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Effect of upstream turbine tip speed variations on downstream turbine performance

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Abstract

A wake study and combined power output analysis of an array of two model wind turbines is presented. In a wind farm arrangement wakes behind the upstream turbines directly affect the performance and structural loads of the downstream turbines. In this analysis the characteristics of the mean and turbulent wake flow behind an upstream model turbine is directly related to the performance characteristics of a downstream rotor located at three different downstream locations. First the influence of the upstream turbine's tip speed ratio variation from design conditions on the wake flow and the downstream turbine performance is analyzed. Thereafter, also the turbulence intensity level at the wind tunnel inlet is varied from low (laboratory conditions, TI=0.23%) to high (atmospheric conditions, TI=10.0%). Finally, the combined power output of the two turbine array is evaluated for a matrix of the different scenarios.

A significant influence of the background turbulence level on the wake recovery is observed, especially for the intermediate separation distance of x/D=5. Controlling the upstream turbine's tip speed ratio away from its design point does not result in a significant increase in combined power output. Only for the case of low turbine separation distance (x/D=3) and low background turbulence the added kinetic energy in the wake can be recovered by the downstream turbine. For higher turbine separation distances and higher background turbulence, the added kinetic energy diffuses into the freestream flow and cannot be recovered anymore. In average, the combined efficiency is observed to increase by about 2.5% with every additional rotor diameter of turbine separation distance. Thus, this analysis suggests an accurate management of the upstream turbine tip speed ratio in dependence of background turbulence and turbine separation distance when optimizing the power output of a wind farm.

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1. Introduction

Energy losses due to wake interactions are currently a widely discussed issue in the design of wind farms. For wind directions resulting in full wake shadow of the downstream turbines the total wind farm power extraction can be reduced up to 15-20% [1]. The overall wind farm power production is governed by a number of physical mechanisms affecting the interaction of the highly turbulent wake flow and the downstream turbines' performances. The mean velocity deficit in the wake needs more than 10D to recover to conditions similar to the freestream, while even higher distances are necessary until the wake turbulence becomes insignificant [2]. However, due to constrictions in area use and infrastructural costs an economical optimum is often reached for smaller turbine spacing distances. Most offshore wind farms are usually spaced around 7-8D in the main wind direction, in some installations like the Lillgrund wind farm even lower turbine spacings are found (4.3D in main wind direction, 3.3D in cross wind direction) [3]. For this purpose a set of wind tunnel wake and performance measurements is presented focusing on the wake-rotor interaction and total array efficiency of the two-turbine setup.

2. Methodology

The experiments are carried out in the wind tunnel laboratory at the Norwegian University of Science and Technology (NTNU). The wind tunnel has a cross section of 2.7 x 1.8 m^2 and is 11.1 m long. The closed-loop wind tunnel is driven by a 220 kW fan being able to generate maximum wind speeds of about $U_{max} = 30$ m/s [4]. During the present tests the reference wind speed is kept constant at $U_{ref} = 11.5$ m/s, which is shown to result in a Reynolds-number-independent turbine performance [4]. Two model wind turbines of the rotor diameter of D = 0.90 m are investigated. Each turbine comprises over a three-bladed rotor based on the NREL S826 airfoil. A detailed description of the model geometry is given in [5]. The turbines' rotational speed is controlled via a 0.37 kW motor-generator connected to a frequency inverter. This makes it possible to operate the rotors up to 3000 rpm while the generated excess power is burned off by an external resistor. The pitch angle of the blades is kept constant at $\beta = 0°$ during the entire measurement campaign while the rotational speed of both turbines is schematically varied. The first turbine is set up 2D from the inlet of the tunnel as shown in Fig. 1. Horizontal line profiles of the wake flow are measured at the hub height h=0.826 m by the means of hot wire anemometry at the three downstream distances 3D, 5D and 9D. Time-averaged mean flow velocity U_{mean} and the streamwise turbulence intensity TI [%] are analysed at these positions for two different inlet configurations: low background turbulence level (TI = 0.23%) and high background turbulence level (TI = 10.0%). The high background turbulence level is generated by a regularly meshed grid installed at the test section inlet. The design tip speed ratio of both turbines is $\lambda_{T1,design} = \lambda_{T2,design} = 6.0$. Besides the design case at $\lambda_{T1,design}=6.0$, the wake flow behind the upstream turbine is analyzed for lower than optimum ($\lambda_{T1,low}=5.0$) as well as higher than optimum ($\lambda_{T1,high}=7.0$) tip speed ratios.

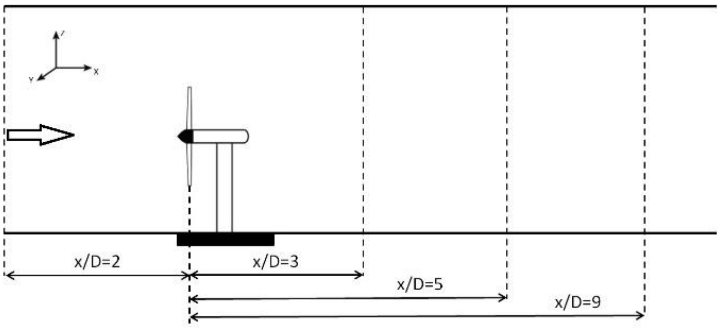

Fig. 1. First turbine setup and wake measurement stations.

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