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A study of the performance benefits of closely-spaced lateral wind farm configurations

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ABSTRACT

Scaled wind turbine experiments were conducted in order to evaluate the beneficial effect of closely-spaced lateral wind turbine configurations on the performance of a wind farm. Two outer wind turbines were spaced apart with a particular gap distance and the longitudinal setback of a central rotor was varied at each gap width. The turbine placement resulted in tip-to-tip separation distances that ranged from 1 diameter (D) to 0.25D. Additionally, the performance of a wind farm layout in rough and smooth boundary layers, designed to mimic onshore and offshore conditions, respectively, was evaluated. It was observed that a narrow gap between several laterally-aligned rotors creates an in-field blockage effect that results in beneficial flow acceleration through the gap. This increase in speed increases the power output of the central turbine when its longitudinal setback is between 0D and 2.5D. A cumulative increase in power output of 17% was observed when 3 rotors were aligned in a lateral plane with a blade tip separation of 0.5D or 0.25D, compared to the same number of rotors in isolation. While the benefits of closely-spaced wind turbines were observed in both of the tested boundary layers, the performance benefits with a smooth boundary layer were smaller than with a rough boundary layer. These results may lead to new wind farm design methodologies for certain topology- and wind distribution-specific sites and suggest that wind turbines can be closely-spaced in the lateral direction in order to obtain substantial increases in power.

1. Introduction

Traditional wind farm design guidelines have resulted in wind farms with downstream turbine separation distances of 7 diameters (D) to 10D and lateral separation that is typically 4D to 7D [1]. While new large offshore wind farms typically favour a grid-like layout, many onshore wind farms have an irregular layout, with varying lateral and longitudinal separation. The velocity deficit in a wind turbine wake reduces the power that can be generated by downstream turbines in a wind farm. This downstream velocity deficit can lead to power losses in wind farms that are approximately 15–35% when compared to the same number of turbines in isolation [2,3]. As a result, an improved understanding of the flow through a wind farm and the development of wind turbine wakes may lead to more efficient wind farm layouts.

The development and growth of wind turbine wakes is frequently assessed using scaled turbines and a number of existing experiments have considered the wake development downstream of a single rotor. An experiment conducted by Chamorro and Porté-Agel measured the evolution of the wake downstream of a small-scale wind turbine using hot-wire anemometry (HWA) in neutral and stable boundary layer conditions [4]. Tip vortex propagation downstream of two-bladed rotors has been evaluated by several authors in Refs. [5–7]. Previous work by the current authors investigated the effects of blockage and Reynolds number on the development of the near wake region with scaled, three-bladed wind turbines [8]. The results of the blockage study indicated that expansion in the near wake was narrowed by the freestream acceleration that is a product of increased tunnel blockage when blockage exceeded 10% [8].

The improved understanding of wake development downstream of single rotors has led to a number of wake interference experiments. These wake interaction studies have predominantly focused on understanding the effect of an upstream turbine wake on the power deficit experienced by a longitudinally-aligned, downwind rotor. One such experiment was conducted by Maeda

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Nomenclature

α	power law coefficient
D	diameter [m]
δ	reference height [m]
ΔP	change in power [%]
G	gap width [m]
λ	tip speed ratio
N	number of turbines
P_{elec}	electrical power [W]
P_{meas}	measured power [W]
P_{single}	power from an isolated turbine [W]
R	radius [m]
S_{tip}	blade tip separation distance [m]
U_{δ}	velocity at a reference height [m/s]
U_{hub}	velocity at hub height [m/s]
V	voltage [V]
ω	rotational velocity [rad/s]
Ω	resistance [Ω]
X	downstream axial location [m]
Y	lateral position [m]
z	vertical location [m]

et al. using two rotors with longitudinal separation [9]. The longitudinal separation between the rotors was varied from 3D to 10D and the downstream rotor was also given a lateral offset ranging from ±2D from the centreline. The study was designed to measure the blade loads in full-wake and partial-wake flow conditions. The effects of the wind inclination angle due to terrain effects on wind farm performance were evaluated by Tsalicoglou et al. using two rotors in a tow tank [10]. The downstream separation varied from 3D to 6.5D and the flow inclination angle was 15°. The study demonstrated that the downstream rotor in axial flow generated 45% less power than the upstream rotor, but that the power loss was reduced in inclined flow due to deflection of the wake from the upstream rotor. A wake interference study was conducted by Adaramola and Krogstad using two wind turbines with a longitudinal offset of 3D to 9D [11]. The work conducted in Ref. [11] evaluated the effect of the operating conditions of the upstream rotor on the downstream rotor's performance, including the effects of tip speed ratio, yaw angle, and blade pitch angle. Although scaled rotors are used in many experiments, static mesh simulators have also been used to produce representative wakes in the laboratory. Aubrun conducted experiments on scaled static mesh models in flow conditions representative of an offshore ABL [12]. A parametric study was conducted in Ref. [12] in order to evaluate the effect of the mesh disc porosity on the velocity deficit in the wake and a subsequent study was conducted with a 3 × 3 wind farm with 3D hub-to-hub spacing in the lateral and downstream directions.

Despite the increasing number of wake interaction studies available in literature [13,14], the effect of lateral spacing between wind turbines within a row has not been thoroughly evaluated. The hub-to-hub spacing between wind turbines in a wind farm is typically on the order of 4D to 7D for irregular, onshore wind farms. Hossain et al. examined the use of a wall of microturbines in order to provide a windbreak for agricultural or urban purposes while still generating electricity [15]. A 5 × 5 vertically-mounted array of 5 cm diameter, four-bladed, wind turbines was tested in a wind tunnel with a 0.2D gap width between blade tips. Downstream HWA and particle image velocimetry measurements demonstrated that wake recovery was significantly delayed downstream of the array compared to the wake recovery downstream of a single rotor [15]. Although the static mesh simulator wind farm described by Aubrun in Ref. [12] had a lateral separation between adjacent rotor edges of 2D, lateral interference effects were not noted. As part of a marine current turbine study, Bahaj et al. tested the effect of a tandem rotor arrangement with a gap width that ranged from 0.5D to 0.0125D [16]. Interference effects from one rotor to the main test rotor were not apparent in Ref. [16], however. A marine current turbine experiment conducted by Myers and Bahaj investigated the use of two-row arrays with a gap width of 1.5D and a longitudinal offset of 3D for the centre rotor using porous metal discs to represent the effect of marine turbines [17]. The work presented in Ref. [17] indicated that the thrust coefficient of the central disc could be increased due to accelerated flow through the upstream gap.

The current manuscript proposes a method that may enhance the power output of a wind farm by reducing the lateral spacing between wind turbines. The reduced spacing compared to current farm layouts creates an effective in-field blockage phenomenon that results in a local increase in the wind speed at the rotor plane and a subsequent increase in power. A parametric study of lateral and longitudinal wind turbine separation distances was conducted and the effect of the lateral gap between three rotors on their power output was assessed. The paper describes the wind tunnel experiment that was conducted, the three-bladed rotors that were used in the study, and the results of the study. The effect of longitudinal separation on the power output of a downstream rotor, the effect of a narrow upstream gap on a downstream rotor, and the parametric study of closely-spaced three-rotor arrangements will all be discussed.

2. Description of the experimental setup

The wind farm experiments were conducted in the atmospheric boundary layer wind tunnel at Carleton University. This Section will describe the wind tunnel geometry, the flow conditioning elements, the design of the scaled wind turbines, and the wind turbine arrangements.

2.1. Atmospheric boundary layer wind tunnel

Wind turbines operate in the atmospheric boundary layer, which causes fluctuating turbine loading. The atmospheric boundary layer (ABL) can have a height that ranges from 500 m to several kilometres and has a profile that depends on atmospheric stability and the roughness of the local topography [18]. The open-circuit atmospheric boundary layer wind tunnel at Carleton University was used in the current study in order to simulate the effects of a neutral atmospheric boundary layer. The ABL tunnel has a maximum speed of 17 m/s, a fetch distance of 9.76 m and a rectangular test section with a width of 1.68 m, a height of 1.13 m, and a length of 2.44 m. The wind tunnel has an upstream contraction ratio of 7.1:1 and is powered by a 30 kW motor coupled to a 1.67 m diameter fan. An image of the wind tunnel can be seen in Fig. 1(a).

A scaled boundary layer was created in the wind tunnel using triangular spires and distributed roughness elements along the floor of the wind tunnel, as seen in Fig. 1(b). The boundary layer profile that is formed downstream of the spires will have a power law velocity profile defined by Equation (1), where α is the power law coefficient, z is the height above the tunnel floor, U is the velocity at a particular height within the boundary layer, and U_{δ} is the velocity at a reference height δ. The spires were designed using the empirical design methodology described in Ref. [19] and the distributed roughness elements consisted of small 2.5 cm angle brackets. Two different boundary layers were considered in the current study and were selected to mimic onshore forested terrain (rough) and offshore (smooth) conditions, respectively. The rough