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A review of large-scale wind integration studies

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ABSTRACT

Wind integration studies are an important tool for understanding the effects of increasing wind power deployment on grid reliability and system costs. This paper provides a detailed review of the statistical methods and results from 12 large-scale regional wind integration studies. In particular, we focus our review on the modeling methods and conclusions associated with estimating short-term balancing reserves (regulation and load-following). Several important observations proceed from this review. First, we found that many of the studies either explicitly or implicitly assume that wind power step-change data follow exponential probability distributions, such as the Gaussian distribution. To understand the importance of this issue we compared empirical wind power data to Gaussian data. The results illustrate that the Gaussian assumption significantly underestimates the frequency of very large changes in wind power, and thus may lead to an underestimation of undesirable reliability effects and of operating costs. Secondly, most of these studies make extensive use of wind speed data generated from mesoscale numerical weather prediction (NWP) models. We compared the wind speed data from NWP models with empirical data and found that the NWP data have substantially less power spectral energy, a measure of variability, at higher frequencies relative to the empirical wind data. To the extent that this difference results in reduced high-frequency variability in the simulated wind power plants, studies using this approach could underestimate the need for fast ramping balancing resources. On the other hand, the magnitude of this potential underestimation is uncertain, largely because the methods used for estimating balancing reserve requirements depend on a number of heuristics, several of which are discussed in this review. Finally, we compared the power systems modeling methods used in the studies and suggest potential areas where research and development can reduce uncertainty in future wind integration studies.

Contents

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1. Introduction

As a result of state renewable portfolio standards and federal tax credits, there is growing interest, and investment, in renewable sources of electricity in the United States and worldwide. Wind is the fastest growing renewable sources of electric energy in the U.S., with wind power capacity increasing from 8.7 GW in 2005 to 60 GW in 2012 [1]. However wind power is intermittent and variable: wind turbines do not produce power at all times of day and, even when power is being produced, output can change rapidly. The U.S. electricity infrastructure, which was developed throughout the 20th century, was designed around power plants that generally have limited capability to rapidly change their output power. In order to accommodate 20–40% wind power, as envisioned in a number of state renewable portfolio standards, electricity systems will require significant changes in technology, operating policies, and infrastructure. Therefore careful study is required to design a system that can maintain reliability under these circumstances.

While there are many ways in which expanded wind generation could affect grid reliability, the effects generally fall into two broad categories. First, rapid changes in wind plant output can affect the balance between supply and demand. Since this balance must be maintained in order to maintain grid reliability, understanding the rate at which balancing resources need to increase as wind integration increases can facilitate effective planning. Second, wind plants can affect the patterns of power flow and voltages in a power network in ways that might, if not properly accounted for, result in equipment damage and trigger instability or cascading blackouts.

Failure to accurately assess and prepare for the operational impacts of wind development is likely to inhibit wind power deployment. If the reliability effects of wind remain highly uncertain or are overstated, wind investment may be slowed. If the effects of wind integration are understated and initial investments in wind result in unexpectedly high costs or operational instability, barriers to wind deployment are likely to increase. To understand these risks, and develop strategies for mitigating them, numerous government agencies and industry organizations have studied the challenges and opportunities for integrating wind energy into electric power systems. This paper provides a critical review of a dozen of these studies.

A previous paper by Holttinen et al. [2] also reviews a broad set of large-scale wind integration studies. That work, however, focused primarily on European studies completed before 2007. Also, a 2012 review [3] compared the transmission costs from 40 wind integration studies. This paper expands on this prior work by reviewing major quantitative wind integration studies from the U.S. and Europe, with a particular emphasis on the operational impacts of wind integration, changes in reserve requirements necessary to maintain system reliability, and the statistical challenges associated with developing and analyzing time-series wind power profiles. Each of the studies is summarized and compared with regard to their data sources, methods and conclusions. Based on comparisons among these studies, we suggest areas where methodological improvements are warranted in future studies, and areas where additional research is needed to facilitate future improvements in wind integration studies.

We review 12 wind integration studies, some of which also include expanded solar power, published since 2005. These are the