FULL SCALE VERIFICATION OF WIND FARM PRODUCTION PREDICTIONS

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INTRODUCTION

Production estimates of wind farms are a topic of utmost importance for obvious reasons. Due to computational limitations, wind farm production estimates have up to now entirely been based on a *stationary* description of the wind farm flow field assuming *neutral* atmospheric stratification. A large number of models within this model segment have been proposed ranging from simple engineering models to fairly complex CDF based models. The CFD models are typically adapting the RANS approach with the turbulence closure being based on some variant of the Boussinesq approximation. However, in-stationary flow field effects are known to be of importance especially for wind turbine fatigue load predictions [1], and atmospheric stability effects were demonstrated to influence wake losses significantly in a study based on data from the Danish Nysted wind farm [2].

MODELS

The development of two new models has opened for a more detailed and accurate description of wind farm flow fields, in which buoyancy effects and in-stationary effects may be included.

The first model is Fuga [3], which is a linearized RANS type of CFD model based on a mixed spectral formulation that makes it approximately one million times faster than a conventional RANS CFD model and at the same time circumvent the problem of numerical diffusion. A dedicated turbulence closure allows buoyancy effects to be approximated in a simple and efficient manner.

The second model is the ‘poor man’s LES’ [4] – often denoted the dynamic wake meandering model (DWM) – which is a computationally affordable approach including the basic features of the CFD LES approach in an engineering manner. Combined with an aerodynamic rotor model it features full aerodynamic description of the wind farm turbines including control. The basic idea behind the DWM model is to model the in-stationary wind farm flow characteristics by considering turbine wakes as passive tracers continuously emitted from the wind farm turbines, each with a downstream transport process dictated by a combination of large scale turbulent eddies (lateral and vertical transportation; i.e. meandering) and Taylor advection. Buoyancy effects are included in a physical way by modeling the buoyancy effects on the large scale turbulence eddies driving the wake meandering.

MEASUREMENTS

The performance of Fuga and DWM, when used for wind farm *power production* predictions, are analyzed in detail. For this purpose model production predictions are compared with full-scale production measurements from the Dutch off-shore Egmond aan Zee wind farm [5].

The Egmond aan Zee wind farm consists of 36 Vestas V90 turbines, and the available measurement data set cover a full year of production data for all turbines. The farm layout is shown in Figure 1.

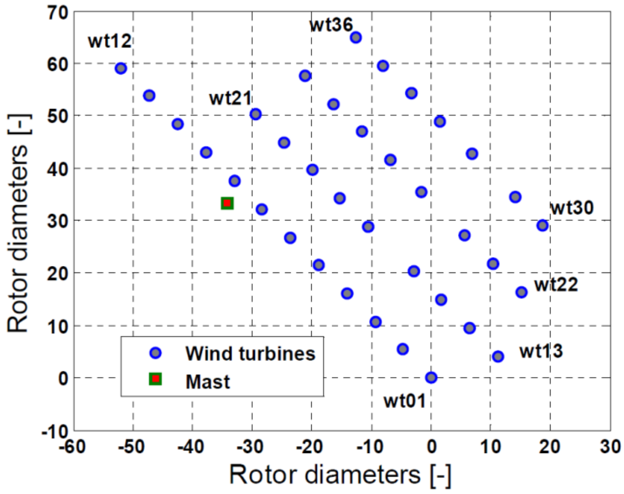

Figure 1: Wind farm layout.

REULTS

The production of the *entire wind* farm is investigated for a full polar (i.e. as function of mean inflow wind direction). For each inflow direction the investigation further includes all measured mean wind speeds and atmospheric stability conditions. The atmospheric stability conditions are defined in terms of the Monin-Obukhov length, and up to seven different stability classes are investigated – depending on which of these are represented in the full scale data.

Based on the statistics of the wind farm production conditioned on wind direction, atmospheric stability class and ambient wind speed, the aggregated annual wind farm production predicted by the two models is compared with the measured value. Finally, the annual wind farm production conditioned on stability class is analyzed by mutual comparisons of model predictions and measurements.

Figure 2 shows the wind farm production versus direction as predicted by Fuga and DWM as well as the corresponding measured production versus direction based on a 5^{o} direction binning. The analysis of the full-scale data is based on approximately 6000 10-minute average values and includes all stability conditions (i.e. averaged over all observed stability classes). In general both model predictions reflect the measured polar well. However, the significant production drops associated with mean wind directions 139^{o} and 319^{o}, which relates to a wind direction along the NW-SE wind turbine rows (cf. Figure 1), is somewhat more pronounced in the model predictions than in the measurements. This is presumably related to the fact that the available *one-point* mean wind direction observation is not fully coherent with the actual mean wind direction at each turbine position for the considered 10-minute time spans, thus in turn introducing a "smearing" effect on the wake losses. Note in this respect that the wind farm covers an area of the order of 15 square kilometers, with the longest row of turbines being 7 kilometers.

The lack of full mean wind direction coherence is linked to the fact that the boundary layer flow field is in-stationary with the additional consequence that the recorded one-point direction signal may contain large scale trends which, however, may be compensated for through suitable averaging. Even though the DWM model includes in-stationary effects, it only includes such effects on scales that may be represented in the simulation time span (i.e. usually 10 minutes), which is, however, fully sufficient for wind turbine fatigue load predictions.

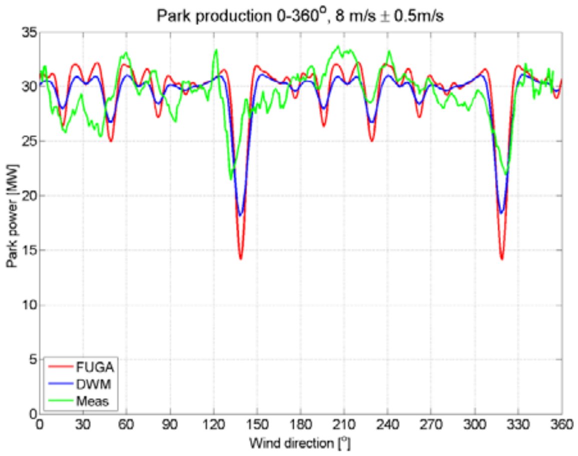

Figure 2: Wind farm production as function of mean wind direction.

Comparing the two model predictions a close agreement is seen. The only notable difference is that the DWM results are slightly "smoother" than the Fuga results, which is attributed to the fact that DWM includes "wake meandering" caused by the large scale turbulent eddies with frequencies down to the inverse of the simulation time.

Finally, the wind farm production averaged over wind direction has been computed assuming a uniform wind direction probability density function. The result is 29.30MW, 29.56MW and 29.26MW for measurements, Fuga and DWM, respectively. This is surprisingly close and is very promising for the future development of these models.

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