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Supervisory controller for reduction of wind turbine loads in curtailed operation☆

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ABSTRACT

There are situations in which wind turbines must curtail their power, i.e. produce less power than is available from the wind. In such cases the wind turbine power can be increased or decreased if required. This gives an opportunity to strike a balance between varying power production and reducing wind turbine structural loading. To that end, a supervisory controller is designed that issues power references to the wind turbine and can be easily installed on already operational wind turbines. The wind turbine with a supervisory controller produces the required mean power, while reducing wind turbine loads by adding power variations. The extensive, realistic simulations are done to evaluate the influence of the proposed controller on the fatigue loads, extreme loads and the overall wind turbine operation. The results indicate that a significant reduction of fatigue loads can be achieved, which can increase the operating life of the structure. Furthermore, the proposed supervisory controller can be utilized as the main building block of a wind farm controller, which meets the grid code requirements and can be easily installed on very large wind farms due to minimal requirements on the farm-wide communication.

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1. Introduction

A typical objective of variable speed megawatt wind turbine operation is to maximize power production while respecting limitations arising from wind turbine mechanical and electrical design. Because of the limitations on allowable rotational speed, torque and power, at high winds turbines are required to limit the power extracted from wind by pitching the rotor blades (Burton, Sharpe, Jenkins, & Bossanyi, 2001).

There are certain situations when maximizing the power production up to the turbine limits is not desirable, or even allowed. In such cases a wind turbine is in *curtailed operation*, which is an operating regime in which the wind turbine has an ability to temporarily increase its power production, but is not allowed to maintain the production on higher power level due to external factors. Some examples when the wind turbine needs to operate in curtailed operation are the following:

- The transmission system operator can require curtailment of wind farm power. Such ability is prescribed by the grid codes of several transmission systems, see e.g. E.ON Netz (2008), Eltra and Elkraft System (2004), and National Grid plc (2008). The power curtailment can be utilized to support grid frequency, limit the variability of active power in the system and to mitigate technical difficulties such as grid congestions. The curtailment of wind farm power can in principle be done by curtailing the individual wind turbines or by shutting down some turbines, but the solution with turbine power curtailment is far more favourable considering both the structural loads and the response time. Typical situations in which the wind farm power curtailment is requested are e.g. windy nights with low power demand when the electricity price can become negative, or an overload in a remote part of the grid where wind farms are typically located.
- Depending on the generator design, many wind turbines have an ability to temporarily increase the power production above nominal. For such wind turbines the typical operation at above nominal wind speed can be considered as curtailed operation, because a (temporary) increase of the power output is allowed.

In curtailed operation there exists an external requirement on the average power production, but all scenarios allow certain power

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variability. For example, when a wind turbine is participating in grid control, the small variations in wind turbine or wind farm power are not an issue due to the large inertia of the grid. Also, a wind turbine with an appropriate margin in electrical design can also temporarily increase or decrease the electrical power. Therefore, it makes sense to investigate how allowing power oscillations can benefit the structural loads of a wind turbine.

This paper provides conclusions of a study on the trade-offs that occur in an attempt to utilize power variations to reduce structural loads. The external "add-on" to a classical wind turbine controller is designed, which is referred to as a *supervisory controller*. The wind turbine keeps its classical controller, while the supervisory controller is added in an outer loop of a hierarchical control system. This controller setup results in several beneficial features for the controller design implementation:

- The supervisory controller can be installed as an add-on to already operational wind turbines, without making any changes to the baseline wind turbine controller. Thus, minimal wind turbine downtime is expected.
- The safety chain of the baseline wind turbine controller remains intact and functional and does not require redesign. Therefore, there is minimal risk related to supervisory controller installation.

The supervisory controller uses the typical interface and the sampling time of a wind farm controller. The control signal is the *power demand* P_{dem}. Modern megawatt wind turbines allow on-line external modification of their power demand, which is in most countries indeed required by the grid codes, e.g. E.ON Netz (2008), Eltra and Elkraft System (2004), and National Grid plc (2008). A supervisory controller is related only to one wind turbine. However, if it is installed at every wind turbine in a wind farm, it can be considered as a fully decentralized wind farm controller, which obtains its mean references from a slow-scale centralized wind farm controller.

In authors' previous work the potential of such supervisory controller design is shown. The controller design basics were published in Spudić, Jelavić, and Baotić (2011, 2012) and initial results were described. In this paper we bring the conclusions of this study, with a thorough analysis of the occurring trade-offs. The wind turbine performance is validated by using a comprehensive aeroelastic simulation model for turbine design and certification, which provides very realistic and reliable evaluation of wind turbine performance. Building on the controller setup reported in Spudić et al. (2012) and based on gathered insight in the system behaviour, the controller setup was improved to obtain the prime performance throughout the operating range of the wind turbine. In this paper the effects of the proposed controller are analysed on a comprehensive set of loads and operating conditions. In particular, (i) the performance is evaluated on a set of operating conditions that cover the full load region of the wind turbine (note that by design the supervisory controller cannot be used in a partial load operating region), (ii) the analysis of the influence on both fatigue and extreme loads is performed, (iii) the loads are analysed in a number of points of the wind turbine structure, which together provide a representative picture of the overall wind turbine structural loading, and (iv) the use of supervisory controller as a decentralized wind farm controller is discussed and analysed. Two different supervisory controllers were tested, corresponding to different sets of weights in the objective of the MPC controller, which reveal the possible trade-offs in terms of load reduction versus the amplitude of control actions.

The application of MPC methodology for wind turbine control was reported many times, often with the reduction of structural loads as the main design objective. The MPC methodology is appealing for the wind turbine operation optimization since it allows the minimization of a performance criterion in the presence of constraints. The constraints are always present in the wind turbine operation and arise from the limitations of available power, as well as from the limitations of the machine. The replacement of the classical wind turbine controller with a scheduled MPC controller was proposed in Kumar and Stol (2010). The improvement of control using wind field predictions was shown in Spencer, Stol, Unsworth, Cater, and Norris (2013). The recent work in Schlipf, Schlipf, and Kühn (2013) and Verwaal, van der Veen, van Wingerden (2014) demonstrates, respectively, in simulation and experiment, the benefits of using preview of the wind speed from LIDAR measurements within the MPC methodology framework. Furthermore, the MPC methodology was used also in dedicated algorithms for loads reduction, such as individual pitch control (Friis et al., 2012).

Unlike the work presented in this paper that considers the design of the wind turbine supervisory controller, all the references found in the literature, to the best of the authors' knowledge, propose the model predictive control designs for a wind turbine controller. This makes significant differences in the controller design approach. The wind turbine controller has to ensure stable operation of the wind turbine and provide damping of the natural frequency oscillations of the structure. Therefore, the wind turbine controller based on the model predictive control needs to have a complex wind turbine model that accounts for nonlinearities, needs to take into account uncertainties in the wind predictions and, finally, operates at a very small sampling time. This makes a problem hard and there is a significant gap between such solutions and the implementation in commercially available wind turbines. The supervisory controller proposed here considers the controlled wind turbine as a plant, which makes the control problem "easier" – the controlled plant is stable and exhibits the dynamic behaviour closer to linear. On the other hand, the supervisory controller has in general a smaller potential for load reduction – it uses the slower sampling time and has an inherent coupling between the wind turbine actuators (pitch angle and torque) due to the underlying wind turbine controller. However, in this work it is shown that the reductions can still be significant. Furthermore, the MPC at the wind turbine level often relies on feedback through additional sensor measurements, which in the proposed approach is not required.

The paper is structured as follows: Section 2 provides the description of the control setup and the objectives of the controller design. Section 3 describes the control problem formulation and design procedure. Section 4 describes the validation setup. Sections 5–7 bring the analysis of the results. In Section 5 the normal operating conditions under turbulent wind are considered and the influence on wind turbine fatigue loads is analysed. In Section 6 the simulations of extreme wind conditions are analysed, which provide conclusions about wind turbine extreme loads. In Section 7 the use of the supervisory controller as a decentralized wind farm controller is analysed and the results are evaluated against the grid code requirements for the curtailed operation. Section 8 concludes the paper.

2. Control setup and objectives

A state of the art multi-megawatt wind turbine with doubly fed induction generator and controllable pitch angle is considered. The rotor of the doubly fed induction generator is connected to the grid through a frequency converter, which enables control of generator torque. The pitch of the blades is controlled through an electrical or a hydraulic servo system. The 5 MW wind turbine

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