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Regarding the influence of the Van der Hoven spectrum on wind energy applications in the meteorological mesoscale and microscale

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A R T I C L E I N F O

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A B S T R A C T

We demonstrate the use of high frequency data (HFD) to reproduce the power spectrum shown by Van der Hoven in 1957. His work represents the basis of wind energy standards such as averaging and variability in the frequency domain. Our results unveil discrepancies with Van der Hoven's approach, which can be related to constraints in the computing capabilities in the 1950's. We show a major eddy-energy peak at a period of 2 days and a smaller eddy-energy peak contribution at frequencies higher than the region known as the spectrum gap. The variance calculated by the area under the curve indicated that the spectral energy is mainly due to the Power Spectral Density (PSD) values located in the microscale region. We calculated the economic value of this energy based on the turbulence kinetic energy of the wind data set. We also conclude that, given the results of the present study, HFD analysis in the frequency domain uncover eddy energy peaks that determine energy fluctuations in the short and long terms. This information is lost every time data are erased from current monitoring systems.

1. Introduction

While wind power is becoming increasingly significant in the electricity market, the challenges regarding the intermittency of the wind resource influence the power delivery from wind turbines [1]. This influence causes higher maintenance costs due to frequent changes in the dispatch since the wind turbine has to respond to wind variations. Several forecasting techniques have been developed to estimate the wind speed in the range of a few hours to several days and even weeks [2–5]. These methods generally offer results in the time domain and their main inputs are 10 min wind speed averages. The increased randomness of wind in finer temporal windows makes forecasting unfeasible, and the study of wind speed in the frequency domain can fill this gap. Moreover, the wind power spectrum can be used to plan reliable schedules through fluctuation forecasts [6] and the identification of periodic deterministic components of a time series [7].

Power spectrum analysis for wind data has been recognized as a very useful tool to aim a more detailed description of wind speed variability [1,6,7]. It enhances both the study of identification of variation patterns and the distribution of turbulent energy over the frequency domain [8]. In 1957, Isaac Van der Hoven gave the first recognized step to analyze the wind spectrum in a wide range of frequencies [9]. The study was carried out with wind speed data measured during hurricane Connie and contained different average ranges. One of the main uses of the Van der Hoven spectrum in the wind industry was to set the 10 min averages as the main input to characterize important parameters such as the turbulence intensity and the Weibull parameters. The 10 min period is found in the middle of the so-called Van der Hoven gap, where the contribution to wind energy fluctuations is considered negligible [1,6,9–12]. More recent studies of wind power spectra has been carried out under special circumstances such as the study of Li, Xiao et al. [13], where the authors took wind data from a typhoon to model wind loads over tall structures. The authors developed their study focusing mainly on the inertial subrange of the spectra, where the energy transfer from larger to smaller eddy is predominant.

A reproduction of the Van der Hoven spectrum is illustrated in Fig. 1, including the differentiation between the meteorological mesoscale and the microscale. The first one corresponds to phenomena with space scales between 3 km and 100 km, and with time scales longer than about 1hr, while the latter covers the smaller values of space and time [14]. We added the region in the frequency domain where dynamic characteristics of a wind turbine model shown elsewhere [15–17] must be considered to model its

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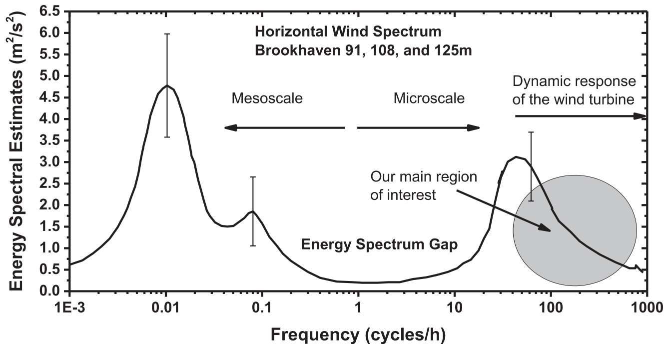

Fig. 1. Reproduction of the Van der Hoven Spectrum at Brookhaven National Laboratory [9], edited for our purposes. The ordinate contains the spectral estimates, expressed in units of energy per frequency per unit mass.

power production accurately. Outside such frequency range the influence of the wind's dynamic effects becomes negligible [17]. It is also noticeable that the units illustrated in the ordinate in Fig. 1 are equivalent to the power of the signal divided by its corresponding frequency. In this way, when the area under the curve is calculated, the result is the total energy variance in the frequency domain. Although the units of the abscissa are not represented in standard units, we keep using them to easily compare our results with the ones illustrated in Fig. 1.

Some authors have used the Van der Hoven spectrum as a reference for their wind data analysis in the frequency domain [6,10,12]. To our knowledge, there is no evidence in the literature that aims to update that study, considering that the mathematical capabilities used for the analysis are obsolete and inaccurate. Our study discusses the completeness of the spectrum curve presented in 1957 emphasizing the energy gap. Our hypothesis states that the actual eddy-energy peak distribution over the frequency domain can be different from the original reference and its description must be reconsidered on a case by case basis. Van der Hoven calculated the spectral estimates using the computing tools available at the time during the occurrence of a particular meteorological phenomenon, delivering a study under very specific meteorological conditions. To our knowledge, there is no recent study that validates the spectrum gap with finer data nor using current computer tools available for the analysis.

Wind resource analyses of many site studies are widely reported in the literature and carried out using basically the same techniques [18]. However, more attention must be focused on the study of wind variability in the frequency domain. Moreover, for most of the studies reported in literature, wind averaged data is typically used to describe wind conditions in both the time and frequency domains. Such averages are normally calculated from HFD, which is measured in meteorological stations and then discarded by the data acquisition system (DAQ). Our approach includes the exclusive use of HFD in the calculation, allowing us to run the same computing routine with one data set divided in several time periods. Evidence of HFD use in wind spectra analysis can be found in literature. Larsen et al. [19] developed a study using HFD and 10 min average wind speeds and temperature to model their mesoscale spectra. The authors calculated the spatial variability of wind and temperature in a range up to a few hundred kilometers paying special emphasis in the presence of gravity waves.

2. Motivation

Abderrazzaq and Aloquili developed an experimental study which concluded that 30% of the faults (turbine stoppage) and energy losses in the wind turbine's system are due to pitch errors [20]. Blade root bending moments have a response of a few seconds to sudden changes of the blade pitch angle in modern turbines [21]. During this response time, the electronic components of the wind turbine's system have to respond to such variations as well. As a conclusion, better control of the pitch angle will bring a smoother response of the wind turbine forced with wind speed variations. Wind turbines have response times corresponding to different wind variation periods [15]. The study of such variations in the frequency domain must be carried out to identify patterns in the wind speed [1] and reduce faults caused by pitch misalignments. This topic is also addressed in the present study.

The frequency spectra analysis of wind corresponds to its dynamic variations, while the resource assessment studies the static characteristics from a statistical approach. It was first stated by Healey [22] that the excess kinetic energy in the fluctuations of wind speed, above the hourly average, may be important, depending on the turbulence intensity and response time of the wind turbine. This same approach was continued in the work of Rosen and Sheinman [16,17], concluding that ignoring wind's dynamic nature due to turbulence results in over predictions of more than 10%. In the present work, we study the wind spectra to identify the frequency of the main contributions to the variability and increase the information available regarding the wind variability.

3. Statement of the problem

The Van der Hoven spectrum is characterized by a gap in the energy contribution from a period of 2 h to approximately 5 min. This means that the eddy-energy variation doesn't have any significant contributions at the corresponding frequencies. This information is nowadays incomplete, considering that non-zero energy fluctuations can be observed in the spectrum gap. On the other hand, the excess kinetic energy in the wind that is not detected by traditional wind resource methods. This methods include the calculation of the wind speed averages, turbulence intensity, and the Weibull parameters, neglecting the dynamic characteristics of wind and their effects on the wind turbine performance.

4. Methodology

High frequency data (1 Hz and 5 Hz) were used to calculate the power spectral density (PSD) of the wind speed at 3 different wind sites. The frequency range of interest is that located within the spectrum gap observed in Fig. 1. The description of the data is shown in Table 1, along with the time of the year when it was collected and the length of the samples. Our source files contain a larger data volume, but only representative segments were taken for the study. The data was collected and provided by Vestas – Canadian Wind Technology, Inc. The HFD is proprietary information and the locations of the site studies will not be disclosed. Information on the topography and other characteristics of the terrain were not available in the data sets. However, our methodology does not consider these characteristics, as it can be applied to any HFD set. The numerical calculations were carried out in Matlab as the main data and code processor.

Period lengths in which the data is divided are defined as follows:

$$T_k = \frac{T}{k}, \quad k = 1, 2, \ldots, N \tag{1}$$

$$f_k = \frac{1}{T_k} \tag{2}$$

where T_k is the length of each k-period, measured in seconds, in which the total data length T is divided, k is the number of periods