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Active Power Control of Waked Wind Farms ⋆

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Abstract: Active power control can be used to balance the total power generated by wind farms with the power consumed on the electricity grid. With the increasing penetration levels of wind energy, there is an increasing need for this ancillary service. In this paper, we show that the tracking of a certain power reference signal provided by the transmission system operator can be significantly improved by using feedback control at the wind farm level. We propose a simple feedback control law that significantly improves the tracking behavior of the total power output of the farm, resulting in higher performance scores. The effectiveness of the proposed feedback controller is demonstrated using high-fidelity computational fluid dynamics simulations of a small wind farm.

Keywords: Wind farm control, control of renewable energy resources, analysis and control in deregulated power systems, control system design, wind energy

1. INTRODUCTION

Wind energy is expected to be the largest European source of energy by 2030 and is therefore largely responsible for enabling Europe to achieve its goal of having at least 27% of its electrical energy generated by renewable sources [Pineda, 2015]. However, the present high costs of offshore wind energy inhibit further deployment of large-scale offshore wind power plants. The uncertainty of the power output of a wind farm also adds to utility grid power balancing costs. This uncertainty is caused by, among other factors, the variability of the wind flow within a wind farm [van Kuik et al., 2016]. Nonetheless, with an increased understanding of flow dynamics, better forecasts can be made of the available wind power in a farm and in combination with control strategies, wind farms should even be able to provide grid balancing services [Boersma et al., 2017]. With ever-increasing penetration levels of wind energy, there will be a need for this ancillary service.

Using active control to balance the total power generated with the power consumed on the grid is called active power control (APC). There are several types of APC [Aho et al., 2013]. In this paper, we focus on automatic generation control (AGC), or frequency regulation, in which the wind farm should track a power reference signal provided by the transmission system operator (TSO). This typically means that a certain power reserve should be present with respect to the available power within a wind farm. An implementation of a single-turbine controller capable of providing power reserve and AGC response is given in Aho et al. [2013, 2016].

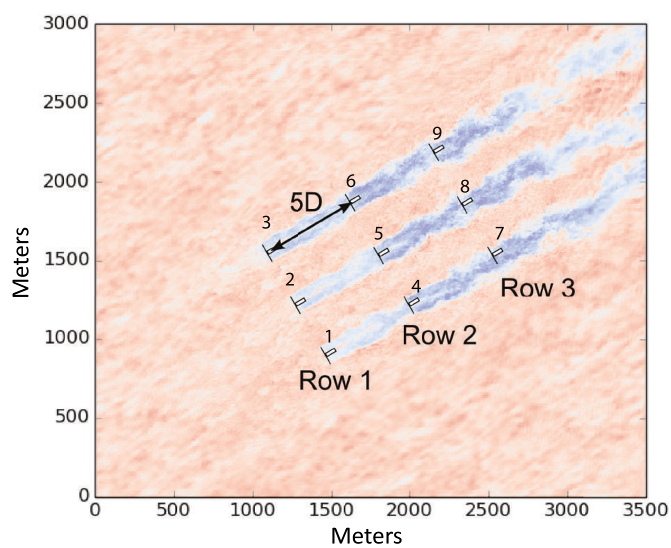

Fig. 1. Layout of the simulated 3-by-3 wind farm. Background is an instantaneous horizontal slice of flow output taken from a Simulator fOr Wind Farm Applications (SOWFA) simulation for the "high-waking" situation. Turbine rows and individual turbine numbers are indicated.

Fleming et al. [2016] present an initial computational fluid dynamics (CFD) simulation study of AGC being provided at a wind farm level. In that paper, the turbines are coordinated through an open-loop supervisory controller that evenly derates the turbines and evenly distributes the power set point requirements to the individual turbines. The goal of the control problem is to track an AGC signal that can specify an increase

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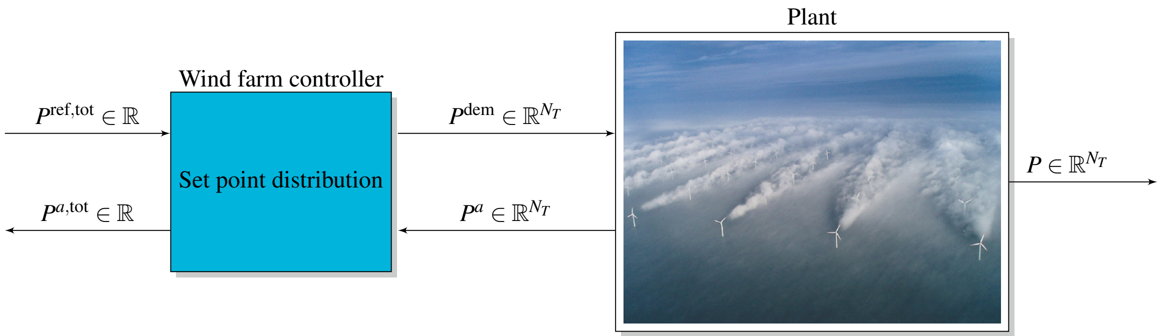

Fig. 2. General overview of the wind farm controller (includes photograph of the Horns Rev 1 offshore wind farm, Christian Steiness).

and/or decrease relative to the nominal de-rated power. Each individual turbine has its own local feedback controller to track its own power reference set point. To track an increasing power reference, it is necessary to have enough power in reserve. If all turbines are de-rated equally, this requires de-rating to a level such that all the turbines have enough wind power in reserve.

Two cases were evaluated in Fleming et al. [2016] for a 3-by-3 wind farm (as shown in Fig. 1 for the "high-waking" case). In the first "low-waking" case, the wind direction was chosen such that the amount of turbine-to-turbine waking was very limited. In the second "high-waking" case, the wake interaction was strong. In that paper, each turbine is de-rated to the same level and is tasked with individually providing one-ninth of the required AGC response.

In the "low-waking" case, this approach yielded very good wind farm power tracking performance. As discussed in Aho et al. [2016], individual turbines are capable of good AGC responses if enough wind is available, and further, the "low-waking" results demonstrate that the aggregate wind farm power is better than any individual turbine in terms of grid performance scores. However, we do note that the performance could be further improved. The turbulent flow includes lulls occurring spatially that cause durations of low power on some turbines, which could be compensated for if other turbines responded to this situation.

In the "high-waking" case, this open-loop approach of even de-rating and power set point distribution was found to be unacceptable. It is difficult to choose an appropriate uniform open-loop reserve level for the entire farm, such that each turbine can meet its power reference because of the turbine-to-turbine interaction through wakes. Feedback control at the wind farm level could significantly improve the wind farm power tracking performance by effectively changing the individual turbine power set points to address wind lulls that may occur in one part of the farm.

Recent papers that have proposed feedback to optimize the local set points have assumed that the individual turbines have enough available power to track their set point [Madjidian, 2016, Hansen et al., 2006, Spudic et al., 2010]. In this paper, we consider the "high-waking" case, wherein on average there is enough available power to track the set point. However, as a result of local effects, some individual turbines fail to follow their set points. It is evident from Fleming et al. [2016] that two problems need to be solved to deliver a quality AGC response in the "high-waking" case. The first is set point selection and the distribution thereof, and the second is the design of a wind farm feedback controller that can appropriately adjust the turbine set points to address underperformance (due to lulls) that may be occurring at some turbines. The main contribution of this paper is a simple feedback controller that leads to good wind farm power tracking performance in "high-waking" scenarios for different distributions of the AGC set point.

The outline of this paper is as follows. Set point selection is discussed in Section 2, and a simple wind farm feedback controller is presented in Section 3. In Section 4, CFD simulation results in a "high-waking" scenario show that feedback can significantly improve the wind farm power tracking performance. The paper is concluded in Section 5.

2. SET POINT SELECTION

As stated in the introduction, in order to have the total power output of the wind farm follow a demanded trajectory, an overall wind farm controller must coordinate the power set points of the individual turbines such that their power production sums to the desired amount. The coordination is made complicated when the turbines interact through wake losses.

Given the wind direction and speed, a set point selection algorithm must

(1) estimate the total power available now and in the immediate future,
(2) from this, determine the plant-wide power reserve level needed to provide AGC reliably well, and
(3) determine the optimal collection of set points to distribute to the individual turbines.

These steps most likely must be done through reference to a continuously updated wake model. This process is the subject of the EU PossPow project [Bozkurt et al., 2014].

Choosing the optimal collection of set points is a challenge, as the interaction between wake models and changes in power set points / axial induction is still active research (see Annoni et al. [2016], and Vali et al. [2016]). In Fig. 2, a simple (ideal) wind farm control architecture is presented that is used by many others (e.g., Madjidian [2016], Hansen et al. [2006], Spudic et al. [2010]). The wind farm controller receives the power generation command in combination with the AGC command from the TSO, also denoted as the overall power reference, $P^{\text{ref,tot}} \in \mathbb{R}$, while the wind farm controller communicates back a predicted available power, $P^{a,\text{tot}} \in \mathbb{R}$, of the whole wind farm by using, for example, a dynamic model in combination with a Kalman filter [Boersma et al., 2016, Doekemeijer et al., 2016].