Renewable Energy 62 (2014) 331–340

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Meteorologically defined limits to reduction in the variability of outputs from a coupled wind farm system in the Central US

Junling Huang [a], Xi Lu [a], Michael B. McElroy [a,b,*]

[a] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[b] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA

ARTICLE INFO

Article history:
Received 28 February 2013
Accepted 8 July 2013
Available online 8 August 2013

Keywords:
Interconnection
Transient waves
Meteorologically defined limits

ABSTRACT

Studies suggest that onshore wind resources in the contiguous US could readily accommodate present and anticipated future US demand for electricity. The problem with the output from a single wind farm located in any particular region is that it is variable on time scales ranging from minutes to days posing difficulties for incorporating relevant outputs into an integrated power system. The high frequency (shorter than once per day) variability of contributions from individual wind farms is determined mainly by locally generated small scale boundary layer. The low frequency variability (longer than once per day) is associated with the passage of transient waves in the atmosphere with a characteristic time scale of several days. Using 5 years of assimilated wind data, we show that the high frequency variability of wind-generated power can be significantly reduced by coupling outputs from 5 to 10 wind farms distributed uniformly over a ten state region of the Central US in this study. More than 95% of the remaining variability of the coupled system is concentrated at time scales longer than a day, allowing operators to take advantage of multi-day weather forecasts in scheduling projected contributions from wind.

1. Introduction

Some 13,131 MW of wind generating capacity were added to the US electrical system in 2012, an increase of 93% compared with the same period in 2011. Total installed capacity for wind power in the U.S. amounted to 60,007 MW by the end of 2012, equal to approximately 6% of total U.S. power generating capacity. Lu et al. [1] argued that an onshore network of GE 2.5 MW turbines installed in the contiguous U.S. could supply as much as 16 times total current U.S. demand for electricity. A study by the U.S. Department of Energy concluded that wind could account economically for 20% of total U.S. demand for electricity by 2030 [2], while Short et al. [3] argued that as much as 25% of demand could be met feasibly by 2050.

The current electrical system requires an essentially instantaneous balance of supply and demand dictated largely by the latter. Opportunities for storage of electricity when supply exceeds demand are limited, while options to modulate demand are also minimal. Baseload demand is accommodated in the present system mainly by a combination of contributions from nuclear and coal with an additional contribution in some regions of the country from hydro. Gas-fired systems provide the fast response required to adjust to short and intermediate-term fluctuations in demand. The challenge posed by the need to incorporate a significant source from wind relates to the intrinsic variability of this source. Production of electricity from an individual wind farm can vary over a wide range on time scales as brief as minutes or as extensive as days or even longer [4].

A number of authors have pointed to the advantages that could be realized by combining outputs from a series of spatially separated wind farms [5–14]. Katzenstein et al. [10] reported a frequency dependent analysis of the smoothing in output that could be obtained by coupling up to 20 spatially separated wind farms in Texas. Linking up as few as 4 of these farms resulted in a reduction of 87% in the variance of hourly output as compared to that associated with a single installation. Adding the remaining 16 facilities resulted in only a minimal reduction in the overall variance (8%). Kempton et al. [11], using 5 years of wind data from 11 meteorological stations distributed over 2500 km of the US East Coast, concluded that when outputs from an array of wind farms distributed along the coast were coupled, the output from the interconnected system was much more stable than that from any individual location. The correlation between individual station outputs decreased exponentially on a scale of 430 km as determined by properties of the related synoptic weather systems.

---

[*] Corresponding author. School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA. Tel.: +1 617 494 4359.
E-mail address: mbm@seas.harvard.edu (M.B. McElroy).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.07.022

Archer and Jacobson [12] considered the benefits of connecting wind farms from up to 19 sites in the mid west characterized by annually averaged wind speeds in excess of 6.9 m/s (class 3 or greater) at 80 m. They concluded that on average 30%, as much as 47%, of the connected output could be deployed as reliable base-load power. Hart and Jacobson [13] found that combining complementary renewable resources, such as wind, solar and hydro, can help mitigate the variability problems associated with any one of these options. Fertig et al. [14] reported that interconnecting wind plants on a large scale would reduce the most extreme hour-to-hour changes in energy output and increase the percentage of reliable power. Previous studies exploring the issue of interconnections focused on the statistical analysis of wind data and did not explicitly address the physical factors responsible for the observed variation of surface winds.

This study addresses the issue of interconnection with specific attention to the physical factors that determine the temporal variability of winds in the near surface region of the atmosphere. Surface winds are influenced by the passage of transient waves and by boundary layer turbulence triggered by these waves [15–17]. An understanding of these physical factors can help interpret the findings of the previous studies. We consider specifically how transient waves influence instantaneous power output. We show that there is a limit to the extent that the intrinsic variability of power output can be reduced, and quantify how this reduction in variability responds to different levels of wind farm coupling.

2. Materials and methods

2.1. MERRA reanalysis data

This study was based on meteorological data from the Modern Era Retrospective-analysis for Research and Applications (MERRA) compilation covering the period Dec 2002 to Nov 2007. Boundary layer winds and geopotential heights included in this compilation were obtained on the basis of retrospective analysis of global meteorological data using Version 5.2.0 of the GEOS-5 DAS. Geopotential heights are available on a 3-hour basis with a resolution of 5/4° latitude by 5/4° longitude, while boundary layer winds are calculated hourly at a resolution of 1/2° latitude by 2/3° longitude. Data on surface roughness are also included in the dataset. The MERRA assimilation was adopted in the present analysis to take advantage of the relatively high spatial and temporal resolution available with this product.

2.2. Calculation of wind power

In calculating the potential electricity generated from wind, we chose to use power curves and technical parameters for the GE 2.5 MW turbines (rated wind speed 12.0 m/s, cut-in wind speed 3.5 m/s, and cut-out speed 25.0 m/s). The power curve of the wind turbine, provided by the manufacturer, available at http://www.ge-energy.com and included in Supporting Information (SI), defines the variation of power output as a function of wind speed. The usefulness of adopting the GE 2.5 MW power curve in analyzing wind power has been tested and justified elsewhere [18].

Boundary layer wind data are available on an hourly basis for altitudes of 2 m, 10 m, and 50 m. We chose to extrapolate the results from 50 m to estimate the wind speed at 100 m as appropriate for the hub height of the GE 2.5 MW turbines. The extrapolation was implemented using the logarithmic relationship appropriate for a neutral stability condition assuming a surface roughness of Z_0:

$$V_{100} = V_{50} \times \frac{\ln(Z/Z_0)}{\ln(Z_{50}/Z_0)} \tag{1}$$

where V_{100} and V_{50} indicate hourly values for the wind speed at 100 m and 50 m respectively, Z and Z_{50} define the elevation of the turbine hub (100 m) and the reference 50 m altitude, and Z_0 defines the surface roughness length, values for which are taken from the MERRA tabulation.

The power yield at any given time is expressed as a fraction of the rated power potential of the installed turbines. This quantity, the instantaneous capacity factor (CF), is given by

$$\mathrm{CF} = \frac{P_{\mathrm{real}}}{P_{\mathrm{rated}}} \tag{2}$$

where P_{real} denotes the power actually realized, and P_{rated} refers to the power that could have been realized had conditions permitted the turbine to operate at its name plate capacity. The instantaneous capacity factors presented here are calculated as functions of time on an hourly basis.

2.3. Region of interest

The earlier analyses [12,14] are extended to explore the advantages that could be realized by coupling an array of wind farms over the wind-rich Central Plains region of the US. For present purposes we identify the region of interest as the combined states of Montana, Wyoming, North Dakota, South Dakota, Minnesota, Wisconsin, Iowa, Illinois, Missouri, Nebraska, Kansas, Oklahoma, and Texas. To illustrate the influence of transient waves and the benefit of interconnection, we select ten farms, one per state, distributed over the study region as indicated in Fig. 1. Though these wind farms are located in three different electrical interconnections (*Western Interconnection, Eastern Interconnection, and ECORT*), it is assumed in this study that all of the wind farms located within the Central Plains region could be coupled.

3. Results

3.1. Meteorology of wind energy in US

3.1.1. Examination of transient waves

The boundary layer wind, e.g. 100 m wind, as indicated earlier, is controlled by two factors: conditions in the free atmosphere which vary on a time scale of a few days with a spatial scale of about 1000 km, and conditions at the surface which are responsible for small scale and fast varying turbulence in the boundary layer

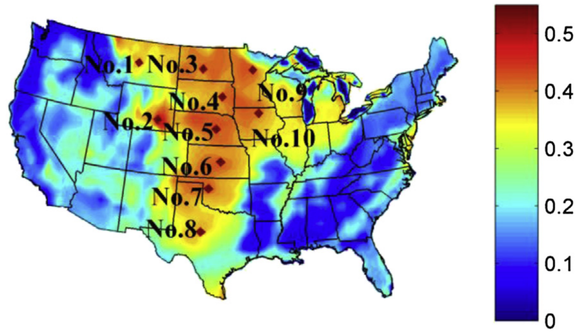

Fig. 1. Color coded values for capacity factor (CF) as a function of position averaged over the 5 year period Dec 1 2002 to Nov 30 2007. Positions of individual locations considered in this paper are indicated by the dots, one per state.