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Novel stochastic methods to predict short-term solar radiation and photovoltaic power★

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ABSTRACT

Solar forecasting has evolved towards becoming a key component of economical realization of high penetration levels of photovoltaic (PV) systems. This paper presents two novel stochastic forecasting models for solar PV by utilizing historical measurement data to outline a short-term high-resolution probabilistic behavior of solar. First, an uncertain basis functions method is used to forecast both solar radiation and PV power. Three possible distributions are considered for the uncertain basis functions - Gaussian, Laplace, and Uniform distributions. Second, stochastic state-space models are applied to characterize the behaviors of solar radiation and PV power output. A filter-based expectation-maximization and Kalman filtering mechanism is employed to recursively estimate the system parameters and state variables. This enables the system to accurately forecast small as well as large fluctuations of the solar signals. The introduced forecasting models are suitable for real-time tertiary dispatch controllers and optimal power controllers. The PV forecasting models are tested using solar radiation and PV power measurement data collected from a 13.5 kW PV panel installed on the rooftop of our laboratory. The results are compared with standard time series forecasting mechanisms and show a substantial improvement in the forecasting accuracy of the total energy produced.

1. Introduction

Among different forms of clean energies, solar energy has attracted a lot of attention because it is sustainable and renewable, but the potential of using this form of renewable energy depends on its effective integration into power distribution systems without impacting voltage and frequency limits. However, the application of solar photovoltaic (PV) to the electric grid also has drawbacks, in particular the variability of power output adds stress and uncertainty to system. A major part of solar PV production is characterized by a large degree of intermittency driven by the natural variability of climate factors such as air temperature, wind velocity, precipitation, and evaporation [1]. The variable nature of solar PV could hamper further deployment due to the increase in reserves needed on the electric grid to compensate for fluctuations in the power output. Therefore, solar forecasting has evolved towards becoming a key component of economical realization of high penetration levels of PV systems [2].

Due to the intermittency of the power output of some renewable sources, micro-grid systems have become one of the main forms for the increasing share of distributed renewable systems [3]. As the amount of solar generation increases in relation to bulk generation, real-time controllers for dispatch will be needed to minimize the impact of short-term fluctuations in solar output. The performance of these real-time controllers will be improved by

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short-term solar output forecasting. Moreover, the recently opened Energy Imbalance Market (EIM) allows for generation and demand balancing across Balancing Authority Areas (BAA) on 15 min and 5 min timescales with California Independent System Operator (CAISO) oversight [4]. One of the main challenges is therefore to perform forecasts as accurately as possible to overcome potential variability and uncertainty of renewable energy generation [5,6].

This paper examines the stochastic modeling and short-term high-resolution forecasting of solar radiation and PV power output. We introduce two stochastic state-space models to characterize the behaviors of solar radiation and PV power output. The short-term high-resolution forecasting models are suitable for the development of optimal power controllers for PV sources. They can also be utilized for automatic generation control (AGC), better energy management system, unit commitment, power scheduling and dispatching [7,8].

1.1. Overview of solar forecast methods

Various algorithms have been introduced to forecast solar radiation and PV generation [9] reviewed the state-of-the-art methods for short term solar/PV forecasting. Solar radiation in spatially distributed locations can be forecasted using neighboring spatial location information. Sky camera and satellite data can help reveal spatio-temporal characteristics of the solar radiation. Solar forecasting with satellite imaging or sky cameras has become a hot topic recently for data acquisition and cloud movement [2,10–15]. Analytical models have been developed for arbitrary cloud configuration and can also predict diffuse irradiance based on the information about cloud coverage [16]. Later, similar numerical solution has been extended to account for cloud movement [17].

Besides using ground-based images, there also exist approaches that only rely on a sensor network. For instance Ref. [18], established intra-hour forecasts using a network of 80 rooftop PV systems spread over a large area. More sensor network based forecasting methods have been proposed in Refs. [19–21], which rely on information from a collection of neighboring sites. Very short-term sub-5-min forecasting has been conducted in Ref. [12] using emerging sky camera technology.

Similarly, multiple linear regression methods including support vector machine (SVM) [22] were used to study the solar power output characteristics, combined with weather data and solar radiation data. Moreover, hybrid forecasting techniques have been investigated recently, including k-means algorithm [23], Artificial Neural Networks (ANNs) model [5], k-nearest neighbors (kNN) [24], as well as SVM with Wavelet Transform (WT) algorithm [25,26], to increase the forecast accuracy. However, most of the aforementioned methods required large amount of data samples, and the fitting results were sensitive to pathological data [27]. Besides many assumptions, such as linear cloud edge, that have to be made, various types of error will be embedded in different phases of such methods, especially during the conversion from cloud condition to ground-level radiation [28].

The solar/PV forecasts have attracted substantial attention from stochastic modeling and forecasting studies. The works in Refs. [29–31] represent solar radiation using hidden Markov models (HMMs). The works in Refs. [32–34] represent solar radiation using autoregressive integrated moving average (ARIMA) model. Lastly, the work in Ref. [35] presents a stochastic solar radiation forecasting framework based on conditional random fields (CRFs). These works provide accurate models and forecasting that capture the hourly, daily, and seasonal solar PV trends. However, they lack accurate high-resolution modeling and forecasting of fast and large fluctuations of solar radiation/PV power that often occur as illustrated in Fig. 1 for a typical summer day.

Moreover, a method based on a combination of an ARMA model and a Kalman filter has been introduced for the scope of solar radiation and temperature forecasting. The ARMA model is built with a high order parameters (p, q) in order to retrieve the state-space parameters needed to run the Kalman filter. [36] has presented a work which extends previous studies [37,38], to solve the problem of bias removal from the Kalman forecasts.

The closest related prior work to the present paper is the state-space modeling framework recently published in Ref. [39], where the linear Kalman filter is used to perform forecasting for different time horizons, between one minute and one hour ahead. They considered two sets of inputs, one that consisted only of past PV measurements and another which also incorporated cloud cover and air temperature values from a nearby meteorological station. They used a Kalman filter, where parameter tuning was addressed via two methods: an AR model and an expectation maximization (EM) algorithm.

1.2. Motivation and research objective

Most of the aforementioned techniques require additional measurements or sensor networks other than purely local solar radiation/PV power generation as in our paper. This increases the deployment complexity in both hardware and software, not to mention some unrealistic assumptions, such as linear cloud edge and various types of error embedded in different phases of these methods [28]. The advantage of our algorithm is that it is ‘data-driven in real-time and adaptive’, i.e., directly uses the collected data from local interested site to generate solar forecasting. While the methods mentioned above are offline needing training sets and cross validation on the top of using more information. This motivates us to develop novel low data demanding algorithms to improve the efficiency and accuracy of short-term high-resolution solar radiation/PV power forecasting. A new data-driven stochastic framework for short-term forecasting of solar radiation and PV production is laid out.

In this paper, we focus on designing a robust stochastic forecasting model which can accommodate the factors affecting PV output for higher forecast accuracy. In order to avoid requiring exogenous influential features namely the cloud cover and the temperature, we introduce a unique stochastic framework to forecast the solar radiation and the PV production. For this scope, a methodology based on statistical inference techniques is built, specifically, the uncertain basis functions method and Kalman filtering based EM algorithm. Both of the two introduced algorithms work adaptively and recursively to track the latest dynamics of the solar radiation and PV generation.

We begin with the uncertain basis functions technique, which takes into account the uncertain physical properties of the system of solar and PV power. In contrast with traditional works, where basis functions (e.g., radial basis function [40], and wavelets [41]) are fixed, we assume that the basis functions are random, according to three different probability distributions, i.e., *Uniform, Gaussian* and *Laplace* distributions.

The state-space model is dedicated to describing the system with all the parameters needed to capture the statistical properties and system dynamics. Thereafter, as a second phase, we talk about the methodology to estimate the needed parameters which quantify the dynamics of system. A filter-based EM mechanism is employed to estimate the parameters and state variables in the state-space model. The mechanism results in a finite dimensional filter which only uses the first and second order statistics. As mentioned in Ref. [39], the advantage of using linear discrete-time Kalman filter is mainly related to its ability to do future forecasting in real-time online in a memory-less way.