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Daily irradiance test signal for photovoltaic systems by selection from long-term data

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ABSTRACT

When performing tests on a photovoltaic energy conversion system, it is useful to have a daily-term irradiance profile which, in some way, represents the typical behavior of this variable at a desired geographic location, including fast changes caused by weather. Therefore, the objective of this work is to propose a simple methodology, to choose a representative daily-duration irradiance signal, from long-term irradiance data. This is accomplished, by means of quantifying the irradiance variability, and considering the total daily energy. A method to combine these two factors, is proposed and employed in the selection the most representative day; it is also used to search for extreme condition days.

1. Introduction

Solar irradiance at the earth's surface, depends mainly on astronomical variables, and atmospheric phenomena like turbidity and weather [[1], pp.59]. In tropical regions, the second factor has a stronger influence. As a consequence, the change in total daily extraterrestrial irradiation, along the year, is small compared to the variations of irradiation at earth's surface.

Therefore, the effects of atmospheric phenomena, should be considered in the experimental evaluation of photovoltaic (PV) energy systems. This is specially important when they use batteries as energy storage, because the magnitude of irradiance can affect the charge and discharge rates, which influences the batteries' efficiency [[2], sec.1.21] [3].

Due to the above reason, the objective of this work is to propose a way of obtaining a daily-duration irradiance signal, which can be used to test PV energy systems, in a reduced time span, under fair and realistic conditions from a specific geographic location.

Using a representative signal also reduces bias in the comparison of different MPPT algorithms, power electronics converters topologies, or the efficiency of batteries. Because, when comparing between systems of this kind, an arbitrarily selected irradiance profile may favor or hinder a specific system.

Particularly, the results of this investigation will be useful to evaluate four different strategies to manage an off-grid water pumping system. The irradiance signal will be used as an input to a programmable power supply, capable of PV array emulation, allowing to conduct experiments under repeatable and controlled conditions.

The duration of the test signal is chosen to include the effects of sun's movement in the sky, since this affects the batteries' charge and discharge cycle. Rapid changes in irradiance are also considered, since they allow evaluating the transient response of the system's components and algorithms. It should be noticed that slower phenomena, like those related to the time scale of the PV system's life span, are not accounted for within a daylight duration signal.

The signal of a representative day is not meant to be an extreme case, but rather a “normal” or average behavior of the irradiance at a particular location. Consequently, knowledge of this behavior must be obtained from long-term measurements, conducted in the place of interest.

Obtaining a representative day signal, can be achieved by the following methods: Select it from the measured data, in a way, that the chosen day approximates the “normal” or average behavior of long-term data; or generate it by means of a synthetic model of the irradiance behavior, as regarding to [4–6] among other works.

The first approach is employed in this investigation. Selection is made by proposing a quantitative metric of “closeness” to average or “normal” behavior, and then applying it to the measured data, in order to identify the most representative day. That definition of

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"closeness" uses a measure of *variability*, which is proposed in this paper, and the daily total energy, creating a new combined criterion that allows selecting the most representative day in a large set of data. The criterion is also employed to find extreme-case days which may be used to test a PV energy system under harsh conditions.

2. Some definitions of *variability* and *stability of the radiative regime*

Definitions of the *variability* of an intermittent power source, can be found in Refs. [7–10]. Also, under the term *Stability of the Radiative Regime*, which is reciprocal to the *variability*, but concerning the same concept, works [11–13] propose different ways to classify days according to their *variability*.

The quantitative definitions of *variability* given in Refs. [7–9], are applied to power generated by wind turbines. However the authors of [7,8] claim that they can be applied to other intermittent power sources. On the other hand [9] is more specific to wind energy context.

The definition given in Ref. [7] enhances a commonly used metric called "coefficient of variation" (defined as *standard deviation / mean* of long-term data), by also accounting for the variations in power that occur at frequencies higher than a cycle per day. This is achieved by comparing the integral of power spectral density of these fast variations, to the integral of the total spectral density for all frequencies.

A different method is used in Ref. [8], which makes a statistical characterization of the difference between the maximum and minimum values of power, during a given time interval, for all points in the signal. This means that the metric proposed by the authors, depends on the width of the time window.

In Ref. [10] two indexes to quantify irradiance variability are presented. The first one, makes a subdivision of days in equal time intervals, then, for each one, the variance and mean value of irradiance are calculated, finally, a weighted average of the variance values is calculated, using the irradiance's mean as weights. The authors affirm that this method is well suited for solar heating systems.

The second method from Ref. [10] is a total harmonic distortion (THD) calculation of the daily irradiance, which considers as distortion the third and higher harmonics. This can be said to be similar to the method from Ref. [7].

Four ways to quantify the *stability of the radiative regime*, of a single day, are summarized in Ref. [11]: averaged cloud shade, simulated observed cloud cover amount, daily clearness index and fractal dimension of global solar irradiation. Afterwards, this work proposes a new criterion, the daily average value of the sunshine stability number ζ. A brief review of these five methods is given bellow.

The average cloud shade, is based on a boolean parameter called the sunshine number ξ, which indicates if the irradiance level exceeds a given threshold (120 W/m^2), this criteria is then averaged over a given time interval. In the case of [11] it is the daylight length.

The observed cloud amount is based on estimations by eye, which are subject to error. As a remedy [11] uses a mathematical relationship to calculate the observed cloud amount based on the average cloud shade.

The instantaneous clearness index k_t, further explained in section 3.1, is integrated with respect to time along the day, to obtain the daily clearness index k_{day}.

The fractal dimension method, also explained in Ref. [12], relates to the length of the line that corresponds to the irradiance signal in an irradiance vs. time plot. If there are more frequent and/or larger changes in the signal value, then the path traversed by it, grows longer, producing a larger value of the fractal dimension.

The sunshine stability number ζ is a boolean parameter which describes the fluctuation between samples of the sunshine number ξ. Then ζ values are averaged (producing a non boolean result) during a given time interval, in this case the daylight duration. Also, computations of disorder and complexity of ζ are performed in Refs. [11,13], but the authors point out that they give similar results to the averaged ζ which is easier to obtain.

2.1. Selection of the variability definition

The method from Ref. [7] is employed to evaluate the variability of a long term signal, instead of doing it on a daily basis, as is needed in the present investigation. To use this method in the choice of a daily signal, would mean to calculate an estimate of the spectral power density for each day in the available data, which is a cumbersome task. This also happens in the second method from Ref. [10], where the THD for each day has to be calculated.

Other methods do not account explicitly for the behavior of irradiance as a function of time, instead they deal with its summary statistics, calculated over a given time window. This is the case of: [8], the first method presented in Ref. [10], the average cloud shade, observed cloud amount and daily clearness index methods from Ref. [11]. For example, if the time window is broad (even reaching the full daylight duration), there is knowledge related to the total amount of time that the sky was covered, but there is no clear information on how frequent and fast were the transitions between clear and covered skies.

Trying to choose an appropriate length for the time window must take into account the final application area, since PV systems are specially susceptible to fast transients, as concluded in [[14], pp.279]. The same author claims in Ref. [15] that the sampling window must be 5 s or less, in order to detect most transient processes. Therefore, the use of time window averaging methods may hide important information concerning the operation of solar PV systems.

The sunshine stability number ζ explained in Refs. [11,13] is different from the previous methods because it carries information about temporal changes, boldly speaking, it can be considered as the absolute value of time derivative of the sunshine number ξ. But since its value is boolean, the information about the magnitude of changes in irradiance is lost. This is also a problem in the average cloud shade and observed cloud amount methods.

The fractal dimension from Refs. [11,12], has information about temporal changes and, unlike the ζ method, it accounts for the magnitude of changes in irradiance. Unfortunately its computation can be cumbersome because different values of the time interval must be used, which means repeating the calculations for each day and each different time interval.

In the search for a method that includes information about the speed, number and magnitude of changes in irradiance, and that is also easy to compute, we propose a simple definition of variability which is explained bellow in section 4.1. Afterwards this definition is complemented with the total daily energy, since it is a very important variable extensively used in the sizing of PV systems.

3. Methodology

Irradiance was measured with a Kipp & Zonen CM3 thermopile type pyranometer [16], located at the top of a six floor building in Bogotá, Colombia (latitude: 4°35′ N, longitude: 74°04′W), during a whole year (from 2016-08-19 to 2017-08-18) in order to avoid