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On the use of the coefficient of variation to measure spatial and temporal correlation of global solar radiation

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ABSTRACT

In this work we perform a statistical analysis of global solar radiation measured at two sites, Petit Canal and Pointe a Pitre, 38 km distant from, Guadeloupe, French West Indies. We have established a correlation model based on the coefficient of variation assuming a time scale separation. The coefficient of variation is calculated on 10 min interval with data measured at 1 Hz. This analysis highlights the dynamic correlation that can occur between measurements from two different sites with a time step of 1 s. From these results, knowing the coefficient of variation on a site, we have established a new correlation model on this parameter for another site. A diagram linking the standard deviation for the studied sites, for a given coefficient of variation is proposed for correlated and non-correlated cases. Moreover this analysis evidences the existence of a threshold time under which there is no significant correlation. The methodology and the model can be applied to any other sites to establish diagrams of the coefficient of variation.

This model can be useful in choosing new sites of PV production in establishing correlation from on site to another.

1. Introduction

Because of clouds, solar radiation is a multiscale fluctuating process especially under a tropical climate [1]. Indeed, rapid changes in the local meteorological condition as observed in tropical climate can provoke large variation of solar radiation. The amplitude of these variations can reach up to 700 W/m^2 [1,2]. Moreover, these solar radiation variations can occur within short a time interval (from few seconds to few minutes), depending on the clouds size, their speed and their number. The typical time scales associated with these solar radiation variations also vary significantly with the geographical location.

Studies of solar energy systems are traditionally performed using daily or hourly data [3,4]. These data do not take into account the fluctuations mentioned previously. It has been shown that the fractional time distribution for instantaneous radiation differs significantly from that obtained with daily values.

Since solar energy systems are sensitive to instantaneous radiation fluctuations, simulations of these systems with daily or hourly data can lead to significant error especially under a tropical climate. Indeed rapid variation of solar energy induces rapid and large variation of the output of such systems. For example solar cells (photovoltaïcs), used for electrical production, have very short response time and their electrical output will follow almost instantaneously the variations of solar radiation.

With a high density of photovoltaics generation in a power distribution grid, rapid fluctuations of the produced electrical power can lead to unpredictable variations of node voltage and power. In small grids as they exist on islands (such a Guadeloupe, FWI) such fluctuations can cause instabilities in case of intermediate power shortages with insufficient back-up capacity available. To manage the electrical network and the alternative power sources requires a better identification of these small time scales variations. This stresses the need for power system operators to develop real time estimation tools for such disturbances.

Over the last years, some work has been dedicated in establishing correlation between sites as a function of distance [5,6] and in parameterization of short-term irradiance variability [7]. There has been resurgent interest in modeling and quantifying subhourly variability using different methods and metrics. In Ref. [8] the authors use a frequency analysis based on spectral and coherence functions. This study showed high correlations for time scale greater than 3 h 4 h, 6 h, 12 h and 24 h which are the main time scales in the irradiance signal.

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Other studies have quantified the solar radiation variability with a prediction goal. Methods such as wavelets [9], fractal or multifractal parameters [10,11] or hybrid models [12] were used for a given site.

The Marquez formula [13] is also used to measure the variability, it is defined with the variation of the clear sky index CSI, $diff = CSI(t) - CSI(t-1)$ and $V = \sqrt{mean(diff^2)}$.

An extension of this metric (called P) proposed by Perez et al. [7] is based on the dispersion of the quantity diff $P = std(diff)$. Four metrics are used to characterize intra-hourly variability, including the standard deviation of the global irradiance clear sky index, and the mean index change from one time interval to the next, as well as the maximum and standard deviation of the latter. Different time scales are studied from 20 s to 15 min.

In the present work we compare and analyze the two first statistical moments of the solar radiation parameters measured at two sites, Petit Canal and Pointe a Pitre in the Guadeloupean archipelago with a time step of 1 s. We have established a correlation model for the coefficient of variation defined over a 10 min period.

The paper is organized as follow: the methodology is exposed in section 2, the theoretical frame is exposed in section 3. Section 4 presents the solar radiation measurements, in section 5 the results are presented and section 6 presents the discussion and conclusion.

2. Methodology

In the present work, we compare and analyze the solar global radiation signals G_1, G_2, measured at two sites in the Guadeloupean Archipelago. This study put tests the existence of a dynamical correlation between G_1 and G_2. To do so, we calculate for each signal, the global solar radiation fluctuation $G'_{[T_1;T_2]}$ for time scales T inferior to 10 min, 20 min, 30 min, …, 3 h. The cross-correlation coefficient $C_{G_1G_2}$ is used for each time scale T. From this result, we determine the time scale threshold T_{trs}: for$T < T_{trs}$, the two signals are decorrelated and for $T > T_{trs}$, the two signals are correlated. To evaluate the scattering effect of two sites, we determine the coefficient of variation for the sum signal G_{1+2}.

Finally, we propose analytical relationship of coefficient of variation I_{1+2} for two cases i) two signals statistically independent with different momentum, ii) two signals correlated with different momentum.

3. Theoretical framework

3.1. Decomposition of solar radiation signal using moving average filter

The moving average of the instantaneous solar radiation G, at a given instant t for a given averaging time T, is defined as [5,6]:

$$\overline{G_T}(t) = \frac{1}{N}\sum_{i=t-\frac{T-1}{2}}^{i=t+\frac{T+1}{2}} G(i) \tag{1}$$

Using the decomposition of Reynolds, the instantaneous solar radiation G can then be expressed as [5,6]:

$$G(t) = \overline{G_T}(t) + G'_T(t) \tag{2}$$

where $G'_T(t)$ are the solar radiation fluctuations for time scales smaller than T while the moving average $\overline{G_T}(t)$ gives the solar radiation evolution for time scales larger than T. This decomposition is illustrated in Fig. 1a, where $\overline{G_T}(t)$ is superimposed to $G(t)$ for a measurement duration of one day and for $T = 3600$ s. Fig. 1b illustrates the fluctuations obtained from equation (2).

Besides, the difference between two moving average having respectively averaging time T_1 and T_2, operates as a band pass filter giving the fluctuation for time scales ranging on $[T_1, T_2]$:

$$G'_{T_1-T_2}(t) = \overline{G_{T_1}}(t) - \overline{G_{T_2}}(t) \tag{3}$$

3.2. Coefficient of variation defined for two sites

In this study we consider solar radiation time series of 10 min length defined arbitrarily. Consider $G_1\begin{cases}\overline{G}_1\\ \sigma_1\end{cases}$ and $G_2\begin{cases}\overline{G}_2\\ \sigma_2\end{cases}$ two signals measured at site 1 and 2, respectively. We can define, for each G_1 and G_2, from the two first statistical moments $\overline{G}$ and σ, the coefficient of variation, a normalized measurement of dispersion of a probability distribution as:

$$I = \frac{\sigma}{\overline{G}}$$

here an analogy is made with the field of the turbulence. Classically, in the turbulence field, a turbulent intensity parameter expressing the ratio standard deviation to the mean value of the wind speed is a metric to characterize a turbulence level for flows with high variability, such as wind tunnel or atmospheric wind [14,15]. Here this parameter can be used for measuring the degree of variability of the global solar radiation and for classifying the variability level. In the turbulence field, one can distinguish three classes: i) $0 < I < 5\%$ corresponds to a weak level of variability, ii) $5 < I < 10\%$ corresponds to a medium level of variability and $I > 10\%$ corresponds to a high level of variability. In this study, we translate this coefficient to global solar radiation and hence we introduce a new way to measure the variability of solar irradiance.

This parameter is computed for the first time with global solar radiation data and could be an interest for the solar energy community. It could be a simple way in order to qualify and classify the variability level of sites.

Consider the aggregated signal G_{1+2}.G_{1+2} *is defined by* $G_{1+2}\begin{cases}\overline{G}_{1+2}\\ \sigma_{1+2}\end{cases}$ with $G_{1+2} = G_1 + G_2$ and $\overline{G_{1+2}} = \overline{G_1} + \overline{G_2}$

Let us define σ_{1+2} the standard deviation of signal G_{1+2}. By definition, the standard deviation of signal G expresses as follows:

$$\sigma_G = \sqrt{\overline{\left(G - \overline{G}\right)^2}}$$

thus,

$$\sigma_{1+2} = \sqrt{\overline{(G_1+G_2)^2 + \left(\overline{G_1+G_2}\right)^2 - 2(G_1+G_2)\overline{(G_1+G_2)}}}$$

This equation becomes

$$\sigma_{1+2} = \sqrt{\overline{G_1^2} + \overline{G_2^2} + 2\overline{G_1G_2} + \overline{G_1}^2 + \overline{G_2}^2 + 2\overline{G_1}\overline{G_1} - 2\,\overline{G_1\overline{G_1}} - 2\,\overline{G_1\overline{G_2}} - 2\,\overline{G_2\overline{G_1}} - 2\,\overline{G_2\overline{G_2}}}$$