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Spectral coherence model for power fluctuations in a wind farm

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ABSTRACT

This paper provides a model for the coherence between wind speeds located in a horizontal plane corresponding to hub height of wind turbines in a large wind farm.

The model has been developed using wind speed and power measurements from the 72 Wind Turbines and two of the meteorological masts from Nysted offshore wind farm during 9 months.

The coherence model developed in this paper is intended for use of power fluctuations in large offshore wind farms. In this way, analysing the current coherence models it is shown the needing of a new one, adapted to the characteristic distances and the related time scale.

1. Introduction

Nowadays the concern about the effects of the pollution (like the global warming effect) and the knowledge of the limitations of the fossil resources are creating a strong tendency in Europe towards the use of renewable energy sources. Therefore, there has been a great growth in the Wind Energy development, and it is expected to go on rising. Such growth makes essential to research deeply into this energy technology from the point of view of an important component of the electrical system, instead of considering only the local voltage quality as it was done previously (Sørensen et al., 2007).

A major issue in the control and stability of electric power systems is to maintain the balance between generated and consumed power. Because of the fluctuating nature of wind speeds, the increasing use of wind turbines for power generation has risen the interest in the fluctuations of their power production, especially when the wind turbines are concentrated geographically in large wind farms. That fluctuation can also be a security issue in the future for systems with weak interconnections like Ireland or the Iberian Peninsula. Moreover, wind power fluctuations increases operational reserve requirements in power systems (Holttinen et al., 2008).

As example of the significance of these power fluctuations in Energinet.dk (the Danish Transmission System Operator), according to Akhmatov et al. (2004), Energinet.dk has observed that power fluctuations from the 160 MW offshore wind farm Horns Rev in West Denmark introduce several challenges to reliable operation of the power system in West Denmark. And also, that it contributes to deviations from the planned power exchange with the European Network of Transmission System Operators for Electricity (ENTSOE). Moreover, it was observed that the time scale of the power fluctuations was from tens of minutes to several hours.

And in those fluctuations the importance of the spatial correlation of the wind speed in that time frame is shown by the fact that the power fluctuations of the 160 MW wind farm was significantly greater than the fluctuations in a similar capacity of Wind Turbines (WTs) distributed in smaller onshore wind farms. Those conclusions point out that the research of the spatial correlation is a main topic for the power fluctuation analysis.

In this way, models of coherence have been used within the modelling of wind farms regarding power fluctuation. Sørensen et al. (2002) developed a wind speed model for a wind farm using a coherence model. In this case, the aim of the model was to simulate the oscillations in the shorter time scales related with the power quality characteristics. Sørensen et al. (2008) show how the spectral coherence can be included into an overall model for simulating power fluctuations in 2 h intervals. Furthermore, the spectral coherence model suggested here is used by Vigueras-Rodríguez et al. (2010) in an aggregated overall model which is validated for its use on power fluctuations. For analysing extended regions, longer time intervals could be considered under different approaches (Vincent et al., 2011; Sørensen et al., 2009).

The novel contribution of this paper is based on providing a spectral coherence model between wind speeds suitable for its use in power fluctuations from large offshore wind farms. In order to develop that model, real data collected from Nysted offshore wind farm is analysed.

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The rest of the paper is organised as follows. In Section 2, coherence models found in the literature are introduced, evaluating their suitability for power fluctuations studies. Section 3 shows the experimental data used and their characteristics. Procedure for calculating spectral coherence parting from the available experimental data is described in Section 4. The results are shown and analysed in Section 5. From these results, adequate spectral coherence models are suggested and optimised in Section 6. Section 7 shows a comparison between the suggested models and the literature ones. Conclusions are given in Section 8.

2. Coherence models for power fluctuation

Besides the practical observation of the link between the power fluctuation and the spectral coherence above cited, different theoretical and practical observations have appeared in some papers (Nanahara et al., 2004; Sørensen et al., 2008). These works confirm that the seeking of power fluctuations models is totally linked with the coherence models in a wind farm scale.

The spectral coherence relates the crossed power spectral density (CPSD) of two different time series with their power spectral density (PSD). CPSD is defined as the Fourier transform of the cross-correlation between both time series. Analogously, PSD is defined as the Fourier transform of the auto-correlation of a single time series. PSD and CPSD are represented in frequency domain, and so is spectral coherence.

Particularly, the spectral coherence between the wind speed in two different points is given by

$$\gamma(f) = \frac{S_{ab}(f)}{\sqrt{S_{aa}(f) S_{bb}(f)}} \tag{1}$$

where $S_{ab}(f)$ is the crossed power spectral density between the wind speed in points a and b, and $S_{aa}(f)$ and $S_{bb}(f)$ are the power spectral density of the wind in each point for the frequency f.

Regarding the current coherence models, most of them are based in modifications to the Davenport (1961) model. Davenport suggested the exponential behaviour given by the following expression

$$|\gamma| = e^{-a\ d{\cdot}f/V} \tag{2}$$

where a that is usually called decay factor, is a constant, d is the distance between both points and V is the average wind speed.

However, this model, and most of its derived models (Solari, 1987), do not explain the dependence between decay factor and inflow angle found in real data in the scale of a wind farm (Vigueras-Rodríguez et al., 2006). That is due to the fact that the models were fitted for other applications, for instance the model developed by Solari (1987) faced wind gust loading in a wind turbine. For this application, inflow angle influence was negligible as far as wind is supposed to be almost perpendicular to the "rotor disk". Within this application quick variations of wind speed and small distances are analysed. At this paper, focused in wind power fluctuations of large wind farms, inflow angle influence need to be considered, as well as larger distances. Moreover, the variations of wind speed which are important for wind power fluctuation are quite slower than for gust loading.

Nevertheless, the modifications suggested by Schlez and Infield (1998) introduced that dependency expressing the decay factor a as a function of the inflow angle:

$$a = \sqrt{(a_{long} \cdot \cos\alpha)^2 + (a_{lat} \cdot \sin\alpha)^2} \tag{3}$$

being a_{long} and a_{lat} respectively the decay factors for the longitudinal and the lateral cases given by

$$a_{long} = (15 \pm 5) \cdot I_V \tag{4}$$

$$a_{lat} = (17.5 \pm 5)\ (\mathrm{m/s})^{-1} \cdot I_V \cdot V \tag{5}$$

being $\overline{V}$ I_V the turbulent intensity defined by $I_V = \sigma_v / V$, where σ_V is the standard deviation of the wind velocity.

Despite this empirical model introduced the inflow angle dependence, it was based on a very limited distance scale and a low height. In fact, the experiments were carried out with distances up to 100 m and with a height of 18 m above ground in Rutherford Appleton Laboratory test site. Therefore, the scale of the experiment is significantly smaller than the size of current wind farms. Moreover, the existing observations in larger distances (Vigueras-Rodríguez et al., 2006; Nanahara et al., 2004) pointed out to a different behaviour.

So, in this paper the spectral coherence between wind speeds with distances between near 0.5 km and 6 km, with a height of 69 m, is studied, with the aim of suggesting a suitable model for analysing power fluctuations from large offshore wind farms.

3. Experimental data used

The data used in this work is based in the Nysted wind farm, which is an offshore wind farm compound of 72 Siemens SWT-2.3-82 fixed speed wind turbines, with a global nominal power of 165.6 MW and distances between the wind turbines between 0.48 km and 7.73 km.

This work is based, mainly, on the wind speed measured by each WT nacelle (69 m above sea level), as well as the velocity and wind direction acquired in the meteorological masts MM_2 and MM_3 (70 m above sea level). The layout of the WTs and the meteorological masts is shown in Fig. 1.

The measurements, which correspond to 9 months in 2005, have been obtained through the data acquisition system used by the wind farm main controller, which logs the data with a 1 Hz sampling frequency.

4. Procedure of the coherence measuring

The measured data has been divided into 2-hour intervals. The selection of the length of the intervals is as a compromise. On one hand, the segments should be long enough to include the power fluctuations which were identified by the Danish TSO Energinet.dk to influence the cross boarder flow between Denmark and Germany (Akhmatov et al., 2004). On the other hand, the segment

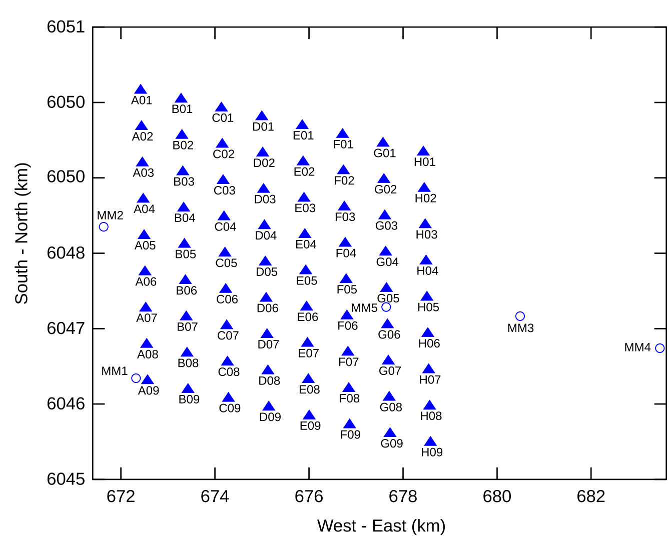

Fig. 1. Layout of the Nysted wind farm.