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A simple and efficient procedure for increasing the temporal resolution of global horizontal solar irradiance series

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ABSTRACT

The intermittent nature of instantaneous solar radiation has a considerable impact on the nonlinear behavior of solar energy conversion systems. The time resolution of the Numerical Weather Prediction Models (NWPM) or satellite derived solar irradiance data are typically limited to 1-h (at best 15-min). Unfortunately, this resolution is not sufficient in the design and performance of many solar systems. In this study, a new methodology has been developed to increase the temporal resolution of GHI series from 1-h to 1-min. This methodology uses the clearness index k_t (the ratio of GHI to top-of-atmosphere irradiance on the same plane) to characterize the GHI high-frequency dynamics from a 1-year measurement campaign at a given site. The evaluation of the method with 2 years of measured data in different climatic zones has resulted in KSI(%) (Kolmogorov–Smirnov test Integral parameter) and normalized root mean square deviation values below 8.0% and 1.7% respectively for each month, with negligible bias. Indicators of overall performance show an excellent agreement between measured and modeled 1-min GHI data for each month: average values for Nash-Sutcliffe efficiency, Willmott index of agreement and Legates coefficient of efficiency are found to be 0.94, 0.99 and 1.00, respectively.

1. Introduction

Global horizontal solar irradiance (GHI) exhibits a great variability at high-frequency due to the dynamic effects of passing clouds (Fig. 1). Rapid changes in solar power output can impact markets with sub-hour intervals, reserve requirements, net load variability, regulation requirements, and the operation of other generators [1,2]. To capture these potentially challenging events, high temporal resolution GHI data is needed.

Unfortunately, short-term radiation data is not as readily available as hourly data. The time resolution of the Numerical Weather Prediction Models (NWPM) or satellite derived solar irradiance data are typically limited to 1-h (at best 15-min). This time resolution excludes much sensitive information which can introduce erroneous estimation of the functioning of solar conversion systems that respond quickly and non-linearly to incident solar radiation [3,4], especially photovoltaic systems [5]. Besides, photovoltaic (PV) power fluctuations caused by cloud transients can cause power quality and voltage regulation-related problems in distribution systems [6].

The power output variability from PV plants is a concern to grid operators, as unanticipated changes in the PV output can strain the grid. Therefore, it is important to statically characterize the GHI fluctuations at high temporal resolution. It is worth mentioning that PV power variability can be counteracted by fast-ramping generation sources, and by storage systems, but these options are quite expensive and substantially increase plant cost [7]. Besides, the usability parameter (the solar fraction of the radiation incident on the surface that exceeds a specified threshold or critical level [4]) has been evaluated at several frequencies, showing that both daily and hourly values lead to a conservative estimate of usability [4,8].

Recent results point to the importance of local distribution and type of clouds in 1-min solar irradiance distributions, and highlight the role of local atmospheric clear sky transparency in differentiating these distributions [9]. Therefore, the local characterization of the intermittent nature of solar irradiance at high-frequency is required in the definition of appropriate operating strategies for solar power plants [10–12]. In particular, it allows the simulation of certain aspects of plant operation, such as transient effects, and the evaluation of energy management options [3,4,9,11–13].

Measurement networks or stations with well-maintained, high accuracy measuring equipment providing 1-min measured GHI

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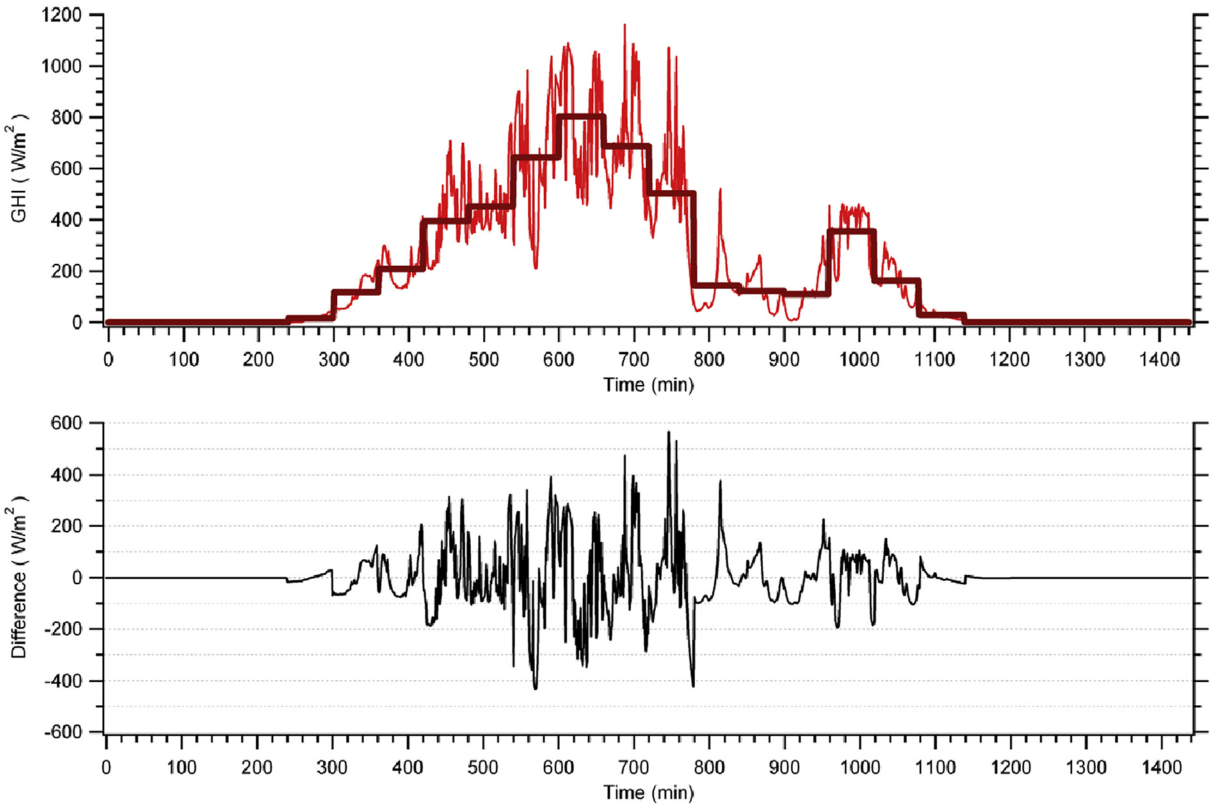

Fig. 1. 1-min and hourly-average GHI values measured at BSRN Carpentras station (top), and their difference (bottom).

data are rare, although a wide variety of agricultural research stations is available [14]. Consequently, several models have been proposed in the literature to synthetically generate high-frequency GHI series of similar statistical characteristics to the typically measured series. Skartveit and Olseth [15] developed a stochastic model for generating 5-min global horizontal irradiance from the corresponding hourly averages based on data measured in Atlanta, Geneva and San Antonio. Polo et al. [16] proposed a method for generating GHI values at 10-min intervals from the hourly mean values by means of adding a random fluctuation to the hourly interpolated values. Perpiñan et al. [17] applied the wavestrapping technique on the clearness index k_t, the ratio of GHI to top-of-atmosphere irradiance on the same plane [18], to reproduce the fluctuation behavior of the measured GHI series.

In parallel, several metrics have been proposed to quantify the effect of 1-min GHI variability, depending on the issue of concern (flicker, load balancing, etc.). For quantifying solar variability, ramp-rate (RR) statistics and the clear-sky index are commonly used [7], but they are worth to mention other parameters such as the autocovariance and autocorrelations in the time series of k_t detailed in Ref. [19]. Woyte et al. [20] used wavelet-based spectral analysis for the estimation of power flow fluctuations introduced by direct solar energy systems. Tomson et al. [21] described the distribution of ramp magnitudes for 5-min average solar irradiance. Lave et al. [22] computed clear-sky indices at 1-s resolution to estimate the smoothing of aggregated power output due to geographic dispersion in a distribution feeder.

This paper presents a methodology for generating synthetic GHI time series at 1-min temporal resolution from 1-h GHI series. This methodology is based upon the characterization of the high-frequency dynamics of k_t, and uses the GHI data obtained in a one-year measurement campaign at the given site. From this characterization, it is possible to generate compatible GHI series at a temporal frequency up to the measured values compatible with low-frequency (from sub-hourly to daily temporal resolution) GHI series at the site. The methodology proposed is validated by comparing the statistical characteristics of the synthetically generated GHI series to those of the ground measured ones in four locations with different climatic conditions.

2. Materials and methods

2.1. Experimental procedure

The methodology for increasing the temporal resolution of GHI series is adapted from a methodology recently proposed for increasing the Direct Normal solar Irradiance temporal resolution [23,24], based upon a non dimensional analysis. The steps followed in the construction of the synthetic series are detailed below:

Step 1.- Calculation of the time-normalized k_t series in the location. The time-normalized k_t of measured high-frequency daily GHI curves is based on the nondimensionalization of the temporal scale by dividing the elapsed Universal Time (UT) since sunrise by day length. As shown in Fig. 2, this non-dimensionalization scheme transform every daily high-frequency GHI curve into a dimensionless curve where the dimensionless time scale goes from 0 to 1. The dimensionless GHI scale goes from higher than 0 to higher than 1. k_t values higher than 1 are related with transient situations under partial cloud cover with clouds close to the sun position that in a short