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A YAW CONTROL APPROACH USING ECONOMIC ASPECTS

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Abstract

The share of wind energy in modern societies energy supply increases constantly. Whereas blade pitch and torque control of wind turbines are extensively covered within literature, yaw control is rarely discussed. Yaw is controlled in order to increase the turbines energy output, yet turning a heavy nacelle with a large rotor into the wind also consumes significant amounts of energy. Furthermore, there is the desire to reduce wear in gears, bearings, and brakes. To make matters worse, the sensitivity of the turbine's power generation on the yaw angle depends on the overall wind velocity in a non-linear way. Practical problems like sensor noise and the avoidance of cable twist occur as well. Therefore, we developed an energy optimized control scheme based on a dead-band controller with hysteresis and an integrated positioning feed forward algorithm. For the control design, the DLR EWITAC Library was used that enables the object-oriented modelling and simulation of wind-turbines based on the Modelica standard. The controller was designed using simplified models and validated with the computer simulation of a fully flexible wind turbine combined with a stochastic wind model.

1 Motivation

Wind energy implies renewable, green energy. Energy, whose relevance is increasing rapidly due to climate change and the growing environmental awareness of the population. Yet, wind turbines do not produce as much power as many other energy sources. To enable wind turbines to reach full capacity, controllers are crucial. Whereas most of research focuses on the dynamic and complex pitch control, the yaw control is rarely discussed. Due to its slow dynamics, yaw control is often mistaken as trivial.

Thereby yaw control is not yet flawless. Most papers do not consider an optimization in accordance with economic aspects. Also, the resulting behaviour of the wind turbine that should follow the control command without overshoots to a preferably ideal position is barely considered. Furthermore, tearing of the cables, the interaction between pitch and yaw control, the sensible activation of the brake, etc. are an issue. This paper addresses these challenges.

Naturally, the wind turbine should be able to generate the maximum power at any time with respect to the power curve. This power is not only dependent from the efficiency, but also from the available wind speed and direction [1]. It is especially in the partial load region crucial to align the turbine with the wind since the generated power is proportional to the cube of the cosine of the yaw angle. The yaw alignment in larger turbines is controlled actively with a yaw motor [1]. However, if the yaw actuation is active all the time it would increase wear and reduce the turbine life time [2]. Therefore, the wind turbine should not be too sensitive to wind direction changes but still sensitive enough to have good tracking properties [3].

The mass moment of inertia causes time delays, oscillations and torque. If the wind turbine is turning too fast it would invoke large gyroscopic forces [4]. It is undesired that the turning stirs up eigenstates. To prevent this, a slow turning is essential. Also, the deceleration to stop should be gradual and not abrupt. If the nacelle is turning in the same direction for several rounds the wires, which run between nacelle and tower, twist and tear [1]. The yaw control should be automatic, and adaptive to different environments and turbine types. Security issues should be considered and prevented [4].

Based on these considerations, eight main requirements were identified for yaw control:

- good tracking properties and adequate response times of the wind turbine for wind direction changes
- no tracking of short term variation in wind direction and turbulences
- no overshoots regarding the position of the nacelle
- no induced oscillations in the structure of the wind turbine due to turning
- affordable, straightforward and flexible yaw control
- secure and safe system
- low torque on tower nacelle interface
- angular velocity of tracking system of 1°/s [4-7]

Important issues like the replacement of sensors with other measurements and a reduction of the necessary torque during the yaw turning by using pitch control are investigated as well. Reducing the energy demand economically is defined as the overall main requirement of the controller. Therefore, the controller should be activated if the power loss due to the misalignment of the nacelle is higher than the energy needed for turning the nacelle.

Different concepts concerning yaw control suggested by other researchers served as inspiration for the actual controller design. These concepts will be introduced in a short overview. Then it is shown how the control concept is derived, tested and verified in Modelica. The flexible wind turbine model of the DLR SR (German Aerospace Centre, Institute of System Dynamics and Control) is used for this.

2 State of Art

Public available research concerning yaw control is limited. The proposed applicable controllers can be categorized in two main groups: simple control strategies like Proportional control or Proportional-Integral control [1, 2, 4- 6] and optimisation based approaches [8, 9]. Especially in books, simple control strategies are mentioned as the state of the art. R. Gasch and J. Twele assume a Proportional Integral Derivative (PID-) control [6]. Erich Hau specifies the yaw control for bigger plants as Proportional-Integral (PI-) controller [4]. Burton expects a dead-band controller to be used in wind turbines [5].

Also, researchers as Rijanto et al. explored the possibilities of a dead band controller for positioning control of the wind turbine. They design a yaw positioning control system for a 100kW horizontal axis wind turbines based on on/off control with dead band and hysteresis in their paper. The controller has four modes: maximizing power, minimizing power, anti-twist and shut down for security reasons. The first two modes are realized as dead band control with hysteresis. Rijanto et al. state that the controller is stable according to the Nyquist criterion [1]. Yet, it is not clear how the researchers determined their controller specific parameters and how robust these are. The anti-twist laws lack the use of prediction and heuristics.

Bu et al. used a stepping motor [2]. The sensor on top of the nacelle measures the wind angle deviation. The controller should reduce this measured angle to zero. To enhance the lifetime of the wind turbine, there is a range of tolerance (15°) where the controller does not react. The controller has the modes: turn clockwise, turn counter-clockwise, cross wind and anti-twist [2]. Experiments show that the controller is functioning [2], but the validation was only made with constant wind angle deviations. Also the controller is not able to reach a deviation of zero since it stops at 15°. This causes performance losses and high torques and forces on the structure.

Farret et al. used optimization tools for yaw control [8]. Instead of using sensors, their controller maximizes the power with the simple hill climbing algorithm [8]. They also take the stochastic nature of the wind and the inertia of the nacelle into account [8]. Problems evolve due to the interaction of wind direction, speed and power. If wind direction and speed change simultaneously it is possible that the controller is not activated due to any change in the power. Yet, more power could be generated then. Also, the wear due to turns in the wrong direction is high. Furthermore, there is no clear power maximum for turbines at their power limit.

Mesemanolis and Mademlis use a similar approach. They measure the wind speed but not the direction and combine a maximum power point tracking with a power maximizing approach [9]. Since the sign of the turning direction cannot be determined the turbine turns in one direction and checks if the power is increasing [9]. The wind speed in the experiments was with a maximum of 9 m/s very small [9]. Similar considerations as for Farret et al. hold here.

In summary, public available concepts represent mostly only partial solutions.

3 Model

The used simulation model is from the DLR SR-wind energy library [10]. It uses the 5MW NREL (National Renewable Energy Laboratory) turbine as reference. This upwind offshore turbine has three blades and a height of 85 m [7]. The turbine is modelled in the open source language Modelica [11].

The model itself is structured hierarchically. The topmost level can be seen in fig. 1. The turbine comprises several modules like tower, nacelle, rotor, drive train and the torque-pitch controller with its sensors. The world-module defines an inertial system and gravity. The environment is modeled using a local wind part and a global atmosphere. Local wind specifies local effects as tower dam on the wind turbine; the global atmosphere defines global properties as the wind speed, direction and wind shear

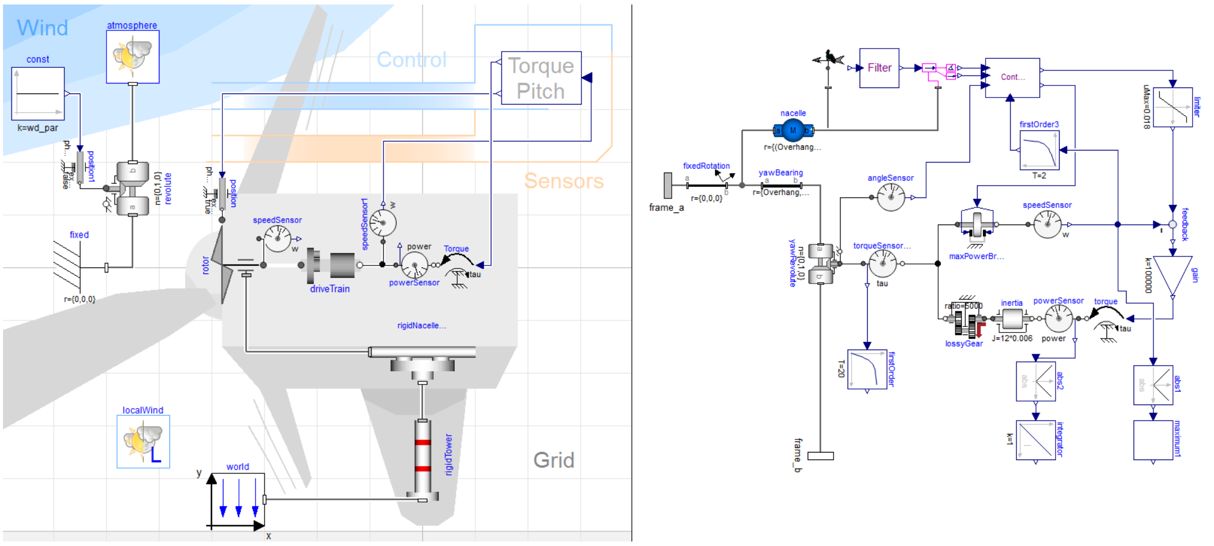

Figure 1: Wind turbine model (left) and nacelle model (right)

[10]. The aerodynamics of the model take also pre-cone and shaft tilt of the rotor into account [10]. Flexible or rigid components can be chosen to model blades and tower.

The yaw controller is incorporated in the nacelle subsystem. Figure 1 (right) shows the nacelle with the controller. It consists basically of a mass, which also comprises the inertia, and connects to rotor and tower. The alignment of rotor and nacelle is set by the shaft tilt, the alignment between nacelle and tower by the yaw bearing and yaw revolute. Furthermore, the nacelle includes wind direction and speed sensors, a parking brake and a motor. The motor is modeled in a simple way: it consists of a torque source and a gain as inner loop. The gain has no physical resemblance. The used data is mainly gained from the NREL-documents and interpolated Liebherr data sheets [7, 12]. The control of the position loop is the main task of this research.

4 Control Concept

The scheme of fig. 1 stipulates velocity to be the controller output. This velocity is compared with the real velocity of the yaw engine and limited to a maximum speed of 1°/s due to the high inertia of the wind turbine and the rotor. The parking brake keeps the turbine at standstill if the controller is not active. The controller, therefore, needs to control the activation of the parking brake as well. To avoid the tear of the cables a monitoring system called anti-twist is employed. As a maximum the turbine is allowed to turn 2 ½ times in the same direction. This is, compared to the literature, a conservative approach [1]. The three sub-controllers are prioritized according to their importance: anti-twist is a safety relevant system and has priority over the actual controller and the brake. The brake is the least important system for the control and only gets activated if the other systems are inactive. The control approach needs knowledge about wind direction and speed, measured by two sensors. Since the sensors are located on the top of the nacelle, the wind direction is measured directly as relative angle deviation. The typical feedback part of the controller [13] is therefore incorporated in the sensor. To avoid high frequency disturbances by the stochastic nature of the wind a low pass filter is set before the controller. Its time constant is, in accordance to the controller of E. Hau, 10 seconds [4].

The easiest control design would therefore just be a feedthrough of the measured wind derivation to the speed loop. Yet this would lead, due to inertia and the ever changing wind, to a permanently actuating controller, which enhances wear. A hysteresis as well as a dead band can solve these problems.

The conditions on the branches of the hysteresis are a function of the wind direction and speed. The controller has the wind direction and speed as an input, as well as the nacelle angle and rotational speed relative to the tower. Since the input of the nacelle speed is noisy, it is filtered by a low pass filter with a two seconds time constant. The limiter limits the velocity output (desired yaw rate) to a maximum of 1°/s. The other output controls the brake. The controller comprises the three main subsystems anti-twist, yaw control and brake control. The anti-twist is periodically triggered by a Boolean pulse signal and can override the other control laws when required. The yaw control system interacts also with the brake by Boolean output for its deactivation. A real value sets the desired yaw-rate.

The central part of the control system is the yaw control law. It consists of a set of threshold values which determine when the wind turbine should align itself with the wind. In contrast to other approaches, this control law results from economic considerations. It states that the turbine should be only aligned with the wind direction when the energy for its alignment does not exceed the power generation losses due to a misalignment of the turbine. Hence, the power generations of the aligned and the non-aligned turbine are needed. Latter depends on the wind direction and wind speed. It is, furthermore, necessary to identify the total power to turn the turbine from the misaligned position to the aligned position.

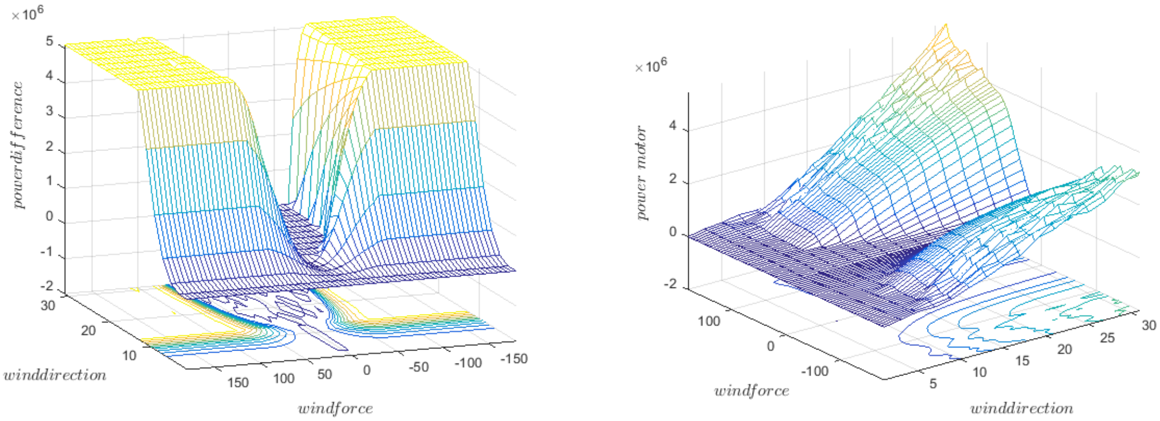

Figure 2: (a) power difference in the aligned and nonaligned case (b) required motor energy

Figure 2a shows the power difference of these two cases and 2b the required power of the motor to turn the nacelle. The engine power is asymmetrical and direction depended, which was expected since the torque is depended on the wind direction as well. Reasons for this behavior can be found in the aerodynamical behavior of the turbine blades, the structure of the whole turbine and the rotor turning.

To compare the engine power and the power difference due to the misalignment, it is necessary to convert the power difference into an energy difference. This can be done by multiplying the power difference with the time in which it subsides. Figure 3a shows the results as 2D plot for different subsiding times. The smallest possible time is 10 seconds due to the filter time constants. Fortunately the changes in the intersection are small when the time grows. Polynomial functions and thresholds are fitted to the intersection curves. Turning is not reasonable between ±9° wind direction deviations or beyond 3 m/s wind speed.

For the upper threshold of the wind speed the following polynomial function is found:

$$wf\_par\_max = 7.8 \cdot 10^{-7}\,(wd\_par \cdot (180/\pi))^4 + 0.0004 \cdot (wd\_par \cdot (180/\pi))^2 + 12 \qquad (1)$$

The parameter *wf_par_max* gives the upper threshold for the wind speed, *wd_par* is the measured wind direction deviation. The control law coincides with the results of other researchers which also state that there is no need to turn the turbine for small wind direction deviations. The upper threshold is similar to the boundaries of region III – the part of the energy curve where more power is generated than converted.

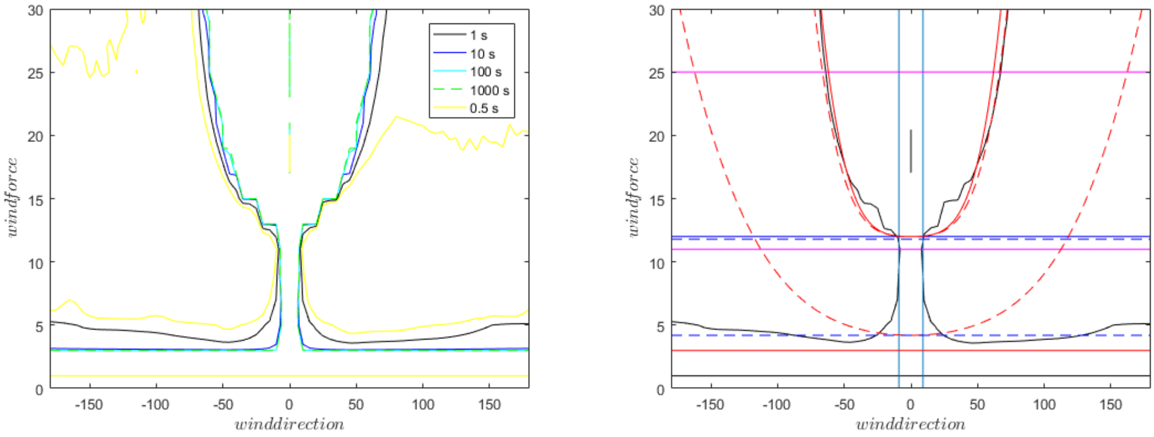

Figure 3: two dimensional graph of the intersections (a) and with approximation (b)

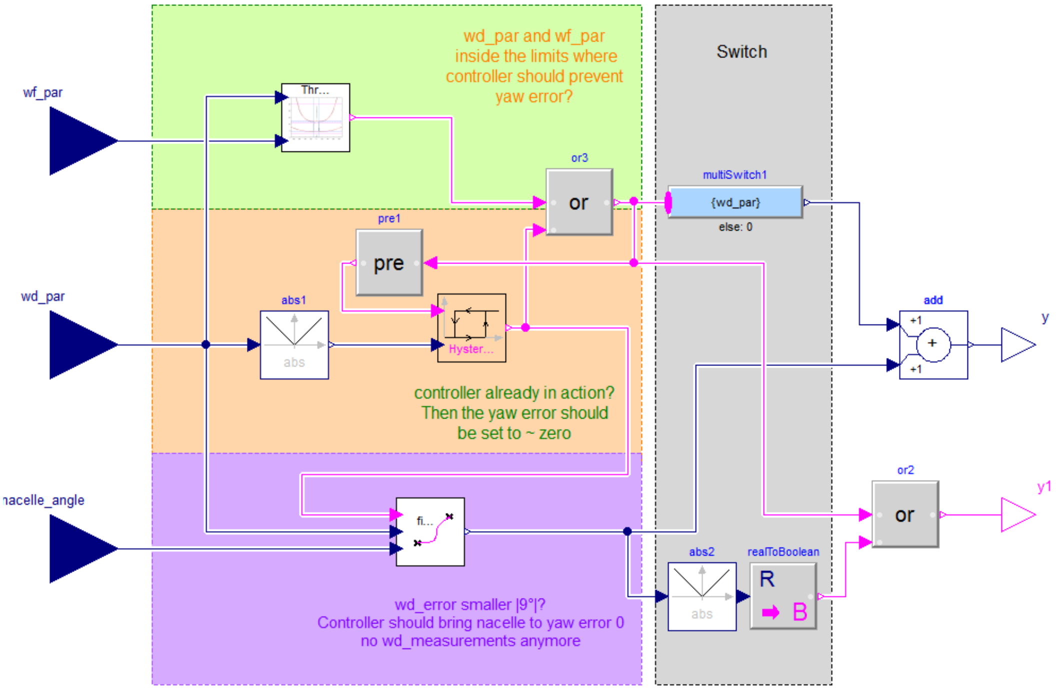

Figure 4: Subsystem controller

The controller itself consists of three subsystems (see fig. 4). If the controller is activated, it first of all checks if turning is necessary. This happens in the thresholder block according to the found thresholds. If turning is needed the measured wind direction deviation is feedthrough to the controller. It is not possible to reach zero deviation by a feedthrough. Hence, a third block is implemented. It consists of an open-loop controller and is activated for the last 9° of the turning. When the deviation is less, the desired position at this moment is saved and the open-loop controller turns the nacelle to this position. If there is a change in the wind direction during the last 9° of turning, it is not considered anymore. Therefore, oscillations are prevented in the yaw turning. To take stick-slip effects, calculation errors and noise into account all real-to-Boolean blocks have some small thresholds.

The Anti-twist block consists of rules based on the wind speed. It integrates the measured nacelle angle. Since there is no yaw alignment for wind speeds less than 3 m/s and also only little torque, the anti-twist turns the turbine back if the absolute value of the total angle is higher than 360°. If the absolute value of the total nacelle angle is higher than 540° and the wind speed is less or equal to 12 m/s, the nacelle turns as well. The value 12 m/s is the border between region II and region III for wind deviations higher than |9°|. For values higher than 720° the nacelle turns back immediately. The anti-twist turning happens in such a manner that the end position is shifted approximately 360° but also has zero wind direction deviation. The desired end position is determined before the turning. Changes in the wind direction during the turning are not taken into account.

The brake is the most straightforward subsystem. It activates if the other subsystems are not active. To avoid damage to the turbine it only brakes if the yaw rate is below 0.03°/s.

5 Test and Verification

The controller was tested and verified with numerous test cases which demonstrate the ability of the controller to perform its basic tasks of controlling, braking and anti-twist and its adaptability to high jumps in the wind direction, wind deviations above 90° and stochastic signals. The rigid body model was used for testing, the flexible body model for the verification. For illustration, the results of one case are shown here. This particular case was designed to test the characteristics of the first order filter for the wind speed. The wind speed is therefore noisy (Gaussian noise) with an expectation of 15 m/s and standard deviation of 0.8 m/s. The wind direction is deterministic with jumps at the times 100 s, 200 s, 250 s and 400 s. The first jump goes from 0° to 35°. The next jump is 60°, which means to a total wind direction deviation of 95°. The jump afterwards decreases the wind direction with -45° and the last jump with -10°. The simulation time is 510 seconds.

Figure 5 shows the results. The low pass filter works reliable. The results are as expected. At the time of 200 s the controller activates and releases the brake. The nacelle is turned to align with the wind. Small changes in the wind speed occur due to coupling effects. The filter delays the measurement of the wind direction. The next jump happens before the controller has reached its desired position. Due to this, it is not possible for the controller to settle at the ideal position. Instead it is turned to a deviation angle of 11.5°.This is below the threshold. The controller is not activating itself again. Still the turbine gives the maximum possible power. The last jump does not activate the controller anymore, due to the established prior offset.

6 Discussion

The found results of all test cases are promising. The controller is able to perform well in all test cases. Yet, in order to understand the results, it is necessary to show the limits of the test cases. The standard deviation was set in a way that the low pass filters can deal with it (0.8 m/s for the wind speed and later 3° for the wind direction). At a certain amount the low pass filter won't be able to filter it completely and the input signals get noisier. The filter time constants should be chosen in a way that they can deal with the occurring noise in reality. Also the measurement errors need to be determined in real life applications and set accordingly.

An important point is that the controller remains inactive between ± 9°, since the commonly used sensors are erroneous. New systems as LIDAR and SONAR provide better results. Yet, the classical anemometers are not very precise in the wind direction measurements especially caused due to rotor movement [14]. Deviations of a few degrees in the wind direction measurements are usual. It could be that for real world applications a different filter type (f.e. extended Kalman filter) is beneficial.

An even more important limitation is the verification model. Although it is not the same model as the design model, it is still very similar. It should be a part of future work to verify the controller in a

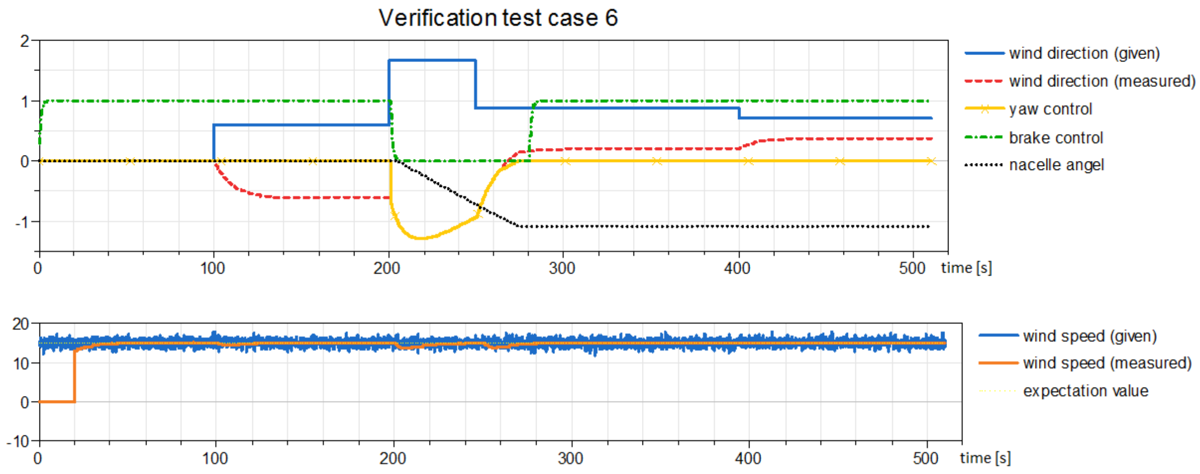

Figure 5: Results of test case 6

different environment or in experiment. Since the proposed controller is very robust it is likely that the results will show similar outcomes.

Emergency stops were not part of this research. Furthermore, analysis done with the model showed that an interaction of yaw and pitch control is not needed, due to a high torque in the aligned case.

7 Conclusion

The found control concept is robust and able to feature different types of motor. It uses mostly simple control components, which is cost effective and increases the reliability. The control law is applicable to a wide range of turbines due to the steepness of the intersecting curves. It is based on economic aspects which enhance power generation dependent on the costs and, therefore, helps to make wind energy more competitive. The found controller extends current research and coincides with it in many aspects. The controller should be tested in a different environment and on a real turbine in future.

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