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Fluctuations in instantaneous clearness index: Analysis and statistics

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Abstract

Solar radiation is characterized by short fluctuations introduced by passing clouds. An analysis of these fluctuations with regard to solar energy applications should focus on the instantaneous clearness index. Its probability distribution for a given mean clearness index is, as a first approximation, independent from the season and partly also from the site. This is verified for four annual datasets from three different sites.

An analysis of fluctuations in solar radiation must focus on their amplitude, persistence, and frequency of occurrence rather than their location in time. The Fourier analysis cannot satisfactorily provide this information since time series of the instantaneous clearness index exhibit no periodicity. Instead, a localized spectral analysis based on wavelet bases rather than on periodic-ones has been applied. This analysis allows the decomposition of the fluctuating clearness index signal into a set of orthonormal subsignals. Each of them represents one specific scale of persistence of the fluctuation.

The annual mean square values of all subsignals have been analysed, permitting the allocation of the signal's power content to the different scales of persistence of a fluctuation. These annual mean values agree well for the different datasets, indicating the existence of statistically significant mean square values of the fluctuations as a function of their persistence.

The analysis offers a valuable tool for the estimation of power flow fluctuations introduced by direct solar energy systems. With further elaboration it may be applied by power system operators for network planning in distribution grids with a high density of embedded generation.

Keywords: Fluctuations; Spectral analysis; Wavelets; Clearness index; Solar radiation

1. Introduction

1.1. Problem description

The intermittent nature of solar radiation has often been cited as one of the drawbacks of the large-scale application of photovoltaics (PV) and other forms of direct solar energy. With a high density of PV generation in a power distribution grid, slow variations during days and weeks represent an additional challenge for maintaining the energy balance in the system. Fast and short irradiance fluctuations as they are introduced by moving clouds can lead to unpredictable variations of node voltages and power, mainly in weak residential and rural grids with high series resistance. In small grids and micro-grids as they exist for example on islands or in remote areas, such fluctuations can even cause instabilities in case of intermediate power shortages with insufficient back-up capacity

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Nomenclature

G	global irradiance on an arbitrarily oriented surface
$I_0 = 1367\ \mathrm{W/m^2}$	solar constant
E_0	eccentricity correction factor
θ_i	angle of incidence of the sun rays on an arbitrarily oriented surface
k	instantaneous clearness index
$\bar{k}$	mean clearness index of a set of instantaneous values k
$m = 1/\cos\theta_z$	air mass
θ_z	solar zenith angle
F	cumulative frequency
τ	time constant of a first-order thermal differential equation, applied for pyranometer correction
t	time
$x(t)$	value of a function x at time t
$x[n]$	nth number in a discrete sequence, $n \in \mathbf{N}$
T_0	length of a signal $x(t)$
N	length of a sequence $x[n]$
ΔT	sampling period for discretization: $n\Delta T = t$, $N\Delta T = T_0$
$\psi(t)$	mother wavelet, base function for an orthonormal wavelet transform
$\psi^*(t)$	complex conjugate of $\psi(t)$
θ	time shift of a wavelet base
j	level of scale of a wavelet decomposition, $j \in \mathbf{Z}$
2^j	scale or scale factor of a wavelet at the decomposition level j
$j_0 = \log_2 N$	largest possible decomposition level for a sequence of length N
$w_j(\theta)$	subsignal from wavelet decomposition as a function of time at the level of scale j
$W^{\theta}_{2^j}\{x(t)\}$	stationary wavelet transform of a function x from the time domain into the time-scale domain
$I^{\theta}_{2^j}\{x(t)\}$	wavelet periodogram, estimator for the local spectral density (LSD) of $x(t)$
T	persistence of a bimodal fluctuation
T_j	characteristic persistence of a fluctuation at scale 2^j
$\mathrm{cf_p}(j)$	fluctuation power index: mean spectral density of a signal on scale 2^j
$\mathrm{cf_e}(j)$	fluctuation energy index: mean energy bound and freed again during a fluctuation on scale 2^j
RMS	root mean square
PSD	power spectral density
LSD	local spectral density
a.s.l.	above sea level

available. Although these effects have been found to be negligible in many situations (Hübert, 1995), worst-case scenarios are still of major concern for many power system operators. In order to schedule adequate measures for grid reinforcement in time while avoiding too cautious and cost intensive measures, power system operators need tools for a realistic estimation of such disturbances.

1.2. Related studies

Two studies assessing cloud-induced power fluctuations in distribution grids with high PV connection density were performed by Jewell and Ramakumar (1987) and Kern et al. (1989). They modelled clouds by primitive geometries, moving over the area under examination. The studies mainly focus on fluctuations in power and their impact on economic dispatch. General conclusions on the statistical frequency and persistence of fluctuations in irradiance and power flow could not be drawn.

Beyer et al. (1994) modelled the contours of clouds as fractals, taking into account the irregular shape and distribution of clouds. Synthetic cloud patterns generated by Beyer et al. (1994) formed the input of in-depth studies of the voltage behaviour in distribution grids with high PV connection density by Hübert (1995). According to Hübert (1995), in typical European distribution networks, PV-induced voltage fluctuations are mostly not an issue.

A set of specifications for the description of fluctuations was proposed by Kitamura (1999). Fluctuations in power are described by three parameters: magnitude, duration of a transition between clear and cloudy, and speed of the transition, defined as the ratio of magnitude and duration. A similar approach named ‘ramp analysis’ was proposed by Beyer et al. (1991) and later applied by Scheffler (2002). Both approaches provide the speed of irradiance variations as valuable additional information. A drawback of these approaches is that they are “partly based on subjective judgement” (Beyer et al., 1991).

A statistical approach was applied by Otani et al. (1997) and Endo et al. (1997). They characterize irradiance data by their fluctuation factor which is the root mean square (RMS) value of the high-pass filtered time series of solar irradiance. These authors further propose the power spectral density (PSD) of the irradiance time-series as a potential tool for the analysis of cloud fields without further elaborating this approach.

An approach that combines advantages of Beyer et al. (1994), Otani et al. (1997), and Kitamura (1999), is the analysis of fluctuations of the instantaneous clearness index by means of a wavelet transform (Woyte et al., 2001). Similar to fractal cloud patterns, this approach allows the analysis of all scales of fluctuation in time, from very short variations up to long fluctuations. Similar to the fluctuation factor as defined by Otani et al. (1997) the localized