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Citation for the original published paper (version of record):
Stotsky, A., Egardt, B. (2013). Individual pitch control of wind turbines: Model-based approach. Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering, 227(7): 602-609. http://dx.doi.org/10.1177/0959651813484111

Original Article

Institution of MECHANICAL ENGINEERS

Journal of SYSTEMS AND CONTROL ENGINEERING

Proc IMechE Part I:
J Systems and Control Engineering
227(7) 602–609

DOI: 10.1177/0959651813484111
pii.sagepub.com
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Individual pitch control of wind turbines: Model-based approach

Alexander Stotsky and Bo Egardt

Abstract

Significant fore-and-aft tower vibrations of large wind turbines due to wind shear can be reduced using individual pitch control, in which the pitch angle of each blade is adjusted individually. A short survey of the existing individual pitch control strategies is presented, and a new architecture with preview measurements of the wind speeds at different heights is proposed in this article for the turbine tilt moment reduction. The approach includes look-ahead calculations of the desired blade loads and pitch angles as well as preprocessing algorithms for calculation of the derivative of the desired pitch angle. Wind speed measurement records, performed at two different heights with Risoe P2546 cup anemometer, are directly used in the turbine simulations. It is shown that the variations of tilt moment can be essentially reduced using the approach described in this article.

Keywords

Wind turbine, individual pitch control, preview measurements, turbine load prediction, tilt moment reduction

Date received: 8 October 2012; accepted: 19 February 2013

Introduction

This section describes motivation for a new individual pitch control (IPC) design and gives an overview of the previous articles and contributions of this article.

Motivation

Fore-and-aft and side-side turbine vibrations due to the non-uniformity of the wind speed (wind shear and turbulence, where wind shear refers to a change (increase) in wind speed with height (from the surface to the upper levels)) reduce the lifetime of the turbine and have a negative impact on the power production. The wind speed changes more significantly with height. This in turn necessitates the development of the turbine control systems for damping fore-and-aft tower vibrations for turbines with long blades.

Previous and related work

A collective pitch control is able to cope with uniform (over the rotor disk) disturbances only. Uneven loads can be mitigated via IPC, where the control system adjusts the pitch angle of each blade.[1–15] IPC reduces maintenance costs and increases efficiency and lifetime of the turbine components through significant contribution to the load reduction.

A periodic loading appears on the blades with the rotation of the turbine rotor. This periodic loading has a number of harmonics[4] with a first/dominating harmonic at the frequency of the wind turbine rotational speed. IPC's aim is to reduce the amplitude of the first harmonic (and possibly higher harmonics) of the load at the frequency of the wind turbine rotational speed. Therefore, the design of IPC is simply a calculation of the amplitude signal at a given frequency using load measurements. IPC determines the periodic pitch movement of the blade which counteracts the periodic component of the loads. IPC is usually based on the blade load measurements provided by fibre optic sensors or strain gauges. The d–q transformation to direct and quadrature axes, which is a transformation of variables between rotating and fixed frames of reference, is applied for calculation of the tilt and yaw turbine moments. The errors between actual and desired tilt and yaw turbine moments are regulated via proportional integral controller whose output results in pitch

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demands after application of the inverse d–q transformation. These demanded pitch positions are added to the collective pitch angle demand and sent to each pitch actuator.

Using the strain gauge resistors is a standard way for measurement of the blade loads, where the resistance changes in the case of loading. These strain gauges are not durable sensors and are sensitive to ageing and corrosion. The fibre optic strain gauges (appeared recently on the market[7]) are based on the spectrum analysis of light reflection influenced by mechanical strain (deformation). Despite the fact that this measurement technique is the most promising one, it has the following drawbacks: missing data, low accuracy and precision, sensitivity to temperature variations, complicated data/signal processing algorithms, unreliable instrumentation, high cost and long installation time.

Inconsistency of the load measurements as well as the significant sensor, communication and actuation delays might reduce the effectiveness of IPC. This in turn necessitates the development of IPC, which is based on the blade load models (where the blade load is modelled as a function of the wind and rotor speeds and pitch angle position) and the preview wind speed measurements to proactively adjust the pitch angles. Time-advanced measurements of the wind speeds at different heights in front of the turbine provide the preview information of the wind speed distribution and can be used for load prediction and performance improvement of the pitch regulation. Moreover, the model that is inverse to the blade load model can be used for prediction of the pitch demand as an alternative method to the inverse d–q transformation mentioned above. The first attempt to utilize a preview information for IPC was made in Laks et al.[16] However, the study was limited to a certain type of the idealized wind speed measurements, and insufficient attention was paid to the limitations associated with the LIDAR sample rates and other factors.

A new IPC architecture and main contributions

The IPC architecture proposed in this article is based on two wind speeds, which are measured at two points located at a distance in front of the turbine at the heights which are equal to the hub height with the half of the blade length added/subtracted (see Figure 1). Wind speed measurements are directly used in the turbine simulations. The wind speed changes significantly as a function of the altitude (for two wind speeds measured at different heights, see Figure 2), and the difference between these two wind speeds is also significant for turbines with long blades. This difference results in a significant tilt moment, which can be compensated by IPC. The wind speeds which are expected to arrive to the turbine site after some time are calculated then using a classical frozen turbulence assumption,[17] similar to the expected wind speed calculation applied in the collective pitch control. It is assumed that the

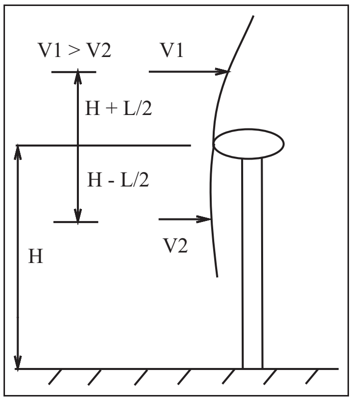

Figure 1. Wind shear is associated with two wind speeds V_l and V_2 located at the heights which are equal to the hub height H with the half of the blade length $L/2$ added/subtracted.

frozen turbulence concept can be applied separately to these wind speeds. Finally, the expected periodic individual blade wind speeds defined at the centre of each blade in rotating frame can be calculated using two expected wind speeds. Predicted blade loads can be modelled using upwind speed measurements and static maps (steady-state model of the blade loads).[18]

Note that the detailed load modelling involves usually a combination of blade element and momentum theory for determination of the loads locally along the blade span. Despite the fact that such models provide detailed description of the dynamic loads, they are very complicated and unsuitable for the control design. The steady-state model of the blade loads can be seen as a mean value, and control-oriented model (the model that determines the control signals) captures the most significant (low frequency) component of the blade load signal. A significant wind turbulence might introduce substantial fluctuations in the blade loads, but these fluctuations occur around the mean values.

Choosing the desired value of the flapwise bending moment, the desired individual blade pitch angle profiles are calculated using the inverse of the steady-state load model. The same desired value of the flapwise bending moment for all the blades implies 0 value of the desired tilt turbine moment. Deviations between the desired and actual turbine speeds and blade pitch angles as well as the upwind speed measurement inaccuracies due to a low sampling rate together with load modelling errors result in variations of the tilt moment. Therefore, a high-performance regulation is required for both turbine speed and pitch control loop. Fortunately, time-advanced measurements of the wind speeds allow application of the preprocessing techniques for improvement of the quality of the signals and their derivatives. The high-performance derivative signal of the desired blade pitch angle essentially improves the performance of the blade pitch regulation.

Main contribution of this article is a new IPC architecture with preview measurements of the wind speeds

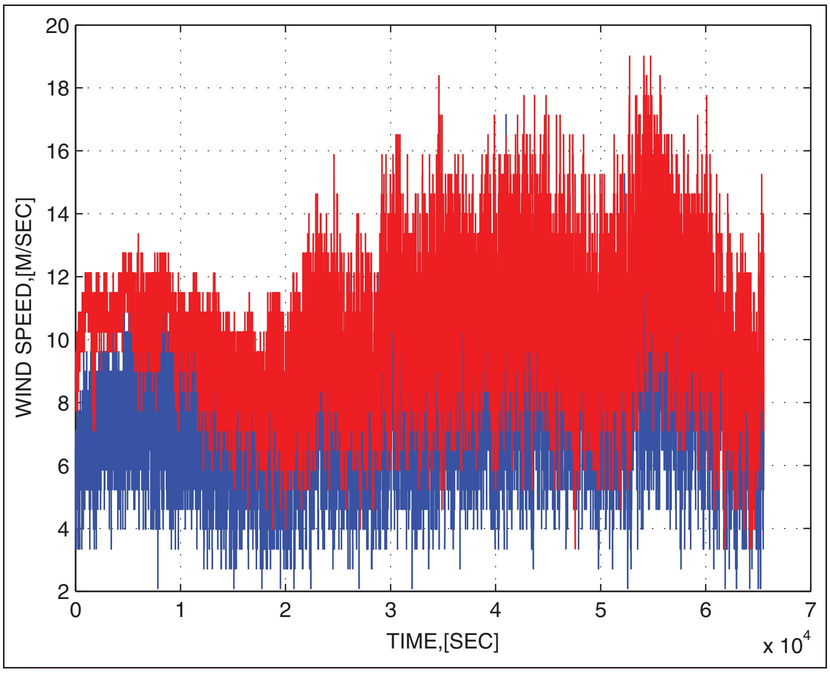

Figure 2. Wind speed measurements performed in Sweden with Risoe P2546 cup anemometer. The sampling rate is 1 Hz. Wind speeds at 40 and 80 meters above ground level (MAGL) are plotted with blue and red lines, respectively.

at different heights. This architecture has the following two new features:

- Time-advanced modelling/calculations of the desired blade loads and pitch angles aiming to the turbine tilt moment reduction.
- Spline-based preprocessing of the desired pitch angle that allows essential improvement of the pitch regulation performance.

This article is organized as follows. The turbine model and problem statement are given in section 'Wind speed measurements, turbine model and problem statement'. Look-ahead calculations and the pitch angle control are described in sections 'Look-ahead calculations' and 'Individual pitch angle control', respectively. This article ends with simulation results and brief discussion in sections 'Simulation results' and 'Conclusion and discussion', respectively.

Wind speed measurements, turbine model and problem statement

Wind speed measurements

Two wind speeds are measured at the heights which are equal to the hub height with the half of the blade length added/subtracted (see Figure 1). The wind speed increases with height, and the difference between these speeds is also significant for large turbines with long blades. The wind speed measurements performed at 40 and 80 meters above ground level (MAGL) with Risoe P2546 cup anemometer with the sampling rate of 1 Hz are shown in Figure 2 and are directly used in the turbine simulations.

Turbine load modelling

Two wind speeds described above are the input to the turbine load model. The periodic individual blade wind speeds $V_i, i = 1,2,3$ defined at the centre of each blade in rotating frame can be calculated using these two wind speeds, which together with the turbine rotor speed ω_r are associated with the individual blade tip-speed ratio λ_i as follows

$$\lambda_i = \frac{\omega_r R}{V_i} \tag{1}$$

$$M_{f,i} = f(V_i, \omega_r, \beta_i) \tag{2}$$

where R is the rotor radius. Moreover, the individual blade wind speed together with the pitch angle and rotor speed defines the individual blade flapwise bending moment $M_{f,i}$ in equation (2).

Steady-state (static) load model is proposed in this article for description of the flapwise blade root bending moment. This type of loading is periodic due to the periodicity of the individual blade wind speeds. Similar models can be found in Van Engelen[4] and Jelavic et al.[11]

Finally, the tilt load can be calculated using the transformation between the rotating and fixed frames and the individual blade flapwise bending moments. Therefore, the contributions of the flapwise bending moments on the blades to the tilt moment M_{tilt} on the fixed part of the wind turbine structure are calculated as follows

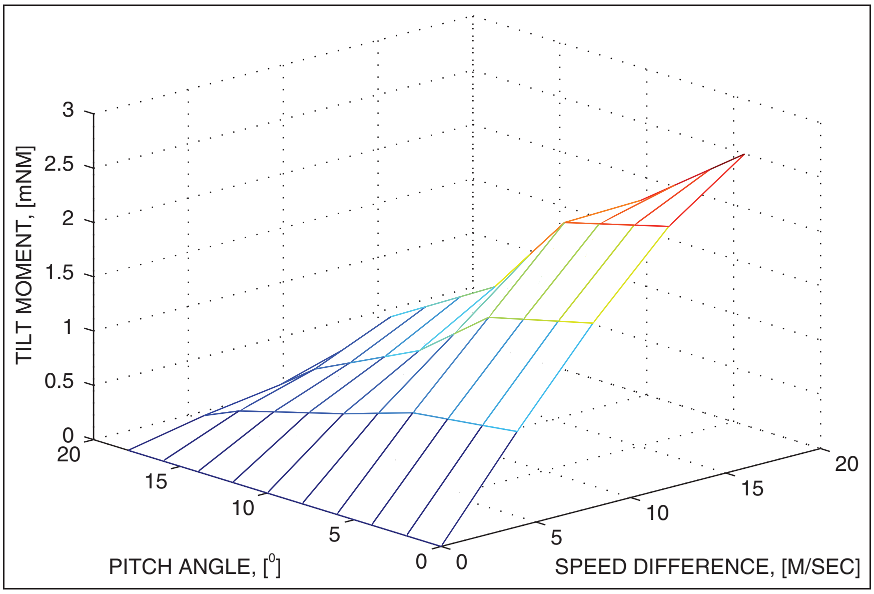

Figure 3. Mean value model of the tilt moment due to non-uniformity of the flapwise bending moment. Tilt moment is calculated using equation (3) at a constant wind speed at the hub height $(V_1 + V_2)/2$ (see Figure 1) and plotted as a function of the difference $V_1 - V_2$ and the blade pitch angle. Tilt moment is calculated for constant turbine speed which is chosen to maximize the power efficiency for the wind speed at the hub height.

$$M_{tilt} = \sum_{i=1}^{3} M_{f,i} \cos\theta_i \tag{3}$$

where θ_i is the azimuth angle of the i-th blade, $i = 1, 2, 3$. Note that the resulting contribution to the tilt moment is equal to 0, if the flapwise bending moments are the same for all the blades.

For the sake of simplicity (but without loss of generality), the contributions of the edgewise bending moments to the tilt moment are not considered in this article. These contributions are essentially smaller compared to the contributions of the flapwise bending moments (especially for small pitch angles) and might be accounted as an additional term in equation (3).

Mean values of the tilt moment in equation (3) as a function of the difference between two speeds at different heights $V_1 - V_2$ (see Figures 1 and 4) and the blade pitch angle are plotted in Figure 3 for a constant turbine speed. Note that the turbine tilt moment appears due to the difference between two wind speeds V_1 and V_2. Large difference in wind speeds (see the first subplot in Figure 4) results in significant amplitude of the periodic individual blade wind speeds V_i and ratios λ_i. This in turn creates a periodic individual blade flapwise bending moment $M_{f,i}$ (see the second subplot in Figure 4), which results in large mean values of the turbine tilt moment (see the third subplot in Figure 4).

Figure 3 shows that the tilt moment is also a function of the blade pitch angle, and the gradient in the direction which represents the speed difference is larger for small pitch angles. The flapwise bending moment decreases together with its contribution to the tilt moment if the pitch angle increases. Simultaneously, the contribution of the edgewise bending moment increases for larger pitch angles. Main idea of the IPC is compensation of the fluctuations of the individual blade flapwise bending moments (see the second subplot in Figure 4), which contribute to the turbine tilt moment by means of the circular movement of the pitch angle of each blade.

Note that IPC implies intensive actuation and should be activated only in the case where a sufficiently large tilt moment is expected. An absolute value of the tilt moment can be overbounded as shown in Figure 3 (similar to overbounding of the blade loads described in Stotsky and Egardt[18]), which allows the calculation of the activation threshold in terms of the difference between the speeds at different heights $V_1 - V_2$ for a given pitch angle.

Pitch actuator model

Pitch actuators are the same for all the blades and are modelled as a first-order lag with the rate and range constraints

$$\dot{\beta}_i = -\frac{1}{\tau}\beta_i + \frac{1}{\tau}u_{id}(t - t_d) \tag{4}$$

$$|\beta_i| \leqslant C_\beta, |\dot{\beta}_i| \leqslant C_{\dot{\beta}} \tag{5}$$

where $u_{id}(t - t_d)$ is an actuator control input, τ is a time constant, t_d is a communication delay and C_β and $C_{\dot{\beta}}$ are the positive constants which define the range and rate constraints, respectively, and $i = 1, 2, 3$ is the blade number.

IPC problem statement

The problem is to find the individual pitch angles β_i in order to regulate the tilt moment M_{tilt} to 0

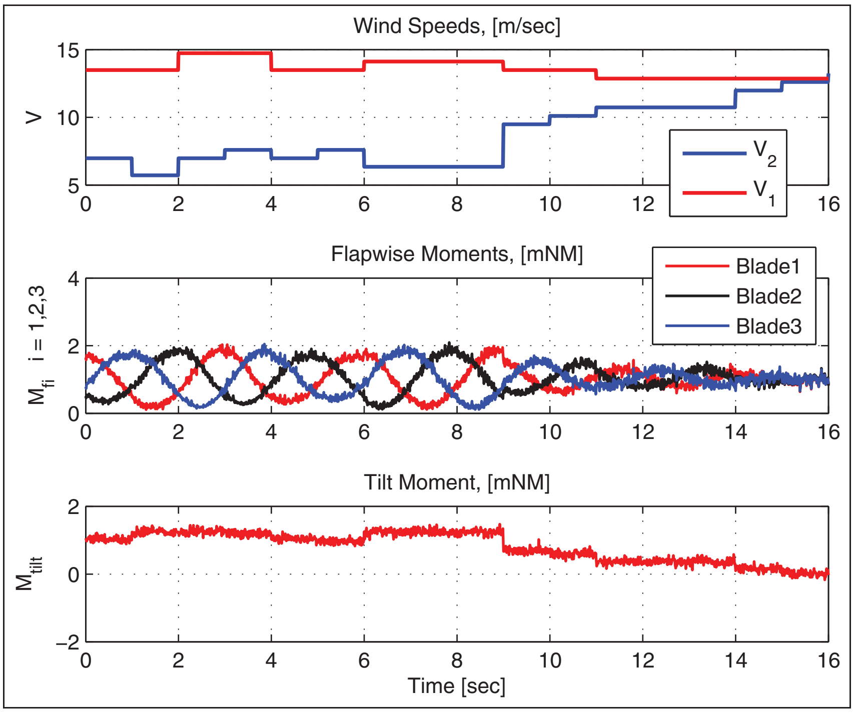

Figure 4. Simulations using measurements of the wind speeds at different heights, V_1 and V_2. Wind speeds are plotted in the first subplot. Individual blade flapwise bending moment $M_{f,i}, i = 1, 2, 3$ is plotted in the second subplot, and resulting tilt moment is plotted in the third subplot.

$$M_{tilt} = \sum_{i=1}^{3} M_{f,i}\cos\theta_i = 0 \quad (6)$$

using preview measurements of the wind speed.

Look-ahead calculations

Look-ahead modelling of the blade load: generation of the desired individual blade pitch angle profile

Two wind speeds are measured at a distance in front of the turbine at the heights which are equal to the hub height with the half of the blade length added/subtracted. The wind speeds which are expected to arrive to the turbine site after some time can then be calculated using a classical frozen turbulence assumption,[17] similar to the expected wind speed calculation applied in the collective pitch control. Finally, the expected periodic individual blade wind speeds $V_{ie}, i = 1, 2, 3$ defined at the centre of each blade in rotating frame can be calculated using two expected wind speeds.

Predicted blade loads can be modelled using upwind speed measurements and static maps that describe the flapwise bending moment as a function of wind speed, desired turbine speed and pitch angle, $M_{f,id} = f(V_{ie}, \omega_{rd}, \beta_i)$. The desired individual blade pitch angle profile β_{id} is calculated using the surfaces which are inverse to the flapwise bending moment surfaces

$$\beta_{id} = f^{-1}(V_{ie}, \omega_{rd}, M_d) \quad (7)$$

Equation (7) has the following input variables: the expected individual blade wind speed V_{ie}, the desired turbine speed ω_{rd} that is calculated using a mean value of two expected wind speeds and corresponds to the maximum efficiency and the desired flapwise bending moment M_d.

According to the definition of the inverse function $f^{-1}(\cdot)$, the following relation holds

$$M_{f,id} = f(V_{ie}, \omega_{rd}, \beta_{id}) = f(V_{ie}, \omega_{rd}, \underbrace{f^{-1}(V_{ie}, \omega_{rd}, M_d)}_{=\beta_{id}}) = M_d \quad (8)$$

which means that all the desired individual blade flapwise bending moments $M_{f,id}$ are equal to the desired value of the flapwise bending moment M_d. The desired tilt moment M_{tiltd} is calculated then as follows

$$M_{tiltd} = \sum_{i=1}^{3} M_{f,id}\cos\theta_i = M_d \sum_{i=1}^{3}\cos\theta_i = 0 \quad (9)$$

where θ_i is the azimuth angle of the i-th blade and $\sum_{i=1}^{3}\cos\theta_i = 0$.

Note that the desired blade pitch angles β_{id} are periodic functions of time due to the periodicity of the expected individual blade speeds V_{ie}. These desired pitch angles are the commands to the pitch actuators, and the actual pitch angles converge to the desired ones. Hence, the actual flapwise bending moments $M_{f,i}$ converge to the desired flapwise bending moments $M_{f,id} = M_d$. Therefore, the actual tilt moment M_{tilt}

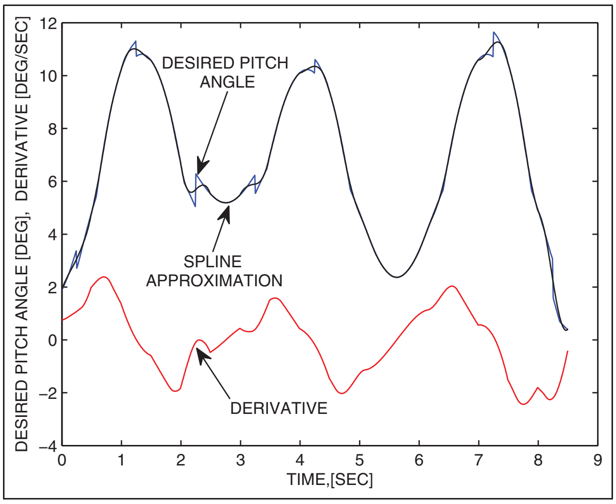

Figure 5. The desired pitch angle profile of the first blade is plotted with a blue line. The spline approximation is plotted with a black line. The derivative is plotted with a red line. The values of the derivative are divided by five.

converges to the desired tilt moment M_{tiltd}, which is equal to 0 as it is shown in equation (9), and the control aim of equation (6) is reached.

Also note that upwind speeds are measured with a relatively low sampling rate of 1 Hz, and the update rate of the desired individual blade pitch angle profile β_{id} is much higher. This introduces switching events between the periodic trajectories of the desired pitch angle profiles (see a blue line in Figure 5). Therefore, the desired trajectory becomes discontinuous and should be smoothed for improvement of the pitch regulation. Such a smoothing together with calculation of the derivative of the desired pitch angle trajectory can be done using spline interpolation method described in section 'Calculation of the derivative of the desired individual blade pitch angle'.

Finally, upwind speed measurements with low sample rate are not accurate for wind fields with high turbulence intensity. Moreover, Taylor's frozen turbulence concept assumes that advection contributed by turbulent circulations is small, and therefore, the wind travels towards the turbine with the average wind speed. This frozen turbulence assumption which is applied to two wind speeds at different heights in this article is not accurate enough[19] and hence might result in deterioration of the IPC performance.

Calculation of the derivative of the desired individual blade pitch angle

Spline interpolation method (see Stotsky and Egardt[18] and references therein) is one of the most prospective methods for both estimation of the derivatives of noisy signals and smoothing. The method is based on online least-squares polynomial fitting over the moving in time window of a certain size. The signal of the desired pitch angle is approximated via a polynomial of a certain order as a function of time. The derivatives are calculated analytically.

A preview-based measurement strategy allows preprocessing of the desired blade pitch angle and calculation of the high-performance derivative signal. The performance of this estimation is illustrated in Figure 5, which shows that the desired pitch angle profile can be well approximated using the smooth spline of second order. All the switching events present in the desired pitch angle trajectory are smoothed for improvement of the performance of regulation. Moreover, the smooth derivative signal is also calculated using the same second-order spline. This spline also provides the second derivative of the desired blade pitch angle, which can be used for further improvement of the pitch regulation with the actuator model of a second order.

Individual pitch angle control

The desired blade pitch angle as an input to the pitch actuator in equation (4) is chosen as follows[18]

$$u_{id} = \beta_{id} + \tau\dot{\beta}_{id} \tag{10}$$

where $\dot{\beta}_{id}$ is an estimate of the derivative of β_{id}, calculated via the spline interpolation method described in section 'Calculation of the derivative of the desired individual blade pitch angle', and $i=1, 2, 3$ is the blade number. Substituting u_{id} in equation (4) yields the following exponentially stable closed-loop dynamics

$$\dot{\beta}_i - \dot{\beta}_{id} = -\frac{1}{\tau}(\beta_i - \beta_{id}) \tag{11}$$

when compensating a communication delay time t_d with the preview technique. Usually, a desired/command pitch angle β_{id} is sent only to the pitch actuator ($u_{id} = \beta_{id}$), which implies a slow response of the actuator and deteriorates the IPC performance. Introduction of the derivative term $\tau\dot{\beta}_{id}$, which is calculated in preprocessing, essentially improves the transient performance of the pitch actuation.

Simulation results

Simulation results of the preview IPC system are shown in Figure 6. Two wind speeds are measured at a distance in front of the turbine at 40 and 80 MAGL. Expected wind speeds, calculated separately using frozen turbulence assumption, are plotted in the first subplot of Figure 6. The difference in wind speeds produce higher blade bending moments at higher heights and hence a significant tilt moment on the fixed part of the turbine structure. This tilt moment is plotted with a red line in the third subplot of Figure 4. The tilt moment is close to 0 if the wind speeds are approximately the same at different heights (see the time interval between 33rd and 36th second). The blade pitch angles as the outputs of the pitch actuators in equation (4) with IPC actions

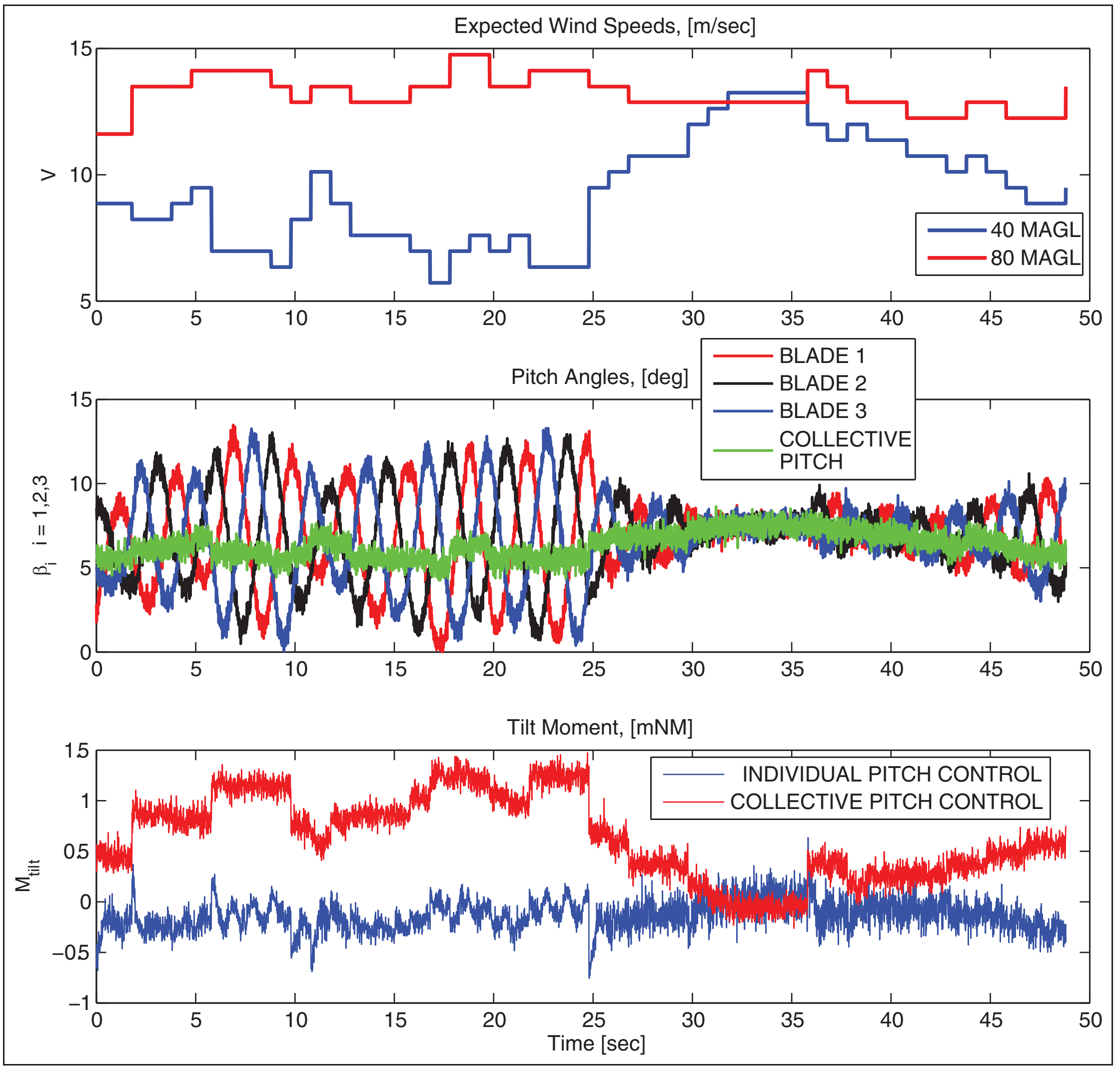

Figure 6. Performance of the individual pitch control. Expected wind speeds at different heights are shown in the first subplot. Blade pitch angles and tilt moments are shown in the second and third subplots, respectively.

in equation (10) are plotted in the second subplot of Figure 6, which shows that the amplitude of the IPC oscillations increases with a difference between the wind speeds plotted in the first subplot. These periodic control actions produce almost uniform bending moments on the blades and hence reduce the tilt moment which is plotted with a blue line in the third subplot of Figure 6. The advantage of IPC is proved via comparison of the resulting tilt moments in the third subplot of Figure 6.

Finally, the advantage of the IPC with preview information is justified in Figure 7, which shows the comparison of two tilt moments. The tilt moment which is plotted with a blue line corresponds to the pitch control system (10) with the derivative of the desired blade pitch angle $\dot{\beta}_{id}$. Preview information was used for calculation of the high-performance derivative of the desired pitch angle. Note that the error model (11) for the pitch angle mismatch is exponentially stable in this case. The tilt moment which is plotted with a red line corresponds to the pitch control system (10) without derivative of the desired pitch angle (without preview information). The high-performance derivative (the derivative

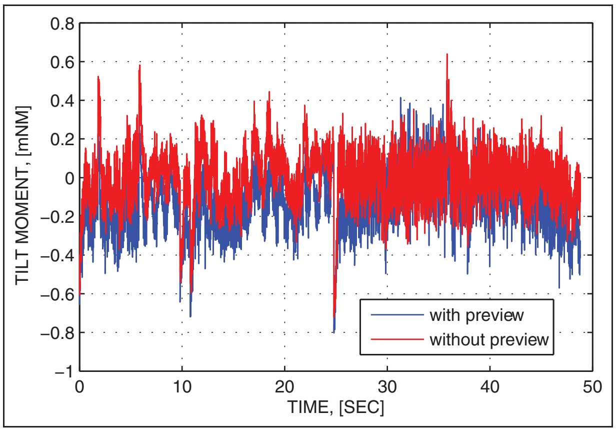

Figure 7. Comparison of two tilt moments produced by the wind speeds plotted in the first subplot of Figure 6. Tilt moments of IPC systems with and without preview information are plotted with blue and red lines, respectively.

without a phase lag) cannot be calculated without preview information.[18] A lack of preview information introduces errors in closed-loop pitch control system (11). On the contrary, introduction of the preview wind speed measurements in IPC results in reduction of the variations of the turbine tilt moment (see Figure 7).

Conclusion and discussion

IPC is widely used as one of the main tools for reduction of the structural damages that occur due to the turbine cyclic loading. The performance of the existing IPC algorithms is improved in this article via introduction of the preview wind speed measurements and look-ahead calculations. Potential load reduction due to the IPC performance improvement enables further increase of the size of wind turbines with reduction of the structural costs.

The approach presented in this article has a number of drawbacks, which are listed below. The errors between expected and actual wind speed that arrives to the turbine site result in inaccuracies in the prediction of the individual blade wind speeds, tip-speed ratios and finally flapwise bending moments. Moreover, uncertainties in the blade load model introduce additional errors in the prediction of the flapwise bending moment. All these inaccuracies might result in the erroneous desired pitch angle trajectories and hence in significant fluctuations of the turbine tilt moment. Introduction of the blade load measurements and suitable signal processing techniques to the model-based approach with preview measurements described in this article might be the next step in further improvement of the IPC performance.

Acknowledgements

The authors are grateful to Carl-Johan Cederstrand, Johan Sehlstedt and Stellan Wickström from WindVector AB and to Christof Sihler from GE Global Research for interesting discussions and providing wind speed measurements at different heights.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This work was supported by the Swedish Wind Power Technology Center (SWPTC).

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