Model Based Active Power Control of a Wind Turbine

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Abstract—In recent decades there has been increasing interest in green energies, of which wind energy is one of the most important. Wind turbines are the most common wind energy conversion systems (WECS) and are hoped to be able to compete with traditional power plants in future. This demands better technology to increase competitiveness of wind power plants. One way to increase competitiveness of wind power plants is to offer grid services (also called ancillary services) that are normally offered by traditional power plants. One of the ancillary services is called reserve power. There are instants in the electricity market that selling the reserve power is more profitable than producing with the full capacity. Therefore wind turbines can be down-regulated and sell the differential capacity as the reserve power. In this paper we suggest a model based approach to control wind turbines for active power reference tracking. We use model predictive control (MPC) as our control method. We compare three different control strategies, namely Max-Ω, Constant-Ω and Constant-λ and discuss their drawbacks and benefits by presenting analysis of the steady state operating points and simulations on a high fidelity wind turbine model.

I. INTRODUCTION

In recent decades there has been increasing interest in green energies, of which wind energy is one of the most important. Wind turbines are the most common wind energy conversion systems (WECS) and are hoped to be able to compete with fossil fuel power plants on energy price in near future. This demands better technology to reduce the electricity production price. The production price can be reduced by maximizing the generated power and minimizing dynamic loads and subsequently increasing life span of the turbines. It seems possible to increase competitiveness of wind power plants by offering grid services (also called ancillary services) and enter wind power plants into the ancillary market [1]. This will result in better incentives for power plant owners to employ wind turbines even more. Besides, in some countries such as Denmark and Ireland as the penetration of the wind energy in the utility grid is increasing, participation of wind turbines and wind farms in the ancillary services for power grid stability has become inevitable [2]. The ancillary services are normally provided by traditional power plants, however with proper controller design wind power plants can also contribute to the ancillary services [1]. The special nature of wind turbines enables them to provide some of the services for grid stability even better than the traditional power plants. For example due to the nature of the wind turbines, their power can be ramped up quickly. Besides because of the big inertia in the rotor of the turbine, if designed properly, they can provide inertial response to the grid [3]. For a survey on frequency and voltage control and information on inertial responses see [4]. One of the ancillary services is called reserve power. There are instants in the electricity market that selling the reserve power is more profitable than producing with the full capacity. Therefore wind turbines can be down regulated and sell the differential capacity as the reserve power. In order to provide power reference tracking and down-regulation services, new challenges in the wind turbine control arises. The interested readers are referred to [3] for a tutorial on wind turbine control for supporting grid stability. In [5] and [6] the authors suggest methods for power reference tracking. In this paper we will discuss a model based down regulation approach based on different wind turbine control strategies. Down regulating or de-rating a wind turbine in the full load region is straightforward. For down regulation in this region, it is sufficient to modify the generated power set point and keep the the rotational speed set point at its rated value. This strategy is the industry standard. However this will result in a rough transition between the partial load and the full load, especially when the wind speed increases or decreases rapidly [5]. These transitions subsequently increase the dynamic loads on the turbine. Another strategy to down regulate a wind turbine is to change both the rotational speed and the generated power set points. We will show that the latter makes a smooth transition from the partial load to the full load region, however we will also show that it will result in a poor performance which makes the strategy inferior to the first strategy. In this paper we also suggest a third strategy which keeps the benefits of the former strategy and provides a smoother transition between the full load and the partial load. The control strategy determines steady state operating points of a wind turbine as functions of wind speed. Different control methods (e.g. model predictive control, LQG or PI) could be used to implement the control strategies.

There are several methods of wind turbine control, ranging from classical control methods, [7] which are the most commonly used methods in real applications, to advanced control methods, which have been the focus of research in the past few years [8]. Advanced model-based control methods are thought to be the future of wind turbine control, as they
can conveniently employ new generations of sensors on wind turbines, e.g. LIDAR [9], new generation of actuators, e.g. trailing edge flaps [10], provide a framework for defining conflicting objectives of wind turbine control and they also treat the turbine as a MIMO system. Model predictive control (MPC) has proved to be an effective tool to deal with multivariable constrained control problems [11]. As wind turbines are MIMO systems [12] with constraints on inputs and outputs, using MPC seems to be effective. In this paper we employ MPC to implement the different control strategies. The outline of the paper is as follows: We will start by explaining the control method and objectives in II. Section III presents control strategies for controlling active power of wind turbines. We will discuss three different down regulation control strategies. Steady state operating points of the different strategies will be presented and compared. In section IV performance of the controller based on different strategies will be compared. And in V we will discuss the results.

II. CONTROLLER DESIGN

In this section we begin by introducing model predictive control briefly and afterward the wind turbine control objectives are explained. The controller designed in this section will be used in section III to implement the suggested control strategies.

A. Model Predictive Control

MPC is based on an iterative finite horizon optimization of a cost function subject to plant dynamics and constraints [13]. The basic idea is to use the current measurement or estimate of the state of the plant $x_k$, solve a finite horizon optimization problem, find a sequence of inputs $u_0, u_1, \ldots, u_{N-1}$, apply the first element of the sequence and repeat the procedure again. The optimization problem of a linear MPC could be formulated as:

$$
\min_{u_0, u_1, \ldots, u_{N-1}} \| x_N \| Q_f + \sum_{i=0}^{N-1} \| x_{k+i} \| Q + \| u_{k+i} \| R
$$  \hspace{1cm} (1)

Subject to 
$$
x_{k+1} = Ax_k + Bu_k \hspace{1cm} (2)$$
$$
u_{k+i} \in \mathbb{U} \hspace{1cm} (3)$$
$$
x_{k+i} \in \mathbb{X} \hspace{1cm} (4)$$

in which $A$ and $B$ are state space matrices, $x_k$ and $u_k$ are the state and input of the system at instant $k$, $N$ is the prediction horizon, $Q_f$ is the weight on the terminal cost, and $Q$ and $R$ are the weights on state and input deviations respectively. Assuming that we use norms 1, 2 and $\infty$, the optimization problem becomes convex providing that the sets $\mathbb{U}$ and $\mathbb{X}$, admissible input and state sets, are convex. Convexity of the optimization problem makes it tractable and guarantees that the solution is the global optimum. More details on the control method can be found in [14].

B. Control objectives

The most basic control objective of a wind turbine is to maximize captured power and minimize loads in order to increase the life time of the wind turbine. This means producing electricity as close to the rated value as possible and reducing fatigue loads in order to increase the lifetime of the turbine. To achieve these objectives wind turbine operations can be divided into two basic regions, the partial load region and the full load region. In the partial load region, the objective is to maximize captured power when the wind speed is not high enough to produce the demanded power. This is also called maximum power point tracking (MPPT). However in the full load region in which wind speed is above rated, the control objective becomes regulation of the outputs around the steady state values determined by the control strategies while trying to minimize dynamic loads on the structure. These objectives should be achieved against fluctuations in wind speed which act as a disturbance to the system.

III. CONTROL STRATEGIES

Control strategy of a wind turbine determines its steady state operating points and the conditions of its transition from the partial load region to the full load region. More specifically by control strategy we mean choosing appropriate steady state values for the rotational speed of the rotor and the generated power as a function of wind speed. This subsequently determines steady state values for the pitch of the blades and the reaction torque of the generator. The choice of the control strategy has a big influence on the operation of the turbine because as we will see in the next section, it determines the position of the operating points on the $C_p$ curve as a function of wind speed. Therefore it can determine the operating region of the turbine with respect to the stall region and also change the dynamics of the turbine. The method of switching from the partial load region to the full load region is also part of the control strategy and this has a big influence on the transient loads on the turbine around the rated wind speed where the turbine experiences the biggest loads. In this section we will explain the different down regulation control strategies.

A. Control strategies for down regulation

In the nominal operation of a multi-megawatt wind turbine, normally the rated rotational speed is reached with before the rated power and therefore there is a region where the rotational speed is constant and we can maximize the generated power. However when down regulating a wind turbine, below a certain ratio, the demanded power $P_d$ is reached for wind speed $v_d$ at a rotational speed $\omega_d$ before we reach the rated rotational speed $\omega_{rated}$ ($\omega_d < \omega_{rated}$). At this stage, one control objective for wind speeds bigger than $v_d$ can be defined to keep the generated power constant at $P_d$. However there is a degree of freedom on how to choose the set point of the rotational speed. When we reach the demanded power, we no longer stay on the maximum value of the $C_p$ curve and we have to descend from this point by choosing appropriate blade pitch $\theta$ and/or tip speed ratio (TSR) $\lambda = R \omega / v_c$. The different methods on how to change the rotational speed as a function of the wind speed and
how to descend the $C_p$ curve determines the three different down regulation strategies we present here. Therefore the different control strategies are the same for wind speeds below $v_d$. After descending from the maximum point, for each wind speed, the turbine should move to a specific $C_p$ value which is calculated as $P_d/P_w(v_e)$ value. $P_w(v_e)$ is the total available power on the rotor disc for wind speed $v_e$. This means for each wind speed there is a level curve on the $C_p$ surface that satisfies the demanded power. See for example figure 1 in which contour curve of $C_p = 0.4$ is plotted. Different control strategies in this paper are actually different methods to choose the blade pitch and the tip speed ratio on this level curve.

1) Maximizing the rotational speed (Max-$\Omega$): In this control strategy after reaching $P_d$, we solve the following optimization problem:

maximize $\omega(\lambda, \theta)$
subject to $\omega \leq \omega_{\text{rated}}$
$\omega \geq \omega_{\text{min}}$
$C_p(\lambda, \theta) = P_d/P_w$

This means that the rotational speed of the turbine is maximized for each wind speed and it is bounded by the rated rotational speed. When we reach the rated rotational speed $\lambda$ and $\theta$ are found uniquely. In figure 2 the red curve with square markers shows the steady state points of the tip speed ratio and the blade pitch for different wind speeds and demanded power of 0.5MW. In practice we might never down regulate a wind turbine to 10% of its capacity, however we have chosen this value only for demonstration purposes.

2) Constant rotational speed (Constant-$\Omega$): In this control strategy we keep the rotational speed constant after we have reached $P_d$. Therefore $\lambda$ becomes a unique function of wind speed as $\lambda(v_e) = R\omega_{\text{rated}}/v_e$. Having the $\lambda(v_e)$, we can find the pitch of the blade on the contour curve of figure 1. Normally two values for the pitch is found, one in the normal operating side of the $C_p$ curve, which we choose and one in the stall region. In figure 2 the blue curve with triangle markers shows the steady state points of the tip speed ratio and the blade pitch of this strategy for different wind speeds.

3) Constant tip speed ratio (Constant-$\lambda$): In this control strategy we keep the tip speed ratio constant after we have reached $P_d$ at $\lambda = \lambda_{\text{max}}$. Therefore $\lambda$ becomes a unique function of wind speed as $\lambda(v_e) = R\omega_{\text{rated}}/v_e$. Having the $\lambda(v_e)$, we can find the pitch of the blade on the contour curve of figure 1. Normally two values for the pitch is found, one in the normal operating side of the $C_p$ curve, which we choose and one in the stall region. In figure 2 the blue curve with triangle markers shows the steady state points of the tip speed ratio and the blade pitch of this strategy for different wind speeds.

B. Comparison of the three control strategies

In this section we compare steady state values for Max-$\Omega$ and Constant-$\Omega$ strategies for down regulating a wind turbine to 10% of its production capacity. As mentioned earlier
Fig. 5: Steady state values of the blade pitch as a function of the wind speed for the different strategies. Red-squares is the maximum \( \omega \) strategy, green-circles is the constant \( \lambda \) strategy and blue-plus is the constant \( \omega \) strategy.

Fig. 6: Aerodynamic gain from pitch to the power, \( \partial P/\partial \theta \), as a function of the wind speed for different strategies. Red-squares is the maximum \( \omega \) strategy, green-circles is the constant \( \lambda \) strategy and blue-plus is the constant \( \omega \) strategy.

this value of down regulation is chosen for demonstration purposes only and we might never down regulate a turbine to this value. As it could be seen in figure 3, after reaching \( v_d = 7 \text{m/s} \) where the wind turbine starts to produce its demanded power \( (P_d) \), the rotational speed for the Constant-\( \Omega \) strategy is kept constant. This will make a smooth transition between the partial load and the full load regions. This also means a smooth curve for the steady state values of the generator reaction torque (see figure 4). On the contrary, for the Max-\( \Omega \) strategy, as wind speed reaches \( v_d = 7 \text{m/s} \), the steady state rotational speed (as a function of wind speed) increases with a sharp slope, figure 3. This also means that in order to produce a constant power (in the full load region), the generator reaction torque should decrease sharply as wind speed increases, figure 4. The rapid changes in the rotational speed and generator torque over a small interval of the wind speed result in a rough transition between the two regions which increase transition loads on the turbine. On the other hand, the Max-\( \Omega \) strategy operates the wind turbine farther from the stall region than the Constant-\( \Omega \) strategy, see figure 2, and consequently decreases the risk of going into stall by extreme operating gusts. Besides, the bigger inertia in the rotor of Max-\( \Omega \) strategy can be used to provide inertial response for the grid. After the inertial response when we extract kinetic energy and slow down the turbine, we are actually ascending the \( C_p \) curve and therefore the turbine will produce more power to participate in the primary response. While for the Constant-\( \Omega \) case the rotational speed decreases for inertial response there is a high chance that the turbine goes into the stall region.

Another way to compare the two aforementioned strategies is to compare their resulting dynamical models. As it is seen in figure 6, the aerodynamic gain from pitch to the power for the two strategies are different and it is less for the Constant-\( \Omega \) strategy. This means for achieving the same power regulation, higher pitch activities are needed for this strategy. In section IV the two strategies are implemented on a wind turbine and simulations are given to show the performance of the controllers based on the two strategies. Besides the aforementioned strategies, another strategy is to keep the \( \lambda \) constant. This means we do not have rapid acceleration and deceleration of the rotor when wind speed is around \( v_d \). Besides the characteristics of this strategy (green with circle marker curves in figures 3-6) are very similar to the Max-\( \Omega \) which is favorable except around \( v_d \) where the transition between the full load and the partial load occurs. As it can be seen in the figures 3 and 4 the steady state values for the rotational speed and the generator reaction torque of the Constant-\( \lambda \) gives a smoother transition than the Max-\( \Omega \) approach. As it is seen in figures 2 and 5 the steady state values for the two Constant-\( \lambda \) and Max-\( \Omega \) strategies are the same when wind speed reaches the rated value, it is because when wind speed reaches the rated value these two strategies are exactly the same and their difference is in the transition from \( v_d \) to \( v_{\text{rated}} \) where the Constant-\( \lambda \) gives a smoother transition.

**IV. Simulations**

In this section simulation results for comparing Max-\( \Omega \) and Constant-\( \Omega \) strategies are presented. Constant-\( \lambda \) strategy gives the same results as the Max-\( \Omega \) strategy except for wind speeds in the interval of \([v_d, v_{\text{rated}}]\), and since the simulations presented in this paper are only for wind speeds in the full load region, the results for Constant-\( \lambda \) is not given. The controllers are implemented in MATLAB® and are tested on a full complexity FAST [15] model of the reference wind turbine [16]. The tuning matrices are taken to be \( Q = \text{diag}([13.75 \ 51.00 \ 0.0155 \ 0.4950 \ 23.51]) \) and \( R = \text{diag}([0.1 \ 200]) \). Other simulation numeric are given in table I. Simulation results are shown for two scenarios, one with step change in the demanded power and one stochastic hub height wind speed. The stochastic wind scenarios is taken from the IEC standard [17].

**A. Step change in the demanded power**

In this simulation scenario the wind speed is kept constant at \( v_e = 15 \text{m/s} \) and the demanded power is \( P_d = 2.5 \text{MW} \). At \( t = 50s \) there is a step in the demanded power to \( P_d = 4 \text{MW} \)

**TABLE I: Parameters of the model predictive controller**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction horizon</td>
<td>40</td>
</tr>
<tr>
<td>Pitch limits</td>
<td>[-5°, 90°]</td>
</tr>
<tr>
<td>Pitch rate limits</td>
<td>±8°/s</td>
</tr>
<tr>
<td>Generator torque limit</td>
<td>15kN.m/s</td>
</tr>
</tbody>
</table>
and at $t = 100s$ the demanded power is set to $P_d = 2.5\text{MW}$ again. Figures 7-11 compares performance of the controller for Max-$\Omega$ and Constant-$\Omega$ strategies. As it can be seen, the performance of the controlled system is better for the Max-$\Omega$ strategy. Figure 12 shows the operating points on the $C_p$ curve for the two strategies. It is evident that with the Constant-$\Omega$ strategy the wind turbine goes into the stall region (the area below the green with asterisks marker line) and this explains the poor performance of the controller.

B. Stochastic wind speed

In this simulation scenario performance of the control systems are compared for hub height stochastic wind speed produced by TurbSim [18] based on the IEC61400-1 Standard [17]. Table II gives a comparison of the performance based on different measures. As it is seen in the table, standard deviations of the rotational speed and the generated power of the Max-$\Omega$ strategy are less than those of Constant-$\Omega$ while pitch travel and drivetrain DEL (damage equivalent load) and tower base DEL are less. This means that in every aspect the Max-$\Omega$ strategy performs better than the Constant-$\Omega$ strategy. However as $t$ was mentioned earlier Constant-$\Omega$ strategy has a smoother transition between the full load and the partial load and therefore performs better in that region.

V. DISCUSSION

In section III-A we outlined three different control strategies and in III-B we gave a comparison among them. As we mentioned, Max-$\Omega$ strategy gives steady state points which are the farthest from the stall region and also the fact that the rotational speed is at its rated value is favorable for inertial response. Besides if the rotational speed decreases because of losing kinetic energy for the inertial response, basically the turbine ascends the $C_p$ curve and produces more power for the primary response. However when it comes to transition between the partial load region and the full load region, the Constant-$\Omega$ gives a smoother transition. One way
to combine these two favorable features, good performance in the full load region and smooth transition, we suggest the Constant- strategy. As it is seen in figure 2 this strategy is taking a path for descending the maximum $C_p$ curve between the Max-$\Omega$ and Constant-$\Omega$ strategies curves. This approach can be refined even better by defining $\lambda$ as a function of wind speed and therefore reaching the rated rotational speed for smaller wind speeds than the rated (for low turbulence weather regimes) or larger wind speed values (for high turbulence weather regimes).

**REFERENCES**


