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Statistical analysis of the amount of the power generated by the wind power plant, according to weather conditions

***Abstract**. The article presents the results of a statistical analysis, which was done using the Statistica program. The purpose of this analysis is to show, which atmospheric conditions have an influence on generated power in wind farms. The degree of this influence was also determined. The analysis was based on data, from a real wind farm – located in Poland.*

Streszczenie.** W artykule przedstawiono wyniki analizy statystycznej wykonanej z wykorzystaniem programu Statistica mającej na celu pokazanie, które z warunków atmosferycznych i w jakim stopniu mają wpływ na wielkość mocy generowanej przez farmę wiatrową. Analiza została przeprowadzona w oparciu o dane pomiarowe pochodzące z rzeczywistego obiektu – pracującej na terenie Polski dużej farmy wiatrowej. **(Analiza statystyczna wielkości mocy generowanej przez elektrownię wiatrową z uwzględnieniem warunków atmosferycznych)

Keywords: renewable energy, weather conditions, wind turbine, statistical analysis
Słowa kluczowe: energia odnawialna, warunki atmosferyczne, turbina wiatrowa, analiza statystyczna

Introduction

The term *atmospheric conditions* is generally understood as weather phenomena occurring in a given area. If the observation is done over many years (at least 30 years) – the results of that observation can be generalized, and defined as the characteristic climate for given area. Atmospheric conditions considered in the analysis were: air temperature, humidity, atmospheric pressure, wind speed and direction, cloud cover and precipitation, their type and level.

Observation and analysis of weather phenomena is an important issue, when considering the problems associated with renewable energy sources, especially with wind power. In [1] equation (1) was given. Based on this equation, the power of the wind turbine depends mainly on wind speed, and that relationship is strongly non-linear.

$$P_w = c_p \frac{\pi}{8} \rho D^2 v^3 \tag{1}$$

where: c_p – general conversion efficiency of wind energy into mechanical energy, ρ – air density [kg/m3], D – rotor diameter [m], v – wind speed [m/s].

Equation (1), does not include, among others, the minimum wind speed at which the turbine can successfully generate energy or the loss of energy within the mechanical components. For a certain range of wind speeds, the generated power is fixed. In addition, the wind turbine blade stops at high wind speeds, for safety reasons. In addition Formula (1) does not include some range of wind speed, for which, amount of the generated power is limited, and the maximum wind, when turbine must be stopped.

The analysis was done using the *Statistica* program, based on real data from a real wind farm. It is an interesting example of the verification of a theory in practice. The aim of the analysis is the determination of a mathematical model, describing turbine power, which takes into account the real work conditions of wind turbines.

In many articles, statistical analyses related to wind power can be found – for example [2] ÷ [8]. The material presented in this paper fits into this theme, however the concept of research contained in the article was reversed, as having available the appropriate measurement data from an existing wind farm, demonstrated the correctness theoretical dependence and agreement of characteristics declared by manufacturer with real data.

Characteristics of the wind farm

The measurements which form the basis of the calculations and analysis were made at a wind power plant located in southeast part of Poland. This plant consists of 15 wind turbines with a DFIG-type generator (fig.1). The height of each tower is 100 meters, the rotor blades have a length of 45.2 m and a blade turning radius of 92.5 m. The minimum speed of the wind, which is needed to start energy generation is 3 m/s, the rotor is stopped when the wind speed is 24 m/s and resumes when that speed reaches 22 m/s. For some range of wind speed (from 12 m/s to 24 m/s) amount of generated power is constant. [9]

The electrical energy generator, used in the plant is called a DFIG (Double Fed Induction Generator) and is based on a wound rotor motor. Stator windings are directly connected to the grid. Rotor windings are connected by slip rings to an AC-DC-AC converter, whose output is connected to the grid. Such a solution is the most commonly used in the wind energy industry. [3]

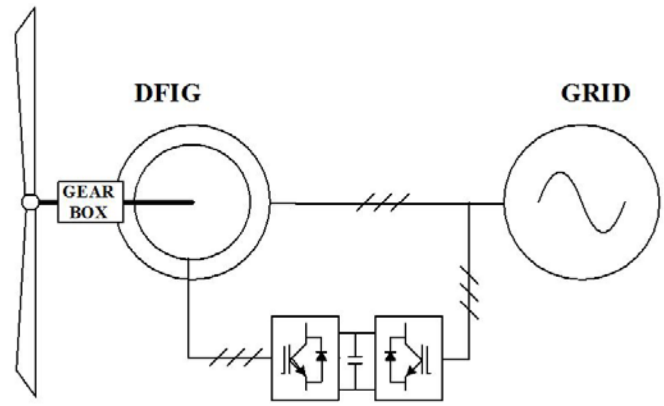

Fig.1. Wind turbine with a DFIG-type generator [10]

Statistical analysis of the measurements of the power generated by the wind farm depending on selected weather conditions

On the basis of the data obtained from the wind farm an attempt was made to create a regression model, that takes into account weather condition data (speed PW, direction of wind KW, air pressure CŚ and temperature T), which would allow for the prediction of the level of generated power. It should be identical to the relationship between generated power and wind speed as reported by the manufacturer in the form of the following graph fig.2.

Initially it was assumed, that the dependent variable (generated power) is affected by more than one variable (4 weather conditions: speed PW, direction of wind KW, air pressure CŚ and temperature T), the multiple regression module from the *Statistica* program was used.

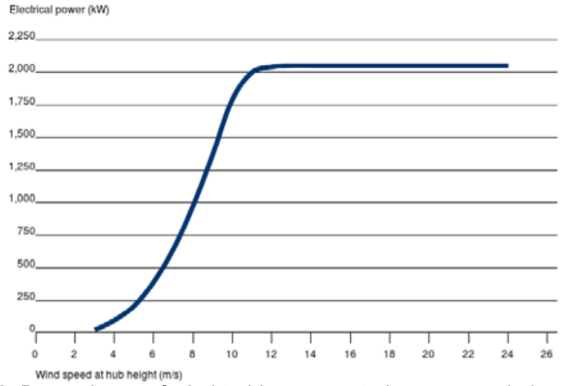

Fig.2. Dependence of wind turbine generated power on wind speed [9]

Measurement was held for a year, in selected day of every month by 24 hours.

To properly verify the model, it is not enough to check only the significance of the hypotheses, speaking about the existence of dependence between variables (in *Statistica* program in the tables important relationships are marked in red), but also, there is a need to turn attention to test F. The hypothesis, which underlies the test, concerns the significance of the multiple regression function. The greater the value of the tested statistic, and the lower the probability of the test in relation to the assumed level of significance, the more significant is the resulting regression function. Besides the F test, another issue that must be considered is data redundancy – determining which of these independent variables has no significant influence on the dependent

Table 1. Multiple regression – analysis results of relation between generated power and speed PW, direction of wind KW, temperature and air pressure CŚ

	Regression Summary for Dependent Variable: P (wind) R= ,94821625 R^2= ,89911406 Adjusted R2= ,89763588 F(4,273)=608,26 p<0,0000 Std. Error of estimate: ,27337					
N=277	b*	Std. Error of b*	b	Std. Error of b	t(273)	p-value
PW	1,154	0,034	0,132	0,004	34,152	0,000
KW	-0,098	0,044	-0,000	0,000	-2,255	0,025
T	-0,164	0,028	-0,011	0,002	-5,952	0,000
CŚ	-0,113	0,050	-0,000	0,000	-2,279	0,023

The header of table I contains the calculated factors concerning the applied multiple regression model:

- P – dependent variable, spreadsheet name in parentheses,
- R – multiple correlation factor is a measure of the relationship between the dependent and independent variables,
- R^2 – shows what part of the changing of the dependent variable is explained by the independent variables,
- Adjusted R2 – interpreted similarly to R^2, but has the advantage that it does not increase due to the subsequent addition of independent variables for analysis,
- F(x,y) – F test statistic value,
- p – probability of F test,
- Std. Error of estimate – measures the dispersion of observed values around the regression line.

The meaning of column headings:

- b* - regression factor, after data standardization,
- b – regression factor,
- t(x) – value of test t statistic, that tests the significance of the correlation between variables,
- p-value – t test probability.

Results of the statistical tests which explore the significance of the relations between variables, shows that there is some dependence between generated power and all of the independent variables. However, in that type of regression, it is necessary to check that the established model does not have redundant variables.

Table 2. Redundancy – analysis results of relation between generated power and speed PW, direction of wind KW, temperature and air pressure CŚ

	Redundancy of the independent variables; DV: P (wind) Variable R-square - between the current variable and all other variables in the regression equation			
Variable	Tolerance	R-square	Partial Correlations	Semi-partial Correlations
PW	0,324	0,676	0,900	0,657
KW	0,194	0,806	-0,135	-0,043
T	0,487	0,513	-0,339	-0,114
CŚ	0,150	0,850	-0,137	-0,044

Created table II contains 4 variables: Tolerance, R-square, Partial Correlations and Semi-partial correlations. The smaller the Tolerance is, the more its changing is related to other independent variables. This may mean that it is a redundant variable. Tolerance is calculated as 1-R2, so the larger the coefficient, the greater the probability that the given variable is redundant. The partial correlations coefficient shows to what degree the given independent variable explains the dependent variable taking into account the remaining relations of the independent variables. The semi-partial correlations factor, shows to what degree the independent variable explains the dependent variable but the influence of the remaining variables is excluded.

In studied relations, the Semi-partial correlations factor of both wind direction and air pressure are much smaller in comparison with other variables. In order to show the results obtained, a scatter plot was made. It shows the relation between generated power and the variables selected for exclusion (fig. 3-4).

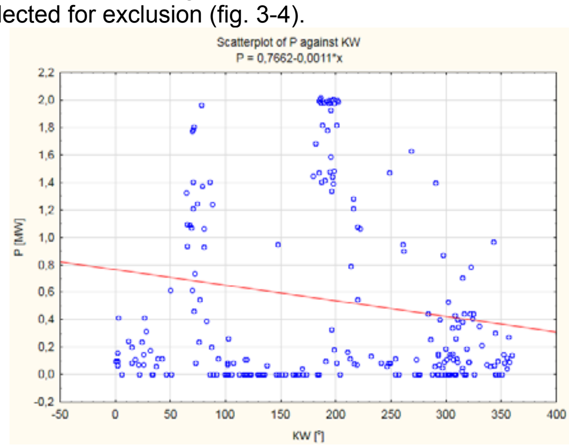

Fig.3. Scatter plot – relation between generated power (P) and wind direction (KW)

Sample distribution on the charts, confirms the hypothesis, that the wind direction and air pressure variables do not affect power generated by the turbine. This is the reason to exclude those variables from further analyses, and to take wind speed and temperature into account. Their tolerance, partial and semi-partial correlations factors are much greater than those of wind direction and air pressure. However, this does not mean, that there is not a redundant variable among them. Further analyses must be made.

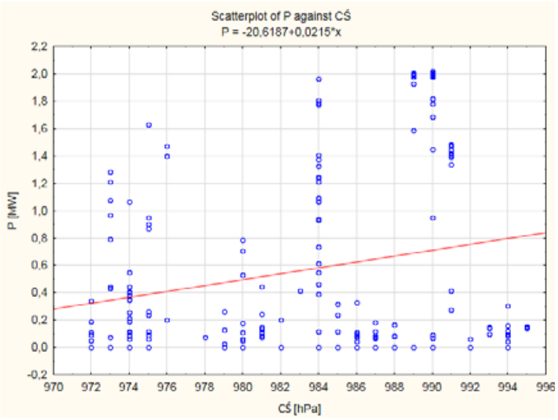

Fig.4. Scatter plot – relation between generated power (P) and air pressure (CŚ)

Table 3. Multiple regression – analysis results of relation between generated power, wind speed PW, and temperature T

	Regression Summary for Dependent Variable: P (wind) R= ,94283713 R^2= ,88894185 Adjusted R2= ,88813415 F(2,275)=1100,6 p<0,0000 Std.Error of estimate: ,28578					
N=277	b*	Std. Error of b*	b	Std. Error of b	t(275)	p-value
PW	1,032	0,023	0,118	0,003	45,538	0,000
T	-0,249	0,023	-0,016	0,001	-11,002	0,000

The model, which considers the other two variables (PW, T), more accurately describes the relation – the value of F test is greater than before. Similarly as before, the tests show that there is some dependence between generated power and wind speed or temperature. The next step was to analyze redundancy.

Tolerance and R-square factors are equal for both variables. However, Partial- and Semipartial correlations factors are much smaller for temperature. The temperature variable may be redundant too.

The generated scatter plot (fig. 5) confirms that, the generated power and temperature are not substantially related. Temperature must be rejected from the analysis.

Table 4. Redundancy – analysis results of relation between generated power, wind speed PW and temperature T

	Redundancy of the independent variables; DV: P (wind) Variable R-square - between the current variable and all other variables in the regression equation			
Variable	Tolerance	R-square	Partial Correlations	Semi-partial Correlations
PW	0,787	0,213	0,940	0,915
T	0,787	0,213	-0,553	-0,221

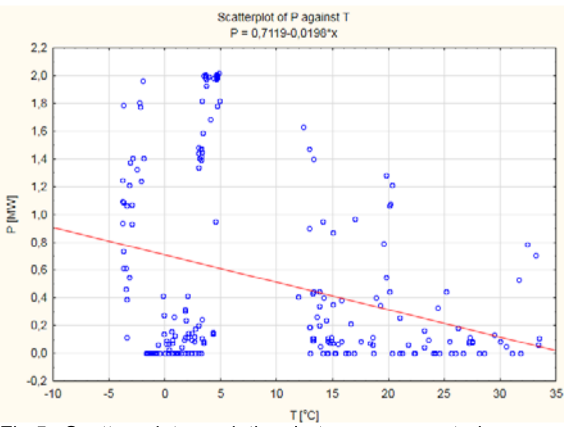

Fig.5. Scatter plot – relation between generated power (P) and temperature (T)

For a certain range of wind direction, temperature or air pressure, increase of generated power in the Fig. 3 ÷ 5 was noted. To finally reject influence these parameters on power, surface plots: P = f (PW, KW), P = f (PW, CŚ) and P = f (PW, T), were made (Fig. 6 ÷ 8). In all cases, only increasing of the wind speed, caused raising of generated power of the turbine.

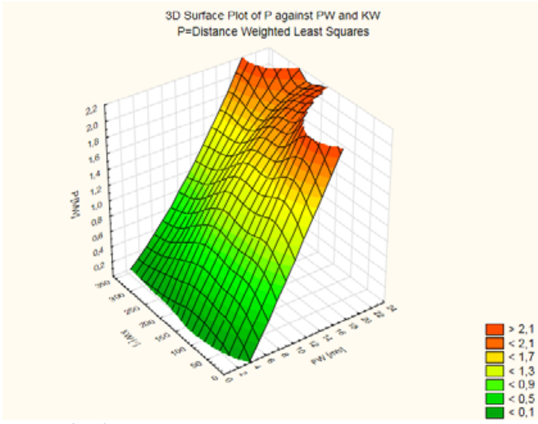

Fig.6. 3D Surface Plot – relation between generated power (P), wind speed (PW) and wind direction (KW)

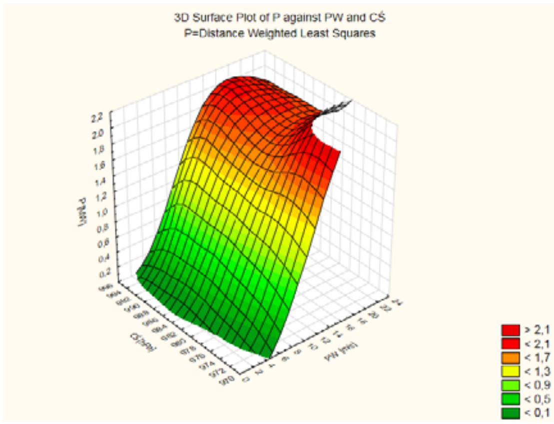

Fig.7. 3D Surface Plot – relation between generated power (P), wind speed (PW) and air pressure (CŚ)

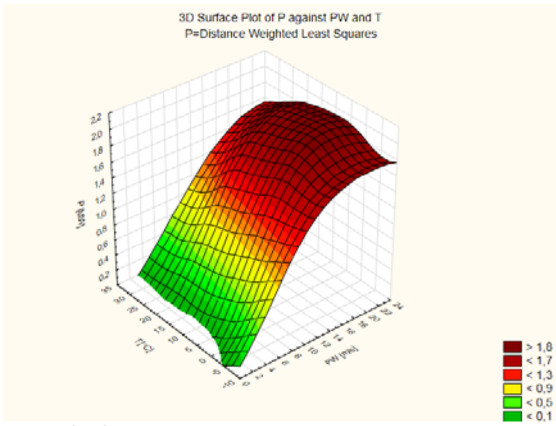

Fig.8. 3D Surface Plot – relation between generated power (P), wind speed (PW) and temperature (T)

Relation between the generated power and wind speed

Further analysis results confirm the correctness of the decision to exclude temperature. Following figures (fig. 9 ÷ 13) show attempts to find polynomial, that describes dependence between turbine power and wind speed.

Describing analyzed dependence with linear function is not satisfactory. That linear model does not consider that the generator is turned off after exceeding the maximum wind speed for energy generation and regulation of angle of attack in rotor blades for wind speed above 12 m/s.

Table 5. Multiple regression – analysis results of relation between generated power and speed PW

	Regression Summary for Dependent Variable: P (wind) R= ,91654732 R^2= ,84005898 Adjusted R2= ,83947949 F(1,276)=1449,6 p<0,0000 Std.Error of estimate: ,34233					
N=277	b*	Std. Error of b*	b	Std. Error of b	t(276)	p
PW	0,917	0,024	0,105	0,003	38,074	0,000

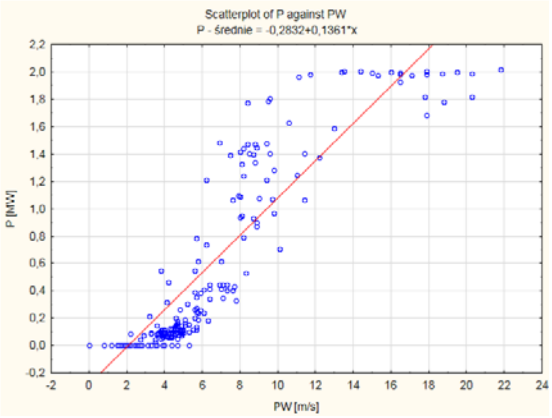

Fig.9. Scatter plot – relation between generated power (P) and wind speed (PW), matching with the linear function

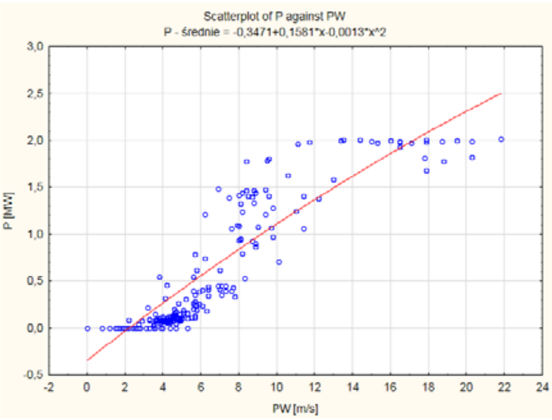

Fig.10. Scatter plot – relation between generated power (P) and wind speed (PW), quadratic function fit

The quadratic function fit did not significantly change the curve (Fig. 10), so it was decided to fit polynomials of higher degrees.

The polynomials of 3rd, 4th and 5th degrees (Fig. 11 ÷ 13), for low wind speed, similarly describe the studied relations. Some differences arise, after reaching the maximum power generated by the turbine – 2 MW. The maximum of the 3rd degree polynomial, exceeds the maximal capacity of power generated, but shows a decrease of power at higher wind speeds. The polynomial of the 4th degree, reproduces well the fragment where the turbine operates with maximum output, but for wind speeds around 21 m/s function reaches the local minimum, and starts to grow – this is not consistent with the assumption that for wind speeds above 24 m/s the turbine is stopped. Some similar features are shown with the 5th degree polynomial – but in the range where the generated power stabilizes, the mapping is worse than with the 4th degree polynomial. Such a situation, likely has to do with the fact that there are missing samples for high wind speed – when the. turbine is stopped. The data from this range should be obtained for better reproduction of the model. Unfortunately, situations when there is a need to stop the turbine are rare in the area where the measurements were performed. That situation did not take place during measurements

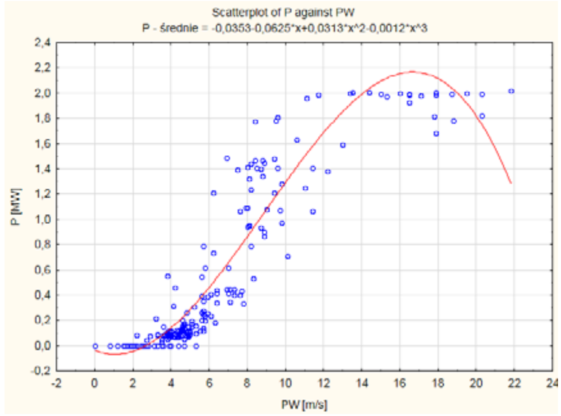

Fig.11. Scatter plot – relation between generated power (P) and wind speed (PW), polynomial of 3rd degree fit

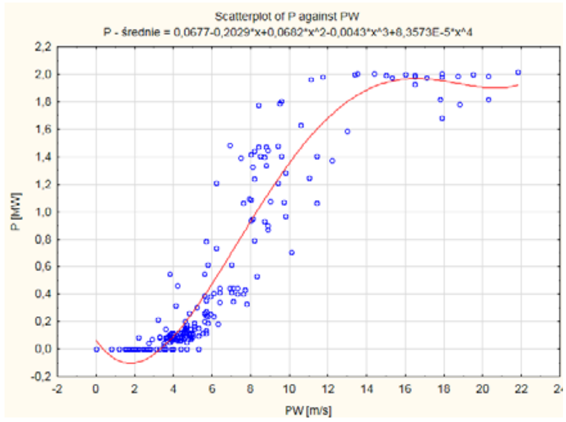

Fig.12. Scatter plot – relation between generated power (P) and wind speed (PW), polynomial of 4th degree fit

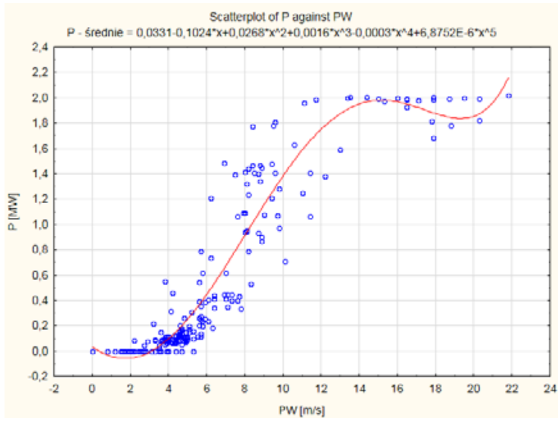

Fig.13. Scatter plot – relation between generated power (P) and wind speed (PW), polynomial of 5th degree fit

Because of data gaps in some ranges of the wind speed, the established model failed to include that case when the turbine is stopped due to safety reasons. The manufacturer declares that speed to be equal to 24 m/s. It can be assumed, that the established model works for wind speeds from 0 to 24 m/s, and that for speeds above the maximum, the generated power from the turbine is 0.

On the basis of the results of the analysis it can be stated that a polynomial of degree 4 best maps the dependence of the turbine power on the wind speed. However, amount of turbine generated power, that shows figure 2, should be considered in three ranges. These ranges are results of wind speed and the turbine work character changes. Following ranges were designated:

- 0 ÷ 3 m/s – wind speed too low – turbine does not work,
- 3 ÷ 12 m/s – turbine produces electrical energy, and it is strongly nonlinear relation
- 12 ÷ 24 m/s - generated power is constant, what is result of angle of attack control of rotor blades.

Following figures (fig. 14 ÷ 16) show results of approximation of measured turbine generated power, that is divided into designated ranges.

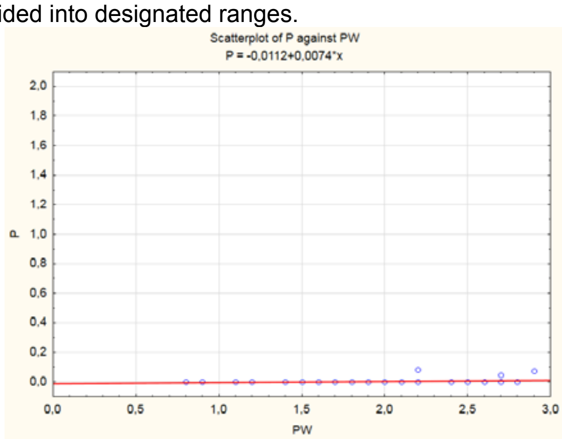

Fig.14. Scatter plot – relation between generated power (P) and wind speed (PW), linear function fit in first range

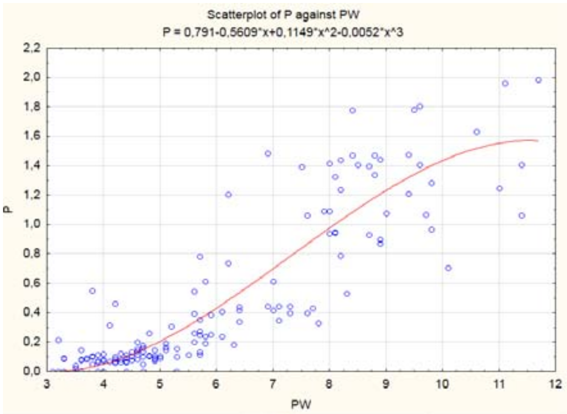

Fig.15. Scatter plot – relation between generated power (P) and wind speed (PW), polynomial of 3th degree fit in second range

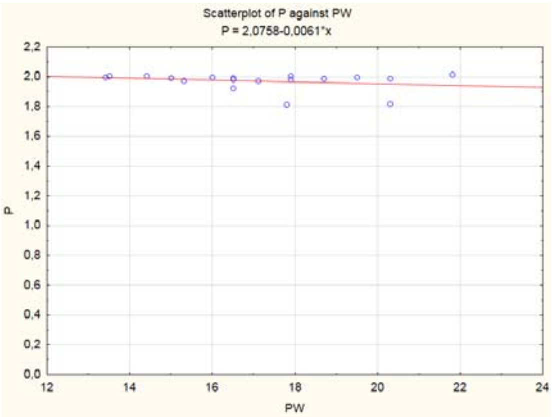

Fig.16. Scatter plot – relation between generated power (P) and wind speed (PW), linear function fit in third range

Summary

Results of the statistical analysis, done using the *Statistica* program based on data from a real wind farm, shows that the main weather condition affecting turbine generated power is wind speed. Other parameters, which were analyzed, such as temperature, air pressure, or even wind direction, have no much effect on generated power. The relation between turbine power and wind speed, is the best described by the 4th degree polynomial:

$$P = 0{,}0677 - 0{,}2029v + 0{,}0682v^2 - 0{,}0043v^3 + 8{,}36 \cdot 10^{-5} v^4 \quad (2)$$

However, if turbine work character is included, relation between generated power and wind speed is the best described by 3th grade polynomial in second range, what is compatible with theoretical relations (1) and characteristic specified by the manufacturer (fig. 2). Outside this range that equation does not apply, because of working automation of the turbine to guarantee safe work.

The paper is an example of the use of the *Statistica* program to analyze different kinds of phenomena, where the standard description of these phenomena was based on physical models. The concept of research contained in the article was reversed, as having available the appropriate measurement data from an existing wind farm, demonstrated the correctness of the equations and theoretical analysis.

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