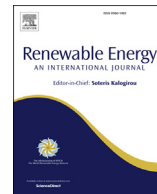




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On using Pareto optimality to tune a linear model predictive controller for wind turbines

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ABSTRACT

Optimal operation of wind turbines is important in order to minimize cost of energy, which is one of the major focus areas of the wind industry. Model predictive control (MPC) is a candidate for a control solution which effectively balances the different and potentially conflicting objectives, e.g. generated power and structural loads. This article presents a method on how to tune multi-objective MPC problems using Pareto curves. The approach is applied to a realistic wind turbine MPC problem, in which a joint power and tower fore-aft fatigue load optimization is performed. The controller is evaluated on a high fidelity model using a Vestas wind turbine simulator. In addition to the multiple control objectives, a number of constraints are considered as well. The evaluation shows a good potential of using model predictive control for this problem compared with an industrial baseline controller as, it approximately obtains the same mean generated power, while lowering the tower fore-aft fatigue loads. The computed Pareto curves of the trade-off between tower fore-aft fatigue load and mean generated power for a number of different weight matrices, demonstrate a potential tool for tuning MPC solutions for a wind turbine.

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1. Introduction

Reducing cost of energy has been a continued focus for the wind turbine industry over the last years. This naturally drives the interest in optimizing power generation while keeping structural loads under levels given by the design of the wind turbine structures. A solution to this joint optimization has importance in the entire operational range of the wind turbine. The largest impact is, however, in the switch region between partial load and full load operation as the thrust is highest here. The thrust depends on the wind speed and the pitching. In partial load operation, the blades are pitched at their optimal position. Consequently, the highest thrust are obtained at the highest wind speed in the partial load region, which is at the switching point between partial and full load operation. Partial load refers to operation below rated wind speed in which the wind turbine tries to optimize the power generation,

while full power refers to operation above rated wind speed of which the nominal power is generated. In the joint optimization problem, minimizing fatigue loads on the tower while maximizing power generation are conflicting objectives. In addition to optimizing the wind turbine performance with respect to the objectives, the controller is also required to operate within a number of constraints on control actuators and system states. MPC has previously shown to be a candidate to solve this optimization problem, but relative weighting of the different objectives in the optimization problem has proved to be difficult.

Model predictive control is often applied to multi-objective control problems, where relevant weights on the different objectives can be found either up front or during a tuning process. MPC seems to be a good solution to control design for such problems seen from an academic point-of-view, as it under certain conditions gives the optimal control solution, given the specified problem. However, from an industrial point-of-view the tuning of the weights can, however, be challenging as many industrial control applications have multiple conflicting objectives. Furthermore, the objectives used in the evaluation of a plant's performance are often not fully included in the cost function formulation used in the MPC solution. Thus, the weights somehow have to reflect higher level objectives used in the evaluation of the control system. This leads to

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problems when tuning the controller, where the performance depends on the trade-offs between the different control objectives. For this situation, it can be helpful to draw the Pareto front, where each point on the front corresponds to a specific combination of the weights.

In this article, an approach for tuning an MPC solution for a wind turbine based on the Pareto front between power and structural tower loads is proposed. The approach uses the gradient of the Pareto front to find weights which gives a balanced trade-off between the different weights. This is a novel approach for tuning of MPC solutions.

Model predictive control for wind turbines has been the focus in a considerable number of scientific publications. In Ref. [1] a pole placement based tuning of an MPC for switch less control of wind turbines, with respect to partial and full load operation, is reported. A Full Load Control (FLC) without wind speed predictions was reported in Ref. [2] and with wind speed predictions based on LIDARS in Refs. [3,4]. Switchless control considering tower fore-aft displacement is the focus of [5], in which a data driven model is used for the prediction. In Ref. [6], it is shown that with a perfect wind estimation, MPC can lead to high load reductions. This work has been evaluated using the aero-elastic code Flex5, see Ref. [7]. Non-linear MPC has been used to tackle the non-linearities in the wind turbine in Refs. [8–10]. In Ref. [11], feedback linearization is used to turn the nonlinear problem into a linear problem and subsequently a linear MPC solution is applied. In both [12] and [13], robust MPC algorithms are designed for different robustness issues in the wind turbine application. Smooth transitions between partial and full load control has been addressed using MPC in Refs. [14,15]. The first is evaluated with the HAWC2 turbine simulator and includes dynamic inflow in the design. The latter considers tower fore-aft displacements of a floating wind turbine [16], uses MPC to design an alternative individual pitch control scheme. MPC has been used for accommodating extreme loads and actuator limits in Ref. [17]. In Ref. [18], MPC is used to handle the repetitive nature of the wind turbine, in terms of handling, e.g., wakes which partly covers the rotor field. This results in the same load reductions as with an IPC algorithm but with less pitch activity. Explicit Model Predictive Control for Wind Turbines was covered in Ref. [19], which lowers the computational complexity of the MPC algorithm.

The work presented in this article, provides essential contributions to the existing literature on wind turbine MPC. The idea of using Pareto Fronts as a systematic tuning approach for a wind turbine MPC solution is new, and provides a substantial tool for designing wind turbine controllers based on the MPC methods. Selection of the weights in the cost function is a known problem in general for MPC applications, and at least in the case of wind turbines, the proposed tuning approach has shown great potentials. Secondly, the proposed MPC solution is benchmarked towards an industrial based wind turbine controller on an industrial aero-elastic simulation code.

Two actuators are normally used to control the power generation of a wind turbine. These are; the generator torque and the collective pitch angle of the blades. The first actuator is used to control the wind turbine until the rated power is reached. The turbine keeps the blade pitch angles at an optimal value, and when rated power is obtained, the generator torque is kept constant while the pitch angles are used to manipulate the airfoils. Thereby, the generated aerodynamic torque is maintained constant, and the rotor speed is kept at its rated value [20]. In addition to be used to control the rotor speed, the pitch angles also alters the thrust force on the rotor and thus, influence the tower fore-aft displacement and velocity. Consequently, the pitch angle can be used to control the tower fore-aft movements and thereby reduce the fatigue loads on it at the cost of decreased power generation.

In Ref. [5], a robust model predictive controller is designed and demonstrated using a Vestas high fidelity wind turbine simulation model. The used prediction model is based on data driven system identification using simulation data from this high fidelity model. Based on the same prediction model, a nominal model predictive controller is computed. In this article, we apply the proposed Pareto front based tuning approach to this MPC design and the Vestas simulation model. The MPC performance with respect to generated power and relevant fatigue loads are computed for different relative weightings of power generation and tower fore-aft velocity. The fatigue loads are evaluated using Damage Equivalent Loads (DELs). In this article, it is investigated how different weightings in the cost function influence the performance of mean Power, tower fore-aft DEL and blade flap and edgewise DEL. These data are used to generate a number of Pareto curves showing the relation between generated power and the respective DEL values. We use the Pareto curves to select the tuning of the MPC to provide the desired trade-off between the DELs and the generated power. We present an approach to obtaining this tuning where the gradients in relevant Pareto fronts are used to find the best tuning.

In Section 2, the proposed Pareto based tuning is presented and in Section 3, the used wind turbine system and model is introduced. The evaluated wind turbine MPC is presented in Section 4. The evaluation of Pareto fronts is presented in Section 5 where the Pareto fronts are also related to the wind turbine design process. Section 6 presents the obtained Pareto curves, which are analyzed and discussed. Conclusions are given in Section 7.

2. Pareto optimality based MPC tuning

The MPC formulation provides an optimal control signal given the control problem. In the case of multi-objective control problems, the ratio between the different weights used in the cost function will balance the different control objectives. If a sweep of weight ratios between the objectives is performed, one or more Pareto front(s) are computed. A simple case of this situation is present if only two performance objectives are evaluated, and the corresponding weights are scaled with factors ρ and $(1-\rho)$. A Pareto curve is illustrated in Fig. 1. In this case a simple linear prediction model with linear constraints and a quadratic cost function is formed. The performance in terms of power generation and costs, is evaluated based on a high fidelity model using a “complicated” cost function.

The simplified model used in the MPC setup is a linear model linearized for a number of optimal points of operation depending

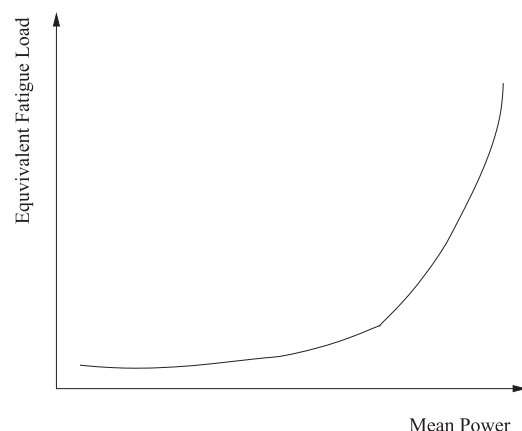


Fig. 1. Illustration of the Pareto Curves obtained by the performance evaluations depending on ρ .

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