P_m is the turbine output power, P_t is the generator input power, and P_e is the generator output power. C_p is the coefficient of performance of the turbine, η_m is the transmission efficiency and η_g is generator efficiency. At its nominal speed, the turbine is at maximum efficiency and the power output is at rated value. From the block diagram shown in Fig. 2, the electrical power output can be written as (Johnson & Gary 1985; Suchitra & Jangamshetti 2008);

$$p_e = p_w \eta_m \eta_g c_p \text{ k}_w \quad \textbf{(6)}$$

Where $p_w = P_D A \text{ k}_w$ **(7)**

Where A is blade swept area in m^2.

2.3 Reliability Modeling

If f denotes the probability density function for the failure of the device under observation. Then failure probability is = $\int_0^t f(x)d(x)$

Further, reliability = 1- failure probability

The probability of the wind turbine generator functioning for at least t hours is expressed mathematically (Srinath 2005). The power output of a wind turbine generator is dictated by the intermittent nature of wind and the wind power penetration may continue to increase in coming years. This will attract more attention in reliability evaluation.

3. Illustration

The available field data from literature (Jangamshetti & Rau 1999) is used for analysis. Table 1 shows wind statistics. Analytically computed monthly means and standard deviations using equation (2) of the test site is given in Table I. The monthly arithmetic mean wind speed ranges between 4.5461 m/s in October and 10.5473 m/s in July, with an annual average of 7.077 m/s. Weibull parameters corresponding to cubic means are computed and given in Table 2.

Table 1
Monthly means and standard deviations of wind speed data

Month	Arithmetic Mean $\bar{V}$ (m/s)	Cubic Mean $\bar{V}_3$ (m/s)	Cubic Standard Deviation σ
January	5.1427	5.7955	2.0396
February	5.2659	6.3556	2.7814
March	4.7767	6.0523	2.9158
April	6.2008	7.8349	3.8077
May	9.4697	10.9003	4.2843
June	9.6657	10.4821	3.1620
July	10.5473	11.7628	3.9213
August	9.4452	10.4108	3.4333
September	7.1930	8.2827	3.3136
October	4.5461	5.6524	2.6543
November	6.8517	7.5004	2.3033
December	5.8205	6.6385	2.4651

Table2
Weibull Parameters for The Test Site

Month	k	c
January	3.1085	6.4796
February	2.4533	7.1633
March	2.2102	6.8338
April	2.1894	8.8468
May	2.7570	12.2484
June	3.6749	11.6195
July	3.2969	13.1139
August	3.3358	11.5997
September	2.7045	9.3133
October	2.2725	6.3811
November	3.6044	8.3230
December	2.9325	7.4414

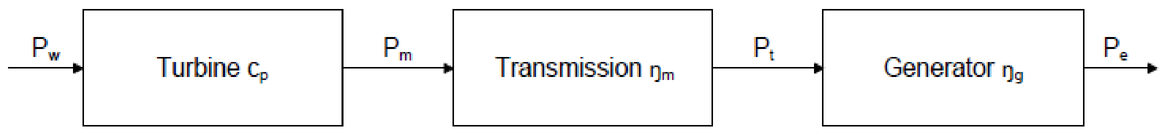

Fig. 2 Block diagram of wind electric system

Table3
Monthly Wind Power Density And Electrical Power Generated Per Unit Swept Area

Month	wind Power Density P_D (kw/ m²)	Power Per unit Swept Area P_{esa} (kw)
January	327.44	118.99
February	501.07	182.07
March	460.80	167.46
April	1005.21	365.29
May	2350.19	854.06
June	1745.29	634.24
July	2638.29	958.75
August	1815.72	659.83
September	1043.63	379.26
October	369.24	134.18
November	647.06	235.14
December	510.58	185.55

Table 3 shows the wind power density of each month and corresponding electrical power generated per unit swept area P_{esa}. To calculate electrical power output the assumed values of C_p= 0.45, η_m = 0.85, η_g = 0.95 are considered (Johnson & Gary 1985; Suchitra & Jangamshetti 2008).

The monthly arithmetic means, cubic means and standard deviations of wind velocity are given in Table1. The mean value, variance and standard deviation of $\bar{v}$ are given below. Mean value of $\bar{v}$ is taken as $\bar{v}_1$, $\bar{v}_1 = \frac{1}{N}\sum \bar{v}_i = 7.077$

Variance = 4.2670

Standard deviation, S = 2.0657

For reliability calculations, the value of standard deviation or a fraction of standard deviation is taken as the class interval and is with respect to the mean.

4. Result and Discussion

From Table 4 reliability versus corresponding wind velocity v_2 is plotted and is given in Fig.3. Fig.4 shows the variation of generated power per unit swept area P_{esa} as a function of cubic mean wind velocity $\bar{v}_3$. From Fig. 3 and Fig. 4 it is observed that reliability and generated power per unit swept area can be expressed as a quadratic function of wind velocity.

From this a functional relationship between reliability R and power per unit swept area P_{esa} was identified. The relation between R and P_{esa} is plotted in Fig.5. The mathematical model is given by:

$$R=109.7\ e^{(-0.003496P_{esa})} \quad \textbf{(8)}$$

After accessing wind energy potential in a site, we determine the power rating of turbine to be installed. It is a tedious process to identify a suitable site-matching wind turbine for a particular value of power generation. The developed equation helps us to select a suitable turbine for most reliable power generation. The major advantage of this method is that once we know the nominal power and rotor blade swept area, we can calculate the reliability of power generation.

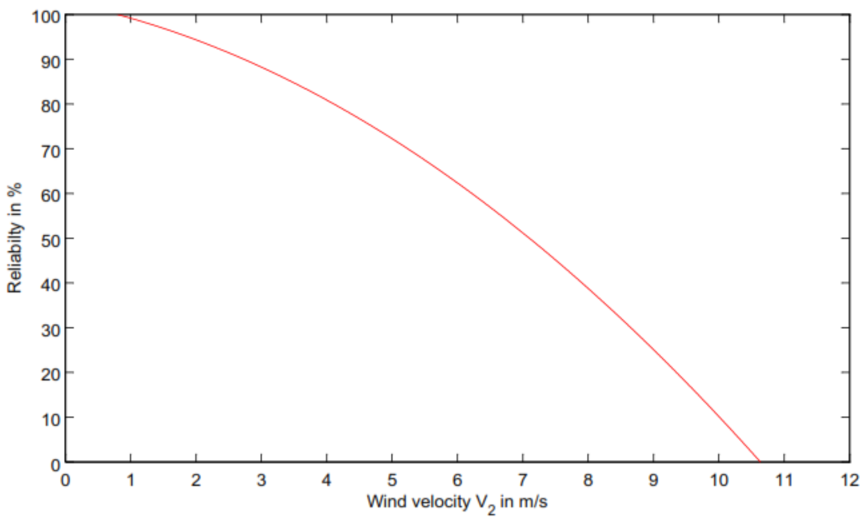

Fig. 3 Reliability versus wind velocity

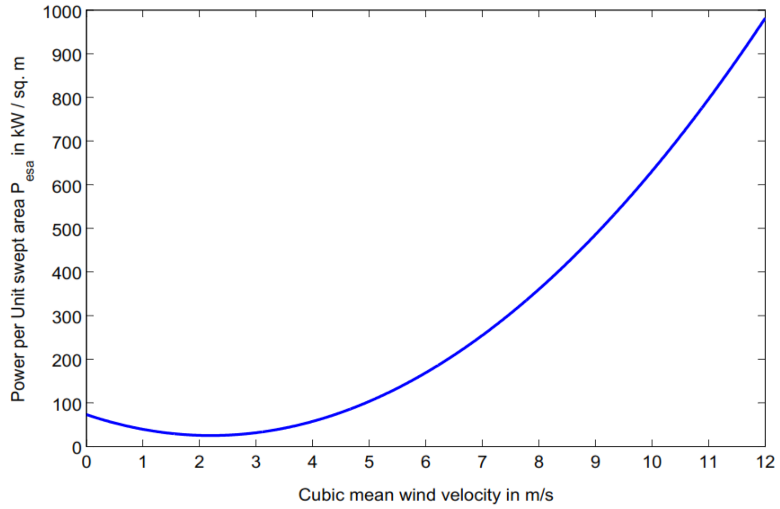

Fig. 4 Power per unit swept area versus wind velocity

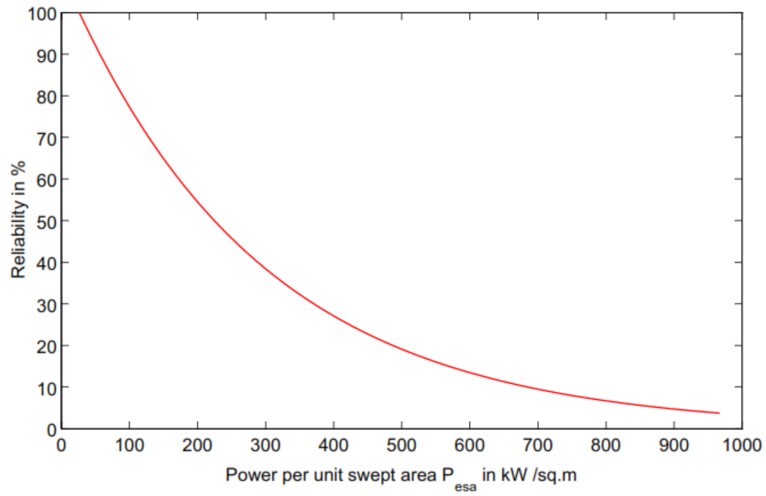

Fig. 5 Reliability versus power per unit swept area

Table 4
Reliability calculations

Class Interval With Respect to Mean	Wind Velocity v_2 (m/s)	Frequency n	Cumulative Frequency N	Failure Probability	Reliability R
$\bar{V}$	0		0	0.0000	1
		2			
$\bar{V}_1 - s$	5.0113		2	0.1667	0.8333
		3			
$\bar{V}_1 - s/2$	6.0441		5	0.4167	0.5833
		2			
$\bar{V}_1$	7.0770		7	0.5833	0.4167
		1			
$\bar{V}_1 + s/2$	8.1098		8	0.6667	0.3333
		0			
$\bar{V}_1 + s$	9.1427		8	0.6667	0.3333
		3			
$\bar{V}_1 + 3s/2$	10.1755		11	0.9167	0.0833
		1			
$\bar{V}_1 + 2s$	11.2084		12	1.0000	0.0000

5. Conclusion

A mathematical relationship between reliability and wind power per unit swept area was presented. The methodology of analysis was based on the computation of monthly wind power per unit swept area and the reliability evaluation using failure probability analysis. Monthly wind power per unit swept area was obtained by using cubic mean cube root of wind speed. Since wind speed varied from time to time and season to season, this intermittent nature degraded the system reliability. Moreover, reliability of a power system decreased with increased system load. The presented mathematical equation can be used as a tool for turbine selection for enhancing the reliability of individual power generation as well as the overall power system.

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