Influence of Different Wind Turbine Types Failures on Expected Energy Production

Danijel Topić; Damir Šljivac
Faculty of Electrical Engineering
Josip Juraj Strossmayer University of Osijek
Osijek, Croatia
daniel.topic@etfos.hr; damir.slijivac@etfos.hr

Abstract—The paper presents a basic stochastic model of the influence of the failure statistics of the different wind turbine types and its components on the expected energy production. Based on the reliability performance surveys conducted in several European countries [1] the influence of the most unreliable component, the gearbox in particular has been examined taking into account the different behavior of the different wind turbine types (with and without gearbox) at different wind speeds with associated Weibull probability distribution. The load factors and expected energy not supplied has been calculated for two different commercial wind turbine types and compared.

Keywords—wind speed, Weibull distribution, wind turbine types, component failures, expected energy production.

I. INTRODUCTION

In order to determine the best possible option between numerous possible commercial wind turbines of same or similar size for the micro-location the usual approach is to consider the cost-benefit of the investment costs and the expected revenue from the location/country renewable (i.e. wind in particular) incentive scheme based on the tariffs and expected wind turbine energy production at the particular micro-location. Due to the tremendous advance in the technology and the wind power market there was a limited statistical validity data at first but that is changing recently due the increased number of installed power plants and their continuous long-term performance [1]. This enabled the authors to start investigating the appropriate stochastic models for improved cost-benefit analysis when choosing the best wind turbine type by taking into account not only the expected behavior and power output of the wind turbine but also the contribution of the wind turbine components expected failure duration and frequency.

II. WIND THEORY AND WEIBULL DISTRIBUTION

A. Wind power and wind energy

Due to the earth’s rotation, every movement in the Northern Hemisphere is directed toward the right. This phenomenon of deformation force is known as the Coriolis force. In the Northern Hemisphere the wind has a counter-clockwise direction of rotation as we approach the area of low pressure. In the Southern Hemisphere the wind has a clockwise direction around the area of low pressure.

Wind turbine gains its input power by converting the wind force into the rotary force which acts at the rotor blades. The amount of energy transferred by the wind on the rotor depends on the area of a circle swept by the spinning rotor, wind speed and air density. At normal atmospheric pressure and temperature of 15°C the air weighs about 1.225 kg/m³, but with increasing humidity, the density also increases. It also applies that the air is denser when it is colder rather than when it is warmer. At high altitudes the air pressure is lower, and the air is thinner.

Wind turbine distorts the wind path before the wind reaches the rotor blades. That means that you can’t use all the available wind energy. Wind energy is the kinetic energy which is dependent on the square of wind speed. The amount of air molecules that are moving through some area A during a time t is the power of the wind. For wind power it can be written [1]:

\[ P = \frac{0.5 \rho v^2 A}{t} = \frac{0.5 \rho V v^2}{t} \]  

(1)

Where:

- \( \rho \) – Air density
- \( V \) – Air volume of a cylinder with base area \( A \) and length \( l \).

Replacing the volume \( V \) in expression (1) with the product of area \( A \) and length \( l \), we obtain the expression for wind power:

\[ P = \frac{0.5 \rho V v^2}{t} = \frac{0.5 \rho A l^2}{t} = 0.5 \rho A v^3 \]  

(2)
From the expression (2) it can be seen that the wind power depends on the third potency of the wind speed, air density and swept area $A$.

**B. Wind speed distribution**

To describe the wind speed a number of different distributions have been tried, but only two of them are used to describe the wind speed. These are the Weibull and Rayleigh distributions.

![Example wind speed frequency calculated using Weibull and Rayleigh distribution](image)

These two distributions give poor estimate of power for low mean wind speeds. At the higher wind speeds, these two distributions give sufficient estimate of wind speed. Rayleigh distribution is simpler because it depends only on one parameter, that is an average wind speed. Rayleigh distribution is represented by expression (3):

$$F(v) = \Delta v \frac{\pi}{2 \nu_a} \exp \left[ -\pi \left( \frac{v}{\nu_a} \right)^2 \right]$$  \hspace{1cm} (3)

Where:

- $F(v)$ – frequency of occurrence with each wind speed $v$
- $\nu$ – center of bin $\Delta v$
- $\Delta v$ – width of class or bin
- $\nu_a$ – average wind speed

Weibull distribution is described by two parameters, the shape parameter $k$ and the scale parameter $c$. The parameter $k$ is dimensionless parameter, while the measure unit of the scale parameter $c$ is m/s. Weibull distribution is described by equation (4):

$$F(v) = \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right]$$  \hspace{1cm} (4)

Figure 2 shows examples of the Weibull and Rayleigh distribution.

**III. SIMPLIFIED STOCHASTIC MODEL OF WIND TURBINE**

For the measurement location Borajica the wind speed measurement results are known. Data for the wind speeds are obtained according to [2]. Wind speeds are measured in 10-minutes intervals during the period from 1 of June to 29 of August 2008.

Using MATLAB script and obtained wind speed data’s [2] the Weibull parameters, the scale parameter and shape parameter, which describe the wind behavior for particular location, can be determined.

MATLAB takes into account the results of wind speed measurements at 10 minute intervals and using script text_wbl it adjusts them to the Weibull distribution giving the shape and scale parameter.

Does the calculation of Weibull parameters from the MS Excel-file 'Mjerenja_brzine_vjetra.xls'. Spreadsheet 'Borajica', for 4 selected wind speeds {'010a','010a','044a','046a'}

After determining the $k$ and $c$ parameters of Weibull distribution, the probability of selected wind speeds and thus probability of selected WT power can be determined.

From the measurement data for the height of 46 m on the location Borajica and for the average wind speeds taken in measurement period, the following parameters of the Weibull distribution have been obtained: $k=1,7645$ and $c=7,934$.

Now, we get the table for the particular probability of wind speed classes (bins) for the known Weibull parameter $k$ and $c$.

**TABLE I. PROBABILITIES OF PARTICULAR WIND SPEED CLASSES**

<table>
<thead>
<tr>
<th>Class, $i$</th>
<th>Wind speed range</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 1</td>
<td>0,023241</td>
</tr>
<tr>
<td>2</td>
<td>1 - 2</td>
<td>0,057275</td>
</tr>
<tr>
<td>3</td>
<td>2 - 3</td>
<td>0,079516</td>
</tr>
<tr>
<td>4</td>
<td>3 - 4</td>
<td>0,093174</td>
</tr>
<tr>
<td>5</td>
<td>4 - 5</td>
<td>0,099419</td>
</tr>
<tr>
<td>6</td>
<td>5 - 6</td>
<td>0,099427</td>
</tr>
<tr>
<td>7</td>
<td>6 - 7</td>
<td>0,099403</td>
</tr>
<tr>
<td>8</td>
<td>7 - 8</td>
<td>0,08653</td>
</tr>
<tr>
<td>9</td>
<td>8 - 9</td>
<td>0,076292</td>
</tr>
<tr>
<td>10</td>
<td>9 - 10</td>
<td>0,065154</td>
</tr>
<tr>
<td>11</td>
<td>10 - 11</td>
<td>0,054042</td>
</tr>
<tr>
<td>12</td>
<td>11 - 12</td>
<td>0,043626</td>
</tr>
<tr>
<td>13</td>
<td>12 - 13</td>
<td>0,034332</td>
</tr>
<tr>
<td>14</td>
<td>13 - 14</td>
<td>0,026373</td>
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<tr>
<td>15</td>
<td>14 - 15</td>
<td>0,019792</td>
</tr>
<tr>
<td>16</td>
<td>15 - 16</td>
<td>0,014528</td>
</tr>
<tr>
<td>17</td>
<td>16 - 17</td>
<td>0,010437</td>
</tr>
<tr>
<td>18</td>
<td>17 - 18</td>
<td>0,007343</td>
</tr>
<tr>
<td>19</td>
<td>18 - 19</td>
<td>0,005662</td>
</tr>
<tr>
<td>20</td>
<td>19 - 20</td>
<td>0,003422</td>
</tr>
<tr>
<td>21</td>
<td>20 - 21</td>
<td>0,002268</td>
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<tr>
<td>22</td>
<td>21 - 22</td>
<td>0,001476</td>
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<tr>
<td>23</td>
<td>22 - 23</td>
<td>0,000942</td>
</tr>
<tr>
<td>24</td>
<td>23 - 24</td>
<td>0,000391</td>
</tr>
<tr>
<td>25</td>
<td>24-25</td>
<td>0,000364</td>
</tr>
<tr>
<td>26</td>
<td>25 &lt;</td>
<td>0,000525</td>
</tr>
</tbody>
</table>
To consider the impact of wind stochastic on the WT produced electricity two real world WT's, Turbine A (2MW) and Turbine B (2MW) were chosen. These WT's are very similar, the only difference between them, which we are taking into account, is that the turbine B is equipped with the gear mechanism for transforming power, while the turbine A does not have the gear mechanism. Another difference that will be also taken into account is the difference in their power output curves. Figure 3 shows the dependencies of output power on wind speed for given wind turbines.

Now we can get the probability table of individual powers (states) of both wind turbines for the parameters and $k=1.7645$ and $c=7934$ of the Weibull distributions, which describes the wind behavior.

State 1 represents those wind speeds for which the WT output power $P=0$. This is state when the wind speed lies between $0 \text{m/s}$ and the cut-in wind speed $v_{ci}$, and when the wind speed lies above the WT's cut-out wind speed $v_{co}$. The probability that the WT output power $P=0$ is equal to the sum of the probability of wind speed between $0 \text{m/s}$ and the cut-in speed $v_{ci}$, and probability when the wind speed is above the WT cut-out wind speed $v_{co}$, and can be determined according to expression:

$$p_1 = \sum_{P=0} p_i = \sum_{v} \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $0 \leq v < v_{ci}$ \& $v_{co} \leq v$.

State 2 represents those wind speeds for which the WT provides the output power in range of $0<P<20\%P_r$. The probability that the WT output power is in the range $0<P<20\%P_r$ is equal to the sum of the probabilities of wind speeds for which the WT achieves the power in that range and can be determined according to expression:

$$p_2 = \sum_{P=0.2} p_i = \sum_{v} \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $v(P=0)<v<P=0.2P_r$.

State 3 represents those wind speeds for which the WT provides the output power in range of $20\%P_r<P<40\%P_r$. The probability that the WT output power is in the range $20\%P_r<P<40\%P_r$ is equal to the sum of the probabilities of wind speeds for which the WT achieves the power in that range and can be determined according to expression:

$$p_3 = \sum_{P=0.2} p_i = \sum_{v} \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $v(P=0,2P_r)<v<P=0,4P_r$.

State 4 represents those wind speeds for which the WT provides the output power in range of $40\%P_r<P<80\%P_r$. The probability that the WT output power is in the range $40\%P_r<P<80\%P_r$ is equal to the sum of the probabilities of wind speeds for which the WT achieves the power in that range and can be determined according to expression:

$$p_5 = \sum_{P=0.4} p_i = \sum_{v} \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $v(P=0,4P_r)<v<P=0,8P_r$.

State 5 represents those wind speeds for which the WT provides the output power in range of $80\%P_r<P<100\%P_r$. The probability that the WT output power is in the range $80\%P_r<P<100\%P_r$ is equal to the sum of the probabilities of wind speeds for which the WT achieves the power in that range and can be determined according to expression:

$$p_5 = \sum_{P=0.8} p_i = \sum_{v} \Delta v \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $v(P=0,8P_r)<v<P=1.0P_r$.

State 6 represents those wind speeds for which the WT provides the rated output power. The probability that the WT output power equals rated power, is equal to the sum of the probabilities of wind speeds between rated speed $v_r$ and cut-out speed $v_{co}$, and can be determined according to expression:

$$p_6 = \sum_{v} \frac{k}{c} \left( \frac{v}{c} \right)^{c-1} e^{-\left( \frac{v}{c} \right)^c};$$

for $v_r \leq v < v_{co}$.
The calculated probabilities values for output power of each WT according to expressions (5) – (10) are assigned to the respective states of the stochastic model as shown in Tables 2 and 3.

### TABLE II. Stochastic Model of Turbine B

<table>
<thead>
<tr>
<th>State (i)</th>
<th>Power range [%P_d]</th>
<th>Probability (p_i)</th>
<th>Wind speed range (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0,205937</td>
<td>0&lt;v&lt;3,5 &amp; 25&lt;v</td>
</tr>
<tr>
<td>2</td>
<td>0&lt;qv&lt;20</td>
<td>0,315718</td>
<td>3,5&lt;v&lt;6,7</td>
</tr>
<tr>
<td>3</td>
<td>20&lt;qv&lt;40</td>
<td>0,138255</td>
<td>6,5&lt;v&lt;8</td>
</tr>
<tr>
<td>4</td>
<td>40&lt;qv&lt;80</td>
<td>0,161518</td>
<td>8,5&lt;v&lt;10</td>
</tr>
<tr>
<td>5</td>
<td>80&lt;qv&lt;100</td>
<td>0,087903</td>
<td>10,8&lt;v&lt;13</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0,092596</td>
<td>13&lt;v&lt;25</td>
</tr>
</tbody>
</table>

### TABLE III. Stochastic Model of Turbine A

<table>
<thead>
<tr>
<th>State (i)</th>
<th>Power range [%P_d]</th>
<th>Probability (p_i)</th>
<th>Wind speed range (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0,160558</td>
<td>0&lt;v&lt;3 &amp; 25&lt;v</td>
</tr>
<tr>
<td>2</td>
<td>0&lt;qv&lt;20</td>
<td>0,340258</td>
<td>3&lt;v&lt;6,5</td>
</tr>
<tr>
<td>3</td>
<td>20&lt;qv&lt;40</td>
<td>0,133040</td>
<td>6,5&lt;v&lt;8</td>
</tr>
<tr>
<td>4</td>
<td>40&lt;qv&lt;80</td>
<td>0,169825</td>
<td>8&lt;v&lt;10,5</td>
</tr>
<tr>
<td>5</td>
<td>80&lt;qv&lt;100</td>
<td>0,103621</td>
<td>10,5&lt;v&lt;13</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0,092596</td>
<td>13&lt;v&lt;25</td>
</tr>
</tbody>
</table>

Figure 4 graphically shows the probabilities of particular states for stochastic models of both wind turbines.

![Graph showing probability of WT power](image)

Figure 4. The probability of WT power

Expected annual energy production of wind turbine can be calculated using the following expression:

\[
W = \sum_{i=1}^{n} p_i \cdot P_{m_i} \cdot 8760 = \sum_{i=1}^{n} p_i \cdot P_{m_i} \cdot 8760 \tag{11}
\]

Where:
- \(W\) - expected energy production
- \(P_{m_i}\) - mean power of \(i\)-th state
- \(p_i\) - probability of \(i\)-th state

It is important to mention that the expression (11) applies to the use case when no other outages due to component failure of a wind turbine were taken into account.

### TABLE IV. Expected Load Factor – Without Expected Downtime

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Load factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURBINE A</td>
<td>36.17</td>
</tr>
<tr>
<td>TURBINE B</td>
<td>34.15</td>
</tr>
</tbody>
</table>

Expected load factor for both WT is shown in Table IV. Load factor can be calculated by:

\[
LF = \frac{W}{8760 \cdot P_i} = \frac{\sum_{i=1}^{n} p_i \cdot P_{m_i} \cdot 8760}{8760 \cdot P_i} \tag{12}
\]

According to [2] the statistical data for the frequency and duration of interruptions of individual WT components were obtained, as shown in Table 5. The data sources used in [2] are:

- Driftpupföljning av vindkraftverk, årsrapport (Wind power operations, yearly report), Sweden – A early published report from Elforsk, which concerns statistical data of performance, failures and downtimes for almost all wind power plants situated in Sweden.
- Felanalys (Failure analysis), Sweden – A database of all reported failures in Sweden since 1989 maintained by Swedpower AB. The database was created in 1997 but also contains failures that occurred prior to the starting date as far back as 1989. This database is also a part of the source for Driftpupföljning av vindkraft, årsrapport but it contains more information about the failures compared to what is published in the yearly report.
- Tuuliviihdon tuotantotilastot Vuosiraportti (Wind power production statistics yearly report), Finland – A yearly published report from VTT, which concerns statistical data of performance, failures and downtimes for wind power plants situated in Finland.
- Windenergie Report Deutschland (Wind energy report Germany), Germany – A yearly published report from Institut für Solare Energieversorgungstechnik (ISE), which concerns statistical data of performance, failures and downtimes for wind power plants situated in Germany.

According to Table 5 it can be obtained that the average downtime frequency of WT due to component failure is \(f=1,207\text{n/yr/turbine}\), and the average downtime duration (unavailability) because odd WT component failure is \(U=146,25\text{h/yr/turbine}\).

If the wind turbine is constructed without the gear mechanism, then for this turbine according to Table 5 we can get following data’s:

- \(f=1,102\text{n/yr/turbine}\), while the downtime duration of wind turbine (unavailability) is: \(U=96,45\text{h/yr/turbine}\).
From previously obtained data can be seen that wind turbine which is build up with a gear mechanism does not have much more failures per year than the wind turbine which is build up without the gear mechanism, but in that case the WT downtime durations are significantly different.

Expected energy not supplied due to failures can be calculated as follows:

\[ W' = \sum_{i=1}^{6} p_i \cdot P_{ref} \cdot U \]  

(13)

Where:
- \( W' \) – expected unsupplied energy
- \( U \) – unavailability
- \( P_{ref} \) – mean power of \( i \)-th state
- \( p_i \) – probability of \( i \)-th state

For wind turbine containing the gear mechanism (Turbine B) the expected unsupplied energy according to (13) is:

\[ W' = \sum_{i=1}^{6} p_i \cdot P_{ref} \cdot U = \sum_{i=1}^{6} p_i \cdot P_{ref} \cdot 146.25 \]  

(14)

For wind turbine without the gear mechanism (Turbine A) the expected unsupplied energy according to (8) is:

\[ W' = \sum_{i=1}^{6} p_i \cdot P_{ref} \cdot U = \sum_{i=1}^{6} p_i \cdot P_{ref} \cdot 96.45 \]  

(15)

Expected load factor for both WT due to failures is shown in table VI. Load factor can be calculated by:

\[ LF = \frac{W - W'}{W'} = \frac{\sum_{i=1}^{6} p_i \cdot P_{ref} \cdot (U - (8760 \cdot U))}{W'} \]  

(16)

In figure 5 the comparison of load factors for both turbines is shown.

### Table VI: Expected Load Factor - With Expected Downtime

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Load factor [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURBINE A</td>
<td>35.77</td>
</tr>
<tr>
<td>TURBINE B</td>
<td>33.38</td>
</tr>
</tbody>
</table>
IV. CONCLUSION

This paper has presented comparison of two similar real wind turbines. Comparison of expected annual energy production without influence of failures and with influence of failures is shown. Also the stochastic model of wind turbine dependent on wind speed has been developed with and without effects of failures on expected energy production and load factor. The model has been applied on two types of turbine: with and without gearbox, as it is the most unreliable component according to the statistical data used [2]. Future research should include development of complex reliability model for wind turbine including both wind behavior and failures using Monte Carlo simulation.

REFERENCES