Experimental analysis of time delays in wind turbine wake interactions

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Abstract. Wind farm control is a current hot topic that deals with the capacity to improve the overall wind power production of a farm by controlling individual wind turbines in order to mitigate their wake effects. The dynamic properties of these different strategies need to be taken into account in order to improve wind farm control models. In this work a post-processing of SCADA data acquired with a high sampling frequency on two neighboring wind turbines is performed through inter-correlation functions in order to assess the time delays between the wind turbine responses depending on wind direction and wind speed.

1. Introduction & work objectives
Nowadays to deal with cost reduction and development constraints the principal solution is to densify wind farms \cite{1}. This strategy brings some inconveniences such as wake interactions that leads to power losses and fatigue increase. To reduce these side effects wind farm control is the envisaged solution. Indeed, these control strategies aim to improve the overall wind power production of a farm by controlling individual wind turbines in order to mitigate their wake effects. Two strategies are mainly studied, the induction control that is based on a power curtailment strategy and the yaw control that is based on a wake steering strategy. The potentiality of wind farm control has already been investigated and confirmed by simulations \cite{2,3} and full scale field tests \cite{4-6}. The dynamic properties of these different strategies are now taken into account in some wind farm control models \cite{7} but some parameters need to be refined. For instance, the time delays between a manoeuvre of an upstream wind turbine and its effect on the downstream one can be approached by a pure advection hypothesis, assuming that the time delay is equal to the time for the air masses advected at the free wind speed to transit from the upstream to the downstream wind turbine. Some previous works suggested to use a proportion (80\%) of the free wind speed as advection speed \cite{7}, or an average between the free wind speed and the wake speed \cite{8}. Furthermore, the wind turbine dynamic response will also impact the overall time delay. Consequently, this parameter needs to be further studied and better quantified. Through the post processing of a field database collected during the French national project SMARTEOLE on two full-scale wind turbines, the overall time delay between the dynamics of two wind turbines will be assessed. Correlation functions between both wind turbine power time series acquired at a sampling frequency of 1Hz are performed and time delays
between the wind turbine responses are assessed. By classifying the set of time series according to the wind direction and the wind turbine operating point, the influence of the wake interaction on the time delay between the wind turbine responses will be studied.

2. Approach & methods
2.1. Experimental setup
The measurement campaign took place on a wind farm (WF) located in the north of France (Figure 1) with measurements done between January 2017 and November 2018 and already used in [9] and [10]. The WF (Engie Green owned) is called Sole du Moulin Vieux (SMV) and is located on the western limit of the Ablaincourt-Pressoir municipality. It is made of seven wind turbines (WTs) named SMV1 to SMV7 which are sited from north to south and spaced approximately 4.3 D apart. These SENVION MM82 WTs (guaranteed power curve in figure 2b) have a diameter (D) and hub height (HH) of D = 82 m and HH = 80 m; and their nominal power is 2050 kW which is reached for a nominal wind speed of 14.5 m s⁻¹, while their cut-in wind speed is 3.5 m s⁻¹.

Figure 1: Layout of the SMV wind farm and location of wind measurement devices. Inter-distances between the wind turbines are expressed in rotor diameters (with D=82 m), while red arrows indicate the wind direction with maximum wake interaction between the turbines. The location of the ground based lidar Windcube V2 is also indicated.
The site is not complex, with a very flat terrain composed mainly of grasslands, with the exception of a small forest located south of the farm. The long term observed wind, illustrated on the wind rose of figure 2a, shows that the prevailing wind directions come mainly from the south west. This corresponds mostly to the alignment between turbines SMV5 and SMV6 which is 207° with respect to the north, consequently this layout makes it possible to observe a very strong and frequent wake effect between these two turbines.

Figure 2: Wind resource at the site of Ablaincourt-Pressoir and guaranteed power curve of the wind turbines.

2.2. Identification of reference wind turbines
A crucial point of this work was the supervisory control and data acquisition (SCADA) time series classification according to wind direction and wind speed. Indeed measurements of two different wind turbines in the same WF can be discordant for multiples reasons, so an inaccurate choice of the reference WT can trick the classification. Concerning the wind speed just the presence of the wake of an other WT can affect the measurements, while for wind direction some undesired bias on the vane position can false the measurements. In order to reduce the possible sources of error in the estimation of the wind characteristics the SCADA data-set quality was tested taking as a reference a ground based lidar (Windcube V2) whose location is indicated on figure 1. Indeed over a quite large period of measurement (May 2017 - Jan 2018) both SCADA and Windcube data were available. The lidar provides averages over ten minutes of wind speed and direction at different heights. The SCADA average wind measurements for the same ten minutes intervals were compared to the lidar measurements at the range 80 m only, to be consistent with the wind turbine hub heights. For each wind turbine in the farm, the difference in measured wind speed and direction was calculated for each sample, and then this data-set was classified according to the Windcube wind direction and binned over 20° sector, giving a single mean error value per wind turbine for each direction sector. Some considerations regarding the lidar position have to be done before analyzing the results. Indeed, according to the farm layout in figure 1, the lidar is generally in the wake of one or more WT for mostly the wind sectors [20°:180°]. This affects its measurements, especially concerning the wind speed, and thus those sectors are disregarded in the following analysis. The first evaluation was focused on the wind direction measurement: this measurement being less sensitive to wake effects it was chosen to establish a single reference WT in order to proceed with the classification of the entire SCADA data-set over wind sectors. The wind direction was evaluated looking at the mean absolute error (MAE) between the seven WT SCADA measurements and the Windcube. Figure 3 shows the result of this analysis. Looking at the MAE, and taking into consideration the position of...
the Windcube, the WT SMV3 is a good choice as reference since its MAE is generally among the smaller for most of the bins, and in particular for the sector of maximal wake interaction. Focusing on the wind sector [180°:340°] (Windcube upwind) it shows a maximum error below 8°.

![Figure 3: SCADA wind direction measurements mean absolute errors (MAE)](image)

The same kind of evaluation was done as regards to the wind speeds. The percentage error of the SCADA wind speed measurements with respect to the Windcube was calculated for each sector. Figure 4 shows the results of the analysis. Three different WT references has been taken according to the wind sectors in order to consistently take into account the wake effects within the wind farm. Indeed, looking at sector [220°:320°], where there are no supposed wake interactions, SMV4 represents a good choice (measurement error generally less than 2%) as a reference for this sector. Just by symmetry considerations, SMV4 has been also chosen as reference for the sector [40°:140°] since the Windcube is an unreliable reference for this sector. Then according to the farm layout and the observed results, it is reasonable to take SMV1 as reference for northern wind sectors [340°:20°] and respectively SMV7 for southern sectors [160°:200°].
Figure 4: SCADA wind speed percentage mean errors

The table below recaps the chosen reference wind turbines for each wind sector.

Table 1: Summary of the reference turbines chosen for wind speed and wind direction measurements, depending on the wind direction sector.

| Wind direction sector | Reference wind turbine |
|-----------------------|------------------------|
| North [340°; 20°]     | SMV1                   |
| East [40°; 140°]       | SMV4                   |
| South [160; 200°]      | SMV7                   |
| West [220; 320°]       | SMV4                   |

2.3. Data filtering & processing

Once determined the proper references for the estimation of wind characteristics it was possible to process the whole SCADA database. The database contains ten minute averaged and standard deviation data for each WT and high frequency sampled data (1Hz) for WT SMV5 & SMV6 only. Before using the inter-correlation functions on the active power signals of these two turbines for each ten minutes interval, some filtering had to be made. The filters that were applied to the data are listed below:

(i) Both wind turbines had to be operational.
(ii) No movement of the nacelle position of both turbines had to be observed.
(iii) Any abnormal turbine behavior (such as curtailment) was filtered out.
(iv) Only periods with a wind speed between 10 ms\(^{-1}\) and 12 ms\(^{-1}\) (measured at the identified reference wind turbine) were kept in the analysis. This is done in order to observe both high wake effects and sufficiently high power production at the downstream turbine.
Furthermore a data quality check was applied to the 1Hz active power time series. Indeed, to properly study the correlation it was necessary to have a continuous sampling (600 samples for 10 minutes period at 1Hz) without gaps and duplicated values. So, over each ten minutes period, the high frequency time series were analyzed to remove duplicates and detect the presence of missing data in the time-series. Any ten minute time series with gaps longer than one second were rejected, as concern the others, contingent gaps were filled by linear interpolation.

2.4. Calculation of inter-correlation between the turbines

After the data filtering and processing it was possible to proceed on the calculation of the inter-correlation levels for each selected period. Any possible trend in the power signals was first removed in order to focus on the power fluctuations of both wind turbines. The inter-correlation in function of the time delay $\tau$ between the de-trended (continuous linear trends removed on 10-min signals) power signals $P_{SMV6}$ and $P_{SMV5}$ was calculated as in eq(1):

$$\Gamma(\tau) = \int P_{SMV6}(t) P_{SMV5}(t - \tau) dt$$ (1)

The maximal value of $\Gamma(\tau)$ was calculated for each correlation function. Periods with correlation peaks below 0.5 were rejected, while for the others the time delay $\tau$ correspondent to the peak was retrieved. The filtered correlation statistics were binned over 20° wind sector (using the reference wind turbine SCADA data). Sector with less than 10 samples were rejected because they were considered as non-statistically representative. In the end, after all these restrictive filters only five sectors corresponding to the most prevailing wind directions were obtained (see figure 2a).

3. Results

Figure 5a shows the inter-correlation levels between the wind turbine power signals measured on SMV5 and SMV6. Each dot corresponds to the average of the 10 minutes periods correlation statistics over a wind direction sector of 20°. For an easier representation the absolute values of the inter-correlations statistics are shown. Indeed, according to the wind sector SMV6 can be either upwind or downwind compared to SMV5 causing negative inter-correlation statistics.

Figure 5: Polar plot of inter-correlations levels (a) and time response in seconds (b) between the 1Hz power signals of wind turbine SMV6 and SMV6 with wind speed between 10$m/s$ and 12$m/s$.

Dots represents the inter-correlation statistics, colored lines the $T_{adv}$ estimations thresholds. For the time response each circle represents ten seconds.
Results show inter-correlation levels around 0.6 for all the sectors matching the filtering conditions independently of the wake interactions presence. Figure 5b shows the average measured delay between the active power signals variations of SMV5 and SMV6 obtained by their inter-correlations. As a general approach this work aims to evaluate whether this time delay could be related to physical phenomena, in particular the advection time between the two wind turbines. As possible evaluation of the quality of the results, it was chosen to compare the data with a classical estimation of the advection time based on the wind speed. The advection time, intended as the time for the air masses to transit from the location of the upstream turbine to the position of the downstream one, was so estimated by the measurement of the reference SCADA wind speed. As mentioned at the start of the paper, one solution to estimate the advection time in wake interaction conditions is to use a portion (80%) of the free stream velocity ($U_\infty$) as done in [7]. Having considered in this work only wind speeds between 10 $ms^{-1}$ and 12 $ms^{-1}$ the advection time ($T_{adv}$) corresponding to these thresholds was estimated. Figure 6 schematize the calculation of the stream-wise distance $\Delta X$ between SMV5 & SMV6. Knowing the geometrical spacing between the wind turbine $WT_{Dist} = 3.7D$ (at 207°) and the wind direction $WD$, by simple trigonometric it possible to retrieve $\Delta X$ as in eq(2). Then $\Delta X$ is divided for the advection speed $U_{adv}$ to retrieve $T_{adv}$ (represented by the colored lines in figure 5b). Concerning the advection speed, for the wake interactions sectors [200°:220°] and [20°:40°] it was taken 0.8$U_\infty$ while for the other sectors just $U_\infty$.

$$\Delta X = WT_{Dist} \cos(WD - 207^\circ)$$ (2)

Finally looking at the time response results it can be found a general accordance between the classical estimation of $T_{adv}$ and the time response between the wind turbines. Focusing on the wake regions, the results show as the wake interaction affects the wind turbine dynamic. Indeed, the presence of the wake not only (as well known) decrease the power availability on the downstream turbine, but reduce its time response and this reduction can be retrieved by the evaluation of the power time series such as the aerodynamic advection time. The importance of the evaluation of this parameter directly by the power time series is given by the fact that these are generally the most reliable SCADA data and they can be easily integrated in the machine control system.
4. Conclusion
A post-processing of SCADA data acquired with a high sampling frequency on two neighbouring wind turbines is performed through inter-correlation functions in order to assess the time delays between the wind turbine responses depending on wind direction and wind speed. Furthermore, the influence of the level of wake interactions is discussed in terms of inter-correlation statistics showing a general accordance with the classical advection considerations. The obtained results show that this kind of analysis can contribute to refine the dynamic parameters of the wind farm control models. For several reasons (among other the storage) it is not trivial to have available a large 1Hz database. So the purpose of this work was to evaluate the potentiality of this approach on the exploitation of the power measurements to retrieve the wind turbine response especially in wake interactions condition. For these considerations this work has to be considered as a preliminary study. Right now, another acquisition campaigns is on going with 1Hz SCADA being recorded on all wind turbines in the farm. Hopefully, the study of this new database will help in pushing further this first analysis.

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