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A statistical approach for hourly photovoltaic power generation modeling with generation locations without measured data

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Abstract

The use of solar energy is becoming increasingly widespread in many countries at the time of writing. Due to its stochastic nature, the increasing amount of solar generation in the generation mix has to be taken into account when planning electric power systems at both distribution and transmission system levels. The presented Monte Carlo simulation based statistical methodology is able to analyze photovoltaic generation scenarios comprising new generation locations without measured data from those locations. The introduced model is able to assess the spatial and temporal correlations between the generation locations in geographical areas of varying size and amount of installed photovoltaic generation. The model is verified against measured solar irradiance data from Finland. In addition, the paper couples a polycrystalline silicon photovoltaic panel power generation model with the statistical model and presents a case study to illustrate the applicability of the methodology for analyzing large scale solar generation.

Keywords: Monte Carlo simulation; Photovoltaic generation; Solar irradiance; Time-varying autoregressive model

1. Introduction

Solar power generation is gaining popularity among households and industry alike. Energy producers are also increasing investment in solar power in many countries (Bazen and Brown, 2009; Mekhilef et al., 2011). The constant increase of solar power generation in the generation mix demands a better understanding of the stochastic behavior of large scale solar power and its impacts on the power system, especially when there is also a large amount of stochastic wind generation installed in the system. In particular, analysis of the contemporaneous solar energy generation in multiple generation locations and their temporal and spatial behavior are essential. However, when new generation is planned, it is likely that there are no measurements available from the potential locations. Therefore, it is important to be able to model the generation in locations without measured data (non-measured locations).

There are various published models and methodologies for the statistical analysis and modeling of solar irradiance and photovoltaic generation (Cheng et al., 2012; Ji and Chee, 2011; Mora-López and Sidrach-de-Cardona, 1998). Short term forecasting models for solar irradiance have also been widely studied and published (Dong et al., 2013; Reikard, 2009; Yang et al., 2014). Methodologies which are able to provide long term statistical analysis and synthetic time series in minute or hourly resolution

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are presented in Fernández-Peruchena et al. (2015) and Ngoko et al. (2014). However, models which are able to provide representative long term simulation results comprising non-measured locations with both temporal and spatial correlations modeled accurately cannot be found in the literature.

To respond to the need to optimally plan solar installations in the long term, this paper presents an easily applicable methodology to simulate large scale photovoltaic generation in locations that lack measured weather data. The paper presents a statistical Monte Carlo simulations based model, which is shown to be able to produce simulated solar irradiance data with all the important statistical characteristics. The statistical model is combined with a power generation model to form a methodology that can be utilized in power system planning when new solar generation is imposed on the system. It can also be used by power producers to analyze planned generation locations. This kind of modular and easily applicable methodology is a new addition to the existing literature.

The presented methodology is based on the approach used with wind power simulations in Ekström et al. (2015) and Koivisto et al. (2014). However, major modifications and additions are required, as both the statistical qualities of the data and the phenomena involved are completely different when solar generation is analyzed.

For clear-sky irradiance, the model presented in Rigollier et al. (2000) is used, as it does not require input parameters that should be estimated from on-site measurement data. Therefore, it is applicable for modeling non-measured locations. The measured solar irradiance data (this paper considers data from Finland) is first transformed to clear-sky index data, which is the measure of the ratio of the measured irradiance and the estimated clear-sky irradiance. With this approach, the deterministic components, e.g., the structures in the data caused by the movements of the sun and the earth, are removed, and the stochasticity (caused by, e.g., cloud movements) is left in the clear-sky index data. Also, in the clear-sky index data, the originally non-stationary irradiance data becomes stationary and the probability density functions (PDFs) of the marginal distributions are more representative for all parts of the year. A similar approach has been used for wind power in Koivisto et al. (2015). Empirical cumulative distribution functions (ECDFs) are fitted for the clear-sky index marginal distributions of the measured solar irradiance. The estimation of the out-of-sample percentiles for the probability distributions is not required as the clear-sky index data are by definition between zero and one, and the measured data includes measured values from the full range of supported data. ECDFs have also been used with marginal distributions in Li et al. (2012).

Stochastic renewable generation in multiple locations is analyzed with the copula method in Li et al. (2012), Papaefthymiou and Kurowicka (2009) and Wu et al. (2015). In this paper, the marginal distributions depicting the solar irradiance conditions in the individual locations, and the dependency structures (containing both temporal and spatial dependencies) between the locations are separated using a similar approach. The temporal dependency structures are analyzed with autoregressive (AR) models, which have also been used in Klockl (2008) and Villanueva et al. (2012). The spatial correlations are analyzed by estimating the correlation matrix between the locations. The spatial correlations are added in simulation using the Cholesky decomposition of the correlation matrix, as in Villanueva et al. (2012).

To achieve a modular nature in the presented methodology, the transformation from solar irradiance to generated power is separated from the statistical model for solar irradiance. The modular structure is essential and extends the applicability of the methodology, as different solar generation systems require completely different generation modeling.

In this paper, an established generation model for crystalline silicone photovoltaic (PV) panels presented in Mattei et al. (2006) is selected. To enable versatile applicability, the power generation model is modified to be able to transform the simulated solar irradiance data to a power time series and to allow the utilization of sun tracking or different tilt angles for the panels and different ambient temperature profiles for the locations.

The paper is structured as follows. Section 2 introduces the statistical Monte Carlo simulation based model for the solar irradiance simulations, and also shows the simulation of non-measured locations with the model. Section 3 presents the Monte Carlo simulation results, used for the verification of the model for the two measured locations omitted the estimation of the model to provide proper out-of-sample testing. Section 4 considers a power generation model for polycrystalline silicon PV panels, which is used with the statistical solar irradiance model. Section 5 assesses six scenarios to illustrate the applicability of the methodology. Section 6 provides a discussion on the possible applications of the introduced methodology and future work. Finally, Section 7 presents the conclusions obtained in the paper.

2. The solar irradiance model

This section presents the statistical solar irradiance model considered for the simulation of non-measured locations and the data used in the estimation of the model.

2.1. The data

The data used in the estimation and verification of the presented model are obtained from the Finnish meteorological institute. The data consist of measured hourly global irradiance time series from eight locations in Finland. The measured global irradiance data is presented in more detail in Table 1 and the measurement locations are shown in Fig. 1. The data is denoted as $\boldsymbol{E}_t = [E_{1,t}, \ldots, E_{k,t}]'$, where