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An improved model for the synthetic generation of high temporal resolution direct normal irradiation time series

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Abstract

Several studies have confirmed the relevant impact of the resolution and frequency distribution of solar radiation data on the results of detailed production models. Many of the available direct normal irradiance (DNI) databases generated from the satellite images have an hourly resolution. In the present work, we have proposed improvements to an existing model for the generation of 10-min synthetic DNI data from the hourly average DNI values. In the original model, the irradiance is divided into a deterministic and a stochastic component, i.e., the contribution from the hourly mean and stochastic fluctuation obtained from the mean depending on the sky condition, respectively. We have implemented several improvements, and the most relevant is the consistency of the synthetic data with the state of the sky. The adaptation and application of the model to the location of Seville show significant improvements over its predecessor as it achieved 7% rRMSD in hourly values and 1% rRMSD in daily values and presented a realistic frequency distribution in the 10-min resolution. In comparison with the original model, the application of the improved model showed significant performance improvements without any further adaptations to other locations with different climatological characteristics than Seville.

Keywords: DNI; High frequency; Solar radiation models; Cloud transients

1. Introduction

The direct normal irradiance (DNI) time series are the basic inputs for the simulation of solar thermal electricity (STE) plants. The simulation models have different requirements in terms of time resolution of DNI time series depending on their use or application. Studies by Meyer et al. (2009) and Gall et al. (2010) have emphasized the need to use time series with a time step shorter than 1 h for detailed performance simulations. Many performance models used in the commercial projects for assessing contractual performance require a one-year time series with a resolution time of 5–15 min, as a reasonable compromise between the computational cost and accuracy.

On the other hand, STE plant operators frequently use irradiance predictions based on the satellite estimates or meteorological and solar radiation models to operate in electricity markets or define subsequent operational strategies. Most of DNI prediction models are based on the short-term weather forecasts, which hardly exceed an hourly time step (Vincent, 2013) even though most of the simulation tools require higher frequency.

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The need for high-frequency DNI data is reflected in the latest publications of models for generating synthetic solar irradiance data focused on high temporal resolutions (Bright et al., 2015; Fernández-Peruchena et al., 2014, 2015; Grantham et al., 2013). Many of these models are based primarily on autoregressive moving average (ARMA) or Markov transition matrix (MTM) techniques, which provide time series with increased temporal resolutions. This leads to the introduction of improvements that helps in modeling the dynamic behavior of the solar radiation (Ngoko et al., 2014; Morf, 2013; Glasbey and Allcroft, 2008). Ngoko et al. (2014) proposed a second-order MTM model that included statistical characteristics associated with the atmospheric condition (clear, cloudy, overcast) leading to the improvement in the first-order MTM model employed by Richardson and Thomson (2011) for generating 1-min values. The use of wavelets and artificial neural network (ANN) techniques for the generation of solar radiation values is mainly focused on the forecast applications. However, in most of the cases, these models deal with daily or hourly global horizontal irradiation (GHI) data (Mellit et al., 2005; Linares-Rodríguez et al., 2011).

The solar thermal energy concentrating technologies exploit only the direct component. This component has unique statistical properties (Skartveit and Olseth, 1992), showing steeper gradients than the global radiation during the cloud transients. There exists a correlation between DNI and GHI that helps in obtaining one from the other with acceptable results; this is supported by the model study conducted by Skartveit and Olseth (1992) on the synthetic generation of irradiance values at different time intervals. Several authors have generated DNI values synthetically at a high frequency from the global irradiance values, but only a few authors have focused their models on the generation of high resolution DNI series from low-resolution DNI values.

Morf (2013) generated sequences of instantaneous global solar irradiance values on a horizontal plane that can be split into beam and diffuse components. The model was divided into a stochastic and a deterministic component related to the Angström-Prescott regression. The cloud cover was used as a stochastic driver for the generation of an on/off sequence of beam irradiance (Morf, 2011); the probability of beam irradiance is represented as the complement to one of the cloud covers. Bright et al. (2015) generated minute irradiance time series on an arbitrary plane from the previous estimation of both direct and diffuse components. This methodology used weather observation data to generate cloud transients sequences using the Markov chains. Fernández-Peruchena proposed the generation of 1-min resolution DNI series from the daily (Fernández-Peruchena et al., 2014) and hourly (Fernández-Peruchena et al., 2015) means of DNI values. The method was based on the previous generation of a database of dimensionless high frequency daily curves or series of DNI values obtained from the observed data. The days were selected based on the closest Euclidean distance between the daily and hourly means of the generated and measured series. The results obtained with this model were satisfactory in terms of variability and frequency distributions; however, the authors provided no results in relation to the deviation observed between the synthetic and measured hourly and daily means, which is one of the major targets of the present work.

Polo et al. (2011) proposed a model that was relatively indistinct to GHI and DNI. The model generated 10-min data from the hourly values while maintaining the statistical characteristics of an observed data set. Conceptually, DNI was divided into a deterministic and a stochastic component: the contribution from the hourly mean and stochastic deviation from the mean, respectively. The main problems detected with this model were the difference between the daily and hourly cumulative values of the measured and synthetic datasets that reached 2–4% in daily totals and 15% in hourly values, and the mismatches in their frequency distribution in the 10-min resolution.

In the present work, we propose some improvements to the above-mentioned model, based on the knowledge of the unique features of DNI behavior. The implementation of the improvements has been governed by two conditions: (1) the hourly values of the original series should be conserved reasonably in the synthetic one, and (2) the dynamics of the fluctuations of DNI must be consistent with the state of the sky. Therefore, we propose several improvements oriented toward the adjustment of the model under different sky conditions, a parameter for the distinction of hazy days based on the hourly DNI values only, and an improvement to restrict the values of the stochastic component of the model whenever required.

As a result, we present an improved model for the synthetic generation of 10-min DNI values from the hourly DNI data. The model, which solves the weaknesses of its predecessor, has been validated in five locations with different climatic conditions, showing a satisfactory performance regardless of the location in which it was used. This result was obtained despite the fact that the model has only been trained with data from one of these locations.

2. Meteorological database

The data set used for the training of the model consists of the 10-min and 1-h averages of DNI measurements registered every 5 s during 13 years (2000–2012) at the meteorological station of the Group of Thermodynamics and Renewable Energy of the University of Seville. The model improvements have been checked with the corresponding values for the year 2013 and later validated in five different locations in Spain covering latitudes from 37°N to 43°N. The selected sites are presented in Table 1.

All the data used in this work have been subjected to quality-control procedures following the BSRN recommendations (Moreno-Tejera et al., 2015).