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Mitigating adverse wake effects in a wind farm using non-optimum operational conditions

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ABSTRACT

Non-optimum operation of wind turbines is used in wind farm control to mitigate adverse wake effects, which result in a lower annual energy yield of wind farms. The current study investigates an operational strategy where upstream turbines are operated at non-optimum conditions thereby weakening the wakes. This approach is demonstrated for an existing wind farm in complex terrain. The computational fluid dynamics method allows the atmospheric flow and wakes, as well as their interaction with the terrain, to be accurately and simultaneously simulated. For a given wind direction, a 12.5% reduction relative to optimum in the power coefficient of an upstream turbine results in a 2.5% increase of the sum power production of the upstream and downstream turbine. The non-optimum operation can be accomplished with a 3.5° change in the blade pitch angle of the upstream turbine. The demonstrated approach in this work is thus well suited for the development of more advanced and complex operational strategies for other existing wind farms.

1. Introduction

With an annual growth rate of 23% from 2005 to 2014, total global installed wind capacity has reached 369 GW at the end of 2014 (GWEC 2014). Hence wind energy is among the most widely used renewable energy technologies. Moreover, wind energy's cost of electricity has become directly competitive with conventional sources of power generation for many markets. In wind farms, the interaction of wind turbine wakes with turbines results in power losses of up to 30–40% and up to 80% higher fatigue loads (Elliott 1991). As global installed wind power capacity increases the mitigation of wake effects in wind farms is of more importance. Approaches to optimise the layout of wind turbines in a wind farm maximise an objective function that is often a combination of energy production and operating costs, hence the focus is on improving operation of the overall wind farm (Mosetti et al., 1994; Beyer et al., 1996; Grady et al., 2005; González et al., 2010).

For wind speeds below rated wind speed, modern turbine controllers maximise the power production of each individual wind turbine (Pao and Johnson 2009). On the other hand in wind farm control the operation of the whole wind farm is optimised by using a coordinated control algorithm that specifies the operating point of each turbine. An advantage of an optimisation strategy based on controlling the operation point is its applicability to existing wind farms.

The objective function in wind farm control either (i) maximises the total wind farm power output or (ii) follows a specified power for the wind farm's total power output while minimising the fatigue loads for the wind turbines in the wind farm. Control strategies developed with the latter approach (Spudic et al., 2012; Horvat and Spudic, 2012; Soleimanzadeh and Wisniewski, 2011; Soleimanzadeh et al., 2012) derate upstream turbines in order to reduce the turbulence levels in the wake and consequently the fatigue loads on downstream turbines, while still operating the wind farm at a specified power. In the former approach, that is wind farm control that targets maximisation of the farm's total power output, the control is based on the hypothesis that some non-optimum operating conditions of upstream turbines increase total power production. As such numerical (Fleming et al., 2014, 2015; Jiménez et al., 2010; Porté-Agel et al., 2011) and experimental (Wagenaar et al., 2012; Adaramola and Krogstad, 2011) studies have investigated the use of manually induced yaw misalignment at upstream turbines to produce a skewed wake and thereby increase the power production of downstream turbines. Another strategy is to reduce the power extraction of upstream turbines so that downstream turbines are exposed to higher wind speeds in the weakened wake. Simulation using an actuator disc wind turbine model (Corten and Schaak, 2003; Johnson and Thomas, 2009) or semi-empirical wake models (Seem et al., 2013; Madjidian and Rantzer, 2011; Marden et al., 2013; Mirzaei et al., 2015) showed an increase in total wind

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Nomenclature

a	axial induction factor
c_P	power coefficient
k	turbulent kinetic energy
P	power
u	wind speed
λ	tip speed ratio
ΩR	blade tip speed
ω	omega

Abbreviations

ASL	Above sea level
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
IWTM	Immersed wind turbine model
RANS	Reynolds-Averaged Navier-Stokes
TSR	Tip speed ratio
WTG	Wind turbine generator

farm power. However these models do not accurately account for the aerodynamic interaction between wind turbines, in particular for multiple wake interactions. Thus, there is a large mismatch between the predicted and actual output powers of a wind farm (Beaucage et al., 2012). These simplified models therefore limit the more general applicability of derived control strategies to real wind farms. However, experiments in wind tunnels (Adaramola and Krogstad, 2011; Corten and Schaak, 2003; Barth et al., 2007) and full scale experiments (Schepers and Van Der Pijl, 2007) have shown viability of the approach. The below optimum power extraction was achieved by operating the turbines with a non-optimum blade pitch angle or a non-optimum tip speed ratio (TSR). However the use of downscaled models of wind turbines in wind tunnel tests results in lower Reynolds number compared to the full-scale, and as a result in differences of the turbine performance (Alfredsson et al., 1982). A wind farm control strategy developed in a wind tunnel will thus be different from the full scale. Full scale experiments for testing of wind farm control strategies are on the other hand prohibitively expensive.

Computational fluid dynamics (CFD) approaches to assess control strategies do not have the above limitations and thus are well suited for the design and testing of wind farm control strategies. In (Goit and Meyers, 2014) a gradient based optimisation

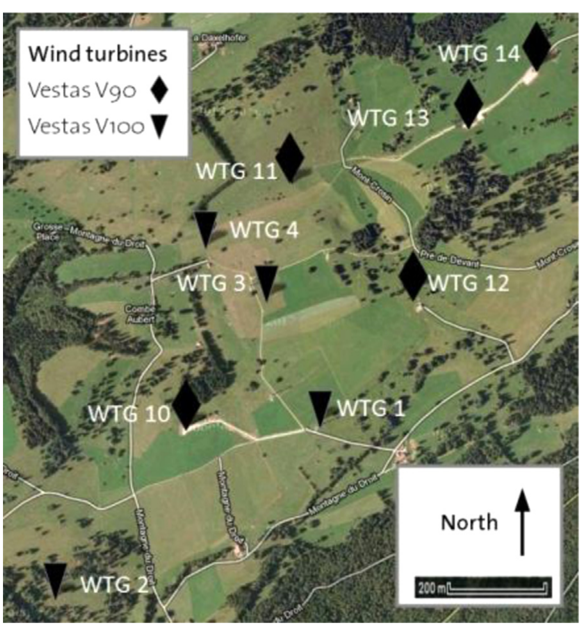

Fig. 1. Layout of the central portion of the wind farm located in complex terrain in western Switzerland.

Table 1
Summary technical data of simulated wind turbines.

Type	Quantity	Rated Power (MW)	Rotor diameter (m)	Hub height (m)	Cut-in/Rated/ Cut-out wind speeds (m/s)
Vestas V90	5	2	90	95	4/12/25
Vestas V100	4	1.8	100	95	4/12/25

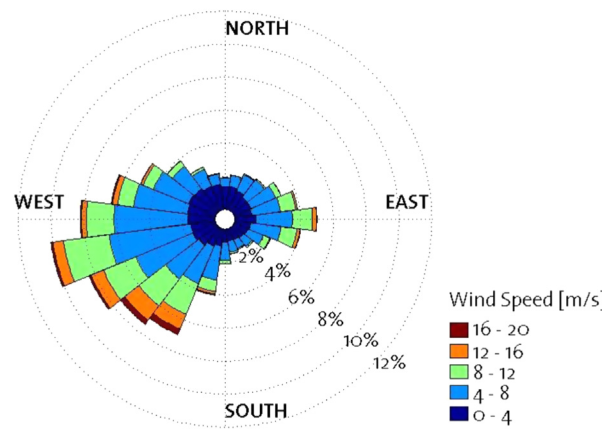

Fig. 2. Wind rose based on three-year measurements at wind farm site.

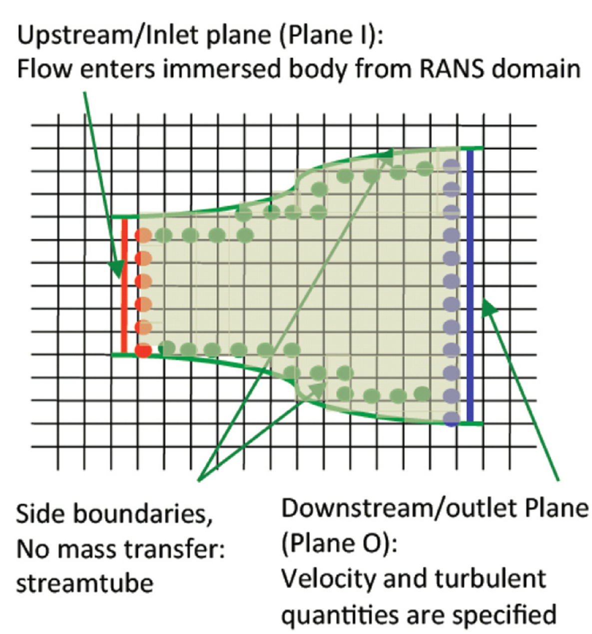

Fig. 3. Schematic of the immersed wind turbine model superposed on the Cartesian grid (Jafari et al., 2013).The immersed body is a stream-tube around the rotor plane of a wind turbine. The predicted near-wake velocity field is mapped at the outlet plane (Plane O) onto the RANS computational domain. The far-wake region is resolved on the computational grid by the RANS solver.