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Wind Turbine Control for Highly Turbulent Winds

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The constant expansion of wind power plants and ever increasing energy needs result in a need for wind turbine installation in areas with complex terrain and highly turbulent winds. Wind turbine control during such winds is very difficult task that often cannot be efficiently accomplished by classic wind turbine control system. This paper presents a novel approach to the wind turbine control intended for a wind turbine operation during strong and gusty winds. The approach relies on a combined use of generator electromagnetic torque and pitch control. Generator electromagnetic torque is used as an intermittent braking torque that assists pitch actions during wind gusts. The proposed control approach can cause an electrical system overload if not designed appropriately. Therefore a methodology for the control system tuning that can guarantee safe operation of the system has been developed. The paper firstly describes the classic wind turbine control system and outlines the process of the control system design. Secondly, the proposed control approach is explained and controller tuning process is described. It is finally validated against the performance of a fine tuned classic control system. Testing of the control system is performed according to international standards using a professional wind turbine simulator.

Key words: Wind turbine control, Pitch control, Torque control, Wind gust compensation

Upravljanje vjetroagregatom pri izrazito turbulentnim vjetrovima. Neprekidni porast kapaciteta vjetroenergetskih postrojenja uvjetovan rastućim potrebama za električnom energijom dovodi do zahtjeva za instalacijom vjetroagregata u predjele sa složenim reljefom koji uvjetuje vrlo turbulentne vjetrove. Upravljanje vjetroagregatom pri takvim vjetrovima vrlo je složen zadatak koji često nije moguće ostvariti klasičnim sustavom upravljanja. U ovom radu opisan je novi pristup upravljanju vjetroagregatom namijenjen za rad vjetroagregata pri izrazito turbulentnim vjetrovima. Pristup se zasniva na kombiniranom upravljanju elektromagnetskim momentom generatora te kutom zakreta lopatica vjetroturbine. Pritom se elektromagnetski moment generatora koristi pri udarima vjetra kao privremeni kočni moment koji potpomaže aerodinamičko kočenje ostvareno zakretanjem lopatica vjetroturbine. Opisani pristup upravljanju vjetroagregatom otvara mogućnost električnog preopterećenja generatora i frekvencijskog pretvarača ukoliko sustav upravljanja nije adekvatno projektiran. Stoga je u radu izveden postupak projektiranja sustava upravljanja koji jamči siguran rad sustava u svim pogonskim uvjetima. U radu je najprije opisan klasični sustav upravljanja vjetroagregatom te postupci za njegovo projektiranje. Nakon toga, objašnjen je predloženi novi koncept upravljanja te je opisan postupak projektiranja sustava upravljanja. Predloženi koncept upravljanja ispitan je pomoću profesionalnog simulatora vjetroagregata i uspoređen s klasičnim sustavom upravljanja. Simulacijska analiza napravljena je prema međunarodnim normama za vjetroagregate.

Ključne riječi: upravljanje vjetroagregatom, upravljanje zakretanjem lopatica, upravljanje momentom generatora, radna područja vjetroagregata, kompenzacija utjecaja udara vjetra

1 INTRODUCTION

The use of wind power for electricity generation has been constantly and rapidly increasing over the last decades. According to the present power system development strategies and the goals set by the international authorities this trend is likely to continue. Traditionally wind turbines have been installed in flat areas with moderate steady winds such as northern plains of Denmark and Germany. Great increase in the installed wind energy capacity over the last decade has resulted in a depletion of such favorable sites for wind turbine installation. Therefore, new wind power plants are often installed in areas with complex terrain, on top of hills or quite close to settlements and roadways. Due to complex terrain, winds in such areas are usually unsteady and very turbulent with sudden and large gusts. Croatian coast, which has lately become very interesting for wind turbine installations, is an example of a complex terrain with very turbulent and gusty winds such as Bora. Highly turbulent winds are very unfavorable for a turbine operation since the wind turbine control system is not always capable to react upon rapid changes in the wind speed. Rising of the wind speed (wind gust) can often cause a wind turbine rotor overspeed. This increases the wind turbine structural loading and can provoke a safety stop and a consequent loss in the wind turbine production. On the other hand, sudden falling of the wind speed causes a wind turbine suboptimal operation because of the large deviations from the setpoint. To allow for a satisfactory operation of wind turbines under very turbulent winds, the wind turbine control system needs to be modified and augmented with additional functionalities. One novel approach for the wind turbine control aimed at tackling rapidly changing winds is described in this paper. The approach relies on a coordinated control of blade pitch angles and generator electromagnetic torque that can assure a better compensation of the wind gusts influence on the wind turbine behavior and improve the power control under unsteady winds.

The paper is organized as follows. In the second section a wind turbine operation is briefly described and the wind turbine basic control principles are explained. In the third section a mathematical model of a wind turbine needed for the control system design is derived. The fourth section deals with the design process of the wind turbine control system. In this section the control system design specifics in different operating regions of a wind turbine are described and system performance is validated using a professional simulation tools. In the fifth section a concept of wind gust compensation using coordinated control of blade pitch angle and generator torque is introduced. The proposed concept is analyzed by simulation and compared to the classic control approaches. Some conclusions are drown in the last section.

2 BASICS OF WIND TURBINE OPERATION AND CONTROL

Conversion of wind energy into mechanical energy of a rotating wind turbine rotor is governed by the principles similar to ones assuring flight of an airplane. Namely, wind turbine blades have similar airfoils as airplane wings. Such airfoils cause different air stream velocities on the upwind and on the downwind side of the blade. As a consequence lift and drag forces on the blade are developed that resolve into the force causing rotor torque and the force that imposes thrust upon the rotor. The actual energy conversion process is very complex and its mathematical description requires implicit relations known as the Blade element and momentum theory (BEM) [6, 12]. Although it can describe wind turbine system in detail, BEM results in implicit mathematical equations not very suitable for control system design and analysis. Therefore this approach to modeling of the wind turbine operation will not be pursued in this paper.

A very useful wind turbine model that offers insight in wind turbine operation principles can be derived starting from an analysis of energy and power balance in the system. Wind energy E_w, which is in fact the kinetic energy of the air passing at constant speed v_w through the circular plane swept by the wind turbine rotor with radius R, is equal to:

$$E_w = \frac{m_{air} {v_w}^2}{2} = \frac{1}{2}\rho_{air}\left(R^2 \pi x_{air}\right){v_w}^2, \qquad (1)$$

where ρ_{air} is the air density, while x_{air} is the displacement of air in the wind direction. Time derivative of the expression (1) yields the expression for wind power:

$$P_w = \frac{dE_w}{dt} = \frac{1}{2}\rho_{air}\left(R^2\pi\frac{dx_{air}}{dt}\right){v_w}^2. \qquad (2)$$

Since dx_{air}/dt is in fact the wind speed v_w, wind power can be written in the common form as:

$$P_w = \frac{1}{2}\rho_{air}R^2\pi {v_w}^3. \qquad (3)$$

The expression (3) describes very important phenomenon that will in many ways determine wind turbine operation and control. This phenomenon is the cube dependency of wind power upon wind speed. Due to such rapid and nonlinear increase in wind power with increase in its speed, wind power will be very small during slow winds and too high during strong winds. This introduces two different operation regions of wind turbine with contrary demands on the control system. During slow winds the control system aims at maximization of wind turbine power. Contrary, during strong winds the control system seeks to constrain wind turbine power in order to avoid the generator overload.

Wind turbine power control is possible due to the fact that wind turbine power can never be equal to wind power given by the expression (3). The reason for this is the very nature of wind energy conversion process as explained in detail in e.g. [6]. To describe the consequences of this process on the wind turbine operation, a dimensionless parameter called *Power performance coefficient* - C_P is usually used that relates wind turbine power P_t to wind power P_w:

$$P_t = P_w C_P. \qquad (4)$$

The power performance coefficient C_P is very common in wind turbine operation analysis. The theoretical maximum for C_P is determined by the Betz's law [6] and equals $16/27$. In practice wind turbines do not reach this limit but approach the value of 0.5 at best.

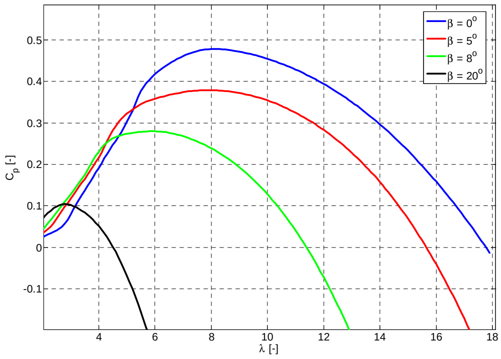

Fig. 1. Power performance coefficient dependency on tip speed ratio and blade pitch angle

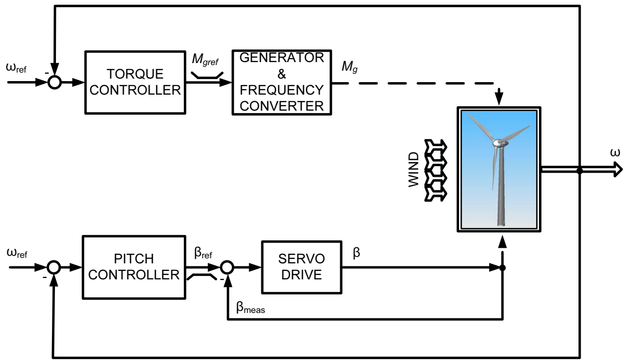

Fig. 2. Wind turbine control system principle scheme

The power performance coefficient C_P is not a constant parameter but its value is dependant on wind speed, rotor speed and blades pitch angle [6]. Blade pitch angle is the angle by which the entire blade is turned around its longitudinal axis. Pitching of a blade alters the angle between blade chord and air stream. This angle is termed "angle of attack" and aerodynamic efficiency of a blade is strongly dependant on this angle. Therefore, pitching of rotor blades can be used to control and limit wind turbine power. It is indeed a very efficient way of control because a turn of only $1°$ significantly decreases wind turbine power, while the turning of the blades to $90°$ ("feathering position") practically stops wind turbine rotation.

Therefore, the pitching of rotor blades can be used as a powerful aerodynamic brake.

When the dependency of power performance coefficient upon wind turbine variables is considered, wind speed and rotor speed are usually lumped together by introducing a new parameter λ, termed *Tip speed ratio* (TSR). It represents the ratio between blade tip speed and wind speed, [6]:

$$\lambda = \frac{\omega R}{v_w}. \tag{5}$$

Typical dependence of power performance coefficient upon tip speed ratio with pitch angle used as an additional parameter is shown in Fig. 1.

As it can be seen from equation (4) and Fig. 1, wind turbine power can be influenced by three means: wind speed, altering of the rotor speed and pitching of the blades. Wind speed is uncontrolled exogenous input that can be treated as disturbance from control system point of view. On the other hand, rotor speed and pitch angle can be controlled and thus used as an actuating variable. Pitching of rotor blades is possible due to fact that most of nowadays wind turbines have blades that are not fixed to the hub but are mounted on a slewing ring driven by electric or hydraulic motors. Rotor speed of modern wind turbines can be varied because their generator is not directly connected to the grid but AC-DC-AC frequency converter is used that decouples the generator frequency from the grid frequency.

Depending on the operating region one of the control actuating variables will be dominantly used. During low wind speeds there is no point in pitching the blades but they should be kept at values that assure the optimal C_P curve (the so called *fine position*, usually close to $0°$). Therefore power optimization must be sought through adaptation of rotor speed for any given wind speed in order to maintain tip speed ratio at the value for which C_P curve has its maximum (see Fig. 1). During strong winds wind power can become even order of magnitude higher than wind turbine rated power. Therefore, wind turbine power has to be constrained. The limitation of power is obtained by pitching of the rotor blades. As it can be seen in Fig. 1 pitching of rotor blades changes active C_P curve that wind turbine obeys. With increase in pitch angle the system shifts to C_P curves with lower values. This enables wind turbine to operate at its rated power with given wind power and tip speed ratio.

Based on given description of wind turbine control paradigm, a principle scheme of wind turbine control system can be derived as shown in Fig. 2.

As it can be seen from Fig. 2, wind turbine control system basically consists of two control loops. For both control loops the rotor speed is the controlled variable. However, they are often referred to as pitch and torque control loops based on the variable used to control the rotor speed. Those control loops operate simultaneously but depending on the operation region one of them is dominant. During weak winds the torque control loop is used to control the turbine speed to values that will result in maximal wind power capture. During strong winds this control loop was traditionally used just to hold the generator torque at its rated value. This classic approach will be modified in this paper as will be demonstrated later on. The pitch control loop is used for setting the adequate pitch angle that will keep the rotor speed at its rated value under all operating conditions determined by various winds. This control loop thus assures control of wind turbine power to the rated value during strong winds provided that generator electromagnetic torque is properly controlled as well.

Almost all modern wind turbines apply some variation of the basic control structure shown in Fig. 2. Explained control principles result in wind turbine steady state behavior illustrated by characteristics shown in Fig. 3.

From those characteristics it is possible to distinguish two operating regions with corresponding control loop activities. The border of the two operating regions is the lowest wind speed at which wind turbine rated power is achieved and pitch control becomes active. This wind speed is termed *Rated wind speed*. Therefore, the two described operating regions are usually referred to as below and above rated operating regions.

To achieve demonstrated wind turbine steady state behavior along with satisfactory dynamic behavior control system needs to be designed carefully. A prerequisite for efficient wind turbine control system design is suitable wind turbine mathematical model that is derived in the next section.

3 WIND TURBINE MATHEMATICAL MODELING

Mathematical model of wind turbine used in this paper will be derived departing from energy conversion description initiated in the previous section. This approach, encouraged in many references (see e.g. [7]), has proved adequate for control system design and analysis purpose.

Starting from equation (3) and (4) aerodynamic torque M_t that drives the rotor can be expressed as:

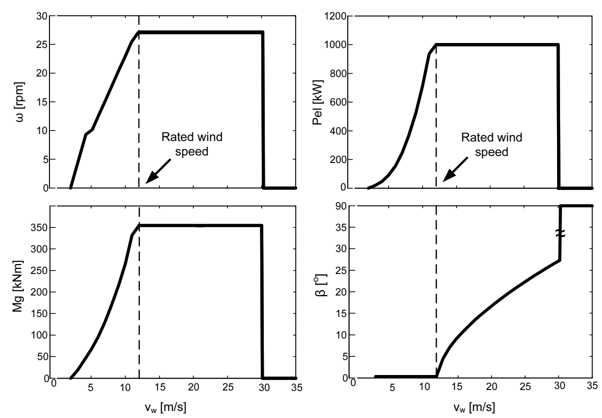

Fig. 3. Wind turbine steady state characteristics

$$M_t = \frac{P_t}{\omega} = \frac{1}{2}\frac{\rho_{air} R^2 \pi v_w^3 C_P\left(\lambda,\beta\right)}{\omega}. \tag{6}$$

Rearrangement of expression (6) yields:

$$M_t = \frac{1}{2}\rho_{air} R^3 \pi v_w^2 \frac{C_P\left(\lambda,\beta\right)}{\lambda}. \tag{7}$$

The ratio between power performance coefficient and tip speed ratio forms a new dimensionless parameter that is known as *Torque coefficient* C_Q [6]:

$$C_Q\left(\lambda,\beta\right) = \frac{C_P\left(\lambda,\beta\right)}{\lambda}. \tag{8}$$

Aerodynamic torque, calculated according to (8), is counteracted by generator electromagnetic torque M_g and the difference between them accelerates or decelerates the rotor:

$$J_t \dot{\omega} = M_t - M_g - M_l, \tag{9}$$

where J_t is total moment of inertia of rotor and generator observed from rotor shaft, while M_l is the loss torque. In this paper wind turbine with generator that is directly coupled with turbine rotor is considered. This turbine setting (known as direct drive system) uses synchronous multi-pole generator that rotates at small speed of turbine rotor. Since rotor and generator speeds are the same no distinction between them is made throughout the paper. Because there is no gearbox between rotor and generator their moments of inertia can just be summed together in order to calculate total moment of inertia J_t. In this turbine setup the rotating shaft is in fact the wind turbine hub that is very massive and stiff. For the modeling purposes it can be considered as completely stiff and no torsional vibrations need to be modeled without making any significant error. This is very favorable for wind turbine control since torsional oscillations pose serious problem for the control of standard geared turbines. The loss torque M_l, caused mostly by friction is rather small and can be neglected as well.

Before going any further in modeling of the system an important issue has to be addressed. Namely, the expression (7) would be strictly valid only for wind turbines with absolutely stiff tower and blades. Since the real structure is far from being absolutely stiff, relative motion of turbine structure in respect to wind has to be taken into account. Therefore the speed of undisturbed wind (v_w) in the expression (7) has to be replaced by the relative wind speed which is equal to:

$$v'_w = v_w - \dot{x}_t - \dot{x}_{bl}, \tag{10}$$

where x_t and x_{bl} are tower and blades displacements in the wind direction. Tower oscillations in wind direction are much more expressed than blades oscillations. The reason for this is higher stiffness of fiberglass made blades in comparison to steel towers that allows for neglecting of blades flexibility when considering wind turbine control. As wind turbines grow in size this assumption becomes less valid since increase in blade size reduces its stiffness.

Detailed description of tower oscillations requires use of model with distributed parameters that describes tower properties in terms of mass and stiffness distribution. Such a model is not suitable for control system design so it will be substituted by model with concentrated parameters. It can be done by decoupling complex tower oscillations into sum of simple oscillations ("vibration modes") using methodology known as modal analysis [1, 8, 9]. Analysis of standard wind turbines of different types shows that the first tower vibration mode is by far the most pronounced one. The contribution of all other models seems negligible compared to the contribution of the first mode. This is especially true from control system point of view since higher vibration modes fall well out of the control system bandwidth. Therefore in this paper tower oscillations in wind direction will be modeled as simple oscillatory system [21]:

$$M\ddot{x}_t + D\dot{x}_t + Cx_t = F_{x,t} + \frac{3}{2h_t}M_{y,t}, \qquad (11)$$

where M, D i C are tower modal mass, damping and stiffness respectively, $F_{x,t}$ is the rotor thrust force, h_t is the tower height while $M_{y,t}$ is flapwise bending moment on tower top.

The last term in the expression (11) is an approximation of the angular displacement of tower top ("tower nodding") with linear term. The term $3/2h_t$ is exactly valid only for uniform prismatic beam (see e.g. [11,21]). Nevertheless, it has been demonstrated that this approximation can be used for modeling of tower nodding as well.

Rotor thrust force $F_{x,t}$ can be modeled in the similar fashion as aerodynamic torque M_t [6]:

$$F_t = \frac{1}{2}\rho_{air}R^2\pi v_w^2 C_t(\lambda, \beta), \qquad (12)$$

where C_t is dimensionless *Thrust coefficient*, [6].

The tower oscillations perpendicular to wind direction can be modeled in similar way [21]:

$$M\ddot{y}_t + D\dot{y}_t + Cy_t = -\frac{3}{2h_t}M_g + F_{y,t}, \qquad (13)$$

where M_g is generator electromagnetic torque and $F_{y,t}$ is the aerodynamic force acting upon tower top in the direction perpendicular to wind.

Expressions (7), (9), (11), (12) and (13) form the simplified nonlinear modal of a direct drive pitch controlled wind turbine. For the sake of clearness model is summarized below taking into account the fact that wind speed experienced by the rotor is a sum of wind speed and tower nodding speed:

$$\begin{aligned} J_t\dot{\omega} &= M_t - M_g, \\ M_t &= \tfrac{1}{2}\rho_{air}R^3\pi C_Q(\lambda, \beta)\cdot(v_w - \dot{x}_t)^2, \\ F_{x,t} &= \tfrac{1}{2}\rho_{air}R^2\pi C_t(\lambda, \beta)\cdot(v_w - \dot{x}_t)^2, \\ M\ddot{x}_t + D\dot{x}_t + Cx_t &= F_{x,t} + \tfrac{3}{2h_t}M_{y,t}, \\ M\ddot{y}_t + D\dot{y}_t + Cy_t &= -\tfrac{3}{2h_t}M_g + F_{y,t}. \end{aligned} \qquad (14)$$

Torque and thrust coefficients C_Q and C_t used in the derived model are usually provided by wind turbine blade manufacturers or can be calculated using professional simulation tools. Comparison of the results obtained by model (14) with the results of much more detailed aeroelastic models used in professional wind turbine simulation tools showed that the model (14) captures wind turbine dominant dynamics under various operating conditions [14]. Therefore, it will be the basis for control system design that is carried out in the following sections.

4 WIND TURBINE CONTROL SYSTEM DESIGN

In this section the design process of standard wind turbine control system design will be outlined. The design process will be described for two operating regions - below and above rated wind speed.

4.1 Wind turbine control below rated wind speed - Torque control

As stated before, below rated wind there is not enough power in wind to run the turbine at its rated speed. Therefore control system's task below rated wind speed is the maximization of wind turbine power. From the shape of C_P curve shown in Fig. 1 it can be seen that it has an unique and distinctive maximum. This motivates the control approach - wind turbine should be controlled in a way that results in optimum value of tip speed ratio i.e. the value at which C_P obtains its maximum. The control algorithm that achieves this goal may deceivably seem straight forward: From known optimal value of tip speed ratio

λ_{opt} and measured value of the instantaneous wind speed $v_{w,meas}$, the optimal value of rotor speed can be calculated from (5) as:

$$\omega_{opt} = \frac{\lambda_{opt} v_{w,meas}}{R}. \quad (15)$$

Optimal value of rotor speed calculated in this way can be used as reference value in a control loop that uses generator electromagnetic torque as the actuating variable.

Although simple to understand, this control approach is not suitable for practical implementation. The reason for this is the fact that wind speed is very hard-to-measure variable. Namely, wind speed is normally measured using anemometers placed on top of the nacelle, few meters behind the rotor. Therefore wind speed measurement signal carries inevitably delayed information about the wind speed at rotor that is relevant for wind turbine operation. Moreover wind turbine rotor acts effectively like a low pass filter while the anemometer itself introduces certain amount of averaging so the measured signal lacks information about faster wind speed changes. Finally, anemometer gives information about wind speed only at one point while wind field varies with space as well as with time.

All mentioned reasons make wind speed measurement very unreliable variable that can be only used as orientational value for monitoring of a wind turbine operation. Therefore, control that assures power optimization must be sought in different way. However, the first idea for control approach will be used to derive a feasible control algorithm.

For this purpose, assume that wind turbine rotor speed is controlled in closed loop with its reference value calculated according to (15). Furthermore, assume that the controller and turbine dynamics are infinitely fast. In that case rotor speed will always be equal to its reference value that is in this case equal ω_{opt}. The driving torque M_t that assures this value of rotor speed is given by expression (7) that can be rearranged into the form suggested by [3]:

$$M_t = \frac{1}{2} \frac{\rho_{air} R^5 \pi \cdot C_P(\lambda, \beta)}{\lambda^3} \omega^2. \quad (16)$$

If the rotor speed is controlled to its optimum value according to (15) it means that tip speed ration is at its optimum value equal λ_{opt}. Substituting optimum values for ω and λ into (16) yields:

$$M_t = \frac{1}{2} \frac{\rho_{air} R^5 \pi \cdot C_{P,\max}}{\lambda_{opt}^3} \omega_{opt}^2. \quad (17)$$

The expression (17) gives the value of aerodynamic torque that results in maximum C_P i.e.the optimal value of aerodynamic torque. It can be written in a common form as [3]:

$$M_t = K_\lambda \cdot \omega_{opt}^2, \quad (18)$$

where:
$K_\lambda = \frac{1}{2} \frac{\rho_{air} R^5 \pi \cdot C_{P,\max}}{\lambda_{opt}^3}$ is known as the *Optimal mode gain*.

It should be noted that expression (18) does not contain wind speed as a parameter although it has been derived assuming perfect wind speed measurement. Moreover, since the optimal values of tip speed ratio does not depend on the particular value of rotor speed, the expression (18) is valid for any given value of rotor speed. Therefore, the optimal value of the aerodynamic torque can be calculated as:

$$M_t = K_\lambda \omega^2. \quad (19)$$

In steady state, generator electromagnetic torque is equal to the aerodynamic torque minus the loss torque that is small enough to be neglected. This means that the optimal power production in steady state can be achieved if generator electromagnetic torque follows the parabolic law given by (19).

The expression (19) is the hearth of wind turbine control below rated wind speed. Although it assures the optimal wind turbine power only in steady state, it has been demonstrated that it can be very efficiently used for dynamic control as well (see e.g. [3, 6, 17]). It is usually implemented as a look-up table scheduled on rotor speed.

If the generator torque is controlled according to (19) the quality of control depends on wind variations and the inertia of wind turbine rotor. Also, it depends on the shape of C_P characteristics, namely whether its maximum is steep or laid. Some promising methods for improving wind turbine control below rated wind speed can be found in [4]. They rely on using information about rotor acceleration to achieve virtual reduction in turbine inertia. Although promising in theory such approaches are very sensitive to measurement noise, which limits their practical applicability.

The described torque control algorithm assures the optimal turbine production in steady state and satisfactory dynamic behavior in the major part of the below rated operating region. However, its performance at the edges of the operating region is not always satisfactory a different approach is required. Namely, the constraints imposed on the wind turbine system interfere with the optimal torque control and require control law modifications in some situations. The main constraints are the ones imposed on rotor speed due to the noise and structural loads. To explain the need to constrain rotor speed consider as an example a 1 MW wind turbine with rotor radius of 28 m. Rated wind speed for this turbine is assumed to be 11.3 m/s. Maximum value of C_P is assumed to be 0.46 reached at the optimal value of tip speed ratio of 8. Keeping the optimal tip speed ratio all the way to the rated wind speed would mean that at the wind speed of 11.3 m/s the rotor speed would be equal 30.8 rpm. This value of rotational speed is very high since it would result in a blade tip speed of 90.4 m/s, which would introduces high level of acoustic noise and blade erosion due to collision with small particles in the air. Therefore, rated rotor speed needs to be reduced (usually $24 - 27$ rpm for 1MW wind turbine depending on its proximity to the settlements).

The reduction of rotor speed can be done in two ways. One is to maintain the optimal torque characteristic up to the rated rotor speed and to start pitching the blades when the rated rotor speed is exceeded. This is, however, not reasonable approach because tracking of the optimal value of the tip speed ratio results in wind turbine power that is lower than rated. In the former example, if the rated rotor speed is 24 rpm it is reached at wind speed of 8.8 m/s resulting in power of only 473 kW. From this simple calculation it is obvious that this approach would mean limiting the wind turbine power at less than half of its rated value, which is not reasonable from turbine efficiency point of view.

Therefore, another approach is used in practice that is described in detail in [3]. In this approach rotor speed is constrained to the rated value by abandoning the optimal tip speed ratio once the rated rotor speed is reached. Maintaining the rotor speed at its rated value, according to (5) means reduction of the tip speed ratio, which in turn results in a reduction in the power performance coefficient C_P according to the shape of its characteristics shown in Fig. 1. To maintain rotor speed at its rated value while wind speed is increasing it is necessary to increase generator electromagnetic torque thus matching the increased aerodynamic torque that would accelerate the rotor.

This approach can be clearly illustrated using the wind turbine steady state characteristics shown in Fig. 4. The characteristics in Fig. 4 show the dependency of the wind turbine aerodynamic torque upon the rotor speed. This dependency changes with a change in wind speed so the wind turbine characteristic must be presented by a family of curves. In the same figure the optimal generator torque characteristic (19) is plotted. An intersection of the aerodynamic torque curve and the generator electromagnetic torque curve is a stable operating point for wind turbine. From Fig. 4 it can be seen that if the optimal generator torque characteristic is followed, operating point falls above rated rotor speed already for winds higher than 10.5 m/s. Since the rated wind speed is 11.5 m/s in this example it is obvious that the generator torque characteristic needs to be modified. An ideal modification is shown

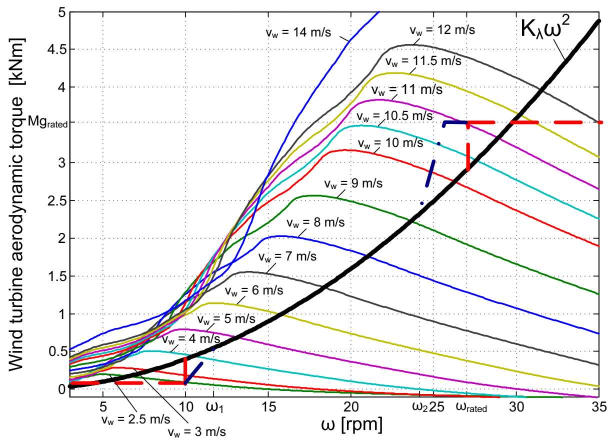

Fig. 4. Static dependency of the aerodynamic torque on the rotor speed below rated wind speed

as dashed red line in Fig. 4. As it can be seen this modification is not a bijection so it cannot be implemented in a form of a look-up table. The possible ways to address this problem are modifications of the optimal characteristic, i.e. abandoning the optimal torque curve before the rated rotor speed. This is a very simple solution that allows for an implementation of the torque characteristic in a look-up table. However, it degrades the behavior of the turbine because the optimal operation is abandoned earlier than necessary. The transient characteristic needs to be less steep as the rotor inertia increases to enable wind turbine rotor to follow demanded changes in the rotor speed. This increases losses and makes wind turbine less efficient. One possible modification of the optimal torque characteristic near the edge of the operating region is shown with blue dash-dotted line in Fig. 4.

To overcome the mentioned drawbacks of the simple modification of the optimal torque characteristic, an approach suggested in [3] can be applied. In this approach torque is controlled according to the optimal characteristic (18) all the way to the rated rotor speed. When the rated rotor speed is reached, rotor speed control in closed loop becomes active and regulates the rotor speed to its rated value. In this way a vertical part of the generator torque curve at rated rotor speed can be achieved as shown in the Fig. 4. The controller applied is usually of PI type with torque reference being its output. This improves the wind turbine efficiency below rated but is also sensitive to wind turbine rotor dynamics. Similar control logic is applied at the other end of the operating region i.e. near to the minimum operating rotor speed. More details on generator torque control can be found in e.g. [3, 6].

To test the described control system a professional simulation tool for wind turbines GH Bladed [5] is used in this paper. GH Bladed relies on a very complex aerodynamic and structural wind turbine model supplemented with detailed models of control and electrical subsystems. Moreover, it incorporates realistic wind models that allow for description of temporal and spatial wind variations. All this makes results of simulations performed in GH Bladed very reliable and in accordance with the behavior of real wind turbines (as has been recognized by Germanischer Llyod and other major certification institutions). Therefore in this paper GH Bladed is used as a test bed for analyzed control algorithms. The algorithms are tested using aeroelastic model of 1MW direct drive wind turbine.

To illustrate the specifics of the wind turbine control below rated wind speed turbine was excited by an artificial wind speed changes that doesn't appear in nature but offers very good insight in wind turbine operation. The used wind speed changes very slowly with linear increase from the value of 3 m/s up to 12 m/s followed by the linear decrease with the same gradient. The responses of rotor speed, tip speed ratio and wind turbine power are shown in the Figs. 5 - 7.

As it can be seen from the Figs. 5 - 7, designed control system assures tracking of the optimal tip speed ratio ($\lambda_{opt} = 7.9$ in this example) in the major part of the below rated operating region. When the rated wind speed is approached the optimal tip speed ratio is abandoned and the rated rotor speed is maintained by increased torque. From Fig. 6 and Fig. 7 it can be seen how the use of closed loop controllers improves wind turbine efficiency by assuring the tracking of the optimal tip speed ratio in broader region of wind speeds what results in increased wind turbine production. The figures also show the response of the turbine that is controlled by using only the optimal torque characteristic (18). As it can be seen this approach yields quite unsatisfactory results with lower achieved power due to the premature pitching of the blades.

4.2 Wind turbine control above rated wind speed - Pitch control

Above rated wind speed pitching of the rotor blades is used to control rotor speed to its rated value under all wind conditions. Although the controlled variable is again rotor speed, this control approach is usually refereed to as pitch control. Contrary to the torque control that is mostly done in an open loop, pitch control of wind turbine needs to be done in a closed loop. Standard solutions use PI or PID controllers that are well established in practice.

Two wind turbine characteristics need to be considered carefully while designing the pitch controller. The first one is the strong nonlinearity of the process caused by the cube relationship between wind power and its speed (3), as well as the specific shape of C_P characteristics shown

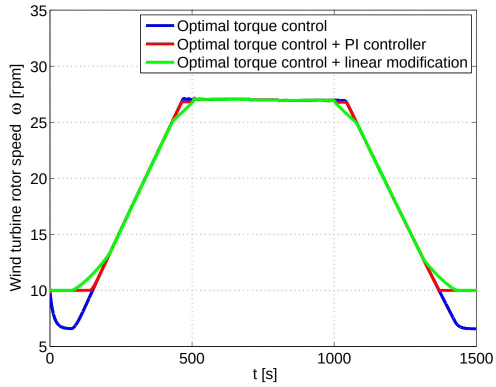

Fig. 5. Wind turbine rotor speed during linear wind speed change below rated wind speed

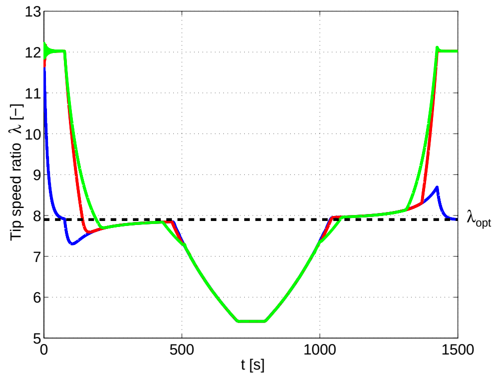

Fig. 6. Tip speed ratio λ during linear wind speed change below rated wind speed

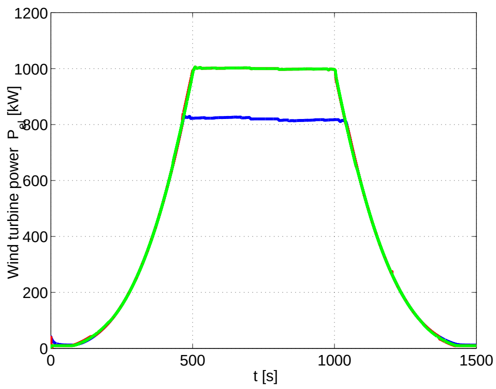

Fig. 7. Wind turbine power during linear wind speed change below rated wind speed

in Fig. 1. In order to control such nonlinear process with linear (e.g. PI) controller some certain parameter adaptation needs to be applied. The very common way of parameter adaptation is the gain scheduling [2]. In this approach controllers are designed for many operating points determined by wind speed. In operation controller parameters are selected based on current operating point. The problem with this approach lies in the fact that wind turbine operating point is determined by wind speed that is not easy to measure as previously noticed. Therefore in practice controller parameters are usually scheduled based on measured pitch angle. This is possible because above rated wind speed there is unambiguous relationship between wind speed and pitch angle. This relationship is strictly valid only in the steady state but numerous applications proved its applicability even for wind turbine dynamic control (see e.g. [7, 10]).

The second wind turbine characteristic that strongly influences pitch control is the mentioned influence of tower oscillations on the wind turbine operation through the influence of relative wind speed experienced by turbine rotor.

This strongly complicates the pitch controller design since tower nodding is dependant on pitch angle since the pitch angle influences rotor thrust force $F_{x,t}$. Due to the pitch angle influence on rotor thrust force it becomes possible to obtain positive feedback and to enhance tower nodding by unappropriate blade pitching. This would lead to catastrophic consequences and must be avoid in any case. At the same time by appropriate pitch control an active damping of tower oscillations can be achieved as described in e.g. [4, 13].

A prerequisite for pitch controller design is a suitable linear model of the wind turbine since most of the used algorithms are nowadays of a linear type. The linear model of wind turbine can be obtained by linearization of the nonlinear model (14). Inspection of the model (14) shows that only the second and the third expression need to be linearized while other equations are valid in the same form for small displacements of particular variable around operating point as are for the absolute values of the variable.

Linearization of the second equation from (14) around selected operating point (OP) yields:

$$\begin{aligned}\Delta M_t = &\left.\frac{\partial M_t}{\partial v_w}\right|_{OP}(\Delta v_w - \Delta\dot{x}_t) + \\ &+ \left.\frac{\partial M_t}{\partial \beta}\right|_{OP}\Delta\beta + \left.\frac{\partial M_t}{\partial \omega}\right|_{OP}\Delta\omega.\end{aligned} \tag{20}$$

Analogously, the linearization of the third equation from (14) yields:

$$\begin{aligned}\Delta F_{x,t} = &\left.\frac{\partial F_{x,t}}{\partial v_w}\right|_{OP}(\Delta v_w - \Delta\dot{x}_t) + \\ &+ \left.\frac{\partial F_{x,t}}{\partial \beta}\right|_{OP}\Delta\beta + \left.\frac{\partial F_{x,t}}{\partial \omega}\right|_{OP}\Delta\omega.\end{aligned} \tag{21}$$

To save on a notation following substitutions are introduced:

$$\begin{aligned} M'_w &= \left.\tfrac{\partial M_t}{\partial v_w}\right|_{OP} & F'_w &= \left.\tfrac{\partial F_{x,t}}{\partial v_w}\right|_{OP} \\ M'_\beta &= \left.\tfrac{\partial M_t}{\partial \beta}\right|_{OP} & F'_\beta &= \left.\tfrac{\partial F_{x,t}}{\partial \beta}\right|_{OP} \\ M'_\omega &= \left.\tfrac{\partial M_t}{\partial \omega}\right|_{OP} & F'_\omega &= \left.\tfrac{\partial F_{x,t}}{\partial \omega}\right|_{OP}. \end{aligned} \tag{22}$$

Partial derivatives (22) can be obtained from wind turbine mathematical model (14). The needed partial derivatives of torque and thrust coefficient in respect to particular variable can be found numerically by approximating derivative with difference.

Adding the remaining three equations from (14) the linear wind turbine model can be completed. It is summarized in the expression (23). To economize on a notation in expression (14), differential operator Δ is omitted with a remainder that the model is valid only for small deviations around operating point.

$$\begin{aligned} &J_t s\omega(s) = M_t(s) - M_g(s), \\ &M_t(s) = M'_w[v_w(s) - sx_t(s)] + M'_\beta\beta(s) + M'_\omega\omega(s), \\ &\left(Ms^2 + Ds + C\right)x_t(s) = F_{x,t}(s), \\ &F_{x,t}(s) = F'_w[v_w(s) - sx_t(s)] + F'_\beta\beta(s) + F'_\omega\omega(s). \end{aligned} \tag{23}$$

Tower naying dynamics is left out of the model since it is not relevant for pitch controller design. From the expression (23) it is easy to obtain wind turbine model in the state space form defined as:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}.\end{aligned} \tag{24}$$

Derived wind turbine model has three states: rotor speed, tower top displacement in the wind direction and tower nodding speed: $\mathbf{x} = \begin{bmatrix} x_t & \dot{x}_t & \omega \end{bmatrix}^T$.

Model inputs are wind speed, pitch angle and generator torque: $\mathbf{u} = \begin{bmatrix} v_w & \beta & M_g \end{bmatrix}^T$.

System matrices follow directly from (23):

$$
\begin{aligned}
A &= \begin{bmatrix} 0 & 1 & 0 \\ -\frac{C}{M} & -\frac{D+F'_w}{M} & \frac{F'_\omega}{M} \\ 0 & -\frac{M'_w}{J_t} & \frac{M'_\omega}{J_t} \end{bmatrix}, \\
B &= \begin{bmatrix} 0 & 0 & 0 \\ \frac{F'_w}{M} & \frac{F'_\beta}{M} & 0 \\ \frac{M'_w}{J_t} & \frac{M'_\beta}{J_t} & -\frac{1}{J_t} \end{bmatrix}, \\
C &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \\
D &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.
\end{aligned}
\tag{25}
$$

The derived state space model is very convenient for various control designs, e.g. simple PI controllers to more advance approaches such as LQG [15].

Here, a design of a PI controller will be outlined since it stands as industrial standard and is applied in the most of the running wind turbines.

The demands on a pitch controller are fast compensation of the influence of wind speed changes to wind turbine speed and power as well as appropriate damping of the tower oscillations. Those two objectives are contrary for a PI controller and an acceptable tradeoff between control dynamics and damping of tower oscillations needs to be found. This can be done by standard pole placement methods using available software tools such as Control System Toolbox in Matlab [20]. This is however only an initial controller tuning that needs to be optimized taking into account the influence of controller actions on an overall system behavior. The wind turbine behavior needs to be examined in terms of:

- Extreme structural loads
- Tower and blades oscillations
- Material fatigue
- Wind turbine energy yield

Results obtained through these testing present input data for sizing of the wind turbine components that determines wind turbine layout and in turn influences its dynamic. Therefore, an iterative process is formed through which the optimal controller parameters need to be found [14]. The described process is very complex and requires involvement of different expertise and numerous design tools.

In the following figures few examples of well tuned control system performance is illustrated. The model of the

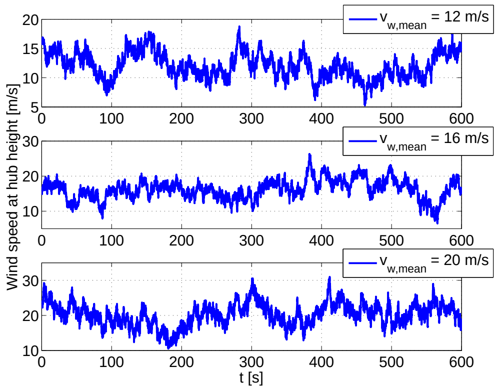

Fig. 8. Turbulent winds used in simulations

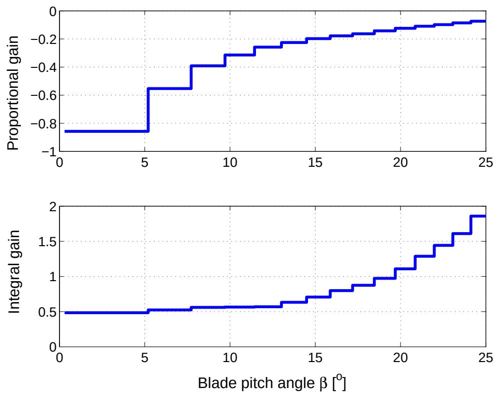

Fig. 9. Pitch controller parameters in dependency of operating point

examined 1 MW wind turbine simulated in GH Bladed is excited by realistic 3D turbulent wind field generated according to international standards for wind turbines [19]. The figures show three simulation cases that differ in mean wind speed and turbulence intensity as shown in Fig. 8. The wind turbine is controlled using PI controller with gains scheduling. The dependency of controller parameters upon pitch angle are shown in Fig. 9. Below rated wind speed the torque is controlled according to the optimal characteristic (18) with modifications on the edge of the below rated operating region according to the characteristics shown in the Fig. 4. An extract form long simulation runs is shown in the figures 10 - 12 where key turbine variables - rotor speed, pitch angle, generator torque and power are shown.

The simulation runs shown in the Figs. 10 - 12 are just small part of several hundreds of simullation runs that are required according to standards [19] to prove wind turbine behavior satisfactory. The controller tuning shown in Fig. 9

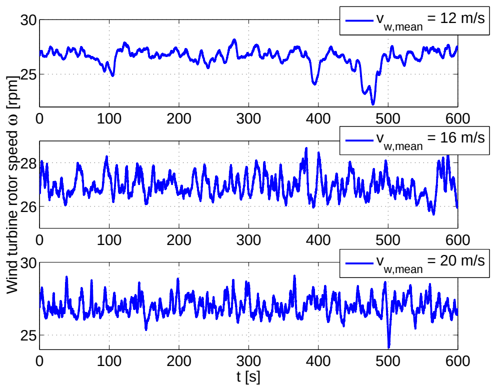

Fig. 10. Wind turbine rotor speed during turbulent wind

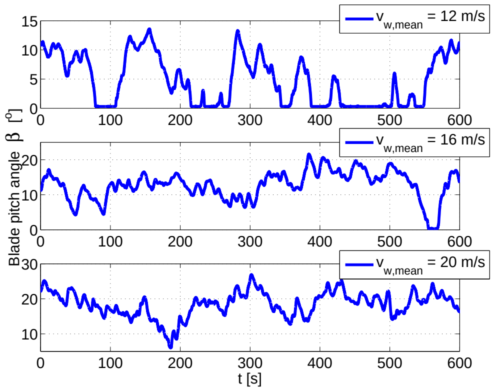

Fig. 11. Blade pitch angle during turbulent wind

was found to be optimal tradeoff between various objectives in the previously described iterative design process.

The simulation results shown in the Figs. 10 - 12 have been selected here since they show some interesting aspects of wind turbine dynamic behavior. Those aspects are summarized below.

The rotor speed in all runs remains in a narrow band of 1 rpm around its rated value in spite to large wind speed variations visible from the Fig. 8. Especially interesting is the simulation run with turbulent wind with mean value of 20 m/s. As it can be seen from the third chart in Fig. 8, wind speed in 10 min varies from 10 to 30 m/s meaning that in only ten minutes wind speed can vary through the entire above rated operating region. This is a clear motivation for application of gain scheduling and the shown rotor speed behavior suggests that it has been implemented in the proper way.

Te pitch angle behavior, shown in Fig. 11, shows moderate and uniform pitching dynamics without jerks or oscillations. Demonstrated pitch behavior is very favorable

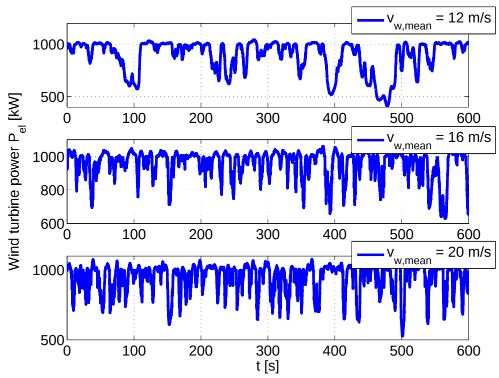

Fig. 12. Wind turbine power during turbulent winds

because it reduces pitch system wear and tear while obtaining satisfactory control of wind turbine rotor speed.

The maximal observed value of the rotor speed is 2.1 rpm above rated rotor speed meaning that the rotor speed overshoot is only 7.8 %. This could be considered as very small and satisfactory at first sight. However, it should be considered that wind turbine rotor speed has relatively small margin above rated value before overspeed protection is activated. Therefore rotor speed excursions above rated rotor speed should be analyzed in terms of maximal allowable overshoot that will trigger the overspeed protection. The observed overshoot in this case is 35 % of the maximal overshoot what can be considered satisfactory.

However other simulations with more severe wind conditions confirmed the well known fact that pitch control is not always capable to cope with sudden and large wind gusts. Such gusts cause very large overshoots in rotor that often trigger the overspeed protection causing turbine stop. This fact gains in its importance as wind power plants are being installed in locations with complex terrain and very turbulent winds. Therefore in the next section a novel approach to solving the problem of wind turbine operation during highly turbulent winds is proposed. The approach relies on the use of generator electromagnetic torque as intermittent wind gust compensator.

5 WIND GUST COMPENSATION USING GENERATOR TORQUE

In section 4 the classic approach to torque control has been described where torque control is active only below rated wind speed. In the above rated operation region generator torque has been traditionally limited to its rated value. Several different approaches have been reported in the literature where torque control is active above rated wind speed as well. The motivation for torque control above rated in such works is damping of drivetrain oscillations (see e.g. [3]) or better transition between two operating regions (see e.g. [18]. In this paper a different approach is proposed in which generator torque is used to avoid large rotor overspeeds caused by wind gusts.

The motivation for this approach is straightforward and comes from the fact that the generator torque opposes aerodynamic torque that drives wind turbine rotor (see (9)). The use of generator torque for this purposes becomes appealing knowing that generator torque control (using frequency converter) has very fast dynamics with dominant time constants in the millisecond range.

The generator torque can not be used for compensation of permanent changes in wind speed because it would cause generator and frequency converter overloading. Therefore generator torque controller that is active above the rated wind speed should have P or PD action. In this way it is active only during rotor speed excursions over the rated value. The pitch control remains the main wind turbine actuating variable that has to compensate wind speed changes. However in this approach it is assisted by the generator electromagnetic torque increase that reduces rotor speed overshoots allowing for less aggressive pitch actions at the same time. This is favorable because it reduces loading of the pitch system thus reducing its wear and tear.

In this paper the simplest possible torque controller suitable for this purpose is considered - a proportional controller. Using such a controller the generator torque above rated rotor speed is controlled as:

$$M_g = K_{Mg} \left(\omega_{nom} - \omega_{meas} \right) \tag{26}$$

where ω_{nom} is the rated (nominal) rotor speed and K_{Mg} is the torque controller gain. Below rated rotor speed the usual rotor speed control is applied as described in the subsection 4.1.

It should be mentioned that theoretically much better results could be obtained if PD controller is applied. In practice such a controller is very sensitive to noise, which significantly deteriorates its performance making it not suitable for real applications.

Introduction of the proportional torque control above rated rotor speed results in change of wind turbine dynamics. This can be seen if the expression (26) is substituted in the linearized wind turbine model (23). From linearized model (23) it is possible to calculate transfer function of rotor speed change in respect to wind speed change:

$$G_w^{'}(s) = \frac{M_w^{'}}{J_t s - \left(K_{Mg} + M_{\omega}^{'} \right)}. \tag{27}$$

In the derivation of the expression (27) tower flexibility was neglected. This is not a reasonable assumption and is

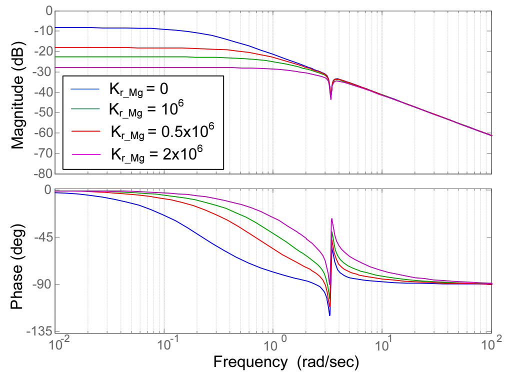

Fig. 13. Influence of torque control above rated rotor speed on wind turbine dynamics

done here only to make the results more transparent. In the controller design process tower flexibility definitely needs to be considered. From the expression (27) it is clear that introduction of torque control in the proposed way results in reduction in system gain and modification of its dynamics. This can be clearly seen in Fig. 13 showing frequency characteristics of the transfer function (27) with four different values of generator toque controller gain K_{Mg}.

From Fig. 13 it is clear that the bigger the torque controller gain K_{Mg} gets the system will be less sensitive to changes in wind speed, which is intuitively clear. The problem is of course the overloading of the generator and frequency converter caused by every exceeding of the generator rated torque and/or rotor rated speed. Frequency converter is the critical component for overloading due to very small time constants of its power electronic switches. Nevertheless, it does allow certain overloading that is usually defined in a form of overpower as a function of time it can be withstood (e.g. 150% of rated power during 2 s). The torque controller needs to assure that such limitations are not violated under any operating condition. From the given description the main objectives for the torque controller design can be defined:

1. Prevent overloading of the frequency converter under all operating conditions;

2. Achieve tradeoff between improvement in wind turbine dynamic behavior and increased electrical loading of the generator and frequency converter.

Designing the controller that meets stated objectives is a quite complicated task due to several reasons. Like first wind turbine electrical power that determines loading of the generator and frequency converter is a product of generator torque and its speed. In the proposed concept of torque control both of these variables change during change in wind speed. Secondly, with the introduction of proportional torque controller above rated rotor speed system dynamics changes, which influences the pitch control system.

Two approaches to controller design have been investigated in this work: static and dynamic analysis. The approaches are outlined below.

5.1 Wind gust compensator design - a static analysis

In this approach only the maximum allowable power for the frequency converter is considered. The torque controller gain is selected in a way that this maximum power is not reached even at maximum rotor speed. The concept of maximum rotor speed is quite problematic and difficult to define. Namely, to prevent overloading of the system under all operating conditions it is necessary to consider wind turbine operation even in the case of control system partial or complete failure. In such situations rotor speed can rise in an uncontrolled manner so it might seem that maximum rotor speed can not be defined. However, every wind turbine must be equipped with an independent hardwired safety system (usually called "safety chain") that reacts on detected system failures and forces the system into safe state. One of the indications of a failure is the rotor overspeed. The activation of the safety system disconnects the generator and frequency converter from the grid and activates emergency dissipation of the energy stored in converter's DC link. Therefore the rotor speed at which overspeed protection is activated is relevant for frequency converter loading and can be used as maximum rotor speed in further analysis. Having defined maximum rotor speed torque controller gain can be simply calculated as the ratio of maximum allowable power and the rotor speed at which overspeed protection is activated.

Although intuitively reasonable, this approach to torque controller design has many drawbacks. Like first it neglects the turbine dynamics thus completely ignoring the second objective for the controller design. Secondly, by considering extreme values of wind turbine speed and power it yields very conservative tuning of the controller. Torque controller tuned in this way results in very little improvement in wind turbine behavior during normal operating conditions. From above description it is obvious that much more elaborate approach is needed that relies on dynamic analysis of wind turbine operation.

5.2 Wind gust compensator design - a dynamic analysis

The first step in this approach is to calculate the modification of the system dynamics due to inclusion of the proportional torque controller. It can be calculated in the same way as the transfer function (27) was derived. The transformation of the system with inclusion of torque controller is illustrated in Fig. 14.

Since the system dynamics change due to modified torque control it is necessary to re-tune the pitch controller (based on chosen criteria) for each value of torque controller gain K_{Mg}. After tuning of the controllers wind turbine model is simulated with chosen wind speed change. From the simulation results it is possible to identify duration of the overpowers of certain magnitude. The described procedure needs to be repeated for a range of values of the torque controller gain. This procedure results in a family of curves relating particular value of torque controller gain K_{Mg} with magnitude of overpower and its duration. From such characteristics it is possible to select the optimum value of K_{Mg} according to the overload characteristics of the frequency converter.

This approach yields much better results than static approach since it takes into account the changes in system dynamics and adjusts the pitch controller parameters accordingly. Therefore coordination between pitch and torque controller is achieved. However, it doesn't provide explicit guarantees for the first design objective by itself.

To assure that the first objective is met, i.e. that frequency converter won't be overloaded in any situation it is necessary to simulate extreme situations during described controller tuning. The extreme situations are defined by transient winds with large magnitude of speed change in rather short time. Such transients are defined by international standards for wind turbines [19] and are meant to encompass all possible severe wind gusts that are likely to happen in wind turbine's lifetime.

One of the most severe gusts that has been taken into account during controller tuning is the so called *extreme operating gust -EOG* shown in the Fig. 15. As it can be seen from Fig. 15 magnitude of wind speed change is extremely large and depends on starting wind speed. This wind transient is intended to model extreme wind gusts that have probability of occurring once in 50 years [19]. Including

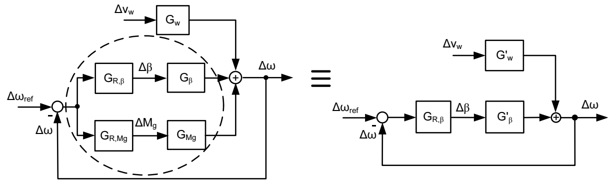

Fig. 14. Transformation of wind turbine dynamics due to inclusion of proportional torque controller above rated rotor speed

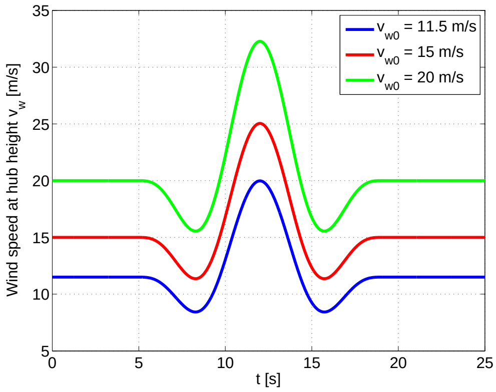

Fig. 15. Extreme operating gust with return period of 50 years (according to standards IEC-61400-3)

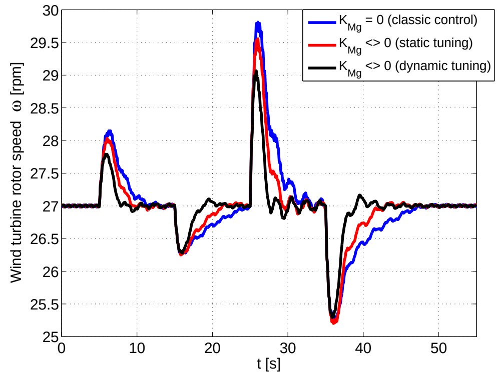

Fig. 16. Rotor speed response on a step change in wind speed

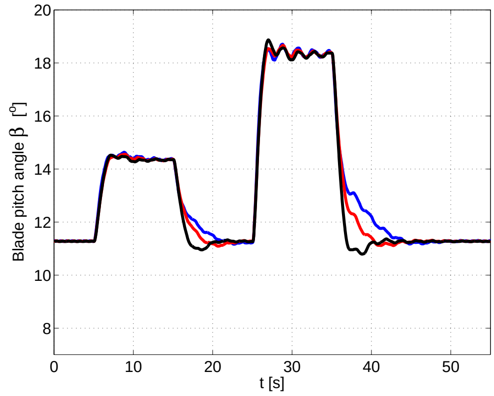

Fig. 17. Blade pitch angle response on a step change in wind speed

the simulations with the extreme wind conditions in the controller design process both design objectives are met.

It is worth mentioning that torque controller gain obtained by this approach is several times larger than the gain obtained by static analysis.

Wind turbine operation with proposed torque controller was tested through numerous simulation runs in GH Bladed. Few illustrative results are presented below. Firstly on the Figs. 16 - 18 responses to the step change in wind speed is shown. The wind speed magnitude is firstly increased from 15 m/s to 17 m/s at 5^{th} second and it is stepped back to 15 m/s after 10 seconds. This can be considered a moderate change in wind speed. After that, at 25^{th} second wind speed magnitude is increased by 5 m/s and stepped back to the starting value after 10 s. This is quite severe wind speed change resembling a strong gust. The figures 16 - 18 show wind turbine responses with two sets of parameters - obtained by static and dynamic analysis. For comparison the responses of the wind turbine with classic control system (i.e. without generator torque control above rated rotor speed) is shown as well.

The response on Fig. 16 show that inclusion of torque control above rated rotor speed reduces rotor speed overshoot by approximately 30%. Pitch actions are moderate with almost the same dynamics as without torque control above rated rotor speed. Maintaining the same dynamics of the pitch system was chosen in this work as one of the criteria for pitch controller design. It is also possible to demand slower pitch dynamics if the original dynamics is found to be too aggressive. This was not the case here. The price for the improved system dynamics is the increased electrical loading of the system as can be seen from Fig. 18. This overloading is tolerable since it falls bellow overload curve of the frequency converter considered during control system design. A notable improvement of the system behavior can be observed during decreases in wind speed, after 15^{th} s and 35^{th} s. As it can be seen from Fig. 16, the rotor speed undershoot is almost the same as without torque control above rated rotor speed but the settling time is at least twice shorter. This might seem surprising since additional torque controller is active only above rated rotor speed while below rated rotor speed generator torque is controlled in the same way as in the classic control approach. The reason for observed behavior is the fact that with the inclusion of the proportional torque controller above rated rotor speed, pitch controller has been re-tuned to cope with changed system dynamics.

In the classic approach to pitch controller design torque is assumed to be constant. This is however not true during the decreases in wind speed when rotor speed falls below its rated value. In these situations pitch controller is faced with system dynamics that differs from the one it was tuned for. The outcome is deteriorated dynamic behavior of the

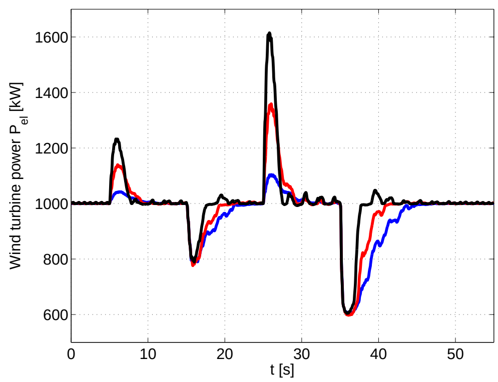

Fig. 18. Wind turbine power response on a step change in wind speed

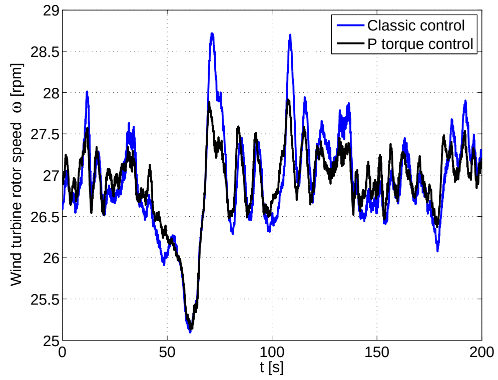

Fig. 19. Wind turbine rotor speed during turbulent wind

system. With torque control above rated rotor speed pitch controller is designed taking into account that generator torque changes with change in wind speed. It turns out that the obtained torque controller gain K_{Mg} has similar value to the slope of the torque curve below rated rotor speed. Therefore, it handles much better decreases in wind speed resulting in faster control of turbine speed and power to their rated values. This is a big advantage because it reduces losses in wind turbine production making it more efficient.

The Figs. 16 - 18 also confirm the stated fact that controller tuning according to static analysis results in very little improvement in system behavior.

After initial analysis with deterministic wind speed changes, numerous simulation runs with turbulent winds defined by standards [19] have been performed. An illustrative extract from one of them is shown in the Figs. 19 - 21.

Although Figs. 19 - 21 show only a small portion of one of the simulation runs, they confirm stated advantages of the proposed torque control above rated rotor speed. The biggest improvement can be observed in situations when wind speed changes fast from the value that is below rated wind speed ($\bar{v}_w = 11.5$ m/s in this example) to the value well above rated wind speed. Examples of such behavior can be observed between 60$^{\text{th}}$ and 80$^{\text{th}}$ second as well as between 100$^{\text{th}}$ and 110$^{\text{th}}$ second.

Without torque control above rated rotor speed such wind gusts cause large rotor overspeeds that often provoke safety stop of the wind turbine. This is due to the fact that the sensitivity of aerodynamic torque to the pitch angle changes is smallest around rated wind speed and it increases away from it due to system nonlinearity [6]. Besides that, while wind speed is below its rated value blades are fixed at fine position and pitch motors are usually parked using a mechanical brake. Therefore, additional time is needed for their reaction in comparison to normal operation above rated wind speed when pitch system is constantly active. The proposed torque control concept copes well with this problem providing auxiliary braking moment in the period before pitch system can react.

Described improvements in system behavior can be observed in all simulation runs under various wind conditions. Below is a summary of characteristic values of wind turbine variables derived from a large set of simulation runs set according to [19] for the case study of 1 MW direct drive wind turbine. The simulations showed that an average reduction of rotor speed overshoot is 31% while in some cases reduction is up to 47%. Besides that, an average reduction in rotor speed variance of 25% is obtained, which indicates better control of the rotor speed. At the same time pitch angle variance is reduced on average by 8% indicating that the pitch system is less active, which is favorable in terms of its wear and tear. The increase in electrical loading of the generator and frequency converter proved to be completely tolerable. The overload characteristic of the frequency converter was not violated in any of the extreme wind simulations. In normal operation maximum values of electric power were on average just 5.8% above the power that is tolerable permanently. At the other hand mean value of the power is increased by 4.5%, which is a considerable gain. Indeed, performed annual energy yield calculation proved that by inclusion of generator torque control above rated rotor speed energy yield is increased from $2 - 4\%$ depending on annual wind distribution on a particular

location. Knowing that the annual income from a wind turbine production is substantial, obtained increase in turbine's energy yield is significant.

Besides increased electrical loading, the potential drawback of the proposed concept is the increased mechanical

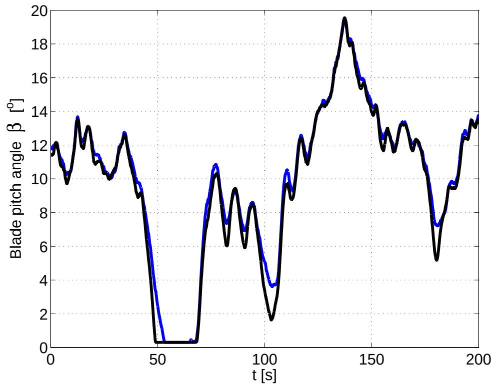

Fig. 20. Blade pitch angle during turbulent wind

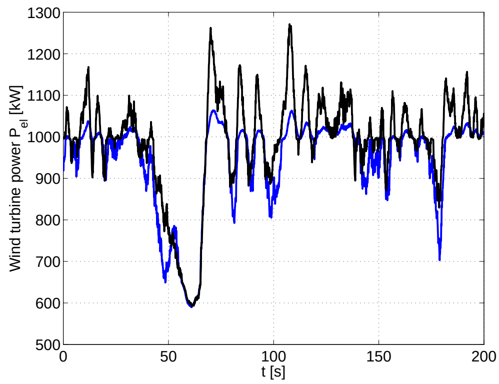

Fig. 21. Wind turbine power during turbulent wind

loading of the drivetrain as a reaction to increased variability of the generator electromagnetic torque. Those loads have to be withstood by the bolts connecting wind turbine stator with the main carrier. The mechanical loading at this point for the observed turbine has increased up to 17% by inclusion of the torque control above rated rotor speed while its variance has increased by 12%. This is considerable increase but favorable is the fact that this connection, according to standards ([16, 19], has to be designed to withstand more severe loads originating from wind turbine failures. One of those failures is the generator short circuit when loading at this point gets several times larger than the generator rated torque. Compared to this, increase in mechanical loading due to described torque control is negligible.

It should be noted however that drawn conclusions about advantages of the proposed control method are only valid for direct drive wind turbines. Application of the described control strategy to wind turbines with gearboxes is questionable due to many issues such as drive train oscillations and gearbox teeth wear and tear.

6 CONCLUSIONS

In this paper a novel approach for the wind turbine control during highly turbulent winds is presented. Prior to that a systematic description of the classic wind turbine control system is provided. The process of the control system design is described in detail with emphasis on different controller design approaches depending on the wind turbine operation region. The performance of a tuned control system is tested through the extensive simulations, as defined by international standards and performed using professional simulation tool. Simulation results were analyzed in terms of system dynamics, extreme loading and annual energy yield. Although classic control system assures satisfactory behavior of the system in many aspects, it has been shown that it can barely cope with highly turbulent winds with large wind gusts. To improve wind turbine behavior in such situations a control approach is proposed that utilizes the generator electromagnetic torque as an additional intermittent braking torque during wind gusts. The problem in this approach is the potential overload of the generator and frequency converter requiring systematic approach to the control system design. In the paper a control system design process is presented that assures the safe operation of the system under all operating conditions since it incorporates simulations to extreme wind gusts in the design procedure. Moreover, in the presented approach the changes in the system dynamics due to inclusion of an additional torque control are taken into account and the pitch controller parameters are re-tuned accordingly. Control system tuned in this way assures reduction of rotor speed overshoot during wind gusts and better control of rotor speed and power to their rated values during turbulent wind. Besides improvement in rotor speed control during wind gust, big improvement in rotor speed and power control is obtained during decreases in wind speed. All this results in an increase in the mean wind turbine power, which improves turbine's annual energy production and its cost efficiency.

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