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Wind turbine envelope protection control over the full wind speed range

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ABSTRACT

Ensuring safe operation at all times and in all conditions is one of the primary goals of wind turbine control systems. This paper presents a novel approach for wind turbine control based on the concept of envelope riding. The proposed approach utilizes on-line numerical optimization to predict at each time instant the extremal wind speed that would lead the machine to encounter the envelope of its safe operating range. Based on this extremal condition, control inputs are computed that maintain the response within the safe region at all times, at the most riding its boundary but without ever leaving it. The method is capable of keeping the machine within its safe envelope within the entire range of operating wind speeds, including both rated and cut-out conditions.

The new method is verified with the help of numerical simulations conducted with a high-fidelity aeroservoelastic environment. Comparisons are made with standard control algorithms for the prevention of excessive loading, including peak-shaving and soft cut-out schemes. Results illustrate the ability of the proposed approach in reducing loads and improving power output.

1. Introduction

Avoiding excessive loading is crucial for ensuring the safe operation of wind turbines and for prolonging their lifetime. Numerous control algorithms have been proposed in the literature for reducing wind turbine loads, considering both fatigue (e.g. by individual pitch control [1–3] or by the damping of tower oscillations [4,5]) and ultimate states. This paper focuses on the latter case, and it presents an addition to standard wind turbine power control algorithms that prevents the exceedance of predetermined safe limits.

Most ultimate state control algorithms presented in the literature aim at the lowering of loads in critical operating regions. For example, curtailing of wind turbine power output is used in Refs. [6,7], while cyclic pitch control is used to decrease average loading in Ref. [8], which in turn also reduces ultimate loads. It should be remarked that these methods do not control ultimate loads per se, as in fact load alleviation is obtained only indirectly through some other mechanism – for example by reducing power. Although such methods seem to offer interesting performance, there appears to be room for improvement. In addition, loads are not the only parameters that should be monitored, as other states (for example, rotor speed), should be maintained within preset limits at all times to ensure the safe operation of a wind turbine.

This paper presents a control algorithm for the envelope protection of a wind turbine based on convex optimization. This controller acts as an add-on to a baseline power control algorithm, which is in charge of the standard regulation of the wind turbine throughout its entire range of operating wind speeds. As long as the machine states remain within predefined limits, which define the safe envelope of the wind turbine, the proposed algorithm makes no control action. However, when the algorithm detects an increased danger of exceeding the envelope, the machine is governed so as to keep its response confined at all times within the envelope itself.

The idea of using optimal control for the reduction of wind turbine loads has already been discussed in the literature. Most notably, model predictive control has been investigated because of its ability to explicitly handle constraints and to use wind speed preview information (for instance, obtained from LiDAR measurements) [9–12]. Robust control approaches, as described in

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Notation

C_F	Aerodynamic thrust coefficient	η	Power reference
C_Q	Aerodynamic torque coefficient	λ	Tip speed ratio
F_t	Aerodynamic thrust	ω	Angular velocity
I	Performance index	ρ_a	Air density
J_t	Combined rotor, generator and drive train inertia	$\Delta(\cdot)$	Increment wrt a steady state value
K_P	Proportional gain	$(\cdot)^\mathrm{II}$	Quantity referred to Region II
P	Power	$(\cdot)^\mathrm{III}$	Quantity referred to Region III
Q_a	Aerodynamic torque	$\dot{(\cdot)}$	Derivative wrt time, $\mathrm{d}\cdot/\mathrm{d}t$
Q_g	Generator torque	$\ddot{(\cdot)}$	Second derivative wrt time, $\mathrm{d}^2\cdot/\mathrm{d}t^2$
R_r	Rotor radius	$(\cdot)^*$	Extremal value
T_I	Integral time constant	$(\cdot)^T$	Transpose
T_s	Sampling time	$(\cdot)_\mathrm{d}$	Discrete time quantity
T_w	Prediction horizon	$(\cdot)_\mathrm{n}$	Nominal quantity
r	Input vector	$(\cdot)_\mathrm{opt}$	Optimal quantity
t	Time	$(\cdot)_\mathrm{r}$	Reference quantity
v_w	Effective wind speed	$(\cdot)_i$	Quantity at the ith interpolation time instant
x	State vector	$(\cdot)_k$	Quantity at the kth sampling instant
x_t	Tower top displacement	$\widehat{(\cdot)}$	Measured value
y	Monitored output	ETM	Extreme turbulence model
β	Blade collective pitch	LiDAR	Light detection and ranging
		NTM	Normal turbulence model

Refs. [13–15], try to reduce loads in the presence of modelling uncertainties and unknown disturbances. This is typically achieved by assessing a set of possible disturbances and associated system trajectories, and finding control actions that will produce a satisfactory behaviour in all possible situations. Our proposed approach differs from these methods, because an optimal control problem is defined on top of an existing underlying wind turbine controller. This allows one to re-use existing proven wind turbine control technology, which is very important for practical applications. In fact, wind turbine manufacturers may be hesitant to radically change controllers that have been used extensively and for which they have acquired confidence and substantial practical knowledge. In fact, control laws have profound effects not only on wind turbine operation, but also on design and certification.

A method for the detection of unsafe situations based on numerical optimizations is presented in Ref. [16], where linear matrix inequalities are used to efficiently solve the problem even for high order systems. However, the approach still remains computationally intensive, and only the detection of unsafe situations, without their prevention, is presented.

Improving on this situation, an optimization-based control algorithm for preventing overspeed is presented in Ref. [17]. In this case, the envelope is not defined by loads, but by rotor speed. During the design phase, a set of all possible state and control action combinations that do not violate constraints is found. During on-line operation, the current state and control actions proposed by the standard underlying rotor speed controller are checked to verify if they fall within the safe pre-computed set or not. If needed, an optimization problem is then solved to find new control actions that will keep the system within the pre-computed set, thereby avoiding overspeed. As the expensive numerical work can be done off-line, the on-line computational complexity to verify if a point lies in the pre-computed set is very modest, resulting in fast execution times. However, an optimization is still required whenever there is a danger of exceeding a predefined limit. Additionally, it appears that the monitoring of an arbitrary combination of states might results in prohibitive costs and a much increased complexity.

Reference [18] presents a less computationally demanding approach for detecting and preventing possible unsafe situations in high winds. The method is based on the use of a simplified wind model, which in turn requires certain assumptions on the wind speed. Due to its simplicity, a closed form solution can be found for the detection of dangerous wind conditions, resulting in a very modest computational effort. A more general method for control around cut-out has been presented in Ref. [19], which does not require assumptions on the wind speed. As a result of its higher complexity, in this case an on-line optimization for the detection of dangerous conditions has to be solved numerically at each time step. However, since the optimization problem is convex, its solution can be computed efficiently in real-time in a deterministic number of operations [20,21]. Both of these optimization-based control algorithms for envelope protection are somewhat akin to the so called *soft cut-out* algorithms. However, in sharp contrast to soft cut-out that is invariably based on static characteristics calculated off-line (c.f. [6,22]), these methods constantly monitor the wind turbine state and react accordingly. In doing so, they are able to limit the wind turbine response while minimizing their interaction with the underlying standard power controller, in turn achieving a higher energy yield.

The idea of using convex optimization for envelope protection has been explored further in Ref. [23], where the control algorithm of Ref. [19] was adapted to work also around rated wind speed. The main purpose of this new control approach was to replace the so called *peak shaving* or *thrust clipping* schemes, whose goal is to reduce the extremal values of the rotor thrust that are typically present around rated wind speed. Similarly to soft cut-out strategies, standard peak shaving algorithms are also designed off-line (c.f. [7,24]). On the other hand, the optimization-based approach proposed in Ref. [23] improves on this situation by monitoring states at all times. This is achieved by using optimal control to detect extreme wind events that would lead the system to encounter its envelope boundary.

The present paper extends the optimization-based envelope protection method described in Refs. [19,23]. This generalized formulation amounts to a unified approach to limit states in any operating region of the wind turbine. Besides a generalization of