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Towards realistic designs of wind farm layouts: Application of a novel placement selector approach

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ABSTRACT

The optimal arrangement of wind turbines plays a significant role in obtaining the expected output power from wind farms. This paper addresses challenges related to typical restriction assumptions of turbine arrangement in wind farms with candidate selection approach. An applicable hybrid (quadratic assignment problem-genetic algorithm) evolutionary method with an initial candidate points selection (ICPS) approach is proposed and applied to four case studies to obtain optimal layout designs with maximum efficiency. The current study considers not only the previously utilized indicators found in the literature, such as wake effects, turbine hub height and rotor diameter, but also accounts for additional criteria such as the load-bearing capacity of soil and restrictions regarding the existence of prohibited places as well as varying wind velocities and directions. This is done to make the approach more applicable for realistic cases, and also to incorporate the preferences of expert designers. The results suggest that superior performance is attained with the proposed algorithm compared to previous similar studies. An efficiency improvement of about 3% is achieved for case one, and the algorithm provides reasonable optimal wind farm design layouts for cases two, three, and four where more restrictions exist.

1. Introduction

Renewable energy, as an alternative to hydrocarbon and nuclear energies, has attracted the attention of many energy policy-makers in recent decades. Increases in the planet's temperature, rising prices of fossil fuels, industrialization, population growth, and increasing environmental concerns (e.g., the Gulf of Mexico oil spill and the Fukushima nuclear accident) have made many feel that humankind needs to shift towards sustainable energy [1–3]. Prices of renewable energy utilization, including the harvesting of wind energy resources, are declining as a result of technology development, leading to potential competitions between utilization of non-exhaustible and non-renewable energy sources globally. Wind energy systems worldwide attained a capacity of 196 GW at the end of 2010, including a 38 GW increase in 2010 which represents a yearly increase of 23.5% [4].

Finding an appropriate arrangement of wind turbines is one important factor for reducing costs and enhancing the output power of a wind farm. In addition to better space concentration, employing several well-placed individual wind turbines beside each other addresses the necessity of operating wind turbines in geographically-limited areas with rich wind energy potential. Operating several turbines in a wind farm also offers cost-effectiveness in terms of maintenance and operation. The generated power from the turbines of a wind farm is often lower than expected, partly due to inappropriate placement of the turbines, downstream wake fronts caused by upstream turbines, changes in angle of attack, atmospheric turbulence and tower wakes. The significance of diameter and downstream wake effect depends on the specifications of upstream turbines. Among these parameters, the intensity of wakes and the turbulent flow structures have been reported to be responsible for between 5% and 22% of the losses [5]. Fig. 1 illustrates a schematic of the wake front effect and its negative impact on the wind velocity approaching a downstream turbine [6].

Since the wake effect has an important effect on the output power from a wind farm, it is worth optimizing turbine placement in a wind farm so as to reduce energy costs and increase the generated power simultaneously. Finding viable solutions can

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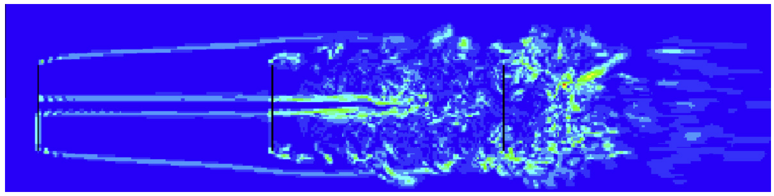

Fig. 1. Downstream wakes [6].

provide economic benefits which can enhance the development and implementation of wind farms.

Several report regarding design and evaluation of wind farms performance have been published, many of which focus on the variety of factors involved. Although land availability and power loss reduction are also issues associated with the implementation of wind farms, the problems associated with these factors have been addressed successfully previously; the main approaches involve using simple methods such as organizing turbines in rows and at great distances from each other. However, the complexity, nonlinearity and multi-factor aspects of this problem make optimization worthwhile. Despite the different approaches to optimizing wind farms, there has been an increasing tendency in recent studies to utilize evolutionary algorithms, in part due to their ability to deal with many criteria and to handle complex problems reasonably well. Most recent studies have shown that a disordered configuration and utilization of turbines with different hub heights can be beneficial for wind farms, decreasing power losses.

Some notable studies have been reported. For instance, Grady et al. [7] indicated that a genetic algorithm (GA) can reasonably determine appropriate wind turbines configurations for wind farms. The evaluated function in their study was the ratio of total cost to total generated power, and they considered three wind-resource scenarios: constant velocity–direction, constant velocity with variable direction, and variable velocity–direction. In another study, Chen et al. [8] investigated the optimization of wind farm layouts by considering various hub heights with a GA to maximize the generated power. They reported positive effects from utilizing different hub heights, so as to avoid the deployment of downstream turbines in the wake of upstream ones. The extracted power from turbines on a wind farm depends further on the type of turbines installed. Employing different hub heights optimally can appropriately address wake challenges particularly when land availability is limited.

To quantify the positive effect of changing the radius of the turbine rotor on a defined indicator (e.g., the ratio of total generated power by the farm to the sum of the power generated by separately operated turbines), Chowdhury et al. [9] utilized a particle swarm optimization (PSO) approach for optimization of a wind farm layout. González et al. [10] proposed utilizing an evolutive algorithm (EA) to find the best design of wind farm layout, while maximizing economic returns for a given investment. In that study, various decision variables were considered, such as number and type of turbines, hubs height, geographical location and side costs of implementation of a wind farm like auxiliary roads to transfer turbine equipment. In another study, Chowdhury et al. [11] utilized a PSO approach for the simultaneous optimal siting and selection of turbines for wind farms at a commercial scale. They claimed their proposed layout could enhance capacity by 6.8%. Via utilization of a GA and based on a global wind farm cost model, González et al. [12] proposed an optimal wind farm layout. They considered initial investment and present value of yearly net cash flow over the wind-farm life span to deal with restrictions such as load-bearing soil capacity, forbidden placement areas, different roughness lengths for every wind direction and the number of wind turbines respecting wake decay effects. Pookpunt and Ongsakul [13] considered uniform and non-uniform wind speeds with variable wind directions in optimization problems for a wind farm containing 100 square cells. A linear wake model was utilized in that study for calculating the downstream wind velocity. The authors applied a binary PSO method with time-varying acceleration coefficients to indicate superiority of their proposed approach to obtain maximum power output of the turbines with a minimum investment. To maximize the efficiency of wind farms, Eroğlu and Seçkiner [14] examined an ant colony optimization (ACO) based approach with three scenarios, and reported superior performance of the ACO algorithm in reaching the optimal wind farm layouts and maximizing the output power by considering wake losses and wind direction.

In the current study, we propose a novel method for the optimal design of wind farm layouts. In our approach, all reported effective indicators, including hub height of the turbines, rotor radius of the turbines, the load-bearing soil capacity, variations of wind direction and speed, and environmental restrictions, are considered simultaneously to permit determination of the best realistic layout. Four case studies are used to illustrate the approach.

2. Modeling of power and wake effect

The downstream turbines in a wind farm are subject to reduced wind energy density due to effect of the wake front caused by upstream turbines. Fig. 2 illustrates downstream and upstream turbines accompanied with power and velocity reduction profiles as the air passes through the turbine blades [15].

The power loss caused by the wake effect of upstream turbines has been reported to be around 20%, and as high as 40% for extreme cases [16]. Increases in wakes and flow turbulence raise component fatigue of downstream turbines. While passing through a turbine's blades, wind transfers part of its energy which could be recovered partially after a distance depending on how great the distance is. Therefore, wake effects and turbine distances from each other should be treated as significant factors in design of optimal wind farm layouts.

Considering D as the diameter of a turbine rotor, the model proposed by Frandsen et al. [17] performs better in wake modeling

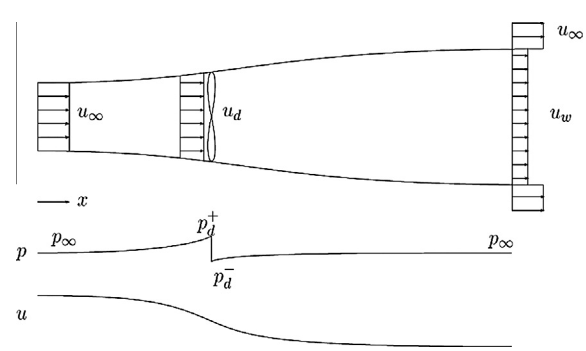

Fig. 2. Power and velocity reduction after upstream turbines [15].