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A novel control strategy approach to optimally design a wind farm layout

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ABSTRACT

Recently wind energy has become one of the most important alternative energy sources and is growing at a rapid rate because of its renewability and abundancy. For the clustered wind turbines in a wind farm, significant wind power losses have been observed due to wake interactions of the air flow induced by the upstream turbines to the downstream turbines. One approach to reduce power losses caused by the wake interactions is through the optimization of wind farm layout, which determine the wind turbine positions and control strategy, which determine the wind turbine operations. In this paper, a new approach named simultaneous layout plus control optimization is developed. The effectiveness is studied by comparison to two other approaches (layout optimization and control optimization). The results of different optimizations, using both grid based and unrestricted coordinate wind farm design methods, are compared for both ideal and realistic wind conditions. Even though the simultaneous layout plus control optimization is theoretically superior to the others, it is prone to the local minima. Through the parametric study of crossover and mutation probabilities of the optimization algorithm, the results of the approach are generally satisfactory. For both simple and realistic wind conditions, the wind farm with the optimized control strategy yield 1–3 kW more power per turbine than that with the self-optimum control strategy, and the unrestricted coordinate method yield 1–2 kW more power per turbine than the grid based method.

1. Introduction

The depletion and pollution of traditional fossil fuels have enabled researchers and scientists to focus more on alternative renewable energy studies in an attempt to replace fuels like oils, coals and natural gases. Of the different renewable energy sources, wind energy shows the most prominent growth trend due to its cost-effectiveness and abundancy over other sources. It has been reported that over 35 GW of wind power capacity was installed around the world by 2013, and the average annual growth in the last ten years up to 2012 was 25% [1,2]. The exploitation of wind energy is mostly achieved by wind turbines placed in clusters or arrays, in order to take full advantage of the local abundant wind resources as well as available land and infrastructure [3]. However, the dense placement of wind turbines in close proximity to one another can cause wind shadowing of upstream turbines to downstream turbines, known as wake interventions or wake effects [4]. Wake power losses not only reduce the wind power capture efficiency, but also increase the overall cost of wind power utilization affecting its economic competitiveness towards other energy sources. To address this issue, researchers have attempted to improve wind farm performance by weakening wake interventions between turbines using two approaches [5,6]. One approach has been to optimize wind farm layouts by changing wind turbine positions. The other approach has been to optimize the control strategy by changing operations for different wind turbines.

The study of wind farm layout optimization began with Mosetti et al. [7], who applied the Genetic Algorithm (GA) [8] to optimize the wind turbine positions for a square-shaped wind farm. The optimization results indicated great improvements for both total wind farm power production and the cost per unit power compared to random wind farm layouts under all three tested wind conditions. Beyer et al. [9] reported a layout optimization study for three wind farms with different shapes and sizes, with the coordinates of

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wind turbines used to denote the wind turbine positions instead of the grid as in the previous study. The ‘expert guess’ wind farm layout, which used the typical area value of the square of 3–4 rotor diameter per wind turbine, was introduced to qualitatively demonstrate the improved performance of the optimized wind farm. The results showed a big wind farm efficiency increase of more than ten percent for the second optimized wind farm layout. Following this work, a large number of researchers have targeted the wind farm layout optimization problem by employing other optimization algorithms [10–12] or changing the wind farm models [13,14]. All wind farm layout optimization studies in the literature assume uniform operation for all turbines to ensure maximum power is produced in every turbine. Hereafter, the control strategy that enables the maximum wind power produced for single wind turbine is named self-optimum control strategy. However, it has been proven that the self-optimum wind farm control strategy is not the optimum choice for overall wind farm power production when taking the wake effect into account, which will be further discussed in Section 2.

The improvement in wind farm performance achieved by control optimization has also been verified experimentally by researchers. A wind tunnel test with 3 × 8 turbines was done by Corten [15] under the constant wind speed and constant wind direction. By employing the optimized control strategy, that is pitching the blade angle of the first row of turbines to the maximum, the total wind farm power output increased by roughly 4.6%. In Refs. [16], Corten studied the effect of pitching angles on the total wind farm power output quantitatively for an array of 2 × 7 wind turbines. When the first two turbines were both pitched at +2.5°, the greatest increase of 2.0% was obtained for the total power production. The Energy Research Centre of the Netherlands (ECN) conducted a full scale field test which consisted of five pitch controlled 2.5 MW turbines in a row at a spacing of 3.8 rotor diameters [17]. It was found that the optimized wind farm power output could increase up to 0.5% incorporating all wind directions. The large discrepancy between the wind tunnel test and the field test for the percentage increase in output power can be explained by the realistic wind condition in the field, which is extremely different from the simplified constant wind condition in the wind tunnel. So in the field test, the result indicates the average power increase for all wind speeds and all wind directions, and hence should be less than that of the wind tunnel test. However, all the aforementioned control optimization studies are based on the fixed wind turbine positions and exclude the effect of the wind turbine placements on the total optimization results, which makes it less comprehensive. There is no literature on studying the optimal wind farm design by considering both wind farm layout and control optimizations. As for the other factors like fatigue loads of wind turbine components, which is also an extremely important index to evaluate while optimally designing the wind farm with wake interactions, they are beyond the scope of this paper and hence are not considered.

Therefore, this paper aims to fill the research gap of studying the wind farm design by considering the optimization of both wind farm layout and control strategy, and compare the effectiveness of different optimization methods that are developed. The remainder of the paper organized as follows. Section 2 describes the research problem targeted in the paper in detail. Section 3 reports the applied genetic algorithm, solution codifications, genetic operators and optimization process for different wind farm optimizations and design methods. The optimization results of the simple and realistic case studies are presented and discussed in Section 4. Finally, Section 5 draws the conclusions. The Appendix introduces how the wind farm power and optimization objective function are calculated, as well as the detailed Weibull distribution applied in the realistic case study.

2. Problem description

2.1. The wake model

For wind farm optimization studies using computational approaches, one of the most critical procedures is to establish the wind farm wake model using explicit mathematical expressions. This avoids the costly process of building the physical wake model. Among the applied wake models, the PARK model [18–20] is most widely used for wind farm optimization studies due to its cost-effectiveness and accuracy compared to the real wind farm data.

The PARK model assumes a linear expansion of the wake (see Fig. 1). Using momentum conservation, the wind velocity at the location of an upstream turbine wake is given by:

$$v_1 = v_0\left[1 - 2a\left(\frac{r_0}{r_0 + \alpha x}\right)^2\right] \tag{1}$$

Where v_0 is the free stream wind speed and v_1 is the wind speed in the wake. r_0 is downstream turbine rotor radius, α is the wake spreading coefficient, x is the distance between the two wind turbines parallel to the wind direction, and a is axial induction denoting the percentage of wind speed decrease from free stream air to air at the rotor, which can be represented by:

$$a = \frac{v_0 - u}{v_0} \tag{2}$$

According to actuator disk theory [22], the single wind turbine power efficiency C_p and thrust efficiency C_T are related to the axial induction as follows:

$$\begin{aligned} C_P &= \frac{P_{\text{turbine}}}{P_{\text{wind}}} = 4a(1-a)^2 \\ C_T &= \frac{\text{Thrust Force}}{\text{Dynamic Force}} = 4a(1-a) \end{aligned} \tag{3}$$

2.2. Optimization of wind farm control strategy

According to Eq. (3), the theoretical maximum power efficiency (C_p equals to 16/27) can be achieved when axial induction a equals 1/3, which is known as the Betz limit. Therefore for a single wind

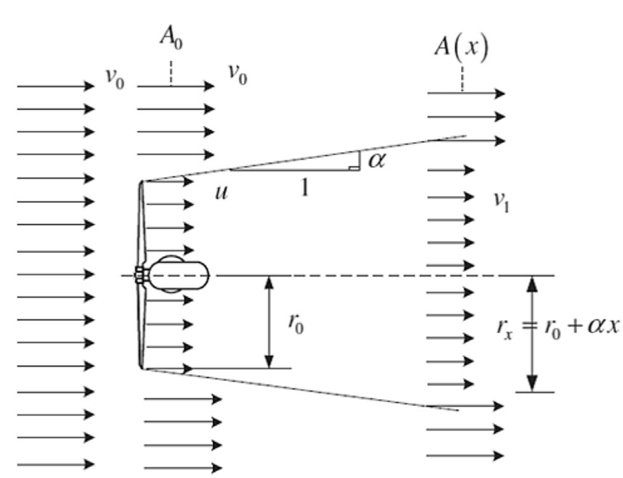

Fig. 1. Diagram of PARK wake model [21].