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Maximizing the overall production of wind farms by setting the individual operating point of wind turbines

Javier Serrano González [a], Manuel Burgos Payán [a, *], Jesús Riquelme Santos [a], Ángel Gaspar González Rodríguez [b]

[a] Department of Electrical Engineering, University of Seville, Spain
[b] Department of Electronic Engineering, University of Jaen, Spain

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ABSTRACT

The classical operation strategy of wind farms seeks each wind turbine to convert as much aerodynamic power as available from the incoming airflow. But this does not warranty that the power converted by the whole wind farm be a maximum due to the interaction between turbines (wake effect). Unlike the conventional operation, this paper proposes the individual selection of the operation point of each turbine so that the overall production of the wind farm is maximized. To reach that goal, the power produced by some upwind turbines is slightly reduced in order to increase the available aerodynamic power for the downwind turbines, which results in an increase of the overall wind farm energy extraction. The optimization is performed by means of a genetic algorithm that selects the optimal pitch angle and tip speed ratio of each individual wind turbine, in order to maximize the overall wind farm production.

As an important side effect, the proposed method, firstly intended to the maximization of the production of the wind power plant, also allows decreasing the added turbulence produced by wakes. As a consequence, the mechanical efforts acting on turbines are diminished and the overall wind farm availability (production) is increased.

1. Introduction

The current value of rated power of individual wind turbines (WTs), around 5 MW in case of offshore facilities, requires the installation of a large number of turbines in a relatively small area: a 1 GW wind farm (WF) would need 200 WTs of 5 MW. Under these circumstances, the wake effect plays a key role in terms of produced energy by a WF, since the energy captured by a WT leads to a decrease of the wind speed downstream. As a result, WTs located downstream produce less energy that if they were in air free-flow.

In case of onshore WFs, the energy losses due to wake effect are about 5–10% of the production [1], while in offshore WFs, the wake effect losses can reach higher values, approximately 15% [2]. This is because the degree of compactness (number of turbines per unit area) of offshore facilities is usually higher due to its high implementation costs.

During the design stage of a wind farm, in order to decrease the wake effect losses, it would be desirable to separate the WTs as far as possible. However, due to constraints such as surface availability, cost of electrical connections and the present value of electrical losses over the span life of the installation [3,4], the maximum distance among WTs is limited.

The usual operating mode of each WT in a wind farm is to set the pitch angle and the tip speed ratio so that the WT tries to capture the maximum aerodynamic power as available from the air inflow. It means that every WT operates with the maximum power coefficient, when the wind speed is lower than the rated wind speed, or it operates at rated power, for higher wind speeds. However, in a WT cluster, this operation mode may not maximize the overall production of the WF, because the energy captured by each WT decreases the aerodynamic power available to other downwind turbines due the wake effect.

This paper proposes a new method of individual control for each WT in a WF so that the total power generated by the plant is

* Corresponding author. Tel.: +34 954481278; fax: +34 954487284.
E-mail addresses: javierserrano@us.es (J. Serrano González), mburgos@us.es (M. Burgos Payán), jsantos@us.es (J. Riquelme Santos), agaspar@ujaen.es (Á.G. González Rodríguez).

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increased compared to the case in which each wind turbine tries individually to capture as much aerodynamic power as available. The underlying idea of the proposed operation strategy is to slightly reduce the power generated by some of the upstream WTs (reducing also this way the speed deficits or wake effect losses) so that the power generated by the reminder downstream turbines could be increased. As a consequence, the overall production and efficiency of the WF result improved.

The concept of individual control power of WTs was initially suggested by Steinbuch et al. [5] by selecting the tip speed ratio of each wind turbine by a trial and error method. However, according with the conclusion presented by the authors, the increase in the output power was not significant. In 2004, Corten et al. [6] presented experimental results showing the possibility of increasing the generated power and reducing the loads by individually selecting the tip speed ratio of each wind turbine. In early 2011, Larsen et al. [7] presented the technical report corresponding to the TOPFARM project that deals with optimal topology design and control of wind farms. This study showed that it is possible to increase the overall efficiency of a WF through the individual control of the generated power by each WT; however this report does not provide further details on how this control strategy can be implemented or what would be the degree of the production improvement. In 2011, Madjidian and Rantzer [8] proposed the control of the generated power by the WTs in order to increase the overall efficiency corresponding to a row of wind turbines. With the purpose of evaluating the wake effect, the authors suggested a recursive model dependent on the thrust coefficient of the WTs. Through this wake model, the authors proposed a global control of the wind farm by using the same set point for all WTs. In 2012, Lee et al. [9], presented a strategy of individual control of each of the WTs by optimizing the pitch angle of each turbine by means a genetic algorithm, using a wake model based on the Eddy Viscosity Model. In that work, the authors considered the case of a row of wind turbines achieving an improvement in the aerodynamic power of 4.5%, regarding the conventional operating strategy (COS).

A model-free approach was presented in 2013 by Marden et al. [10]. By this model-free approach, the optimization can be performed based on measured production by each wind turbine and iterative correction actions over the axial induction factor. Two learning algorithms are employed: (i) safe experimentation dynamics for a model-free approach with communication and (ii) termed payoff-based distributed learning Pareto optimally in case of a model-free approach with limited communication. The analyzed test case shows the effectiveness of this approach. However, as Marden et al. [10] acknowledge such a model-free approach would require steady ideal wind conditions during long periods of time in order to be performed in actual wind farms. Gebraad et al. [11] use a similar approach than the introduced by Marden et al. [10]. Instead of a Game Theory approach, the gradient-based allows a faster convergence as the optimization process proposed than Marden et al. [10].

Park et al. [12] proposed in 2013 the maximization of the production by controlling the yaw offset angle and the induction factor by a cooperative control strategy. Goit and Meyers [13] presented in 2014 an iterative gradient-based method to maximize the power production by considering the thrust coefficient as optimization variable. The same as in the work presented by Lee et al. [9], the wake effect is modelled by Eddy Viscosity simulations.

In this paper an operation strategy similar to that developed by Lee et al. [9] is proposed. Nevertheless, the PARK model [14–16] has been used to calculate the wake effect.

Currently a lot of research is focused on developing new analytical and simulation models to estimate the wake deficit. Models based on Computational Fluid Dynamics (CFD) have been proved to be more accurate than analytical models when estimating the wake effect. However, the massive computational effort required by CFD simulations makes impractical the use of such techniques for an optimization problem where the wake effect has to be recursively recalculated. Under these circumstances, the PARK model has been the most employed model for optimization problems involving the assessment of the wake effect as it is also the case of the wind turbines micro-sitting problem [17–20]. Additionally, the PARK model is widely used for commercial software packages such as WAsP [21], WindPro [22] and Meteodyn [23] to assess the production of wind farms.

In addition, since the power coefficient, C_P, depends on two control variables the pitch angle, β, and the tip speed ratio, λ, the proposed strategy selects these two parameters for each WT that optimize the total power of the wind farm. This additional variable, λ, introduces a supplementary difficulty during the optimization process of the problem. However, it also introduces an additional degree of freedom that enhances the overall efficiency compared to that reported in previous works. Unlike the approaches proposed by Refs. [10–13], where the maximization is based on achieving the optimal values of the axial induction factor or the thrust coefficient, the operation strategy presented in this paper aims to provide directly the variables used to control the wind turbines: the pitch angle and the tip speed ratio.

2. Wind farm operation

The power captured by a WT, P_{WT}, as a function of the power coefficient, $C_P(\lambda,\beta)$, can be expressed as:

$$P_{WT} = \frac{1}{2} C_P(\beta, \lambda) \rho \pi R^2 v^3 \quad (1)$$

being v the wind speed, R the radius of the turbine and ρ the air density. As an example, Fig. 1 shows the value of the power coefficient, C_P, depending on the tip speed ratio, λ, and the pitch angle, β, for the NREL 5 MW reference turbine [24].

The actual power extracted by a WT calculated by means of Eq. (1) is influenced by various operating restrictions. As shown in Fig. 2, the power curve is defined by two operating areas: zone of operation at maximum power coefficient, $v \in [v_{cut\text{-}in}, v_{rated})$, and rated-power operating zone, $v \in [v_{rated}, v_{cut\text{-}out}]$.

2.1. Captured power and wake effect

The influence that each wind turbine has on downwind turbines (wake effect) must be evaluated to calculate the total energy of the wind farm.

For a point located in the wake stream of a turbine following the initial expansion area (2–3 rotor diameters), the reduction of the wind speed can be calculated assuming that the kinetic momentum of the air mass remains unchanged [14–16]. For longer downwind distances, the resulting wind speed at a distance, d, of the turbine that creates the wake is calculated by Frandsen et al. [14] as:

$$\frac{v(d)}{v_0} = \frac{1}{2} + \frac{1}{2}\sqrt{1 - 2C_T(\beta, \lambda)\left(\frac{D_0}{D_W(d)}\right)^2} \quad (2)$$

where v_0 is the free flow wind speed, D_0 is the diameter of the rotor, C_T the is the thrust coefficient and $D_W(d)$ the wake diameter at a distance, d, behind the upwind turbine, which in turn is calculated as:

$$D_W(d) = D_0 + 2kd \quad (3)$$

being k the entrainment constant, whose typical value are $k = 0.075$ for onshore facilities and $k = 0.05$ in case of offshore WF [21]. The resultant wind speed from the partial or cumulative interference of