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Optimal output power of not properly designed wind farms, considering wake effects

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ABSTRACT

The goal of this paper is to present an algorithm for increasing output power in wind farms with high wake losses. In some wind directions, wake effects cannot be neglected because the distance between turbines may be less than 5–8 times of rotor diameter. The purpose of presented algorithm is to determine coefficient of performance (C_P), thrust coefficient (C_T), pitch angle (β) and rotational speed (ω) of each turbine by using wake effects equations so that wake losses in the wind farm becomes minimum which result in increasing output power of wind farm. PSO algorithm is used for optimization. Finally, a sample wind farm consisting of 16 turbines is used as a case study and the results show that there is a noticeable increase in the amount of wind farm output power rather than the time which no control and optimization is used. The conclusion is that the presented algorithm is suitable for wind farms with high wake losses and little distance between their turbines and is very effective for increasing their output power.

Introduction

Wind energy usage for power generation has been rapidly and wildly increased around the world since the 20th century because of its reproducible, resourceful and pollution-free characteristics. By the end of 2007, the overall worldwide wind power installation capacity is surpassed 94GW [1]. As a result, it should be cost effective and economical in order to compete with different kinds of energy resources. On the other hand, the fossil energy resources are decreasing and environment deteriorating promotes the development of renewable energies [2]. So, making wind farms more efficient and increasing wind farm energy output has become more important in recent years. Because, if a power plant is supposed to participate in electricity market, it should be cost-effective. By increasing wind farm energy output, the cost of energy per kilowatt will be reduced and the investor will gain more profit in electricity market. The purpose of this paper is to increase wind farm output power with high wake losses.

A lot of works has been done before for optimization of wind farms. In [3], the author presented a method in order to determine optimal placement of wind turbines in a wind farm. In [4], fuzzy control is used that optimizes total generated power of a wind farm. In some installed wind farms such as Madison in New York or Manjil in north of Iran, there is not enough space between turbines in all directions and just the prevailing wind is concerned [5]. So, the space between turbines is less than 5–8 times of rotor diameter in non-prevailing wind directions. Therefore, if the wind blows in these directions, there will be a considerable amount of wake losses in the wind farm [2]. Since most of wind farms are designed according to their prevailing wind and wind direction varies randomly during the day, this problem is almost widespread around the world.

Wind energy comes from the extraction of kinetic energy from the wind. This results in lower wind speeds behind a wind turbine and less energy capture by downstream turbines in a wind farm. This effect is called wake effect [6]. This wake loss may even lead to stop some downstream turbines due to the reduction in wind speed. As a result, they do not produce any power and become useless. For example, most of the downstream turbines in Manjil wind farm are often useless and do not generate power. So, wake effect sometimes decreases wind speed behind upstream turbines which makes wind speed less than cut-in wind speed for downstream turbines. It is often possible to decrease wake effects by reducing coefficient of performance (C_P), thrust coefficient (C_T) and output power of upstream turbines by using wake effects model's such as Jenson model. Reducing wake effect may cause downstream turbines which were stationary at first to rotate and consequently produce power [7]. This may lead to more output power for a wind farm in compare with situation in which some turbines were

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stationary. So the main idea of this paper and the presented algorithm is to change the wind speed distribution along wind farm by applying wake effects equations. These equations determines the value of C_T of each turbine in order to maximize overall output power of turbines which is equal to wind farm output power. So far, no work has been done in minimizing wake losses in a previously designed wind farm. So the proposed algorithm is an innovative one and also could be used for wind turbine placement in planning purposes.

In conclusion, it is sometimes possible to gain more output power from a wind farm by reducing generated power of upstream turbines through decreasing their C_T and C_P, and increasing wind speed and C_P of downstream turbines. As will be discussed later, C_P can be controlled through pitch angle (β) and rotational speed (ω). Therefore, in order to determine the C_P of each turbine, a relation between β, ω and C_P is required. The purpose of this paper is to present an algorithm to determine the C_P and C_T of each turbine in a wind farm which leads to minimum wake losses and maximum output power for wind farm. It is required to solve an optimization problem to find the most suitable C_P's. In this paper, PSO algorithm is used and the objective function is the overall output power of wind turbines. The constraints in this optimization are wake effects equations. Since wake effect is also dependent on wind direction, so wind direction is required in addition to wind speed as inputs for the optimization.

Section 'Equations' describes the required equations in this algorithm with the more focus on wake effect model. Section 'Wind speed and direction data' discusses about input data for this algorithm which are wind speed and direction. Optimization problem is explained in section 'The optimization problem' and an algorithm for simulation is presented in section 'Algorithm of simulation'. The proposed algorithm is applied to a sample wind farm in section 'Case study' and the results of simulations are presented. Finally, conclusion about the paper is discussed in section 'Conclusions'.

Equations

In order to compute wind farm energy output we need to know wind speed and direction, wake effect model and power model of a wind farm. In this section, wake effect model and also different equations which is applied in this paper are described.

Wind speed and direction

Wind speed and direction are required in evaluating the generation amount of wind farm. However, the height of wind measurement instrument is usually different from the hub height of wind turbine. Thus, it is necessary to transfer the wind speed from instrument height to hub height. The power law represents a simple model for the vertical wind speed profile. Its basic form is [8]:

$$U(z) = U(z_r) * \left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

where $U(z)$ is the wind speed at height z, $U(z_r)$ is the reference wind speed at height z_r and α is the power law exponent. For wind directions, they are almost not changed with elevation.

Wake effect model

Obviously, wake losses vary with changes in wind direction. Therefore, wind direction must be considered in our study. Upstream turbines take some of the wind energy and reduce wind speed behind them. As a result, different turbines receive different wind speeds in a particular wind farm depending on the amount of turbines which are planted in front of them [10].

According to Jenson model [9], shaded area will grow bigger by increasing the distance between two turbines. Instead, its effect will dwindle while distance between turbines increases. Practically, wake effect will be neglected if distance between turbines is more than five times of rotor diameter. The velocity deficit becomes [1]:

$$dV = U_0 - U_X \tag{2}$$

$$= U_0 * \left(1 - \sqrt{1 - C_T}\right) * \left(\frac{D}{1 + 2KX}\right)^2 * \left(\frac{A_{\text{overlap}}}{A_{\text{rotor}}}\right) \tag{3}$$

where U_0 is the initial free stream velocity, U_x is the velocity in the wake at a distance X downstream of the upwind turbine, D is the diameter of the upwind turbine, K is the wake decay constant (in this paper, K is set to 0.075), A_{overlap} is the shaded area and defined as Fig. 1.

The important fact in (3) is that the velocity deficit behind a wind turbine has a straight relationship with C_T of that turbine which means it also is a function of C_P. In other words, it is possible to decrease wake effects and consequently increase wind speed for downstream turbines by reducing C_P and C_T of upstream turbines. So, it is sometimes possible to make stationary downstream turbines to rotate and produce power by reducing the C_T of upstream turbines. This reduction leads to greater amount of wind speed for downstream turbines which surpasses turbines cut-in speed. In this case, total generated power of a wind farm may be more than the case in which some turbines were stationary and others produce their maximum capacity. This model assumes that the kinetic energy deficit of interacting wakes is equal to the sum of energy deficits of the individual wakes. Thus, the velocity deficit at the intersection of several wakes is [9].

$$1 - \frac{U_x}{U_0} = \sqrt{\sum_{i=1}^{N} [(1 - U_i/U_0)]^2} \tag{4}$$

Thrust coefficient

According to (3), C_T is the main factor that can be controlled in order to change the velocity deficit behind a turbine. So, it is important to know how it can be determined. In this section, some equations for changing and controlling the amount of C_T will be presented.

A relationship between C_T and axial induction factor (α) is presented as (5) in [11]:

$$C_T = 4\alpha(1 - \alpha) \tag{5}$$

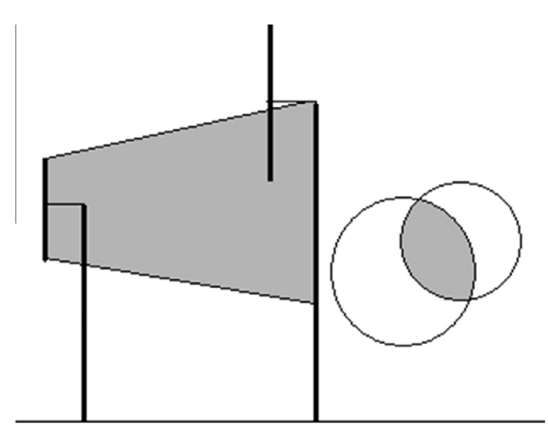

Fig. 1. Area overlapped by the turbine and shadow cone.