Comparison of Wind Turbine Energy Calculation Methods

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Abstract: - The wind turbines have to compete with many other energy sources. Performance characteristics such as power output versus wind speed or versus rotor angular velocity must be optimized in order to compete with other energy sources. There are many methods for calculating the output energy from wind turbines. Weibull probability density function, capacity Factor and the Mathematical Model for Wind Power methods are presented. A new method depending on curve fitting is presented in this paper for calculating the output energy. The output energy of each method is calculated and compared with a reference data generated from the Wind Atlas Analysis and Application Program (WASP) to verify the most accurate method. Four Vestas's wind turbines were selected to evaluate the validity of the different calculation methods.

Key-Words: - Wind Turbine, Power Curves, Weibull Probability Density Function, Capacity Factor

1 Introduction

Wind energy has served mankind well for many centuries by propelling ships and driving wind turbines to grind grain and pump water. Wind power has many benefits that make it an attractive source of power for both utility-scale and small, distributed power generation applications. The beneficial characteristics of wind power include Clean and inexhaustible fuel, Local economic development, Modular and scalable technology, Energy price stability, Reduce reliance on imported fuels [1].

Today, wind turbines have to compete with many other energy sources. It is therefore important that they be cost effective. They need to meet any load requirements and produce energy at a minimum cost per dollar of investment. Yearly energy production and its variation with annual wind statistics must be well known.

Computing the power output of a wind turbine generator (WTG) is one of the most important issues which could affect the scheduling of the grid incorporated with wind farm and finding a proper method to model and convert wind energy to electricity is most significant and challengeable.

Potential assessment of the wind power for installing WTGs and estimating WTGs output have been carried out by many studies [2].

Energy output estimation for wind turbines of different power ranges has been subject of a number of articles. Many methods and models have been discussed in previous studies which are not accurate to predict the wind power output [3].

Different models used to describe the performance of WTG by previous researchers. In wind energy engineering, wind speed distribution is modeled by the Weibull distribution and commonly used in the practical studies related to the wind energy modeling [4].

Wind turbines power curves were modeled with seven power curve model and energy output results were compared with Wind Atlas Analysis and Application Program (WASP) results in [3]. Different studies assumed that wind power curve has a linear, quadratic or cubic relationship with wind speed. Most of previous studies showed and proved the fact, which is really vital to determine the accurate value of wind turbines energy output [5]. The use of the manufacturer's power curve is the easiest approach to find the power output of WTG at the specific wind speed. However, for a specific WTG, a model should be developed according to its power output performance curve, which is given by the manufacturer [6].

In this paper, four methods for calculating the wind turbine energy are introduced. Weibull probability density function, capacity Factor and the Mathematical Model for Wind Power methods are introduced in addition to a new method depending on curve fitting. The energy output results from the different four methods were compared with the WASP program results. Four Vestas's wind turbines were selected evaluate the validity of the different calculation methods.

2 Wind Speed Characteristics Of The Zafarana Site

Data have been collected for Zafarana site in Egypt. The measurements of hourly wind speed, air temperature, and air pressure were taken in an open area at a height of 24.5 m above ground level. The Egyptian Meteorological Authority provided the data for a period of one year. Figure (1)show the wind speed characteristic for this site.

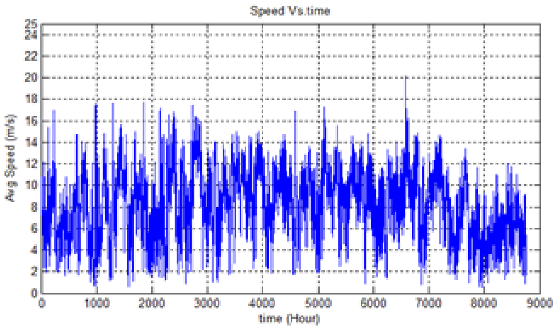


Fig.1. Annual wind speed of the selected site

3 Site Parameters

The mean and variance of the wind speed at the selected site is used to determine the Weibull parameters c and k [1].

The Weibull parameters are characterized by two parameters: the shape parameter k (dimensionless) and scale parameter c (m/s).There are several methods available for determining the Weibull parameters c and k were reported in literature [7].

The Weibull parameter rsc and kare necessary for modeling the wind turbines power curves in the four calculation methods. The k parameter is calculated using equation 1, as follow:

$$k = \left(\frac{\sigma}{\bar{u}}\right)^{-1.086} \qquad (1)$$

Where:

$\bar{u}$ is the average speed at the selected site in m/s.

σ is the standard deviation.

This is a reasonably good approximation over the range $1 \leq k \leq 10$. Once k has been determined, equation. 2 can be solved for c, as follow:

$$c = \frac{\bar{u}}{\Gamma(1 + 1/k)} \qquad (2)$$

Where:

Γ is the Gamma function

The flow chart shown in figure (2) explains how to calculate the shape parameter k and scale parameter c.

4 Weibull Probability Density Function Method

There are several density functions which can be used to describe the wind speed frequency curve. The two most common are the Weibull and the Rayleigh functions.

The Weibull is a two parameter distribution while the Rayleigh has only one parameter. This makes the Weibull somewhat more versatile and more accurate than Rayleigh. The Weibull probability density function is defined by the following equation:

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (3)$$

For

$$(k > 0, u > 0, c > 1)$$

Where:

*f(u)*is theprobability density function.

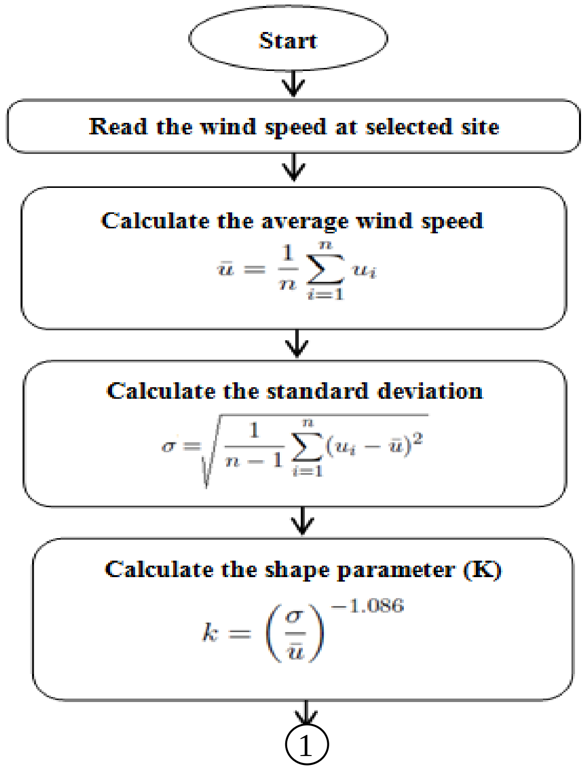
*u*is the measured speed at the selected site in m/s.

k is theshape parameter.

c is thescale parameter in m/s.

The probability density function then used to calculate the annual energy of the wind turbine using equation. 4 below:

$$E=\sum_{uc}^{uf} f(u) * 8760 * Pe(u) \qquad (4)$$



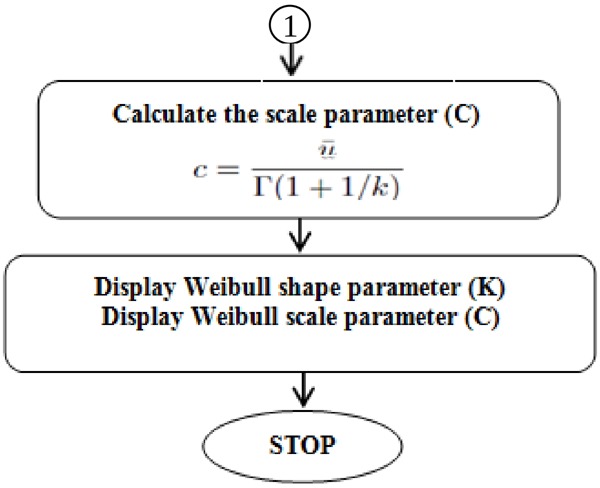


Fig.2. Flowchart for calculating the shape parameter and the scale parameter.

Where
E is the total annual energy in Kwh.
uc is the cut in speed in m/s.
uf is the cut out speed in m/s.
P_e is the turbine electrical power in Kw.

The following table shows the power-speed data given by the manufacture for a 225Kw Vestas's wind turbine.

Table 1. 225Kw Vestas's power table

Per KW	u_c m/s	u_f m/s	u_r m/s	K	C m/s	CF	E kwh
225	3.5	25	14	2.77	9.26	0.289	0.57 $X10^6$

The probability density function for a 225Kw wind turbine at the selected site is shown in figure (3) below:

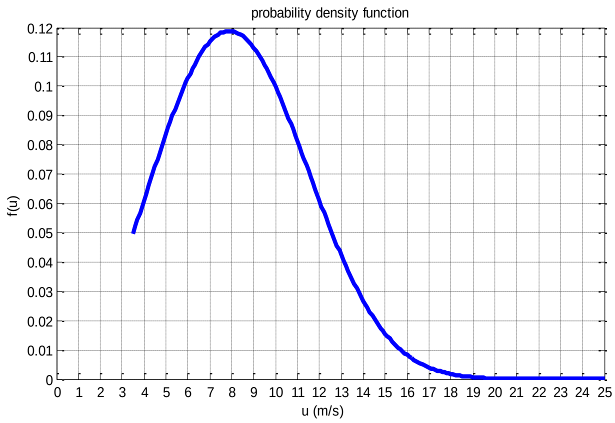


Fig.3. 225Kw vestas's wind turbine propablity density function.

From table 1 and figure (3), the output energy calculated for the 225kw turbine will be$0.8564X10^6$ Kwh.

5 Capacity Factor Method

The second proposed method is the capacity factor which is depend on the cut in speed, rated speed, cut out speed, turbine rated power, shape parameter and the scale parameter.

The capacity factor is defined by the following equation.

$$CF = \left\{ \frac{\exp[-(u_c/c)^k] - \exp[-(u_R/c)^k]}{(u_R/c)^k - (u_c/c)^k} - \exp\left[-\left(\frac{u_F}{c}\right)^k\right] \right\} \quad (5)$$

Capacity factor is defined as the ratio of the average power output to the rated output power of wind turbine. The capacity factor then used to calculate the annual energy of the wind turbine using equation. 6 below:

$$CF = \frac{E}{P*8760} \quad (6)$$

Where
CF is the capacity factor.
E is the total annual energy produced in Kwh.
P_{er} is the turbine rated power in Kw

Table 2. Site and 225Kw wind turbine parameters.

u	3.5	4	5	6	7	8	9	10
P_e	2	5	17	32	53	82	115	148
u	11	12	13	14	15	16	17	18
P_e	181	205	218	225	225	225	225	225
u	19	20	21	22	23	24	24	25
P_e	225	225	225	225	225	225	225	225

From the site parameters (K and C) and the wind turbine parameters the capacity factor is calculated and it will be equal 0.289, then the output energy calculated and it will be equal 570000 Kwh.

6 The Mathematical Model For Wind Power method

It is convenient to define a model for $\mathbf{P_e}$ that can be used in discussing any wind system. $\mathbf{P_e}$is assumed to vary as $\mathbf{u^K}$ between cut-in and rated wind speeds. This model can be used in discussing any wind system. The annual energy of the wind turbine is calculated by this method.

The Mathematical model for wind power is defined by the following equations.

$$P_e = 0 \qquad (u < u_C)$$
$$P_e = a + b\,u^K \qquad (u_C < u < u_R)$$
$$P_e = P_{er} \qquad (u_R < u < u_F)$$
$$P_e = 0 \qquad (u > u_F)$$

ISBN: 978-1-61804-279-8

The coefficients (a& b) is given by: -

$$a = P_{er}\left\{\frac{u_C^K}{(u_C^K - u_F^K)}\right\}$$

$$b = \frac{P_{er}}{(V_R^k - u_C^K)}$$

If the speed higher than cut out speed the turbine is shutdown to prevent structural damage. This condition normally occurs only a few hours during the year, and therefore does not have a large influence on energy production.

The 225Kw turbine is modeled by the above mathematical equations and the figure (4) below shows the modeled result and the actual curve given by the manufacture.

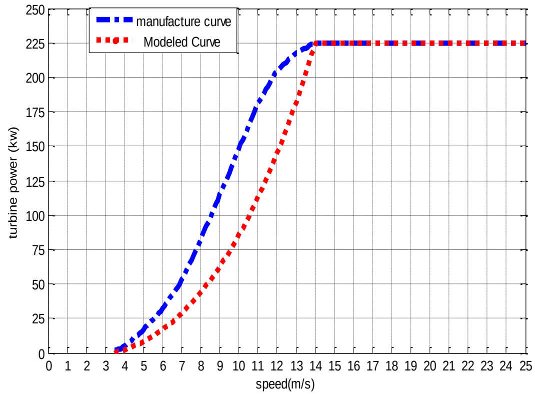


Fig.4. Mathematical model and actual power curve for the 225Kw vestas's wind turbine.

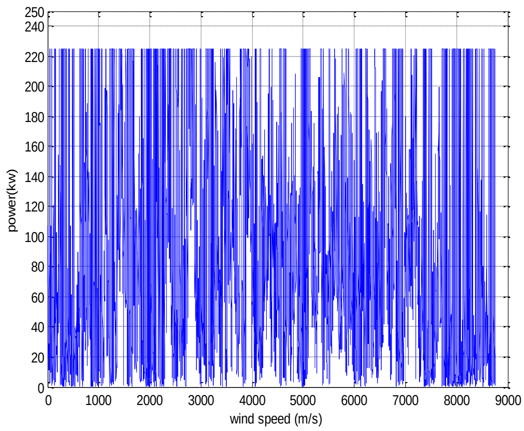


Fig.5. Calculated instantaneous annual output power for the 225Kw wind turbine by the mathematical model.

The calculated instantaneous output power of the 225 Kw turbine can be calculated easily from the above mathematical model equations as shown in figure (5). The annual energy then can be easily calculated and it found to be 0.7473 X10^6 Kwh.

7. The Curve Fitting Model Method

A new method for calculation the turbine energy is presented in this section. The new method is depending on fitting the power curve of any selected wind turbine. Curve fitting is used to find the best fit line or curve for a series of data points. The curve fit will produce an equation that can be used to find points anywhere along the known wind turbine curve/data points given by the manufacturers.

The equation produced by the curve fitting has a general form described in eq.

$$\begin{aligned} P_e &= 0 && (u < u_C) \\ P_e &= k_0 + k_1 u + k_2 u^2 + \ldots\ldots + k_n u^n && (u_C < u < u_R) \\ P_e &= P_{er} && (u_R < u < u_F) \\ P_e &= 0 && (u > u_F) \end{aligned}$$

Where

$k_0 : k_n$ is the equation constants.
U is the wind speed.
P_e is the turbine electrical power in Kw.
Uc is the cut in speed.
Uf is the cut out speed.

The more complex of the curvature of the data points, the polynomial order will be higher for best fitting. There are no data restrictions associated with the curve fitting.

The 225Kw turbine is modeled using curve fitting method as shown in figure (6) below. It is clear from the figure that the modeled curve is almost the same as the actual manufacture curve and this mean that the output results expected to be very accurate.

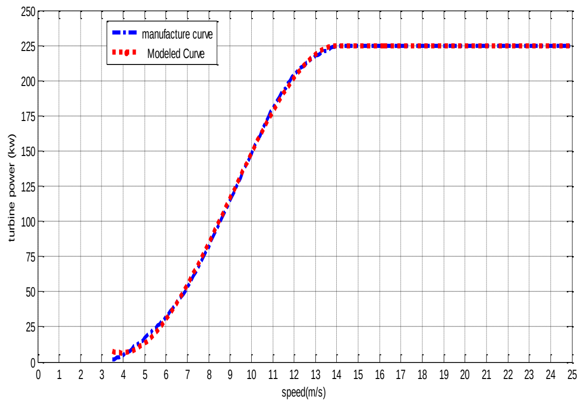


Fig.6. Curve fitting model and actual power curve for the 225Kw vestas's wind turbine.

The instantaneous power annually can be calculated and drawn as shown in figure (7). The annual energy in this case will be 0.87868X10^6 Kwh.

ISBN: 978-1-61804-279-8

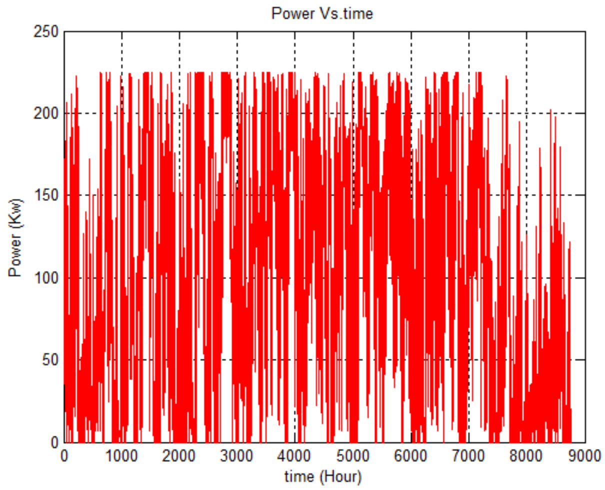


Fig.7. Calculated instantaneous annual output power for the 225Kw wind turbine by the curve fitting.

8 Comparison Between The Calculation Methods

The results of the pervious methods compared with a reference results generated from the WASP program to verify the best method with minimum error. Table (3) is exploring the calculated annual output energy and the percentage error for each method.

The percentage error is calculated by the equation as follow:

$$Error\ (\%) = 100\ x\ \frac{E_{WAsP} - E_{Method}}{E_{WAsP}}$$

Where

E_{WASP} is the energy calculated by the WASP program.

E_{Method} is the energy calculated by each method

Table 3. Calculated output energy in (Kw) for each selected turbine using the different calculation methods

	Weibull Probability Density Function	*Capacity Factor*	*Mathe-matical Model*	*Curve Fitting*	*WASP Program*
Vestas 225kw	0.8564X10^6	0.57X10^6	0.7473X10^6	0.87868X10^6	0.86X10^6
Vestas 500kw	1.8864X10^6	0.9878X10^6	1.7334X10^6	1.938X10^6	1.93X10^6
Vestas 850kw	3.65X10^6	2.54X10^6	3.323X10^6	3.734X10^6	3.84X10^6
Vestas 2MW	10.603X10^6	7.37X10^6	9.116X10^6	10.809X10^6	11.62X10^6

Table (4) is showing the percentage error for each method. From the table it can be shown that the minimum error for all the selected wind turbines is that the one calculated by the curve fitting method. So, it can be considered that the curve fitting method is the most accurate method for calculating the output energy for wind turbines.

Table 4. Energy percentage error of each calculating method for each selected turbine

	Weibull Probability Density Function	*Capacity Factor*	*Mathematical Model*	*Curve Fitting*
Vestas 225kw	0.046%	33.4 %	12.7%	2.649 %
Vestas 500kw	2%	33 %	10%	0.67 %
Vestas 850kw	4.9%	33.8 %	13.4 %	2.7 %
Vestas 2MW	8.7%	36.5 %	21.5%	7.26 %
Average error	***3.9 %***	***34 %***	***14.4 %***	***3.3 %***

9 Conclusion

In this paper four methods for calculating energy output from wind turbines are presented. These methods are Weibull probability density function, Capacity Factor, The Mathematical Model for Wind Power and The curve fitting model. The output energy generated from each method is compared with the WASP program as a reference to verify the most accurate method. The curve fitting method produces the minimum error and considered the most accurate method for calculating the output energy of the wind turbines.

10 Acknowledgement

This paper was supported by the deanship of scientific research at Salman bin Abdulaziz University under the research project no. 2014/01/734.

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