Solar Energy 155 (2017) 985–1001

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Analytic model for correlations of cloud induced fluctuations of clear-sky index

Boudewijn Elsinga *, Wilfried G.J.H.M. van Sark

Utrecht University, Copernicus Institute of Sustainable Development, PO Box 80.115, 3508TC Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 16 June 2017
Accepted 9 July 2017

Keywords:
Solar photovoltaics
Auto-correlation
Cross-correlation
Cloud modeling

ABSTRACT

We have derived an analytic model to describe the correlation of cloud-induced fluctuations on photovoltaic (PV) system power generation versus distance or time lag in terms of the parameters that describe the clouds (duration, opacity, ramp smoothness and lag). Clouds are modeled as clear-sky index deviations with sigmoidal ramps. The found auto-correlation function is suited to deterministically describe the correlation versus distance or time lag over a short period of recent time (up to several hours depending on the amount of clouds and the temporal resolution of the data) to a very high level of detail, as opposed to other methods that use a statistical approach. The sensor-pair cross-correlation of a cloud with variable width (and/or specified to a more complex or two-dimensional localized shape) can also be fully understood. Application of the model is investigated in terms of relative aggregate variability of an ensemble of (virtual) PV-systems for one, two or three subsequent clouds. This analysis explicitly relates the shape of clouds to the dimensions of a dense PV-network which is beneficial for understanding variability of PV-systems in a large plant or dense urban region.

1. Introduction

With increasing amount of photovoltaic (PV) systems in operation globally, the total global installed capacity, which was 307 GW_p by the end of 2016 and projected to grow to multiples of this value the coming decades SPE (2017), more and more attention is given to the nature and impact of variability of the electrical power output of these systems on individual and aggregate level (Mills and Wiser, 2010; Hoff and Perez, 2010; Perez et al., 2012; Elsinga and Van Sark, 2014; Widén et al., 2015; Widén, 2015; Lohmann et al., 2016). Strong fluctuations (or *ramp rates*) of irradiance and hence generated electrical power as a result of moving clouds can lead to problems in (weak) electricity networks and can hinder the further deployment of PV, especially used in the distribution grids (Lave and Kleissl, 2010; 3E, 2015). Knowledge of the localized simultaneity of fluctuations in relation to cloud velocity is therefore important and it is our aim to contribute to this subject by analyzing the nature of the correlations of these fluctuations as a function of PV-system separation (in time or in distance).

This subject has been reported by several authors by means of statistical auto-correlation methods in which (auto) correlation functions are assumed rather than defined (Hoff and Perez, 2010; Lonij et al., 2013; Arias-Castro et al., 2014; Widén, 2015). In this paper we derive a new method that evolved from a bottom-up analytic approach for finding a correlation function based on assumptions of the time series of the shadows of moving clouds.

2. Clear-sky index and correlation

The clear-sky index time series, here denoted as k_t^*, is defined as the Global Horizontal Irradiance (GHI), I normalized by the clear sky GHI, I_{clear}, see Eq. (1). This is a useful quantity in order to detrend the deterministic part of the GHI time series consisting of the diurnal pattern.

$$k_t^* = \frac{I_t}{I_{clear,t}} \quad (1)$$

The clear-sky index fluctuation (step-change) at a measurement location i is defined as the difference of sequential (Δt averaged) k_t^* values at temporal resolution $\Delta t : \Delta k_{i,t}^* = k_{i,(t+1)}^* - k_{i,t}^*$. The (empirical) Pearson correlation coefficient between the clear-sky index time series of a pair of PV-systems i and j is stated in Eq. (2). The fluctuations could, in principle, be divided by Δt, but this factor would occur squared both in the numerator and the denominator and thus drop out of Eq. (3), which is the explicit form of ρ_{ij} that sums over the entire length T of the time series, $k_{(i,j),t}^*$, with $\overline{k} = 1/T\sum_{t=1}^{T} k_t$ the mean.

* Corresponding author.
E-mail address: b.elsinga@uu.nl (B. Elsinga).

http://dx.doi.org/10.1016/j.solener.2017.07.035
0038-092X/

$$\rho_{ij} = \frac{\mathrm{Cov}(\Delta k^*_{i,t}, \Delta k^*_{j,t})}{\sqrt{\mathrm{Var}(\Delta k^*_{i,t})\mathrm{Var}(\Delta k^*_{j,t})}} \quad (2)$$

$$= \frac{\sum_{t=1}^{T}\left[\left[\Delta k^*_{i,t} - \overline{\Delta k^*_i}\right]\left[\Delta k^*_{j,t} - \overline{\Delta k^*_j}\right]\right]}{\sqrt{\sum_{t=1}^{T}\left[\Delta k^*_{i,t} - \overline{\Delta k^*_i}\right]^2 \sum_{t=1}^{T}\left[\Delta k^*_{j,t} - \overline{\Delta k^*_j}\right]^2}} \quad (3)$$

Apart from clear-sky index, correlation relations can be found for other (congruent) time series, like (normalized) power production or hourly energy production, but this paper will focus on clear-sky index fluctuations as that gives a location and orientation independent measure of performance of PV-systems.

2.1. Time lag versus distance lag

PV-systems in the context of this research are spatially fixed. In that respect it makes sense to discuss correlation in relation to inter-system (or station-pair) distance. This distance was calculated following the curvature of the Earth. The analytic correlation model that is described in this paper, however, is based on time lag and temporal shape of the clear-sky index time series. It is assumed that the shade-velocity, or ground-projected cloud velocity (v_c) is constant. This way, the results can be interpreted both in terms of time lag τ_{ij} and distance d_{ij} and are mathematically identical under $\tau_{ij} \leftrightarrow d_{ij}/v_c$. When the PV-system pairs are further specified to a inter-pair direction $\hat{d}_{ij} = \vec{d}_{ij}/|\vec{d}_{ij}|$ within ±5° of a global (wind) direction, the projected distance can be defined as: $d_{ij} \rightarrow d_{ij}|\cos(\alpha_{ij})|$, where α_{ij} is the angle between the chosen wind direction vector and the vector from location *i* to *j*, or equivalently: $\cos(\alpha_{ij}) = [\vec{v}_c \cdot \hat{d}_{ij}]/|\vec{v}_c|$.

2.2. Examples from literature

Scattering of correlation versus PV system pair distance data, at coarse temporal resolution (>30 min) has been reported to result in first order exponential decay of correlation, or (de) correlation of fluctuations of power or clear-sky index as a function of inter-system distance (Murata and Otani, 1997; Wiemken et al., 2001; Glasbey et al., 2001; Mills and Wiser, 2010; Lave and Kleissl, 2013; Perez and Fthenakis, 2015; Munkhammar et al., 2017). However, simulation or observation of data at finer temporal resolution (seconds to minutes) shows more detail in the (empirical) correlation: Hoff and Perez (2010), Lonij et al. (2013) show a distinct effect of the correlation to cross the $\rho = 0$ line and find anti-correlation for system-pairs along the wind direction (*along-wind*). Perez et al. (2012) show that the correlation between pairs of PV-systems in a virtual network follows an intricate form, containing much more information than only the zero-crossing ($\rho = 0$) or the first order decay (see e.g. Fig. 2. in that paper, or Fig. 1 here). Fig. 1 a and b show examples of correlation $\rho(d_{ij})$ as a function of distance for cross-wind and along-wind situations. A clear "dip" can be seen for the along-wind condition, followed by "noise" around $\rho = 0$ that hints at more structure, for larger d_{ij}. This has been investigated further by Hinkelman (2013) with high resolution data in which the wind direction was accounted for. Although these studies show in detail the shape of the correlation, they do not explain in detail the correlation function and how it relates to the underlying process of moving clouds: most of the correlation functions used are based on statistical (auto) correlations or a fit thereof.

The following subsections contain a brief discussion of approaches by Lonij et al. (2013), Arias-Castro et al. (2014) and Widén (2015) to describe the (auto) correlation function of moving clouds in a statistical sense, followed by our own deterministic approach.

2.2.1. Lonij et al. 2013

Lonij et al. (2013) propose a (statistical) mixed spatio-temporal correlation function of clear-sky index time series of the form:

$$f(\vec{\Delta x}, \tau) = A\mathrm{Exp}\left(-\frac{|\vec{\Delta x} - \vec{v}_c\tau|}{\sigma_x} - \frac{|\tau|^q}{\sigma_t^q}\right) \quad (4)$$

This function combines first order (de) correlation over spatial lag $\vec{\Delta x}$ (including cloud drift with wind velocity $\vec{v}_c$) as well as time lag to the power *q*. Time lag in our paper is denoted as τ, contrary to the notation by Lonij et al. (2013), who use Δt; moreover, we use Δt for temporal resolution that is noted as $\bar{t}$ in their paper. Scaling parameters σ_x and σ_t are to be derived from statistics on historic

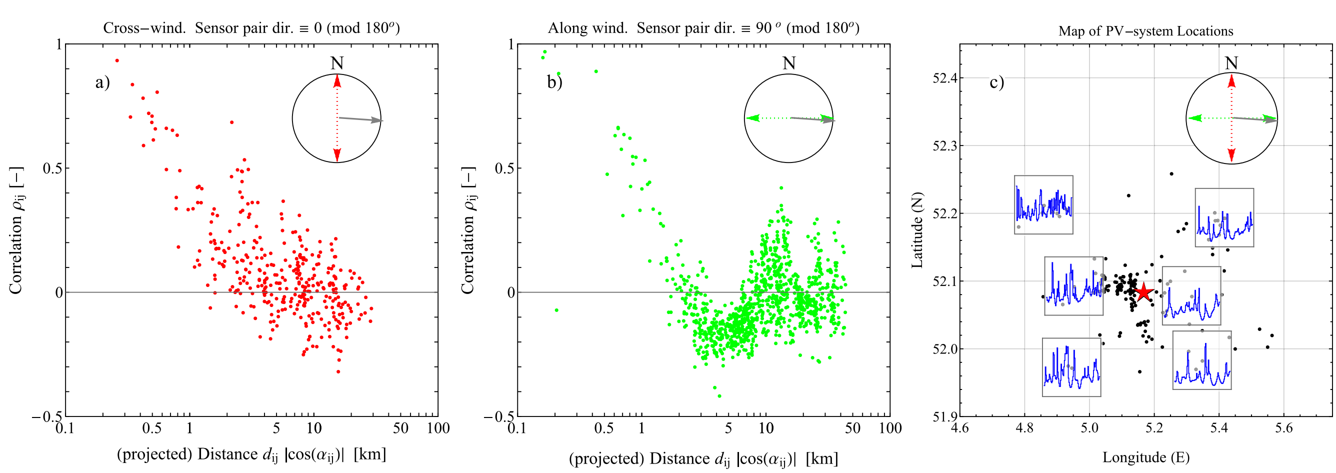

Fig. 1. (a & b) Semilogarithmic saxophone-shaped plots of inter-system correlation ρ_{ij} versus inter-system distance d_{ij}, projected on the wind direction for approx. 150 PV-systems on June 3rd, 2015 between 10:00 and 13:20 (UTC), at data temporal resolution $\Delta t = 120$ s. Selection of locations within ±5° in the cross wind (a) or along the wind (b) direction (indicated by arrows). The cloud motion direction, found by cloud camera image tracking at the location of the red star (UPOT) was very consistently 94° (Eastward motion) in that period (indicated by the gray arrow). Fig. (c) shows an equirectangular map of the PV-systems, with example time series at some of the locations. The details of the collected data (AC Power from PV-systems converted into k^*) are described in Elsinga et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)