University of Strathclyde

Department of Electronic and Electrical Engineering

EE577

Computer-Based laboratory session report

Modeling a Wind Turbine using GH-BLADED

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Abstract

The purpose of the laboratory sessions was to enhance our knowledge on wind turbines, in particular the rotor aerodynamic, wind turbine anatomy, principle of operation and strategy of control of typical 3-blade variable speed turbine. It was also to give an insight in the advantage of using variable speed turbines over fixed speed turbines, phenomena of shear effect and pitching strategies. The understanding was supported by software dedicated for the simulations of the wind turbines, GH-Bladed. The report presents a set of exercises with supporting output results from bladed, analysis and calculations, as well as description of each exercise. The real world example scenarios were discussed.

1. Introduction

Energy consumption is growing every year, and that trend will probably not stop in coming years. According to International Energy Outlook 2013 (IEO2013), an EIA's project (Energy Information Administration) released in 2013, world energy consumption will grow by 56 % between 2010 and 2040. The fastest-growing energy sources are renewable energy and nuclear power, each increasing 2.5 % per year **[5].**

Renewable energy promotion is highly supported by the European Parliament and of The Council European Union. On January 10, 2007, the European Union commission communicated a strategy to increase overall share of energy from renewable sources to 20 %, and to 10 % for energy from renewable sources in transport **[6]**. Wind energy, as a relativity new generation technology requires further research to increase the efficiency, reduce cost of production and make it possible to become significant source of power.

2. Simulations and results:

2.1. Exercise 1.

The aim of that exercise was to describe the general characteristics of the wind turbine. After loading the model, one had to click on specified tabs, and write down main attributes. Next step was to describe their meaning.

Total hub height: 61.5 m

Wind speed will depend on that parameter according to the log law (unless shear is applied).

Rotor position: upwind

The advantage is that the wind is not disturbed by the tower; therefore, more wind energy may be converted into the electrical energy. On the other hand, when the wind achieves very high speed, the downwind position is considered to be better, because the thrust force will not cause the blade to hit the tower. Most of the wind turbines are upwind.

Cut-in wind speed: 4 m/s

Minimal wind speed that the turbine is still operating.

Cut-out wind speed: 25 m/s

Maximal wind speed that the turbine is still operating.

Rotor diameter: 80 m

One of the most significant parameters of the wind turbine. Achieved power is inextricably linked to the rotor diameter. The bigger is the rotor diameter, the more power turbine can achieve. On the other hand, the bigger is the rotor, the higher are stresses on the material, and the resistance to stresses does not increase proportionally. It means that rotor with high diameters are less reliable.

Number of blades = 3

The number of blades is linked to the solidity factor. When the solidity is high, so is the torque, however, the rotational speed is small. Small number of blades are desirable, because high rotational speed reduces the required the gearbox ratio, however, 2-bladed design may result in the 'see-saw' motion. Some people claim that the best solution is the usage of many blades of small individual solidity, but that would increase the cost of production of the wind turbine **[1, 2]**.

Tilt angle = 4 degree

Small inclination of the rotor is needed in order to increase the distance between the blades and the tower for a high thrust force.

Overhang = 3.7 m

The distance between the blades and the tower is crucial especially for the gale winds, because the thrust force may bend the blades so much, that they will hit the tower.

Gearbox ratio = 83.33

Gearbox is needed in order to provide higher rotational speed for the shaft of the generator. There is normally power electronic block that will adjust the frequency of the voltage to the grid requirement, however thanks to the gearbox, the generator can have smaller volume.

Generator: For the variable speed turbine, user manual includes 2 types of generators, doubly-fed induction generator and synchronous generator with fully rated converter.

Blade Length = 38.75 m

Blade mass = 6547 kg

Rotor mass = 33640 kg

Mass of nacelle and rotor = 105640 kg

Tower mass = 143777 kg

Total mass of turbine = 249417 kg

The masses of the individual elements are linked to the amount of stresses subjected to them when the turbine is operating. It also gives an idea, of how difficult is to transport and place the elements e.g. blades.

Control:

a) For Variable speed, optimum tip speed ratio for the wind below the rated speed, and maintaining the maximum power for the wind above the rated speed (by pitching). Minimum and maximum pitch rate are -8 deg/s and 8 deg/s. Response to pitch position demand is first order type (the only possible option for educational option).

Pitch control, above rated speed:

Demanded generator torque = 13403 Nm.

Demanded generator speed = 1500 rpm.

b) For Fixed speed, rotor wind speed is fixed with given rotor speed for exercise 4, pitching.

2.2. Exercise 2

In that exercise it was needed to run the 'steady power curve' and 'power production loading' for uniform wind speeds from 4-24 m/s (with a step of 2m/s), and extract the values of power and wind speed, then plot them. The difference between the ideal power and actual power were described together with the basic operation of the wind turbine.

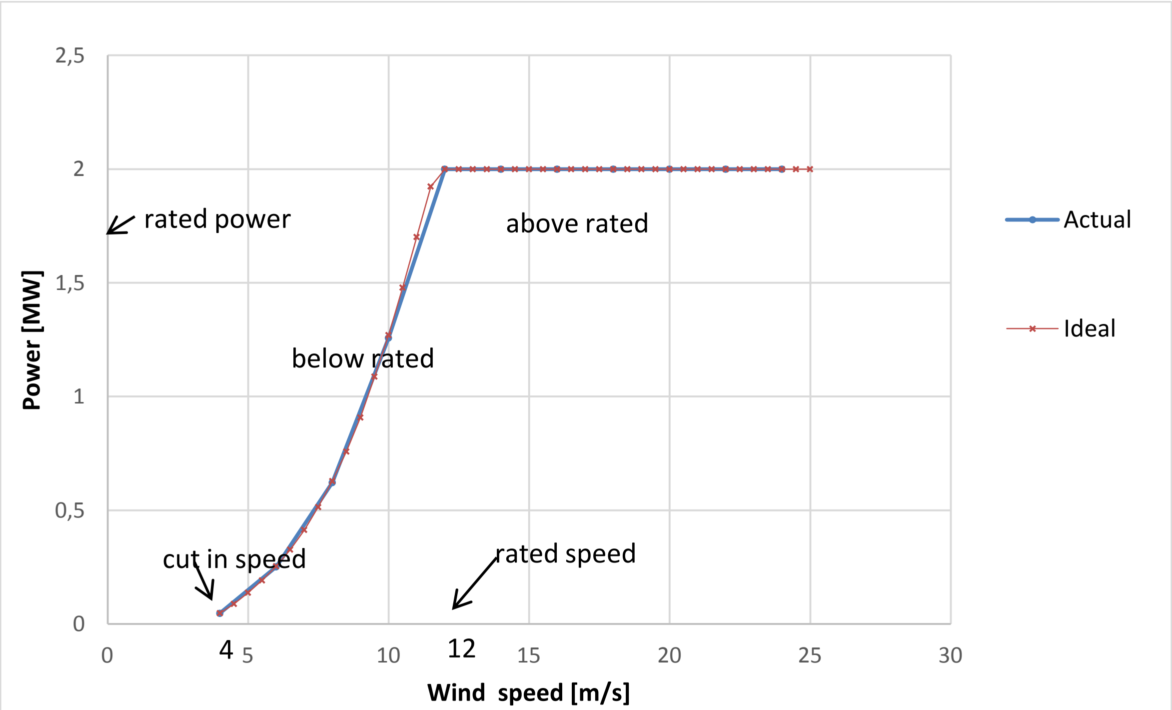


Fig. 1 - Power curve, $P = f(U_\infty)$.

The ideal curve as well as the actual curve are very similar. The latter seems to produce less power, however, the main difference between them is the number of measured points. One can expect that the higher is the sampling frequency (more points), the smoother the shape of curves is.

The rated wind speed is the speed of wind for which the maximum power can be achieved for a given turbine. Theoretically, wind turbine may extract more power, operating at higher speed, however, that may lead to excessive stresses due to high rotational speed and can damage the turbine. Rated power is the maximum power extracted by the given turbine.

Rated wind speed = 12 m/s

Rated power = 2 MW

For the speed below the rated wind speed, the generator adjusts its torque controlling the rotor speed in such a way that it tracks the maximum tip speed ratio, which is linked, to the power coefficient (described further in *section 2.3*). Above the rated speed, pitching is slowing down the blades in order not to exceed maximum power. If for some reason, pitching fails in that region, it may result in run away and destroying the blades.

2.3. Exercise 3.

In that exercise it was needed to run the 'steady power curve' and extract the values of power coefficient and tip speed ratio, and then plot them. C_p-λ curve was described and rotational speed for the optimal tip speed ratio was calculated.

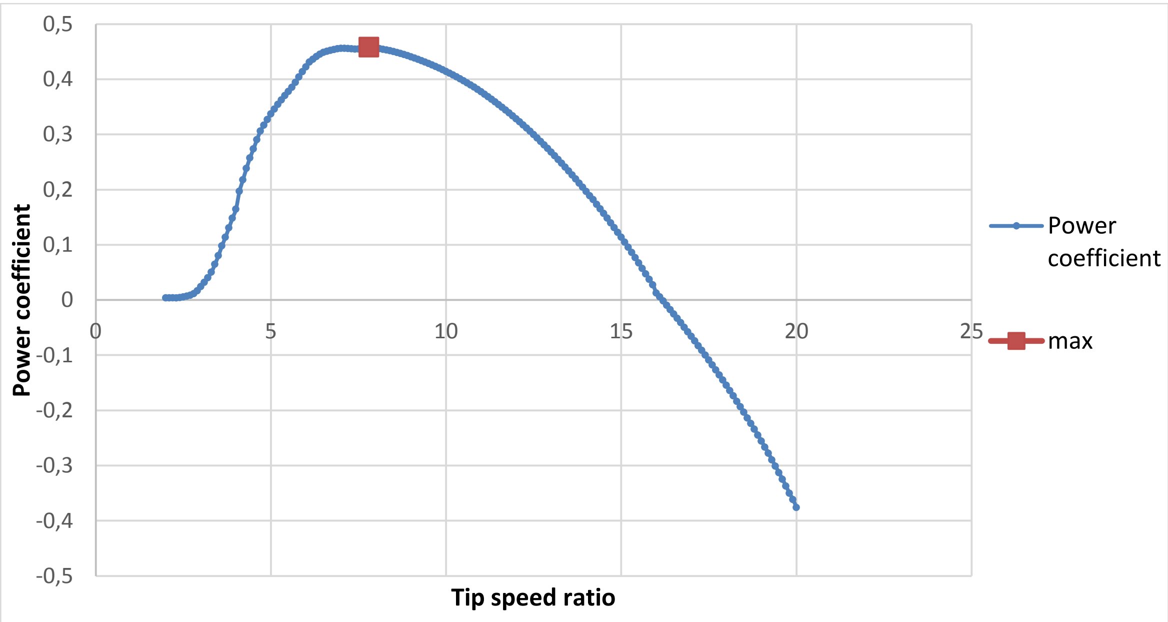


Fig. 2 - C_p-λ Curve, $C_p = f(\lambda)$.

Maximum power coefficient equals to **0.458**, for the tip speed ratio of **7.8**. Tip speed ratio λ largely determines angle of attack α at each blade station **[2].** When the power coefficient is negative, it means that the power would have to be provided from the grid to the generator (acting as motor) in order to increase the rotor speed.

λ < 7.8	**λ = 7.8**	**λ > 7.8**
High angle of attack	Optimal λ	low angle of attack
Stalled	Optimum Lift to Drag Force	Drag negates torque
High drag force	Moderate thrust	High thrust
Low thrust	Maximum power factor	Low power factor
Low power factor		

Table. 1 - 3 regions of C_p- λ Curve ***[2].***

One can divide the C_p-λ Curve into 3 regions, when the λ is below the optimal, equal to optimal and higher than optimal value. When the speed of wind is below rated, the generator torque will be controlled in such a way that it will track the curve in order to operate in the optimum λ that provides maximum power factor. Rated wind speed may be calculated using the equation 3.1:

$$P_{rated} = \frac{1}{2} C_{pmax} \rho_{air} A U_{rated}^3 \tag{3.1}$$

ρ_{air} - air density = 1.2041 kg/m^3

A - Swept Area = πR^2 (R is blade length)

$$U_{rated} = \sqrt[3]{\frac{2P_{rated}}{C_{pmax}\rho_{air}\pi R^2}} = \sqrt[3]{\frac{2*2000000}{0,458*1.2041*\pi*37.5^2}} = 11,796 \text{ m/s} \tag{3.2}$$

Rotational speed may be calculated using the equation 3.3:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{R\Omega}}{\boldsymbol{U_\infty}} \tag{3.3}$$

U_∞- Wind speed, before being disturbed [m/s]

R - Rotor radius [m]

Ω - Rotational speed [rad/s]

$$\Omega = \frac{U_\infty \lambda}{R} = \frac{11,796*7.8}{40} = 2.3 \, rad/s \tag{3.4}$$

Conclusion:

The C_p-λ curve is extremely important for the control and achieving maximum power, because thanks to that it can produce considerably more power.

2.4. Exercise 4.

In that exercise it was needed to run the ‘steady power curve’, and extract the values of power and wind speed for fixed speed turbines with various generator speed. The difference between generation and advantage of using variable speed turbine were described. Proposed type of fixed speed generator was proposed for various wind speed.

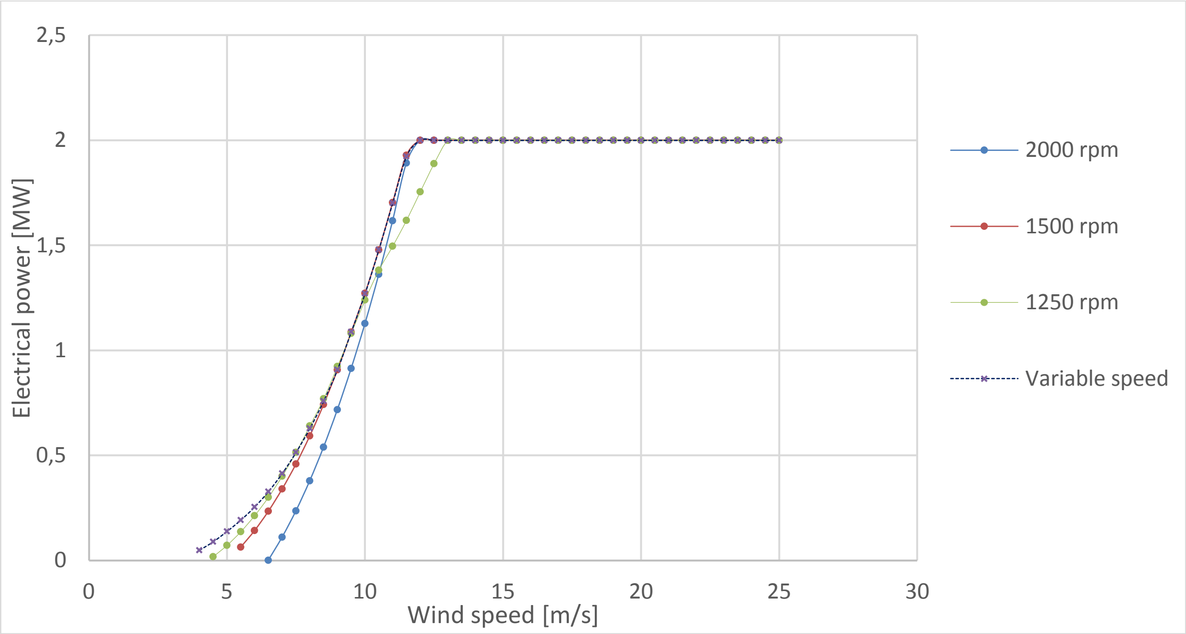


Fig. 3 - Power curve for varying rotor speed, $P = f(U_\infty)$.

The curves show that the variable speed wind turbine achieves higher power for any wind speed when compared to the fixed speed type. The drawback of that solution is the necessity of installing control system. Variable speed turbines are able to capture around 6% more energy **[1]** compared with fixed speed, stall regulated machine. It is debatable whether installation of appropriate control system is economically worthwhile, but most of the turbines available on the market have it.

For fixed speed turbines, the generator speed will be always operating at the same speed, no matter what the wind speed is. It means that the maximum tip speed ratio and corresponding power factor can be achieved only for one particular wind speed. If the generator operates at low speed, then the optimal power is achieved for low wind speed, but low. If the same generator is operating at higher wind it has to operate at stall conditions (not optimal tip-speed ratio), and produce less power. On the other hand, if the turbine with high rotational speed is operating at low wind speed, it will be highly inefficient due to drag losses **[1]**. One can see, that for fixed speed turbines it is extremely important to forecast wind speed in specified location to capture maximal power, and operate as close to the optimal speed as it is possible most of the time. The loss of power will be greater if one set the operating point lower than optimal, than when it is set to be higher than optimal. It is because, 10 % power loss will produce higher power loss for greater power.

	Lower wind speed (4-8 m/s)	Medium wind speed (8-10 m/s)	Higher wind speed (10-15 m/s)
Proposed rotor speed	1250 rpm	1500 rpm	1500 rpm

Table. 2 - 3 regions of C_p-λ Curve.

The optimal tip speed ratio is low for lower rotor speed (1250 rpm), it means that it would extract more power for low wind speed than other turbines (1500 rpm and 2000 rpm). The cut-in wind speed is also reduced, which can increase the energy capture. For turbine with higher rotational speed (1500 rpm), the optimal λ is shifted and it can achieve more power for medium wind speed than the 1250 rpm turbine. Because the rated speed is set to be 2 MW, it is not possible to see the advantage of using rotor speed equal to 2000 rpm for higher wind speed. If rated power was shifted, then the peak value of power for 2000 rpm fixed speed turbine would appear higher than other generators (as presented in fig. 4). Because, that is not the case, for higher wind speed also 1500 rpm generator speed is proposed.

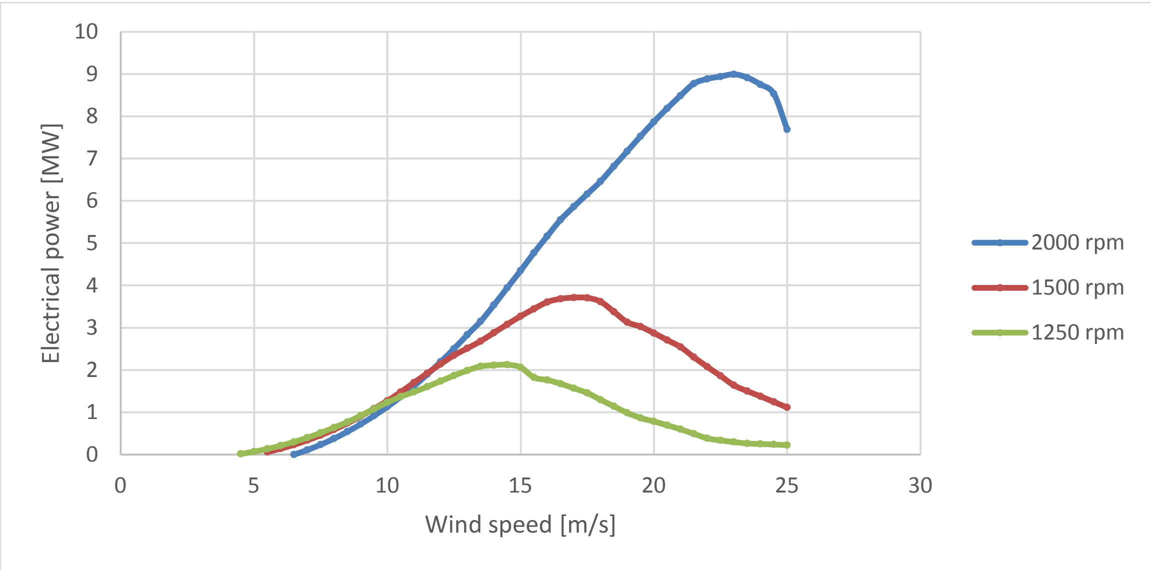


Fig. 4 - Power curve for varying rotor speed, for demanded electrical power = 2 GW (shifting the rated wind speed).

In the exercise the rated wind speed is set to be quite small, therefore, power will remain constant above that speed, due to pitching. However, without the pitching, power should diminish after reaching its maximal value.

Conclusion:

It is crucial to estimate the wind speed in specific location in order to extract more power, especially for fixed speed turbines. It is worth to mention that the usage of optimal λ tracker gives better result and is widely used, even though it increases the cost of extra machinery.

2.5. Exercise 5.

In that exercise, it was needed to run the 'steady power curve' and extract the values of rotor speed and torque, then plot them. The differences between the ideal and actual torque and rotor speed were described. Specific points on torque-rotor speed plot were marked and named, full operation strategy of the wind turbine was described.

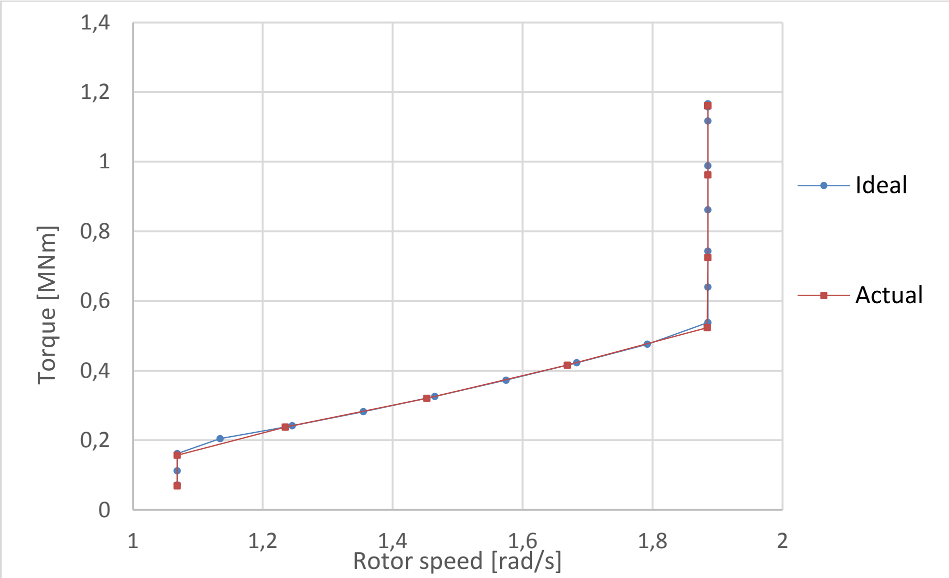


Fig. 5 - T = f(Ω).

The ideal curve as well as the actual curve are very similar. The latter seems to produce less torque, however, the main difference between them is the number of measured points. An <u>aerodynamic torque and the low speed shaft torque</u> are the same things for the steady state conditions, they are not identical for turbulent stresses that are not considered in this simulation.

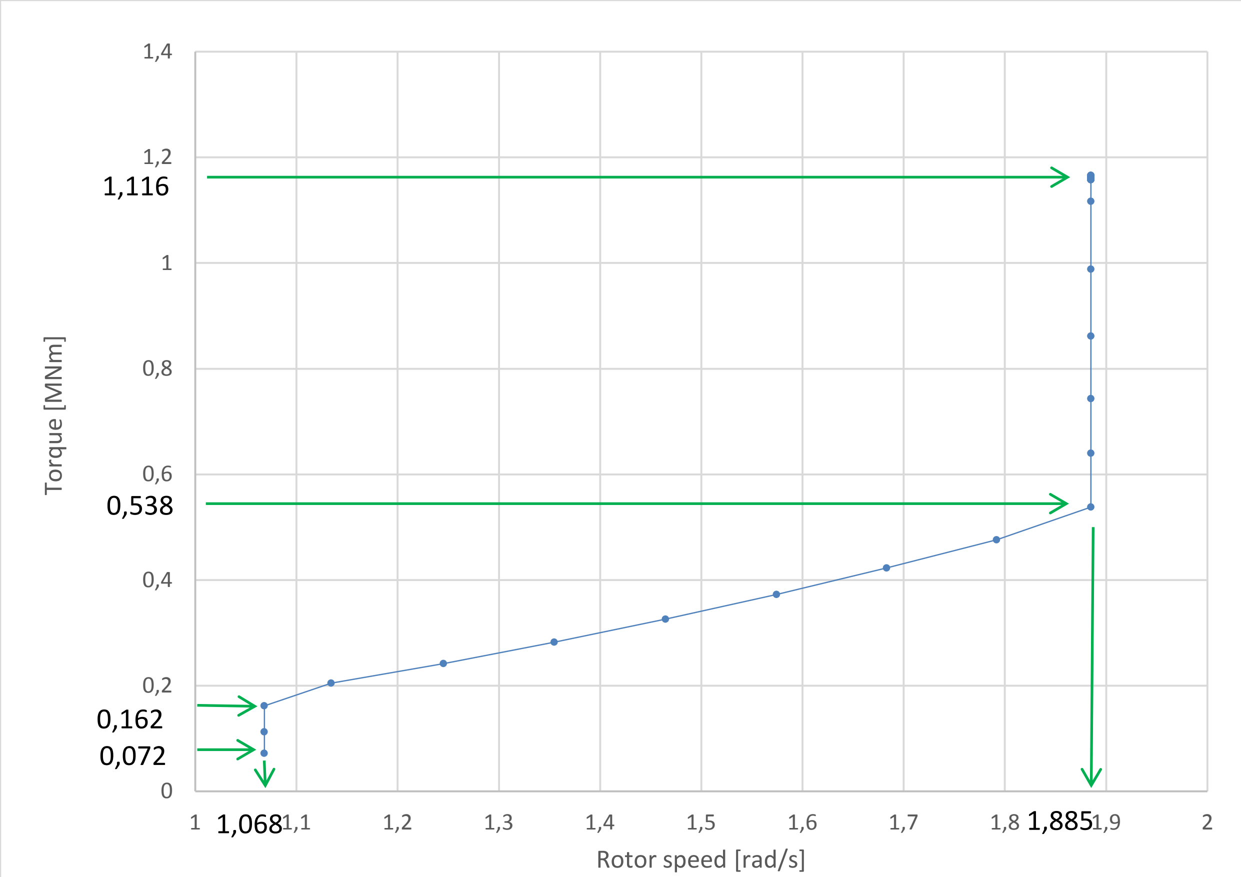


Fig. 6 - T = f(Ω), only actual curve.

The regions are shown in table 3, and the detailed operating strategy is described below, together with additional comparative graph.

Conditions	**Ω = 1.068 rad/s**	**1.068 rad/s < Ω < 1.885 rad/s**	**Ω =1,885 rad/s**	**Ω = 1.885 rad/s And T=1.16 MNm**
Regions	**First constant speed region.** Wind speed below the minimal operating speed.	**Optimal Cp_{max} tracking**	**Second constant speed** Wind speed above the rated speed	**Pitching**

Table. 3 - Regions of T - Ω *Curve.*

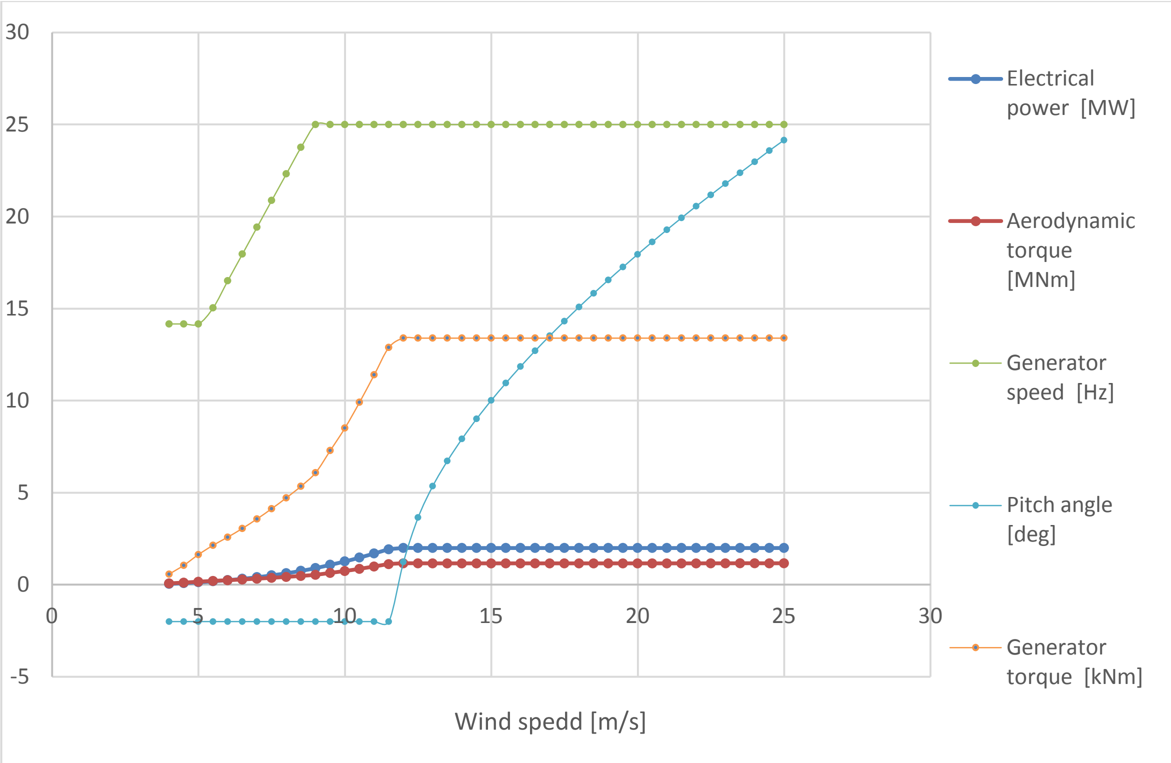


Fig. 7 - Additional comparative graph.

Both graphs 6 and 7, give an insight into the operation of the variable speed wind turbine. Starting from the cut-in wind speed (4 m/s), as the wind speed is increasing, the aerodynamic torque is increasing until the wind speed achieves about 5 m/s. Up to that time, the torque was not sufficient to turn the rotor faster. Then the rotor speed starts to increase, as well as generator speed. This region is called the Optimal Cp_{max} tracking, because generator speed is controlled in such a way that it produces a torque that will oppose the aerodynamic torque, thus slowing down (or speeding up) the rotor speed in order to operate in Optimal λ. Optimal λ will provide Optimal C_p, that means the optimal power is obtained.

At wind speed of about 9 m/s, the generator speed (and rotor speed) already reaches its maximum. It means that, as the wind speed further increases, the rotor speed cannot be increased any further and it remains constant at 1.885 rad/s (knowing that the gearbox ratio = 83.33), that value corresponds to the demanded generator speed = 1500 rpm. From that point there is a sharp increase of the slope of the aerodynamic torque. It will increase further until the power reaches its maximum (P=ωT). When the rotor speed = 1500 rpm and generator torque = 13403 Nm (At rated wind speed [12 m/s]), the power reaches its maximum, the pitching starts working, effectively slowing down the turbine. If the pitching failed, the torque could achieve so high values, that it could destroy the turbine.

2.6. Exercise 6

The aim of the exercise was to calculate expected annual energy production of the wind turbine, average power and capacity factor, using Weibull probability function. At first the speed at hub height was calculated, then the parameters of Weibull probability function needed to calculate the probability for every wind bin.

Parameter	Value	Additional descirption
$U(z_1)$ - wind speed	7.5 m/s	From the exercise
Z_1 - height at measured wind speed	20 m	From the exercise
Z_0 - roughness height	0.08	Typical values for long grass 0.04 to 0.1**[3]**. Assumed to be constant, but in reality depends on height.
Z_2 - Hub height	61.5 m	From Blade model
k - weibull distribution with a shape parameter	1.8	From the exercise
A - Availability	97 %	From the exercise

Table. 4 - Parameters and values used in calculations.

Calculating the wind speed at hub height

$$\frac{U(z_2)}{U(z_1)} = \frac{\ln\left(\frac{z_2}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)}, \quad \text{Log law } \mathbf{[3]} \tag{6.1}$$

$$U(z_2) = U(z_1)\frac{\ln\left(\frac{z_2}{z_0}\right)}{\ln\left(\frac{z_1}{z_0}\right)} = (7.5)\frac{\ln\left(\frac{61.5}{0.08}\right)}{\ln\left(\frac{20}{0.08}\right)} = 9.03\ m/s \tag{6.2}$$

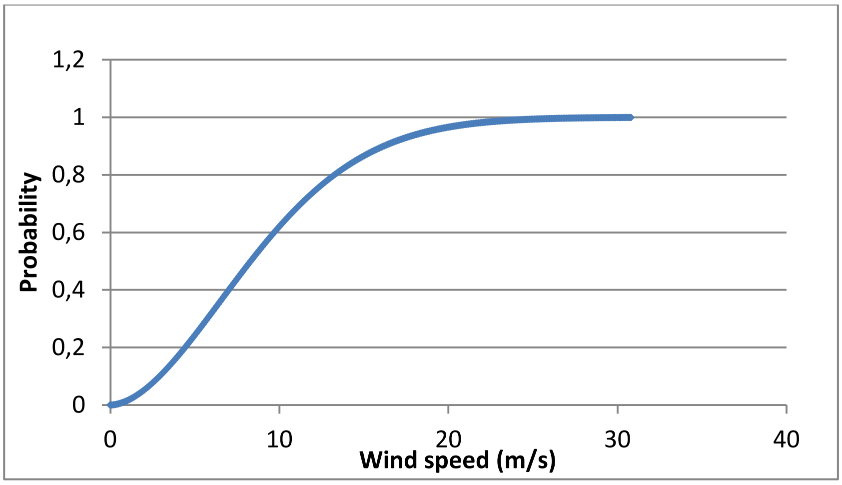
Calculating the scale parameter for given wind speed:

$$C \sim 2\frac{U(z_2)}{\sqrt{\pi}}, \qquad \text{for } 1.6 \leq \text{k} \leq 3\ \mathbf{[4]} \tag{6.3}$$

$$C \sim 2\frac{9.03}{\sqrt{\pi}} = 10.18 \tag{6.4}$$

Having calculated the shape and scale parameters, it is possible to draw a cumulative probability function using the equation given below:

$$CDF = 1 - e^{-(\frac{U}{C})^k} \tag{6.5}$$



Wind speed [m/s]	CDF
0	0
4	0.169
5	0.242
7	0.399
9	0.550
11	0.682
13	0.788
15	0.866
17	0.919
19	0.954
21	0.975
23	0.987
25	0.993

Fig. 8 - Cumulative probability function, CDF = $f(U_\infty)$. Table 5 - Calculation of the CDF.

It is worth mentioning that the CDF was calculated for the wind speeds that slightly differs from the wind speeds proposed in exercise 2. They are chosen to be different in order to create wind speed bins that the center of, is the wind speed proposed in exercise 2. The boundary wind speeds are used for calculating the CDF. For instance, for wind speed equal to 6 m/s and its corresponding power mean value, bin with the boundaries of 5 and 7 are created, assigning to them the given power mean value.

U (m/s)	**Power (MW) [from exercise 2 c]**	**Probablilty (CDF(A)-CDF(B))**	**Hours available [h]**	**Energy (MWh)**
0-4	0,00	0,1697	1441,8954	0,0000
4-5	0,05	0,0729	619,6015	29,4809
5-7	0,25	0,1564	1329,0434	335,0651
7-9	0,62	0,1519	1290,3866	803,0269
9-11	1,26	0,1321	1122,2801	1411,8284
11-13	2,00	0,1052	893,5087	1787,0173
13-15	2,00	0,0776	659,1751	1318,3502
15-17	2,00	0,0534	454,0993	908,1987
17-19	2,00	0,0346	293,6587	587,3173
19-21	2,00	0,0211	178,9565	357,9129
21-23	2,00	0,0121	103,0714	206,1428
23-25	2,00	0,0066	56,2370	112,4739
>25	0,00	0,0065	55,2864	0,0000
Hours per year [h]	8760		Sum of Energy [MWh]	7856,8146
Avalibility [%]	97		Average power [MW]	0,896896639
hours available [h]	8497,2		Capacity factor [%]	44,84483196

Table 6 - Calculation of the expected annual energy production.

After choosing the bin boundaries and assigning the power from the exercise 2 c), the probability of occurrence particular wind speed was calculated with the equation given below:

$$P = CDF(A) - CDF(B) \tag{6.6}$$

For example, for bin 5-7 m/s:

$$P(5-7) = \left(1 - e^{-\left(\frac{5}{c}\right)^k}\right) - \left(1 - e^{-\left(\frac{7}{c}\right)^k}\right) = 0.399 - 0.242 = 0.1564 \tag{6.7}$$

Next step was to calculate the hours available per year. Assuming that 1 year has 8760 hours:

$$\text{Hours available } = \text{A} * \text{hours per year} \tag{6.8}$$

$$\text{Hours available } = 0.97 * 8760 = 8497.2 \text{ h} \tag{6.9}$$

Then, it was possible to calculate the hours available for each bin, by multiplying the hours available by the probability of occurrence for each bin. The energy is the product of available hours and the mean power for particular bin. At the end, the sum of energies was calculated and the average power, as well as capacity factor was calculated using the formulas below:

$$Average\ power = \frac{Total\ energy}{Total\ available\ time} = \frac{7883.0182\text{ MWh}}{8760\text{ h}} = 0.897\text{ MW} \tag{6.10}$$

$$Capacity\ factor = \frac{Average\ power}{Rated\ power} = \frac{0.897\text{ MW}}{2\text{ MW}} * 100 = 44.84\ \% \tag{6.11}$$

2.7. Exercise 7.

In that exercise it was needed to run the ‘power production loading’ once with exponential vertical shear and once without that option and extract aerodynamic torque. Then the values were loaded to matlab and transformed into frequency domain using FFT function (Commented code is available in the apendix). Finally impact of shear on wind turbine was described.

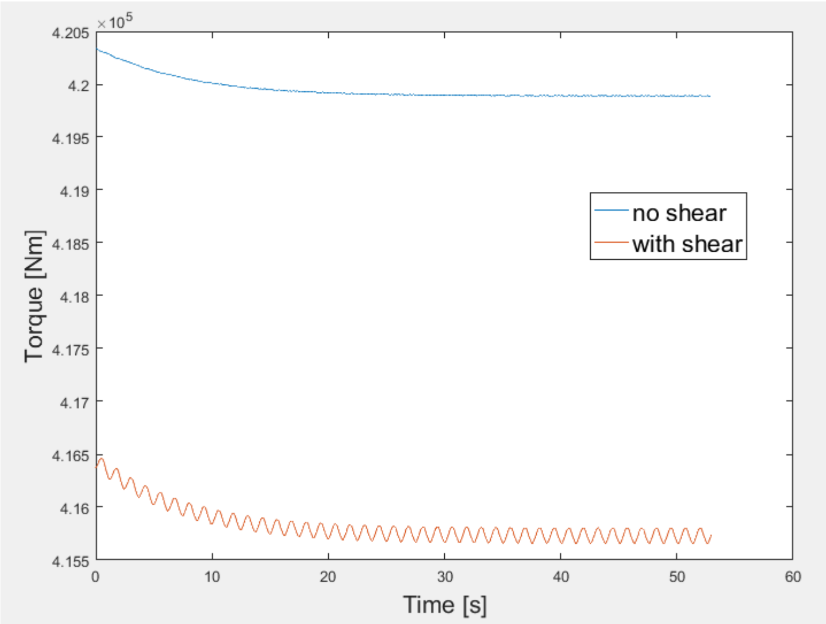


Fig. 9 - T = f(t).

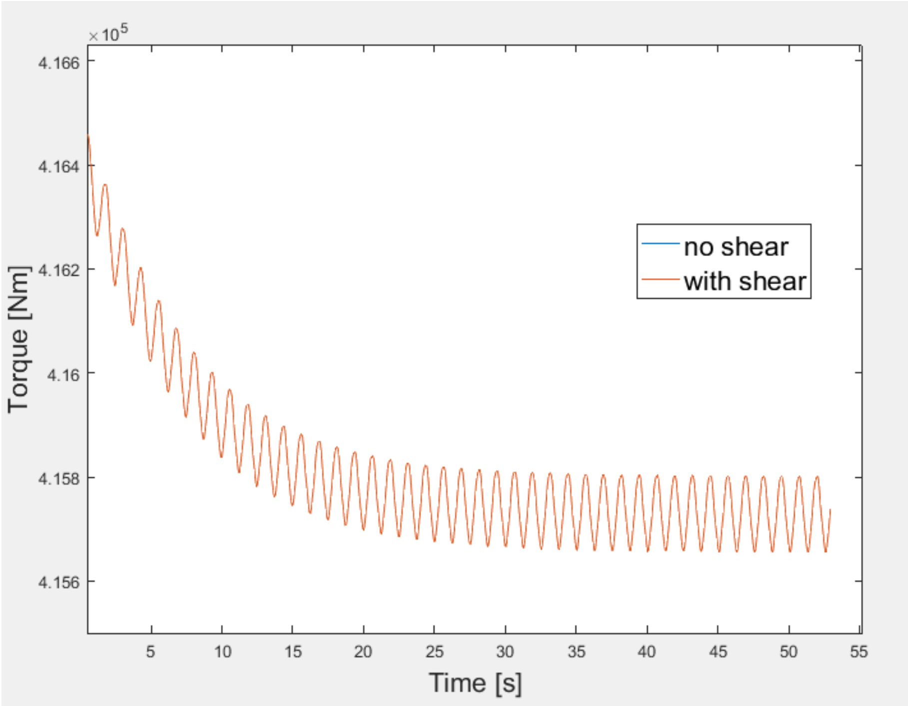


Fig. 10 - T = f(t), zoomed for shear.

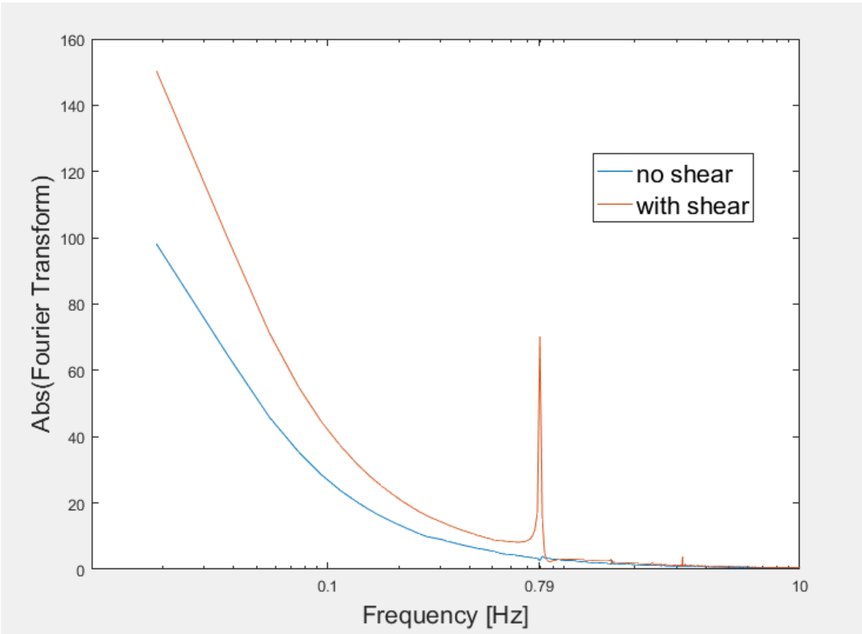


Fig. 11 - T = f(frequency).

There are more harmonics for the simulation with shear, which is caused by turbulent flow of the wind. Taking into account shear, means that there is a different wind speed in the different part of the blades. This asymmetric pressure will cause an oscillation of blades.

The torque with no shear is generally higher, but after performing Fourier transform it turns out that, torque for the simulation with shear is higher for all spectrum of frequencies (Except for 0 Hz). It has considerable peak at 0.79 Hz. The rotational speed at wind speed equal to 8 m/s is 1,68317 rad/s. That corresponds to 0.26788 Hz, which is approximately one third of the peak frequency.

$$0.26788\ Hz * 3 = 0.80\ Hz \sim 0.79\ Hz \tag{7.1}$$

One can assume that the peak frequency is associated with the frequency of rotation multiplied by the number of blades (3). The turbulent changes of the torque will cause additional stress to the wind turbine, mitigating the expected lifespan of the wind turbine. The higher the rotational speed (that depends on wind speed), the higher additional stresses are.

Conclusion:

This simulation shows that, unfortunately deeper understanding of the aerodynamics of wind turbine is not straightforward. Shear effect has to be taken into consideration, because the additional stresses decrease the reliability of the turbine which is a crucial factor, when the asset is planned to be installed. That effect is more severe for high rotational speed.

2.8. Exercise 8.

In that exercise it was needed to load the turbulent wind file, run the 'power production loading', and extract the values of wind speed, torque, blade pitch angle and demanded blade pitch angle, then analyze the data and plot them. The pitching strategy and its advantages were described.

Actuators installed in wind turbines are able to change the position of blades in such a way that the angle of attack can be reduced, hence reduce lift coefficient and torque **[1]**. It is crucial to slow down the rotor, for the above rated wind speed (high torque) to avoid high stresses, and possible damages.

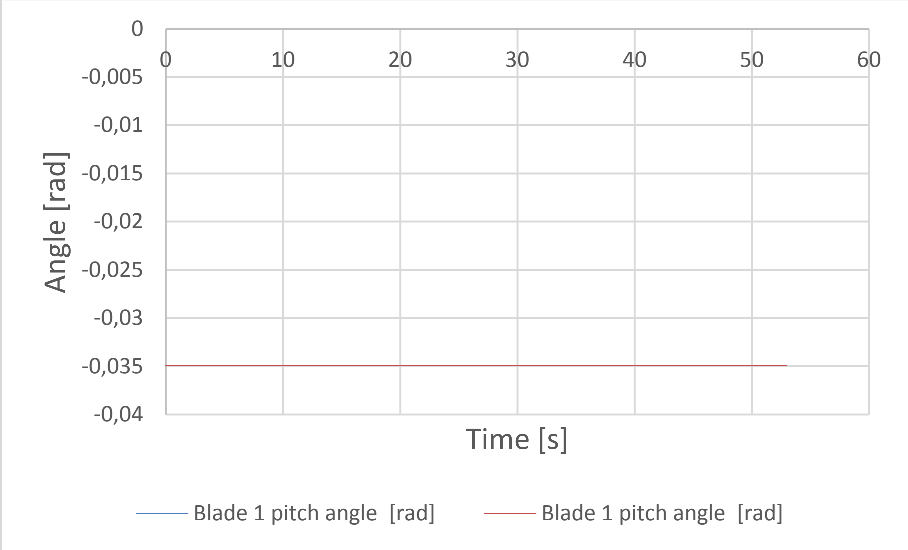


Fig. 12 - Blade pitch angle = f(t), mean wind speed = 8 m/s.

For the wind speed that is below rated, pitching remains constant at minimal value because there is no need of slowing down the rotor.

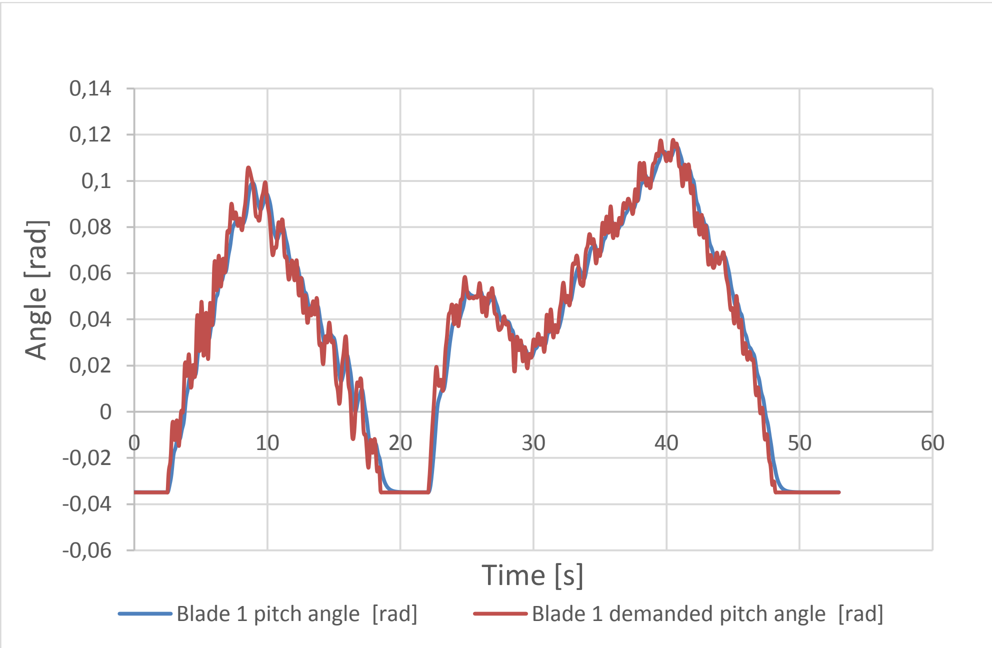


Fig. 13 - Blade pitch angle = f(t), mean wind speed = 12 m/s.

For higher wind speed, blade pitch angle is changing. The demanded pitch angle curve is much more turbulent than actual blade pitch angle, but it is possible to see that the shape is quite similar. Actual blade pitch angle is smoother, it is because the actuators are physical machines, and they have some inertia causing impossible to change the position of the blades in infinitely small time (that would mean infinite acceleration). In some intervals e.g. from 20 s to 21 s, the pitch angle has a constant value of -0,034907 rad. It means that the torque value is below demanded generator torque (13403 Nm).

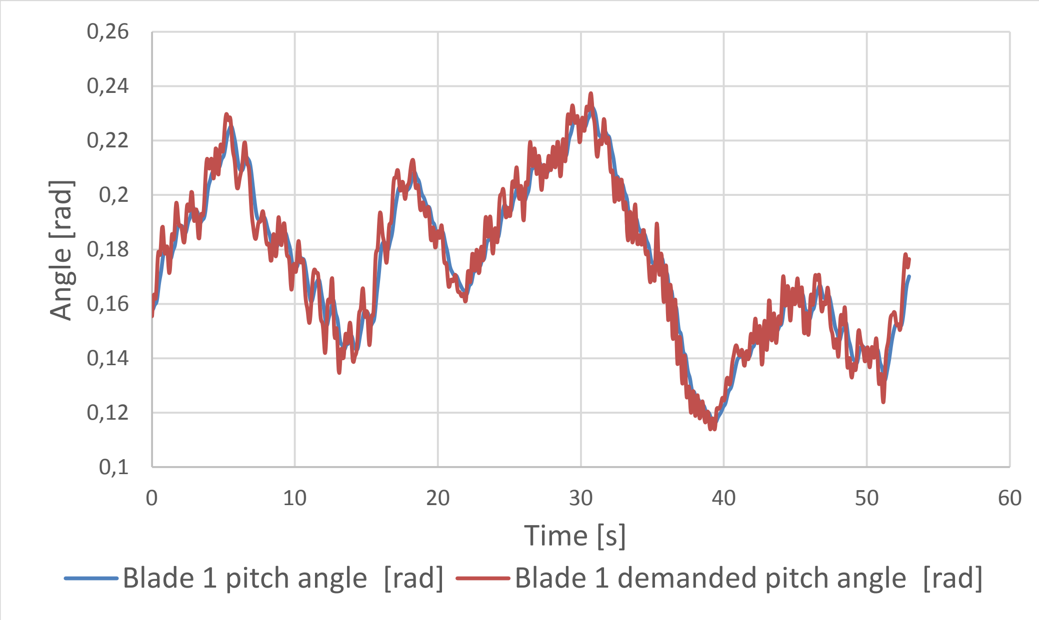


Fig. 14 - Blade pitch angle = f(t), mean wind speed = 15 m/s.

The idea of operation for mean value of wind equal to 15 m/s is very similar to the 12 m/s. Pitch angle is generally higher, and it has to operate for all the time. It means that without the pitching the generator's torque would always be higher than the demanded generator torque value.

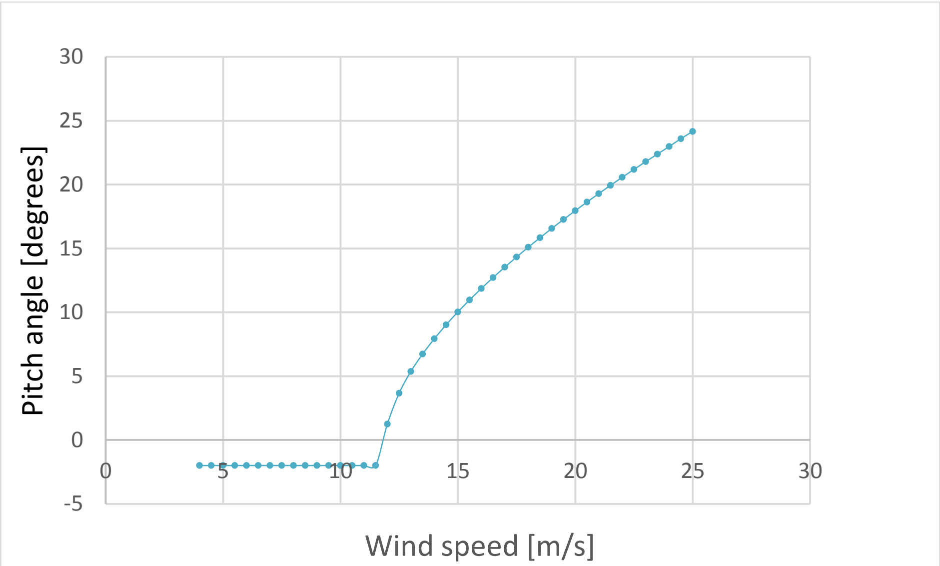


Fig. 15 - Blade pitch angle = f(U), ideal curve.

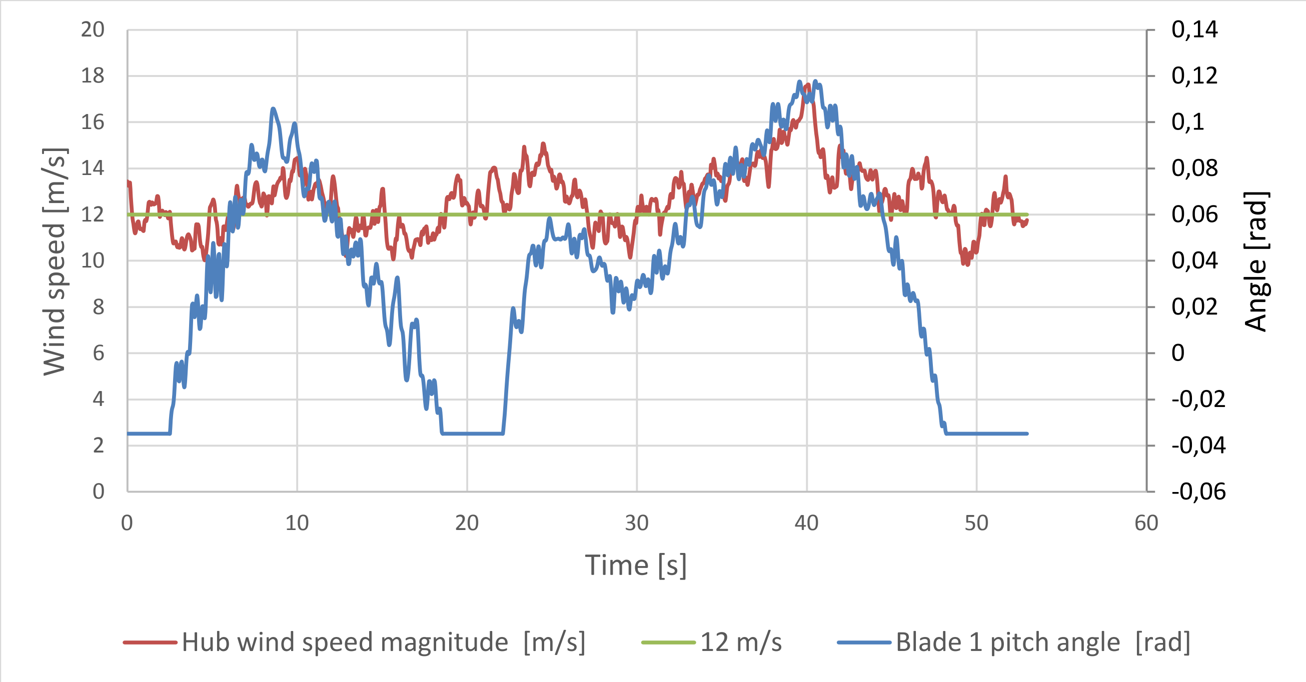


Fig. 16 - Blade pitch angle = f(t), Wind speed =f (t), mean wind speed = 12 m/s, turbulent curve.

The ideal correlation between pitch angle and wind speed is depicted in fig. 15, but there is no direct correlation between wind speed and pitch angle, for turbulent changes of wind. The interval between 20 s and 21 s in figure 16, shows that when the wind speed is above rated, the pitch remains at the same position of minimal angle (does not slow down the rotor). The lack of correlation of wind speed and pitch angle for turbulent behavior is depicted in figure 17.

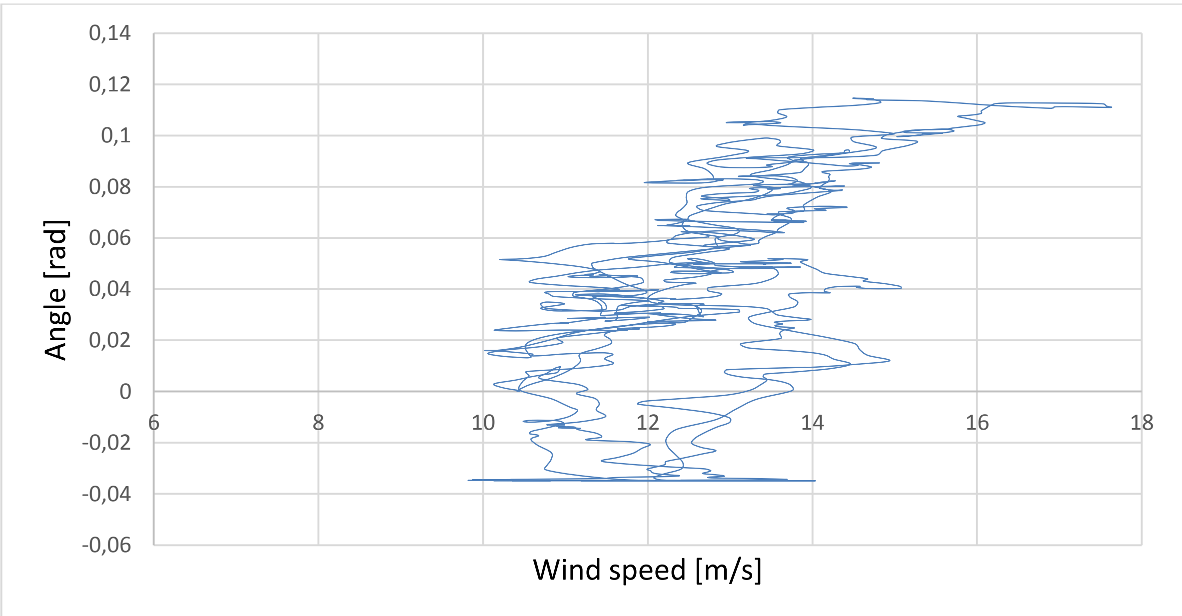


Fig. 17 - Blade pitch angle = f(U), mean wind speed = 12 m/s, turbulent changes.

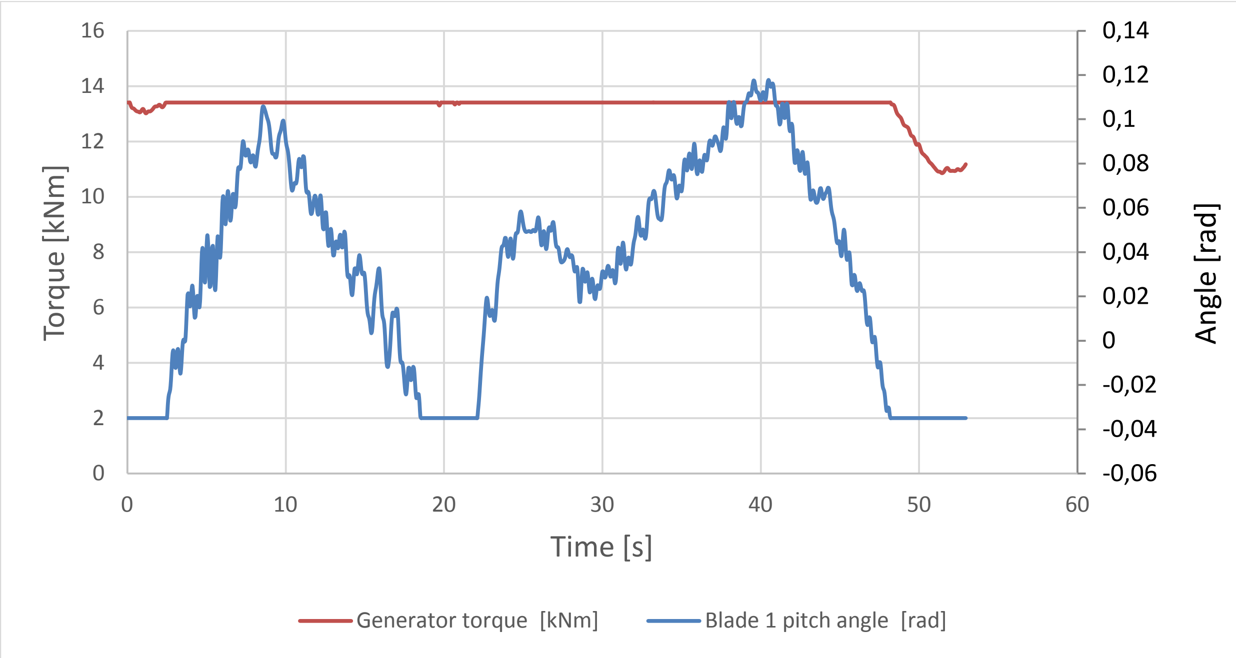


Fig. 18 - Blade pitch angle = f(U), Torque = f (t) mean wind speed = 12 m/s, turbulent changes.

The input to the calculation of the demanded pitch angle is the torque. Obviously, for higher wind speed the torque also should be higher, however, the goal of the pitching is to make sure that the demanded generator torque value is not exceed, using PI control. One can see on the figure 18, that the actuators are activated only when the torque is on the verge of exceeding the demanded generator torque value. Whenever the torque is smaller, the pitch angle remains constant at the value of -0.034907 rad.

Conclusion:

Pitching slows down the rotor, to mitigate stresses caused by high rotational speed, and protect the turbine from damages. Pitching can produce 5 % more energy than stall-regulated version for variable speed turbine, although it has some disadvantages such us extra weight near the tip or difficulty to accommodate the actuator in the blade profile. It is also necessary to design fast response closed loop control **[1]**.

3. Conclusions

The laboratory sessions provided a glimpse into the basic operation of the wind turbines, showing the basic strategies of control, as well as giving the idea of some phenomena that are not so straightforward to model e.g. shear effect. GH-Bladed provided a real world simulation output of a typical, widely used asset, showing why it is so popular.

References

[1] T. Burton, *Wind Energy Handbook*, 1st ed. Chichester[etc.]: John Wiley & Sons, 2004, page 103-105, 349-350.

[2] J. Feuchtwang, Wind Energy and Distributed Energy Resources, *Wind Turbines II Blade Element Theory*, class lecture, University of Strathclyde, 2016/2017.

[3] J. Feuchtwang, Wind Energy and Distributed Energy Resources, *Wind resource I - structure & statistics*, class lecture, University of Strathclyde, 2016/2017.

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[5] U.S. Energy Information Administration, *EIA projects world energy consumption will increase 56 % by 2040 - Today in Energy - U.S. Energy Information Administration (EIA)*, 2013. [Online]. Available: http://www.eia.gov/todayinenergy/detail.cfm?id=12251. [Accessed: 06-Dec-2016].

[6] Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, L 140/16.

Appendix

```
%Ex 7 Wind.
time = xlsread('ex7.xlsx',1,'A5:A1064');
Tnoshear = xlsread('ex7.xlsx',1,'B5:B1064');
Twithshear = xlsread('ex7.xlsx',1,'E5:E1064');


L=1060; %number of measurments
ff1=fft(Tnoshear, L); %FFT no shear
ff2=fft(Twithshear, L); %FFT +shear shear
f=(20*(0:(L/2)))/L;      %Calculating frequencies (up to half of the
                        %sampling frequency, because
                         %the other half (up to sampling frequency) will be
                         %simmetrical.

P1=abs(ff1/L);  %interested only in the absolute value.
P2=abs(ff2/L);

P3 = P1(1:L/2+1);
P3(2:end-1) = 2*P3(2:end-1);

P4 = P2(1:L/2+1);
P4(2:end-1) = 2*P4(2:end-1);

%Plotting
figure(1);
plot(time,Tnoshear); hold on;
plot(time,Twithshear);
xlabel('Time [s]','FontSize',16); ylabel('Torque [Nm]','FontSize',16);
legend({'no shear','with shear'}, 'FontSize', 16);


figure(2);
semilogx(f,P3); hold on;
semilogx(f,P4); hold off;
legend({'no shear','with shear'}, 'FontSize', 16);
xlabel('Frequency [Hz]','FontSize',16); ylabel('Abs(Fourier
Transform)','FontSize',16);
xticks([0.1 0.79 10 100]);
```

Fig. 1 - Mfile, used to produce plots for exercise 7.