The wind energy system performance overview: capacity factor vs. technical efficiency

Ciprian Nemes [1], Florin Munteanu

***Abstract*—**The main objective of the paper is to develop a probabilistic model for capacity factor and technical efficiency estimation for a wind turbine located in a specific area, model based on the output power distribution of wind turbine. This model was applied for a wind turbine located to a region in the North-East of Romania, the model results being validated by results from Monte-Carlo simulation. Finally, the model was used to evaluate the effects of wind turbine generator parameters, for a given wind profile, on the capacity factor and technical efficiency values.

***Keywords*—** wind energy, Weibull distribution, output power distribution, capacity factor, technical efficiency.

I. Introduction

ENVIRONMENTAL factors such as global warming and pollution have heightened the need to introduce into the generation mix a greater percentage of renewable sources. In the last time, wind power has drawn much attention as a promising renewable energy resource, which has shown some prospects in curtailing fuel consumption and reducing the emission of pollutants into the atmosphere. Unlike other renewable energy sources, wind energy has become competitive with conventional power generation sources and therefore application of wind turbine generators has the most growth among other sources. Wind is one of fastest growing energy source and is considered as an important alternative to conventional power generating sources.

The energy production from a wind turbine or a wind park, in a specific location, depends by many factors. The main factors include the wind speed conditions from the area, and most importantly, the characteristics of the wind turbine generator itself, particularly the cut-in, rated and cut-off wind speed parameters. The output power of a wind turbine generator does not vary linearly with the wind speed. The output power increases with the wind speed between the cut-in speed and the rated wind speed, after that the power output remains constant at the rated power level, until the cut-out speed, when the turbine is stopped for safety reasons [1,2]. Different types of wind turbines are commercially available on the market. It is therefore desirable to select a wind turbine which is best suited for a particular location in order to obtain a maximum power from power transposed by the wind. These important aspects bring suitability concerns regarded by the energy potential of a specific location and the selection of the suitable wind turbine for a specific wind profile.

A measure of the suitability of wind turbine to a specific location is given by the capacity factor and efficiency values. The capacity factor is defined as the ratio of the expected output power over a period of time to the rated power of wind turbine generator. All power plants have capacity factors, and they vary depending on resource, technology and purpose. Typical wind power capacity factors are 20-40%, with values at the upper end of the range in particularly favourable areas [4]. The capacity factor is not an indicator of efficiency. A measure of turbine efficiency is the power coefficient. This coefficient indicates how efficiently a turbine converts the wind energy into electricity. This coefficient varies with the wind speed [2]. Efficiency is the expected power coefficient, over a period of time, and is defined as ratio of the useful output energy to the input wind energy.

In literature are presented various approaches for capacity factor and efficiency estimations, mostly obtained from simulations techniques based on wind speed data [5,6] and sometimes from computational models [1,7], that need numerical integration techniques or some approximations.

Having in view the stochastic nature of the primary energy, the probabilistic methods can be proper solutions for capacity factor and efficiency evaluations. In the paper, a probabilistic model is developed to evaluate these values and to analyze the dependence of the wind turbine generator characteristics. The proposed model is based on probability density function of output power generated by the wind turbine. In order to validate the model, the results model were compared with the results of the other model, namely with Monte Carlo technique. The model has the advantage that can be easily implemented in computer programs and require a computing time considerably less than in the case of simulation or numerical methods.

Selection of the optimal wind turbine was discussed in different manner in various papers, among which the maximization of capacity factor and/or efficiency [5,6,7]. The choice of turbine involves choosing parameters that lead to maximizing these factors. The turbines must be chosen with the parameters that match those of wind profile area. Based on these issues, in the paper, a numerical analysis is realized to have a comparison between effects of different parameters of the wind turbine generator on capacity factor and efficiency values, analyzing the importance and weight of each parameter of those values.

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II. WIND AND OUTPUT POWER WIND TURBINE PROBABILISTIC CHARACTERISTICS

The output power from a wind turbine depends by the availability of the energy source, namely the wind speed and the power-wind characteristics of the wind turbine generator.

A. *Probabilistic model of wind speed*

Wind is a turbulent movement mass of air resulting from the differential pressure at different locations on the earth surface. One of the main characteristics of wind is that it is highly variable in time and space, the variation of wind exists from instantaneous, hourly, daily to seasonal, and its properties vary from one location to another. The wind property of interest in the power generation problems is the wind speed probabilistic model.

The speed of the wind is continuously changing, making it desirable to be described by the probabilistic models. The probability density function of wind speed is important in numerous wind energy applications. A large number of studies have been published in scientific literature related to wind energy, which propose the use of a variety of functions to describe wind speed frequency distributions [9],[10]. The conclusion of these studies is that the Weibull distribution of two parameters may be successfully utilized to describe the principle wind speed variation. The Weibull probability density and cumulative distribution function are given by:

$$f_W(v) = \frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right];\ F_W(v) = 1-\exp\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right] \quad (1)$$

The scale parameter α (m/s) and a shape parameter β (dimensionless) of the Weibull distribution can be found using different estimation methods [2],[4]. Each method has a criterion, which yields estimates that are best in some situations. Different results are produced based on that criterion. The most commonly methods are Maximum Likelihood Estimator, Method of Moments, Least Squares Method or Regression Method. The Maximum Likelihood Estimator is so commonly applied in engineering and mathematics problems [6], so, this method is used in this paper to establish the parameters of wind speed distribution.

In many studies, the shape parameter is often chose to 2 and therefore a Rayleigh distribution can be used, with a same accuracy and with a simpler model.

The wind blows faster at higher altitudes because of the reduced influence of drag of the surface and lower air viscosity. The effect of the altitudes in the wind speed is most dramatic near the surface and is affected by topography, surface roughness, and wind obstacles such as trees or buildings. The most common expression for the variation of wind speed with hub height is the power law having the following logarithmic profile model [8],[9].

$$v(z) = v(z_r)\cdot\left(\ln\left(z/z_0\right)/\ln\left(z_r/z_0\right)\right) \quad (2)$$

where $v(z)$ and $v(z_r)$ are the wind speeds at a desired z and registered z_r height, and z_0 is the surface roughness length, a characterization of a ground terrain.

To establish the parameters of probability density distribution is necessary an accurate dataset of wind speed. The wind speed database can be obtained from meteorological station, where, usually, the measurement point (anemometer) height above the surface may be to 10 m or 50 m. Depending by the wind measurement level, the speed data must be adjusted for the change in height desired according to a logarithmic profile previously mentioned.

B. *Wind speed-power relationship*

The power transported by an air stream flowing with a given speed, v, can be calculated according to [1] using the following simple expression:

$$P_V = 1/2\ A\cdot\rho\cdot v^3 \quad (3)$$

where ρ is the air density and A the area of the air stream, measured in a perpendicular plane to the direction of the wind speed.

The calculation of the mechanical power that can be extracted by the rotor of a wind turbine, requires Betz' law to be taken into account. This law specifies that only a maximum 16/27 of the wind energy can be converted into mechanical power. This value is known as the Betz limit. In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%.

The mechanical power is converted in electrical power by generator, so, the output electric power of a wind turbine is a function of the wind speed. The power curve gives a relation between the wind speed and the output electric power, a typical curve of the wind turbine generator is nonlinear related to the wind speed. However, the assumption of the linear characteristic of power with the wind speed, brings a significantly simplifies of calculations, without roughly errors. The power output characteristic can be assumed in such way:

- it starts generating power when the speed wind exceeds the minimum wind speed, namely cut-in speed ($v_{cut\text{-}in}$);
- the power output increases with the wind speed, when wind varies between cut-in and rated speed wind (v_{rated}), value for that the power achieves the rated power (P_{rated}).
- the rated power of a wind turbine, generally the maximum power output of a generator at highest efficiency, is produced when the speed lies between rated and cut-off wind speed ($v_{cut\text{-}off}$).
- cut-off wind speed is the maximum wind speed at which the turbine is allowed to produce power, usually limited by engineering design and safety constraints.

Thus, the electric power P_E may be calculated from the wind speed as follows:

$$P_E(v) = \begin{cases} \dfrac{P_{rated}\cdot(v - v_{cut-in})}{(v_{rated} - v_{cut-in})} & for \quad v_{cut-in} < v < v_{rated} \\ P_{rated} & for \quad v_{rated} < v < v_{cut-off} \\ 0 & other\ else \end{cases} \quad (4)$$

This curve comes available from the wind turbine manufacturer or plotted using recorded wind speed and corresponding output power data, a typical curve of the wind turbine generator is shown in the figure 1.

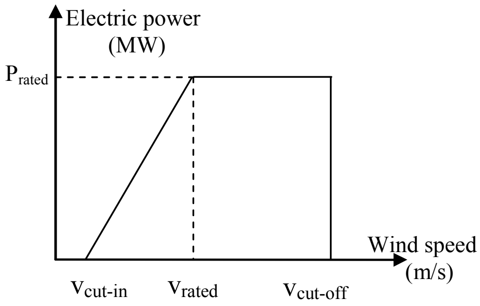


Fig. 1 The power curve of a wind turbine

Equations (3) and (4) express the instantaneous values of wind power and electric output power, as a function of the instantaneous wind speed. However, the wind speed may vary during a period of time. To consider this effect, we are going to work with the wind speed probability distribution function.

C. Probabilistic model of wind power and wind turbine output power

The probability distribution functions of wind power and of the wind turbine output power can be obtained using the analytical dependence between wind speed, wind power, and the output power respectively, operating a change of variables.

Lets assume that v is a continuous random variable with cumulative distribution function, $F_V(v)$ and that $P=J(v)$ defines a one-to-one transformation from a region of the wind-space, to a region of the power-space, with inverse transformation $v=J^{1}(P)$, the cumulative distribution function of power can be calculated according [16],[17]:

$$F(P) = \Pr(P < p) = \Pr(J(X) < p) = \\ = \Pr(X < J^{-1}(p)) = F_W(J^{-1}(p)) \quad (5)$$

In order to obtain the probability density function, a differential of cumulative distribution function must be operated. In figure 2 is presented the intuitive process of the random variables transformation, the wind speed variables being transformed in wind power variable P_W, on the right, respectively in the output electrical power variable P_E, on the left.

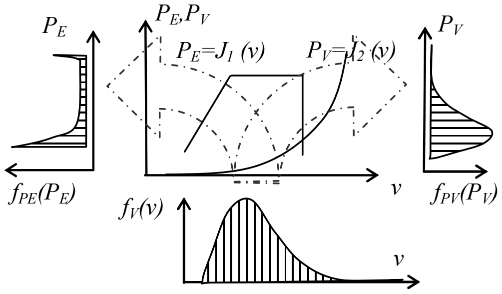


Fig. 2 Transformation of the wind speed variable

If (5) is applied for the wind power relationship (3), having in view the Weibull distribution, the probability density function of the wind power may be expressed as a function of the variable P_V:

$$f_{PV}(P_V) = \frac{2\beta}{3A\rho\alpha^3} \cdot \left(\frac{2P_V}{A\rho\alpha^3}\right)^{\frac{\beta}{3}-1} \cdot \exp\left[-\left(P_V / A\rho\alpha^3\right)^{\frac{\beta}{3}}\right] \quad (6)$$

Therefore the power transported by the wind can be represented by a Weibull distribution, with α' and β' parameters given by:

$$\alpha' = 1/2 \cdot A \cdot \rho \cdot \alpha^3, \quad \beta' = \beta/3 \quad (7)$$

where ρ is the air density, A the area of the wind turbine rotor, and α, β are the wind distribution parameters.

The output power probabilistic model for a wind turbine and its practical evaluations were developed and evaluated by authors in [11],[12]. Similar results has also been obtained by others authors in [13],[14].

The possible values of $F_{WT}(P)$ may be roughly classified in 0, P_{rated} and in the interval that lies between mentioned values, respectively. Each possible value has been evaluated, having in view the probability to achieve that value. The cumulative distribution function of the output power of the wind turbine is:

$$F_{PE}(P_E) = \begin{cases} 1 - \left\lfloor F_W(v_{cut-off}) - F_W(v_{cut-in}) \right\rfloor & for \quad P_E = 0 \\ F_{WT}(0) + F_W(W) - F_W(v_{cut-in}) & for \quad 0 < P_E < P_{rated} \\ 1 & for \quad P_E = P_{rated} \end{cases} \quad (8)$$

The probability density function results from differential of cumulative distribution function:

$$f_{PE}(P_E) = \begin{cases} \Re 1 & for \quad P_E = 0 \\ \left[\frac{\left(v_{rated} - v_{cut-in}\right)}{P_{rated}}\right] \cdot f_W(W) & for \quad 0 < P_E < P_{rated} \\ \Re 2 & for \quad P_E = P_{rated} \end{cases} \quad (9)$$

where:

- $\Re 1 = 1 - \left\lfloor F_W(v_{cut-off}) - F_W(v_{cut-in}) \right\rfloor = F_{PE}(0)$, represents the value of output power cumulative distribution function in the 0 point,
- $\Re 2 = F_W(v_{cut-off}) - F_W(v_{rated\ -0}) = 1 - F_{PE}(P_{rated\ -0})$, represents the increase value of the cumulative distribution function in the P_{rated} value, and
- $W = \left(\left(v_{rated} - v_{cut-in}\right) \cdot \frac{P_E}{P_{rated}} + v_{cut-in}\right)$.

III. Capacity factor and Efficiency evaluations

Capacity factor and efficiency depend both on the wind speed distributions in the area and the turbine parameters. To illustrate the effect of wind turbine parameters on capacity factor and efficiency values, a probabilistic model for these indicators is developed. The capacity factor (*CF*) of wind turbine is the ratio of expected output power over a period of time to rated power. The efficiency (*EF*) of wind turbine is the ratio of useful output energy to the input wind energy, or expected power output from wind machine to expected power available in wind over a period of time. The expected output power is used in both on the capacity factor and efficiency evaluations, so, it will be firstly evaluated.

A. The expected output power of a wind turbine

The expected output power of a wind turbine depends on the output power values and the probability to achieve that power, described by the probability distribution functions of output power. The expected output power ($E(P_E)$) from a wind turbine generator can be estimated from its power-wind and wind characteristics, being represented by the probability distribution of wind speed. This is given by [3] as:

$$E(P_E) = \int_0^{P\,rated} P_E \cdot f_{PE}(P_E)dP_E \qquad (10)$$

where P_E is the output power function variable and $f_{PE}(P_E)$ is probability density function of output power from wind turbine.

Having in view the expression of output power distribution function, from (9), the expected output power can be obtained by:

$$E(P_E) = 0\cdot\Re 1 + \int_0^{\Pr ated} P_E \cdot f_{PE}(P_E)dP_E + P_{rated}\cdot\Re 2 = \\ = P_{rated}\cdot\int_{v_{cut-in}}^{v_{rat}} \frac{v - v_{cut-in}}{v_{rated} - v_{cut-in}}\cdot f_W(v)\cdot dv + P_{rated}\cdot\Re. \qquad (11)$$

where $f_W(v)$ is a probability density function of wind speed.

Taking into account that $dF_W(v) = f_W(v)\cdot dv$, the equation (11) may be written as:

$$E(P_E) = P_{rated}\cdot\left[F_W\left(v_{cut-off}\right) - \int_{v_{cut-in}}^{v_{rated}} \frac{1-\exp(-(v/\alpha)^\beta)}{v_{rated} - v_{cut-in}}dv\right] = \\ = P_{rated}\cdot\int_{v_{cut-in}}^{v_{rated}} \frac{\exp(-(v/\alpha)^\beta)}{v_{rated} - v_{cut-in}}dv \quad - P_{rated}\cdot\exp(-(v_{cut-off}/\alpha)^\beta) \qquad (12)$$

The integration can be accomplished by making the change in variable $y = (v/\alpha)^\beta$, and therefore $dy = \beta(v/\alpha)^{\beta-1}d(v/\alpha)$.

After substitution of integration limits and their reduction to the minimum number of terms, the result is:

$$E(P_E) = \frac{P_{rated}\cdot\frac{\alpha}{\beta}\Gamma\left(\frac{1}{\beta}\right)}{v_{rated} - v_{cut-in}}\cdot\left[P\left(\left(\frac{v_{rated}}{\alpha}\right)^\beta,\frac{1}{\beta}\right) - P\left(\left(\frac{v_{cut-in}}{\alpha}\right)^\beta,\frac{1}{\beta}\right)\right] \\ - P_{rated}\cdot\exp(-(v_{cut-off}/\alpha)^\beta) \qquad (13)$$

where $\Gamma(\,)$ and $P(\,)$ are the gamma and the lower incomplete gamma functions, respectively [15].

B. The expected output power model of a wind turbine

As it has been presented in (6), considering the wind power having a Weibull distribution, the expected value of the wind power can be expressed as a function of the parameters α', β' and the Gamma function:

$$E[P_V] = \alpha'\Gamma\left(1+\frac{1}{\beta'}\right) \qquad (14)$$

C. The probabilistic model for capacity factor and technical efficiency

The capacity factor of a wind turbine means its energy output divided by the theoretical maximum output, if the wind turbine generator were running at its rated (maximum) power during all the time. So, the capacity factor is the ratio of the expected output power over a period of time to the rated power of wind turbine generator.

$$CF = \frac{E(P_E)}{P_{rated}} = \frac{\frac{\alpha}{\beta}\Gamma\left(\frac{1}{\beta}\right)}{v_{rated} - v_{cut-in}}\cdot\left[P\left(\left(\frac{v_{rated}}{\alpha}\right)^\beta,\frac{1}{\beta}\right) - P\left(\left(\frac{v_{cut-in}}{\alpha}\right)^\beta,\frac{1}{\beta}\right)\right] \\ - \exp(-(v_{cut-off}/\alpha)^\beta) \qquad (15)$$

The efficiency is a measurement of how much energy from the wind is converted in electrical power energy. For that, the expected output power must be divided to the expected wind power input to measure how technically efficient is the wind turbine.

$$EF = \frac{E(P_E)}{E(P_V)} = \frac{\frac{P_{rated}}{v_{rated} - v_{cut-in}}\cdot\frac{\alpha}{\beta}\Gamma\left(\frac{1}{\beta}\right)}{\alpha'\cdot\Gamma\left(1+\frac{1}{\beta'}\right)}\cdot\left[P\left(\left(\frac{v_{rated}}{\alpha}\right)^\beta,\frac{1}{\beta}\right) - P\left(\left(\frac{v_{cut-in}}{\alpha}\right)^\beta,\frac{1}{\beta}\right)\right] \\ - \frac{P_{rated}}{\alpha'\cdot\Gamma\left(1+\frac{1}{\beta'}\right)}\cdot\exp(-(v_{cut-off}/\alpha)^\beta) \qquad (16)$$

The equations (15) and (16) show the results of authors' research based on laborious calculations and detailed analysis of statistical distributions. This relationship represents an equation which shows the effects of cut-in, rated, and cut-off speeds parameters on the capacity factor value. For a given wind regime, with known α and β parameters, we can select that values of v_{cut-in}, v_{rated} and $v_{cut-off}$ that maximize the expected output power, and thereby maximize the capacity factor.

IV. Model Validation and Numerical Example

For validation of probabilistic model, its results have been compared with results from other model. The Monte Carlo simulation has been used to provide information related to the average values of the capacity factor. A Matlab program has been developed to validate the probabilistic model.

The program has been structured by two main functions. First function is based on a probabilistic model previously developed and modelled with (15) and (16), respectively. Second function has been developed based on Monte Carlo simulations technique. This technique generates different values of wind speed, in accordance with their Weibull distribution (with the shape and scale parameters estimated from the real data base) and these wind values are used to generate the output power, having in view the characteristics of the wind turbine generator. The expected output power from a wind turbine is the power produced at each wind speed sample, integrated over all possible wind speeds. The required capacity factor values may be observed from the average of all output power values, over a long number of samples. The efficiency is observed from average of all output power values, and also from all power transported by any values of wind speed. The simulation can be stopped when a specified degree of confidence has been achieved.

The methodology presented in this paper was applied to a real wind turbine and for a real wind speed database, to validate the probabilistic model and to evaluate the influence of main parameters of wind turbine generator to capacity factor and efficiency value. The wind speed database was collected from the north-east area of Romania, for a measurement interval to one hour for the year 2008. The figures 3.a,b present the wind speed collected from wind station height (10m) and adjusted to the hub wind turbine height (80m).

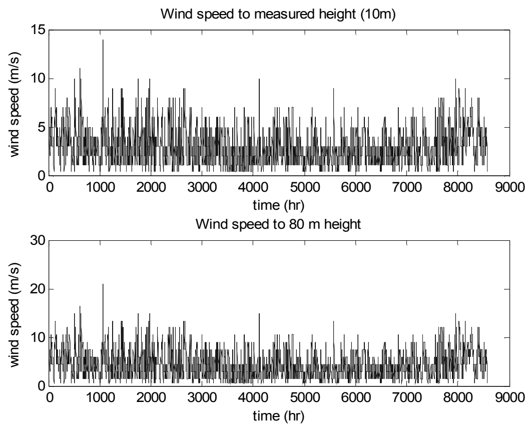


Fig. 3.a,b Wind speed data base from the north-east area of Romania, for 10m, respectively 80 m height

The parameters of the Weibull distribution have been estimated using the hourly wind data base. The probability density and the density function fitted for different wind speed values in 1 m/s steps are presented in figure 4. The probability distribution function used to fit is a Weibull distribution with scale parameter α=4.82253 m/s and a shape parameter β=1.8656.

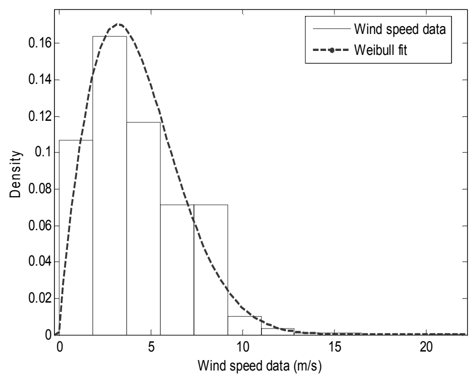


Fig. 4 The wind data base associated distribution

The wind turbine chose for analyze is an active blade pitch control wind turbine, namely 1.5 XLE GE-Energy, manufactured by GE Energy [18], with their technical specifications presented in table 1:

Table 1 Technical specifications of wind turbine GE Energy

Turbine Model	Rated power (MW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-off speed (m/s)	Rotor diameter (m)	Hub Heights (m)
1.5xle - GE Energy	1.5	3.5	11.5	20	82.5	80

The probability density function (PDF) and cumulative distribution function (CDF) of the output power for a 1.5 XLE wind turbine, considering a Weibull distribution with mentioned parameters, are presented in the figure 5.a,b.

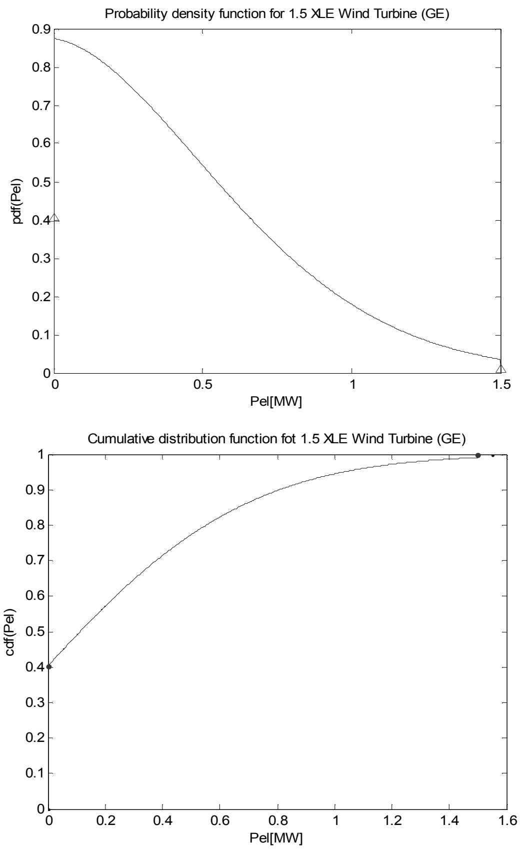
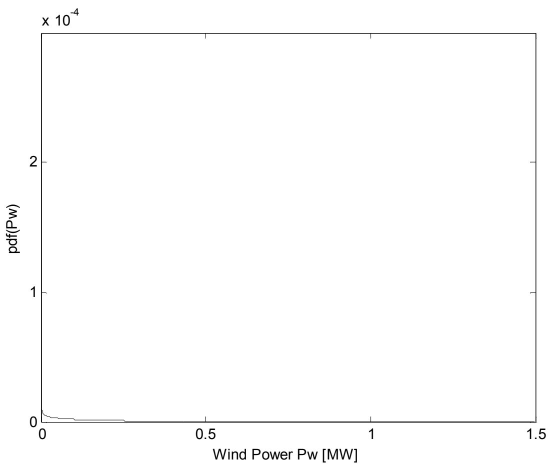


Fig.5.a,b The PDF and CDF of output power wind turbine

Considering the ρ=1.225 kg/m^3 for the air density (at 15°C) and the rotor are A=5346 m^2, in the previous equation (7), the scale parameter and shape parameter of Weibull distribution parameters are obtained as α'=3.6725×10^{5}m/s and β'=0.6219, respectively. The probability density function and cumulative distribution function of the wind power are in accordance with Weibull distribution with mentioned parameters.



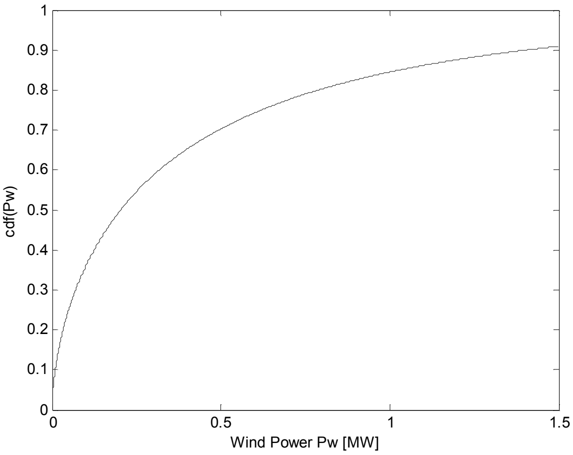


Fig.6.a,b The PDF and CDF of wind power

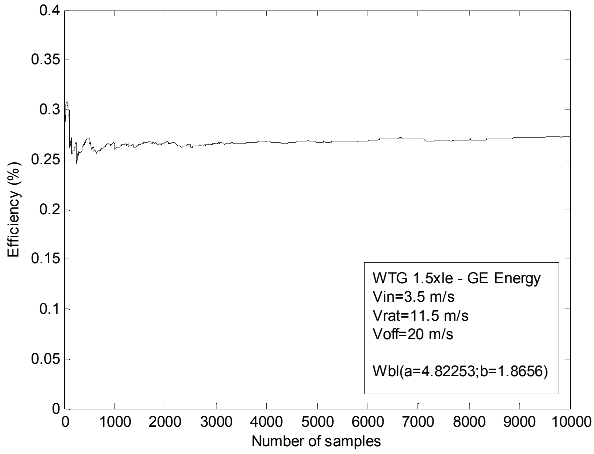


Fig. 8 Efficiency result from Monte Carlo simulation

Using the output power and wind power distribution functions in the probabilistic model previously developed, the capacity factor and efficiency values were evaluated and presented in table 2 and 3. For validation, in the following is presented an example of capacity factor and efficiency evaluation, for a 1.5 XLE GE-Energy wind turbine, using the Monte Carlo Simulation technique (MCS). This technique creates a fluctuating convergence coefficient of variation range for various numbers of samples for capacity factor (in figure 7) and for efficiency (in figure 8). The coefficient of variation of the wind speed generated range can be used to improve the effectiveness of MCS, this being often used as the convergence criterion in simulation techniques.

Number of simulations results from condition that the deviation of the coefficient of variation of *CF* and *EF* ranges to expected value to be under a settled value. Using simulations techniques, for a settled value (0,01%) is obtained about 10.000 necessary samples, the convergence process of *CF* being presented in the figure 7, and for *EF* in figure 8.

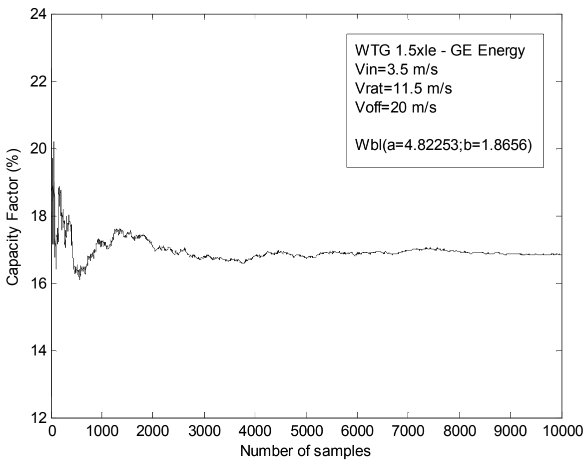


Fig. 7 Capacity factor result from Monte Carlo simulation

The capacity factor values provided by probabilistic model and sequential Monte Carlo simulation are shown in Table 2. For a better comparison between models, three ranges of speed parameters of wind turbine were considered in capacity factor evaluation. Commercial wind turbines typically have cut-in speeds between 2.5 and 4.5m/s, a rated wind speeds between 10 and 15 m/s and a cut-off speeds between 20 and 25 m/s.

Table 2. Capacity factor values from probabilistic model (PM) and Monte Carlo simulation (MCS)

Capacity Factor v_{rat}=11.5m/s $v_{cut\text{-}off}$=20m/s			Capacity Factor $v_{cut\text{-}in}$=3.5m/s $v_{cut\text{-}off}$=20m/s			Capacity Factor $v_{cut\text{-}in}$=3.5m/s v_{rat}=11.5m/s		
v_{cutin}	PM	MCS	v_{rat}	PM	MCS	v_{cutoff}	PM	MCS
2.5	22.3301	22.2012	10	20.4575	20.3350	20	16.8492	16.7547
3	19.5020	19.6152	11	17.9203	17.9318	21	16.8492	16.9726
3.5	16.8492	16.6911	12	15.8886	15.6188	22	16.8493	16.7824
4	14.4048	14.8282	13	14.2455	14.1276	23	16.8493	16.7034
4.5	12.1901	11.9975	14	12.8995	12.8572	24	16.8493	16.8065
5	10.2157	10.3042	15	11.7815	11.7896	25	16.8493	16.7920

As described above, table 3 shows the efficiency values for different values of cut-in, rated and cut-off turbine speeds.

Table 3. Efficiency values from probabilistic model (PM) and Monte Carlo simulation (MCS)

Efficiency v_{rat}=11.5m/s $v_{cut\text{-}off}$=20m/s			Efficiency $v_{cut\text{-}in}$=3.5m/s $v_{cut\text{-}off}$=20m/s			Efficiency $v_{cut\text{-}in}$=3.5m/s v_{rat}=11.5m/s		
v_{cutin}	PM	MCS	v_{rat}	PM	MCS	v_{cutoff}	PM	MCS
2.5	37.5769	37.3589	10	32.1705	32.2894	20	28.3533	28.4966
3	32.8178	32.6990	11	30.1561	29.7850	21	28.3535	27.9834
3.5	28.3536	27.7772	12	28.3536	27.7068	22	28.3536	29.1203
4	24.2402	24.2985	13	26.7372	26.9143	23	28.3537	28.5333
4.5	20.5134	20.8663	14	25.2835	25.4662	24	28.3537	27.9599
5	17.1909	16.3235	15	23.9722	23.5458	25	28.3537	28.2550

It can be seen that the results obtained from both methods are very close. The probabilistic method provides comparative results with Monte Carlo simulation, these proving the accuracy of probabilistic model, developed in equations (15) and (16).

The analytical expressions developed in (15) and (16) were used to study the effect of mean wind speed on both coefficients. Graphic representation of dependence is shown in figure 9, with solid line for efficiency and dashed line for capacity factor.

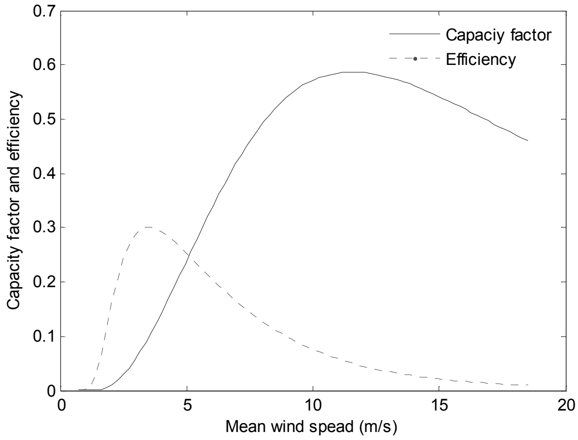


Fig. 9 Effect of mean wind speed on CF and EF

As it can be seen, the wind turbine efficiency is largest (in this case 50%) at a relatively low wind speeds, around some 4 m/s. But, at low wind speeds, efficiency is not so important, because there is not much energy to be converted. At higher wind speeds, the turbine can not convert the excess energy that exceeds the limits of the generator. So, the efficiency is not the best indicator for evaluating the suitability of wind turbine to a specific location. For suitability evaluation, the capacity factor is a better indicator. If the wind turbine is located in an area with an average speed around some 10m/s, the maximum output power will be generated, even if the efficiency is low. So, it is not an aim in itself to have a high technical efficiency of a wind turbine. Since the fuel is free, the technical efficiency is not important, the wind energy can be used or will be lost. What really matters is the amount of generated energy, even with a lower efficiency

Also, the proposed model may be used to analyze the effects of different cut-in, rated and cut-off wind speeds on the capacity factor value. Using a 1.5-XLE GE Energy wind turbine, placed in Iasi location, with previously wind profile, the capacity factor will be 16.85% and the efficiency, 28.35%. for this wind profile, from table 2, it can see, a wind turbine generator can be expected to operate with a maximum capacity factor of 22.33% and a maximum efficiency of 37.57% for a wind turbine generator characterised by a wind speed parameters set to $v_{cut\text{-}in}$=2.5m/s, v_{rated}=11.5m/s and $v_{cut\text{-}off}$=20m/s, respectively. A capacity factor of 22.33% from a 1.5kW wind generator means a mean output power of 0.335 kW or an annual power output of 2934.6 kWh.

The effects of the wind turbine generator parameters on the capacity factor and efficiency are shown in figure 10, and figure 11, respectively. In the same system coordinates is shown the dependence of capacity factor and efficiency for various wind speeds values around of wind turbine generator parameters (cut-in, rated, cut-off speeds).

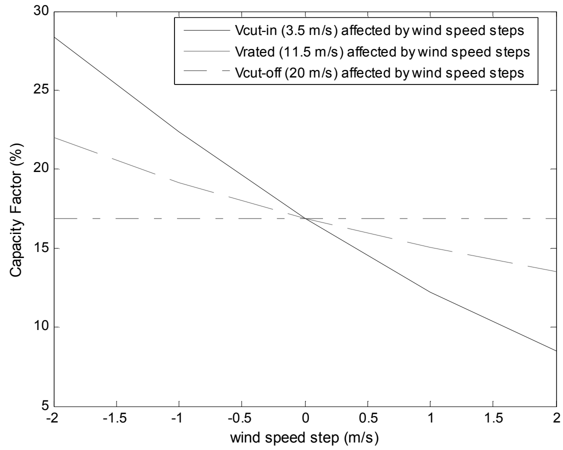


Fig. 10 Effect of wind turbine parameters on capacity factor

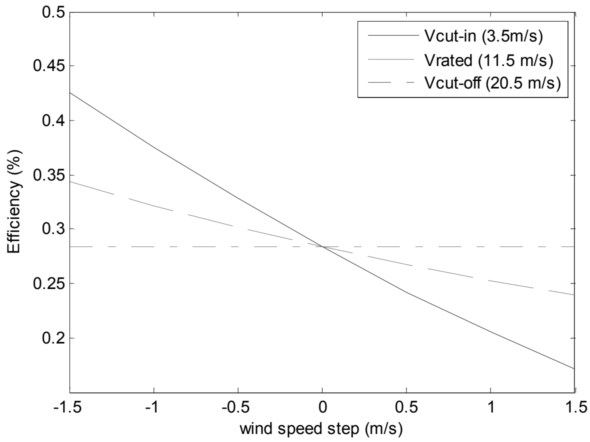


Fig. 11 Effect of wind turbine parameters on efficiency values

As it can be seen from the figure 9, a certain value of capacity factor or efficiency can be achieved by changing the two parameters of wind turbine generator. Most important parameter and providing the greatest degree of freedom is cut-in wind speed. It has been shown that the cut-in wind speed has a significant effect on the capacity factor and efficiency values. Their values decrease approximately linearly as the cut-in wind speed increases.

The second parameter of wind turbine generator with effect on the capacity factor and efficiency is the rated wind speed. It has been shown that the rated wind speed has a relatively small effect on these values. The rated wind speed growth leads to the capacity factor and efficiency values decrease, but this effect is less significant than that of the cut-in wind speed

It has been shown that the cut-off wind speed has no effect on either the capacity factor nor efficiency values. The cut-off wind speed is a safety parameter and is usually large. For relatively few times the instantaneous wind speed at a particular area will be greater than the cut-off speed. The selection of the cut-off speed parameter is therefore less important than that of the cut-in and the rated wind speed parameters.

V. CONCLUSION

Integration of wind energy is an important activity in the developing process of the electric power system. Knowing the capacity factor values is a key factor when examining wind energy potential for a wind turbine located in a specific area. The probabilistic methods are the recommended solution for wind integration analysis, since they can take into account the wind power uncertainty.

This paper presents a probabilistic model to evaluate the capacity factor and technical efficiency of a wind turbine based on the output power distribution. The results were validated using the Monte Carlo simulations, and the analysis demonstrates that the probabilistic model results are very accurate. The model has the advantage that can be easily implemented in computer programs and require a computing time considerably less than in the case of simulation methods.

The electric energy output of a wind turbine for a specific area depends on many factors. These factors include the wind speed conditions at the area, and the characteristics of the wind turbine generator.

The case studies show that turbine cut-in wind speed has a significant effect on the both capacity factor and technical efficiency values while the cut-off wind speed has almost no effect. Significant benefits can be obtained by selecting suitable wind turbine parameters for the specific wind profile.

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