Mathematical Modelling of Wind Turbine Power Curve

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Abstract – We develop new models to estimate the capacity factor using Weibull and Gamma probability density functions and present the results of a comparative study of 9 mathematical models of WTPC using manufacturer’s data from 32 wind turbines, ranging from 330 to 7580 kW. We validate the models by comparing their results with these data. Correlation coefficient ($\mathbf{R}$) and Mean Absolute Percentage Error (MAPE) are used to evaluate their accuracy. Relative Error (RE) is used to evaluate the performance by comparing the Weibull and Gamma distributions using 12 month wind speed data at three hub heights. The results show the power-coefficient based model derived from Weibull and Gamma distributions gives the best performance in estimating capacity factor, while the polynomial model was the least accurate.

Keywords- Weibull distribution; 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 modelling. A. Goudarzi et al. [2] presented a comparative analysis of various models for modelling 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 fourth order polynomial is the most accurate mathematical model. C. Carrillo et al. [4] compared four models namely; polynomial, exponential, cubic, and approximated cubic for modelling 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 the 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 modelling of wind turbine power curves. The MATLAB script file program is built for simulation.

II. DATA COLLECTION AND CASE STUDY REGION

The wind speed data used in this study were measured at Misrata site which is located at the north of Libya during the whole year. They were recorded every 10 minutes at multi hub heights from 10 m to 40 m above the ground. The data are used to evaluate the performance of the proposed models and mathematical formulas used to estimate the capacity factor.

![Figure 1. Typical power curve of a wind turbine.](image-url)
III. NEED OF POWER CURVE MODELLING

The power curve indicates the power response of wind turbine to the different wind speeds. Accurate model of the power curves is needed for wind energy applications. Modelling of the wind turbine power curve is useful for many issues:

A. Assessment of wind energy potential

The power curve of the wind turbine can be used for assessment of wind power. It describes the relationship between wind speed and turbine power output. Power curves are provided by manufacturers in tables or in graphical forms. But mathematical model which accurately represents power curve is required for many problems of wind energy systems, such as assessing the potential of wind energy [5].

B. Estimation of capacity factor

The capacity factor of a wind turbine at any location can be described as the ratio of actual power output from wind turbine over a period of time to the energy which could have been produced by it. The capacity factor of a wind turbine reflects its efficiency, i.e. it indicates how the turbine could exploit the energy available in the wind. The power curve of a wind turbine is used to estimate its capacity factor. If the capacity factor value getting higher, the turbine will be more suitable for the location.

C. Selection of turbines

The power curve can be used for turbine site matching and ranking the potential of wind resource.

IV. WIND SPEED MODELLING

For any given wind speed data it is important to know mean $\langle \nu \rangle$ and standard deviation $\sigma$ of data, they are given by [4, 6, 7]:

$$\nu_m = \frac{1}{n} \sum_{i=1}^{n} \nu_i$$  \hspace{1cm} (1)

$$\sigma = \left( \frac{1}{n-1} \sum_{i=1}^{n} (\nu_i - \nu_m)^2 \right)^{1/2}$$  \hspace{1cm} (2)

where $\nu_i$ is the $i^{th}$ wind speed, and $n$ is the total number of wind speed data.

Wind is stochastic in nature. In order to deal with wind speed, we need to describe its behaviour 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. Weibull distribution is widely used for representing wind speed data. A. Teyabeen [7] 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. For this reason, the Weibull and Gamma distributions will be adopted and applied for next calculations in this study.

D. Weibull distribution

The Weibull probability density function $f(\nu)$ is given by [1, 6, 8]:

$$f(\nu) = \left( \frac{k}{\lambda} \right) \left( \frac{\nu}{\lambda} \right)^{k-1} e^{-(\nu/\lambda)^k}$$  \hspace{1cm} (3)

where $k, \lambda$ are the dimensionless shape and scale (in m/s) parameters of the Weibull distribution, respectively. The Weibull cumulative distribution function $F(\nu)$ is given as [1, 6, 8]:

$$F(\nu) = 1 - e^{-(\nu/\lambda)^k}$$  \hspace{1cm} (4)

The mean wind speed and standard deviation of Weibull distribution are given by [1, 6, 8]:

$$\nu_m = \lambda \Gamma \left( 1 + \frac{1}{k} \right)$$  \hspace{1cm} (5)

$$\sigma = \lambda \left[ \Gamma \left( 1 + \frac{2}{k} \right) - \Gamma^2 \left( 1 + \frac{1}{k} \right) \right]^{1/2}$$  \hspace{1cm} (6)

where $\Gamma$ is the gamma function defined as [6]:

$$\Gamma(t) = \int_{0}^{\infty} x^{t-1} e^{-x} dx$$  \hspace{1cm} (7)

E. Gamma distribution

The Gamma probability density function $f(\nu)$ is given by [6, 7]:

$$f(\nu) = \frac{\nu^{\alpha-1} \lambda^{-\alpha} e^{-\nu/\lambda}}{\Gamma(\alpha)}$$  \hspace{1cm} (8)

where $\nu$ is the wind speed, $\alpha$ and $\beta$ are the dimensionless shape and scale (in m/s) Gamma parameters, respectively, they are given by [6, 7]:

$$\alpha = \frac{\nu_m^\beta}{\sigma^\beta}$$  \hspace{1cm} (9)

$$\beta = \frac{\sigma}{\nu_m}$$  \hspace{1cm} (10)
V. TURBINE POWER OUTPUT AND CAPACITY FACTOR

The power $P(v)$ produced by a wind turbine is usually represented by its power curve. Hence the turbine has four distinct performance regions as shown in Fig.1, given by [1, 7]:

$$P(v) = \begin{cases} 
0 & v < v_{ci} \\
\frac{P_r}{v_{ci}} & v_{ci} \leq v < v_r \\
\frac{P_r}{v_r} & v_r \leq v < v_{co} \\
0 & v \geq v_{co} 
\end{cases}$$  \hspace{1cm} (11)

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, 7]:

$$E_{out} = T \int_{v_{ci}}^{v_{co}} P(v) f(v) \, dv$$

$$= T \int_{v_{ci}}^{v_r} P_r f(v) \, dv + TP_r \int_{v_r}^{v_{co}} f(v) \, dv$$  \hspace{1cm} (12)

The capacity factor reflects how the turbine could exploit the wind energy. It can be estimated based on probability density function, given by [1, 7, 9, 10]:

$$CF_{pdf} = \frac{E_{out}}{P_r \times T}$$  \hspace{1cm} (13)

It also can be estimated based on the measured time-series wind speeds, as follow [11]:

$$CF_{ts} = \frac{AEO}{P_r \times T}$$  \hspace{1cm} (14)

where $AEO$ is the annual energy output, given as [11]:

$$AEO = \sum_{i=1}^{b} MPC_i \times H_i$$  \hspace{1cm} (15)

where $MPC_i$ is the manufacturer power curve value (in W) corresponding to wind speed bin $i$, $H_i$ is the 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 [12–14]:

$$\frac{v}{v_{ref}} = \left( \frac{h}{h_{ref}} \right)^{\varphi}$$  \hspace{1cm} (16)

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 $\varphi$ (dimensionless) is the surface roughness coefficient, it is assumed to be 0.12 in this study [15].

VI. WIND TURBINE POWER CURVE

MATHEMATICAL MODELS

The purpose of this study is to compare nine mathematical models and find out which of them is the most appropriate to represent the behaviour of the power curves given by manufacturers. The proposed models are described in full detail in Appendix-A.

VII. STATISTICAL CRITERIA USED FOR PERFORMANCE EVALUATION

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

F. Mean absolute percentage error

The MAPE is a criterion which represents the mean absolute percentage difference between the manufacturer power curve values $MPC_i$ and the instantaneous power values predicted by the models $P_f$, corresponding to wind speed bin $i$, it is given by [8, 20]:

$$MAPE = \frac{1}{b} \sum_{i=1}^{b} \left| \frac{P_f - MPC_i}{MPC_i} \right| \times 100\%$$  \hspace{1cm} (48)

where $b$ is the number of bins at the range of $[v_{ci}, v_r]$.

G. Correlation Coefficient

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

$$R = \frac{1}{b-1} \sum_{i=1}^{b} \frac{(MPC_i - \bar{MPC})(P_f - \bar{P_f})}{\sigma_{MPC} \sigma_{P_f}}$$  \hspace{1cm} (49)

where $\bar{MPC}$, $\bar{P_f}$ denote the mean value of manufacturer power curve data and power predicted by the mathematical models, respectively. $\sigma_{MPC}$, $\sigma_{P_f}$ 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 $[v_{ci}, v_r]$.

H. 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 [21]:

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15.3

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\[ RE = \left( \frac{CP_{pd} - CP_{re}}{CP_{re}} \right) \times 100\% \]  

(50)

VIII. 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), [22–24]. As an example, the manufacturer power curve of Gamesa: G114 2.0MW is shown in Table I.

<table>
<thead>
<tr>
<th>Wind speed bin (m/s)</th>
<th>Instantaneous power (kW)</th>
<th>Hours per year</th>
<th>Energy (MWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>11.50</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>109.67</td>
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<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>146</td>
<td>706.50</td>
<td>40.45</td>
</tr>
<tr>
<td>4</td>
<td>342</td>
<td>962.00</td>
<td>140.45</td>
</tr>
<tr>
<td>5</td>
<td>621</td>
<td>1029.33</td>
<td>352.03</td>
</tr>
<tr>
<td>6</td>
<td>1008</td>
<td>1036.33</td>
<td>643.56</td>
</tr>
<tr>
<td>7</td>
<td>1487</td>
<td>977.00</td>
<td>984.82</td>
</tr>
<tr>
<td>8</td>
<td>1858</td>
<td>895.00</td>
<td>1330.87</td>
</tr>
<tr>
<td>9</td>
<td>2000</td>
<td>743.00</td>
<td>1380.49</td>
</tr>
<tr>
<td>10</td>
<td>1999</td>
<td>294.17</td>
<td>588.04</td>
</tr>
<tr>
<td>11</td>
<td>1995</td>
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</tr>
<tr>
<td>12</td>
<td>1999</td>
<td>294.17</td>
<td>850.87</td>
</tr>
<tr>
<td>13</td>
<td>2000</td>
<td>210.17</td>
<td>420.33</td>
</tr>
<tr>
<td>14</td>
<td>2000</td>
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<td>309.33</td>
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<td>15</td>
<td>2000</td>
<td>107.33</td>
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<td>45.00</td>
<td>90.00</td>
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<td>1455</td>
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<td>0</td>
</tr>
<tr>
<td>25</td>
<td>1230</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The representation of all manufacturers wind turbines 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. It can be noted that the capacities of turbines vary from 200 kW to 7580 kW, but the most of turbines have rated power of 2 MW. The tower heights of the turbines in database vary from 44 m to 135 m, and the most of wind turbine heights are 80 m. The cut-in wind speeds of the turbines are 2 and 3 m/s. The rated wind speeds vary from 9 m/s to 17 m/s. And cut-out wind speeds are 20 and 25 m/s.
Nine mathematical models presented in section VI are plotted together at turbine characteristics of $P_r = 900$ kW, $v_{cl} = 2$ m/s, and $v_r = 15$ m/s and shown in Fig. 6. It can be noted that there is a difference between the proposed models. Each model of these models is applied to each manufacturer power curve in database. The performance of the models is evaluated using MAPE and correlation coefficient in the range of $[v_{cl}, v_r]$. The correlation coefficient is used to describe the correlation between instantaneous power predicted by each model and the manufacturer power curve values. The correlation coefficient estimated based on Gamma distribution. It can be clearly seen that the power-coefficient model has the lowest values of MAPE and correlation coefficient. The results of performance evaluation of the models are illustrated in Table II, where the best model is introduced in bold. The General model has the highest correlation and the lowest MAPE, thus it can be considered as well fitted with manufacturer power curve in the range of $[v_{cl}, v_r]$. The General model has the highest correlation coefficient. The performance of the models of capacity factor obtained from each mathematical model of capacity factor based on Gamma and Weibull distributions are also applied to each manufacturer power curve in database. The performance of the mathematical models of capacity factor is evaluated using relative error. It is estimated using the capacity factor obtained from time-series wind speeds which given in (14) and capacity factor obtained from each mathematical equation of capacity factor based on Weibull and Gamma distributions. As an example, Table I shows how to estimate the capacity factor of the wind turbine type of “Gamesa G114 2.0 MW” using measured time-series wind speeds which given in (14). From Table I the AEO which described in (15) for the site under consideration is equal to 8643.28 MWh/y then the according capacity factor is equal to 49.33%. The mean and standard deviation values of relative error are estimated based on Weibull and Gamma distributions and illustrated in Table III, where all mathematical equations of the capacity factor are ranked according to their values of the mean of relative error, and the best mathematical equation is introduce in bold. The power-coefficient based model has the lowest values of mean of relative error, thus it can be considered as the best mathematical equation in estimating capacity factor.

### Table II. Summary of MAPE, and Correlation Coefficient: Mean Values.

<table>
<thead>
<tr>
<th>Mathematical model</th>
<th>Mean of MAPE</th>
<th>Mean of correlation coefficient</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>54.25</td>
<td>0.9700</td>
<td>6</td>
</tr>
<tr>
<td>Quadratic</td>
<td>405.21</td>
<td>0.9718</td>
<td>2</td>
</tr>
<tr>
<td>Cubic-I</td>
<td>42.67</td>
<td>0.9408</td>
<td>3</td>
</tr>
<tr>
<td>Cubic-II</td>
<td>45.99</td>
<td>0.9408</td>
<td>4</td>
</tr>
<tr>
<td>General</td>
<td>29.61</td>
<td>0.9725</td>
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<tr>
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<tr>
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<td>0.9522</td>
<td>5</td>
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</table>

### Table III. Summary of Relative Error: Mean And Standard Deviation

<table>
<thead>
<tr>
<th>Mathematical equation of capacity factor</th>
<th>Weibull based approach</th>
<th>Gamma based approach</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relative error</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Mean value</td>
<td>Standard deviation</td>
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<tr>
<td>Linear</td>
<td>16.87</td>
<td>12.20</td>
<td>5</td>
</tr>
<tr>
<td>Quadratic</td>
<td>14.82</td>
<td>9.44</td>
<td>3</td>
</tr>
<tr>
<td>Cubic-I</td>
<td>33.18</td>
<td>10.89</td>
<td>7</td>
</tr>
<tr>
<td>Cubic-II</td>
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<tr>
<td>General</td>
<td>16.16</td>
<td>9.42</td>
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<tr>
<td>Exponential</td>
<td>12.45</td>
<td>8.85</td>
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<tr>
<td>Power Coefficient</td>
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<td>Appr. pow. Coef.</td>
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<td>6</td>
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<tr>
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<td>35.07</td>
<td>11.74</td>
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### Table IV.

<table>
<thead>
<tr>
<th>Weibull based approach</th>
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<table>
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<tr>
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<tr>
<td>polynomial</td>
<td>35.07</td>
<td>11.74</td>
<td>9</td>
</tr>
</tbody>
</table>

**Figure 6.** Representation of all mathematical models of power curve.

**Figure 7.** Shows the relative error of each mathematical equation of capacity factor estimated based on Gamma distribution. It can be clearly seen that the power-coefficient based model has the lowest values of relative error.
comparing with other mathematical models, thus it can be considered as the best model. Whereas the polynomial model is the worst model. This outcome agreed with Ref [4].

IX. CONCLUSION

This paper introduced novel mathematical equations for estimating the capacity factor based on Weibull and Gamma probability density functions. Also, it compared nine mathematical models to find out which is the most appropriate for modelling wind turbine power curves. The accuracy of the proposed models is evaluated using statistical criteria including relative error, mean absolute percentage error, and correlation coefficient. From the results of this study it can be concluded:

1. Among the presented mathematical models of power curve, the General model is well fitted with manufacturers power curves in the range of \([v_{ot}, v_r]\), since it gave the lowest MAPE and the highest value of correlation coefficient.
2. The power-coefficient based model estimated using Weibull and Gamma distributions was the most accurate mathematical model for modelling of wind turbine power curves, since it gave the lowest relative error in estimation of capacity factor.
3. 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

APPENDIX A

WIND TURBINE POWER CURVE MATHEMATICAL MODELS, continued from section VI.

I. 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, 13, 16]:

$$ P_f(v) = P_r \left( \frac{v - v_{ci}}{v_r - v_{ci}} \right) \quad (17) $$

- Weibull Based Approach:

Substituting (17) into (13) and using (3), the capacity factor is given as:

$$ CF = \frac{c(\frac{1}{k} + 1)}{v_r - v_{ci}} \left[ \gamma \left( \frac{v_{ci}}{c}, 1 \right) + \gamma \left( \frac{v_{ci}}{c}, k \right) + v_{ci} \left( e^{-\frac{(v_{ci})^k}{c}} - e^{-\frac{(v_{ci} - v_{ci})^k}{c}} \right) \right] + \frac{v_{ci}^k}{v_r - v_{ci}} \left[ e^{-\frac{(v_{ci})^k}{c}} - e^{-\frac{(v_{ci} - v_{ci})^k}{c}} \right] \quad (18) $$

where $\gamma$ is the lower incomplete gamma function, given as [7, 10, 16, 17]:

$$ \gamma(u, x) = \int_0^x t^{u-1}e^{-t}dt \quad (19) $$

- Gamma Based Approach:

Using equations (8), (13), and (17), the capacity factor as:

$$ CF = \frac{a\beta}{v_r - v_{ct}} \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 1 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) \right] + \frac{v_{ci}}{v_r - v_{ct}} \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 1 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) \right] + \frac{v_{ci}^2}{v_r - v_{ct}} \left[ e^{-\frac{(v_{ci})^k}{c}} - e^{-\frac{(v_{ci} - v_{ci})^k}{c}} \right] \quad (20) $$

J. Quadratic Model

The power output $P_f(v)$ for quadratic model is given as [1, 2, 13, 16, 17]:

$$ P_f(v) = P_r \left( \frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} \right) \quad (21) $$

- Weibull Based Approach:

Substituting (21) into (13) and using (3), the capacity factor is given as:

$$ CF = \frac{c^2(\frac{1}{k} + 1)}{v_r^2 - v_{ci}^2} \left[ \gamma \left( \frac{v_{ci}}{c}, 2 \right) + v_{ci}^2 \left( e^{-\frac{(v_{ci})^k}{c}} - e^{-\frac{(v_{ci} - v_{ci})^k}{c}} \right) \right] + \frac{v_{ci}^2}{v_r^2 - v_{ci}^2} \left[ e^{-\frac{(v_{ci})^k}{c}} - e^{-\frac{(v_{ci} - v_{ci})^k}{c}} \right] \quad (22) $$

- Gamma Based Approach:

Using equations (8), (13), and (21), the capacity factor as:

$$ CF = \frac{a(\alpha + 1)\beta^2}{v_r^2 - v_{ct}^2} \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 2 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) \right] + \frac{v_{ci}^2}{v_r^2 - v_{ct}^2} \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 1 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) \right] + \frac{v_{ci}^2}{v_r^2 - v_{ct}^2} \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 1 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) \right] \quad (23) $$

K. Cubic Type-I Model

The power $P_f(v)$ for the cubic type-I model is given by [10, 13, 16]:

$$ P_f(v) = P_r \left( \frac{v^3}{v_r^3} \right) \quad (24) $$

Weibull Based Approach:
Substituting (24) into (13) and using (3), the capacity factor is given as:

\[ CF = \frac{c_1 \Gamma\left(\frac{3}{c_1} + 1\right)}{v^3} \left[ \nu \left(\frac{\nu c_1}{v^3} \right)^{\frac{3}{c_1}} + 1 \right] - \nu \left(\frac{\nu c_1}{v^3} \right)^{\frac{3}{c_1}} + 1 \] + \left[ e^{-\left(\frac{\nu c_1}{v^3}\right)^{\frac{3}{c_1}}} - e^{-\left(\frac{\nu c_1}{v^3}\right)^{\frac{3}{c_1}}} \right] \] (25)

- **Gamma Based Approach:**

From (8), (13), and (24), the capacity factor as:

\[ CF = \frac{a(\alpha + 1)(\alpha + 2)\beta^3}{v^3} \left[ \nu \left(\frac{\nu c_1}{v^3} \right)^{\alpha + 3} - \nu \left(\frac{\nu c_1}{v^3} \right)^{\alpha + 3} \right] + \left[ \gamma \left(\frac{\nu c_1}{v^3}, \alpha \right) - \gamma \left(\frac{\nu c_1}{v^3}, \alpha \right) \right] \] (26)

**L. Cubic Type-II Model**

The power output \( P_f(v) \) for the cubic type-II model is given by [1, 13]:

\[ P_f(v) = P_r \left(\frac{v^3 - v_{cl}^3}{v_{cl}^3 - v_{cl}^3}\right) \] (27)

- **Weibull Based Approach:**

Substituting (27) into (13) and using (3), the capacity factor is given by:

\[ CF = \frac{c_1 \Gamma\left(\frac{3}{c_1} + 1\right)}{v^3 - v_{cl}^3} \left[ \nu \left(\frac{\nu c_1}{v^3} \right)^{\frac{3}{c_1}} + 1 \right] - \nu \left(\frac{\nu c_1}{v^3} \right)^{\frac{3}{c_1}} + 1 \] + \left[ e^{-\left(\frac{\nu c_1}{v^3}\right)^{\frac{3}{c_1}}} - e^{-\left(\frac{\nu c_1}{v^3}\right)^{\frac{3}{c_1}}} \right] \] (28)

- **Gamma Based Approach:**

Using (8), (13), and (27), the capacity factor as:

\[ CF = \frac{a(\alpha + 1)(\alpha + 2)\beta^3}{v^3 - v_{cl}^3} \left[ \nu \left(\frac{\nu c_1}{v^3} \right)^{\alpha + 3} - \nu \left(\frac{\nu c_1}{v^3} \right)^{\alpha + 3} \right] - \nu \left(\frac{\nu c_1}{v^3} \right)^{\alpha + 3} + \left[ \gamma \left(\frac{\nu c_1}{v^3}, \alpha \right) - \gamma \left(\frac{\nu c_1}{v^3}, \alpha \right) \right] \] (29)

**M. General Model**

The 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, 16]:

\[ P_f(v) = P_r \left(\frac{v^G - v_{cl}^G}{v_{cl}^G - v_{cl}^G}\right) \] (30)

Where \( G \) is the order of power output curve, it is assumed to be 2.055 in this study.

- **Weibull Based Approach:**

Substituting (30) into (13) and using (3), the capacity factor is given as:

\[ CF = \frac{c_1 \Gamma\left(\frac{3}{c_1} + 1\right)}{v^G - v_{cl}^G} \left[ \nu \left(\frac{\nu c_1}{v^G} \right)^{\frac{3}{c_1}} + 1 \right] - \nu \left(\frac{\nu c_1}{v^G} \right)^{\frac{3}{c_1}} + 1 \] + \left[ e^{-\left(\frac{\nu c_1}{v^G}\right)^{\frac{3}{c_1}}} - e^{-\left(\frac{\nu c_1}{v^G}\right)^{\frac{3}{c_1}}} \right] \] (31)

- **Gamma Based Approach:**

By indicating to (8), (13), and (30), the capacity factor is given by:

\[ CF = \frac{\Gamma\left(\frac{3}{c_1} + 1\right)}{c_1} \left[ \nu \left(\frac{\nu c_1}{v^G} \right)^{\alpha + G} - \nu \left(\frac{\nu c_1}{v^G} \right)^{\alpha + G} \right] - \nu \left(\frac{\nu c_1}{v^G} \right)^{\alpha + G} + \left[ \gamma \left(\frac{\nu c_1}{v^G}, \alpha \right) - \gamma \left(\frac{\nu c_1}{v^G}, \alpha \right) \right] \] (32)
N. Exponential Model

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

\[
P_f(v) = \frac{1}{2} \rho A k_p (v^B - v_{ci}^B) \quad (33)
\]

where \( \rho \) is the air density (1.225 kg/m\(^3\)), \( A \) is the swept area (in m\(^2\)), \( k_p \) and \( B \) are constants, given by \((k_p=0.899, B=2.706)\) \([2, 4]\).

- **Weibull Based Approach:**
  Substituting (33) into (13) and using (3), the capacity factor is given as:
  \[
  CF = \frac{\frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B}{v_{ci}^B} \left[ y\left(\frac{v}{v_{ci}}, \alpha + B\right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha + B\right) \right] - \frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B \left[ y\left(\frac{v}{v_{ci}}, \alpha \right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) \right] + \frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B \left[ y\left(\frac{v}{v_{ci}}, \alpha \right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) \right] \quad (34)
  \]

- **Gamma Based Approach:**
  From (8), (13), and (33), the capacity factor as:
  \[
  CF = \frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B \left[ y\left(\frac{v}{v_{ci}}, \alpha + B\right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha + B\right) \right] - \frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B \left[ y\left(\frac{v}{v_{ci}}, \alpha \right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) \right] + \frac{5}{2} \rho A k_p e^{B\left(\frac{v}{v_{ci}}\right)} \left(\frac{v}{v_{ci}}\right)^B \left[ y\left(\frac{v}{v_{ci}}, \alpha \right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) \right] \quad (35)
  \]

O. Power-Coefficient Based Model

A simplified form of the expression given in (33) can be obtained by supposing \( v_{ci} \) equal to zero and \( B \) equal to three which is expressed as \([2, 4, 13]\):

\[
P_f(v) = \frac{1}{2} \rho A c_{p,eq} v^3 \quad (36)
\]

where \( c_{p,eq} \) is a constant equivalent to power coefficient (it is assumed to be 0.40). \([2]\).

- **Weibull Based Approach:**
  Substituting (36) into (13) and using (3), the capacity factor is given as:
  \[
  CF = 2 \rho A c_{p,eq} v^3 \left[ y\left(\frac{v}{v_{ci}}, \alpha + 3\right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha + 3\right) \right] + \left[ y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) - y\left(\frac{v}{v_{ci}}, \alpha\right) \right] \quad (37)
  \]

- **Gamma Based Approach:**
  From (8), (13), and (36), the capacity factor as:
  \[
  CF = \frac{5}{2} \rho A c_{p,eq} \left[ (\alpha + 1)(\alpha + 2) v^3 \right] \left[ y\left(\frac{v}{v_{ci}}, \alpha + 3\right) - y\left(\frac{v_{ci}}{v_{ci}}, \alpha + 3\right) \right] + \left[ y\left(\frac{v_{ci}}{v_{ci}}, \alpha\right) - y\left(\frac{v}{v_{ci}}, \alpha\right) \right] \quad (38)
  \]

P. Approximated Power-Coefficient Based Model

This model can be obtained by approximating equation (36) by assuming \( c_{p,eq} \) equal to the maximum value of power coefficient \( c_{p,max} \) as follow \([2, 4]\):

\[
P_f(v) = \frac{1}{2} \rho A c_{p,max} v^3 \quad (39)
\]

where \( c_{p,max} \) can be directly obtained from the manufacturer data.
Weibull Based Approach:

Substituting (39) into (13) and using (3), the capacity factor is given as:

$$ CF = \frac{\rho A \eta_{\text{m}} c^3}{p_r} \left[ \gamma \left( \frac{v_c}{c}, \frac{3}{k} + 1 \right) - \gamma \left( \frac{v_c}{c} \right)^k, \frac{3}{k} + 1 \right] + \left[ e^{-\left(\frac{v_r}{c}\right)^k} - e^{-\left(\frac{v_{\text{co}}}{c}\right)^k} \right] $$

(40)

Gamma Based Approach:

Using (8), (13), and (39), the capacity factor as:

$$ CF = \frac{0.5 \rho A \eta_{\text{m}}}{p_r} \left[ \alpha (\alpha + 1)(\alpha + 2)^2 \left[ \gamma \left( \frac{v_c}{\beta}, \alpha + 3 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] + \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) - \gamma \left( \frac{v_r}{\beta}, \alpha \right) \right] \right] $$

(41)

Q. Polynomial model

In this model, a second degree polynomial is used to fit the non-linear part, given as [19]:

$$ P_f(v) = P_c(a_2 v^2 + a_1 v + a_0) $$

(42)

where:

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

(43)

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

(44)

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

(45)

Weibull Based Approach:

Substituting (42) into (13) and using (3), the capacity factor is given as:

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

(46)

Gamma Based Approach:

Using (8), (13), and (42), the capacity factor as:

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

(47)
APPENDIX B.

DERIVATION OF CAPACITY FACTORS (CF) BASED ON WEIBULL AND GAMMA DISTRIBUTIONS.

In this section, the derivation of capacity factor of wind turbine generator system according to cubic type-I model given in (25) and (26) will be explained. From (12), (13), and (24) the capacity factor is given as:

$$CF = \frac{1}{v_f^3} \int_{v_{cl}}^{v_f} v^3 f(v) dv + \int_{v_{c}}^{v_{co}} f(v) dv$$  \hspace{1cm} (A.1)

where $f(v)$ is the probability density function of wind speed.

- **Weibull based approach:**

  Substitute Weibull probability density function in (A.1), yield:

$$CF = \frac{1}{v_f^3} \int_{v_{cl}}^{v_f} v^k \frac{k}{c} k^2 e^{-\frac{v^k}{c}} dv + \int_{v_{c}}^{v_{co}} \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} e^{-\left( \frac{v}{c} \right)^k} dv$$  \hspace{1cm} (A.2)

To solve the first integration of (A.2), $I_1$, let

$$t = \left( \frac{v}{c} \right)^k \rightarrow v = ct^{\frac{1}{k}} \rightarrow dv = \frac{c}{k} t^{\frac{1}{k}-1} dt$$

Thus,

$$I_1 = \frac{1}{v_f^3} \int_{v_{cl}^{\frac{1}{k}}}^{v_f^{\frac{1}{k}}} \left( ct^{\frac{1}{k}} \right)^{k^2} e^{-t} \left( \frac{c}{k} \right) t^{\frac{1}{k}-1} dt$$

$$= \frac{c^3}{v_f^3} \int_{\frac{v_{cl}^{\frac{1}{k}}}{c}}^{\frac{v_f^{\frac{1}{k}}}{c}} t^k e^{-t} dt$$

This formula of integration can be divided into two areas, given as:

$$I_1 = \frac{c^3}{v_f^3} \int_{0}^{(v_f/c)^k} t^k e^{-t} dt - \int_{0}^{(v_{cl}/c)^k} t^k e^{-t} dt$$

By comparing this formula with lower incomplete gamma function given by:

$$\gamma(u, x) = \frac{1}{\Gamma(u)} \int_{0}^{x} t^{u-1} e^{-t} dt$$  \hspace{1cm} (A.3)

Thus,

$$I_1 = \frac{c^3 \left( \frac{1}{k} + 1 \right)}{v_f^3} \gamma \left( \left( \frac{v_f}{c} \right)^k, \frac{3}{k} + 1 \right) - \gamma \left( \left( \frac{v_{cl}}{c} \right)^k, \frac{3}{k} + 1 \right)$$  \hspace{1cm} (A.4)

From (A.2) the second integration, $I_2$, given as:

$$I_2 = \int_{v_{c}}^{v_{co}} \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} e^{-\left( \frac{v}{c} \right)^k} dv = \left[ -e^{-\left( \frac{v}{c} \right)^k} \right]_{v_{c}}^{v_{co}}$$

$$= e^{-\left( \frac{v_f}{c} \right)^k} - e^{-\left( \frac{v_{cl}}{c} \right)^k}$$  \hspace{1cm} (A.5)

From (A.4) and (A.5) the capacity factor is given by:

$$CF = \frac{c^3 \left( \frac{1}{k} + 1 \right)}{v_f^3} \gamma \left( \left( \frac{v_f}{c} \right)^k, \frac{3}{k} + 1 \right) - \gamma \left( \left( \frac{v_{cl}}{c} \right)^k, \frac{3}{k} + 1 \right) + \left[ e^{-\left( \frac{v_f}{c} \right)^k} - e^{-\left( \frac{v_{cl}}{c} \right)^k} \right]$$
Gamma Based Approach:

Substitute Gamma probability density function in (A.1), yield:

\[ CF = \frac{1}{\beta^2} \int \frac{1}{\Gamma(\alpha)} \beta^a \int_{v_{ci}}^{v_f} v^{\alpha+2} e^{-\frac{v}{\beta}} dv + \int_{v_{ci}}^{v_f} \frac{v^{\alpha-1}}{\Gamma(\alpha)} e^{-\frac{v}{\beta}} dv \]  \hspace{1cm} (A.6)

To solve the first integration of (A.6), \( I_1 \), let:

\[ t = \frac{v}{\beta} \rightarrow v = \beta t \rightarrow dv = \beta dt \]

Thus:

\[ I_1 = \frac{1}{\beta^2} \int \frac{1}{\Gamma(\alpha)} \beta^a \int_{t(v_{ci}/\beta)}^{t(v_f/\beta)} t^{\alpha+2} e^{-t} dt \]

By dividing this formula of integration into two areas, as follow:

\[ I_1 = \frac{\beta^3}{\beta^{2+\alpha}} \left[ \int_0^{v_{ci}/\beta} t^{\alpha+2} e^{-t} dt - \int_0^{v_f/\beta} t^{\alpha+2} e^{-t} dt \right] \]

Compare this formula with lower incomplete gamma function given in (A.3), yield:

\[ I_1 = \frac{\beta^3}{\beta^{2+\alpha}} \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 3 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 3 \right) \]  \hspace{1cm} (A.7)

The second integration of (A.6), is given as:

\[ I_2 = \int_{v_{ci}}^{v_f} \frac{v^{\alpha-1}}{\Gamma(\alpha)} e^{-\frac{v}{\beta}} dv \]

This formula can be divided into two areas, given as:

\[ I_2 = \int_0^{v_{ci}/\beta} t^{\alpha-1} e^{-t} dt - \int_0^{v_f/\beta} t^{\alpha-1} e^{-t} dt \]

Compare this formula with lower incomplete gamma function given in (A.3), yield:

\[ I_2 = \gamma \left( \frac{v_{ci}}{\beta}, \alpha - 1 \right) \]  \hspace{1cm} (A.8)

From (A.7) and (A.8) the capacity factor is given by:

\[ CF = \frac{a(\alpha+1)(\alpha+2)\beta^3}{v_f^3} \left[ \gamma \left( \frac{v_f}{\beta}, \alpha + 3 \right) - \gamma \left( \frac{v_{ci}}{\beta}, \alpha + 3 \right) \right] + \left[ \gamma \left( \frac{v_{ci}}{\beta}, \alpha \right) - \gamma \left( \frac{v_f}{\beta}, \alpha \right) \right] \]

where:

\[ \Gamma(\alpha + 1) = a\Gamma(\alpha) \]
### TABLE IV. WIND TURBINES DATABASE

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<th>Model</th>
<th>Rated power (kW)</th>
<th>Rotor diameter (m)</th>
<th>Tower height (m)</th>
<th>Cut-in speed (m/s)</th>
<th>Rated speed (m/s)</th>
<th>Cut-out speed (m/s)</th>
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