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A data-driven method to characterize turbulence-caused uncertainty in wind power generation

Jie Zhang [a,*], Rishabh Jain [b], Bri-Mathias Hodge [c]

[a] University of Texas at Dallas, Richardson, TX 75080, USA
[b] North Carolina State University, Raleigh, NC 27695, USA
[c] National Renewable Energy Laboratory, Golden, CO 80401, USA

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ABSTRACT

A data-driven methodology is developed to analyze how ambient and wake turbulence affect the power generation of wind turbine(s). Using supervisory control and data acquisition (SCADA) data from a wind plant, we select two sets of wind velocity and power data for turbines on the edge of the plant that resemble (i) an out-of-wake scenario and (ii) an in-wake scenario. For each set of data, two surrogate models are developed to represent the turbine(s) power generation as a function of (i) the wind speed and (ii) the wind speed and turbulence intensity. Three types of uncertainties in turbine(s) power generation are investigated: (i) the uncertainty in power generation with respect to the reported power curve; (ii) the uncertainty in power generation with respect to the estimated power response that accounts for only mean wind speed; and (iii) the uncertainty in power generation with respect to the estimated power response that accounts for both mean wind speed and turbulence intensity. Results show that (i) the turbine(s) generally produce more power under the in-wake scenario than under the out-of-wake scenario with the same wind speed; and (ii) there is relatively more uncertainty in the power generation under the in-wake scenario than under the out-of-wake scenario.

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1. Introduction

Renewable energy resources have become a primary focus in government policies, in academic research, and in the power industry. Among the renewable energy technologies, wind energy has taken a lead; it currently contributes approximately 4% of worldwide electricity consumption [1]. Wind energy comes from wind power plants that consist of multiple wind turbines distributed throughout a substantial stretch of land (onshore) or water (offshore). The power generated by a wind plant is an intricate function of the configuration and location of the individual wind turbines. The flow pattern inside a wind plant is complex, primarily due to the wake effects and the highly turbulent flow. Wake losses lead to significant energy loss, especially in large-scale wind plants. The average wake loss is approximately 5%–20% of the power output from the whole wind plant, depending on turbine placement and site climatology [2]. The offshore average ambient turbulence is typically between 6% and 8% at heights of approximately 50 m; the onshore average is between 10% and 12% [3]. Within a wind plant, turbulence is characterized by ambient and wake turbulence. Ambient turbulence is defined as the normal turbulence at the site that would be experienced by a single, stand-alone turbine. Wake turbulence is caused by upwind turbines shading those downstream [4]. In the past years, a number of experimental and computational studies have been performed to investigate different wake characteristics within a wind plant, such as velocity deficit, turbulence intensity, multiple wake interactions, and wake width and trajectory at various distances downwind [3–14].

In the presence of turbulence, with the same wind speed, the same turbine might generate different power under ambient turbulence (when the turbine is out of the wake of other turbines) and under wake turbulence (when the turbine is in the wake of other turbines). The research questions for this paper are:

1. Under the same wind conditions, how do ambient and wake turbulence affect the power generation of a wind turbine within a wind plant?

* Corresponding author.
E-mail address: jiezhang@utdallas.edu (J. Zhang).

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2. For in-wake scenarios, how does the turbulence affect the estimation of wind power when the source of the wind speed is local or remote?

A methodology is developed in this paper to analyze the effects of ambient and wake turbulence on the power generation of a wind turbine. Quantifying different sources of uncertainties in wind power generation attributed to turbulence is the major contribution of this study. Three types of uncertainties in turbine power generation are quantified and analyzed: (i) the uncertainty in power generation with respect to the reported power curve; (ii) the uncertainty in power generation with respect to the estimated power response that accounts for only mean wind speed; and (iii) the uncertainty in power generation with respect to the estimated power response that accounts for both mean wind speed and turbulence intensity. The findings from this study could be utilized to (i) develop more accurate wind power forecasting models, and (ii) design optimal wind plant to maximize the power generation. The uncertainty information would also be uniquely helpful for developing a probabilistic wind power forecast that can be used in power system operations. Different studies have been performed in the literature to quantify wind power uncertainties at different spatial and temporal scales for optimal power system operations [15–20]. The developed method in this paper can be applied to multiple wind farms within a balancing authority to more accurately quantify the wind power uncertainty, thereby improving the economic and reliability performance of the power system scheduling.

The remainder of the paper is organized as follows: a brief summary of the wind plant monitoring data is provided in Section 2 ; the methodology for turbulence analysis is developed in Section 3; Sections 4 and 5 present the results and discussion of the single and multiple turbines case studies. Note that, during analysis, the wind speed *vs.* output power data for turbine A07 was found to be erroneous, attributed to the malfunctioning local anemometer. Hence, for the multiple turbines case study, reference to "A01-A09" assumes that A07 is not included.

2. Wind Plant Monitoring Data

The monitoring data from a wind plant in Northern Colorado with approximately 300 MW of capacity was analyzed in this paper [21]. The turbines are spread throughout an area of approximately 17 km by 17 km. There are two meteorological towers at this site. The site map in Fig. 1 shows the relative distances among turbines and meteorological towers. The blue, yellow, and red dots represent 1.5-MW turbines, 1-MW turbines, and meteorological towers, respectively. The 1.5-MW and 1-MW turbines are at heights of 80 m and 69 m, respectively. The turbines are generally lined up in rows that are perpendicular to the prevailing wind direction (northwest) at the site. The average distance between two turbines in the same row is approximately 320 m, or roughly 5 rotor diameters. The distance among rows ranges from approximately 530 m to more than 8,900 m. The two meteorological towers measure wind speed (in m/s) and direction (from 0° to 359°) at 50 m and 80 m at meteorological tower MET01, and at 50 m and 69 m at meteorological tower MET02 [21].

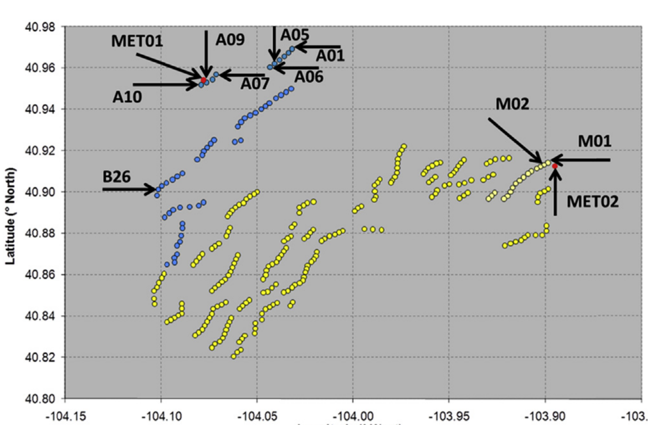

Fig. 1. Turbine and met tower locations [14].

A plant information (PI) system is installed at the wind plant to collect detailed operating information. For each turbine, the collected data include turbine status (availability and online status), rotor speed (rpm), power output (kW), nacelle position (degree), and wind speed from the anemometer on top of each nacelle (m/s). The output of the entire plant is monitored by the utility's supervisory control and data acquisition (SCADA) system and transmitted to its PI system. The wind speed, direction, barometric pressure, and temperature data from the two meteorological towers are also stored by the PI system.

3. Methodology Development for Turbulence Analysis

Using the SCADA data from the wind plant, a methodology was developed to analyze the effects of ambient and wake turbulence on the power generation of a single and multiple wind turbines by observing the following sequences.

3.1. Single turbine — Turbine A10

a) One turbine on the edge of the wind plant was selected, and two groups of wind and power generation data were determined: (i) an out-of-wake scenario, a set of data (wind speed, wind direction, and wind turbine power generation) when the turbine directly faces incoming winds; and (ii) an in-wake scenario, a set of data when the turbine is in the wake of other turbines.
b) For each group of data, two surrogate models were developed to represent the power generation as a function of (i) the wind speed and (ii) the wind speed and turbulence intensity. Regression methods can be used for this purpose, and the support vector regression (SVR) method was adopted in this study.
c) The uncertainty in the surrogate models was quantified, which serves as an approximation of the uncertainty in turbulence effects on wind power generation.

3.2. Multiple turbines - Turbines A01 - A09

a) A group of nine turbines on the edge of the wind plant were selected, and a set of data (wind speed, direction, and and power generation) were determined for an in-wake scenario.
b) For each turbine, four surrogate models were developed to represent the power generation as a function of: (i) turbine measured wind speed, (ii) MET01 tower wind speed, (iii) turbine measured speed and turbulence intensity, and (iv) MET01 wind speed and turbulence intensity. Similar to the single turbine case, SVR was adopted.
c) Similar to the single turbine study, the uncertainty in the surrogate models was quantified to approximate the turbulence-caused uncertainty effects on wind power generation.

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