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Estimation based Individual Pitch Control of Wind Turbine

Original scientific paper

The use of wind power for generating electricity has experienced an uninterrupted and accelerating growth over last few decades and this growth is likely to continue. In order to enable even greater role of wind energy in power production it is necessary to increase the size and unit power of wind turbines. As wind turbines grow in size they are subjected to extreme loads and fatigue caused by nonuniform turbulent winds. Therefore, control algorithms that can assure load and fatigue reduction become a necessity. In this paper the individual pitch control for reduction of the periodic blade and hub loading is explored. To avoid problems related to the required blade loads measurements a method for their estimation based on other process variables is proposed. The performance of the individual pitch controller that uses such load estimations instead of measurements is tested and compared to the collective pitch control and the individual pitch control based on measured loads.

Key words: Wind turbine, Collective pitch control, Individual pitch control, Load estimation

Upravljanje pojedinačnim zakretanjem lopatica vjetroagregata zasnovano na estimaciji opterećenja. Korištenje energije vjetra za proizvodnju električne energije zadnjih je nekoliko desetljeća zabilježilo neprekidan ubrzan rast koji će se po svemu sudeći nastaviti. Da bi se omogućila još veća uloga energije proizvedene iz vjetra u ukupnoj proizvodnji, potrebno je omogućiti proizvodnju većih vjetroagregata s većom jediničnom nazivnom snagom. Povećanjem dimenzija vjetroagregata značajno se povećavaju njihova strukturna opterećenja i zamor materijala uzrokovan nejednolikim turbulentnim vjetrovima. Stoga upravljački algoritmi koji osiguravanju smanjenje opterećenja i zamora materijala postaju neophodan dio sustava upravljanja suvremenih vjetroagregata. U fokusu je ovoga rada algoritam upravljanja pojedinačnim zakretanjem lopatica vjetroagregata kojim se postiže smanjenje periodičkih opterećenja lopatica i glavčine. Jedan od problema kod takvih algoritama upravljanja jest potreba za mjerenjem opterećenja lopatica što zahtijeva složenu i skupu mjernu opremu. Stoga je u ovome radu predložena estimacija opterećenja lopatica na osnovi drugih, lako mjerljivih i dostupnih procesnih veličina. U radu je prikazano upravljanje pojedinačnim zakretanjem lopatica zasnovano na estimiranim opterećenjima. Ponašanje vjetroagregata s upravljanjem zasnovanim na pojedinačnom zakretanju lopatica uz takav algoritam estimacije uspoređeno je s upravljanjem zasnovanim na simultanom te pojedinačnom zakretanju lopatica uz upotrebu mjerenih opterećenja.

Ključne riječi: vjetroagregat, upravljanje zakretanjem lopatica, simultano zakretanje lopatica, pojedinačno zakretanje lopatica, estimacija opterećenja

1 INTRODUCTION

The use of wind power for generating electricity has experienced an uninterrupted and accelerating growth over last few decades. Due to ever increasing power demands and the requirements for reduction of carbon emissions, this trend is likely to continue. However, further increase of the wind power exploitation strongly depends on the ability to produce bigger wind turbines with higher unit power. With increase of wind turbine size the mechanical loading of its structure increases rapidly resulting in extreme values of structural loads and pronounced fatigue. Therefore, the reduction of loads and fatigue emerges as one of the key objectives for control systems of modern wind turbine. To achieve these objectives wind turbine

standard control system needs to be augmented with more advanced algorithms. The reduction of the fatigue that is caused by the rotation of blades in an nonuniform wind field is in the scope of this paper. The paper is organized as follows. In Section 2 a brief overview of a common wind turbine control system is given and the concept of the individual pitch control is explained. In Section 3 the structural loading of the wind turbine is modeled with emphasis put on the load transfer from the rotating to the fixed part of the structure. Section 4 describes the known individual pitch control concept and demonstrates its performance on simulation experiments. In Section 5 a different approach to the individual pitch control is presented that is based on the load estimation. The performance of this control concept

is compared with the classic concept in simulation tests. Some conclusions are outlined in the Section 6.

2 WIND TURBINE CONTROL SYSTEM

Modern wind turbines operate in a wide range of wind speeds, typically from 3 to 25 m/s. The power contained in wind is proportional to the third power of wind speed [1] and therefore increases rapidly with the increase of wind speed. As a consequence, wind turbine operation consists of two very different operating regions. The first operating region is during weak winds when the power contained in wind is lower than the rated power output of the wind turbine generator. Therefore, the main task of the control system in this region is to maximize the wind turbine power output by maximizing the wind energy capture. It can be done very efficiently owing to the ability of wind turbine to change its rotational speed and to adapt to the current wind conditions. In the second operating region winds are strong enough to assure rated power of the wind turbine generator. As wind power increases rapidly with the increase of wind speed, the control system task in this region is to constrain the wind turbine power by constraining the efficiency of the wind energy conversion. An efficient method for constraining the wind power capture, that has become the industrial standard, is pitching of the wind turbine blades i.e. turning them around their longitudinal axis. For a detailed description of the wind turbine control in two described operating regions see [2].

This paper focuses on the above rated operating region because of the high structural loads that arise from strong winds. In this region the classic wind turbine control system, described in e.g. [2], has the only objective to control the rotor speed and thus the wind turbine power to their rated values at any wind conditions. This control concept (with slight modifications) has been applied to practically all pitch controlled wind turbines that are currently in operation and has proven to be successful. However, its inability to directly influence the structural loads and the fatigue makes its application on larger wind turbines less justifiable. This is especially truth for multimegawatt wind turbines whose rated powers reach up to 6 MW while their tower heights exceed 150 m.

Loads upon the wind turbine structure arise from several factors. The main cause of the wind turbine structural loading is the fact that only a portion of the wind power can be transformed into the driving torque of the wind turbine rotor while large amount of it is transformed into the rotor thrust. In addition to this "mean" loading, additional loads are exhibited on the wind turbine due to nonuniform wind field. Namely, wind is not constant air stream but its speed and direction constantly vary in time and space. The temporal variations of the wind speed are usually referred

to as turbulence and are stochastic in nature. Moreover, every point in space observes different turbulent behavior which leads to spatial variations of wind speed. The spatial correlation of wind speeds in two points in space reduces fast as the spatial separation of those points increases. Therefore, the wind speed differences across the turbine rotor get more emphasized as the rotor dimensions increase. Besides spatial variations caused by the turbulent nature of wind, there are certain spatial variations introduced by phenomena that are deterministic in nature. One of such phenomena is the so called wind shear that describes the fact that wind speed is higher in the higher layers of the atmosfere while it gets lower near the ground.

Another deterministic phenomenon influencing the wind speed is the so called tower shadow that describes the reduction of wind speed in front of the wind turbine tower (which represents an obstacle for the free air stream).

Stochastic and deterministic spatial variations of the wind speed cause the wind turbine blades to be under influence of different wind speeds depending on their actual position. This difference in wind speeds upon blades results in different loading of the wind turbine blades depending on their intermittent position. As wind turbine blades rotate, these spatial differences in loads result in periodic blade loading, i.e. wind turbine blades are under influence of loads with oscillating magnitude. Such oscillatory loads are very undesirable since they cause oscillatory stress and strain on the structure which leads to fatigue.

As previously mentioned, the periodic loading due to the variations in spatial wind speed increases with the turbine dimensions. Therefore it is an imperative to reduce such loads to enable further increase of wind turbines' size. Intensive research has lately shown that it is possible to reduce the periodic blade loading by periodic pitching of the rotor blades (see e.g. [3, 4]) In this approach each of the blades needs to be pitched according to the intermittent loads that it experiences. Therefore the blades can not be pitched simultaneously, as in the classic control approach, but individual blade pitching has to be introduced. Hence this approach is called individual pitch control and will be further explained in Section 4. Before that a further insight in the wind turbine loads and loading transfer is given in the next section.

3 WIND TURBINE STRUCTURAL LOADS

The method commonly used for wind turbine modeling is the blade element and momentum theory which yields very reliable and detailed wind turbine models [1,5]. However, such models describe wind turbine behavior by implicit relations that need iterative solving. This makes them unsuitable for controller design. So, another simpler model is considered here that is detailed enough to offer necessary

insight into the physics of wind turbine while still being simple enough to serve as a basis for the controller design. In this approach, suggested in [6] and [7], blade loading can be described by means of the static performance co-efficients relating steady state blade loading to the blade pitch angle β and the tip speed ratio λ which is the ratio between blade tip linear speed (ωR) and wind speed v_w:

$$\lambda = \frac{\omega R}{v_w}. \tag{1}$$

In this paper the mentioned approach is used to model only the loads acting on the blade root. Such loads can be considered as an integral result of the loading along the blade that varies with the radius. The blade root loads are considered in a frame of reference that is accepted by the international standards and is shown in Fig. 1 (a).

According to the explained approach the blade root bending moment of the ith blade can be expressed as [7]:

$$M_{y,i} = \frac{1}{2}\rho_{air}R^3\pi C_{My}\left(\lambda_i,\beta_i\right)v_{w,i}^2, \tag{2}$$

where ρ_{air} is the air density, R is the wind turbine rotor radius while $v_{w,i}$ is the "local" wind speed experienced by the ith blade. Note that (2) describes only the aerodynamic loading i.e. the loading caused by the wind. Besides this, additional loading is caused by gravitational and inertial loading, as it is explained in detail in [9].

The blade root bending moment is critical for the wind turbine loading since it is the source of loads for the rest of the structure as it will be shown later. Therefore, in this paper our primary concern is the reduction of the blade root bending moment, or to be more precise, its oscillations.

The blade root bending moment is defined in the frame of reference that is attached to the first blade and that rotates with it, as it can be seen in Fig. 1 (a). Therefore, the blade root bending moments of the second and the third blade will be 120º out of phase in respect to the first blade (if three bladed rotor without any asymmetry is assumed). To calculate the loading of the fixed part of the wind turbine structure blade loads have to be translated into the fixed frame of reference, shown in Fig. 1 (b). The fixed hub frame of reference is defined in the center of hub - the point that physically does not belong to the wind turbine fixed structure. However, this point is very convenient to gain insight in loading physics. Loads defined in this frame of reference can be easily translated to any point on the fixed structure and augmented for the gravitational and inertial influences (see e.g. [9] for more details). From Fig. 1 it follows that the transformation of loads from the rotational to the fixed part of the wind turbine structure is in fact a projection of loads from the rotational frame of

reference into the fixed frame of reference. This transformation results in the loads on the fixed part of the wind turbine structure in two main axes - y and z that are usually referred to as *tilt* and *yaw* loads:

$$M_{tilt,fix} = \sum_{i=1}^{3} M_{y,i}\cos\left(\omega t + (i-1)\frac{2\pi}{3}\right) -$$
$$- \sum_{i=1}^{3} M_{z,i}\sin\left(\omega t + (i-1)\frac{2\pi}{3}\right), \tag{3}$$

$$M_{yaw,fix} = \sum_{i=1}^{3} M_{z,i}\cos\left(\omega t + (i-1)\frac{2\pi}{3}\right) +$$
$$+ \sum_{i=1}^{3} M_{y,i}\sin\left(\omega t + (i-1)\frac{2\pi}{3}\right). \tag{4}$$

The moment $M_{z,i}$ in the above expressions is the load moment acting in the z axis of the ith blade. It can be shown (see e.g. [9]) that this moment is very small compared to the blade root bending moment M_y and can be neglected without making any serious error.

Neglecting the moments $M_{z,i}$ from expressions (3) and (4), the loads on the fixed part of the wind turbine structure can be expressed as:

$$M_{tilt,fix} \approx \sum_{i=1}^{3} M_{y,i}\cos\left(\omega t + (i-1)\frac{2\pi}{3}\right), \tag{5}$$

$$M_{yaw,fix} \approx \sum_{i=1}^{3} M_{y,i}\sin\left(\omega t + (i-1)\frac{2\pi}{3}\right), \tag{6}$$

or written in a more compact form:

$$\begin{bmatrix} M_{tilt,fix} \\ M_{yaw,fix} \end{bmatrix} =$$
$$\begin{bmatrix} \cos(\omega t) & \cos\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{4\pi}{3}\right) \\ \sin(\omega t) & \sin\left(\omega t + \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} M_{y,1} \\ M_{y,2} \\ M_{y,3} \end{bmatrix}. \tag{7}$$

The expression (7) describes the key mechanism of the load transfer from the rotational part of the wind turbine to its fixed part. As it can be seen by inspection of the
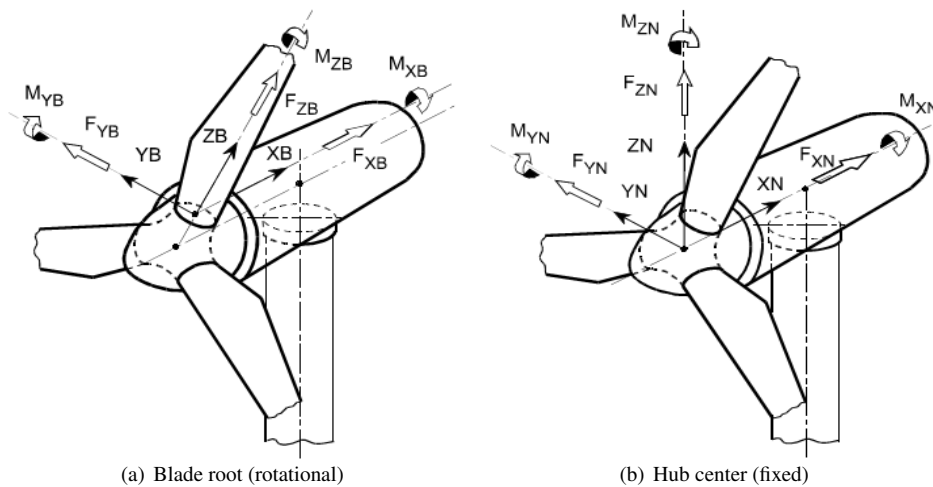
(a) Blade root (rotational)   (b) Hub center (fixed)

Fig. 1. Frames of reference for definition of loads upon the blade root and the fixed part of the structure [8]

expression (7) mean blade root loading is canceled and it is not transferred to the fixed part of the structure.

Moreover, all periodic loads with frequency equaling $3ip, i = 1, 2, 3 \dots$ (where $1p$ denotes the rotor frequency - "once per revolution") are removed from the transformed signal. Higher harmonics of the blade loads with frequency other than $3ip$ are transferred to the nearest harmonic that is multiplier of the frequency $3p$. As an example, frequency $1p$ will be transferred to $0p$ (steady value) while $2p$ and $4p$ will be transferred to the $3p$ harmonic.

The described mechanism of load transfer is demonstrated in Fig. 2. The Fig. 2 shows the blade bending moment and corresponding tilt moment at the fixed part of the structure during steady wind with wind shear and tower shadow influence included one at the time. The shown results are obtained by simulation using professional software for wind turbine simulation and load calculation - GH Bladed [10]. The wind turbine used for testing is 1MW direct drive wind turbine with 57 m rotor radius and 27 rpm rotor rated speed. Tower height is 60 m. Wind turbine model used in Bladed is based on BEM theory and can reliably model complex aerodynamic and structural phenomena.

As it can be seen in Fig. 2. the blade bending moment experiences severe oscillations with frequency equaling the rotational frequency. The influence of wind shear results in almost sinusoidal loading while the tower shadow introduces oscillations of irregular form. At the same time the oscillations of the tilt moment happen at 3 times higher frequency while the mean value of the load moment is different from zero. The described load transfer becomes even more evident if the loading spectra shown in Fig. 3 are observed. As it can be seen, the spectrum of the blade root bending moment caused by wind shear has a dominant

component at the frequency $1p$ while higher harmonics are considerably more damped. At the other hand the spectrum of the blade root bending moment that is caused by tower shadow contains higher harmonics that are equal or even larger in magnitude than the first harmonic. At the same time the loading spectra at the fixed part of the structure contain only harmonics at the frequency $3ip$.

The shown results offer a good insight in the load transfer physics and confirm the previously derived model. However they have been obtained using idealized steady wind that can not be found in nature. Moreover, the causes for spatial wind speed variations were included one at the time to explore their relative contribution to the loading. In nature all the described influences act simultaneously along with the significant contribution from the turbulent wind field.

The resultant loading of the wind turbine structure under all such influences acting together is described in detail in [9]. From the results obtained there it can be concluded that the most pronounced contribution to the blade root loading happens at the frequency $1p$. This loading is the main source of fatigue at blades and the hub. At the same time $1p$ loading from the blades contributes to the mean loading of the fixed part of the structure which is also undesirable. Therefore, the reduction of $1p$ blade loading is the key objective for the control system that aims at fatigue reduction. Such control system is described in the next section. It should be mentioned that some interesting methods for reduction of higher load harmonics (called higher harmonic control - HHC) are presented in [11] and [12]. However, the demands placed on the wind turbine pitch actuators by such methods can be considerable.
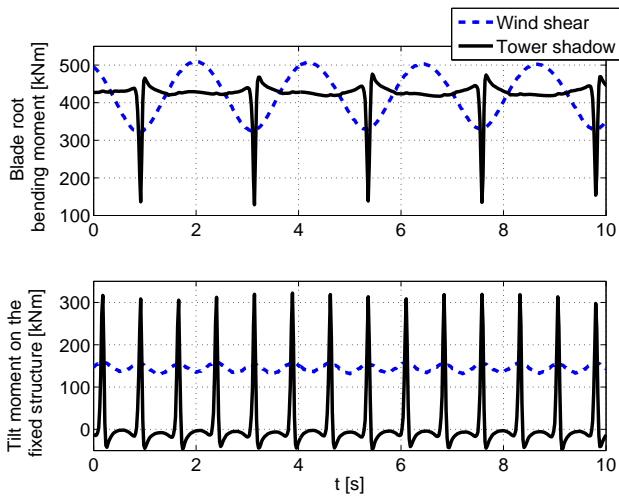
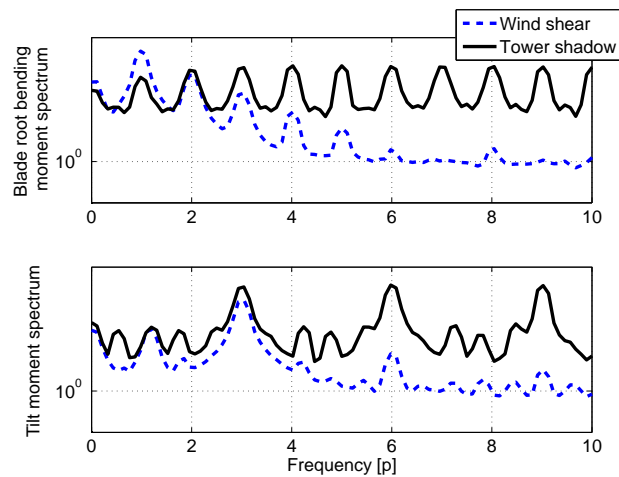*Fig. 2. Blade root bending moment and the tilt moment on the fixed structure during steady wind*

Fig. 3. Load spectra at the blade root and the fixed part of the structure during steady wind

4 INDIVIDUAL PITCH CONTROL

The most common approach in the wind turbine individual pitch control relies on a transformation between frames of reference as described in [3]. In this approach the blade loads that are measured in the rotational blade frame of reference are transformed into the fixed frame of reference. The control algorithms processes variables from the fixed frame of reference. The controller output is then transformed back into the rotational frame of reference where it can be actuated. This approach was originally introduced by Park [13] and has been successfully used for vector control of electric machines.

It is perfectly fitted for the wind turbine application since, as it was shown in Section 3, the transfer of the
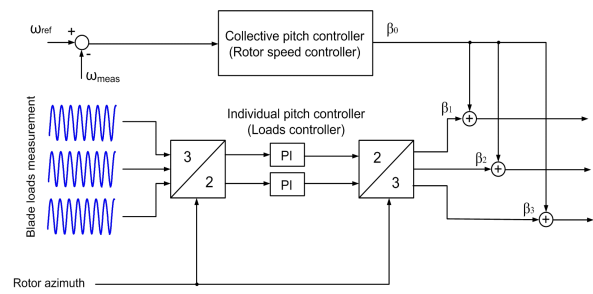
Fig. 4. Individual pitch control principle scheme

loading from the blades to the fixed structure is in fact a physical transformation between the rotational and the fixed frame of reference. The described control method is shown schematically in Fig. 4. The block $3/2$ describes Park's transformation which can be expressed as [3]:

$$
\begin{bmatrix} M_d \\ M_q \end{bmatrix} =
$$

$$
\frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{4\pi}{3}\right) \\ \sin(\omega t) & \sin\left(\omega t + \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}. \tag{8}
$$

where M stands for total blade root bending moment. The inverse Park's transformation, denoted by block $2/3$ in Fig. 4 can be calculated as [3]:

$$
\begin{bmatrix} \beta_{1,ref} \\ \beta_{2,ref} \\ \beta_{3,ref} \end{bmatrix} =
$$

$$
\begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{4\pi}{3}\right) & \sin\left(\omega t + \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} \beta_{d,ref} \\ \beta_{q,ref} \end{bmatrix}. \tag{9}
$$

Besides d and q components considered in the expressions (8) and (9), Park's transformation also produces a zero-sequence component that accounts for mean values. Such a component is not of interest for load reducing controller so it is usually omitted in individual pitch control applications.

In order to obtain oscillatory pitch angle changes with frequency $1p$ that can reduce oscillatory blade loading, the controller output in (d, q) frame of reference has to be of frequency $0p$. Therefore the controller in (d, q) frame of reference has to damp all higher harmonics present in the

transformed spectra starting with $3p$. The question that naturally appears is the structure and parametrization of the load controller in (d, q) frame of reference. In this paper a simple approach suggested in [3] is applied that uses one PI controller for each of the axis. To be able to parameterize PI controller, linear process model is needed that will relate loads to the wind speed, rotor speed and pitch angle changes with all quantities being in (d, q) axes. Linearizing (2) around chosen operating point yields linear process model:

$$\Delta M_{y,i} = M'_{y,w}\Delta v_{w,i} + M'_{y,\beta}\Delta\beta_i + M'_{y,\omega}\Delta\omega, \quad (10)$$

where $M'_{y,w}$, $M'_{y,\beta}$ and $M'_{y,\omega}$ are the partial derivatives of blade root bending moment in respect to wind speed, pitch angle and rotor speed. Applying Park's transformation to (10) yields the blade loading model in (d, q) frame of reference as:

$$\begin{aligned}\Delta M_d &= M'_{y,v} \cdot v_{w,d} + M'_{y,\beta} \cdot \beta_d, \\ \Delta M_q &= M'_{y,v} \cdot v_{w,q} + M'_{y,\beta} \cdot \beta_q,\end{aligned} \quad (11)$$

where $v_{w,d}$, $v_{w,q}$, β_d and β_q are the time varying quantities resulting from transformation of periodic quantities with varying magnitude. Note that by use of Park's transformation the influence of collective pitch angle on the loads has vanished along with the influence of the rotational speed. This describes an important feature of the described control concept. Namely, there is no coupling between the collective pitch control, that is used for control of rotor speed and the individual pitch control that is used for periodic loads alleviation. Therefore the individual pitch controller can be superimposed to the classic pitch control system without any modifications of its structure or parameters. It is also worth noting that wind turbine model in (d, q) frame of reference is of 0th order i.e. it has no dynamics. This is only truth if the pitch actuator servo drive dynamics are neglected. In reality servo drive has certain own dynamics which always introduce a lag between the reference and the actual pitch angle. Therefore a very important part of the individual pitch controller design is the treatment of the servo drives in (d, q) frame of reference.

For load controller design it is not sufficient to simply add the servo drive dynamics in (d, q) frame of reference model (11) but the servo drive model in (d, q) frame of reference needs to be derived. The methodology for deriving the servo drive model in (d, q) frame of reference is described in detail in [14]. Servo drive model in (d, q) system obtained by such a methodology is coupled and the coupling gets more emphasized with increase of the rotor speed and the sampling time.

Coupling in (d, q) frame of reference is a consequence of the lag between the actual and the reference (demanded)
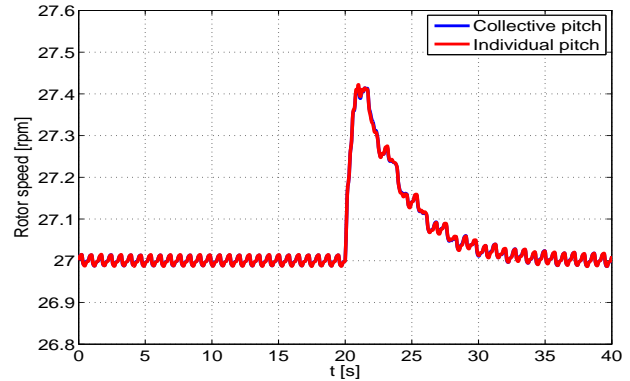

Fig. 5. Rotor speed during stepwise change of wind speed
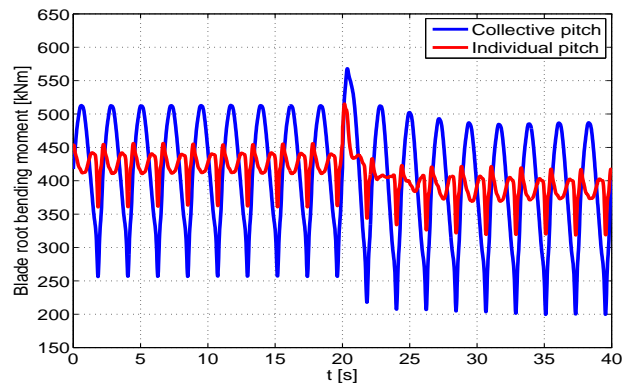

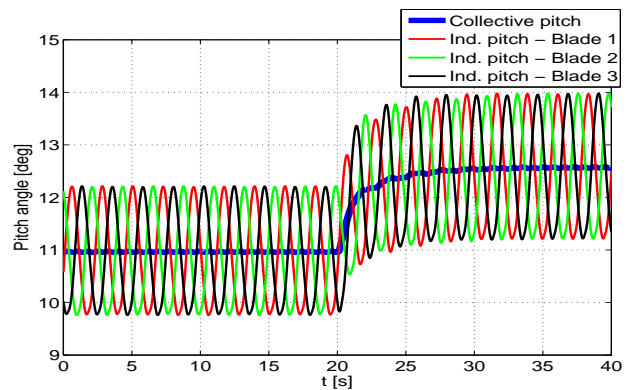Fig. 6. Blade root bending moment during stepwise change of wind speed

Fig. 7. Blade pitch angle during stepwise change of wind speed

pitch angle introduced by the servo drive. As an example consider the reference pitch angle to be a pure sine function. Due to the servo drive dynamics, the actual pitch angle will be the lagged sine function which can be interpreted as the sum of the sine and the cosine functions.
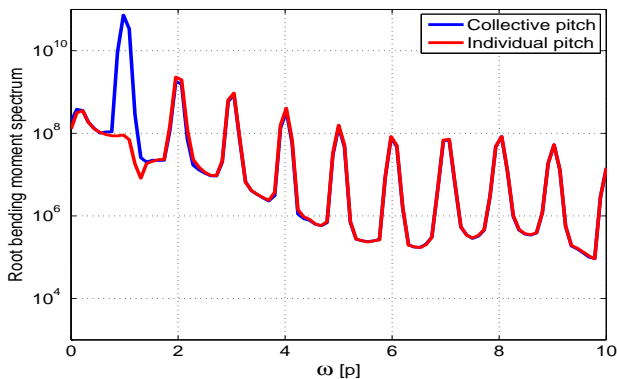
Fig. 8. Blade root bending moment spectrum during step-wise change of wind speed

Fig. 9. Rotor speed during turbulent wind

This coupling has to be accounted for by use of the multivariable controller techniques that yield controllers for variables' decomposition [15]. Such techniques often yield high order controllers that are not practical for implementation. At the other hand the main goal of individual pitch control is the alleviation of the loads with frequency $1p$ corresponding to $0p$ in the (d, q) frame of reference. This fact justifies the use of only static decoupling (decoupling controllers of 0th order) which has proven to be completely satisfactory. Combining process model (11) with the derived servo drive model full process model can be obtained that can be used as a basis for controller design.

An illustration of the individual pitch control obtained by simulations in GH Bladed is given in Fig. 5 - Fig. 7. In these Figs. the wind turbine behavior during steady wind with stepwise change of 2 m/s is shown. The wind shear and tower shadow influence is included simultaneously. The individual pitch controller behavior is compared to the behavior of a classic (collective) pitch controller.

As it can be seen the introduction of the individual pitch controller practically eliminates the $1p$ component from the blade loading. At the same time the rotor speed control is unaffected as was expected due to the explained decoupling between individual and collective pitch control. The achieved alleviation of $1p$ loads is "paid" by the increase in the pitch activity. This activity however has a frequency of $1p$ (typically less than 0.5 Hz in modern wind turbines) and therefore does not impose great demands on the pitch system.

The results of an another simulation run that will be presented here are obtained using the same controller with a realistic turbulent wind field. The wind used in the simulation is the three dimensional turbulent wind created using von Karman spectrum that is considered to be a good approximation of the real atmospheric phenomena [16].

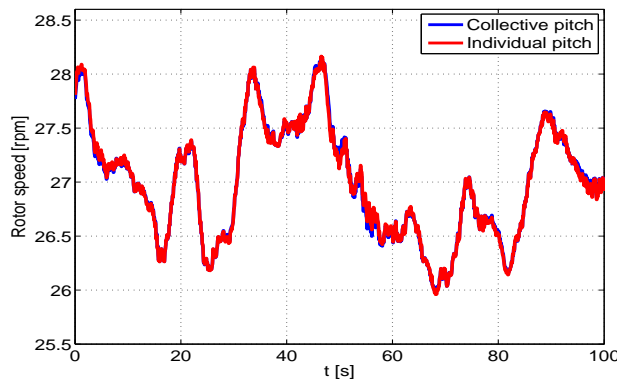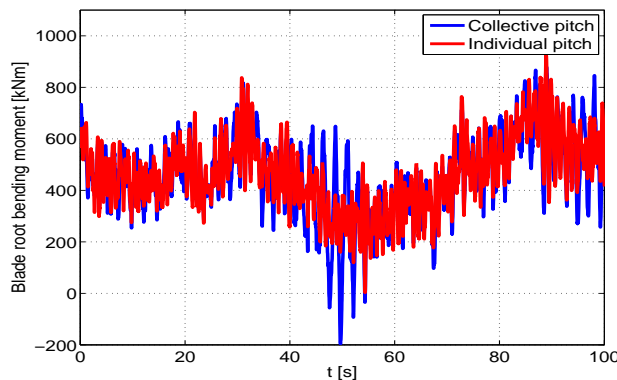The simulated wind also experienced spatial variations

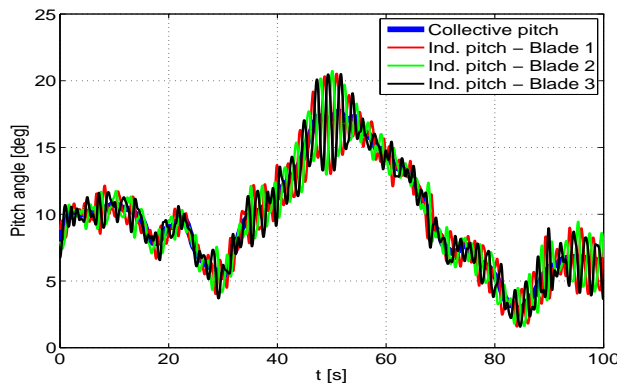*Fig. 10. Blade root bending moment during turbulent wind*

Fig. 11. Blade pitch angle during turbulent wind

due to the wind shear and the tower shadow.

Simulation results are shown in Fig. 9 - Fig. 11 where responses of the wind turbine rotor speed, blade root bending moment and the pitch angle are shown.

From Fig. 10 it can be concluded that the root bending moment oscillations are reduced (especially visible in the part from the 40th to the 60th second) and that it is achieved
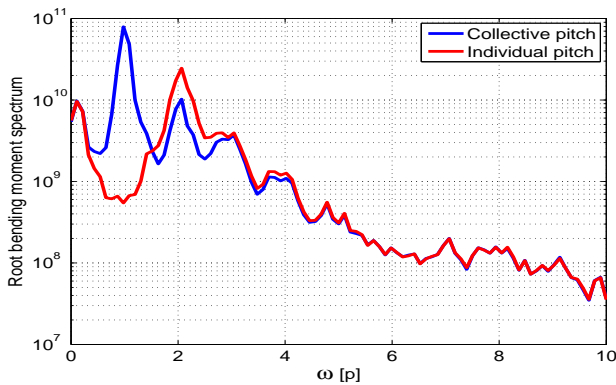
Fig. 12. Blade root bending moment spectrum during turbulent wind

by the cyclic pitch actions shown in Fig. 11. The rotor speed remains the same as with collective pitch control proving the previously mentioned decoupling between the collective and the individual pitch control.

In Fig. 9 - Fig. 11 only a small portion of one simulation run is shown for the case of clarity. To gain better insight in the wind turbine behavior a blade loading moment spectrum is shown in Fig. 12. As it can be seen the dominant blade loading component at $1p$ frequency is practically removed.

Presented results however must be taken with caution. The reason for this is a bit too idealistic setting that was assumed in simulation experiments. The weakest assumption made is that of perfect load measurements from all three blades being available without any noise. It is the fact that lately a great progress has been made in the field of loads measurement based on the fiber optics (see e.g. [17]). However, such measurement equipment is still fairly expensive compared to the price of common control equipment. A potential solution to overcome this problem is the load estimation based on the loads measured at the fixed part of the structure as has been proposed in [3] and further elaborated in [18]. In this paper another approach is described that can work even without any load measurements. It relies on estimation of the deterministic part of the oscillatory loading that can be significant. The estimation is based upon process variables that are normally measured in any wind turbine control system. This approach is described in the next section.

5 ESTIMATION BASED INDIVIDUAL PITCH CONTROL

In this approach the total periodic loading of the wind turbine blades is attributed to the deterministic spatial variations while turbulent contribution is neglected. By doing so an estimation error is inevitably introduced and the

performance of the load alleviating controller is deteriorated. Still, the performance of individual pitch controller based on such load estimations outperforms the collective pitch controller as will be shown. At the same time this approach enables implementation of the individual pitch control without investment in the load measuring equipment.

The motivation for this approach is the large contribution of deterministic spatial wind variations to the periodic blade loading. This fact is clearly illustrated in Fig. 13 that shows the loading spectrum of the root bending moment caused by various contributions. The displayed spectra has been calculated from simulation results obtained in GH Bladed where it was possible to include one influence at the time.

As it can be seen from Fig. 13., the greatest contribution to the periodic blade loading originates from the wind shear. For 1 MW wind turbine this contributes more than the turbulent nature of the wind. This relation will change in favor of the turbulent wind as wind turbine rotor size increases due to larger spatial separation between blades. However, the wind shear influence will remain significant. Another strong influence comes from the yaw misalignment i.e. the difference between the wind turbine rotor axis and the wind direction. Therefore these two contributions will be used to build the load estimator. Tower shadow contributes the least to the periodic $1p$ loading and is very difficult to model in a suitable form so it will not be included.

Wind shear is commonly modeled in two ways: exponential and logarithmic model [1]. The exponential model will be used here that relates wind speed at arbitrary height h to the wind speed at wind turbine hub height h_0 as [1]:

$$v_w\left(h\right) = v_w\left(h_0\right)\left(\frac{h}{h_0}\right)^{\alpha}. \qquad (12)$$

The exponent α in the expression (12) is the wind shear exponent that is used to model the terrain properties [1].

As wind turbine rotates the blade tip at radius R will occupy different heights as follows:

$$h_R(t) = h_0 + R\cos\left(\omega t\right), \qquad (13)$$

with ω being the rotor speed. Every point on the blade will experience different wind speeds analogously to (12). Considering different wind speeds at each point along the blade would be impractical for the purpose of interest. Therefore the resultant influence of the different wind speeds along the blade will be approximated by the wind speed at a single point. This point is chosen to be at $3/4$ of the blade length which is a common approach in wind
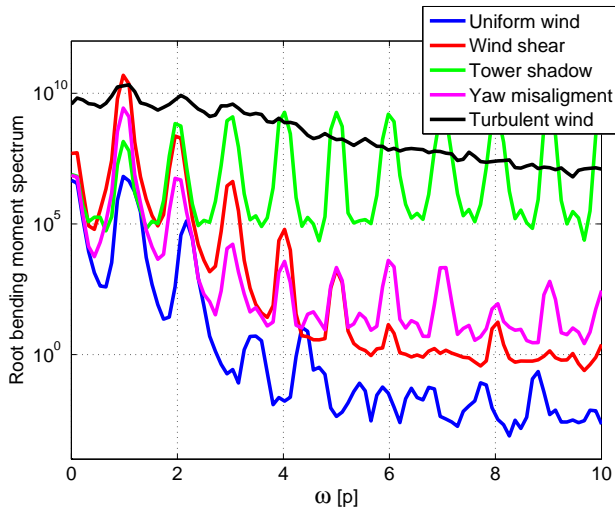
Fig. 13. Blade root bending moment spectrum caused by various contributions

Fig. 14. Wind turbine with yawed rotor seen from above

turbine analysis. Substituting $R = 3L/4$ in the expression (13) and combining (13) and (12) yields:

$$v_{w,i}\left(t\right) = v_{w,i}\left(h_0\right)\left[1 + \tfrac{3L}{4h_0}\cos\left(\omega t + (i-1)\tfrac{2\pi}{3}\right)\right]^{\alpha}. \quad (14)$$

If the exponential function in the expression (14) is substituted by its series expansion and all the higher terms are neglected one obtains:

$$v_{w,i}\left(t\right) \approx v_{w,i}\left(h_0\right)\left[1 + \alpha\tfrac{3L}{4h_0}\cos\left(\omega t + (i-1)\tfrac{2\pi}{3}\right)\right]. \quad (15)$$

Substituting the above expression in the expression for Park's transformation (8) the model of the load caused by the wind shear is obtained in (d, q) frame of reference:

$$\begin{bmatrix} v_{w,d}^{*} \\ v_{w,q}^{*} \end{bmatrix} = \begin{bmatrix} \alpha\tfrac{3L}{4h_0} \\ 0 \end{bmatrix} v_w\left(h_0\right). \quad (16)$$

In expression (16) $v_{w,d}^{*}$ and $v_{w,q}^{*}$ denote the equivalent wind speed in d and q axis (i.e. the magnitude of the sinusoidal wind speed) that would result in the same loading of the blade root as the wind shear does. As it can be seen the wind shear contributes to the loading only in the d axis. This is of course an abstraction since it is derived from assumed wind shear model. However, the exponential wind shear model has proved to be good approximation of the real atmospheric phenomena and the results obtained by such load estimator yield fairly good results as will be shown later.
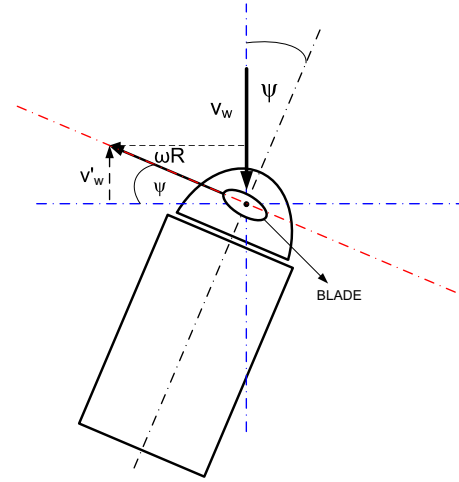
The yaw misalignment contribution to the loading can be derived by observing yawed rotor in an uniform wind stream shown in Fig. 14.

From the basic geometry it follows that yaw misalignment contributes to the loading in both axis [9]:

$$\begin{bmatrix} v_{w,d}^{**} \\ v_{w,q}^{**} \end{bmatrix} = \begin{bmatrix} K_d \\ K_q \end{bmatrix} \sin\left(\psi\right), \quad (17)$$

where ψ is the angle between the rotor axis and the wind direction, while K_d and K_q are constants that can be determined analytically or experimentally. Analogously to the wind shear influence, the yaw misalignment is modeled as a consequence of the sinusoidal wind speed with its d and q component equaling $v_{w,d}^{*}*$ and $v_{w,q}^{*}*$. The angle between the rotor axis and the wind direction (ψ) is usually called the yaw angle and is always measured by wind vanes placed on the wind turbine nacelle. This measurement, although noisy, can be used for load estimation as will be shown later on.

Combining the expressions (16) and (17) with the expression (11) the load model is obtained that uses wind speed at hub height $(v_w(h_0))$ and the yaw angle (ψ) as inputs. Simulation experiments have shown that the yaw angle measurement, although usually noisy, can be used for load estimation [9]. At the other hand wind speed measured by anemometers on the nacelle is not a good representative of the hub height wind speed to be used as the estimator input. Instead of the measured wind speed its estimation should be used. An efficient method for wind speed estimation based on the rotor speed changes is suggested in [19] and has efficiently been used in the work described in [18].

The derived loading model can be used directly or it can be used to build Kalman filter that corrects its estimations based the loads measured on the fixed part of the structure as described in [9]. Both approaches reduce the complexity of the control system since they avoid the use of expensive and sensitive load measurement equipment on wind turbine rotor.

The behavior of the wind turbine with individual pitch control that uses load estimations instead of the measurements is illustrated by two simulation examples. Firstly, the steady wind is considered including all the deterministic influences shown in Fig. 13. To verify the generality of the estimator the wind shear model used in simulation tests was not the same as the one used for load modeling. Instead of exponential wind shear model the logarithmic wind shear model ([1]) was used. The roughness length - the parameter of the logarithmic wind shear model that describes the terrain properties was varied in broad range but the estimation was not seriously corrupted.

In Fig. 15 the blade root bending moment is shown when the individual pitch control is performed based on the measured and the estimated loads. As it can be seen (in this idealized situation) the performance of the control system based on the load estimation is almost identical to the one based on the load measurements.

To test the proposed load estimator in a more realistic setting a numerous simulations with turbulent winds have been carried out and the results are described in detail in [9]. To summarize the results obtained in this way the loading spectra shown in Fig 13 can be used. The Fig. 16 shows the blade root bending moment spectra with individual pitch control based on the load measurements and estimation. As it can be seen the application of the load estimator can not completely eliminate the $1p$ component from the loading spectrum. However, this component is significatively reduced compared to the collective pitch control. The reduction of the $1p$ component is greater for the less turbulent winds what is expected considering the estimator setup.

The presented results were verified by extensive simulation runs defined by international standards [20] and analyzed in terms of loads and equivalent fatigue loading in [9]. The conclusion of this testing is that the individual pitch control based on the proposed load estimator can accomplish reduction of the blade and hub equivalent fatigue fatigue from $10 - 15\%$. This is a significant gain considering that the implementation of the proposed load estimator does not require any investment in equipment for load measurement and no wind turbine downtime is required for installation of such equipment. This makes the proposed concept very suitable for installation on wind turbines that are already in operation.
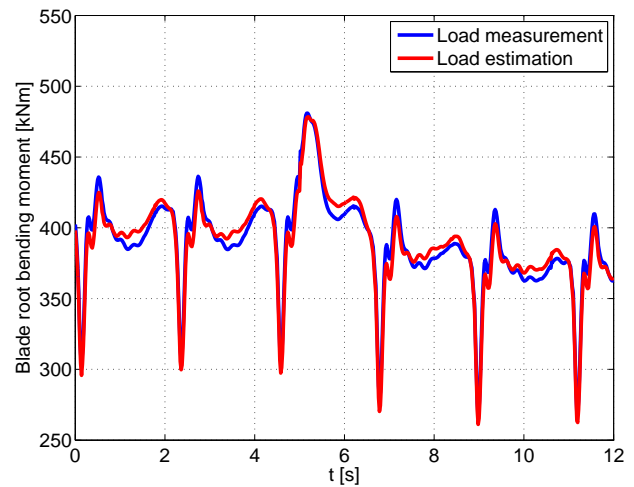

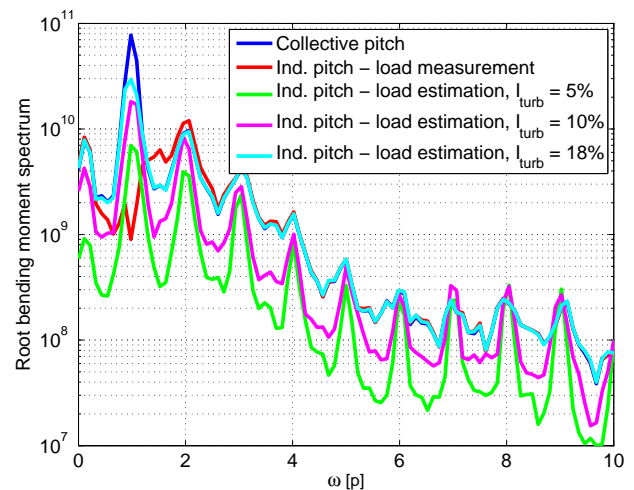Fig. 15. Blade root bending moment during steady wind

Fig. 16. Blade root bending moment spectrum during turbulent winds with different turbulence intensities

6 CONCLUSION

The wind turbine control for reduction of periodic loading is presented. Firstly, the periodic loading of wind turbine blades as a consequence of a nonuniform wind field is explained. After that the mechanism of load transfer from rotational part of the structure to the fixed part is derived. For alleviation of the periodic blade loading the well known individual pitch control is chosen. The approach selected relies on the transformation of measured loads from the rotational into the fixed - (d, q) frame of reference. For the controller design a wind turbine loading model in (d, q) frame of reference is derived with special emphasis put on the modeling of the servo drive dynamics. The parameterized controller was tested on a number

of simulation experiments performed in the professional aeroelastic simulation software - GH Bladed. The control concept confirmed its excellent performance in removing the $1p$ periodic loading of the blades.

The drawback of the described approach is the need for sophisticated (and expensive) load measurement equipment placed on the rotational part of the turbine. Therefore, another approach is presented in the paper that relies on load estimations instead of the measurements. In this approach the total periodic loading of the wind turbine blades is attributed to the deterministic spatial variations while turbulent contribution is neglected. By doing so an estimation error is inevitably introduced but the performance of individual pitch control based on such load estimations still outperforms the collective pitch controller. The estimator models the effects of wind shear and yaw misalignment using standard process variables already available in the control system. The individual pitch control based on the proposed load estimator can accomplish reduction of the blade and hub equivalent fatigue fatigue from $10 - 15\%$. This is a significant gain considering that the implementation of the proposed load estimator does not require any investment in equipment for load measurement and no wind turbine downtime is required for installation of such equipment. This makes the proposed concept very suitable for installation on wind turbines that are already in operation.

ACKNOWLEDGMENT

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