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Field data processing techniques

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Abstract :

The problem of global warming raised up interest to renewable energy. To reduce cost of wind energy is challenge. Before building of wind park such conditions like: average wind speed, direction, time for each wind, probability of icing. Here it is proposed to consider also the influence of the amplitude of wind changes, the number of changes and their duration to be considered. This thesis presents a case based on the weather information from a weather station located at Nygårdsfjellet wind turbine park. Data analysing techniques were applied to determine power required for yaw system based on amplitude and data amount of wind changes. Characteristics of the wind turbine correspond to the actual model of wind turbine installed in the wind park. In this thesis it was identified experimental dependence between time, amplitude of wind changes and angular speed of nacelle rotation. Specific example of the full calculation procedure corresponding to the month of May is enclosed.

Abstract

Field data processing techniques are powerful tools widely apply to many different scenarios. As result of data processing techniques analytical or empirical formulations can be developed or derived. Wind energy generation is one of those areas of application where it is common practice to consider mean weather conditions, such like average wind speed, direction, time duration for each wind and probability of icing, to decide the location of the wind farm. However, the actual behaviour pattern of the weather conditions could also influence the performance of the wind farm. So, having as a test case the weather data corresponding to a year period (2008) in the location of Nygårdsfjellet wind turbine park, data processing techniques will be applied focused in the evaluation of the variation of velocity magnitude and direction on the performance of the wind turbine. The evaluated aspect is the power required to align the turbine with the wind rather than only evaluate the mean value during the studied period. Characteristics of the turbine tested corresponds to the actual turbine installed at Nygårdsfjellet wind farm. Model used corresponds to the theoretical definition of the power. Movements required for the alignment were assumed to be produced by a motor located at the nacelle. Power required for the yaw system for each month of 2008 were calculated and presented graphically. As result of the analysis of a population of 51983 points, which was divided in 12 samples of 4332 points that represent units months. Dissimilar behaviour were identified for different months, however, in general it was identified a quadratic dependency of power losses on angular speed required for the turbine to adjust its position, and therefore on time and amplitude of wind changes.

Aknowledgements

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Thanks to Marina Makarova, Hassan Zakaria for their explanations and help during my studies and last but not least to all my classmates for their support and for their contribution to a nice and cosy atmosphere inside and outside the study room.

Contents

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List of symbols

$\boldsymbol{a_0 \dots , a_n}$	Approximation constants.
$\boldsymbol{A_{daily}}$	Daily amplitude of wind changes.
$\boldsymbol{F(x)}$	Approximated function.
$\boldsymbol{I_{nacelle}}$	Inertia moment of nacelle.
$\boldsymbol{I_{rotor}}$	Inertia moment of rotor.
$\boldsymbol{I_{cm}}$	Rotational inertia around axis through the mass centre of body.
m	Mass of body.
$\boldsymbol{K_{rot}}$	Kinetic energy of rotation.
$\boldsymbol{K_{rot.acceleration}}$	Kinetic energy of rotation during acceleration.
$\boldsymbol{K_{rot.decceleration}}$	Kinetic energy of rotation during deceleration.
$\boldsymbol{l}$	Length of nacelle.
n	Number of data points in sample.
m	Mass of body.
q	Number of independent variables.
P	Power loses in yaw system.
$\boldsymbol{r^2_{Ploss,T_{change}}}$	Squared correlation coefficient between power loses in yaw system and time of wind changes.
$\boldsymbol{r^2_{Ploss,A_{daily}}}$	Squared correlation coefficient between power loses in yaw system and amplitude of wind changes.
$\boldsymbol{r^2_{Ploss,\omega}}$	Squared correlation coefficient between power loses in yaw system and angular speed of nacelle rotation.
$\boldsymbol{T_{change}}$	Time of wind changes.
$\boldsymbol{x_1 \dots . x_n}$	Variables.
$\boldsymbol{\hat{y}}$	Estimated mean value of equation.
$\boldsymbol{\beta_1 \dots . \beta_q}$	Change of mean value of y variable, that corresponds to one unit increase in the independent variable.
$\boldsymbol{\theta_0}$	Angle of turbine rotation around vertical axis at time t_0.
$\boldsymbol{\theta_1}$	Angle of turbine rotation around vertical axis at time t_1.
$\boldsymbol{\omega}$	Angular speed of nacelle rotation.

1 Introduction

Interest to wind energy increased in recent years (Bhaskar K, 2012). It is important to increase efficiency of wind turbines in order to reduce the cost per unit of delivered electrical energy (Ekelund, 2000). Improvements in wind turbines system can be classified on structural and control system improvements. Control system improvements are connected with predictive model of yaw error in a wind turbine (Tinghui Ouyang, 2017), where author derives data processing algorithms for adjusting of yaw position of wind turbine according to changes in wind direction. Turbine orientation on wind required for maximum energy extraction from wind. Different approaches have been used to pursue this purpose, for instance Stubkier (S. Stubkier H. J., 2014) showed an improvement of the efficiency of wind turbine by using a hydraulic soft yaw system, which will damp loads on a system and reduce loads on a turbine structure.

Due to the main goal of the second phase of thesis is to apply field data processing techniques to determine the amount of power required to adjust the yaw for turbines of wind turbines in order to be align with the direction of the wind, a previous review on data techniques was done. This review covered the theoretical concepts needed as well as evaluation of different tools available to apply some of those techniques. To check existence of approximated dependence of power losses as function of angular speed, if it is exist dependences between power losses and time, power losses and amplitude of wind changes, than approximate dependence between them the used of MatLab was proposed in combination with Excel data files.

For the next part of the project will be used weather data from the location of Nygårdsfjellet wind park, where average wind speed was equal 8 m/s. Regarding to the wind turbine installed in this wind park it is known (Nordkraft AS, u.d.).that they start producing at 3 m/s and stop at 25 m/s. The installed capacity of power station today is 32,2 Mw. Average total production is 105 GWh. Currently, this wind farm has 14stk, however the analysis showed here targets a typical behaviour of one wind turbine. Characteristics of the wind turbines are summarised in **Table 4**. Part of power, which is produced by station, is normally used on self-needs functionalities. One self-needs functionality is the orientation readjusting capability of turbine as respond to the wind. Other needs are supplying circuits of relay protection and automatics and warming of dispatcher room.

This thesis is organized in chapters starting with the description of the yaw system, basic construction information and functionalities in the chapter 3. In chapter 4 the presentation of the data, for wind direction, time in different wind classes and total daily amplitude of wind changes for an example, corresponding to a month of 2008, is shown by histograms.

In chapter 5 from information obtained in chapter 4 were calculated monthly and yearly yaw adjusting system power losses. In chapter 6 were analysed regressions between time of wind changes, daily amplitude of changes, angular speed of nacelle rotation and power losses for May 2008 and regressions were obtained. In part 7 the reached conclusions and possibilities for future work are given.

2 Scope

The main goal of the second phase of thesis is to apply field data processing techniques to determine the amount of power required to adjust the yaw for turbines of wind turbines in order to be align with the direction of the wind.

The specific goals can be described as:

- To analyse the wind changes, their amplitude and duration data available
- To find the analytical relation between the required power to adjust the yaw for turbines and the given variables, using as example the characteristics of the turbines installed at Nygårdsfjellet wind park.
- To find the appropriate regression function between daily time of wind changes and power losses in yaw system, total daily amplitude of changes and power losses of system, angular speed of rotor with nacelle and power losses in yaw system.
- To conclude about the influence of high and low amplitude wind direction changes on power losses in yaw system of wind turbine.

3 Yaw system description

According to the definition the yaw system of a wind turbine is the system which allows nacelle to face the wind direction (S. Stubkier H. P., 2014). Typical yaw system consists from: a number of electrical motors, gear units which are connected to a tooth rim through pinions (Liebherr, 2017). Typical yaw system is shown **Figure 1**.

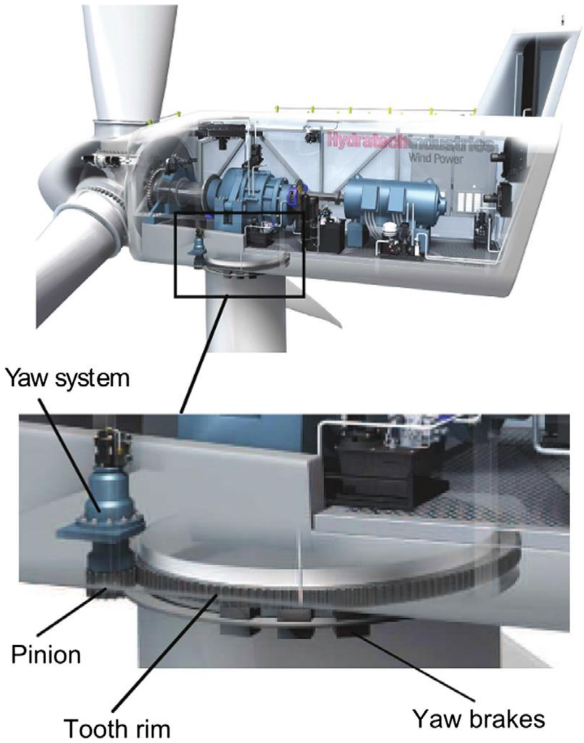

Figure 1 Typical yaw system components (S. Stubkier H. P., 2014)

Each yaw adjusting system is configured according to the power of wind turbine and they include different gearboxes, bearings, electrical motors and lubricating systems. Nowadays trend in yaw systems design is connected with using configuration of active yaw system instead of fixed yaw system (S. Stubkier H. P., 2014). An active yaw system does not use hydraulic breaks in order to block turbine in most persistent wind direction, instead it uses an electrical motor. Hydraulics systems impose more loads on gears and bearings meanwhile motors reduce the load, however the motor can work in generator mode, which will increase risk of accidently motors breakdown. That is why engineers are looking forward to reduce loads on gears and bearings to use hydraulics soft yaw systems.

All mentioned above support to keep actuality of yaw system power losses problem and influence of high and low amplitude wind changes on power losses.

4 Data description

Data from weather station located at Nygårdsfjellet contains: actual power min, max and mean values. Mean values given for each 10 min starting from zero. Data files also include wind speed, direction, average temperature and other data.

Data file include 52261 measuring's which are made for one year with 10 min intervals. Data was divided into classes that represent each month. One class contain approximately 4465 measuring's it can varies because of different days in a month.

For each class were made histograms to show wind direction ranges and the most persistent winds. This was also preparation step for writing Visual Basic Application (VBA) for excel file. Output of the program will be a table containing the duration time of the wind in a appropriate direction interval and the wind direction interval. After, this information was processed graphically. The Microsoft VBA code is given in

Attachment 1.

4.1 Data investigating

As an example of data processing will be described using as example the corresponding sample to the month of May. All other months will be proceed by using the same algorithm. Parameters of interest are time and yaw position of wind turbine.

First calculated summary statistics: mean, standard deviation, maximum and minimum values, range. After this was made histogram. Summary statistics and data for building histogram are summarised in Table 1.

Number of classes was associated with the cardinal directions. It was divided on 16 classes. It means that each interval is equal 22.5 degrees. Data for histogram summarised in **Table 2**.

Table 1 Data for histogram May

Number of data points:	4464
Xmin:	0,00
Xmax:	360,00
Range:	360,00
Number of classes:	16,0
Class width,W:	22,5

Frequency of meeting data in appropriate category from yaw position array counted by using excel function *countifs*.

Table 2 Wind direction frequency in different categories

Min	Max	Wind Name	Wind direction in degrees	Frequency
0,00	22,5	N-NNE	>=0AND<22,5	13
22,5	45,0	NNE-NE	>=22,5AND<45	81
45	67,5	NE-ENE	>=45AND<67,5	40
67,5	90,0	ENE-E	>=67,5AND<90	668
90	112,5	E-ESE	>=90AND<112,5	1440
112,5	135,0	ESE-SE	>=112,5AND<135	16
135	157,5	SE-SSE	>=135AND<157,5	9

157,5	180,0	SSE-S	>=157,5AND<180	5
180	202,5	S-SSW	>=180AND<202,5	6
202,5	225,0	SSW-SW	>=202,5AND<225	9
225	247,5	SW-WSW	>=225AND<247,5	48
247,5	270,0	WSW-W	>=247,5AND<270	454
270	292,5	W-WNW	>=270AND<292,5	1274
292,5	315,0	WNW-NW	>=292,5AND<315	273
315	337,5	NW-NNW	>=315AND<337,5	125
337,5	360,0	NNW-N	>=337,5AND<360	3

Histogram helps to summarize data and give wind direction distribution on Nygårdsfjellet in May (see **Figure 2**). Numbers on the top of each column shows how many measuring are in appropriate interval.

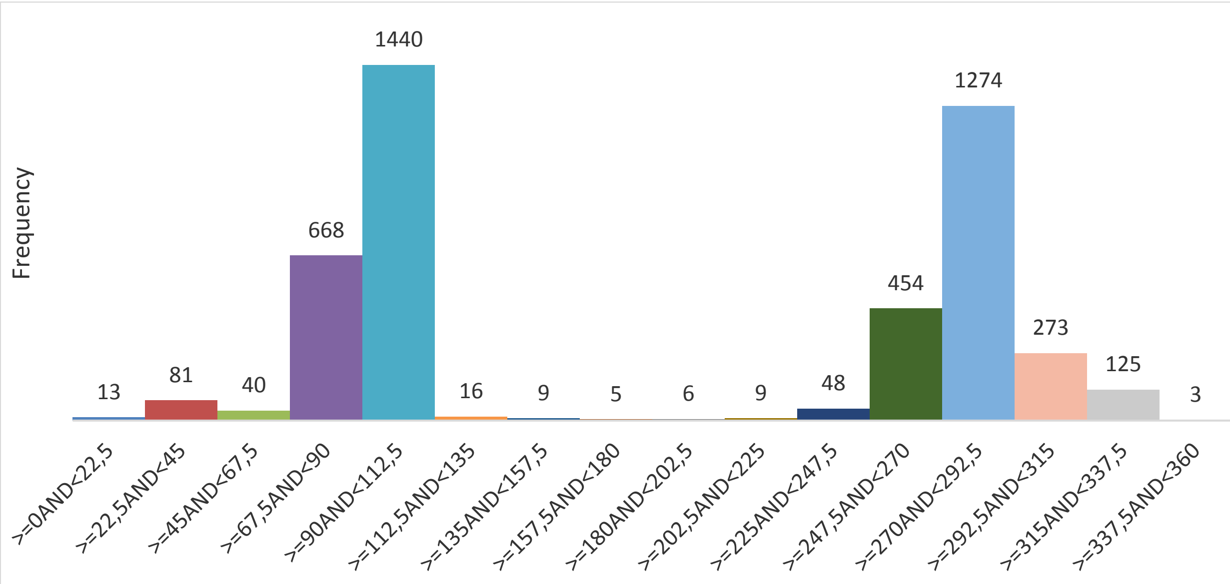

Figure 2 Wind direction distribution on Nygårdsfjellet May 2008

By multiplying the number of measuring’s in an interval by the duration of the interval (ten minutes) and dividing multiplication on 60 to transform this time into hours, the duration of wind on a particular wind direction in hours was found. Result of this manipulation of the data is presented in graph **Figure 3**, keeping the same wind classes.

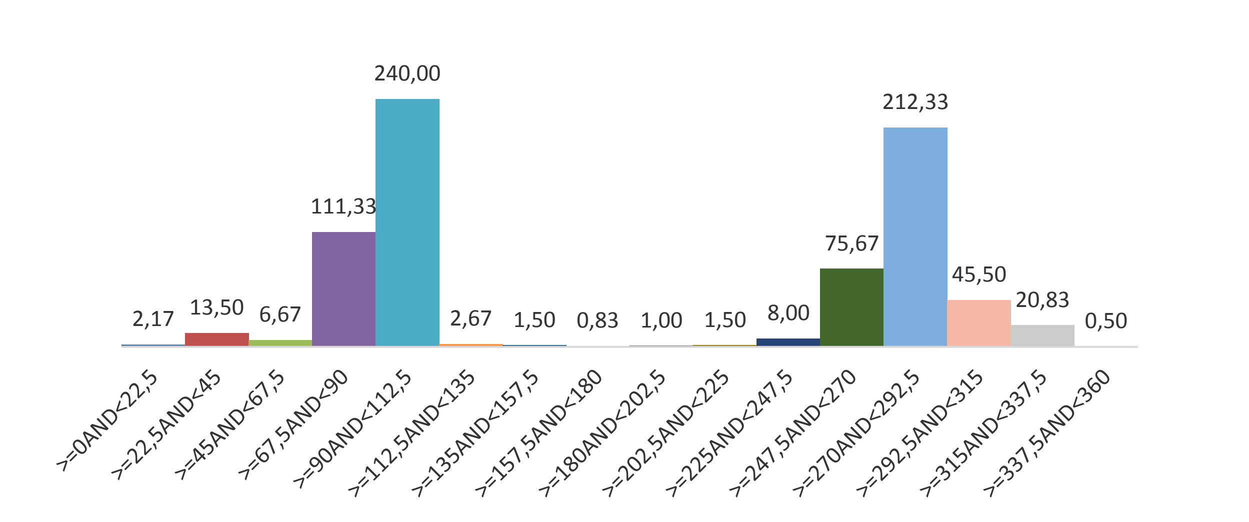

Figure 3 Time in different wind classes on Nygårdsfjellet May 2008

However, graph on **Figure 3** doesn’t give information about time which wind turbine used on reorientation between wind classes.

To determine wind changes from one class to another scatter plots, which shows how wind direction changes during one week, were made. Weekly range was chosen because of better graph representation. Weekly scatter plots for May is shown in

Attachment 1. Changes of wind from class to class were determined from graphs. Changes for May are summarised in **Table 5** in

Attachment 1.

In **Figure 4**, it is possible to visualize total daily amplitudes of wind changes was build histogram for month values.

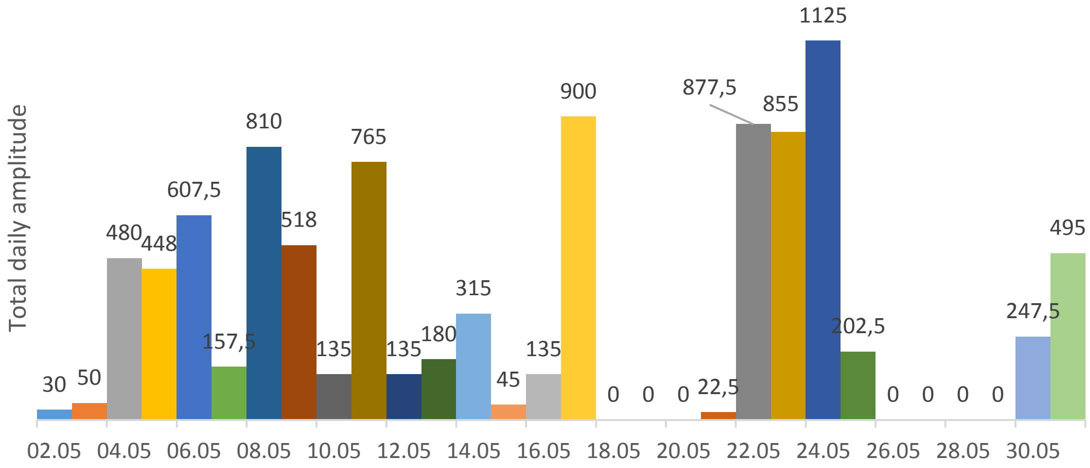

Figure 4 Total daily amplitude of wind changes May 2008

By summing individual month amplitudes, total month amplitude of changes can be found, and this value can be used to determine the required power to readjust the wind turbine.

5 Power losses on readjusting of wind turbine

In this part, it will be calculated the monthly and yearly power required for the wind turbine reorientation and they will be given by a graphical representation of the data.

During reorientation, wind turbine will consume some power P,(w) because the yaw system must produce the needed rotation of the turbine around its vertical axis.

For determining this power some assumptions were made. One assumption was that turbine moment of inertia is known. This assumption is supported on the fact that mass of turbine can be found is known from literature (Simens, 2015). Second assumption is that the turbine rotates in steady state mode around vertical axis.

Kinetic energy of rotation determined by formula (1) from (Wolfson, 2012):

$$K_{rot} = \frac{1}{2} I\omega^2 \qquad (1)$$

where I – inertia moment of rotation object($kg\ m^2$), ω- angular speed (rad/s).

With assumptions that angular speed and moment of inertia are known, kinetic energy for vertical axis rotation of wind turbine for each day of appropriate months can be determined. According to power definition, it can be found power as function of kinetic energy as:

$$P_{rot} = \frac{K_{rot}}{\Delta t} \tag{2}$$

where Δt – daily time in seconds. Power will be reported in Watts (Joule divided by second).

Second scenario of calculating power on reorientation of wind turbine contains more complicated model of rotation which include: acceleration, steady state and breaking mode of using machine. Then kinetic energy of rotation represented by formula (3):

$$K_{rot} = K_{rot.acceleration} + K_{rot.steady\ state} + K_{rot.deceleration} \tag{3}$$

In order to obtain power in Watts each kinetic energy must be divided on appropriate time in seconds, formula (4)

$$P_{rot} = \frac{K_{rot.acceleration}}{t_{acceleration}} + \frac{K_{rot.steady\ state}}{t_{steady\ state}} + \frac{K_{rot.deceleration}}{t_{deceleration}} \tag{4}$$

According to formula (1) can be calculated daily rotational kinetic energy $K_{rot.daily}$. Moment of inertia for rotor with nacelle is calculated by formula from literature (Wolfson, 2012), with the approximation that the nacelle is taken as cylindrical rod with length of 4 meters and a thin disk rotor with radius 46 meters. Inertia moment of nacelle and rotor can be determined by formulas (5) and (6):

$$\mathrm{I_{nacelle}} = \frac{1}{3}\mathrm{ml}^2 = \frac{1}{3}82000 \cdot 4^2 = 437{,}333 \cdot 10^3\ (\mathrm{kg} \cdot \mathrm{m}^2) \quad (5)$$

$$\mathrm{I_{rotor}} = \frac{1}{4}\mathrm{mr}^2 = \frac{1}{4}60000 \cdot 46^2 = 31740 \cdot 10^3\ (\mathrm{kg} \cdot \mathrm{m}^2) \quad (6)$$

where in our case m mass of nacelle and rotor (Simens, 2015), r is radius of disk and l is lengths of rod.

By using parallel axis theorem from (Wolfson, 2012):

$$\mathrm{I} = \mathrm{I_{cm}} + \mathrm{md}^2 \quad (7)$$

where I_{cm}-rotational inertia around axis through the mass centre of the body, m – mass of body in kg, d- distance from I_{cm} to axis around which the body will rotate. Parameters of equation (7) are presented on **Figure 5**. Using the given values then the moment of inertia of the rotor from (7) is then equal:

$$\mathrm{I_{rotor}} = 31740 \cdot 10^3 + 60 \cdot 10^3 \cdot 4^2 = 32700 \cdot 10^3\ (\mathrm{kg} \cdot \mathrm{m}^2) \quad (8)$$

Total moment of inertia for nacelle and rotor can be found by formula:

$$\mathrm{I} = \mathrm{I_{nacelle}} + \mathrm{I_{rotor}} = 437{,}333 \cdot 10^3 + 32700 \cdot 10^3 = 33137{,}333 \cdot 10^3\ (\mathrm{kg} \cdot \mathrm{m}^2) \quad (9)$$

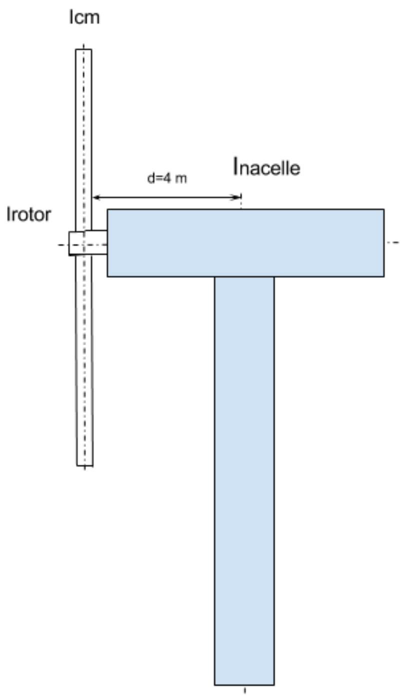

Figure 5 Wind turbine inertia moment

Angular speed of rotation for nacelle and rotor can be determined from definition of angular speed:

$$\omega = \frac{\theta_1 - \theta_0}{t_1 - t_0} (\text{rad/sec}) \tag{10}$$

According formula (10) angular speed is in variation in angles in degrees per second, it means that in order to obtain angular speed in radians per second values should be divided on $57{,}3°$ to get ω in (rad/sec).

Time interval $t_1 - t_0$ is number of wind changes, multiplied by ten in seconds.

After were calculated daily angular speed ω, (rad/s) kinetic energy of rotation by formula (1). Finally, it was obtained rotational power in Watt for each day. Daily power on reorientation of wind turbine in May 2008 is described by graph on **Figure 6**.

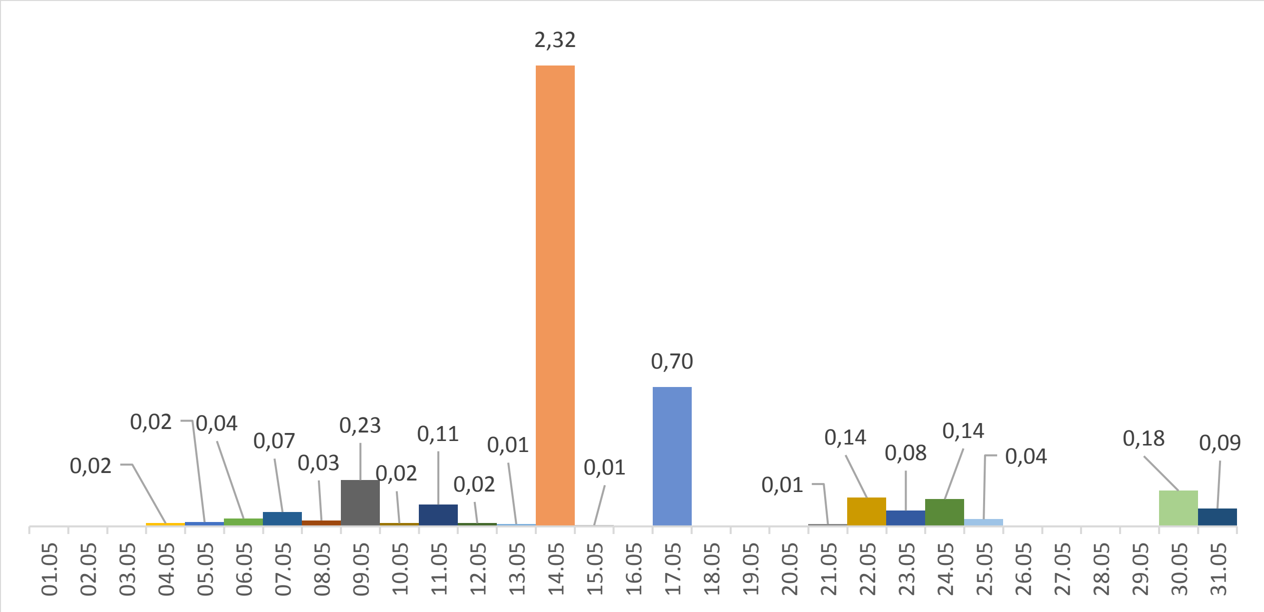

Figure 6 Power on wind turbine reorientation, May 2008

Total kinetic energy of rotation and energy are equal to 5 730 (J) and 4.27 (W).Year distribution of power losses is shown on **Figure 7**. The obtained power losses in yaw system are summarised in a histogram.

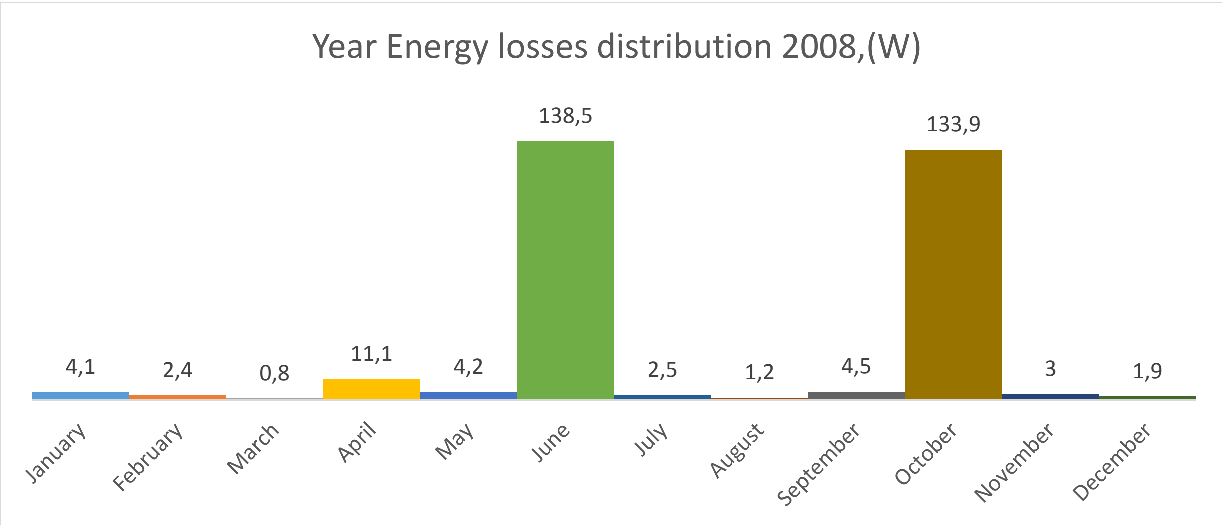

Figure 7 Year power losses distribution on reorientation of turbine

Low power in yaw system can be explained by low calculated moment of inertia for wind turbine, Siemens SWT-2.3-93. Real moment of inertia is a company's protected information. With the use of actual moment of inertia, power required for the yaw system will be more realistic.

6 Data specifying

In this part, regression between time of wind changes, daily amplitude of changes, angular speed and power required for the yaw system for May 2008 will be analysed.

Firstly, possibilities of variables dependence were studied. Theoretically power used on wind turbine reorientation is a function of turbine moment of inertia I and angular speed ω, so, this can be described by formula (11)

$$P_{loss} = f(\, I, \omega^2) \quad (11)$$

Angular speed ω depends from time of changes T_{change} and daily magnitude of changes A_{daily}, than formula (11) can be rewrite like:

$$P_{loss} = f(\, T_{change}, A_{daily}) \quad (12)$$

By using Microsoft excel and *rsq* function, which is giving square of correlation coefficient where checked goodness of estimated regression to the samples data points. Results of power as function of daily time of wind change, daily amplitude of change and angular speed are summarised in a **Table 3**

Table 3 Correlation coefficients for data samples

Square of correlation coefficient, r^2	Result
$r^2_{Ploss,T_{change}}$	0,104
$r^2_{Ploss,A_{daily}}$	0,031
$r^2_{Ploss,\omega}$	0,7841

From results in **Table 3** it can be observed that the is not logical to look for regression in these first two cases. It was decided then, to look for a multiple regression between time of changes T_{change}, daily magnitude of changes A_{daily}, angular speed of changes ω and the power required for the yaw adjusting system P_{loss}. Data for regression analyses for the example case of May is presented in **Table 6** of the

Attachment . Estimated multiple regression equation looks like:

$$\hat{y} = b_1x_1 + b_2x_2 + \ldots + b_qx_q + b_0 \quad (13)$$

where q – number of independent variables, b_0 –point estimate of β_0, mean of dependent variable y, when all the independent variables are equal to zero, b_1, $b_{2,}\ldots b_q$ – point estimates of Slope β_1, β_2,… β_q which is the change in mean value of y variable, that corresponds to a one unit increase in the independent variable x_1, while holding all of the other independent variables constant, $\hat{y}$ – estimated mean value of the dependent equation (Rice, 1987).

Dependence between parameters is described by a polynomial of first order, as shown in formula (14):

$$\hat{y} = 0{,}00147x_1 - 0{,}0012x_2 + 242{,}99x_3 - 0{,}084 \quad (14)$$

Where x_1, x_2, x_3 are appropriately time of yaw system work, daily amplitude of changes in degrees and angular speed rotation of rotor with nacelle.

Formula (14) gives reliable results when x values are entered into equation over the experimental region for each x value, experimental regions for each x is given in **Table** 5

Table 5 Experimental region for independent variables

	Experimental region		
	X1	X2	X3
min	0	0	0
max	80	1125	0,00916

In equation (14) coefficient b_1 is equal to 0,00147, which means that by holding daily amplitude and fixed angular speed for 1 minute increment, power will increase on 0,00147. It means that with increasing of work time, power needed on yaw adjusting will increase. Also with increasing of angular speed power will also increase, as it is shown by coefficient b_3, which is equal to 242,99. This coefficient shows that for fixed time and angular speed, for 1 rad/sec increase power losses will rise on 243 Watt. A negative b_2 coefficient shows that with increasing daily amplitude of change for 1 degree, with fixed time of system work and angular speed, power will decrease on 0,0012 Watt.

From equation (14) can be made conclusion, that power loss in yaw adjusting system will be bigger from many small changes with total amplitude equal to one big change, than for one big change. It means that to rotate turbines nacelle with rotor on 100 degrees for one time, require less power than ten times rotate nacelle with rotor on 10 degrees.

From this follows that placement of wind turbine can be in places with high amplitude of wind changes and not in places with law amplitude and frequent wind changes.

6.1 Approximation of dependence between power and angular speed.

Least square method will be used because large amount of measuring in data set. In order to explain this should be clarified difference between approximation and interpolation.

Interpolation is finding polynomial $y = F(x)$ of certain degree for values of x = (x_0, x_1,…. x_n) and y=(y_0, y_1,…. y_n) (Kreyszig). **Figure 8** shows this definition. The polynomial function must satisfy following conditions:

$$\begin{cases} F(x) = y_0, \\ F(x) = y_1, \\ F(x) = y_n. \end{cases} \tag{15}$$

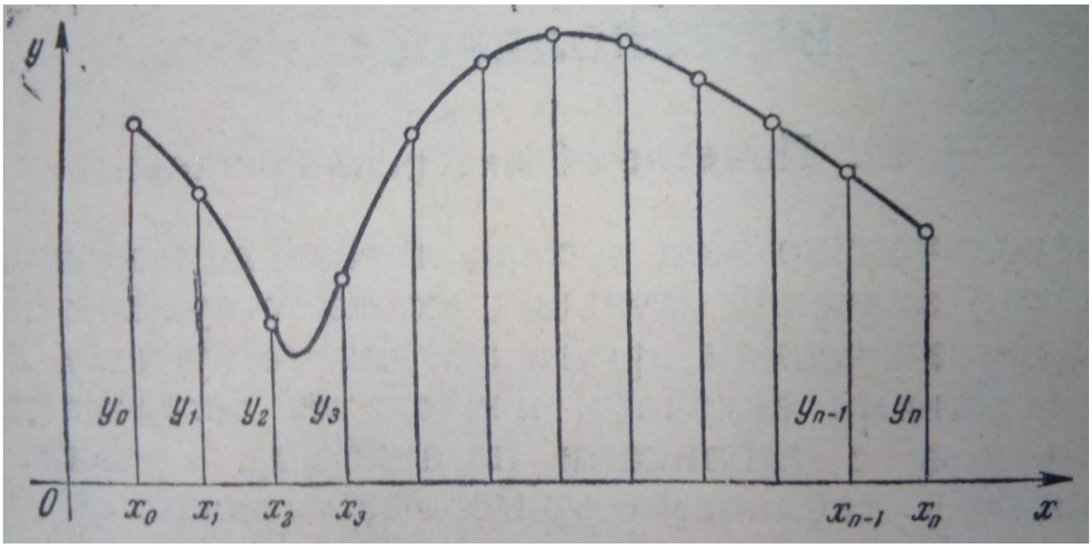

Figure 8 Interpolated curve

In other words interpolation is finding analytical expression for polynomial, which takes the same values in points of interpolation. Polynomial $F(x)$ which satisfies condition expressed in equation (15) are called interpolated polynomial.

Least square approximation and other kind approximations are used because it is required to deal with deviations or errors in data measurements. The task of such data processing is to give written trend of dependence and to eliminate random errors, which are connected with experiment. Often character of dependence is identified from physical nature of experiment.

Each measuring contributes to the final equation, which contains unknown coefficients. With larger amount of measuring's, the number of arguments in system of equations (15) becomes bigger than amount of functions. Most accurate coefficient is found by approximation, which will not satisfy any equation of the system. For example given function with m+1 parameters:

$$y = f(x_i;\ a_0,\ a_1, \dots\ a_m) \quad (16)$$

Parameters $a_0,\ a_1, \dots\ a_m$ are constants which should be found. In order to find them makes measuring's of x and y, by substituting them into (16), will be obtained equation between parameters (17):

$$y = f(x_i;\ a_0,\ a_1, \dots\ a_m),\ i=1,2,\dots n \quad (17)$$

Because of errors in measuring's in the are usually more than number of constants, $n > m + 1$, and system of equations will not be solvable. That why task transforms in task of finding coefficients $a_0, a_1, \ldots a_m$ that will solve this system as close as possible, but not exactly in order to avoid the inclusion of the measuring error. These coefficients will be closer to exact than bigger amount of measuring's is made. Due to this reason it will be used approximation by least square method for obtaining experimental dependences.

Figure 9 presents graphically the dependence between angular speed and power, under the assumption that dependence is described by formula (18).

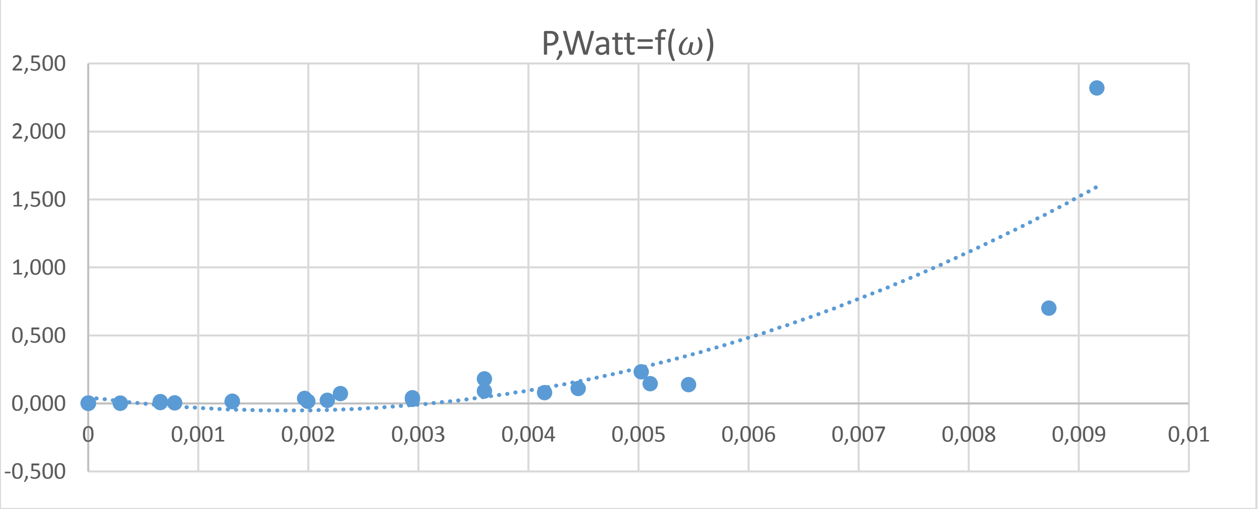

Figure 9 Power losses as function of angular speed

$$P = a + b\omega^2 \tag{18}$$

where a and b are constants, which should be found. By applying least square principle to (18) obtained formula:

$$F(a,b) = \sum_{i=1}^{n} (P_i - a - b\omega_i^2)^2 \tag{19}$$

By differentiation equation (19) with respect to a,b and equalling it to zero will be obtained system of equations (20)

$$\begin{cases} na + b\sum_{i=1}^{n}\omega_i^2 = \sum_{i=1}^{n}P_i \\ a\sum_{i=1}^{n}\omega_i^2 + b\sum_{i=1}^{n}\omega_i^4 = \sum_{i=1}^{n}P_i\omega_i^2 \end{cases} \quad (20)$$

Sums of equation (20) were calculated and summarized in **Table 7** at

Attachment 1. After solving equation (20), with known coefficients a and b equation (18) becomes:

$$P = -0{,}061729 + 17866{,}55\omega^2 \tag{21}$$

The same coefficients were obtained by approximating with help of Mathlab function *lsqnonlin*, used code is placed in

Attachment 2.

By using excel trend line feature, was obtained quadratic function of shape which shown on **Figure 10**.

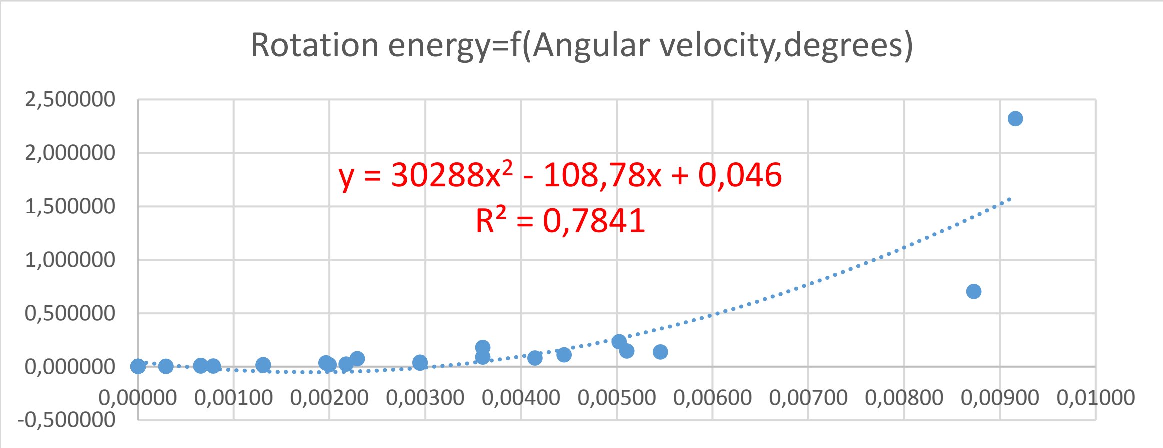

Figure 10 Quadratic function power loses as function of angular speed

Quadratic function is shown in formula (22)

$$P = 30288\omega^2 - 108{,}78\omega + 0{,}046 \tag{22}$$

In order to compere to functions errors of function in equation (21) and equation (22) were calculated. Error calculations are summarised in **Table 8**. It seems that function in equation (21) gives more precise estimated values of dependence between angular velocity and power loses in yaw regulating system.

7 Conclusion and future work

This thesis presents an application of the data processing technique of weather conditions corresponding to the location of a wind turbine farm. Analysis of the raw data pointed out a relevant presence of changes in the magnitude and direction of the wind velocity beside the mean values. These variations were identified to the influential variables on the power required for the turbine to be aligned with the wind direction in order to have the optimal output.

Interpretation of this power can be associated with the concept of power losses of the turbine, due to the fact that this power has to be included to power losses in system.

In practice, rotation of turbine around vertical axis is implemented by the yaw system. To determine power losses required by a yaw system daily information of wind changes, for sample size equivalent to a month were obtained. Calculation procedure was stablished starting with the calculation of the time during which the wind is changing and daily amplitude of the changes. Angular speeds of nacelle was estimated assuming uniform movement conditions.

Direction of the wind was classified using 16 sector of 22.5 degrees each, which corresponds to the cardinal referential directions.

The limit case of reaction of the turbine to a variation of a minimum of 1 degree was imposed. Then, together with the overlapping of geometrical model for inertia, power losses in turbine yaw system were calculated. All new variables data were presented graphically. In this work it was found multiple linear regression, which represents adequately the variation of power losses in yaw system as function of: the total daily amplitude of wind changes, angular speed of nacelle and time of wind changes.

Additionally was obtained experimental dependence between angular speed of nacelle and yaw system power losses. From mentioned finding, it can be said that one large amplitude changes require less power than many small changes with same total amplitude. Therefore, it is preferably to install wind turbines in places with high amplitude of wind changes than in places with low amplitude wind changes. This will lead to lower yaw system loses and can reduce the cost per unit of delivered electrical energy.

As future work, power loses, can be recalculated with using higher moment of inertia, obtained regressions can be checked for each month of the year.

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Appendix 1

Prestudy report Part 1

Excel fiels: windChangesWinterRegressions, WindChanges summer

Attachment 1

Table 4 Nygårdsfjellet wind generator data

Tower height	80 m
Rotor diameter	90 m
Rotor area	6361 m2
Nacelle weight	82 tonn
Tower weight	158 tonn
Rotor weight	60 tonn
Total weight	300 tonn

Table 5 Number of changes and amplitude in May 2008.

Day	Total number of changes	Daily amplitude of changes and amount, (degrees)	Direction	Corresponding degrees
01.05.2008	0	0	E-ESE	90-112,5
02.05.2008	3	3·10	E-ESE to ESE-SE	90-112,5 to 112,5-135
03.05.2008	5	5·10	E-ESE	90-112,5
04.05.2008	7	1·210; 3·67,5; 3·22,5	E-ESE to WNW-NW;WNW-NW to WSW-W; WSW-W to W-WNW; W-WNW to WSW-W;	90-112,5 to 292,5-315; 292,5-315 to 247,5-270; 270-292,5 to 247,5 – 270;
05.05.2008	6	1·65, 1·90; 1·158; 3·45;	WSW-W to WNW-NW;WNW-NW to SW-WSW;SW-WSW to ENE-E; ENE-E to E-ESE;	247,5-270 to 292,5-315; 292,5 – 315 to 225-247,5; 225-247,5 to 67,5-90; 67,5-90 to 90-112,5;
06.05.2008	6	3·45;1·90;1·337,5;1·45	ENE-E to E-ESE; E-ESE to N-NNE; N-NNE to NW-NNW	67,5-90 to 90-112,5; 90-112,5 to 0-22,5; 0-22,5 to 315-337,5
07.05.2008	2	1·112,5; 1·45;	NW-NNW to WSW-W;WSW-W to W-WNW	315-337,5 to 247,5 – 270; 247,5 – 270 to 270- 292,5
08.05.2008	8	1·225; 3·45; 1·90; 1·315; 1·45; 1·90	W-WNW to ENE-E; ENE-E to E-ESE; E-ESE to NNE- NE;NW-NNW to WSW-W;	270-292,5 to 67,5-90; 67,5-90 to 90 – 112,5; 90 – 112,5 to 22,5 – 45; 315-337,5 to 247,5-270;
09.05.2008	3	1·203;1·45;1·270	WSW-W to ENE – E; ENE –E to NNE – NE; NNE-NE to W-WNW;	315-337,5 to 67,5 – 90; 67,5 – 90 to 22,5 – 45; 22,5 – 45 to 270-292,5;
10.05.2008	3	3·45	W-WNW to WNW - NW	270-292,5 to 292,5 – 315;

11.05.2008	5	1·202,5; 1·112,5; 1·315; 1·45; 1·90;	W-WNW to E-ESE; E-ESE to N-NNE;N-NNE to WNW-NW;WNW-NW to NNW- N;	270-292,5 to 90 – 112,5; 90 -112,5 to 0-22,5; 0 – 22,5 to 292,5 – 315; 292,5 – 315 to 337,5 -360; 337,5 -360 to 270 - 292,5;
12.05.2008	3	3·45	W-WNW to WNW-NW	270 – 292,5 to 292,5 – 315;
13.05.2008	4	2·45; 1·45; 1·90	W-WNW to WNW – NW; W-WNW to WSW-W; WSW – W to NW – NNW;	270-292,5 to 292,5 – 315; 270-292,5 to 247,5 – 270; 247,5 – 270 to 315 – 337,5;
14.05.2008	1	1·315	NNW-N to NE-ENE	315 – 337,5 to 45 – 67,5
15.05.2008	2	2·22,5	ENE-E to E-ESE	67,5 – 90 to 90 – 112,5;
16.05.2008	5	1·22,5; 2·67,5; 2·22,5	E-ESE to ENE-E; ENE – E to NNE – NE; NNE-NE to NE-ENE;	90-112,5 to 67,5- 90; 67,5 – 90 to 22,5-45; 22,5 – 45 to 45-67,5;
17.05.2008	3	1·67,5; 6·135; 1·22,5	NE-ENE to N-NNE; N-NNE to ESE-SE;ESE-SE to E-ESE;	45- 67,5 to 0-22,5; 0-22,5 to 112,5 – 135; 112,5-135 to 90 – 112,5;
18.05.2008	0	0	E-ESE	90-112,5
19.05.2008	0	0	E-ESE	90-112,5
20.05.2008	0	0	E-ESE	90-112,5
21.05.2008	1	1·22,5	E-ESE to ENE - E	90-112,5 to 67,5 – 90
22.05.2008	5	1·202,5;1·247,5; 1·315; 1·90; 1·22,5	ENE-E to WSW-W; WSW-W to NNE-NE;NNE-NE to NW-NNW;NW-NNW to WSW-W;WSW-W to W-WNW;	67,5-90 to 247,5-270; 247,5-270 to 22,5-45;22,5-45 to 315 – 337,5;315-337,5 to 247,5 to 270; 247,5 – 270 to 270 – 292,5;
23.05.2008	6	1·67,5; 1·135; 1·112,5; 1·112,5;1·292,5; 1·22,5;	WSW-W to WNW – NW;WNW-NW to N-NNE;N-NNE to ESE-SE;ESE-SE to NNE-NE;NNE-NE to WNW-NW;WNW-NW to W-WNW;	247,5-270 to 292,5-315; 292,5 – 315 to 0-22,5; 0-22,5 to 112,5-135; 112,5-135 to 22,5 -45;22,5-45 to 292,5-315; 292,5-315 to 270- 292,5;
24.05.2008	6	1·22,5; 1·90; 2·270; 1·247,5;1·202,5; 1·22,5;	W-WNW to WSW-W;WSW-W to NW-NNW;2·(NW-NNW to ENE-E);NW-NNW to ESE-E;E-ESE to W-WNW; W-WNW to WSW-W;	270-292,5 to 247,5-270; 247,5-270 to 315-337,5; 2·(315-337,5 to 67,5-90); 315 – 337,5 to 67,5-90; 67,5-90 to 270-292,5; 270-292,5 to 247,5-270;
25.05.2008	3	1·67,5; 1·112,5; 1·22,5	W-WNW to SW-WSW; SW-WSW to	270-292,5 to 225-247,5; 225-247,5 to

			NW-NNW; NW-NNW to WNW-NW	315-337,5;315-337,5 to 292,5-315
26.05.2008	0	0	W-WNW	270-292,5
27.05.2008	0	0	W-WNW	270-292,5
28.05.2008	0	0	W-WNW	270-292,5
29.05.2008	0	0	W-WNW	270-292,5
30.05.2008	2	1·22,5; 1·225	W-WNW to WNW-NW; WNW-NW to E-ESE;	270-292,5 to 292,5-315; 2· (292,5-315 to 270 – 292,5);292,5 – 315 to 90-112,5;
31.05.2008	4	1·225;1·22,5; 1·22,5;1·225	E-ESE to W-WNW; WNW-NW to E-ESE;	90-112,5 to 292,5-315; 292,5 – 315 to 90-112,5;

Microsoft VBA Application

```
Sub Button244_Click()
' MODIFY FROM HERE
tName = "Output Table"
startRow = 3
startColumn = 5
endColumn = startColumn + 13
' MODIFY TO HERE

indexColumn = startColumn
indexRow = startRow
outputIndexRow = 1

Do While Not IsEmpty(Cells(indexRow, 3))

  Do While indexColumn < endColumn
    If Cells.Item(indexRow, indexColumn) = 1 Then
      startTime = Cells.Item(indexRow, 3)

      Do While Cells.Item(indexRow, indexColumn) = 1
        indexRow = indexRow + 1
      Loop

      endTime = Cells.Item(indexRow, 3)
      timeDuration = 0
```

```
      If IsEmpty(endTime) Then
        endTime = Cells.Item(indexRow - 1, 3)
        timeDuration = 10
      End If

      timeDuration = timeDuration + DateDiff("n", startTime, endTime)

      minutes = timeDuration Mod 60
      timeDuration = timeDuration - minutes
      hours = timeDuration / 60

      Worksheets(tName).Cells(outputIndexRow, 1) = hours & " h " & minutes & " min"
      Worksheets(tName).Cells(outputIndexRow, 2) = Cells(2, indexColumn)

      indexRow = indexRow - 1
      Exit Do
    End If

    indexColumn = indexColumn + 1
  Loop
  outputIndexRow = outputIndexRow + 1
  indexColumn = startColumn
  indexRow = indexRow + 1
Loop
End Sub
```

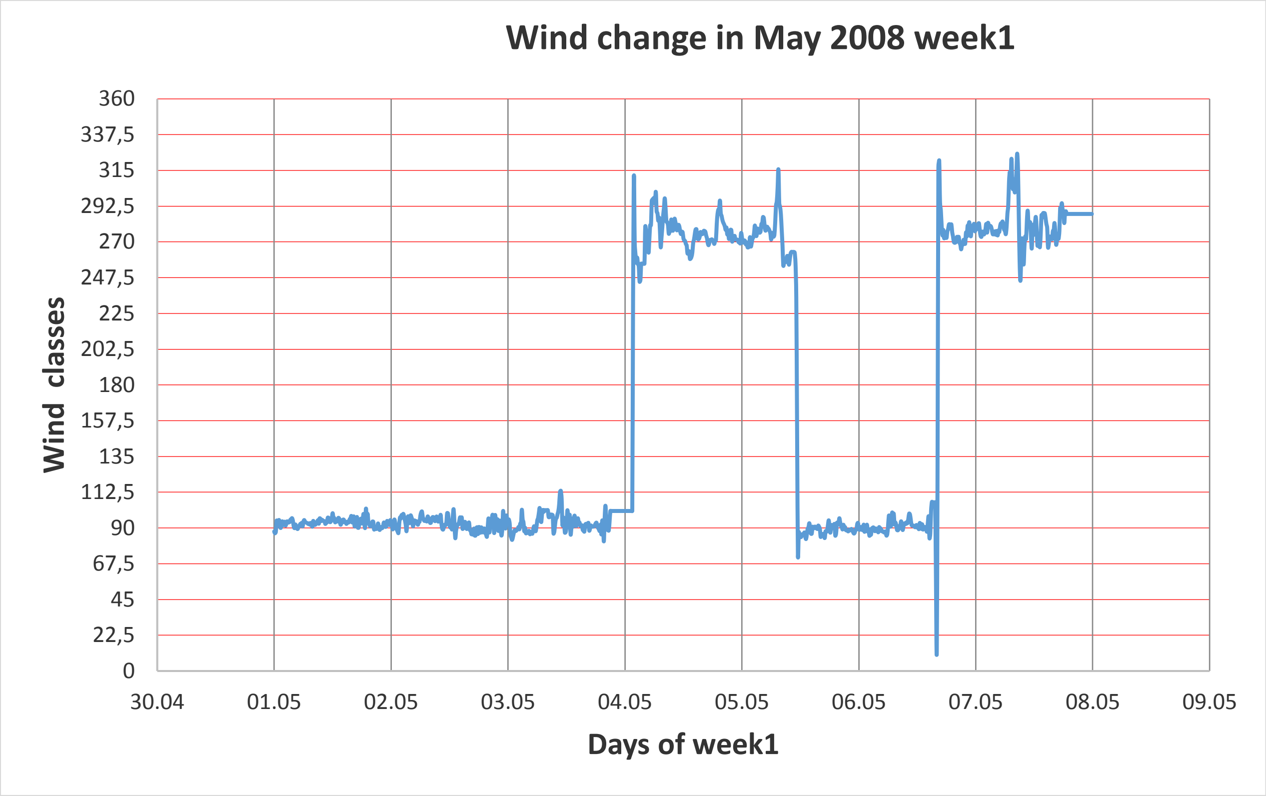
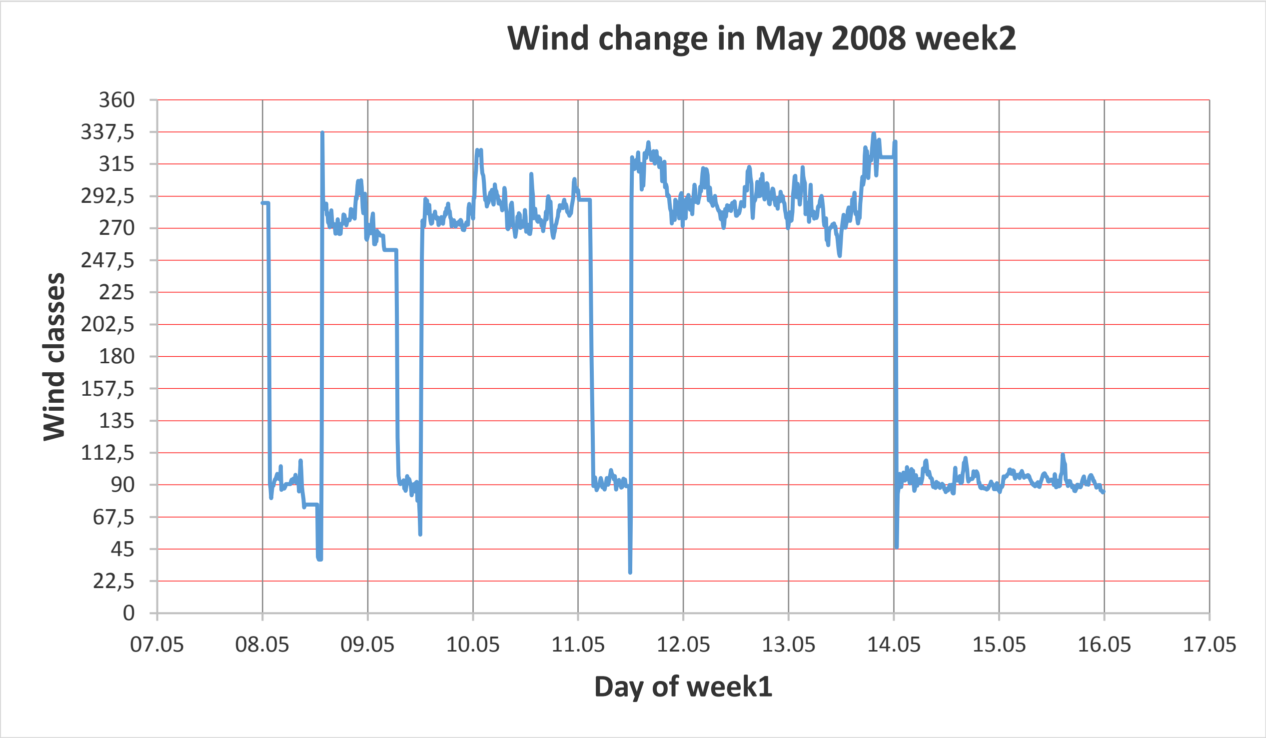
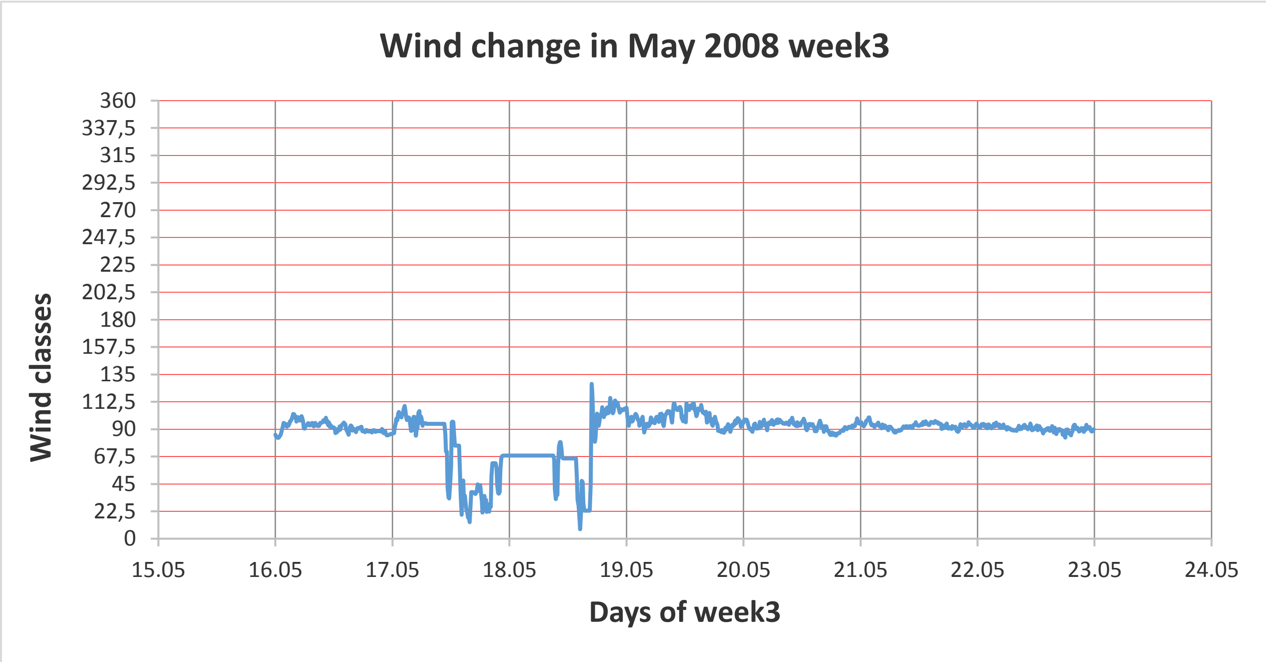


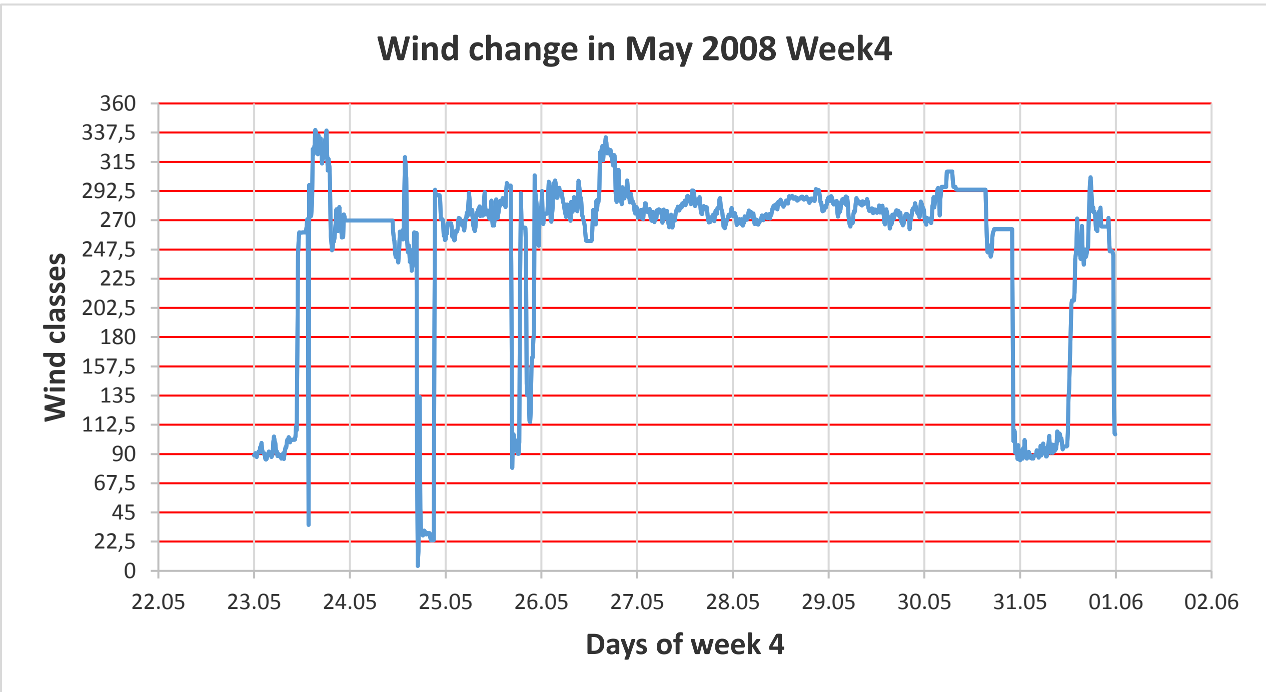
Figure 1 Wind change May 2008 week1



Figur 2 Wind cahnge May 2008 week 2



Figur 3 Winchange May 2008 week 3



Figur 4 Wind change May 2008 week 4

Table 6 Data for regression analysis for May, 2008

i, th sample point	Time, X1	Daily amplitude of changes, degrees, X2	Angular speed, rad/sec, X3	Rotation energy, Watt, Y
1	0	0	0	0,000
2	30	30	0,000290867	0,001
3	50	50	0,000290867	0,000
4	70	480	0,001994515	0,016
5	60	448	0,002171805	0,022
6	60	607,5	0,002945026	0,040
7	20	157,5	0,002290576	0,072
8	80	810	0,002945026	0,030
9	30	518	0,0050223	0,232
10	30	135	0,001308901	0,016
11	50	765	0,004450262	0,109
12	30	135	0,001308901	0,016
13	40	180	0,001308901	0,012
14	10	315	0,009162304	2,318
15	20	45	0,00065445	0,006
16	50	135	0,00078534	0,003
17	30	900	0,008726003	0,701
18	0	0	0	0,000
19	0	0	0	0,000
20	0	0	0	0,000

21	10	22,5	0,00065445	0,012
22	50	877,5	0,005104712	0,144
23	60	855	0,004144852	0,079
24	60	1125	0,005453752	0,137
25	30	202,5	0,001963351	0,035
26	0	0	0	0,000
27	0	0	0	0,000
28	0	0	0	0,000
29	0	0	0	0,000
30	20	247,5	0,003599476	0,179
31	40	495	0,003599476	0,089

Table 7 Constants for finding equation parameters for dependence of W and P

Pi	wi^2	Pi*wi^2	wi^4
0,000	0	0	0
0,001	8,46035E-08	6,58858E-11	7,15775E-15
0,000467256	8,46035E-08	3,95315E-11	7,15775E-15
0,016	3,97809E-06	6,24292E-08	1,58252E-11
0,022	4,71674E-06	1,02393E-07	2,22476E-11
0,040	8,67318E-06	3,46212E-07	7,5224E-11
0,072	5,24674E-06	3,80089E-07	2,75283E-11
0,030	8,67318E-06	2,59659E-07	7,5224E-11
0,232	2,52235E-05	5,85633E-06	6,36225E-10
0,016	1,71322E-06	2,70173E-08	2,93512E-12
0,109	1,98048E-05	2,16625E-06	3,92231E-10
0,016	1,71322E-06	2,70173E-08	2,93512E-12
0,012	1,71322E-06	2,0263E-08	2,93512E-12
2,318	8,39478E-05	0,000194605	7,04723E-09
0,006	4,28305E-07	2,53287E-09	1,83445E-13
0,003	6,16759E-07	2,10086E-09	3,80392E-13
0,701	7,61431E-05	5,33675E-05	5,79778E-09
0,000	0	0	0
0,000	0	0	0
0,000	0	0	0
0,012	4,28305E-07	5,06574E-09	1,83445E-13
0,144	2,60581E-05	3,75017E-06	6,79024E-10
0,079	1,71798E-05	1,35838E-06	2,95145E-10
0,137	2,97434E-05	4,07161E-06	8,84671E-10
0,035	3,85475E-06	1,36775E-07	1,48591E-11
0,000	0	0	0
0,000	0	0	0
0,000	0	0	0
0,000	0	0	0
0,179	1,29562E-05	2,31773E-06	1,67864E-10
0,089	1,29562E-05	1,15887E-06	1,67864E-10
4,269765889	**0,000345938**	**0,000270024**	**1,63085E-08**

Table 8 Comparison of power aproximation functions

I th, sample point	Pi	Wi	Pi calc1	Pi calc2	Pi-Pcalc1	Pi-Pcalc2	Ei1	Ei2
1	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
2	7,788E-04	2,909E-04	-6,022E-02	8,020E-02	-5,944E-02	7,942E-02	7,632E+03	1,020E+04
3	4,673E-04	2,909E-04	-6,022E-02	8,020E-02	-5,975E-02	7,974E-02	1,279E+04	1,706E+04
4	1,569E-02	1,995E-03	9,346E-03	3,835E-01	6,347E-03	3,678E-01	4,045E+01	2,343E+03
5	2,171E-02	2,172E-03	2,254E-02	4,251E-01	-8,345E-04	4,034E-01	3,844E+00	1,858E+03
6	3,992E-02	2,945E-03	9,323E-02	6,291E-01	-5,331E-02	5,891E-01	1,336E+02	1,476E+03
7	7,244E-02	2,291E-03	3,201E-02	4,541E-01	4,043E-02	3,816E-01	5,581E+01	5,268E+02
8	2,994E-02	2,945E-03	9,323E-02	6,291E-01	-6,329E-02	5,991E-01	2,114E+02	2,001E+03
9	2,322E-01	5,022E-03	3,889E-01	1,356E+00	-1,568E-01	1,124E+00	6,751E+01	4,842E+02
10	1,577E-02	1,309E-03	-3,112E-02	2,403E-01	-1,535E-02	2,245E-01	9,734E+01	1,424E+03
11	1,094E-01	4,450E-03	2,921E-01	1,130E+00	-1,827E-01	1,021E+00	1,671E+02	9,330E+02
12	1,577E-02	1,309E-03	-3,112E-02	2,403E-01	-1,535E-02	2,245E-01	9,734E+01	1,424E+03
13	1,183E-02	1,309E-03	-3,112E-02	2,403E-01	-1,929E-02	2,284E-01	1,631E+02	1,931E+03
14	2,318E+00	9,162E-03	1,438E+00	3,585E+00	8,800E-01	1,267E+00	3,796E+01	5,466E+01
15	5,914E-03	6,545E-04	-5,408E-02	1,302E-01	-4,816E-02	1,242E-01	8,144E+02	2,101E+03
16	3,406E-03	7,853E-04	-5,071E-02	1,501E-01	-4,730E-02	1,467E-01	1,389E+03	4,307E+03
17	7,009E-01	8,726E-03	1,299E+00	3,301E+00	-5,978E-01	2,601E+00	8,529E+01	3,710E+02
18	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
19	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
20	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
21	1,183E-02	6,545E-04	-5,408E-02	1,302E-01	-4,225E-02	1,183E-01	3,572E+02	1,001E+03
22	1,439E-01	5,105E-03	4,038E-01	1,391E+00	-2,599E-01	1,247E+00	1,806E+02	8,662E+02
23	7,907E-02	4,145E-03	2,452E-01	1,017E+00	-1,661E-01	9,382E-01	2,101E+02	1,187E+03
24	1,369E-01	5,454E-03	4,697E-01	1,540E+00	-3,328E-01	1,403E+00	2,431E+02	1,025E+03
25	3,548E-02	1,963E-03	7,142E-03	3,763E-01	2,834E-02	3,408E-01	7,987E+01	9,606E+02
26	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
27	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
28	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
29	0,000E+00	0,000E+00	-6,173E-02	4,600E-02	-6,173E-02	4,600E-02	0,000E+00	0,000E+00
30	1,789E-01	3,599E-03	1,698E-01	8,300E-01	9,135E-03	6,511E-01	5,107E+00	3,640E+02
31	8,944E-02	3,599E-03	1,698E-01	8,300E-01	-8,031E-02	7,405E-01	8,979E+01	8,279E+02
							2,495E+04	**5,473E+04**

Mathlab code for finding coefficients for Approximation function $P = a + b\omega^2$

```
P=P;

W=W;

fun=@(x)x(1)+x(2)*W.^2-P;


x0 = [0,0];

options = optimoptions(@lsqnonlin,'Algorithm','trust-region-reflective');

x = lsqnonlin(fun,x0,[],[],options)

%If another algorithm gives the same result

options.Algorithm = 'levenberg-marquardt';

x = lsqnonlin(fun,x0,[],[],options)
```