Predicting the Amount of Energy Generated by a Wind Turbine based on the Weather Data

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Abstract. In this study, a new investigation is underway with the primary objective of the weather parameters impact on the wind turbine power. The robust and straightforward dynamic model for accurate predicting wind turbine output power was presented. The evaluation has been done for the whole environmental components influencing on the model and output power. The selected wind turbine type (RW-5kW) and the predicted energy has been evaluated based on the experimental weather data of the city of Hel in the north of Poland. The results show that the air density has a high influence on the wind turbine output power and this value is affected by several environmental factors such as pressure, humidity, and temperature. It turns out that the temperature is the most influential, while the pressure and humidity have a lower effect and if they are not available in measured data during modelling they can create only 0.5% error.

1. Introduction

Renewable energy systems considered one of the essential tools for sustainable future development. At present, the wind and water energy constitute most of the important renewable energy sources in the world. Mainly the used of wind turbines for clean energy has dominated in the last few decades especially in the last couple years when wind turbine number installation increases globally and to be considered a promising source of renewable energy in the world [1]. In 2016 there was a massive increase in wind power capacity which recorded 65 GW, while the global capacity was around 440 GW [2]. Generally, there are two different designs of wind turbine systems, characterised by the axis direction: vertical axis and horizontal axis. Globally the highest amount of wind energy is captured by using the horizontal axis blades design instead of the vertical axis blades design for the entire area of vertical blades used to always sweep an object in the wind during operation [3,4]. The technical improvements of the wind turbines in the last decades have increased the efficiency and the power output capacity [5]. Wind energy is often used to feed the grid, which the power generated from wind farms or wind turbine units connected with the grid must be integrated appropriately for serving this purpose. More accurate assessments of this type of energy are needed.

In the literature, several studies concentrating on modelling or predicting the wind turbine power has been done. In a study conducted by [6] a parametric model for characterising the wind turbine (WT) power curve to serve planning, online monitoring, and wind energy assessment by using both parametric and non-parametric approaches was proposed. The results proved that the performance of
the model using the backtracking search algorithm (BSA) is superior in comparison to the other analysed models. In [7] authors used an artificial neural network for modelling the wind turbine power curve to improve power curve precision modelling. The results show that the multistage modelling techniques were able to reduce the relative and absolute errors when accurate wind turbine power curves were modelled using six parameters. In [8] authors improve the power of (NREL 5-MW) wind turbine by using the multi-plasma actuators tool. The results illustrated that the induced velocity could be enhanced by placing a (multi-DBD) actuator in parallel and close to the hub of the wind turbine rotor and by increasing the number of actuators, lead to improving the wind velocity profile. In [9] authors analysed the effect of pitch angle on the power performance for the vertical axis wind turbine. The results show that the vertical axis wind turbine optimum fixed pitch angle can improve the performance more than 5%. For enhancing the performance of the vertical axis wind turbine, in [10] authors conducted a two-dimensional numerical study of simple effects on various WT by using blades with cavities instead of conventional aerofoils. The results show that by using simultaneously high velocities of the drag and lift the blades tend to provide the best performance. In [11] a multiscale correlation and turbulence analysis between marine turbine power production and the upstream and downstream of the wind flow has been shown. The study used two simultaneous measurements of the wind flows. An experimental study by using wind tunnels was conducted in [12] in order to find a solution to the unmatched Reynolds numbers for downscaled wind turbine using a laminar and turbulent flow wind turbine single model. The results show that the power coefficient is sensitive to the inflow turbulence intensity and has a highly impact on the flow separation in the wind turbine blade suction side and on the efficiency. In [13] authors used Computational Fluid Dynamics (CFD) modelling to compute flow fields and aerodynamics coefficients of wind turbine aerofoils taking into account the laminar to turbulent transition flow. The results showed that the proposed model is an effective means of predicting aerofoil performance even in stall region (blade surface flow separation) and they illustrated that the difference in the main geometrical parameters has a significant impact on the power generation. A comprehensive review of generic dynamic wind turbine models for the stability analysis of the power system has been presented in [14]. In [15] authors studied the mechanical power loss in wind turbine planetary gears, and for this loss, a reduction of a planetary gear set using standard lubricant for the wind turbine was proposed. The developed model was capable of predicting mechanical and sticky losses as well as energy losses in the gears mesh or losses caused by oil churning and wind drag for the wide range of the wind speed and operating temperatures for the same wind turbine lubricant. Based on the dynamic principle of component analysis for the wind turbine, a statistical modelling for the energy feed to the grid from the wind farm standpoint were conducted in [16]. The results show that the power grid behaviour at the connection point can be represented by 4 out of 9 registered variables: 3-phase currents, 3-phase voltages, frequency and generated (active and reactive) power. For power coefficient evaluation as well as flapping moment coefficient with higher accuracy, in [17] authors prepared a novel composite calculation model which can be used in a wind turbine aerodynamic load analysis and can provide oscillating load and flapping load status information for wind turbine control. The model evaluated the flapping moment coefficient and power coefficient for (NREL 5 MW) wind turbine and manifests a very high level of the accuracy. For estimation wind, turbine power coefficient as a function of tip speed ratio and pitch angle [18] authors developed a new accurate model which can predict wind turbine power coefficient with a very low error. Top predict wind speed and wind power capacity near centre of Taiwan [19] authors developed a model on the basis of the neural network. In [20] three configurations of hybrid power systems has been modelled based on the wind turbine units for three different local residential loads and the results show the wind energy effective more than another renewable resource. In [21] authors optimized hybrid power system based in photovoltaic, wind turbine, and the diesel generator for feed rural area. Results illustrated the wind turbine contributed to feeding the system during the night a period also helped for reducing the cost of energy.

The modelling of the wind turbine output power or the predicted power from the wind farm is the key issue for the wind turbine analysis at the stage of development as well as during operation which
can evaluate the energy production to be performed and may facilitate the discovery of system malfunction or efficiency calculation. In this study, robust and straightforward dynamic model for the prediction of wind turbine power has been presented based on the experimental data. The proposed model investigates all vital environmental components impact the predicted power.

2. Mathematical model

For evaluation of the wind turbine output power and generated energy number of stages of the process (calculation of the wind speed at turbine hub high, calculation of real air density) as well as assumptions (described in detail in the subsequent sub-chapters) is required.

2.1 Hub height wind turbine model

The wind turbine hub height is the height above the ground at which the rotor sits. Hub heights typically range from 25 m (for small wind turbine units, 50 kW or less) and above 100 m (for multi-megawatt wind turbines). It is known that speed increases with the height above ground, and at a higher level, more energy can be produced. However, in the most of the weather stations, the anemometer height is not at the same height as the designed turbine hub. According to the World Meteorological Organization (WMO), the standard anemometer heights 10 meters, while the wind energy potential should be evaluated based on the higher level. For this reason, wind speed needs to be extrapolated with the use of wind velocity data accordingly.

Assuming that the wind speed follows the log-law, eq.(1) the ratio of the wind speed $U_{hub}$ at hub height $Z_{hub}$ to the wind speed $U_{anem}$ at anemometer height $Z_{anem}$ can be described as follows [22]:

$$U_{hub} = U_{anem} \left( \frac{\ln(Z_{hub}/Z_o)}{\ln(Z_{anem}/Z_o)} \right)$$  \hspace{1cm} (1)

where $U_{hub}$ is the wind speed at the hub height of the wind turbine (m/s), $U_{anem}$ is the wind speed at anemometer height (m/s), $Z_{hub}$ is the hub height of the wind turbine (m), and $Z_{anem}$ is the anemometer height (m). The roughness length $Z_o$ (m) can be calculated from wind speed measurements at two heights, by inverting eq.(1). The surface roughness length is a parameter that characterises the roughness of the surrounding terrain. Table 1 contains representative surface roughness lengths for typical situations [23]. Alternatively, wind shear [22, 24] can be described by the wind shear exponent according to the eq.(2):

$$U_{hub} = U_{anem} \left( \frac{Z_{hub}}{Z_{anem}} \right)^{\alpha}$$  \hspace{1cm} (2)

where $\alpha$ is the power-law exponent to be evaluated based on the wind speed measurements for at least two different heights.

| Terrain Description        | Surface Roughness Length (m) | Terrain Description        | Surface Roughness Length (m) |
|----------------------------|------------------------------|----------------------------|------------------------------|
| Very smooth, ice, mud      | 0.00001                      | Crops                      | 0.05                         |
| Calm open sea              | 0.0002                       | Few trees                  | 0.10                         |
| Blown sea                  | 0.0005                       | Many trees, few buildings  | 0.25                         |
| Snow surface               | 0.003                        | Forest and woodlands       | 0.5                          |
| Lawn grass                 | 0.008                        | Suburbs                    | 1.5                          |
| Rough pasture              | 0.010                        | City centre, tall buildings| 3.0                          |
| Fallow field               | 0.03                         |                            |                              |
2.2 Air density
The altitude (elevation above the mean sea level) has a high effect on the air density, which in turn affects the wind turbine output. Therefore the model should consider the altitude when calculating the wind turbine output power. For power curve creation the standard air density ($\rho_\infty=1.225\ \text{kg/m}^3$) is typically used while in the real case the local air density which is not constant and depends on many parameters (humidity, temperature, pressure) should be used. The humid air density that passes through the wind turbine blades can be calculated from the following equation:

$$\rho = \frac{p_d}{R_d T} + \frac{p_v}{R_v T} = \frac{p_d M_d + p_v M_v}{RT}$$  \hspace{1cm} (3)

where $\rho$ is the density of the humid air ($\text{kg/m}^3$), $p_d$ is the partial pressure of dry air ($\text{Pa}$), $R_d$ is the specific gas constant for dry air, 287.058 ($\text{J/kg} \cdot \text{K}$), $T$ is the air temperature ($\text{K}$), $R$ is the specific gas constant for water vapour, 461.495 ($\text{J/kg} \cdot \text{K}$), $M_d$ is the molar mass of dry air, 0.028964 ($\text{kg/mol}$), $M_v$ is the molar mass of water vapour, 0.018016 ($\text{kg/mol}$), $R$ is the universal gas constant, 8.314 ($\text{J/K} \cdot \text{mol}$) and $p_v$ is the pressure of water vapour ($\text{Pa}$).

The pressure of the water vapour $p_v$ and dry air partial pressure $p_d$ can be calculated[27] from the following equations:

$$p_v = \phi p_{\text{sat}}$$  \hspace{1cm} (4)

where $\phi$ is the relative humidity (%) and $p_{\text{sat}} = 6.1078 \cdot 10^{7.5T+237.3}$.

$$p_d = p - p_v$$  \hspace{1cm} (5)

where $p_d$ is the partial pressure of dry air and $p$ denotes the absolute pressure.

2.3 Wind turbine power output
The wind turbine usually provides the amount of power that turbine can generate at the selected wind speed conditions at hub height and in the condition of standard temperature and pressure (STP) for the chosen turbine type. In order to acquire wind turbine power output $P_{\text{output}}$ for the real condition, the power output at standard condition $P_{\text{standard}}$ (evaluated based on the wind turbine power curve) should be multiplied by the air density ratio [25] (real air density to standard air density), according to the equation:

$$P_{\text{output}} = \frac{\rho}{\rho_\infty} \cdot P_{\text{standard}}$$  \hspace{1cm} (6)

where $P_{\text{output}}$ is the wind turbine power output ($\text{kw}$) in real conditions, $P_{\text{standard}}$ the wind turbine power output ($\text{kw}$) at standard temperature and pressure, $\rho$ is the real (variable in time) air density ($\text{kg/m}^3$) and $\rho_\infty$ is the air density($\rho_\infty=1.225\ \text{kg/m}^3$) at standard temperature $T_\infty = 288.15\ \text{K}$ and pressure $p_\infty = 101.325\ \text{kPa}$.

The wind speed between cut-in speed and cut-out speed is the rated output speed [22]. The output power at standard test condition for the selected wind turbine (RW-5kW) is shown in Figure 1. The curve referred to the three ranges of the rated output speed, eq.(7) and was created for the RW-5kW wind turbine unit. The presented model required wind speed measurement or prediction performed based on the wind speed models available in the literature. Additionally, at least instantaneous air temperature has to be measured, however air pressure and air humidity measurements are also welcome. For the current analysis of experiment methodological data for whole year 2015 of the city of Hel (54°36′29″N, 18°48′04″ E) located north of Poland (close to the Baltic sea coast) have been used.
Figure 1. Variable pitch wind turbine output power curve at STC for (RW-5KW).

\[ P_{\text{skw}}(v) = \begin{cases} 
11v^3 - 20v^2 + 15v - 0.09 & \text{for } 0 \leq v \leq 4.5 \\
89v^2 - 3.8 \cdot 10^2v^2 + 5.1 \cdot 10^2 & \text{for } 4.5 < v < 10.57 \\
6.13725 & \text{for } 10.57 \leq v 
\end{cases} \quad (7) \]

3. Results and discussion

For calculation of the real wind turbine power output at the real local weather conditions, the actual instantaneous air density must be evaluated in addition to the wind velocity measurements at the height 10m as illustrated in the previous section. For this case, wind speed has to be extrapolated to the hub height- here \( Z_{\text{hub}} = 20m \). The analysis performed below shows which environmental parameters are essential for local air density evaluation.

3.1 Air density calculation

The air density \( \rho \) of the humid air has a direct influence on the wind turbine power production. There are three parameters which can play an essential role in air density evaluation: air temperature, humidity and pressure. Figure 2 shows the effect of all that parameters on air density for the whole year 2015. In this Figure, the standard and calculated air density based on the experimental measurement including temperature, pressure and relative humidity are presented. The results show that the ambient temperature has the highest impact on the air density, while the pressure and relative humidity have much lower effect. For this reason, at least air temperature data should be taken into account in order to perform an accurate analysis. The instantaneous pressure data increase the solution accuracy, however the observed effect is minor. The lowest effect on calculated density has been observed for the relative humidity.

Figure 2. The air properties (temperature, pressure and relative humidity) effect on the air density.
3.2 Wind turbine hub height

Figure 3 shows the wind speed at the anemometer height ($Z_2=10m$) during the entire period of January 2015. In the same Figure the calculations of the wind speed at the height $Z_1=5m$ and $Z_3=15m$ are presented. The surface roughness length was assumed to be equal to 3.0 (city centre, tall buildings). One may infer from this Figure that, increasing the height, the velocity magnitude as well as the magnitude of the fluctuations increases.

![Figure 3](image)

**Figure 3.** The measured and calculated wind speed at various heights.

3.3 Surface roughness effect

Figure 4 shows the surface roughness length of the surrounding terrain effect on the calculated wind speed. Three different values of roughness were taken into consideration: a few trees $Z_o=0.1$, forest and woodlands suburbs $Z_o=0.5$ and city centre, tall buildings $Z_o=3$ (as shown in Table 1). For this analysis the hub height was $Z_{hub}=20m$. The analysis performed at winter time – during January 2015 – shows that the surface roughness length has a direct influence on the wind speed and city centre, tall buildings terrain recorded the highest value.

![Figure 4](image)

**Figure 4.** The calculated wind speed at various surface roughness length of the surrounding terrain.
3.4 Power law wind profile

The wind share coefficient is subject to a temporal variation at high frequencies, from daily and seasonal changes to turbulence caused by weather patterns. In the literature, the range of this value is between 0.11 to 0.25[26]. In many research works, this value is assumed to be constant, but this assumption may generate additional significant error in the calculation. Figure 5 shows three different values for wind share coefficient $\alpha=0.11; 0.14$ and $0.25$. It can be seen that for the hub height $Z=20m$ the lowest share coefficient $\alpha$ considerably increases the calculated wind speed.

![Wind share coefficient vs. wind speed for January.](image)

Figure 5. Wind share coefficient vs. the wind speed for January.

3.5 Wind turbine power output

This sections how the influence of the weather parameter (temperature, pressure and relative humidity) on the wind turbine power output for two different days during winter and summer. One can observe from the results that during winter day (18 January) the temperature significant influence WT power output while another parameters effect is minor (see figure 6 (a)). During the summer day (18 July) the pressure has the highest impact on the generated power(see Figure 6 (b)) however differences are small.

![Wind turbine power output with for a different air property (a) winter day (b) summer day.](image)

Figure 6. Wind turbine power output with for a different air property (a) winter day (b) summer day.

Figure 7 shows the average monthly wind turbine power generation be means local calculated real and standard air density. One may infer from this Figure that during the winter the average power
output calculated using real density is higher than with standard density, while during summer (June and July) this effect is opposite and minor. The yearly average power with the use of real density is 1.11 kW while the energy produced with the use of standard conditions is 1.08 kW.

Figure 7. Average monthly of the wind turbine power for actual and standard air density.

In Figure 8 the monthly energy generated by wind turbine using real and standard air density for the whole year 2015 is presented. It is worth to notice that the calculated energy production by means actual air density is higher and the yearly energy production is 9736.40 kWh while the energy produced by means standard conditions is 9451.92 kWh.

Figure 8. Monthly average energy generation for real and standard air density.

Figure 9 (a) and (b) shows the monthly output evaluation error and efficiency of the electrical energy production for the (RW-5kW) wind turbine unit respectively. It can observe the air density effect plays a significant role for cold months as lowest for hot months. It should be noticed that for considered location electrical power production during cold months is very high and the positive effect in the total energy production is higher and able to compensate power losses during the hot period as shown in Figure 9 (a). The average yearly wind turbine efficiency $\eta$ is about 22.3%, and the highest value is recorded in January about 38%, while the lowest in May about 10%. Energy production
distribution presented in Figure 9 (b) is very coherent with the yearly profile of energy consumption when most of the energy is consumed (in Poland) in winter seasons.

![Figure 9](image)

**Figure 9.** Power output evaluation error (a), energy production efficiency (b) relative standard density for the (RW-5kW) wind turbine.

4. Conclusions

Wind turbines are one of the most competitive sources of renewable energy. Although many studies have been done analysed wind energy at different parts of the world, different patterns of energy from wind have led to the fact that research is continuing and a large number of problems need to be solved. Within the framework of this research, a robust and straight forward dynamic model for the calculation of wind turbine power output has been presented. Evaluation of environmental components on the output power calculation was performed. The results show that the air density has a high influence on the wind turbine output power and this value is affected by several environmental factors such as pressure, humidity and temperature. In the present paper, the electrical energy generated by (RW-5kW) wind turbine based on the experimental data of weather in addition to comprehensive evaluation of wind turbine performance with the weather properties has been performed. The investigation gives an excellent choice for predicting the amount of energy for any given site based on the real or predicted weather data.

Acknowledgements

The authors are thankful for financial support this research from Polish Ministry of Science, AGH University of Science and Technology Grant No. 15.11.210.436.

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