Preprints of the 2012 20th Mediterranean Conference on
Control & Automation (MED), Barcelona, Spain, July 3-6,
2012

Reduction of wind turbine tower oscillations based on individual pitch control

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***Abstract*—The use of wind power has been increasing rapidly over the last few decades and according to all predictions this trend is likely to continue. At the same time, the need for better cost effectiveness of wind power plants has stimulated growth in wind turbines' size and rated power, thus making wind turbine structure very flexible. Therefore an advanced control system must be used to reduce structural loads and fatigue and enable optimal wind energy conversion in a wide range of wind speeds. One such control system, with emphasis on reduction of wind turbine structural oscillations, is developed in this paper.**

I. INTRODUCTION

The use of wind turbines has grown rapidly in recent decades and that trend is likely to continue. The main reason for this is a constantly increasing power consumption, which necessitates introduction of new power plants. At the same time the climate change concerns prompt for an immediate action in reducing the greenhouse gas emissions. Another important factor is concentration of natural reserves of fossil fuels in just a few supplier countries in the world. In order to take care of climate change and to reduce dependency on energy import, the European Union (EU) has set the goal to achieve 20% share of renewable energies in the overall energy consumtion by 2020 [1]. Since nowadays wind is the most promising renewable energy source, it is expected that wind energy will have a major role in achieving that goal. Wind turbines have no greenhouse gas emmisions and wind is free and practicaly limitless source of energy, so wind turbines represent a good solution for both climate change and energy import dependency.

By the end of 2010 the total power of wind turbines installed in Europe equalled 86 GW. The European Wind Energy Association (EWEA) targets 230 GW of installed wind power capacity in Europe by 2020 and 400 GW of installed wind power capacity by 2030, which would produce 26-35% of the EU's electricity, depending on total demand at the time. Some studies show that Europe has enough wind potential to entirely accomodate energy consumption [2]. European Renewable Energy Council even suggests that it would be possible for EU to achieve energy system that is entirely based on renewable energy by 2050, where wind power is expected to have over 20% share in the electricity generation [3].

Such ambitious goals for renewable energy cannot be achieved with the current state of technology, so a constant research and development is needed. To be able to pursue set goals, wind turbine dimensions and rated power will have to increase. However, with the increase in wind turbine dimensions, the loads that wind turbine has to withstand increase significantly. An attempt to make such large constructions (modern 5 MW wind turbines have tower height over 100 m) rigid would result with massive and expensive structures, which in turn would make the whole wind turbine cost-ineffective. Therefore, modern wind turbine construction is very flexible, and the flexibility becomes more emphasized with the increase in wind turbine size [4]. Because of that, wind turbine control system, in addition to wind turbine power and rotor speed control, has to accomplish other objectives such as reduction of structural loads and reduction of tower and blade oscillations. An advanced control system that actively reduces loads and structural oscillations, will enable further increase in wind turbine dimensions and rated power, making them even more cost-effective.

Presently reduction of wind turbine tower oscillations is mainly achieved through the use of collective pitch control. This paper explores the idea of reduction of tower top oscillations through the use of individual pitch control. Standard control system of modern multi megawatt wind turbines is described in Section II. Wind turbine mathematical model is described in Section III and controllers for reduction of tower oscillations are described in Section IV.

II. WIND TURBINE CONTROL SYSTEM

Wind turbine is a complex nonlinear system that converts wind energy into electrical energy in a wide range of wind speeds. To achieve this, wind turbine blades are shaped similarly to aeroplane wings. Aerodynamic forces on blades are exploited in the process of conversion of wind kinetic energy into kinetic energy of wind turbine's rotor and generator [4].

Power of the wind on the rotor area increases with the third power of wind speed [5]:

$$P_w = \frac{\pi}{2}\rho_a R_r^2 v_{w,c}^3, \tag{1}$$

where ρ_a is the air density, R_r is the wind turbine rotor radius and $v_{w,c}$ is the rotor effective wind speed. The fact that wind power is proportional to the third power of wind speed has significant impact on a design of a wind turbine control system. Namely, wind turbine control system can be

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divided into two very different regions: control during weak winds and control during strong winds. Boundary between two control regions is called *rated wind speed* and it is defined as the lowest wind speed that allows wind turbine to generate its rated electrical power.

During weak winds, i.e. below rated wind speed, power contained in the wind is too low for wind turbine to generate its rated power. Therefore, the wind turbine control system has to maximise wind energy capture. Modern wind turbine generators are typically connected to the grid via frequency converters, which allows them to operate with variable rotor speed (as opposed to wind turbines directly connected to the grid, whose rotor speed is defined by the grid frequency). Variable rotor speed enables wind turbines to adapt to the current wind conditions and thus optimise wind energy conversion. In this control region, rotor blades are pitched in a position that enables maximum energy capture and by changing the generator torque one can obtain maximum wind energy conversion for the current wind speed.

During strong winds, i.e. above rated wind speed, power contained in the wind is greater than rated wind turbine power and according to (1), it increases rapidly with the increase of wind speed. Therefore, the control system has to constrain wind power capture by reducing wind power conversion efficiency. An industrial standard for reducing wind power capture is pitching of wind turbine blades around their longitudinal axis, which reduces wind turbine efficiency. In this control region, typically rated generator torque is used, so pitch controller has to maintain rotor speed on its rated level in order to achieve wind turbine rated power generation. To this end, pitch controller pitches all wind turbine blades in the same way, i.e. blades are pitched collectively.

A principle scheme of the described control system is shown in Fig. 1. Two different control loops in Fig. 1 correspond to two control regions as described above – in each control region only one control loop is dominant. Since wind turbine loads and tower oscillations are more pronounced during strong winds, the focus of this paper is only on pitch control.

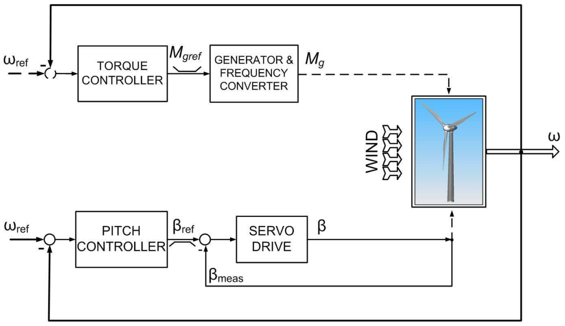

Fig. 1. Wind turbine control system principle scheme.

Control systems of modern multi megawatt wind turbines increasingly use another aspect of pitch control – an individual pitch control, which takes into account the fact that each blade experiences different loading depending on its azimuthal position because the wind speed is not uniform across the wind turbine's rotor area. As a result, asymmetric and periodic loads on wind turbine blades shorten wind turbine lifetime more than constant loads. The main objective of individual pitch control is reduction of such loads. Most individual pitch controllers are focused only on reduction of the first loads harmonic which is defined by the rotor speed.

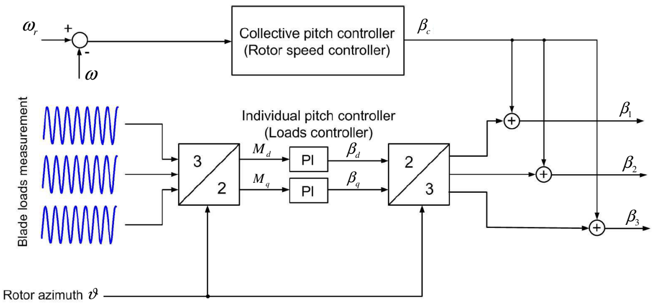

Fig. 2. Principle scheme of an individual pitch control system of wind turbine.

The principle scheme of basic individual pitch controller is shown in Fig. 2. Note that the collective pitch controller (the rotor speed controller) remains active while individual pitch controller calculates addition to collective pitch angles that will compensate loads on each blade. Since the main objective of individual pitch controller is to eliminate the first harmonic of the loads, it is convenient to use Park's transformation [6], [7]:

$$\begin{aligned} M_d &= \sum_{i=1}^{3} M_{y,i} \cos\vartheta_i, \\ M_q &= \sum_{i=1}^{3} M_{y,i} \sin\vartheta_i, \end{aligned} \tag{2}$$

where $M_{y,i}$ is the measured load on i-th blade, ϑ_i is the azimuth of the i-th blade ($\vartheta_3 = \vartheta_2 + \frac{2\pi}{3} = \vartheta_1 + \frac{4\pi}{3}$), and M_d, M_q are loads in Park's (d-q) coordinate system. After the desired pitch angles are calculated in Park's coordinate system, inverse Park's transformation is used:

$$\beta_i = \beta_c + \beta_d \cos\vartheta_i + \beta_q \sin\vartheta_i, \tag{3}$$

where β_c is the collective pitch angle determined by the rotor speed controller and β_i is the pitch angle of i-th blade.

Typical response of control system with individual pitch control is shown in Fig. 3 and Fig. 4. It can be seen that each blade has different pitch angle and it oscillates around collective pitch angle. Since $\frac{1}{3}\sum_{i=1}^{3}\beta_i = \beta_c$, individual pitch control does not interfere with rotor speed control (i.e. collective pitch control). As the result of individual pitch control, loads on rotor blades can be significantly reduced.

Besides the typical controller as described above, control systems of modern wind turbines are typically augmented with additional control objectives related to wind turbine safety and reduction of fatigue. One of such control objectives is the reduction of tower and blade oscillations [8]. Due to the emphasised flexibility of modern wind turbines, it is

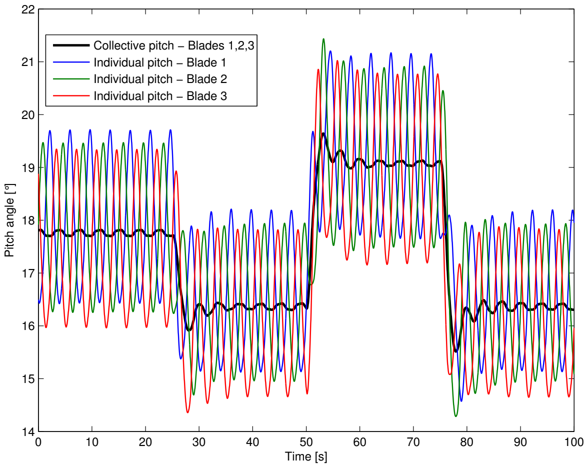

Fig. 3. Comparison between collective and individual pitch control – pitch angles.

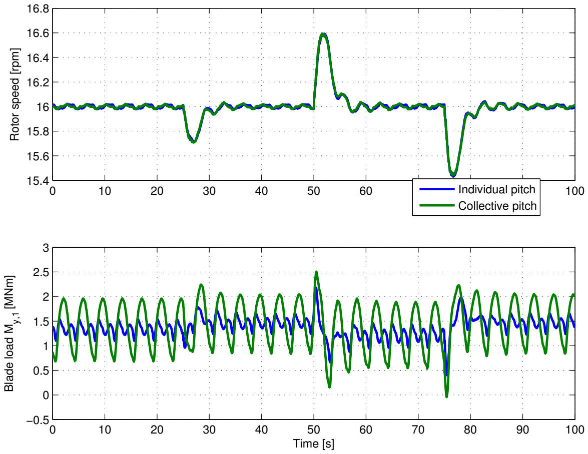

Fig. 4. Comparison between collective and individual pitch control – rotor speed and blade loads.

very important that controllers avoid excitation of structural resonant frequencies and thus reduce the tower and blade oscillations [5]. In this paper, different controllers for the reduction of wind turbine structural oscillations are analysed.

III. WIND TURBINE MATHEMATICAL MODEL

Due to the nature of aerodynamic forces acting on wind turbine blades, wind turbine mathematical models are typically very complex and result in implicit equations. Such models can describe wind turbine behaviour very accurately [9], but due to their complexity, they are not suitable for control system design. In this paper, a wind turbine mathematical model is derived by methods of experimental identification.

A. Wind turbine physics

The main sources of wind turbine loading are aerodynamic loads on wind turbine blades, gravity and inertia. Loads from wind turbine blades are propagated to the rest of the turbine, but due to the rotation of the rotor, loads on non rotating parts of wind turbine (nacelle and tower) have different characteristics and frequency response compared to the loads on wind turbine blades.

When modelling wind turbine flexibility, one has to take into account the flexibility of the blades and the flexibility of the tower, where the tower is generally more flexible than the blades. To describe motion of the blades caused by flexibility, blade coordinate systems are defined as shown in Fig. 5 – one coordinate system is assigned to each blade. Origin of the blade coordinate system is placed in the blade root and the axes are oriented as follows: the abscissa (x-axis) is parallel with wind direction and the applicate (z-axis) is perpendicular to x-axis and it is parallel to with blade longitudinal axis. The ordinate (y-axis) is perpendicular to other two axes and with them forms right-handed Cartesian coordinate system. It should be noted that the blade coordinate system is fixed to the blade, so it rotates together with the blade, i.e. wind turbine rotor. Flexibility of the blade is then observed as the movement of the blade tip along x-axis and y-axis of the blade coordinate system:

$$\begin{aligned} F_{bl} &= M_{bl}\ddot{q}_{bl} + D_{bl}\dot{q}_{bl} + K_{bl}q_{bl}, \\ \begin{bmatrix} x_{bl} \\ y_{bl} \end{bmatrix} &= C_{bl}q_{bl}, \end{aligned} \tag{4}$$

where q_{bl} is state vector that describes blades' flexibility, F_{bl} is effective force causing blades' deformations and M_{bl}, D_{bl}, K_{bl} and C_{bl} are model matrices of appropriate dimensions. Deflection of each blade tip is contained in vectors $x_{bl} = [x_{bl,1} \quad x_{bl,2} \quad x_{bl,3}]^T$ and $y_{bl} = [y_{bl,1} \quad y_{bl,2} \quad y_{bl,3}]^T$.

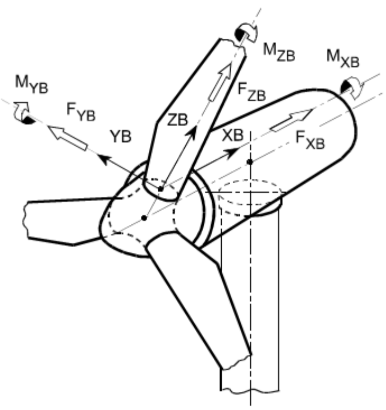

Fig. 5. Blade root coordinate system (Source: Germanischer Lloyd [10]).

To describe the motion of the tower, tower coordinate system is defined as shown in Fig. 6. Origin of the tower coordinate system is in the tower top when wind turbine is not subjected to aerodynamic loads. The abscissa is parallel with wind direction, the applicate is pointing vertical upwards and the ordinate is perpendicular to other two axes and with them forms right-handed Cartesian coordinate system. The tower coordinate system is fixed relative to the ground and the flexibility of the tower is observed as the movement of the tower top along x-axis (x_t) and y-axis (y_t):

$$\begin{aligned} F_t &= M_t\ddot{q}_t + D_t\dot{q}_t + K_tq_t, \\ \begin{bmatrix} x_t \\ y_t \end{bmatrix} &= C_tq_t, \end{aligned} \tag{5}$$

where q_t is state vector that describes tower flexibility, F_t is effective force causing tower deformations and M_t, D_t, K_t and C_t are model matrices of appropriate dimensions.

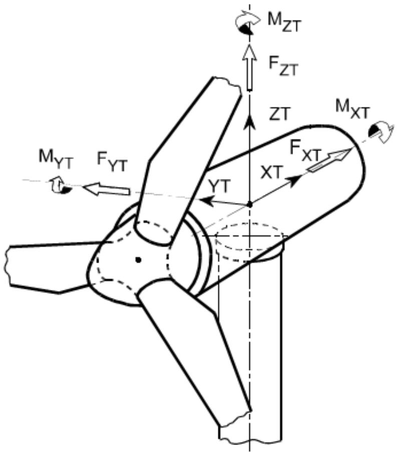

Fig. 6. Tower top coordinate system (Source: Germanischer Lloyd [10]).

It should be noted that movement of blade coordinate systems relative to tower top coordinate system causes azimuth dependant transformations of loads from one coordinate system to another. Since rotor azimuth is never constant while wind turbine is operational, obviously wind turbine mathematical model is time dependant. That causes different frequency response of the loads on the rotating part of wind turbine, compared to the loads on nonrorating part of wind turbine, as it is shown in [11].

Wind turbine considered in this paper is 2.5 MW direct drive variable speed wind turbine.Since shaft flexibility of the considered wind turbine is not significant compared to tower and blade flexibility, it is not described here. Also note that this paper deals with structural wind turbine loads which act on much larger time scale compared to electrical effects in wind turbine generator or frequency converter. For that reason, the electrical effects and the connection to the power grid are also not described here.

B. Identification of Wind Turbine Mathematical Model

To obtain wind turbine mathematical model, it is convenient to use methods of experimental identification [12]. Instead of measurements from real wind turbine, simulation results from complex nonlinear wind turbine models can be used. In this paper, simulations from professional tool GH Bladed [13] are used. GH Bladed incorporates very accurate nonlinear wind turbine model and it is the industry standard software for the design and certification of wind turbines.

The following dynamics are included in the identified model:

- deflections of each blade in x-axis of the blade coordinate system (one mode per blade),
- deflections of each blade in y-axis of the blade coordinate system (one mode per blade),
- tower deflections in x-axis of the tower coordinate system (one mode),
- tower deflections in y-axis of the tower coordinate system (one mode),
- motion of the rotor,
- servo system for each blade (second order system each).

Wind turbine model is identified in the state space with the following states:

- position of each blade tip along x-axis and y-axis of the blade coordinate systems,
- velocity of each blade tip along x-axis and y-axis of the blade coordinate systems,
- position of the tower top along x-axis and y-axis of the tower coordinate system,
- velocity of the tower top along x-axis and y-axis of the tower coordinate system,
- rotor speed,
- pitch angle and pitch velocity of each blade.

Therefore the identified model has 23 states in total. It is already mentioned in the previous subsection that wind turbine tower is more flexible than wind turbine blades. Therefore one could consider using more vibrational modes for description of tower oscillations to achieve more accurate mathematical model. But note that this model is primarily used for control system design and as it is shown in Section IV, the model is adequate for such purpose. As the wind turbines grow in size, the need for introducing more tower (and blade) vibrational modes will be even more emphasized.

As model input, pitch angle reference β_i and effective wind speed $v_{w,i}$ for each blade are chosen – resulting in 6 inputs:

$$u_k = \begin{bmatrix} \beta_1 & \beta_2 & \beta_3 & v_{w,1} & v_{w,2} & v_{w,3} \end{bmatrix}^T . \tag{6}$$

Loads in characteristic points of wind turbine (such as blade root and tower top) are chosen as model outputs.

Since the blade coordinate systems and the tower coordinate system are moving relative to each other, identified model has to have variable parameters which depend on rotor azimuth ϑ:

$$\begin{aligned} \dot{x}(t) &= A(\vartheta)x(t) + B(\vartheta)u(t), \\ y(t) &= C(\vartheta)x(t) + D(\vartheta)u(t), \end{aligned} \tag{7}$$

where x_k, u_k, y_k are the model state, input and output vectors and $A(\vartheta)$, $B(\vartheta)$, $C(\vartheta)$, $D(\vartheta)$ are the model matrices. Also note that rotor azimuth ϑ depends on rotor speed ω, which is one of the model states:

$$\dot{\vartheta}(t) = \omega(t). \tag{8}$$

Since wind turbine mathematical model parameters depend on rotor azimuth position, they are periodic and model matrices can be expressed as:

$$\begin{aligned} A(\vartheta) &= A_0 + A_{cos} \cos\vartheta + A_{sin} \sin\vartheta, \\ B(\vartheta) &= B_0 + B_{cos} \cos\vartheta + B_{sin} \sin\vartheta, \\ C(\vartheta) &= C_0 + C_{cos} \cos\vartheta + C_{sin} \sin\vartheta, \\ D(\vartheta) &= D_0 + D_{cos} \cos\vartheta + D_{sin} \sin\vartheta, \end{aligned} \tag{9}$$

where all matrices on the right side of the equations are constant.

Simulation results from professional simulation tool GH Bladed are used for model identification. To obtain data needed for identification, several experiments are done. First, wind turbine is excited using PRBS (*Pseudo Random Binary Signal*) as blade pitch reference while the wind is kept constant. Signals needed to construct state and output vectors are recorded and used to obtain model parameters. In the next experiment, wind turbine is excited with step changes in wind speed and recorded data are used for augmenting previously identified model with wind speed inputs. The last experiment, which includes various changes in pitch angle references and wind speed, is used to obtain data for model validation.

Mathematical model structure used in identification is chosen with respect to known wind turbine physics, described in previous subsection. Since varying parameters of the mathematical model are caused by wind turbine parts moving relative to each other, wind turbine mathematical model is divided into several submodels, so that each submodel has constant parameters. Parameter variation of the complete wind turbine mathematical model is obtained through appropriate connections among identified submodels. More on identification of wind turbine mathematical model can be found in [14].

The data recorded for model validation shows a good match with identified model (see Fig. 7). Note that the tower top position represents the nonrotating part of wind turbine, while blade deflection represents the rotating part of wind turbine. Therefore, the identified model describes wind turbine dynamics well both for rotating and nonrorating parts of wind turbine.

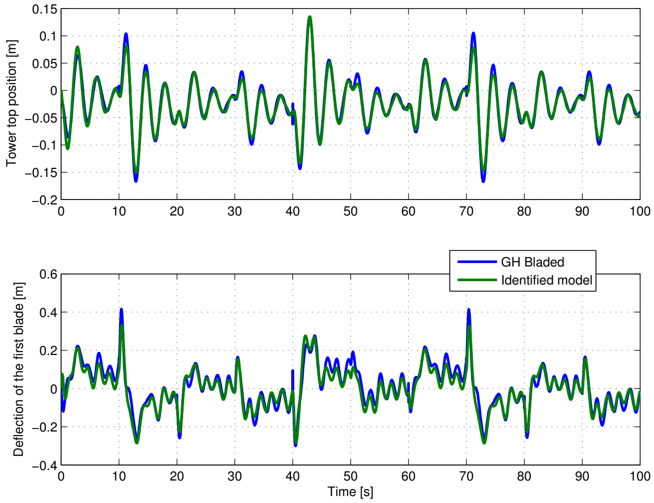

Fig. 7. Validation of identified wind turbine mathematical model.

To design discrete time controller, it is useful to have discrete time mathematical model:

$$x_{k+1} = A_d(\vartheta) x_k + B_d(\vartheta) u_k, \tag{10}$$

where $x_k = x(kT)$ and $u_k = u(kT)$ are state and input vectors observed only on integer multiples of sample time T and $A_d(\vartheta)$, $B_d(\vartheta)$ are model matrices in discrete time domain. Since mathematical model has varying parameters, discrete model matrices $A_d(\vartheta)$ and $B_d(\vartheta)$ are obtained from the solution of the differential equation (7):

$$\begin{aligned} x(kT+T) = {} & e^{A_\Phi(kT+T,kT,\vartheta_0)} x(kT) \\ & + \int_{kT}^{kT+T} e^{A_\Phi(kT+T,\tau,\vartheta_0)} B(\vartheta_0 + \omega\tau) u(\tau) \mathrm{d}\tau, \end{aligned} \tag{11}$$

where $e^{A_\Phi(t_2,t_1,\vartheta_0)}$ defines the zero-input transition of the state vector from $x(t_1)$ to $x(t_2)$ with rotor azimuth equal to ϑ_0 at time $t = 0$:

$$\begin{aligned} x(t_2) &= e^{A_\Phi(t_2,t_1,\vartheta_0)} x(t_1) \\ A_\Phi(t_2,t_1,\vartheta_0) &= A_0(t_2 - t_1) \\ &\quad + \frac{1}{\omega} A_{cos} \left[\sin(\omega t_2 + \vartheta_0) - \sin(\omega t_1 + \vartheta_0)\right] \\ &\quad - \frac{1}{\omega} A_{sin} \left[\cos(\omega t_2 + \vartheta_0) - \cos(\omega t_1 + \vartheta_0)\right]. \end{aligned} \tag{12}$$

Note that in (11) and (12), constant rotor speed is assumed. Otherwise, model matrices would depend both on state and input vector (instead only on rotor azimuth), which would make the model much more complex without considerable improvement in accuracy.

When using discrete time mathematical model, input value $u(t) = u_k$ is constant for all $t \in [kT,\ kT+T)$, so model matrices can be obtained from (11):

$$\begin{aligned} A_d(\vartheta) &= e^{A_\Phi(T,0,\vartheta)}, \\ B_d(\vartheta) &= \int_0^T e^{A_\Phi(T,\tau,\vartheta)} B(\vartheta + \omega\tau) \mathrm{d}\tau. \end{aligned} \tag{13}$$

Note that model matrices (13) can also be expressed in the form:

$$\begin{aligned} A_d(\vartheta) &= A_{d,0} + A_{d,cos} \cos\vartheta + A_{d,sin} \sin\vartheta, \\ B_d(\vartheta) &= B_{d,0} + B_{d,cos} \cos\vartheta + B_{d,sin} \sin\vartheta, \end{aligned} \tag{14}$$

where all matrices on the right side of the equations are constant.

IV. CONTROLLER FOR REDUCTION OF TOWER OSCILLATIONS

Since the pitching of rotor blades greatly influences aerodynamic forces, it is possible to reduce tower oscillations with appropriate pitch control. It is shown, both in literature and in practice, that significant reductions of tower oscillations can be achieved through a collective pitch control at the expense of a slight degradation of the rotor speed control [15]. Namik and Stol [16] suggested that individual pitch control can be used to stabilize offshore wind turbine platform. Their main idea is to generate asymmetric loads on wind turbine rotor that will reduce tilting of the onshore wind turbine platform. A similar idea can be applied to reduce tower oscillations of the onshore wind turbines.

A. *Standard wind turbine control*

Two controllers are used simultaneously – one for the rotor speed control (the collective pitch control) and one for the reduction of aerodynamic loads (the individual pitch control). Both controllers are designed as LQR offset free control [17] and since the identified wind turbine mathematical model (7) is azimuth dependant, obtained controllers are azimuth dependant as well. Measurements of rotor speed, pitch angles, tower top acceleration and blade loads are assumed to be available, while Kalman filter is used for state vector estimation.

Note that neither the collective pitch controller nor individual pitch controller are designed to reduce tower top oscillations. Hence, results obtained with such control system are suitable for comparison with results obtained with controllers for tower oscillation reductions, which are described in the following subsections. Controllers from the following subsections are similar to standard controller from this subsection – only LQR criteria are augmented to achieve tower oscillation reduction through collective pitch control or through individual pitch control.

B. *Tower oscillation reduction through collective pitch control*

Collective pitch control has significant influence on the thrust force that *pushes* wind turbine rotor and nacelle in the wind direction and thus causing tower deformations and oscillations. Therefore adequate collective pitch control can reduce the excitation of the wind turbine tower and thereby reduce tower oscillations. Since collective pitch control also has significant influence on aerodynamic torque, such reduction of tower oscillations can reduce the quality of rotor speed control and trade-off between reduction of tower oscillations and rotor speed control has to be made.

C. *Tower oscillation reduction through individual pitch control*

Instead of influencing on the thrust force, individual pitch control affects asymmetric loads on the wind turbine rotor and thus generate torque which tilts wind turbine nacelle backwards and forwards. By exploiting that fact, it is possible to reduce the excitation for the wind turbine oscillations with adequate individual pitch control. Instead of interfering with rotor speed control, reduced tower oscillations are achieved by allowing higher aerodynamic rotor loads for brief periods, i.e. during wind gusts. Since large aerodynamic loads can reduce wind turbine expected lifetime (as well as excessive tower oscillations), trade-off between aerodynamic loads and reduction of tower oscillations has to be made.

D. *Tower oscillation reduction through combined collective and individual pitch control*

It is shown that both methods for reduction of tower oscillations interfere with other aspects of wind turbine control system – with rotor speed control (collective pitch control) or with aerodynamic loads reduction (individual pitch control). To achieve maximal reduction of wind turbine tower oscillations while maintaining desired quality of rotor speed (power) control and desired level of aerodynamic loads, both collective and individual pitch control can be combined.

E. *Experimental results*

Simulation results for above described controllers are shown in Fig. 8–10. Simulations are performed using professional simulation tool GH Bladed with detailed nonlinear wind turbine mathematical model. Simulations are done both with realistic turbulent wind and with step changes in wind speed, but only results obtained with step change in wind speed are shown here because the effects of the described control laws are more clearly visible. In the shown figures, the wind speed changes from 18 to 20 m/s. As it is discussed earlier, in all cases the reduction of tower oscillations is achieved at the expense of a slight degradation of rotor speed control or loads reduction.

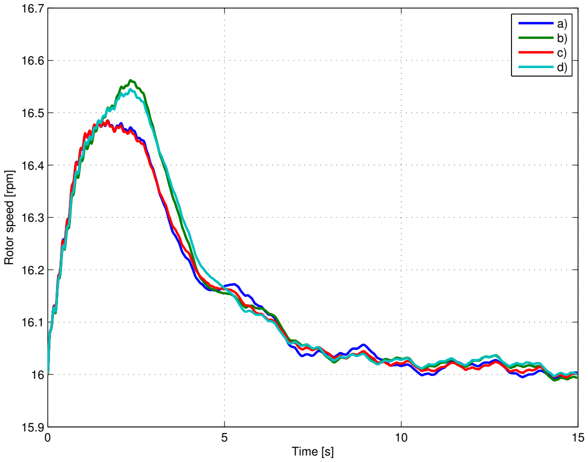

Fig. 8. Rotor speed for different controllers: a) standard wind turbine control; b) reduction of oscillations by collective pitch only; c) reduction of oscillations by individual pitch only; d) reduction of oscillations by collective and individual pitch.

When only collective pitch is used for reduction of tower oscillations, a degradation of rotor speed control can be observed – Fig. 8 shows larger rotor speed deviation from its nominal value. When only individual pitch is used for reduction of tower oscillations, there is no degradation in rotor speed control, but one can observe increase of aerodynamic loads in Fig. 9. It should be noted that loads are decreased once the tower oscillation is reduced.

Figure 10 shows that the maximal reduction of tower oscillations is achieved by combined collective and individual pitch. Besides achieving maximal reduction of tower oscillations, also both rotor speed control and loads reduction are slightly degraded, which is expected. It should be noted that by combining collective and individual pitch, one can make trade-off among reduction of tower oscillations, rotor speed control and loads reduction.

V. CONCLUSION

This paper describes the idea of reduction of wind turbine tower oscillations based on individual pitch control and it

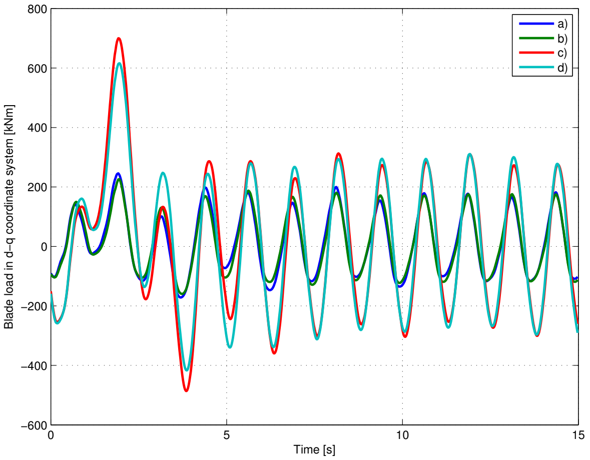

Fig. 9. Blade load in d-q coordinate system for different controllers: a) standard wind turbine control; b) reduction of oscillations by collective pitch only; c) reduction of oscillations by individual pitch only; d) reduction of oscillations by collective and individual pitch.

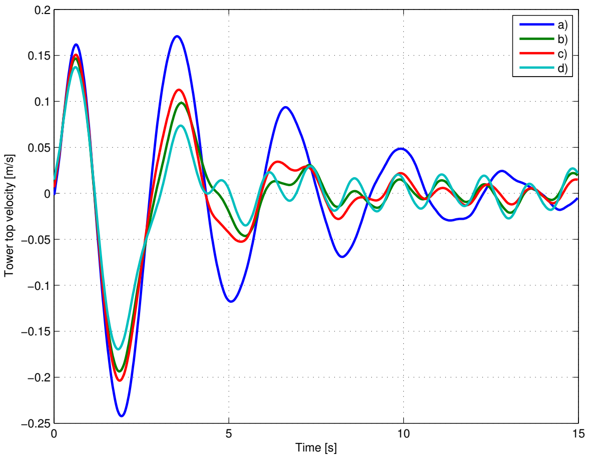

Fig. 10. Tower top velocity for different controllers: a) standard wind turbine control; b) reduction of oscillations by collective pitch only; c) reduction of oscillations by individual pitch only; d) reduction of oscillations by collective and individual pitch.

compares it with widely used reduction of tower oscillations based on collective pitch control. First a basic wind turbine controller for rotor speed control and loads reduction is described. In order to design controller for reduction of tower oscillations, wind turbine mathematical model is described – both theoretical background and experimental identification are reported. Finally, several controllers for reduction of tower oscillations are presented, all based on LQR design. It is shown that both collective pitch control and individual pitch control can reduce tower oscillations at the expense of a slight degradation of rotor speed control and loads reduction, respectively. The best results are obtained when both collective and individual pitch control are used for reduction of tower oscillations.

ACKNOWLEDGEMENTS

This research has been financially supported by projects "Advanced control and estimation strategies in complex systems" (MZOS project 0361621-3012), "Optimization of renewable electricity generation systems connected in a microgrid" (HRZZ project 57094-2011), "ACROSS – Centre of Research Excellence for Advanced Cooperative Systems" (FP7 project No. 285939) and by Končar – Electrical Engineering Institute. This support is gratefully acknowledged.

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