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Evaluation of solar radiation properties by statistical tools and wavelet analysis

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ABSTRACT

With high penetration of PV generation in power grid distribution systems, solar irradiance fluctuations introduced by moving clouds may lead to variations in voltage and power flow in the grid and may affect the stability of the grid system. Predicting the characteristics of the fluctuations requires a mathematical approach, such as the combination of a statistical tool and wavelet analysis. The instantaneous clearness index is a parameter on which the Wavelet analysis is applied, and which is decomposed into components of different scales, corresponding to their persistence. These components are examined to evaluate the magnitude and the persistence of the various fluctuations of the solar radiation. The method presented in the present article can offer a valuable tool for the estimation of power flow as induced by solar radiation fluctuations.

1. Introduction

The intermittent nature of solar radiation may pose difficulties to the utility grid operator when large-scale installations of photovoltaic (PV) systems are interactive with the grid. Solar irradiance fluctuations, induced by moving clouds, may lead to variations in the voltage and in the power flow to the grid, and may thus affect the stability of the grid system. The most significant fluctuations occur under partly cloudy skies (scattered clouds) with durations of several minutes. However, fluctuations lasting several seconds or more than 1 h may also be expected. Solar radiation consists of radiation fluctuations which are of stochastic nature introduced by meteorological conditions, and deterministic radiation originating from astronomical relationships. The fluctuations are characterized by amplitude, persistence (duration) and frequency of occurrences. The sampling time of the solar radiation measurements may affect the results of the analyzed characteristics of the fluctuations. Predicting the characteristics of the fluctuations requires a mathematical approach; such as the combination of a statistical tool and wavelet analysis. The wavelet analysis and the wavelet decomposition of data sequences have already been used for applications such as the analysis of power demand by Degaudenzi and Arizmendi [1]. Croes et al. [2], used the wavelet transform of analytic signals as a basis for the instantaneous active and reactive power definitions. Santoso et al. [3], demonstrated the use of wavelet decomposition and reconstruction on electrical power waveform signals, where events of disturbance, such as impulse transients due to lightning strikes, can occur. It was shown how a compression of such temporal information signals was made possible through wavelet and noise reduction analysis.

Some researchers who are engaged in the fields of solar radiation and photovoltaics modeling, choose to process climatic data sequences purely from the statistical point of view, while others tend to combine statistics together with other mathematical tools so as to process such sequences prior to their analysis. Suehrcke and McCormick [4] showed that 1-min radiation data behave statistically different from lower-frequency data. Gansler et al. [5], discuss the benefit of short-time sampling of radiation data over hourly data in regard to the effect of solar radiation variation on large scale PV systems. Gansler et al., accentuate this benefit by showing how cumulative distribution functions of minute radiation differ from those of hourly data, and tend to have a bimodal shape which better suits the notion of fluctuations. Perpinan and Lorenzo [6] deal with the analysis of the variability of the irradiance and the effect on the PV power using wavelet transform. The authors showed that the irradiance and the power time series are a non-stationary process whose behavior resembles a long memory process, and the time series of global irradiance on a surface can be simulated with a waves trapping technique applied on the clearness index. Perpinan, Marcos and Lorenzo [7] further analyzed the correlation between fluctuations of the electrical power from a series of 70 DC/AC inverters, separated by 200 m to 2.8 km apart in a PV field. The 70 inverters covered a generated power of about 45 MWp from a large PV trackers field, whose recordings served as the experimental database for the analysis. A wavelet-based algorithm was devised to examine the statistical properties and the correlation between the fluctuations in

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Nomenclature

$k(t)$	instantaneous clearness index as function of time
$\overline{k}$	daily mean value of clearness index
$F(k(t))$	cumulative distribution function of the clearness index
$G(t)$	terrestrial global solar radiation on a horizontal surface as function of time
$G_0(t)$	extraterrestrial solar radiation on a horizontal surface as function of time
n	day number in a year
ϕ	Earth's latitude
δ	Earth's declination angle
ω	Sun's hour angle
z	Sun's zenith angle
M	air-mass
j_0	order j_0 of the wavelet decomposition/transform
$\psi((t-\xi)/2^j)$	detail-wavelet function shifted by ξ and scaled by 2^j (jth order)
$\phi((t-\xi)/2^j)$	approximation-wavelet function shifted by ξ and scaled by 2^j (jth order)
$D_j(x[n])[\nu]$	detail-wavelet coefficient of the jth order of data sequence $x[n]$ where the wavelet is shifted by ν
$A_j(x[n])[\nu]$	approximation-wavelet coefficient of the jth order of data sequence $x[n]$ where the wavelet is shifted by ν
$\|x[n]\|_2$	L^2 norm of sequence $x[n]$
$f_P(j, \cdot x[n])$	fluctuation power index of jth order, in relation to data sequence $x[n]$
$\langle x_N \rangle^2$	mean value of the squared elements of a sequence x whose length is N
$f_j(t)$	expected value of a jth order fluctuation on time t

the generated power of each of the inverters. They observed that wavelet correlation values depended on the distance between inverters, the wavelet time scales and the daily fluctuation level.

The article by Lave et al. [8], deals with several topics of high-frequency irradiance fluctuations induced by moving clouds. Clear-sky data is used at a resolution of 1-s in six different locations in California to extract irradiance statistics. Ramp rate of the fluctuations was analyzed, and "geographic smoothing" was presented, a term which relates to the degree of correlation between several sites with respect to statistical features of irradiance fluctuations. Woyte et al. [9–11], present a study to analyze high frequency irradiance data using wavelet transform. Woyte, Belmans and Nijs in Ref. [12] addressed the issue of short time fluctuations and their impact on the variations in the voltage and the power flow to a localized low-voltage grid in residential areas, where PV systems could be potentially installed in a large scale. In Ref. [12], the energy conversion chain from solar irradiance down to the power flow was first modeled and evaluated by means of statistical techniques. For this purpose, a database of solar irradiance on a 30° tilted plane has been recorded with 1 s time resolution over a period of three months in the summer. A time series of the clearness index was derived from the database, which later served as the basis for power/voltage fluctuations assessment and their impact on overloads of grid lines by means of probability methods. Additional mathematical tools were exploited by Cao and Cao in Ref. [13], where wavelet analysis combined with artificial neural networks was used to forecast a day-by-day solar irradiance data. Unlike Woyte et al. [9–11], who focused on the wavelet analysis of the clearness index, data sequences of solar irradiance in Ref. [13] were mapped into time-frequency domains, and an attempt to extract some recurrent patterns of behavior within the solar radiation signals through neural-networks was carried out. Dorvlo, Jervase and Al-Lawati [14] demonstrated the use of neural-networks (NN) alone in solar radiation modeling and prediction, and solar radiation measurements from Oman were used to evaluate the accuracy of their NN based model. It should be mentioned that the above mentioned articles are oriented towards fluctuation analysis of the irradiance signals and not for providing a practical tool for forecasting of the magnitude and duration of the fluctuations. The work introduced by Woyte et al. [9–11], serves as a basis for the present article in attempting to develop such a tool.

The analysis of the fluctuations starts with two dimensionless variables: the instantaneous clearness index, defined as the ratio of the horizontal global terrestrial radiation to the horizontal extraterrestrial radiation, and the daily average clearness index. It is shown that the statistical properties of the instantaneous and the daily average clearness index can act as the basis for the examination of time related solar fluctuations. Various calculations of the fluctuation of the instantaneous clearness index are performed with the use of wavelet analysis [15–19] where the clearness index is decomposed into components of different scales, corresponding to their persistence. These components are examined for their magnitude and duration of the various fluctuations.

The main contribution of this work is in converting the decomposed components of the clearness index into useful information for the operator in distributed grids with high density embedded PV generation. The evaluation of the solar radiation data, as presented in this study, was performed on several years on measurements sampled at 1 min in a desert area at Sede-Boqer, Institute of Desert Research, Israel.

2. Instantaneous clearness index and its statistical properties

The clearness index $k(t)$ was introduced by Liu and Jordan [20] as a parameter that accounts for the stochastic properties conditions at a given site. The instantaneous clearness index $k(t)$ is defined by:

$$k(t) = \frac{G(t)}{G_0(t)} \tag{1}$$

In Eq. (1), $G(t)$ is the terrestrial *global solar radiation on a horizontal surface*. $G_0(t)$ is the extraterrestrial radiation on a horizontal surface at any time between sunrise and sunset, defined as (Duffie and Beckman [21]) :

$$G_0(t) = G_0 \cdot \left(1 + 0.033\cos\left(\frac{360n}{365}\right)\right) \cdot [\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta] \tag{2}$$

where $G_0 = 1367[\mathrm{W/m^2}]$ is the solar constant and ϕ, δ, ω are the *earth's latitude*, *earth's declination angle* and the *hour angle*, respectively; $n \in [1, 365]$ represents the number of the day of the year.

Liu and Jordan [20] observed that the distribution of the daily clearness index can be described analytically for any specified mean value, independent of any geographical or seasonal influence. Hence, in statistical terms $k(t)$ is referred to as a random variable with its probability density at a given site, determined only by its mean daily value $\overline{k}$. Time related variations in the instantaneous clearness index $k(t)$ signal originate from local climatic conditions, namely by passing clouds. In that sense, fluctuations within the instantaneous clearness index signal are merely transitions between cloudy and clear skies.

Fig. 1 shows an example of a time-dependent clearness index signal around noon time, on December 14th 2005 as measured at