Available online at www.sciencedirect.com
ScienceDirect
IFAC PapersOnline CONFERENCE PAPER ARCHIVE
IFAC-PapersOnLine 48-30 (2015) 090–095

Importance of Dynamic Inflow in Model Predictive Control of Wind Turbines

Peter Fogh Odgaard * **Torben Knudsen** *
Anders Overgaard ** **Henrik Steffensen** ** **Marten Jørgensen** **

* *Section of Automation and Control, Aalborg University, Denmark, email: pfo@es.aau.dk*
** *Msc.EE students in 2014 at Aalborg University, Aalborg, Denmark*

Abstract: The efficiency of including dynamic inflow in the model based design of wind turbine controller has been discussed for many years in the wind energy community with out getting to a safe conclusion. This paper delivers a good argument in favor of including dynamic inflow. The main contributions are the use of a very simple inflow model, developed by one of the authors and the use of Pareto fronts to facilitate a safe conclusion. The approach is to compare MPC controllers designed with respectively without including dynamic inflow for a mean wind speed just above rated where this dynamics are most pronounces. For this the well accepted NREL 5MW reference turbine simulated with FAST is used. The main result is a reduction in tower fatigue load at 22% while power error, rotor speed error, generator torque and pitch rate is improved from 2 to 33%.

Keywords: Wind Turbines, Model Predictive Control, Dynamic Inflow

1. INTRODUCTION

Wind energy is one of the fastest growing renewable energy sources. Wind turbines are becoming larger, more complex and operates in many different environments, which gives rise to challenges in controlling and optimizing the power production and reducing the fatigue of the system. In broad terms lower fatigue loads means less use of steel and glass fiber for the wind turbine structures, which again leads to cheaper wind turbines. Consequently focus is drawn to reducing structural fatigue loads without reducing the power generation, as this will lead to lower cost of energy for wind turbines, which again improves the competitiveness of the commercial wind turbines.

A common used method of control is presented in Johnson et al. [2006], where the optimal set point for optimizing the power production is calculated continuously without knowledge of the wind speed, combining this strategy with a number of PID based controllers. By introducing more advanced control methods as optimal, adaptive and nonlinear control it has been made possible to introduce the conflicting objectives of power optimization and fatigue loads reductions in the same control problem. In Bossanyi [2003] individual blade pitch control with the aim of load reduction is introduced. Furthermore, good results are obtained in Friis et al. [2011] using repetitive control combined with MPC, which focus on damping structural vibrations and thereby structural fatigue.

Model predictive control (MPC) has been applied to the wind turbines dealing with the conflicting power optimization and fatigue load reduction problem in a number of publications. Using MPC for switching between partial and full load operation of the wind turbine while reducing tower fore-aft fatigue loads was reported in Adegas et al. [2013]. This paper also presents work on pole placement based objective functions, and a discussion of implementation structures for the MPC solution with the existing wind turbine controller. A Full Load Control (FLC) without wind speed predictions were reported with wind speed predictions based on LIDARS in Soltani et al. [2011]and Madsen et al. [2012]. Switchless control considering tower fore-aft displacement by MPC is the focus of Evans et al. [2015], here the prediction model is data driven. In Korber and King [2010], it is shown that with an perfect wind estimation MPC can obtain high load reductions, this work has been evaluated in Flex5, Øye [1999]. Non-linear MPC has been used to tackle the non-linearities in the wind turbine Henriksen et al. [2011]. In Hansen and Henningsen [2013], feedback linearization is used to turn the nonlinear problem into a linear problem subsequently a linear MPC solution can be applied. In both Mirzaei et al. [2012] and Thomsen [2010].

These proposals works on static models concerning the wind inflow on the blades. Henriksen et al. [2012a] shows the significance of including the dynamic states in the modeling and suggests a simplified model of dynamic inflow for model based control. A more complicated dynamic inflow model is used for MPC design for wind turbine control in Henriksen et al. [2012b]. Here it is found that inclusion of dynamic inflow is beneficial.

In this paper the simple dynamic inflow model from Knudsen and Bak [2013] is included in a prediction model for MPC design for controlling power generation and tower fore-aft movements of a wind turbine. In this work a number of controller weights are computed to find a Pareto Front of the trade off between power generation and tower fore-aft fatigue loads. The approach of using Pareto Fronts in combination with wind turbine MPC designs

10.1016/j.ifacol.2015.12.359

for balancing power generation and fatigue loads, has been investigated in Odgaard et al. [2015]. This proposed design tool is very usable for the wind turbine engineer. These Pareto Fronts are computed both in the case of dynamic inflow included in the prediction model and with model predictive control not taking the dynamic inflow into account in the prediction model. FAST from NREL is used as the simulation tool for the computation of these Pareto Fronts. The main contributions of this paper are 1) MPC control design using a first order dynamic inflow model which is simpler than what is presented so far and 2) comparing the controllers designed with respectively without dynamic inflow by using Pareto fronts which gives a much safe and robust conclusion compared to what is previously presented, as the conclusion of evaluation is only based on a few selected controller tunings.

In Sec. 2 the considered wind turbine control problem is specified and the used design model is introduced. In Sec. 3 the developed MPC solution is presented. The obtained Pareto Fronts of the controller performance are presented in Sec. 4. A conclusion is drawn in Sec. 5.

2. WIND TURBINE CONTROL PROBLEM AND MODEL

Control of wind turbines deals with a number of objectives and tasks. Many of these are conflicting in nature, in this work a subset of these objectives are considered. The idea is to design a model predictive controller which deals with the conflicting objectives of generating nominal power while minimizing tower fore-aft fatigue loads, when operating the wind turbine at above rated wind speed.

The proposed MPC scheme is evaluated using FAST from NREL which is a high fidelity aero-elastic wind turbine model, see Jonkman and Buhl Jr. [2005], and the 5 MW NREL reference turbine is used as the wind turbine platform [1]. The data obtained by the simulations in FAST are used to compute Damage Equivalent Loads (DEL) with respect to the tower fore-aft mode, the tower fore-aft DEL is computed using another tool provided by NREL, called MCrunch, see Buhl [2008].

A linearized prediction model is used. The model include states representing the rotor speed, ω_r, the tower fore-aft displacement, d_t, the tower fore-aft velocity, the generator torque, T_g, the pitch angle, β and a state representing the dynamic inflow, α_f. Where the two last models the dynamics of the actuators. In addition to these standard states the first order dynamic inflow model from Knudsen and Bak [2013] is included. The controlled inputs are generator torque and pitch references, respectively $T_{g,ref}$ and β_{ref}. The wind speed v_w is an non-controlled model input. The model outputs are the generated power, P, the tower fore-aft velocity v_t and the rotor speed ω_r.

Based on the states, inputs and outputs a linear state space representation of the form below is used.

$$\mathbf{x}(k+1) = \mathbf{A}\cdot\mathbf{x}(k) + \mathbf{B}\cdot\mathbf{u}(k) + \mathbf{E}\cdot\mathbf{d}(k), \quad (1)$$

$$\mathbf{z}(k) = \mathbf{C}\cdot\mathbf{x}(k). \quad (2)$$

Where: A, B, C and E are the linear model matrices.

$\mathbf{x}$ are the states.
$\mathbf{u}$ are the control inputs.
$\mathbf{d}$ is the non-control inputs.
$\mathbf{z}$ are the controlled outputs.

$$\mathbf{u} = [T_{g,ref}\ \ \beta_{ref}]^T, \quad (3)$$

$$d = [v_w], \quad (4)$$

$$\mathbf{x} = [\omega_r\ \ d_t\ \ v_t\ \ T_g\ \ \beta\ \ \alpha_f]^T, \quad (5)$$

$$\mathbf{z} = [P\ \ v_t\ \ \omega_r]^T \quad (6)$$

.

3. MPC DESIGN

As the purpose of this work is to compare MPC of wind turbines with and without dynamic inflow included in the prediction model, the focus has not been on development of the MPC theory and implementation. The solution has been based on the scheme, format and notation described and used in Maciejowski [2002]. A tuning of the implemented MPC is done, with regard to horizon lengths, estimation gain, and weights in the cost function. The goal of this work is not to find the optimal tuning of an MPC. It is to find good tuning parameters for the MPCs (with and without dynamic inflow) that operates well and gives comparable Pareto fronts.

The discrete time design model presented in Sec. 2 is used as the prediction model for the MPC design. The objective function is selected such that the maximum power is obtained while the tower fore-aft movements are minimized. The used objective function is given as.

$$\begin{aligned} V(k) = &\sum_{i=N_w}^{N_p} ||\hat{z}\,(k+i|k) - r\,(k+i|k)\,||^2_{Q(i))} \\ &+ \sum_{i=0}^{N_u-1} ||\Delta\hat{u}\,(k+i|k)\,||^2_{R^{\Delta}(i)} \\ &+ \sum_{i=0}^{N_u-1} ||\hat{u}\,(k+i|k)\,||^2_{R(i)} \end{aligned}$$

Where: $\hat{z}$ denotes the predicted output.
r denotes the reference trajectory.
$\hat{u}$ denotes the control input.
$\Delta\hat{u}$ denotes the changes in the control input.
N_p is the prediction horizon.
N_w is the start of the prediction window.
N_u is the control horizon.

The weights Q, R^{Δ} and R are here respectively weights on the trajectory error, the input rate of change and the input size. By adjusting these weights the controller can be tuned towards a desired performance. N_w is set to 1.

3.1 Constraints

Constraints are used in order to specify acceptable inputs and outputs to the controller. Constraints on the input are here determined from the physical specifications of the system, whereas the output constraints have been determined from a mix of physical limits and design goals. For simplicity the generator power constraint is set at

[1] Available at `http://wind.nrel.gov/public/jjonkman/NRELOffshrBsline5MW`