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Title: New Wake Effects Identified Using SCADA Data Analysis and Visualization

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Abstract: Sandia National Laboratories has developed and applied several new analysis and visualization techniques for Supervisory Control and Data Acquisition (SCADA) wind farm data. These techniques include methods for cleaning and correcting SCADA data, as well as visualizing power production over a wind farm. The techniques are unique in that they focus on power production directly, and do not rely on wind speed measurements. A case study has examined data from a 67 turbine onshore US wind farm, recorded over 1.5 years. The analysis has revealed four different types of wake effects. Three types are new, and normally not accounted for in wake analysis. Wake deficits are observed as expected. The three new wake effects are associated with increased power extraction: channel speed up, and single/multiple shear point speed up. The effects are generally not included in wind farm wake models, and are associated with less variability, possible due to turbulence suppression.

3 Learning Objectives:

1. Advanced analysis of wind farm performance,
2. Wake induced increase in turbine performance, and
3. Performance variability decrease in waked conditions.

Extended Abstract:

As wind farms scale to include more and more turbines, questions about turbine wake interactions become increasingly important. Turbine wakes reduce wind speed and downwind turbines suffer decreased performance. The cumulative effect of the wakes throughout a wind farm will therefore decrease the performance of the entire farm. These interactions are dynamic and complicated, and it is difficult to quantify the overall effect of the wakes. This problem has attracted some attention in terms of computational modelling for siting turbines on new farms (Lissaman and Bates, 1977; Vermuelen, 1980; Katic *et al.*, 1986, Barthelmie *et al.*, 2010; Gonzalez-Longatt *et al.*, 2011; Sanderse *et al.*, 2011; Porte-Agel *et al.,* 2013), but less attention in terms of empirical studies and performance validation of existing farms. In this presentation, Supervisory Control and Data Acquisition (SCADA) data from an existing wind farm is analyzed in order to explore wake interactions. Visualization techniques are proposed and used to analyze wakes in a 67 turbine farm. Four wake effects are observed; including wake deficit, channel speed up, and two potentially new effects, single and multiple shear point speed up.

SCADA Data. Data was gathered over a 1.5 year period in 2012 and 2013 from the SCADA system at an onshore wind farm in the United States. The wind farm included 67 horizontal axis, three bladed, variable pitch turbines, along with one meteorological (met) tower. In this study, analysis was performed on subset of the data collected from the turbines: nacelle wind speed, nacelle direction (position), rotor speed, blade pitch, and power output. The met tower collected data on temperature, air pressure, wind speed, and wind direction, but do not play an important role in the analysis. The farm layout is relatively complex, as shown in Figure 1.

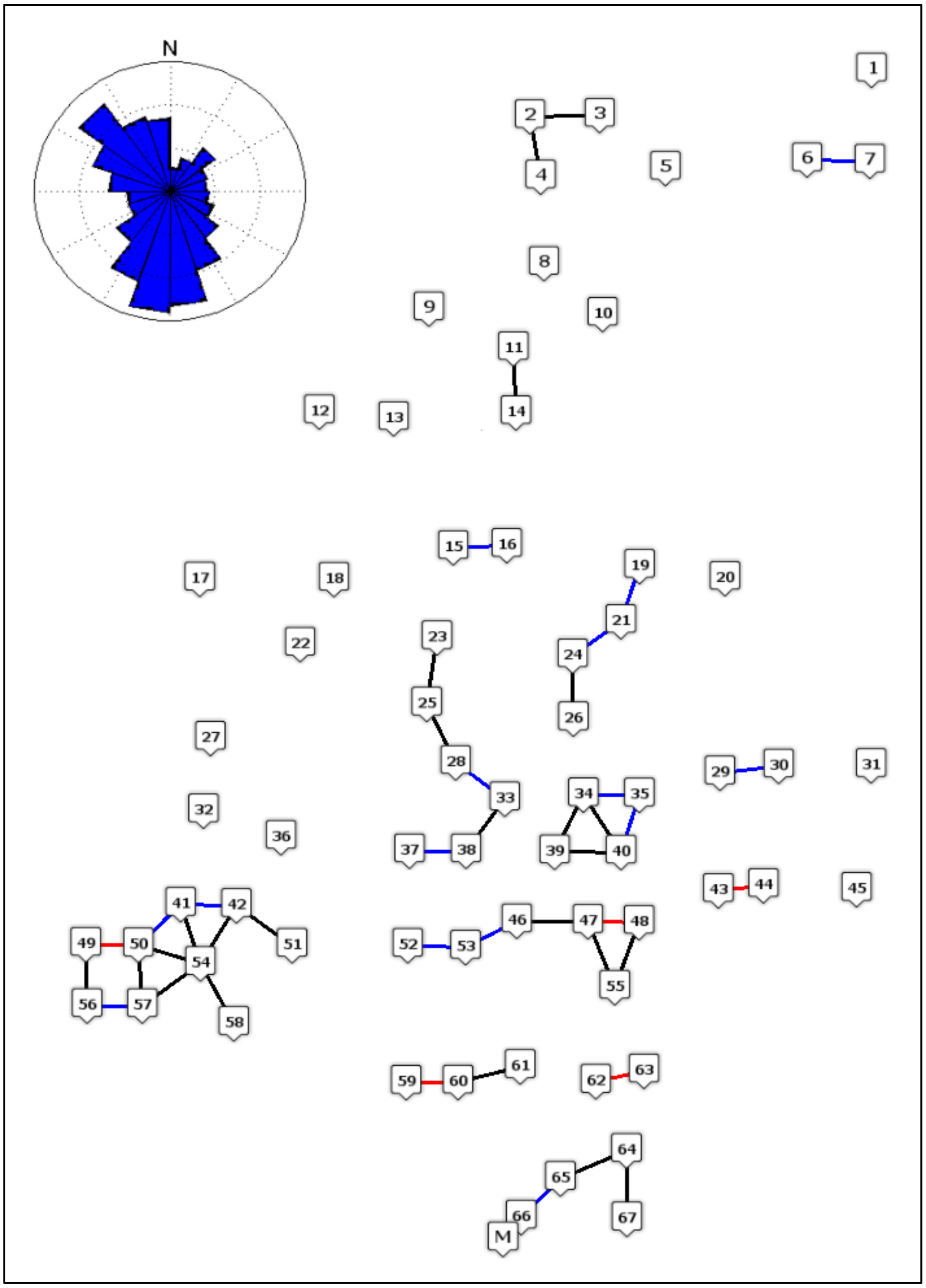

Figure 1. Wind Farm Layout. The relative positions of the turbines are shown, with turbines numbered from 1-67, and the met tower marked M. The site wind rose is shown in the upper left. Turbines in close proximity are connected by lines: turbines within 5 rotor diameters are connected using red lines; turbines between 5 and 6 rotor diameters are connected using blue lines; and turbines between 6 and 7 rotor diameters are connected using black lines. Icons were taken from the Map Icons Collection (http://mapicons.nicolasmollet.com) and are licensed under Creative Commons Attribution (3.0).

Analysis. In the analysis of wind farm performance, it is typical to use individual turbine power curves. The use of power curves implies the accurate measurement of wind speed. Although wind speed can be measured accurately, it is necessarily relative. Further, the relative nature of wind speed measurements can make understanding wake deficits difficult, since a waked turbine will have the same power curve as an un-waked turbine, but have lower relative wind speeds.

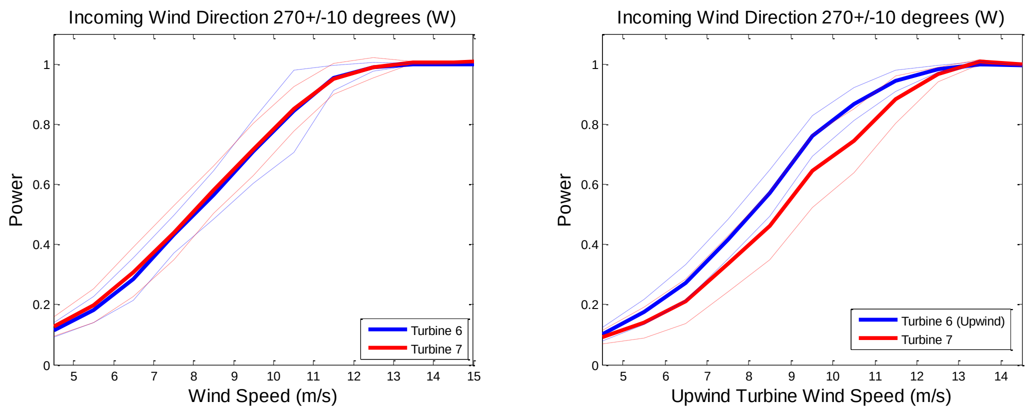

Figure 2. Wake Effect for Turbine 7. On the left, power curves are shown for the upwind turbine 6 and the downwind turbine 7 (given westerly winds). These curves show no wake effect because the individual nacelle wind speed measurements were used, which are relative. On the right, power curves are shown for the same two turbines, this time using the upwind nacelle sensor to measure wind speed. These curves show a wake effect, because the wind speed is now absolute for both turbines. Throughout this figure, the power curves were obtained by averaging the nacelle power measurements over bins with width of 1 m/s.

This presentation will discuss methods for calculating representative wind speeds (e.g. non-relative wind speeds), but also demonstrate how power can be used directly to visualize wake effects. After various pre-processing steps, the directional performance for each turbine is mapped over the entire period of 1.5 years and normalized against average farm performance. This allows the visualization of each of the 67 turbines directional behavior, in terms of power performance, as shown in Figure 3. The methods for filtering the data and performing sensor calibration will be discussed in detail.

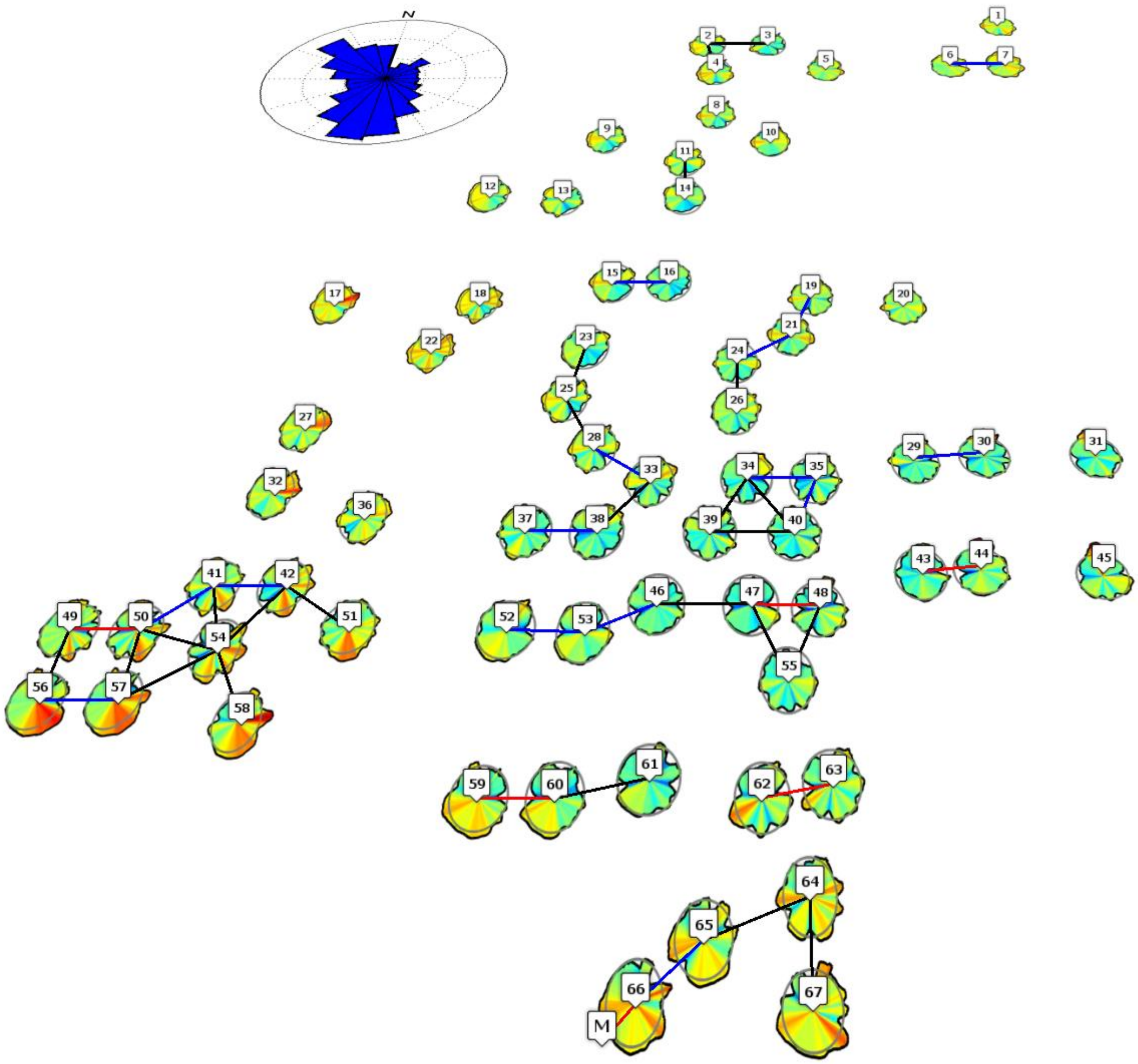

Figure 3. Wake Effect Visualization. This visualization shows the wind farm wake effects using the normalized instant power plots, complete with the labels from Figure 1. The rose plots centered under turbine icons seen in Figure 1. The rose plots are colored according the radial magnitude. For the instant power plots, over-performing turbine directions are colored red, while under-performing turbine directions are colored blue. Grey circles show average performance (instant normal power value of 1). The wind farm terrain imagery (not shown) can also be examined for correlations between performance and local topography. The visualization is rendered in Google Earth (http://www.google.com/earth) and is interactive.

The visualizations shown in Figure 3 have been scrutinized for wake effects. For direct deficits, 854 turbine pairs have been identified. Power decay versus distance for these pairs shows good agreement with expected decay as a function of turbine distance, for example compared to the N.O. Jensen wake model (Katic *et al.*, 1986). The power variability, taken as an expression of the turbulence intensity, also decays as expected with distance (not shown).

In addition to the expected wake deficits, three other situations were identified in the analysis, as illustrated in Figure 4. Each of these effects led to increased turbine performance, even though the turbine is in a waked situation. The first effect is a speedup which occurs in the channel between two upstream turbines. We speculate that the wake from each upstream turbine increases the wind speed and thereby increases the power performance. The second effect occurs due to wind shear from an upstream turbine, which causes over performance of the downstream turbine. The third effect observed is a shear point speedup from multiple upstream turbines or an upstream wind farm. Interestingly, we observe these increased power performance situations are associated with decreased variability. Of course both increased power and decreased variability is highly desirable.

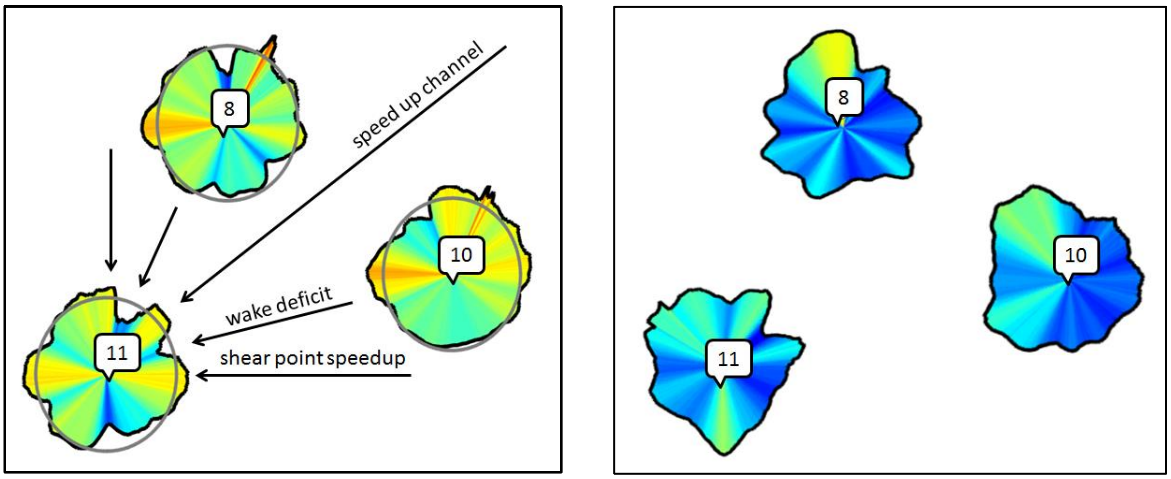

Figure 4. Wake Effects. On the left, three wake effects can be observed using instant normalized power plots for turbines 8, 10, and 11. Wake deficits can be seen as dips in the power production when turbine 11 is in the shadow of turbines 8 or 10; a speed up channel can be seen as a peak in the power production when turbine 11 is facing the midpoint of turbines 8 and 10; and shear point speedups can be seen when turbine 11 is tangent to the wake of turbine 10 or 8. On the right, the corresponding variability in power is shown. For the power variability plots, high variability directions are colored red, and low variability directions are colored blue.

None of the observed positive effects are currently included in existing wake models. Assuming existing wake models predict the average performance correctly, these observations imply that current wake models over-predict direct wake situations because they exclude the positive effects of wakes. Finally, the presentation will illustrate the wind farm performance over a year by various speed up animations, showing turbine wakes and performance, as deduced from analysis. Examples are shown in Figure 5.

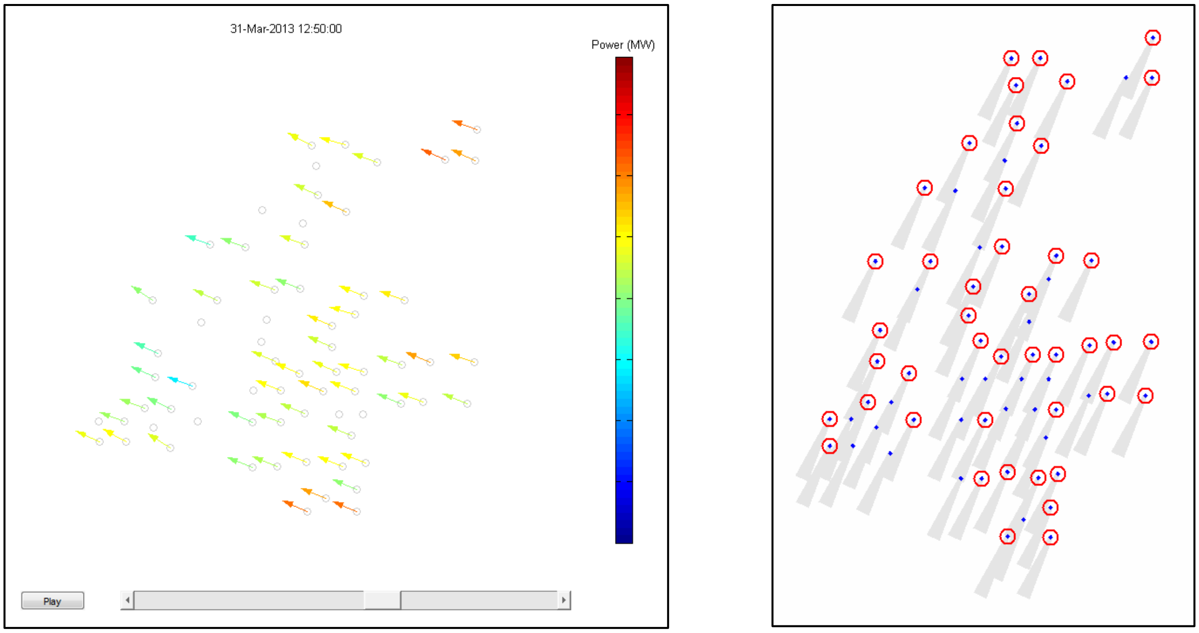

Figure 5. Animations. On the left, a snapshot of turbine power and wind direction at a particular time is shown. Power is color-coded and wind direction is indicated using arrows. On the right, wind shadows are shown for wind out of the North-East. The blue dots are the turbine locations, and the red circles indicate that a turbine is unobstructed 15 rotor diameters upstream.

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