Upstream turbine effect on the downstream turbine performance: a wind farm case optimization

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INTRODUCTION

In a wind farm, wakes interact with each other and directly affect the downstream turbine performances. In this context, a wind tunnel turbine wake study and an analysis of the combined power output of a 2-turbine array are studied. The wake analysis is focused on the description of the wake development at different downstream stations for different turbine operating conditions and flow regimes. The performances of a turbine operating in the wake are analysed for different configurations focusing on the 2-turbine array power output; moreover a wake-rotor interaction is attempted. The array overall efficiency is found to increase by moving the second turbine further downstream, with an increased background turbulence level and by choosing a suitable operating point for each turbine.

METHODS

The experimental analysis is carried out at NTNU aerodynamic labs and the measurement set up is shown in Fig. 1. The reference wind speed is U_{ref} = 11.5 [m/s] (Eq. 1) and 2 model wind turbines of D ≈ 0.9 [m] [1] are used for the investigations. The turbines operating points are set by handling the rotor speed via a frequency converter. No variations in blade pitch angle are contemplate.

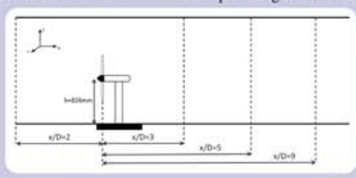

Figure 1: First turbine setup: wake measurements.

The torque (T) and the rotational speed (ω) are directly measured on the turbines shaft and the power coefficient C_P is evaluated (Eq. 2). The model turbines maximum C_P is achieved at TSR = 6 (Eq. 3). Two different turbulent flow conditions have been arranged in the tunnel:

- Wind tunnel (Low) turbulence level (TI = 0.23%).
- Similar-atmospheric (High) turbulence level (TI = 10%)

In both conditions turbine horizontal wakes behind a single turbine are measured using a hot wire anemometer. Relative velocity (U_{rel}, Eq. 1) and turbulence intensity (TI [%], Eq. 4) are analysed at 3D, 5D and 9D behind the turbine. The second turbine is located in the tunnel (Fig. 2) and for each tip speed ratio configuration (λ_1, λ_2) the array efficiency E [%] (Eq. 5) is obtained.

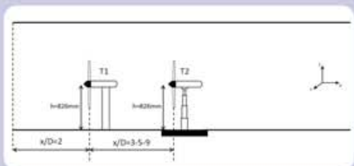

Figure 2: Two turbines setup: array efficiency optimization.

$$U_{rel}[-] = \frac{\bar{U}}{U_{ref}} \quad (1)$$

$$C_P = \frac{T\omega}{\frac{1}{2}\rho U_\infty^2} \quad (2)$$

$$TSR = \frac{\omega * R}{U_{ref}} \quad (3)$$

$$TI[\%] = \frac{u'}{\bar{U}} * 100 \quad (4)$$

$$E = \frac{C_{P,T1} + C_{P,T2}}{C_{P,T1max} + C_{P,T2max}} \quad (5)$$

RESULTS

Single turbine wake development

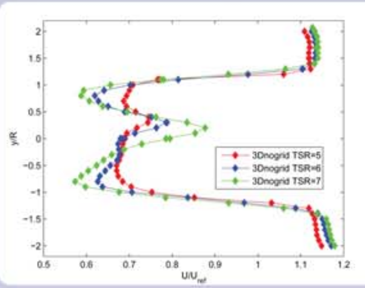

Figure 3: Relative flow velocity, 3D distance behind the turbine working at λ_1= 5,6,7.

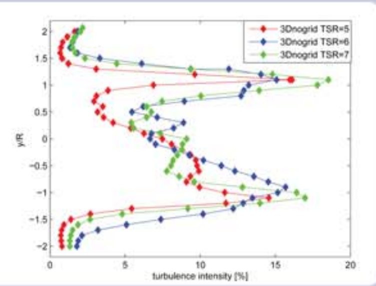

Figure 4: TI, 3D distance behind the turbine working at λ_1= 5,6,7.

- No λ dependency on radial expansion is noticed neither at 3D nor at 9D.
- At 3D (Near wake), by varying λ, the rotor inner sections feed momentum into the wake (Fig. 3) and produce big variations in TI (Fig. 4).
- At 9D (Far wake) behind the rotor, almost no difference is visible with λ variations (Fig. 5, 6).
- Generally, by increasing λ, wakes TI increases, since higher thrusts on the turbine induces strongest mean velocity gradients. Tip peaks and turbulence overall level monotonically increase.

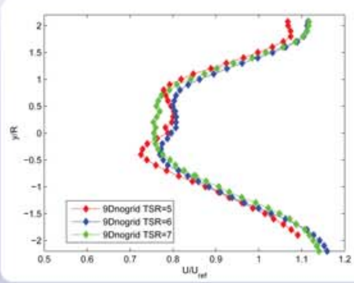

Figure 5: Relative flow velocity, 9D distance behind the turbine working at λ_1= 5,6,7.

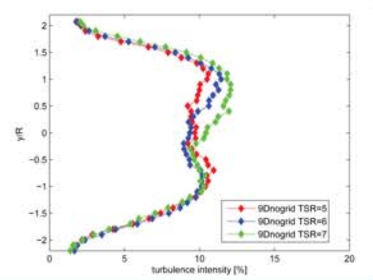

Figure 6: TI, 9D distance behind the turbine working at λ_1= 5,6,7.

Correlation between wake behind the first turbine and the power output of the second turbine

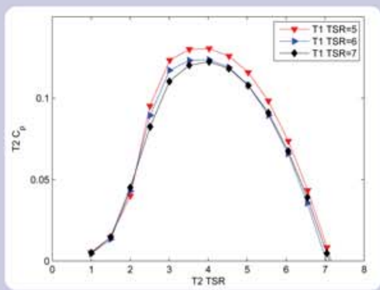

Figure 7: T2 C_P with λ_1= 5,6,7.

At 3D separations even small variations in turbine λ, strongly affect the velocity deficit in the wake (Fig. 3) resulting in a detectable C_P variation for T2 (Fig. 7). Velocity deficit peaks become deeper in the outermost region (0.5<y/R<1) leading to less T2 energy extraction.

Two turbine array case study

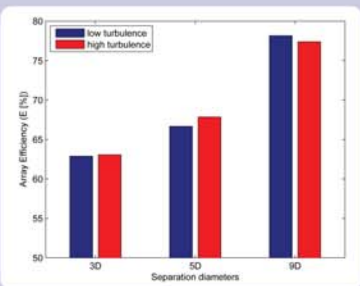

Figure 8: Max array efficiency achievable in each configuration.

Configuration	Max array efficiency [%]	Operating cond. λ_1	λ_2
0.23%, 3D	62.8	5	4
0.23%, 5D	66.5	5.5	4
0.23%, 9D	78	5	5
10%, 3D	63	5.5	4
10%, 5D	67.5	6	4.5
10%, 9D	77	6	5

Table 1: Max array efficiency for λ_1,λ_2 operating condition, each TI and separation configuration.

- Higher turbulence induced by the grid accelerates the velocity deficit recovery until the grid effect is distinct (5D); at 9D the turbulence induced is neglegible.
- A slight λ dependency on E is found. A bigger amount of energy is available for T2 if λ_1 is slightly decreased from optimum, resulting in a higher E (Tab. 1).
- A constant impact of approximately 2.5% wind farm overall efficiency recovery is found for every additional diameter separation distance between the turbines.

CONCLUSIONS

The parametric study points out a strong array efficiency dependency on:

- INFLOW TURBULENCE LEVEL: the higher the turbulence, the faster the velocity recovery, the bigger the array efficiency. High turbulence wind tunnel results are better matching the full scale reality (atmospheric inflow) [2].
- Turbines TSRs: best results of array efficiency are found with the 1st turbine running at λ slightly lower than the optimum operating point, especially for small separation distances.
- Turbines SEPARATION DISTANCE: +2.5% of array efficiency for every additional separation diameter.

Accurate management of all the parameters is advised.

References

[1] Per-Åge Krogstad and Pål Egil Eriksen. "blind test" calculations of the performance and wake development for a model wind turbine. *Renewable Energy*, 50(0):325–333, February 2013.
[2] Jan-Ake Dahlberg. Assessment of the lillgrund wind farm: power performance wake effects. *Vattenfall Vindkraft AB, 6 1 LG Pilot Report*, 2009.