Applied Energy 114 (2014) 700–708

Contents lists available at ScienceDirect

Applied Energy

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

Performance prediction of active pitch-regulated wind turbine with short duration variations in source wind

Sanjoy Roy *

Department of Electrical Engineering, Indian Institute of Technology, Ropar, Pb 140001, India

HIGHLIGHTS

- Uses turbulence intensity as a parametric measure of short duration wind variations.
- Derives statistical expression for the *short duration output power curve* for a WECS.
- Derives statistical expression for the *short duration output power covariance* for a WECS.
- Establishes algorithm for computation of *short duration output power variability*.
- Compares statistical estimates according to IEC 1400-1 with empirical data.

ARTICLE INFO

Article history:
Received 15 March 2013
Received in revised form 19 July 2013
Accepted 6 October 2013

Keywords:
Wind energy
Weibull statistics
Pitch-regulated turbines
Short duration power distortion

ABSTRACT

Short duration wind variations affect real time performance of active pitch-regulated wind turbines in two ways as evident from reported experimental and empirical studies. First the mean output power, which may be referred to as the *short duration output power*, differs significantly from the corresponding zero-turbulence value obtained with ideal source wind streamlines. Second, random variation of output around the mean value appears with a significant standard deviation; the normalised value of which is referred to as the *short duration variability*. In this paper, analytical interpretation of both metrics is presented under assumption of two-parameter Weibull statistics for short duration wind variations. Statistical estimates for the metrics are presented for conditions described by the well known IEC 61400-1 Standards. Finally the statistical estimation procedure is applied to a Vestas V90 3 MW zero-turbulence output curve as an illustrative application example.

1. Introduction

1.1. Challenges posed by short duration wind variations

Randomness inherent in source wind is an unavoidable challenge for large scale integration of wind energy conversion systems (WECS) in conventional power networks [1,2]. By current concepts, this phenomenon is clearly demarcated between *long* and *short duration wind variations*. The former type of variations are noticeable in speed data recorded at hourly or half-hourly time steps, and result in real time operational problems of network congestion and unreliable supply [3–8]. Spatial distribution of wind turbines as well as temporal speed swings are equally important in deciding the impact of long duration wind variations on WECS operation and control. While reliable and thorough on-site records of wind speed are requisite inputs for the studies in question; over long time horizons these are often found to be imprecise representation of wind at the turbine hub. As an alternative, wind speed records over shorter time horizons at nearby measuring stations are processed by *data mining* so as to generate long-term correlated time series applicable at specific WECS installation sites [9]. A second popular alternative is to employ reduced order numerical weather prediction models (often referred to as *mesoscale models*) for generation of long duration wind speed patterns. A comprehensive discussion on a range of such developments is presented in [10].

Short duration wind variations on the other hand, are too rapid for the consequent changes in turbine output to be detected as deterministic time series [11]. More than ten swings of wind speed between 7.0 m/s and 10.5 m/s over time spans as short as 140 ms have sometimes been reported [12]. Physically, *short duration wind variations* include turbulence and gusts, with components that follow from one or more of the following origins [13–15]:

- Ambient turbulence.
- Vertical wind shear.
- Wake development behind swept area of turbines.
- Mutual wakes due to proximity between turbines.
- Complexity of terrain or surrounding vegetation.

* Tel.: +91 1881 24 2174; fax: +91 1881 22 3395.
E-mail address: roys@iitrpr.ac.in

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.10.009

Analysis of the consequent *ten-minute variations* of turbine output power is complicated due to three reasons:

a. Problem of deterministic description [16,17] owing to the rapidity of wind variations.
b. Nonlinearity of the WECS power output curve that "converts" wind speed to output power [16].
c. Automated disconnection and reconnection of the WECS unit [18], as governed by variation of wind speed around the designed *cut-out* value.

In summary, the phenomena of short duration wind variations as well as the consequent operational effects on WECS units are subject of much debate, leading to extremely diverse opinion between those interested [19,20].

1.2. Quantification metrics

Performance evaluation of WECS typically involves two metrics that are "averaged estimates" of real time variables affected by short duration wind variations:

- *Short duration output power*: the mean output power from a WECS unit; utility interest being focused on its deviation from the corresponding ideal zero-turbulence value [16,17,21].
- *Output power variability*: the standard deviation of power output by a WECS unit, normalised by its rated capacity; this being a measure of randomness of power "around" the short duration output power [22–24].

Perhaps somewhat expectedly, *short duration output power* has largely been of interest to research groups that assess "distortion" of output power curve due to wind variations. Simulations and experiments of interest are often performed for single WECS units, as references cited above indicate.

Though interest in *output power variability* is not rare among technology research groups, power utilities and associated consultants have shown concerted effort in real-time evaluation of this metric [22–24]. The effort stems from the operational need to "match" random power output by generators to random demand from system loads, which poses a challenge to large scale integration of WECS units in conventional power networks. For example, if the short duration standard deviation of connected load is represented by ψ_L and that of the i-th wind power source is denoted by ψ_i (each distribution assumed to be approximately normal and uncorrelated with others), then the overall standard deviation inclusive of load and WECS units (indexed as $i = 1,\ldots, N$) is [22]

$$\psi_{Total} = \sqrt{\psi_L^2 + \sum_{i=1}^{N} \psi_i^2} \qquad (1)$$

The standard deviation of *load net of wind generation* is useful to the utility in deciding the regulating reserve. A comprehensive presentation on operational and economic aspects of the problem is available as [25].

The distinct importance of the two metrics follows immediately from the above discussion. *Short duration output power* can be simply viewed as the average output from an active-pitch controlled WECS. The concept should therefore allow one to "correct" ideal zero-turbulence WECS output curves for short duration wind variations. On the other hand *output power variability* allows assessment of overall randomness in utility power inclusive of connected load, and thereby facilitates plans for regulating reserve.

Empirical estimation of either metric involves recording of real-time data ensembles followed by ensemble averaging. With implicit assumption of ergodicity, accuracy of computation depends on the recording time horizon [22–24]. Such estimates are referred to as *ensemble estimates* in the rest of this paper.

1.3. Focus and objective

Accuracy of empirical ensemble estimates is governed by the estimation time horizon and the samples within. Additionally if wind speed data is approximately ergodic, then ensemble estimate of *short duration output power* would approach the *mean output power* at a specific mean wind speed. Similarly, ensemble estimate of *output power variability* would approximate the *normalised standard deviation* of short duration power – given the mean wind speed.

If available as an alternative, a direct computational approach to *statistical estimation* of the metrics may be expected to be accompanied by the following advantages:

1. A significant reduction in computational effort is expected to follow, since data recordings over limited time horizons are not a primary requirement for statistical estimates.
2. Unlike ensemble estimates, statistical estimates have little dependence on the *ergodicity assumption*; that is, wind speed data distribution over time need not be identical to probability distribution of wind speed at an instant.
3. Statistical estimates are in general expected to be free of recording errors.
4. Most importantly, formulations may include suitable *parametric representation* of turbulence in source wind, with consequent computational convenience.

This paper presents closed form analytical expressions for *short duration output power* and *output power variability* applicable to horizontal axis WECS with active-pitch control. The aim of the work is to explain and corroborate empirically observed trends for both metrics by the analysis introduced.

The formulations are based two fundamental assumptions. First, a suitable statistical distribution is assumed for short duration wind variations; with parametric representation for the phenomenon of turbulence. Second, a suitable definition is assumed for the ideal zero-turbulence output curve of a horizontal axis WECS with active-pitch control.

Section 2 provides a detailed review of relevant observations from simulations and field studies, as reported in existing literature. Section 3 formulates closed form expressions for *short duration output power* and *output power variability* of a WECS unit with active pitch-regulation. Section 4 applies the derived expressions to calculate statistical estimates for both metrics under realistic wind conditions at a typical WECS turbine hub, inclusive of short duration variations. Section 5 justifies statistical estimates corresponding to wind conditions according to the IEC 61400-1 Standards, against observed trends of ensemble estimates described in Section 2. It concludes by a computation example involving the well known Vestas V-90 3 MW WECS, so as to illustrate application of the concepts introduced in Section 3.

2. Reported data and existing practices

2.1. The concept of turbulence intensity

If complexity of deterministic bifurcation and chaos theory is to be avoided [26], then the alternative option of statistical analysis allows representation of short duration wind variations in terms