Power curves in a wind turbine array: A numerical study

A R Meyer Forsting[1], **N Troldborg**[1]

[1] DTU Wind Energy, Department of Wind Energy, Technical University of Denmark, Risø Campus, DK-4000 Roskilde, Denmark

E-mail: `alrf@dtu.dk`

Abstract. The impact of measuring a power curve inside a wind turbine array is investigated using computational fluid dynamics. The array consists of five aligned rotors that yaw with the free-stream wind direction. The flow-field in front of a wind turbine array changes with wind direction and hence the individual power output of each turbine. By incorporating the current IEC standards on power performance measurements, the bias in the power performance of turbines in an array over an isolated rotor is determined. The bias depends on the position of the turbine in the array and reaches maximally 1.27%.

1. Introduction

The flow coming towards a wind turbine rotor is continuously decelerated by the rotor's thrust force acting on it. The thrust is in turn a result of the aerodynamic forces acting on the rotor blades. The area over which this effect acts is also referred to as the "induction zone". Medici *et al.* [1] found that the influence of the turbine extends up to 6 rotor radii (R) upstream, using computational fluid dynamics (CFD) and wind tunnel measurements. Field measurements using wind lidars confirmed the presence of the decelerating region in front of the turbine, though the exact extent of it is disputed with Asimakopoulos *et al.* [2] putting it $7R$ upstream and Slinger *et al.* [3] at $3R$. The IEC standards for power performance measurements [4] on the other hand assume the turbine to have a negligible effect beyond $4R$ upstream. Therefore this value also acts as guideline for industry. Nevertheless the standards ignore the effect of surrounding turbines on the induction zone and thus the impact it might have on the individually measured power curve. The authors [5] have previously investigated the power production along a row of five aligned rotors using computation fluid dynamics. They found a variation of the power produced relative to an isolated rotor between -1.1% to 2.0% depending on the wind direction. This was without any wake interaction. The variation could be directly linked to significant alterations in the upstream flow-field. However, the analysis was limited to a single wind speed and therefore its potential impact on the power curve not further investigated.

Consequently this paper determines the individual power curves of rotors situated in an array using the IEC standards for power performance measurements [4]. These power curves are compared to the ones generated for an isolated turbine. The array consists of a row of five aligned rotors and is simulated using CFD with an actuator disc representation of the NREL 5-MW wind turbine. The inflow is varied from orthogonal to the alignment axis of the turbines to 45°.

2. Method

The turbine arrangement chosen in this investigation is very generic, consisting of five rotors with a single axis passing through all their centres. The inter rotor spacing is $6R$. The angle between the line of wind turbines and the main wind direction (θ) is set to 0° and 45°. The turbines yaw in-line with the inflow as shown in Figure 1. Wind speed measurements are taken at $y = -4R$ in front of each turbine (● in Figure 1) at hub height (90 m) and related to the power produced by each rotor. Wind shear is modelled with a logarithmic velocity profile and a roughness length (z_0) of 0.05. The friction velocity is changed such that the velocity at hub height covers the entire operational wind speeds of the NREL 5-MW. The hub height inflow velocity ($V_{\infty,h}$) is varied from the cut-in wind speed of 3 m/s to the rated speed of 11.25 m/s by 1 m/s steps. Above rated the step increases to 2 m/s until the cut-out speed of 25 m/s. Furthermore the solution at each wind speed is assumed to be time invariant. Of the turbines only the rotors are modelled as actuator discs (AD), whereas the turbine tower and the nacelle are ignored. Simplifying the turbine in this way is not expected to impact the results, as the flow on the investigated scale is dominated by the rotors.

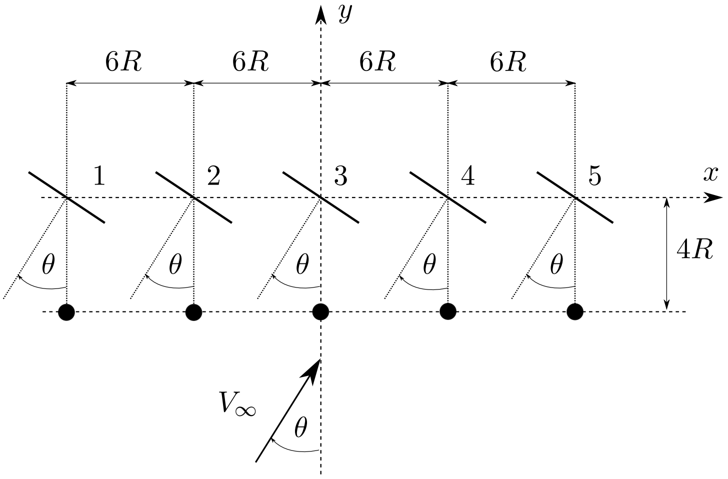

Figure 1. Schematic of the wind turbines' arrangement and reaction to changing inflow directions and the position of the wind speed measurements (●).

2.1. Computational method

2.2. CFD

2.2.1. Flow solver The flow field is solved via the in-house developed finite volume code EllipSys3D. It solves the incompressible Reynolds Averaged Navier-Stokes (RANS) equations over a discretised block-structured domain [6–8]. To avoid velocity-pressure decoupling in the presence of discrete body forces, originating from an actuator disc (AD), a Rhie-Chow algorithm [9–11] is applied to the convective term. A modified $k - \epsilon$ [12] turbulence model is used, which captures turbulence at both, terrain and rotor scales. The rough logarithmic velocity profile models the near ground flows as described by Sørensen [6].

2.2.2. Turbine model The turbine rotors are represented by actuator discs. The discrete body forces acting over the disc are either determined iteratively from the local blade velocities and airfoil data of the NREL 5-MW [13] with a 126 m diameter. The rotations per minute (RPM) and the pitch are defined by the controller.

3. Results

In Figure 2 the percentage change in the power output with measured hub height wind speed for turbines no. 1 and no. 5 is shown with respect to an isolated turbine. These results are obtained with a large inflow angle θ of 45°. In the previous study of the authors [5] these turbines showed the largest changes in power and in the upstream flow-field. Using the reference velocity at hub height at $y = -4R$, as suggested by the IEC standard, the power of both turbines is consistently above that of an isolated rotor. The smallest deviation is found for turbine no.1 with 0.26%, whereas turbine no. 5 presents the largest at 1.27%. For the latter rotor the change in power stays about constant for most of the velocity range investigated.

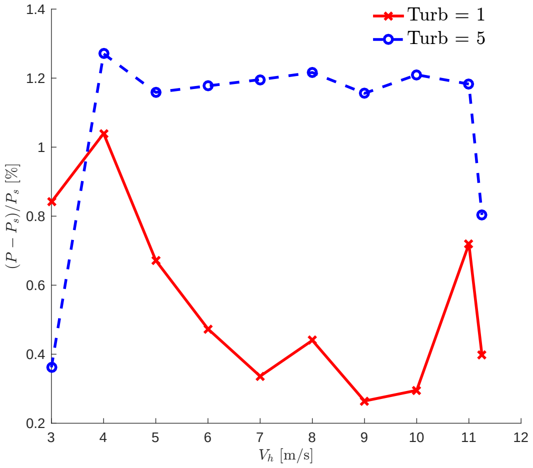

Figure 2. Percentage change in the power output with respect to an isolated turbine as function of the measured hub height wind speed at $y = -4R$ for turbines no. 1 and no. 5. The inflow angle θ is 45° and the results have been calculated with CFD-RANS.

4. Conclusion

To the author's knowledge this is the first investigation of the impact of neighbouring turbines on power curve measurements. Generating power curves for all turbines in an array following the IEC standards for power performance measurements and changing the inflow direction, a shift in the power curves can be registered relative to an isolated turbine. This shift reaches up to 1.27%. Nevertheless it remains to be seen, whether continuously changing inflow directions experienced during real power curve measurements nullify this bias.

Acknowledgments

This work was performed inside the UniTTe project (unitte.dk), which is financed by The Innovation Fund Denmark, grant number 1305-00024B.

References

[1] Medici D, Ivanell S, Dahlberg J A and Alfredsson P 2011 *Wind Energy* **14** 691–697
[2] Asimakopoulos M, Clive P and abd R Boddington G M 2014 Offshore compression zone measurement and visualisation *Proceedings of the European Wind Energy Assosciation 2014 Annual Event* (Barcelona, Spain)
[3] Slinger C, Leak M, Pitter M and Harris M 2013 Relative power curve measurements using turbine mounted, continous-wave lidar *Proceedings of the European Wind Energy Assosciation 2013 Annual Event* (Vienna, Austria)
[4] *IEC 61400-12-1:2005, Power performance measurements of electricity producing wind turbines.*

[5] Meyer Forsting A and Troldborg N 2015 *Journal of Physics: Conference Series (Online)* **625** 012029 ISSN 1742-6596

[6] Sørensen N 1995 *General purpose flow solver applied to flow over hills* Ph.D. thesis RisøNational Laboratory

[7] Michelsen J 1994 Basis3d - a platform for development of multiblock pde solvers Tech. Rep. AFM 92-05 Dept. of Fluid Mechanics, Technical University of Denmark, DTU

[8] Michelsen J 1994 Block structured multigrid solution of 2d and 3d elliptic pdes Tech. Rep. AFM 92-06 Dept. of Fluid Mechanics, Technical University of Denmark, DTU

[9] Réthoré P E and Sørensen N 2012 *Wind Energy* **15** 915–926

[10] Réthoré P E and Sørensen N 2013 *Wind Energy*

[11] Troldborg N, Sørensen N, Réthoré P E and van der Laan M 2015 *Computers & Fluids* **119** 197–203

[12] van der Laan P, Sørensen N N, Réthoré P E, Mann J, Kelly M C, Troldborg N, Schepers J G and Machefaux E 2014 *Wind Energy*

[13] Jonkerman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-mw reference wind turbine for offshore system development Tech. Rep. 500-38060 NREL Golden,USA