

Power Curve Modelling For Wind Turbines

Alhassan Ali Teyabeen

Center for Solar Energy Research
and Studies
Tripoli, Libya
Alhassan.teyabeen@gmail.com

Fathi Rajab Akkari

Department of Electrical and
Electronics Engineering
University of Tripoli
Tripoli, Libya
fathi.akkari@yahoo.com

Ali Elseddig Jwaid

Department of computing and
technology
Nottingham Trent University
Nottingham, UK
ali.jwaid@ntu.ac.uk

Abstract—The wind turbine power curve WTPC describes the relationship between wind speed and turbine power output. Power curve, provided by the manufacturer is one of the most important tools used to estimate turbine power output and capacity factor. Hence, an accurate WTPC model is essential for predicting wind energy potential. This paper presents a comparative study of various models for mathematical modelling of WTPC based on manufacturer power curve data gathered from 32 wind turbines ranging from 330 to 7580 kW. The selected models are validated by comparing the capacity factor obtained using the models based on Gamma probability density function with the capacity factor estimated using manufacturer power curves based on measured wind speed data. The selected models are also validated by comparing the instantaneous power obtained using the models with manufacturer power curve data. The accuracy of the models is evaluated using statistical criteria such as Normalized Root Mean Square Error (NRMSE), relative error (RE), and correlation coefficient (R). The adopted model allows predicting the behavior of wind turbine generated under different wind speeds. Results of the analysis presented in this paper show that the power-coefficient based model presents favorable efficiency followed by general model, since they have lower values of RE in estimation of capacity factor, whereas the polynomial model showed the least accurate model.

Keywords- Gamma distribution; wind energy; capacity factor; power curve model; performance evaluation.

I. INTRODUCTION

The major factors influencing the electrical power produced by wind turbine generator are distribution of a wind speed at the selected site, tower height of wind turbine generator, and power response of the turbine to different wind velocities which described by power curve [1-3]. The power curve of a wind turbine generator is obtained by the manufacturers from field measurements of wind speed and power [4]. Wind turbine generators have different power curves, even turbines with a similar rating may give different output power at the same wind speed. The important characteristic speeds of a wind turbine are its cut-in, rated, and cut-out speed as shown in Fig. 1. At cut-in speed, the turbine starts to generate power. At rated speed, the generated power by the turbine reaches the advertised power. At cut-out speed, the turbine stops producing power.

Several studies have reported in the field of wind turbine power curve modeling. A. Goudarzi et al [2] presented

comparative analysis of various models for modeling of wind turbine power curves with reference to three commercial wind turbines, 330, 800, and 900 kW. They evaluated the performance of the selected models using statistical indicators such as normalized root mean square error. Their results indicated that the forth order polynomial is the most accurate mathematical model. C. Carrillo et al. [4] compared four models namely; polynomial, exponential, cubic, and approximated cubic for modeling of wind turbine power curves. They evaluated the models performance using coefficient of determination as fitness indicator based on manufacturer power curves gathered from nearly 200 turbines ranging from 225 to 7500 kW. The results indicated that exponential and cubic approximation give higher coefficient of determination values and lower errors, and polynomial model shows the worst results.

The purpose of this study is to compare between common nine mathematical models and find out which is the most efficient for modeling of wind turbine power curves. The MATLAB script file program is built for simulation.

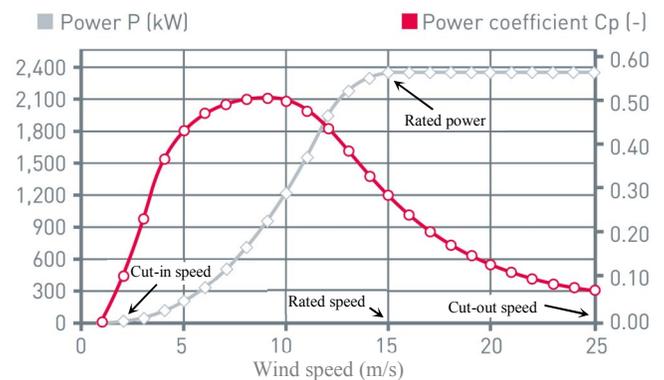


Figure 1. Power curve of wind turbine (ENERCON E-70 2300kW).

II. GAMMA DISTRIBUTION

Wind is stochastic in nature. In order to deal with wind speed, we need to describe its behavior by probability density function (simply, distribution). The distribution which is used to describe wind speed is influencing the assessment of wind energy potential due to the cubic relationship between wind speed and power, thus even small

variation in wind speed may leads to a significant change in power. For this reason, the selected distribution must be well fitted with measured wind speed data. Wind speed data used in this study were measured at hub height of 10 meters and recorded every 10 minutes in Misrata-Libya during the whole year. A. Teyabean [5] proved that the appropriate distribution for the same studied site in this study is Gamma distribution since it gives the best fitting for observed wind speed data. So it will be adopted and applied for next calculations in this study. The Gamma probability density function $f(v)$ is given by [5, 6]:

$$f(v) = \frac{v^{\alpha-1}}{\Gamma(\alpha)\beta^\alpha} e^{-\frac{v}{\beta}} \quad (1)$$

where v is the wind speed, α and β are the dimensionless shape and scale (in m/s) Gamma parameters, respectively, they are given by [5, 6]:

$$\alpha = \frac{v_m^2}{\sigma^2} \quad (2)$$

$$\beta = \frac{\sigma^2}{v_m} \quad (3)$$

where v_m and σ are the mean value and standard deviation of observed wind speed, they are given by [5-7]:

$$v_m = \frac{1}{n} \sum_{i=1}^n v_i \quad (4)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (v_i - v_m)^2} \quad (5)$$

where n is the number of wind speed data. And Γ represents the gamma function defined as [6]:

$$\Gamma(t) = \int_0^\infty x^{t-1} e^{-x} dx \quad (6)$$

III. TURBINE POWER OUTPUT AND CAPACITY FACTOR

The power $P(v)$ produced by wind turbine is usually represented by its power curve. Hence the turbine has for distinct performance regions as shown in Fig.1, given by [1, 5]:

$$P(v) = \begin{cases} 0 & v < v_{ci} \\ P_f(v) & v_{ci} \leq v < v_r \\ P_r & v_r \leq v < v_{co} \\ 0 & v_{co} \leq v \end{cases} \quad (7)$$

where v_{ci} , v_r , and v_{co} , are the cut-in, rated and cut-out velocities, P_r is the rated power (in W), and $P_f(v)$ is the power fitted to manufacturer power curve data by using mathematical equation. The output energy E_{out} (in Wh) produced by the turbine over time interval T is given by [1, 5]:

$$E_{out} = T \int_{v_{ci}}^{v_{co}} P(v) f(v) dv = T \int_{v_{ci}}^{v_r} P_f(v) f(v) dv + TP_r \int_{v_r}^{v_{co}} f(v) dv \quad (8)$$

The capacity factor reflects how the turbine could exploit the energy available in the wind. It can be estimated based on probability density function, given by [1, 5, 8, 9]:

$$CF_{pdf} = \frac{E_{out}}{P_r \times T} \quad (9)$$

It also can be estimated based on the measured time-series wind speeds, as follow [10]:

$$CF_{ts} = \frac{AEO}{P_r \times T} \quad (10)$$

where AEO is the annual energy output, given as [10]:

$$AEO = \sum_{i=1}^b MPC_i \times H_i \quad (11)$$

where MPC_i is the manufacturer power curve value (in W) corresponding to wind speed bin i , H_i is number of hours that the wind speed occurred at bin i , and b is the number of bins.

In most cases the measured wind speed data must be adjusted to the hub height of wind turbine using the following [11–13]:

$$\frac{v}{v_{ref}} = \left(\frac{h}{h_{ref}} \right)^\varphi \quad (12)$$

where v (in m/s) is the wind velocity at the hub height h (in m), v_{ref} (in m/s) is the wind velocity at the reference hub height h_{ref} (in m), and φ (dimensionless) is the surface roughness coefficient, it is assumed 0.12 in this study base on Ref [14].

IV. WIND TURBINE POWER CURVE MATHEMATICAL MODELS

The purpose of this study is to compare between nine mathematical models and find out which of them is the most appropriate to represent the behavior of the power curves given by manufacturers. The proposed models are described below:

A. Linear model

For the linear model, the relationship between the power output and wind speed is linear in the region of $[v_{ci}, v_r]$. The power output $P_f(v)$ in this region is expressed as [2, 3, 12, 15]:

$$P_f(v) = P_r \left(\frac{v-v_{ci}}{v_r-v_{ci}} \right) \quad (13)$$

Substituting (13) into (9) yields the capacity factor as [5]:

$$CF = \frac{\alpha\beta}{v_r-v_{ci}} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 1 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 1 \right) \right] - \frac{v_{ci}}{v_r-v_{ci}} \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (14)$$

where γ is the lower incomplete gamma function, given as [5, 9, 15, 16]:

$$\gamma(u, x) = \frac{1}{\Gamma(x)} \int_0^u t^{x-1} e^{-t} dt \quad (15)$$

B. Quadratic model

The power output $P_f(v)$ for quadratic model is given as [1,2,12,15,16]:

$$P_f(v) = P_r \left(\frac{v^2-v_{ci}^2}{v_r^2-v_{ci}^2} \right) \quad (16)$$

Using equation (9) the capacity factor is given by [5]:

$$CF = \frac{\alpha(\alpha+1)\beta^2}{v_r^2-v_{ci}^2} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 2 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 2 \right) \right] - \frac{v_{ci}^2}{v_r^2-v_{ci}^2} \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (17)$$

C. Cubic type-I model

The power $P_f(v)$ for cubic type-I model is given by [9, 12, 15]:

$$P_f(v) = P_r \left(\frac{v^3}{v_r^3} \right) \quad (18)$$

From (9), the capacity factor is given by [5]:

$$CF = \frac{\alpha(\alpha+1)(\alpha+2)\beta^3}{v_r^3} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 3 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (19)$$

D. Cubic type-II model

The power output $P_f(v)$ for cubic type-II model is given by [1, 12]:

$$P_f(v) = P_r \left(\frac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3} \right) \quad (20)$$

From (9) the capacity factor is given by [5]:

$$CF = \frac{\alpha(\alpha+1)(\alpha+2)\beta^3}{v_r^3 - v_{ci}^3} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 3 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] - \frac{v_{ci}^3}{v_r^3 - v_{ci}^3} \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (21)$$

E. General model

General model is type of power model which describes the power output curve with an indefinite-order of wind speed. It is given by [1, 15]:

$$P_f(v) = P_r \left(\frac{v^k - v_{ci}^k}{v_r^k - v_{ci}^k} \right) \quad (22)$$

where k is the order of power output curve, it is assumed to be 1.4 in this study. By indicating to (9), the capacity factor is given by [5]:

$$CF = \frac{\Gamma(\alpha+k)\beta^k}{(v_r^k - v_{ci}^k)\Gamma(\alpha)} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + k \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + k \right) \right] - \frac{v_{ci}^k}{v_r^k - v_{ci}^k} \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (23)$$

F. Exponential model

When an exponential model is used to model a power curve, the non-linear part $P_f(v)$ is given by [2, 4]:

$$P_f(v) = \frac{1}{2} \rho A k_p (v^B - v_{ci}^B) \quad (24)$$

where ρ is the air density (1.225 kg/m³), A is the swept area (in m²), k_p and B are constants, given by ($k_p=0.899$, $B=2.706$) [2, 4]. Using (9) the capacity factor is given as [5]:

$$CF = \frac{0.5 \rho A k_p}{P_r} \left\{ \frac{\Gamma(\alpha+B)\beta^B}{\Gamma(\alpha)} \left[\gamma \left(\frac{v_r}{\beta}, \alpha + B \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + B \right) \right] - v_{ci}^B \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] \right\} + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (25)$$

G. Power-coefficient based model

A simplified form of the expression given in (24) can be obtained by supposing v_{ci} equal to zero and B equal to three which is expressed as [2-4, 12]:

$$P_f(v) = \frac{1}{2} \rho A C_{p,eq} v^3 \quad (26)$$

where $C_{p,eq}$ is a constant equivalent to power coefficient (it is assumed to be 0.40), [2]. The capacity factor is given as [5]:

$$CF = \frac{0.5 \rho A C_{p,eq}}{P_r} \left\{ \alpha(\alpha+1)(\alpha+2)\beta^3 \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 3 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] \right\} + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (27)$$

H. Approximated power-coefficient based model

This model can be obtained by approximating equation (26) by assuming $C_{p,eq}$ equal to the maximum value of power coefficient $C_{p,max}$ as follow [2, 4]:

$$P_f(v) = \frac{1}{2} \rho A C_{p,max} v^3 \quad (28)$$

where $C_{p,max}$ can be obtained directly from the manufacturer data. Using (9) the capacity factor is given as [5]:

$$CF = \frac{0.5 \rho A C_{p,max}}{P_r} \left\{ \alpha(\alpha+1)(\alpha+2)\beta^3 \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 3 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] \right\} + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (29)$$

I. Polynomial model

In this model, a second degree polynomial is used to fit the non-linear part, given as [17]:

$$P_f(v) = P_r (a_2 v^2 + a_1 v + a_0) \quad (30)$$

where

$$a_2 = \frac{1}{(v_{ci} - v_r)^2} \left[2 - 4 \left(\frac{v_{ci} + v_r}{2v_r} \right)^3 \right] \quad (31)$$

$$a_1 = \frac{1}{(v_{ci} - v_r)^2} \left[4(v_{ci} + v_r) \left(\frac{v_{ci} + v_r}{2v_r} \right)^3 - 3v_{ci} - v_r \right] \quad (32)$$

$$a_0 = \frac{1}{(v_{ci} - v_r)^2} \left[v_{ci}(v_{ci} + v_r) - 4v_{ci}v_r \left(\frac{v_{ci} + v_r}{2v_r} \right)^3 \right] \quad (33)$$

Using (9) the capacity factor is given by [5]:

$$CF = a_2 \beta^2 \alpha(\alpha+1) \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 2 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 2 \right) \right] + a_1 \alpha \beta \left[\gamma \left(\frac{v_r}{\beta}, \alpha + 1 \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha + 1 \right) \right] + a_0 \left[\gamma \left(\frac{v_r}{\beta}, \alpha \right) - \gamma \left(\frac{v_{ci}}{\beta}, \alpha \right) \right] + \left[\gamma \left(\frac{v_{co}}{\beta}, \alpha \right) - \gamma \left(\frac{v_r}{\beta}, \alpha \right) \right] \quad (34)$$

V. STATISTICAL CRITERIA USED FOR PERFORMANCE EVALUATION

The models performance is evaluated by using statistical tests namely; relative error (RE), normalized root mean square error (NRMSE) and correlation coefficient based on capacity factor and instantaneous power curve. These tests are described below:

A. Relative error

The relative error RE is a criterion which represents the relative difference between capacity factor estimated from measured time-series wind speed data CF_{ts} , and capacity factor estimated using the fitted models CF_{pdf} , it is given as [18]:

$$RE = \left| \frac{CF_{pdf} - CF_{ts}}{CF_{ts}} \right| \times 100\% \quad (35)$$

B. Normalized root mean square error

The root mean square error (RMSE) is frequently used to measure the difference between actual values and predicted values by a model. The normalized root mean square error NRMSE can be achieved by normalizing the RMSE value to the range of the observed data [2]. It is given by [2, 19]:

$$NRMSE = \frac{RMSE}{MPC_{max} - MPC_{min}} \quad (36)$$

where MPC_{max} and MPC_{min} are the maximum and minimum values of the manufacture power curve. And RMSE is given as [6]:

$$RMSE = \sqrt{\frac{1}{b} \sum_{i=1}^b (MPC_i - P_{f_i})^2} \quad (37)$$

where MPC_i and P_{f_i} are the manufacturer power curve values and the instantaneous power values predicted by the models corresponding to wind speed bin i , respectively, and b is the number of bins at range of $[v_{ci}, v_r)$.

C. Correlation coefficient

The Correlation coefficient, R , describes the correlation between the data series, it is given by [6]:

$$R = \frac{1}{b-1} \sum_{i=1}^b \frac{(MPC_i - \overline{MPC})(P_{f_i} - \overline{P_f})}{\sigma_{MPC} \sigma_{P_f}} \quad (38)$$

where \overline{MPC} , $\overline{P_f}$ denote the mean value of manufacturer power curve data and power predicted by the mathematical models, respectively. σ_{MPC} , σ_{P_f} denote the standard deviation of manufacturer power curve data and power predicted by the mathematical models, respectively. And b is the number of bins at range of $[v_{ci}, v_r)$.

VI. RESULTS AND DISCUSSION

In order to find out which of the proposed mathematical models is appropriate to represent power curves, the first step is gathering manufacturers power curve data. Thence, a database of 32 WTPC has been used (see Appendix), [20-22]. As an example, the manufacturer power curve of (Gamesa: G114 2.0MW) is shown in Table I. The representation of wind turbine power curves in database is shown in Fig. 2. The histogram of turbine rated power, tower height, and cut-in, rated, cut-out wind speeds of wind turbines in database are shown in Fig. 3-5.

All mathematical equations presented in section IV which proposed for power curve modeling are applied to each power curve in the database. The relative error (RE) which is shown in (35) is estimated based on the capacity factor obtained from each mathematical model and capacity factor obtained from time-series wind speeds. As an

example, the capacity factor of (Gamesa G114 2.0MW) estimated using measured time-series wind speeds which described in (10) is equal to 49.33%, where the AEO is 8643.28 MWh/y (see Table I). The RE of all presented models is estimated based on all manufacturer power curves in database, it is shown in Fig.6. The mean and standard deviation of RE is illustrated in Table II. From results shown in Fig. 6 and illustrated in Table II, it can be clearly seen that the power-coefficient based model gives the lowest RE followed by general model. It is also seen that the polynomial model is the worst, this outcome agreed with Ref [4].

The correlation coefficient is used to describe the correlation between instantaneous power predicted by each model and the manufacturer power curve values in the range of $[v_{ci}, v_r)$. The NRMSE is also presented to estimate the error of all presented mathematical models. The mean value and standard deviation of the correlation and NRMSE for each model are shown in Table III, where the general model has the highest correlation and lowest NRMSE, thus it can be considered as well fitted with manufacturer power curve in the range of $[v_{ci}, v_r)$.

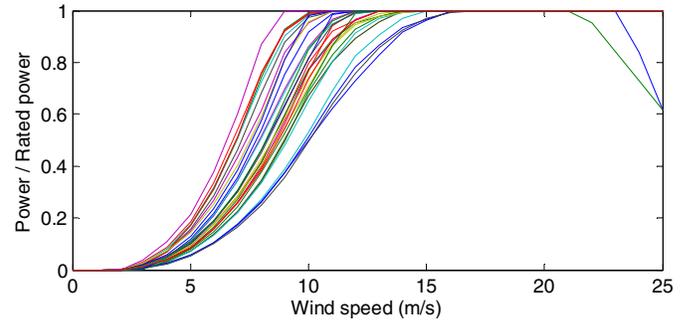


Figure 2. Representation of all power curves in database.

TABLE I. MANUFACTURER POWER CURVE (GAMESA G114 2.0MW), AND THE PRODUCED ENERGY.

Wind speed bin (m/s)	Instantaneous power (kW)	Hours per year	Energy (MWh/yr)	Wind speed bin (m/s)	Instantaneous power (kW)	Hours per year	Energy (MWh/yr)
0	0	11.50	0	13	2000	210.17	420.33
1	0	109.67	0	14	2000	154.67	309.33
2	0	389.83	0	15	2000	107.33	214.67
3	32	706.50	22.61	16	2000	73.17	146.33
4	146	962.00	140.45	17	2000	45.00	90.00
5	342	1029.33	352.03	18	2000	28.50	57.00
6	621	1036.33	643.56	19	2000	13.50	27.00
7	1008	977.00	984.82	20	2000	7.67	15.33
8	1487	895.00	1330.87	21	2000	2.83	5.67
9	1858	743.00	1380.49	22	1906	1.33	2.54
10	1984	534.67	1060.78	23	1681	0.33	0.56
11	1995	426.50	850.87	24	1455	0	0
12	1999	294.17	588.04	25	1230	0	0

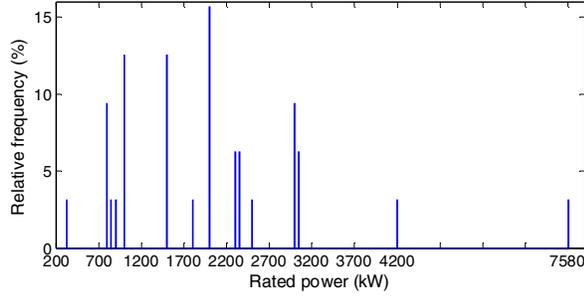


Figure 3. Histogram of turbine rated power.

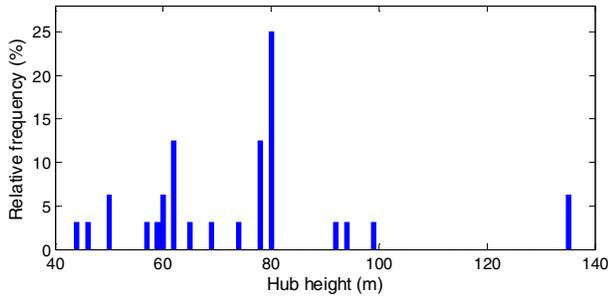


Figure 4. Histogram of tower height.

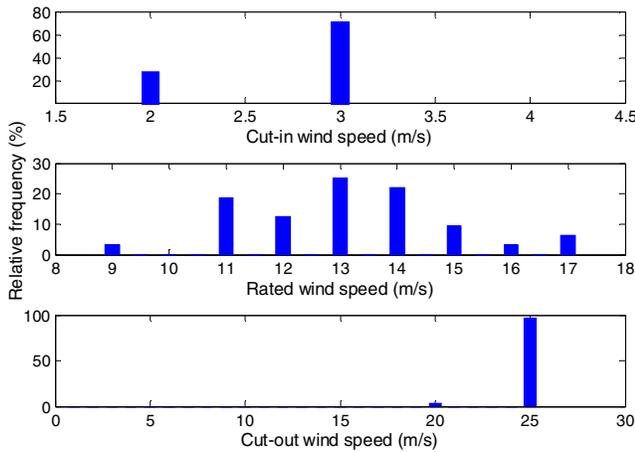


Figure 5. Histogram of cut-in, rated, and cut-out wind speeds.

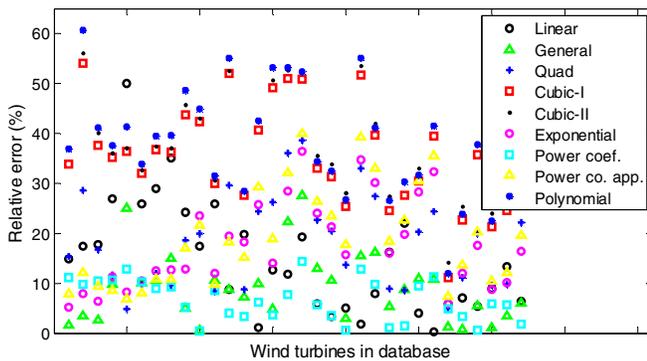


Figure 6. Relative error of all presented models.

TABLE II. SUMMARY OF RE: MEAN AND STANDARD DEVIATION

Math. model	Mean of RE%	Stand. dev. of RE%
Linear	14.70	11.18
General	8.98	6.88
Quadratic	18.00	9.22
Cubic-I	35.86	10.25
Cubic-II	37.73	9.93
Exponential	17.44	8.82
Power Coeff.	6.70	4.06
Approx. power Coeff.	18.98	9.83
polynomial	38.26	11.10

TABLE III. SUMMARY OF NRMSE, AND CORRELATION COEFFICIENT: MEAN AND STANDARD DEVIATION

Mathematical model	NRMSE		Correlation Coefficient	
	Mean	Stand. dev.	Mean	Stand. dev.
Linear	0.1023	0.0225	0.9798	0.0065
General	0.0994	0.0351	0.9819	0.0106
Quadratic	0.1318	0.0503	0.9734	0.0188
Cubic-I	0.2035	0.0558	0.9402	0.0307
Cubic-II	0.2088	0.0551	0.9495	0.0307
Exponential	0.3991	0.1834	0.9402	0.0281
Power Coeff.	0.2651	0.1487	0.9402	0.0307
Appr. pow. Coef.	0.4429	0.2000	0.9517	0.0307
polynomial	0.1959	0.0563	0.9798	0.0285

VII. CONCLUSION

This paper compared nine mathematical models to find out which is the most appropriate for modeling wind turbine power curves. The accuracy of the proposed models is evaluated using statistical criteria including relative error, normalized root mean square error, and correlation coefficient. From the results of this study it can be concluded:

- (1) Among the presented mathematical models, the power-coefficient based model and general model were the most accurate mathematical models for modeling of wind turbine power curves, since they gave the lowest relative error in estimation of capacity factor.
- (2) The polynomial model was found the least accurate model.

ACKNOWLEDGMENT

The authors would like to thank Gamesa for supplying the manufacturer power curve data of “G97 2.0MW”, and “G114 2.0MW”.

REFERENCES

- [1] S. Mathew, “Wind energy: fundamentals, resource analysis and economics,” New York, Springer-Verlag Berlin Heidelberg, 2006.
- [2] A. Goudarzi, A. Ahmadi, “Intelligent Analysis of Wind Turbine Power Curve Models,” *In Computational Intelligence Applications in Smart Grid (CIASG), IEEE*, pp. 1-7, 2014.
- [3] V. Thapar, G. Agnihotri, and V. K. Sethi, “Critical analysis of methods for mathematical modelling of wind turbines,” *Renew. Energy*, vol. 36, pp. 3166–3177, 2011.

- [4] C. Carrillo, A. Montan, J. Cidras, E. Diaz-Dorado “Review of power curve modelling for wind turbines,” *Renewable and Sustainable Energy Reviews*, vol. 21, pp. 572–581, 2013.
- [5] Alhassan A. Teyabeen, “*Selection of appropriate statistical model for wind speed data, and selecting suitable turbine generator at four locations in Libya*”. [Master’s thesis]; Dept. of EE; University of Tripoli, 2017.
- [6] Alhassan A. Teyabeen, “Statistical Analysis of Wind Speed Data,” *IEEE, 6th International Renewable Energy Congress (IREC)*, 2015.
- [7] R. Walpole, R. Myers, S. Myers, and K. Ye, “*Probability & Statistics for Engineers & Scientists*,” Eight edition. Pearson Education International, 2007.
- [8] S. Jangamshetti and V. Rau, “Site matching of wind turbine generators: A case study”, *IEEE Trans. Energy Convers.*, vol. 14, no. 4, pp. 1537–1543, 1999.
- [9] S. Jangamshetti, V. Rau, “Normalized Power Curves as a Tool for Identification of Optimum Wind Turbine Generator Parameters,” *IEEE Trans. Energy Convers.* vol. 16, no. 3, pp. 283–288, 2001.
- [10] Paul Gipe. “*Wind power for home and business:renewable energy for the 1990s and beyond*”. Chelsea Green Pub. Co., 1993.
- [11] C. Justus, A. Mikhail, “Height variation of wind speed and wind distributions statistics”, *Geophysical Research Letters*, 3(5), pp. 261–264, 1976.
- [12] M. Albadi and E. El-saadany, “Optimum turbine-site matching,” *Energy*, vol. 35, pp. 3593–3602, 2010.
- [13] B. Belabes, A. Youcefi, O. Guerri, M. Djamai, A. Kaabeche, “Evaluation of wind energy potential and estimation of cost using wind energy turbines for electricity generation in north of Algeria”, *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1245–1255, 2015.
- [14] A. M. Elmabruk, F. A. Aleej, and K. A. Ibrahim, “Estimation of Wind Energy Potential in Libya,” *IEEE, 5th International Renewable Energy Congress (IREC)*, 2014.
- [15] T. Chang, F. Liu, H. Ko, S. Cheng, and L. Sun, “Comparative analysis on power curve models of wind turbine generator in estimating capacity factor,” *Energy*, vol. 73, pp. 88–95, 2014.
- [16] M. Albadi, “wind turbines capacity factor modeling - a novel approach,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1637–1638, 2009.
- [17] J. Wen, Y. Zheng, and F. Donghan, “A review on reliability assessment for wind power,” *Renew. Sustain. Energy Rev.*, vol. 13, pp. 2485–2494, 2009.
- [18] M. Lydia, S. Kumar, A. Selvakumar, and G. Kumar, “A comprehensive review on wind turbine power curve modeling techniques,” *Renew. Sustain. Energy Rev.*, vol. 30, pp. 452–460, 2014.
- [19] C. Fernandez-Peruchena, M. Gaston, “A simple and efficient procedure for increasing the temporal resolution of global horizontal solar irradiance series”, *Renewable Energy*, vol. 86, pp. 375–383, 2016.
- [20] Gamesa, “General characteristics manual (GCM)”, 2014.
- [21] ENERCON, “ENERCON product overview”, [online], www.enercon.de, 2015.
- [22] LEITWIND, “Manufacturer power curve data”, [online], www.leitwind.com, 2015.

VIII. APPENDIX

TABLE IV. WIND TURBINE DATABASE

Manufacturer	Model	Rated power (kW)	Rotor diameter (m)	Tower height (m)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)	Maximum C_p
ENERCON	E-33 330 kW	330	33.4	44	3	13	25	0.5
ENERCON	E-44 900 kW	900	44	45	3	17	25	0.5
ENERCON	E-48 800 kW	800	48	50	3	14	25	0.5
ENERCON	E-53 800 kW	800	52.9	50	2	13	25	0.49
ENERCON	E-70 2300 kW	2300	71	57	2	15	25	0.5
ENERCON	E-82 2000 kW	2000	82	78	2	13	25	0.5
ENERCON	E-82 2300 kW	2300	82	78	2	14	25	0.5
ENERCON	E-82 2350 kW	2350	82	59	2	14	25	0.5
ENERCON	E-82 3000 kW	3000	82	69	3	16	25	0.483
ENERCON	E-92 2350 kW	2350	92	78	2	14	25	0.47
ENERCON	E-101 3050 kW	3050	101	99	2	13	25	0.478
ENERCON	E-101 3500 kW	3500	101	74	2	15	25	0.47
ENERCON	E-115 3000 kW	3000	115.7	92	2	12	25	0.47
ENERCON	E-126 4200 kW	4200	127	135	3	14	25	0.45
ENERCON	E-126 7580 kW	7580	127	135	3	17	25	0.483
Gamesa	Gamesa97 2 MW	2000	97	78	3	14	25	0.468
Gamesa	Gamesa114 2 MW	2000	114	80	3	13	25	0.47
LEITWIND	LTW77 800 kW	800	76.6	61.5	3	11	25	-
LEITWIND	LTW77 850 kW	850	76.6	61.5	3	11	25	-
LEITWIND	LTW77 1000 kW	1000	76.6	61.5	3	11	25	-
LEITWIND	LTW77 1500 kW	1500	76.6	61.5	3	15	25	-
LEITWIND	LTW80 1000 kW	1000	80.3	65	3	12	25	-
LEITWIND	LTW80 1500 kW	1500	80.3	60	3	12	25	-
LEITWIND	LTW80 1800 kW	1800	80.3	60	3	13	25	-
LEITWIND	LTW86 1000 kW	1000	86.3	80	3	11	25	-
LEITWIND	LTW86 1500 kW	1500	86.3	80	3	13	20	-
LEITWIND	LTW90 1000 kW	1000	90.3	80	3	9	25	-
LEITWIND	LTW90 1500 kW	1500	90.3	80	3	11	25	-
LEITWIND	LTW90 2000 kW	2000	90.3	80	3	13	25	-
LEITWIND	LTW101 2000 kW	2000	101	80	3	11	25	-
LEITWIND	LTW101 2500 kW	2500	101	80	3	12	25	-
LEITWIND	LTW101 3000 kW	3000	101	93.5	3	14	25	-