Model predictive control of a wind turbine modelled in Simpack

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Abstract.

Wind turbines (WT) are steadily growing in size to increase their power production, which also causes increasing loads acting on the turbine’s components. At the same time large structures, such as the blades and the tower get more flexible. To minimize this impact, the classical control loops for keeping the power production in an optimum state are more and more extended by load alleviation strategies. These additional control loops can be unified by a multiple-input multiple-output (MIMO) controller to achieve better balancing of tuning parameters. An example for MIMO control, which has been paid more attention to recently by wind industry, is Model Predictive Control (MPC). In a MPC framework a simplified model of the WT is used to predict its controlled outputs. Based on a user-defined cost function an online optimization calculates the optimal control sequence. Thereby MPC can intrinsically incorporate constraints e.g. of actuators.

Turbine models used for calculation within the MPC are typically simplified. For testing and verification usually multi body simulations, such as FAST, BLADED or FLEX5 are used to model system dynamics, but they are still limited in the number of degrees of freedom (DOF). Detailed information about load distribution (e.g. inside the gearbox) cannot be provided by such models.

In this paper a Model Predictive Controller is presented and tested in a co-simulation with Simpack, a multi body system (MBS) simulation framework used for detailed load analysis. The analysis are performed on the basis of the IME6.0 MBS WT model, described in this paper. It is based on the rotor of the NREL 5MW WT and consists of a detailed representation of the drive train. This takes into account a flexible main shaft and its main bearings with a planetary gearbox, where all components are modelled flexible, as well as a supporting flexible main frame. The wind loads are simulated using the NREL AERODYN v13 code which has been implemented as a routine to Simpack. This modeling approach allows to investigate the nonlinear behavior of wind loads and nonlinear drive train dynamics. Thereby the MPC’s impact on specific loads and effects not covered by standard simulation tools can be assessed and investigated.

Keywords. wind turbine simulation, model predictive control, multi body simulation, MIMO, load alleviation

1. Introduction

The enormous gain in rated power of wind turbines (WT) during the last two decades was mainly enabled by ever growing rotor diameters, which require increasing hub heights. Apart from loads on drive train components growing with higher power in general, the large structures
of the blades and also the tower induce additional loads due to their highly flexible nature. The very low excitation frequencies of the wind loads and the typically low eigenfrequencies of the rotor blades as well as the tower and the supporting machine frame structure lead to interactions between the subcomponents.

The control strategy strongly influences the loads acting on the WT. Thus more attention to research in the field of load alleviation control is spent. Especially with individual pitch control (IPC) being available a lot of attention has been paid to tower bending moment reduction based on IPC, since it can easily be combined with state of the art single-input single-output (SISO) control of WT [1, 2]. It was shown that the load mitigation achieved by using several SISO-control loops can be improved, if advanced multiple-input multiple-output (MIMO) controllers are used to balance load mitigation and power production [3]. Most of these control schemes are tested with FAST, BLADED or FLEX5 and the bending moment reduction is considered as the measure of the controller’s performance. Although these simulation tools are suitable to perform the controller performance analysis, they do not allow for any detailed load analysis e.g. within the drive train. This is because they are not capable of integrating e.g. a full degree of freedom gearbox model and do therefore not allow to investigate load effects which might be compensated by advanced control.

In this paper a Model Predictive Controller (MPC), based on a linear WT control model is presented. It is designed for operation above rated wind speed and aims for tower and blade root bending moment reduction. At the same time power production must not be decreased. This controller is tested and evaluated with SIMPACK, a multi body system (MBS) simulation framework. This allows for simulations comparable to FAST and BLADED, but also to apply sub-models of different accuracy to gain detailed information on specific components. The benefit of such additional information will be investigated for the co-simulation of the MPC implemented in MATLAB/SIMULINK and the MBS model implemented in SIMPACK.

The paper is organized as follows: in section 2 the MBS model built up in SIMPACK is presented. In section 3 a simplified linearized control model for the MPC is introduced. The MPC approach is described in section 4. In section 5 simulation results of MPC using a basic and an extended control model are compared to a baseline control strategy. Conclusions are drawn and an outlook for future works will be given at the end of the paper.

2. MBS-Wind turbine model
The presented work has been carried out on the basis of a multi body simulation (MBS) model of a large wind turbine, namely the IME6.0, that has been modelled in SIMPACK. SIMPACK is
a MBS software system that can be used to model and analyse nonlinear multi body systems in freely definable variable topologies. The integration of flexible structures by a beam or modally reduced finite element (FE) model approach allows the investigation of flexible body deformation [4]. The aim of the IME6.0 is to build up a detailed whole system model framework to investigate the system and particularly the nonlinear drive train dynamics. The IME6.0 has been initially described in [5], the latest approach is presented in [6] and shown in figure 1. It is based on the rotor of the NREL 5MW reference wind turbine [7] and a state of the art WT with a four-point suspension realised by a locating/non locating rotor bearing arrangement and two hydraulic torque supports of the two stages planetary and one spur gear stage gearbox. The development is based on publicly available data as well as data provided by supplier companies. Figure 2 shows the topology of the baseline IME6.0 model with an arrangement such that loads are transferred to the first planetary stage and via the torque support in 6 degrees of freedom (DOF) to the machine frame, while the other stages and the generator are modelled with 1 DOF about the rotational axis. The blades, the drive train components and the supporting machine frame as well as the tower are basically modelled flexible. This allows for detailed investigations of loads and deformation of individual WT components. Nonlinear stiffness characteristics of e.g. the main bearings, gearbox tooth contacts or the gearbox torque support as well as the generator coupling can be taken into account. The variable topology still allows to investigate other WT designs, too. Table 1 summarizes the IME6.0 technical data and table 2 shows the natural frequencies of its main components.

For the work presented, a reduced degrees of freedom model has been used to investigate controller performance. As for typical load calculations, we used a model with 4 modal DOF per blade (2 flapwise and 2 edgewise, derived from a detailed FE model [6]) and 4 modal DOF (2 fore-aft, 2 side-side) for the tower. The detailed drive train model has been substituted by a two-

![Figure 2. Topology of the baseline IME6.0 MBS model](image_url)
mass rotational spring-damper model, where the inertia, stiffness and an approximate damping had been calculated in the detailed model before. The turbine’s foundation is modelled rigid.

Table 1. Technical data of the IME6.0

| technical data IME6.0 |          |
|-----------------------|----------|
| rotor diameter        | 126 m    |
| rotor mass (incl. hub)| ~126 t   |
| nominal rotational speed | 12.1 rpm |
| nominal power         | 6 MW     |
| nacelle mass (wo. rotor) | ~320 t   |
| onshore tower height  | 112 m    |
| onshore tower mass    | ~360 t   |

DFIG generator

| gearbox |          |
|---------|----------|
| 2 planetary | 1 spur |

i_{gearbox} 97.177

Table 2. Natural frequencies of the IME6.0

| component natural frequencies | [Hz] |
|-------------------------------|------|
| rotor                         |      |
| 1. flapwise                   | 0.863|
| 1. edgewise                   | 1.068|
| 2. flapwise                   | 2.612|
| 2. edgewise                   | 3.914|
| tower (incl. top mass)        |      |
| 1. tower fore-aft             | 0.30 |
| 1. tower side-side            | 0.30 |
| 2. tower fore-aft             | 2.37 |
| 2. tower side-side            | 2.40 |
| drive train                   |      |
| 1. torsional                  | 1.35 |

The calculation of the aerodynamic loads is carried out by the AERODYN Code in version 13, which is based on the blade element momentum (BEM) theory and developed and kindly provided by the National Renewable Energy Laboratory (NREL) [8]. It is applied to the model by an own in-house implementation as a user force to SIMPACK. The connection between the aeroelastic-mechanical MBS model and the WT controller modelled in MATLAB/SIMULINK is achieved by the SIMPACK co-simulation interface SIMAT. This interface module allows the exchange of I/O data between the SIMPACK and MATLAB/SIMULINK models in fixed time-steps. The pitch actuators are modelled in MATLAB/SIMULINK by a second order model. To be able to control the blades pitch angles individually, the calculated angles are individually applied as SIMPACK input to a rheonomic joint of each blade. The generator torque is controlled by speed-torque characteristics which try to keep the turbine at an optimal tip speed ratio. The generator dynamics are modelled as first order model.

3. Control model

The wind turbine model used within the MPC framework is a piecewise affine state space model of the IME6.0 described in the former section. It is linearized for a wind speed of 15 m/s. The assumptions made for modeling the aerodynamics, tower, drive train and the actuators generator torque and pitch system are described in detail by Henriksen [9]. His baseline model of 5th order is extended by the 1st order generator model and the pitch actuator model (2nd order). For individual pitch control being relevant throughout this work, the pitch actuator model is defined separately for each blade. Furthermore in the linear control model blades are considered flexible in flap wise direction, which accounts for another two states per blade. Altogether this results in a state vector x with 18 states, defined in table 3. Since flexible blades and their coupling with the rest of the model dynamics are not included in [9], this sub-model is introduced below.

In the linear control model the blades are considered flexible in flap-wise direction, so that mechanical coupling mainly concerns the fore-aft tower dynamics. As figure 3 shows, the tower motion is simplified to a pure translational movement. The blades $i \in 1..3$ are coupled with the tower mass $M_T$ via a spring damper system with stiffness $c_b$ and damping $d_b$ equal for all blades. On each blade $i$ the thrust force $Q_{t,i}$ acts. The force is derived from a characteristic grid and is
Table 3. States

| state | description |
|-------|-------------|
| $\omega_R$ | rotation speed (lss) |
| $\omega_G$ | rotation speed (hss) |
| $\Delta \Phi$ | torsional angle |
| $x_t$ | tower top position |
| $\dot{x}_t$ | tower top velocity |
| $\theta_{1..3}$ | pitch angle for blade 1..3 |
| $\dot{\theta}_{1..3}$ | pitch angle velocity for blade 1..3 |
| $Q_G$ | generator torque |
| $\phi_{1..3}$ | blade angle flap wise |
| $\dot{\phi}_{1..3}$ | blade angle velocity flap wise |

a non-linear function of rotation speed $\Omega_R$, the blade’s pitch angle $\Theta_i$, and the blade effective wind speed $v_{eff,i}$. All those arguments are, or depend on states of $x$. For a given operation point $O(\Omega_{R0}, \Theta_0, v_{eff0})$ the thrust force can be linearized such that

$$Q_{t,i} = Q_{t0,i} + \frac{\partial Q_t}{\partial \Omega_R} \bigg|_{\Omega_{R0}} \cdot \Delta \Omega_R + \frac{\partial Q_t}{\partial \Theta_i} \bigg|_{\Theta_0} \cdot \Delta \Theta_i + \frac{\partial Q_t}{\partial v_{eff}} \bigg|_{v_{eff0}} \cdot \Delta v_{eff,i}$$

(1)

holds. Different from the notation in [9], here $Q_{t0}$ represents the force at a single blade only. Furthermore the effective wind speed $v_{eff,i}$ depends on the individual blade movement $\dot{\phi}_i$ (See equation (4)). The translational coupling of the blades with the tower can be described by

$$\sum_{i=1}^{3} (Q_{t,i} - M_b R_s \ddot{x}_t) = M_t \ddot{x}_t + d_t \dot{x}_t + c_t x_t.$$  

(2)

With the thrust force $Q_{t,i}$ as aerodynamic input and the counteracting inertial force of the concentrated mass $M_b$ of the blade positioned at a distance of $R_s$ on the left side of the equation. Those forces act on the spring damper system, with stiffness $c_t$ and damping $d_t$, which the tower mass $M_t$ is connected with. The torque balance for one blade can be formulated as

$$Q_{t,i} R_d - M_b R_s \ddot{x}_t = I_b \ddot{\phi}_i + d_b \dot{\phi}_i + c_b \phi_i$$

(3)

with the thrust force $Q_{t,i}$ scaled by the lever $R_d$ being the moment caused by the aerodynamics and the mass $M_b$ of the blade $i$ concentrated at the distance $R_s$. The right side of the equation represents the spring-damper system with stiffness $c_b$ and $d_b$ which couples the blade and the tower. Due to the flap-wise movement of each blade, the effective wind speed $v_{eff,i}$ of such is

$$v_{eff,i} = v_{wind} + \dot{x}_t + R_d \dot{\phi}_i.$$  

(4)

The model inputs $u$ are the desired generator torque $Q_{G-ref}$ and pitch angles $\theta_{1..3-ref}$ for each blade.

$$u^T = \begin{pmatrix} \theta_{1..3-ref} \\ Q_{G-ref} \end{pmatrix}$$

(5)
4. Model predictive control

In the Model Predictive Controller the linearized WT-model introduced in section 3 is used to predict the controlled variables of the system. An optimal control sequence

$$\Delta U^* = \Delta U^*_{(k|k)} \ldots \Delta U^*_{(k+H_P-1|k)} .$$

is computed for the prediction horizon $H_P$. For $k \in 1, 2, \ldots$ being the discrete time step, $(\cdot)_{(k+j|k)}$ denotes the prediction of the variable $(\cdot)$ for the time step $k + j$ based on $k$. The control signal $U(k)$ of the controller is $U(k) = U(k-1) + \Delta U^*_{(k|k)}$.

The control model is discretized in time so that it is of the form

$$X(k+1) = A^k \cdot X(k) + B^k \cdot U(k)$$

$$Y(k) = C^k \cdot X(k).$$

Hereby, $X \in \mathbb{R}^n$ denotes the discrete state vector. $A^k, B^k, C^k$, are constant matrices describing the turbine model at time instant $k$. The coefficients of the matrices’ entries correspond directly to the coefficients of the differential equations derived in [9] combined with the equations (1)-(4). The wind speed is only used for linearization at the operation point but not made available to the controller during operation. States and inputs of the control model were introduced in section 3. The controlled outputs are

$$Y = \left( \omega_g, \dot{x}_t, \dot{\phi}_1, \dot{\phi}_2, \dot{\phi}_3, \theta_1 - \theta_2, \theta_2 - \theta_3 \right)^T .$$

In the scenarios simulated in full-load region the generator torque is set constant and only pitch angles are used as control inputs. In order to keep the output power constant the rotational speed $\omega_g$ is to be maintained at rated speed $\omega_{\text{rated}}$ and is therefore of highest priority for the control. Additionally the controller aims to keep tower top velocity $\dot{x}_t$ and blade velocities $\dot{\phi}_{1,2,3}$ zero for the sake of load reduction. Due to linearization, the pitch angles $\theta = (0, 0, 0)$
have the same impact as for instance $\theta = (12, -2, -10)$, which is obviously incorrect. Therefore differences $\theta_1 - \theta_2$ and $\theta_2 - \theta_3$ of the pitch angles are penalized, which shows the desired positive effect in the simulation results.

The optimization is conducted with respect to the quadratic cost function

$$ J = \sum_{j=0}^{H_u-1} \lambda (\Delta U_{(k+j)|k}^T \cdot R \cdot \Delta U_{(k+j)|k}) $$

$$ + \sum_{j=1}^{H_p} \left[ (Y_{(k+j)|k} - Y_{ref})^T Q (Y_{(k+j)|k} - Y_{ref}) \right] $$

subject to

$$ X_{(k+j+1)|k} = A^k \cdot X_{(k+j)|k} + B^k \cdot U_{(k+j)|k} \quad , \quad j = 0, \ldots, H_p - 1 $$

$$ Y_{(k+j)|k} = C \cdot X_{(k+j)|k} \quad , \quad j = 1, \ldots, H_p $$

$$ U_{Min} \leq U_{(k+j)|k} \leq U_{Max} \quad , \quad j = 0, \ldots, H_u - 1 \quad . $$

$H_u$ denotes the length of the control horizon. The weighting matrices $R$ and $Q$ are used to penalize changes $\Delta U$ in the actuator signals as well as deviations from the reference trajectory $Y_{ref}$. The chosen formulation of the MPC is similar to a MPC implementation presented by Albin et.al.[10].

Since the controlled as well as the control variables are weighted differently among themselves due to different prioritization, the weighting matrices $Q$ and $R$ cannot be chosen as identity matrices. For weighting of control variables relative to controlled variables the tuning parameter $\lambda$ can be used [11]. $U_{Min}$ and $U_{Max}$ are constraints on the absolute value of the controller outputs $U(k)$, such as maximum pitch angle and generator torque.

Since this work focuses on the assessment of potential benefit of MPC and the co-simulation of MATLAB/SIMULINK and SIMPACK, it is assumed, that all states $X(k)$ of the model are known, so that no state estimation is necessary. Although this does not allow for practical application, it does allow for estimation of load reduction potential. A simplified block diagram of the whole setup including the MPC with all its variables and the SIMPACK model is shown in figure 4.

5. Results

The results shown are calculated with the SIMPACK MBS model presented and the following three different control strategies: (1) Baseline proportional-integral (PI) control of generator speed using collective pitch angles as control variable, (2) MPC with the basic control model, (3) MPC with the extended control model, taking into account the simplified blade dynamics.

The simulations are calculated for a time duration of 600 s each. Only the last 400 s of the simulation data is used for load reduction analysis, hence only this part of the simulation results is plotted throughout this section. All simulations are carried out with a full-field wind file computed with TURB SIM [12]. Wind characteristics are chosen according to IEC61400 Ina. The hub height wind speed is shown in figure 5 a). The rotor rotational speed for all three controller scenarios is shown in figure 5 b), showing the typical variations due to the incoming wind. The difference in speed among the three implementations is negligibly small. The controllers are tuned, such that the generator torque is kept nearly constant during simulation which leads to a generator output power as illustrated in figure 5 c).

The different effects of the three controllers reveals if tower and blade root bending moments are considered (figure 6 and 7). Figure 6 a) shows the resulting tower root bending moments. The FFT of such, shown in figure 6 b) illustrate the influence the control strategy has on the
loads. As the controller in configuration (1) does not contain any load alleviation strategy, the excitation of the first tower fore-aft mode at 0.3 Hz is the highest, compared to configuration (2) and (3), which both actively control the tower motion. The MPC of (2) is tuned with a significant weight on the tower motion, so that tower excitation can be reduced by approximately 70% compared to (1). As a side effect additional undesired excitations at 0.21 Hz and 0.55 Hz are observed. In comparison the MPC in configuration (3) is tuned more moderately with respect to tower motion. Thereby the tower excitation at 0.3 Hz is reduced by approximately 37%, without significant additional excitation of other frequencies. It is clear, if the MPC in configuration (2) is tuned differently, it is in principle capable of performing just as well as (3), with respect to tower motion.

The real advantage of the MPC of configuration (3) can be observed when the blade root bending moments are considered. Figure 7 a) shows exemplary the root bending moment of blade 1. The FFT of such in figure 7 b) clearly shows, that the MPC of configuration (3) reduces oscillations at the 1-P frequency significantly, by about 27%, simply by taking into account this additional DOF in the control model. Other than (3), (1) and (2) are not designed to be capable of any load alleviation of periodic loads acting on the blades.

6. Conclusion and future work
In this paper, a MPC using an extended control model has been used to control a large 6 MW wind turbine modelled in the MBS framework Simpack at full load operation. The simulations
The results of the MPC controller have been compared with a baseline PI controller and a MPC with a standard model approach. The Results presented show, that the MPC with standard model, only taking into account drive train and tower dynamics, can reduce tower bending moments by up to 70% compared to a baseline PI control. Of course this result was only achieved on the expense of additional frequencies being excited and cannot be used to quantify load reduction to expect in a real world application. Without exciting additional frequencies, the tower bending moment can be reduced by at least 37%. When the MPC uses the extended WT model, also taking into account the blade dynamics, also the 1P-frequency excitation of the blades can be

**Figure 6.** Tower bending moments and FFT for configuration (1), (2) and (3)

**Figure 7.** Blade root bending moments and FFT for configurations (1), (2) and (3)
reduced by over 27% in the wind fields simulated. Still it has to be further discussed in which way the load reduction operation influences the power production.

At the moment the MPC control scheme only uses one linear model for the whole full load region. Although the controller already performs well, online linearization at each time-step will be investigated in future work, in order to improve prediction accuracy. Furthermore, the model states need to be estimated in future work to allow for practical implementation. Thereby it has to be proven that results are comparable for estimated states. In this first approach wind speed was only used for linearization, but was not available to the controller. In future work wind information based on estimation strategies as discussed e.g. in [13, 14, 15, 16], will be made available to the controller to further improve performance.

For the presented work a reduced model of the IME6.0 MBS model has been used. In future the detailed model as presented in section 2 will be used to further investigate load effects on individual drive train components induced by different control approaches.

**Supplementary data**

If you are interested in using the MBS model for your own research on drive train dynamics you are invited to ask for the CAE data of the IME6.0 wind turbine via email to berroth@ime.rwth-aachen.de. We provide CAD and finite element data of the flexible bodies as well as gear geometries.

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