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A wind farm control strategy for power reserve maximization

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ABSTRACT

Nowadays, in many countries wind energy is responsible for a significant part of the electricity generation. For this reason, Transmission System Operators (TSOs) are now demanding the wind power plants (WPPs) to contribute with ancillary services such as frequency support. To this end, WPPs must be able to temporally increase the active power delivered into the grid to compensate consume and demand imbalances. This implies that WPPs now work below their maximum capacity to keep some power reserve to be able to inject extra power into the grid when needed. This reserve depends on the available wind power, which is directly connected with the wind speed faced by each turbine within the WPP. However, wind speed is negative affected by the wakes caused by the upstream turbines. This paper proposes a control algorithm to distribute the power contribution of each turbine seeking to minimize the wake effects and thus maximize the power reserve. The proposed algorithm is evaluated by simulations for the case of a WPP of 12 wind turbines.

1. Introduction

The ever-growing environmental concerns and cost-effectiveness of renewable energy sources (RES), such as wind and solar energies, have led to a significant increase of their penetration levels into the electrical power system. Nowadays, wind power generation supplies more than 10% of the European consumptions and is expected to grow to 33% in 2030 [1]. This increasingly large deployment of RES into the electrical grid has contributed to decrease the dependency on fossil fuels. However, the high penetration of non-synchronous generators replacing conventional power plants, based on synchronous generation, leads to a system inertia reduction and thus affecting power system stability and reliability. RESs, if not properly controlled, inject into the grid highly variable power that may result in significant frequency fluctuations [2]. As a consequence, Transmission System Operators (TSOs) are now requiring wind power plants (WPPs) to participate in the provision of ancillary services, which so far have been relied on conventional sources. Typically, WPPs were operated to maximize the power output with the aim of minimizing wind energy cost. In this new context, the power production should be adjusted according to the TSOs requirements. The development of new wind farm control strategies for supplying automatic and fast response as ancillary service provider is acquiring relevance as a major-focus research topic [3]. There is an increasing interest from grid operators in requiring the WPPs to participate in ancillary services, such as frequency control [4] and voltage support [5].

Depending on the time range, WPP contributions in frequency support can be classified in two groups. WPPs can be used to provide inertial frequency support limiting the rate of fall during the initial instants of a frequency drop. To this end, wind turbines can release within milliseconds the kinetic energy stored in the rotating mass [6]. In order to ensure a more effective inertial frequency support, some authors have proposed optimization procedures to maximize the wind farm power generation and the kinetic energy stored in the turbines [7,8]. WPPs can also provide primary and secondary frequency supports by delivering into the grid additional active power during longer period of time in order to drive the frequency at its nominal setting. To be able to provide this kind of support, WPPs should work in de-loading mode, i.e. below their maximum power production capacity. This implies to keep certain

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amount of power reserve that can be released in case of frequency drops. Clearly, the larger the power reserve, the more effective the frequency support. Therefore, there is interest in maximize this capability of WPPs as it could bring some cost benefits in case of participation of WPPs in balancing markets [9,10].

The maximum power available in WPPs depends on the wind speed faced by each turbine. Within a wind farm, these wind conditions are imposed by the wakes produced by the upstream turbines [11]. In the literature, several strategies have been proposed to minimize the wake effect in order to maximize total power generation and minimize the power losses caused by the wakes. Some of them are based on redirecting the wakes around the downstream turbines by yawing [12,13] or tilting [14,15] the wind turbines, whereas others seek to redistribute the power contribution of each turbine [16,17]. Further, purposely setting the power contribution of each turbine by decreasing the generation of the upstream turbines has shown potential for minimizing the mechanical loads and thus extending the lifetime of the wind farm [18,19].

In this paper, a wind farm control strategy is proposed to maximize the power reserve during de-loading operation while maintaining the total power delivered by the WPP at the point of common coupling (PCC). The proposed approach aims to determine the power set-points for every turbine considering that commonly wind farms operate in waked conditions. With the goal of maximizing the power reserve, the proposed wind farm control strategy distributes the power contribution of each turbine in order to maximize the available power (i.e., the power reserve). The proposed approach was tested for a wind farm model of 12 wind turbines using a simulator that models the dynamic behavior of the wake effect by using the common dynamic wake meandering model [20].

The remainder of this paper is organized as follows. The wind farm model is presented in Section 2. Section 3 describes the proposed wind farm control strategy. In Section 4, the simulation setup is presented and the main results are discussed for the wind farm selected as case study. Finally, the conclusions are drawn in Section 5.

2. Wind farm modeling

The WPP control scheme under study is shown in Fig. 1. According to the utility demands, the TSO requires the WPP to deliver a power P_{dem}. Depending on the available power $P_{\text{av},i}$, the wind farm central controller sets the power set-points for each turbine $P_{\text{r},i}$ in order that the total generated power P_{g} matches the demand P_{dem}.

In circumstances with available power higher than the power demand, the wind farm is able to deliver an extra power for helping in primary frequency support. This extra power capability is referred to as the total power reserve and is given, for a wind farm of N turbines, by

$$P_{\text{res}} = P_{\text{av,tot}} - P_{\text{dem}}, \tag{1}$$

where

$$P_{\text{av,tot}} = \sum_{i=1}^{N} P_{\text{av},i}(v_i). \tag{2}$$

and v_i the wind speed experienced by the turbine.

In high wind energy conditions, WPPs are able to meet the total power demanded by the TSO by de-loading some wind turbines. For wind turbines with this capability, the generated power can be expressed as

$$P_{\text{g},i} = \kappa_1 C_{\text{p}}(a_i) v_i^3 = \min\left(\kappa_1 C_{\text{p,max}} v_i^3, P_{\text{r},i}\right), \tag{3}$$

where $\kappa_1 = (\pi \rho R^2/2)$, ρ is the air density, R is the rotor radius, and C_{p} is the power coefficient. Besides, (3) can be written as a function of the induction factor a_i [21], i.e.

$$C_{\text{p},i} = 4a_i(1-a_i)^2. \tag{4}$$

In normal operation, the induction factor a_i can be assumed taking values between 0 and 1/3. Therefore, (4) is an increasing function of a_i and the maximum value $C_{\text{p,max}}$ is obtained at $a_i = 1/3$. De-loading operations can be achieved by acting, individually [22] or in simultaneously [23], on both pitch and torque control actions to ensure sub-optimal operational conditions. According to (3), the generated power can be set to a given value $P_{\text{r},i}$ if wind conditions allow. This expression also indicates that, for a given v_i, there exists a unique $0 \leq a_i \leq 1/3$ producing $P_{\text{g},i} = P_{\text{r},i}$. The relationship among $P_{\text{g},i}$, v_i and a_i is shown in Fig. 2.

The available power at each wind turbine, i.e., the maximum generation capacity for the wind conditions v_i, is given by

$$P_{\text{av},i} = \min\left(\kappa_1 C_{\text{p,max}} v_i^3, P_{\text{rated}}\right), \tag{5}$$

being P_{rated} the rated power limit. Fig. 3 shows a generic available power characteristics as a function of the wind speed.

Each turbine within a farm has different reserve capacity as wind conditions depend on the geographical distribution of the wind resources and the air flow disturbances caused by the wake effects induced by up-stream turbines. The wake results from the interaction of the incoming wind speed v_i with the wind turbine rotor, such that the wind speed in the outflow field decreases.

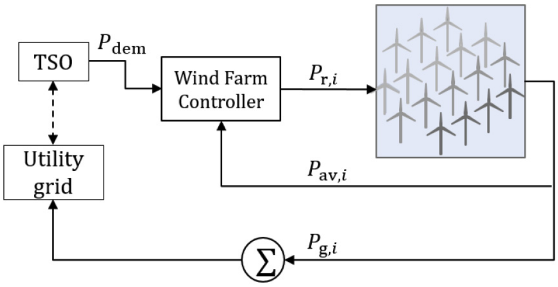

Fig. 1. WPP control scheme under study.

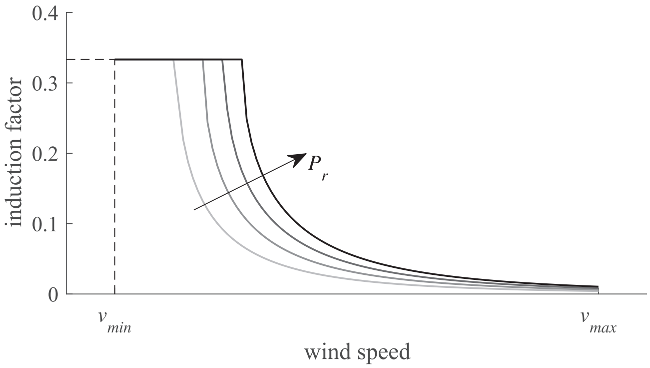

Fig. 2. Induction factor a – wind speed v characteristic for several power set-points P_r. The black line corresponds to the nominal case ($P_r = P_{\text{rated}}$).