Energy Conversion and Management 87 (2014) 697–710

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A hybrid measure-correlate-predict method for long-term wind condition assessment

Jie Zhang [a,*], Souma Chowdhury [b], Achille Messac [b], Bri-Mathias Hodge [a]

[a] National Renewable Energy Laboratory, Golden, CO 80401, USA
[b] Mississippi State University, Mississippi State, MS 39762, USA

ARTICLE INFO

Article history:
Received 30 April 2014
Accepted 21 July 2014
Available online 13 August 2014

Keywords:
Measure-correlate-predict (MCP)
Power generation
Wind resource assessment
Wind distribution
Wind energy

ABSTRACT

This paper develops a hybrid measure-correlate-predict (MCP) strategy to assess long-term wind resource variations at a farm site. The hybrid MCP method uses recorded data from multiple reference stations to estimate long-term wind conditions at a target wind plant site with greater accuracy than is possible with data from a single reference station. The weight of each reference station in the hybrid strategy is determined by the (i) distance and (ii) elevation differences between the target farm site and each reference station. In this case, the wind data is divided into sectors according to the wind direction, and the MCP strategy is implemented for each wind direction sector separately. The applicability of the proposed hybrid strategy is investigated using five MCP methods: (i) the linear regression; (ii) the variance ratio; (iii) the Weibull scale; (iv) the artificial neural networks; and (v) the support vector regression. To implement the hybrid MCP methodology, we use hourly averaged wind data recorded at five stations in the state of Minnesota between 07-01-1996 and 06-30-2004. Three sets of performance metrics are used to evaluate the hybrid MCP method. The first set of metrics analyze the statistical performance, including the mean wind speed, wind speed variance, root mean square error, and mean absolute error. The second set of metrics evaluate the distribution of long-term wind speed; to this end, the Weibull distribution and the Multivariate and Multimodal Wind Distribution models are adopted. The third set of metrics analyze the energy production of a wind farm. The best hybrid MCP strategy from 256 different combinations of MCP algorithms and reference stations is investigated and selected. The results illustrate that the many-to-one correlation in such a hybrid approach can provide a more reliable prediction of long-term on-site wind variations than that provided by the one-to-one correlations. The accuracy of the hybrid MCP method is found to be highly sensitive to the combination of individual MCP algorithms and reference stations used. It is also observed that the best combination of MCP algorithms is influenced by the length of the concurrent short-term correlation period.

1. Introduction

During the past decade, notable progress has been made in developing renewable energy resources; among them, wind energy has taken a lead, and currently contributes approximately 4% of worldwide electricity consumption [1]. However, the available energy from a wind resource varies appreciably during one year. The uncertainties in the wind resource potential and in the operation timeframes are partially responsible for restraining wind energy from playing a major role in the overall energy market. Determining and forecasting long-term wind conditions would serve two important objectives: (i) analyzing the quality of a wind farm site, and (ii) designing an optimum wind farm layout, including selecting appropriate turbine types for the site.

Wind resource assessment is the process of estimating the power potential of a wind plant site. This plays an important role in a wind energy project. In general, wind resource assessment includes (i) on-site wind condition measurement; (ii) correlations between on-site meteorological towers to fill in missing data; (iii) correlations between long-term weather stations and short-term on-site meteorological towers; (iv) analysis of the wind shear and its variations; (v) modeling of the distribution of wind conditions; and (vi) prediction of the available energy at the site. Measure-correlate-predict (MCP) algorithms are used to assess the long-term wind resource at target sites using short-term (one- or two-year) on-site data and concurrent data at nearby meteorological stations (which also have long-term data). The accuracy of

* Corresponding author. Tel.: +1 303 275 4428.
E-mail address: jie.zhang@nrel.gov (J. Zhang).

http://dx.doi.org/10.1016/j.enconman.2014.07.057
0196-8904/

long-term predictions obtained using MCP methods is subject to the (i) availability of a nearby meteorological station; (ii) uncertainty associated with a specific correlation methodology [2]; and (iii) likely dependence of this correlation on physical features such as the topography, distance between monitoring stations, and type of local climate regime [3].

A wide variety of MCP techniques have been reported in the literature, such as: (i) linear regression [4,5]; (ii) variance ratio [5,6]; (iii) Weibull scale [6]; (iv) artificial neural networks (ANNs) [3,4,7]; (v) support vector regression (SVR) [8,9]; (vi) Mortimer [3]; and (vii) wind index MCP [10]. MCP methods were first used to estimate long-term annual mean wind speed [11,12]. Linear regression [13] was presented to characterize the relationship between the reference and target sites wind speeds. Rogers et al. [14] compared four MCP algorithms: (i) a linear regression model; (ii) a model using distributions of ratios of wind speeds at the two sites; (iii) a vector regression method; and (iv) a method based on the ratio of the standard deviations of the two data sets. Perea et al. [5] proposed and evaluated three MCP methods based on concurrent wind speed time series for two sites: (i) linear regression derived from bivariate normal joint distribution; (ii) Weibull regression; and (iii) approaches based on conditional probability density functions. Xydis [15] adopted MCP methods to refill gaps in the wind speed and wind direction measures for four coastal mountainous areas. Carta et al. [16] proposed a Bayesian networks based methodology for long-term estimation of wind speed and wind power generation. Carta et al. [17] also reviewed a wide range of MCP methods used for estimating long-term wind conditions at a target farm site. Ishihara and Yamaguchi [18] recently developed a method to predict the extreme wind speed at an offshore site based on Monte Carlo simulation and MCP. Weekes and Tomlin [19] used MCP methods to assess wind resource for small-scale wind farms, and found that MCP approaches could be a valuable addition to the wind resource assessment toolkit for small-scale wind developers.

Given the unavoidable practical constraints, the overall reliability of the predicted long-term wind distribution remains highly sensitive to the one-year distribution of recorded on-site data. Quantifying and modeling the uncertainty in the MCP methods would better establish the credibility of wind resource assessment and wind plant performance estimation. Kwon [20] and Lackner et al. [21] presented different frameworks to analyze the uncertainty in MCP-based wind resource assessment. The wind resource–based uncertainty models proposed by Messac et al. [22] can be applied also to the long-term data recorded at meteorological stations when MCP methods are used.

1.1. Research objectives and motivation

The existing MCP methods estimate wind data at a farm site using recorded wind data at one reference station without considering the topography, distance, and elevation differences between the two stations. Generally, recorded wind data is available from multiple meteorological stations near the target farm site. It is more comprehensive to use recorded wind data from different reference stations to estimate and predict wind conditions at the targeted farm site.

In this paper, we developed a *hybrid MCP* method and applied it to different stations for wind resource assessment. The hybrid MCP method used recorded data from multiple reference stations to estimate long-term wind conditions at the target farm site. The weight of each reference station in the hybrid strategy was determined based on the (i) distance and (ii) elevation differences between the target farm site and each reference station. The hybrid MCP methodology also (i) considered both wind speed and direction as the components of the hybrid MCP methodology, and (ii) investigated the best combination of different MCP methods and reference stations. The remainder of the paper is organized as follows:

1) The hybrid MCP method is developed in Section 2.
2) The performance metrics for evaluating the effectiveness of the MCP method are presented in Section 3.
3) Section 4 presents the results and discussion on the case studies.

2. Hybrid MCP method

2.1. Overview of the hybrid MCP method

MCP algorithms are used to predict the long-term wind resource at target sites using short-term (one- or two-year) on-site data and concurrent data at nearby meteorological stations (which also have long-term data). The hybrid MCP method developed in this paper correlates the wind data at the target farm site with that at multiple reference stations. This strategy accounts for the local climate and topography. Two types of hybrid strategies are proposed: (i) all component MCP estimations between the target farm site and each reference station use one MCP method (e.g., linear regression, variance ratio, Weibull scale, or artificial neural networks); and (ii) each component MCP estimation (between the target farm site and the reference station) uses different MCP methods, and the best combination of MCP methods among reference sites are determined. The final hybrid MCP estimation is a combination of each component MCP estimations based on the distance and elevation difference between stations. Fig. 1 illustrates the overall structure of the proposed hybrid MCP methodology. The key components of the hybrid MCP method include:

1) Selecting reference sites based on the correlations between the measured short-term wind speeds at the reference sites and the target wind farm site.
2) For each reference site, long-term wind speeds at the target farm site are predicted using a single MCP method. The MCP method can be selected from the following five MCP methods: (i) linear regression; (ii) variance ratio; (iii) Weibull scale; (iv) ANNs; and (v) SVR.
3) Determining the weights of each reference site based on the physical parameters, including the (i) distance and (ii) elevation differences between the target farm site and each reference site.

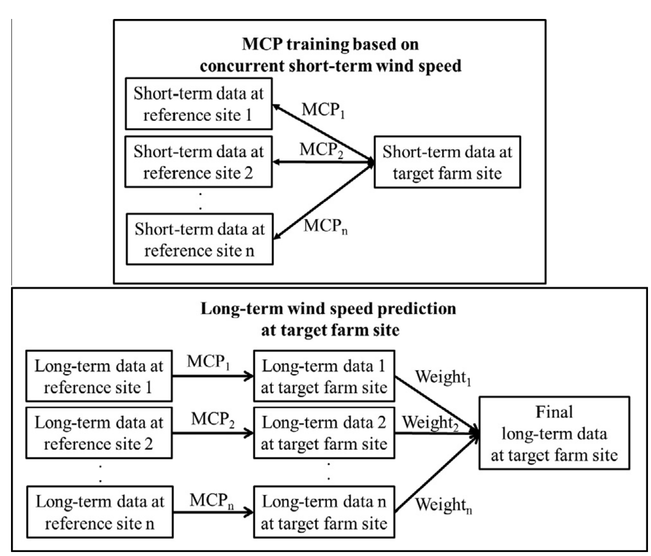

Fig. 1. Overall structure of the hybrid MCP method.