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Variable frequency resonant controller for load reduction in wind turbines

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A B S T R A C T

While most loads on wind turbines are originated from wind speed fluctuations, they show a periodic nature with a time-varying frequency proportional to the turbine rotation. This paper exploits this relation and proposes a modified Resonant Controller able to attenuate these frequency-varying periodic disturbances. The resulting controller is designed for both partial and full load wind speed conditions, therefore, it is able to reject periodic loads even when the wind turbine system is subject to changes in the operating rotation speed. Furthermore, a novel piecewise linear representation of the system is presented allowing a systematic design procedure, based on Linear Matrix Inequalities, in order to compute the control parameters. Simulation results in a 2.5 MW large scale three-bladed wind turbine illustrate the proposed method, which is able to reduce the root mean value of blade load up to 12 times when compared to a traditional LPV controller.

1. Introduction

Further data results evidencing global temperature millennial peaks (Marcott, Shakun, Clark, & Mix, 2013) and a high correlation between ocean temperature changes and atmospheric CO_2 levels (Shakun, Clark, He, Marcott, Mix, Liu, Otto-Bliesner, Schmittner, & Bard, 2012) suggest the urgency of renewable, low carbon footprint, forms of energy production such as solar, wind or wave energy. In the context of wind energy, the solution to achieve kWh price reduction and meet the market expectations has been the upscaling of turbine structures. In turn, this upscaling has been posing the challenge of developing new materials and control schemes able to mitigate the effects of the large loads faced by the turbine structure without compromising energy production (Camblong, Vechiu, Etxeberria, & Martinez, 2014; Ren, Li, Brindley, & Jiang, 2016). A crucial observation is that the significant loads acting on wind turbines are typically originated from deterministic distortions on the wind field such as shear, wake and tower shadow effects. Furthermore, given the fact that a wind turbine is a rotating machine, these loads become periodic disturbances that cause material fatigue and excessive mechanical stress on the system structure. Despite the fact that the magnitude of these disturbances is hard to estimate, they possess a known – albeit variable – fundamental frequency that is directly dependent on the rotor angular speed, a measured variable. This paper will exploit these simple facts and develop a control law based on the internal model principle that is able to significantly reduce the effects of these periodic disturbances.

A problem inherent to control of wind turbines (Bianchi, Battista, & Mantz, 2006) is the high nonlinearity of the blades' aerodynamics. These relations usually are described by typical profiles depending on wind tip-speed ratio and pitch angle. In addition to these nonlinearities, the operating condition must vary according to the nominal wind speed: at the so-called below-rated wind speeds, the control objective is to maximize power production, while at the above-rated wind speeds the objective is to limit the rotor angular momentum, minimizing mechanical loads and maintaining a constant power production. Given the above, one should not be surprised to find in the control literature a myriad of control techniques applied to wind turbines: gain scheduling (Tibaldi, Henriksen, Hansen, & Bak, 2014), nonlinear model predictive control (Schlipf, Schlipf, & Kühn, 2013), data-driven adaptive control (Simani & Castaldi, 2013), fault tolerant strategies (Blesa, Rotondo, Puig, & Nejjari, 2014), among other techniques.

In the past years an increased focus has been given to the problem of load reduction in large scale wind turbines (Bossanyi, 2003; Bottasso, Croce, Riboldi, & Nam, 2013; Spudić, Jelavić, & Baotić, 2015).

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Particularly, the work in Selvam, Kanev, van Wingerden, van Engelen, and Verhaegen (2009) explores the so-called Coleman transformation and proposes a new feedback–feedforward Individual Pitch Control (IPC) aimed at load reduction at above-rated wind speeds. By using the Coleman transformation the authors are able to regard the disturbance signals in a rotating reference frame, where they are no longer periodic (Lu, Bowyer, & Jones, 2015). Another approach able to exploit the rotation of the blades is the well-known Repetitive Controller: a control strategy that adds a delay to the feedback loop (Hara, Yamamoto, Omata, & Nakano, 1988). However, due to the time varying nature of the period of the disturbance acting on wind turbines, either a version of the robust high-order Repetitive Controller (Flores, Salton, & Castro, 2016), or the spatially sampled Repetitive Controller (Chen & Chiu, 2008), or other general delay-varying forms of this controller should be implemented (Wang, Gao, & Doyle III, 2009). Along these lines of thought, and also exploring the IPC capacity of modern wind turbines, a lifted repetitive control scheme is applied to the load reduction at above-rated wind speeds in Houtzager, van Wingerden, and Verhaegen (2013), and a predictive Repetitive Controller is proposed in Navalkar, Van Wingerden, Van Solingen, Oomen, Pasterkamp, and Van Kuik (2014). Both these works combine the Repetitive Controller with some form of online adaptation in order to account for changing turbine dynamics.

Another strategy based on the Internal Model Principle (IMP) is the so-called Resonant Controller. While this control strategy gives the designer more degrees of freedom over the closed-loop sensitivity function, it generally requires a large order controller (along with many tuning parameters) so as to achieve results comparable to the Repetitive Controller (Salton, Flores, Pereira, & Coutinho, 2013). Furthermore, as originally conceived, this controller is only able to reject periodic disturbances that present a fixed frequency. It was already noted, however, that while the loads acting on the turbine have a varying frequency, this frequency is ruled by the rotor speed, suggesting that a frequency-varying (nonlinear) version of the Resonant Controller could be implemented in a straightforward form. The objective of this paper is to develop a framework able to stabilize the complex wind turbine system with an arbitrary number of nonlinear resonant modes, thus reducing the undesired effects of periodic loads acting on the blades of the wind turbine. In pursuance to do so, a modified Multiple-Resonant Controller, henceforth called Variable Frequency Multiple-Resonant Controller, is developed in order to mitigate the effects of periodic loads on wind turbines under varying wind speed conditions. The time-varying nature of the system and intrinsic nonlinearities are dealt with by a linear piecewise approximation, which suits the application of LMI-based robust control synthesis. In comparison with other references, the resulting controller does not require the Coleman transformation neither does it use spatial sampling. It will be shown, regardless, that the proposed controller achieves significant load reduction in a 2.5 MW large scale three-bladed wind turbine.

Notation: x_i denotes the ith component of a vector $\mathbf{x}$. $\mathbf{I}_n$ denotes an identity matrix with order n. $\mathbf{O}_{m\times n}$ denotes a null matrix with m rows and n columns. The transpose of $\mathbf{A}$ is represented by $\mathbf{A}^\top$. $\mathrm{He}\{\mathbf{A}\}$ denotes the symmetric block $\mathbf{A}+\mathbf{A}^\top$. $\mathrm{Co}\{\mathbf{A},\mathbf{B}\}$ denotes a convex hull obtained by the vertices $\mathbf{A}$ and $\mathbf{B}$. $\mathrm{diag}\{\mathbf{A},\mathbf{B}\}$ denotes a diagonal matrix obtained by the elements $\mathbf{A}$ and $\mathbf{B}$. Symmetric elements in a matrix are represented by $\star$. $\bar{x}$ denotes the equilibrium value of x. The trace of matrix $\mathbf{A}$ is represented by $\mathrm{tr}(\mathbf{A})$. $\|\mathbf{x}\|_2 := \sqrt{\int_0^\infty \mathbf{x}^\top\mathbf{x}\,dt}$ denotes the $\mathcal{L}_2$-norm of signal $\mathbf{x}$. Time dependencies will be omitted in order to avoid overloading the notation.

2. System model

The system under consideration is a typical three-bladed horizontal axis wind turbine with two degrees of freedom: the tower fore–aft deflection mode and the turbine rotor speed. The dynamics feature both mechanical and aerodynamic effects, following the approaches adopted in Bianchi et al. (2006) and Østergaard, Stoustrup, and Brath (2009). The reader may consult Tables 1–3 for guidance with respect to the variables that are being considered along with their corresponding units.

Table 1
State-space model variables symbol list.

Symbol	Meaning	Unit
x_1	Rotor speed state	rad/s
x_2	Tower fore–aft deflection state	m
x_3	Tower fore–aft deflection rate state	m/s
u_i	ith blade pitch angle control input	deg
u_4	Generator torque control input	N m
y_i	ith blade load measurement	N
d_i	ith blade wind speed input	m/s
δ	Mean wind speed	m/s

Table 2
Useful auxiliary functions symbol list.

Symbol	Meaning	Unit
$f_{b,i}$	ith blade aerodynamic flapwise force	N
$m_{b,i}$	ith blade aerodynamic leadwise moment	N m
$p_{b,i}$	ith blade captured aerodynamic power	W
λ_i	ith blade tip-speed ratio	–
c_f	Aerodynamic thrust force coefficient function	–
c_m	Aerodynamic moment coefficient function	–
c_p	Aerodynamic power coefficient function	–

Table 3
Constant parameters from a typical 2.5 MW large scale three-bladed wind turbine (Selvam et al., 2009).

Symbol	Meaning	Value	Unit
r_t	Turbine radius	40	m
ρ	Air density	1.25	kg/m^3
m_t	Turbine mass	$1.5657\cdot 10^5$	kg
d_t	Tower damping	$2.8\cdot 10^3$	N s/m
s_t	Tower stiffness	$1.235\cdot 10^6$	N/m
j_r	Turbine rotor moment of inertia	$1.1255\cdot 10^6$	kg m^2

2.1. Nonlinear model

Let $\mathbf{x} = [x_1 \;\; x_2 \;\; x_3]^\top \in \mathbb{R}^3$ be the system state vector, $\mathbf{u} = [u_1 \; u_2 \; u_3 \; u_4]^\top \in \mathbb{R}^4$, be the system input vector and $\mathbf{d} = [d_1 \;\; d_2 \;\; d_3]^\top \in \mathbb{R}^3$ be the system disturbance input vector. Then, it is possible to write the system dynamics in the following compact notation:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u},\mathbf{d}), \tag{1}$$

where the nonlinear vector function $\mathbf{f}(\mathbf{x},\mathbf{u},\mathbf{d})$ is defined as Bianchi et al. (2006) and Selvam et al. (2009),

$$\mathbf{f}(\mathbf{x},\mathbf{u},\mathbf{d}) = \begin{bmatrix} \dfrac{1}{j_r}\left(\displaystyle\sum_{i=1}^{3} m_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d}) - u_4\right) \\ x_3 \\ \dfrac{1}{m_t}\left(\displaystyle\sum_{i=1}^{3} f_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d}) - s_t\, x_2 - d_t\, x_3\right) \end{bmatrix}, \tag{2}$$

with,

$$m_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d}) := \frac{1}{2}\rho\pi {r_t}^3\,(d_i - x_3)^2\, c_m\left(\lambda_i, u_i\right), \tag{3}$$

$$f_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d}) := \frac{1}{2}\rho\pi {r_t}^2\,(d_i - x_3)^2\, c_f\left(\lambda_i, u_i\right), \tag{4}$$

$$\lambda_i := \frac{r_t\, x_1}{d_i - x_3}. \tag{5}$$

The function $m_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d})$ represents the ith blade aerodynamic edge-wise moment and $f_{b,i}(\mathbf{x},\mathbf{u},\mathbf{d})$ the ith blade aerodynamic flap-wise force (in the fore–aft direction). Furthermore, the ith blade tip-speed ratio is defined by λ_i, while $c_f(\lambda_i,u_i)$ and $c_m(\lambda_i,u_i)$ denote aerodynamic efficiency functions. Typical profiles of these functions are depicted in Figs. 1 and 2 considering the blade element model equations in Bianchi et al. (2006) with the system parameters in Table 3.

The objective of the proposed controller is to minimize the fatigue load in each blade due to variations in the aerodynamic flap-wise force