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ScienceDirect

Energy Procedia 137 (2017) 307–314

Energy Procedia

www.elsevier.com/locate/procedia

14th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2017, 18-20 January 2017, Trondheim, Norway

Experimental study on power curtailment of three in-line turbines

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Abstract

A dataset of wind tunnel power and wake flow measurements on a setup of three aligned model wind turbines is presented. The power outputs of the three turbines are in good agreement with measurements from a full-scale wind farm of similar inter-turbine spacing. A comparison of the wake flow behind the first row and the second row shows a significantly higher mean velocity loss behind the second row justifying a further power drop from the second to the third row turbine. Curtailing the front row turbine to smaller than rated tip speed ratios resulted in insignificant total power gains below 1%. Curtailments of both the first and second row turbine indicate that the best combined array power results are achieved for slightly lower than rated tip speed ratios. Although power curtailment is observed to have a rather small potential for power optimization of a wind farm, it could be an effective method for load distribution at constant farm power.

Keywords: Wind turbine wake; Wind farm control; Induction-based wake control, Power curtailment.

1. Introduction

Depending on the inter-turbine spacing, wake interactions between individual turbines are estimated to cause power losses up to 10-20% in large offshore wind farms [1]. Therefore, holistic wind farm control approaches are proposed to optimize the farm's capability of kinetic energy extraction from the wind [2]. Wind farm control methods can, in general, be classified as wake deflection methods like yaw control or axial induction based control

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10.1016/j.egypro.2017.10.355

methods like pitch or torque control of the upstream turbines. Even though the potential for power gains by wake deflection control is estimated to be larger [3], [4], axial induction based curtailment methods have the advantage of a more uniform load distribution over the downstream turbine rotor area. Depending on the turbine type, inter-turbine spacing, and the site-specific wind conditions, axial-induction based control is therefore considered an effective option for power and load control in tightly spaced wind farms.

By reducing the induction of the upstream turbine through tip speed ratio or pitch control, more kinetic energy is left in the wake flow that can be used by the downstream turbines. A previous study by Bartl and Sætran [5] of induction based control on two in-line turbines indicates a higher potential for power gains for tip speed ratio control than for pitch control. An investigation by Hansen et al. [6] highlights that the level of atmospheric turbulence intensity significantly influences the wake recovery and thus the total power output of a wind farm. This is confirmed in a model scale study by Ceccotti et al. [7], in which a curtailment of the first row is shown to be effective for low background turbulence and small turbine separation distances (≤ 3D) only. However, the potential power increase for a two turbine arrangement is observed to be within one percent. In full-scale wind farms measurements on aligned turbines show the biggest power drop between the first and second row [1], [6], [8]. The difference in power production from the second to the third row is considerably smaller, which leads to a more or less stable production for turbine rows located even further downstream. The additional energy extraction by rotors from the third row on seems to be balanced by the entrainment of high kinetic energy fluid from the surrounding freestream flow. Therefore, an investigation of two aligned turbines may not be conclusive for an entire wind farm as also the third turbine power output and further rows could be affected by a curtailment of the front row turbine. In a Large-Eddy-Simulation (LES) of the tightly spaced Lillgrund wind farm Nilsson et al. [9] investigate the potential for increasing the wind farm production by curtailment of the front row turbines. By pitching out the front row turbines, they could not observe a positive contribution to the overall wind farm power production. Another CFD study based on the actuator line technique by Mikkelsen et al. [10] on a row of three aligned turbines shows increased production of the second and third turbine for a pitched first row turbine.

In this collaborative experiment between the Norwegian University of Science and Technology (NTNU) and Middle East Technical University (METU) Center for Wind Energy, measurements on three aligned model wind turbines of identical rotor geometry are carried out. It is investigated whether a curtailment of the first and second row can benefit the combined power output of a row of three aligned wind turbines.

2. Methodology

2.1. Wind tunnel, model turbines and rotor geometry

The test section of the closed-loop wind tunnel at NTNU in Trondheim is 2.71m wide, 1.81m high and 11.15m long. Static pressure holes are installed at two defined circumferences at the inlet of the tunnel in order to control the inflow speed. The wind tunnel is driven by a 220kW fan, which is located behind the test section. The model wind farm consists of the first row turbine (T1) from NTNU and the second (T2) and third row turbine (T3) from METU. The turbines have the exactly same rotor and nacelle geometry. The three-bladed rotors have a diameter of D=0.944 m and turn in the counter-clockwise direction. The rotors are controlled by systems of electric motors and frequency inverters by Siemens (T1, NTNU) respectively Panasonic (T2 & T3, METU). The turbines' rotational speed can be controlled up to about 3500 rpm, while the extensive power is consumed by external load resistances. The turbine blades are based on the NREL S826 airfoil and precision milled in aluminum. Three different sets of experimental performance data of the NREL S826 airfoil for low Reynolds numbers can be found in publications by Ostovan et al. [11], Sarmast and Mikkelsen [12] and Sagmo et al. [13], all of which can be used as input data for Blade Element Momentum (BEM) simulations.

2.2. Experimental setup

Fig.1 shows a side-view of the wind tunnel with the three model turbines installed. The first row turbine (T1) is mounted 2.00D from the tunnel inlet, while turbines T2 and T3 are set up with an inter-turbine spacing of 3.00D.