Influence of Different Wind Turbine Types Failures on Expected Energy Production

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***Abstract*—The paper presents a basic stochastic model of the influence of the failure statistics of the different wind turbine types and it's 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 reliability 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.

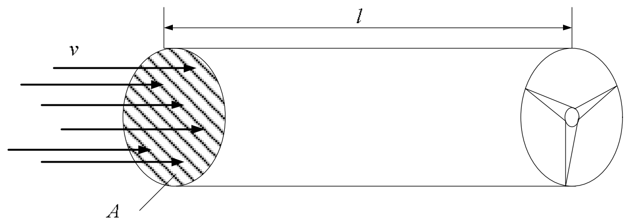

Figure 1. Volume flow of air V through a area A

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]:

$$P = \frac{0,5mv^2}{t} = \frac{0,5\rho V v^2}{t} \tag{1}$$

Where:

- ρ – 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:

$$P = \frac{0,5\rho V v^2}{t} = \frac{0,5\rho A l v^2}{t} = 0,5\rho A v^3 \tag{2}$$

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.

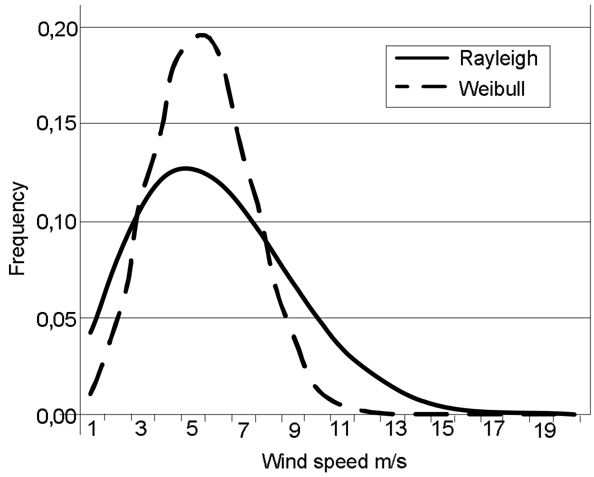

Figure 2. Example wind speed frequency calculated using Weibull and Rayliegh distribution [1]

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 a average wind speed. Rayleigh distribution is represented by expression (3):

$$F(v) = \Delta c \frac{\pi}{2} \frac{v}{v_a} \exp\left[-\frac{\pi}{4} \left(\frac{v}{v_a} \right)^2 \right] \tag{3}$$

Where:

- $F(v)$ – frequency of occurrence with each wind speed v
- v – center of bin Δv
- Δv – width of class or bin
- v_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):

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

Figure 2 shows examples of the Weibull and Rayleigh distribution.

III. Simplified Stochastic Modet 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 *test_wbl* 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 {'ff10a','ff30a','ff44a','ff46a'}

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

Class, i	Wind speed range	Probability
1	0 - 1	0,023241
2	1 - 2	0,057275
3	2 - 3	0,079516
4	3 - 4	0,093174
5	4 - 5	0,099419
6	5 - 6	0,099472
7	6 - 7	0,094703
8	7 - 8	0,08653
9	8 - 9	0,076292
10	9 - 10	0,065154
11	10 - 11	0,054042
12	11 - 12	0,043626
13	12 - 13	0,034332
14	13 - 14	0,026371
15	14 - 15	0,019792
16	15 - 16	0,014528
17	16 - 17	0,010437
18	17 - 18	0,007343
19	18 - 19	0,005062
20	19 - 20	0,003422
21	20 - 21	0,002268
22	21 - 22	0,001476
23	22 - 23	0,000942
24	23 - 24	0,000591
25	24-25	0,000364
26	25<	0,000525

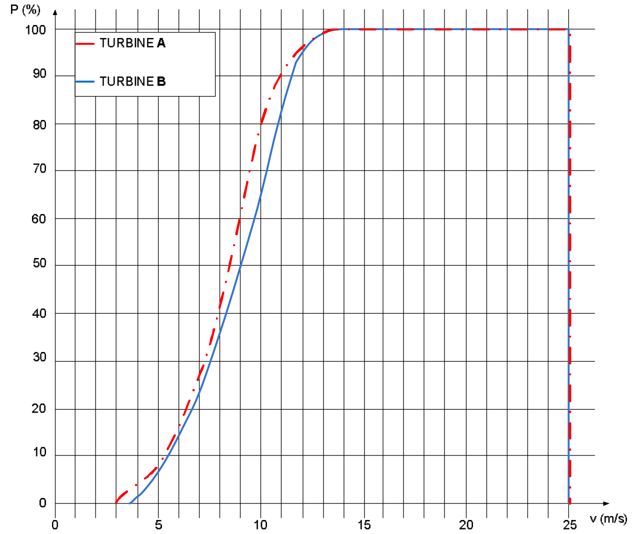

Figure 3. Power curve for wind turbines (Turbine A and Turbine B)

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= 7,934 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 0m/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 0m/s and the cut-in speed v_{ci}, and probability when the wind speed is above the WT cut-out speed v_{co}, and can be determined according to expression:

$$p_1 = \sum p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (5)$$
$$for \quad 0 \le v_i < v_{ci} \quad \& \quad v_{co} \le v_i$$

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:

$$p_2 = \sum_{P=0}^{P=0.2P_n} p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (6)$$
$$for \quad v(P=O) < v_i < v\left(P=0,2P_n\right)$$

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:

$$p_3 = \sum_{P=0,2P_n}^{P=0,4P_n} p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (7)$$
$$for \quad v(P=0,2P_n) \le v_i < v\left(P=0,4P_n\right)$$

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:

$$p_4 = \sum_{P=0,4P_n}^{P=0,8P_n} p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (8)$$
$$for \quad v(P=0,4P_n) \le v_i < v\left(P=0,8P_n\right)$$

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:

$$p_5 = \sum_{P=0,8P_n}^{P=1,0P_n} p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (9)$$
$$for \quad v(P=0,8P_n) < v_i < v\left(P=1,0P_n\right)$$

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:

$$p_6 = \sum p_i = \sum \Delta v \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k}; \qquad (10)$$
$$for \quad v_r \le v_i < v_{co}$$

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

State (i)	Power range [% P_n]	Probability (p_i)	Wind speed range (m/s)
1	0	0,205927	0<v<3,5 & 25<v
2	0<P<20	0,313718	3,5≤v<6,7
3	20<P<40	0,138235	6,7≤v<8,3
4	40<P<80	0,161518	8,3≤v<10,8
5	80<P<100	0,087903	10,8≤v<13
6	100	0,092596	13 ≤v≤25

TABLE III. STOCHASTIC MODEL OF TRUBINE A

State (i)	Power range [% P_n]	Probability (p_i)	Wind speed range (m/s)
1	0	0,160558	0<v<3 & 25<v
2	0<P<20	0,340258	3≤v<6,5
3	20<P<40	0,133040	6,5≤v<8
4	40<P<80	0,169825	8≤v<10,5
5	80<P<100	0,103621	10,5≤v<13
6	100	0,092596	13 ≤v≤25

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

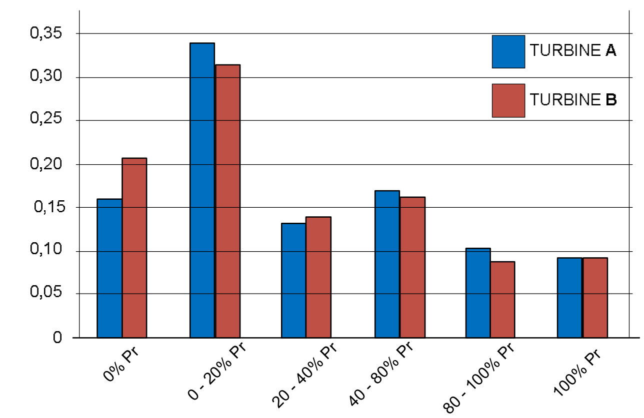

Figure 4. The probability of WT power

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

$$W = \sum_{i=1}^{n} p_i \cdot P_{sri} \cdot 8760 = \sum_{i=1}^{6} p_i \cdot P_{sri} \cdot 8760 \qquad (11)$$

Where:

- W' – expected energy production
- P_{sri} – 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

Turbine	Load factor [%]
TURBINE A	36,17
TURBINE B	34,15

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

$$LF = \frac{W}{8760 \cdot P_r} = \frac{\sum_{i=1}^{n} p_i \cdot P_{sri} \cdot 8760}{8760 \cdot P_r} \qquad (12)$$

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:

- Driftuppföljning 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 Driftuppföljning av vindkraft, årsrapport but it contains more information about the failures compared to what is published in the yearly report.
- Tuulivoiman 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 (ISET), 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=1,207n/yr/turbine, and the average downtime duration (unavailability) because odd WT component failure is U=146,25h/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=1,102n/yr/turbine, while the downtime duration of wind turbine (unavailability) is: U=96,45h/yr/turbine.

TABLE V. STATISTICAL DATA FOR THE FREQUENCY AND DURATION OF WT DOWNTIME

Component	SWEDEN		FINLAND		GERMANY		Average	
	Average downtime per year per turbine [h/yr/turb]	Average number of failures per year per turbine [n/yr/turb]	Average downtime per year per turbine [h/yr/turb]	Average number of failures per year per turbine [n/yr/turb]	Average downtime per year per turbine [h/yr/turb]	Average number of failures per year per turbine [n/yr/turb]	Average downtime per year per turbine [h/yr/turb]	Average number of failures per year per turbine [n/yr/turb]
Hub	0,00	0,001	0,20	0,010	n/a	0,010	0,10	0,007
Blades/ pitch	4,70	0,052	50,30	0,200	n/a	0,220	27,50	0,157
Generator	4,50	0,021	10,40	0,080	n/a	0,050	7,45	0,050
Electric system	7,20	0,067	15,20	0,110	n/a	0,490	11,20	0,222
Control system	9,20	0,050	4,00	0,100	n/a	0,260	6,60	0,137
Drive train	1,20	0,004	0,00	0,000	n/a	0,050	0,60	0,018
Sensors	2,70	0,054	4,90	0,120	n/a	0,160	3,80	0,111
Gears	11,60	0,045	88,00	0,150	n/a	0,120	49,80	0,105
Mechanical brakes	0,60	0,005	6,50	0,040	n/a	0,100	3,55	0,048
Hydraulics	2,60	0,061	30,60	0,360	n/a	0,210	16,60	0,210
Yaw system	6,60	0,026	15,40	0,100	n/a	0,130	11,00	0,085
Structure	0,60	0,006	15,50	0,090	n/a	0,070	8,05	0,055

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:

$$W' = \sum_{i=1}^{n} p_i \cdot P_{sri} \cdot U \tag{13}$$

Where:

- W' – expected unsupplied energy
- U – unavailability
- P_{sri} – mean power o 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:

$$W' = \sum_{i=1}^{n} p_i \cdot P_{sri} \cdot U = \sum_{i=1}^{n=6} p \cdot P_{sri} \cdot 146,25 \tag{14}$$

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

$$W' = \sum_{i=1}^{n} p_i \cdot P_{sri} \cdot U = \sum_{i=1}^{n=6} p \cdot P_{sri} \cdot 96,45 \tag{15}$$

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

$$LF = \frac{W - W'}{8760 \cdot P_r} = \frac{\sum_{i=1}^{n} p_i \cdot P_{sri} \cdot \left(8760 - U\right)}{8760 \cdot P_r} \tag{16}$$

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

TABLE VI. EXPECTED LOAD FACTOR – WITH EXPECTED DOWNTIME

Turbine	Load factor [%]
TURBINE A	35,77
TURBINE B	33,58

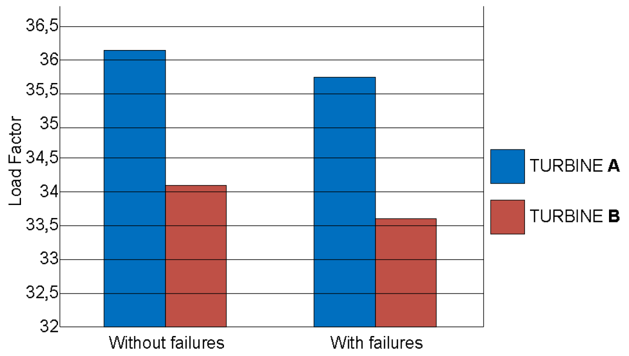

Figure 5. Comparison of LF for both turbines

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.

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