Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 112 (2015) 55–67

SOLAR ENERGY

www.elsevier.com/locate/solener

Recognition and modelling of irradiance transitions caused by moving clouds

Kari Lappalainen *, Seppo Valkealahti [1]

Tampere University of Technology, Department of Electrical Engineering, P.O. Box 692, FI-33101 Tampere, Finland

Received 4 September 2014; received in revised form 17 November 2014; accepted 18 November 2014
Available online 9 December 2014

Communicated by: Associate Editor Jan Kleissl

Abstract

Fast irradiance transitions caused by the edges of shadows of moving clouds have various effects on the operation of photovoltaic (PV) systems. They can lead to situations where the grid inverter is not able to follow the global maximum power point causing extra losses. Fast fluctuations of the power fed to the electric grid can also cause energy balance and power quality problems. Further, partial shading of PV generators causes mismatch losses.

In this paper, a method to recognize irradiance transitions caused by moving clouds from the measured extensive irradiance data is presented. A total of around 40,000 irradiance transitions were recognized from a measured data of 13 months around midsummer in 2011–2013 and their shading strength, duration, time of occurrence etc. have been analysed. It has been found that the duration of irradiance transitions varies a lot from a few seconds up to several minutes. The average duration of irradiance rises is clearly longer than that of falls. Shading strengths of transitions varies quite evenly from very thin shadings up to 90% shading strength and the highest transition rates take place around noon. Furthermore, a mathematical model of the irradiance transitions has been developed and validated with the extensive set of experimental data.

Keywords: Photovoltaic; Partial shading; Irradiance transition; Solar power generation

---

1. Introduction

Shadows caused by moving clouds are the main reason for fast power output variability of photovoltaic (PV) systems. Fast irradiance transitions caused by the edges of moving shadows have various effects on the operation of PV systems. They can lead to situations where the grid inverter is not able to follow the global maximum power point (MPP) causing extra losses. Partial shading of PV generators also causes mismatch losses, which are the difference between the sum of the available maximum power outputs of individual modules and the maximum power output of the PV generator. Further, fast fluctuations of the power fed to the electric grid can cause various problems. As the share of PV power production is growing, technical requirements such as ramp rate control, voltage ride-through capability, and reactive power capability are being mandated to accommodate large amounts of PV production in the power systems (Woyte et al., 2006). On the contrary, the geographic dispersion of grid-connected PV systems has been reported to dampen the effects of irradiance fluctuations (Lave et al., 2012). This is an expected phenomenon for large systems but on a local level with small system sizes more problems can be expected.

---

* Corresponding author. Tel.: +358 401981511.
E-mail addresses: kari.lappalainen@tut.fi (K. Lappalainen), seppo.valkealahti@tut.fi (S. Valkealahti).
[1] Tel.: +358 408490915.

http://dx.doi.org/10.1016/j.solener.2014.11.018

The effects of partial shading have been studied in several papers, e.g. in (Bidram et al., 2012; Ishaque et al., 2011; Mäki and Valkealahti, 2013, 2014; Patel and Agarwal, 2008; Shams El-Dein et al., 2013; Wang and Hsu, 2011; Woyte et al., 2003). In many of these papers, the main objective has been to model the operation of partially shaded PV power generators or to verify the operation of maximum power point tracking (MPPT) algorithms under partial shading conditions. Moreover, the focus has typically been on shading conditions caused by static objects such as buildings. Also the effects of shadows caused by moving clouds on the operation of PV power generators have been studied earlier, e.g. in (Kern et al., 1989; Sánchez Reinoso et al., 2013). The main focus in these studies has been on the effects of moving clouds on the PV power production. The changes in power production due to clouds have been noticed to be large and fast causing problems to the grid operation.

The effects of partial shading on the operation of PV systems caused by moving clouds have been studied typically by theoretical simulations (Lappalainen et al. 2013a, 2013b; Sánchez Reinoso et al., 2013) and even experimentally in some cases (Kern et al., 1989; Mäki and Valkealahti, 2014). It has been found in (Lappalainen et al. 2013a, 2013b) that mismatch losses can be up to 25% during the irradiance transition caused by a moving cloud depending on the generator layout. The sharpness of a shadow, i.e. the width of the shadow edge, has a considerable effect on the mismatch losses, especially in small PV generator arrays (Lappalainen et al., 2013b). The recognition, duration and shape of irradiance transitions have been studied also in Tomson (2010, 2013) and it has been found that the irradiance transitions can be very steep. However, irradiance transitions caused by moving clouds are still quite poorly known and understood.

In this paper, a method is presented to recognize irradiance transitions caused by moving clouds from measured irradiance data. 13 months of data measured during spring, summer and autumn in 2011, 2012 and 2013 has been analysed. A total of around 40,000 irradiance transitions (falls and rises) were recognized and their shading strength, duration, time of occurrence etc. have been analysed. Furthermore, a mathematical model of the irradiance transitions has been developed and validated with the extensive set of experimental data.

2. Recognition of irradiance transitions caused by moving clouds

2.1. Method to recognize irradiance transitions

Full-time irradiance recordings have been analysed to recognize irradiance transitions caused by moving clouds. The method to recognize irradiance transitions uses a sampling frequency of 1 Hz during recognition to ensure reasonable computing time and a sampling frequency of 10 Hz when analysing the recognized irradiance transitions. Equally high sampling frequencies have not been used earlier in comprehensive analysis of irradiance transitions. Tomson (2013) argued that a sampling interval of 5 s or less guarantees recognition of most irradiance transitions. However, it has been found in Lappalainen et al. (2013b) that irradiance transitions can be even shorter than 1 s. Accordingly, a sampling frequency of 1 Hz was found to be high enough to recognize all relevant transitions. In order to be resistant to small insignificant fluctuations of irradiance, a moving average of five seconds is used to recognize irradiance transitions. The method recognizes rough starting and ending points of irradiance transitions based on the changes in the moving average of irradiance. Transitions are identified when the moving average of irradiance changes more than 5 W/m^{2}s. Thereafter, the method uses the original data measured with a sampling frequency of 10 Hz to find more exact points for the start and end of the irradiance transition from the vicinity of rough points. In the case of start of a fall or end of a rise the final maximum point of the transition is the maximum irradiance within 0.5 s from the initial rough point. In the case of end of a fall or start of a rise, the final minimum point of the transition is identified accordingly.

An example of the recognition of an irradiance transition is shown in Fig. 1. First, the rough starting point of irradiance transition from the original data at a sampling frequency of 1 Hz is recognized when the moving average of irradiance increases more than 5 W/m^{2}s (point 1 in Fig. 1(a)). After that the rough ending point is recognized

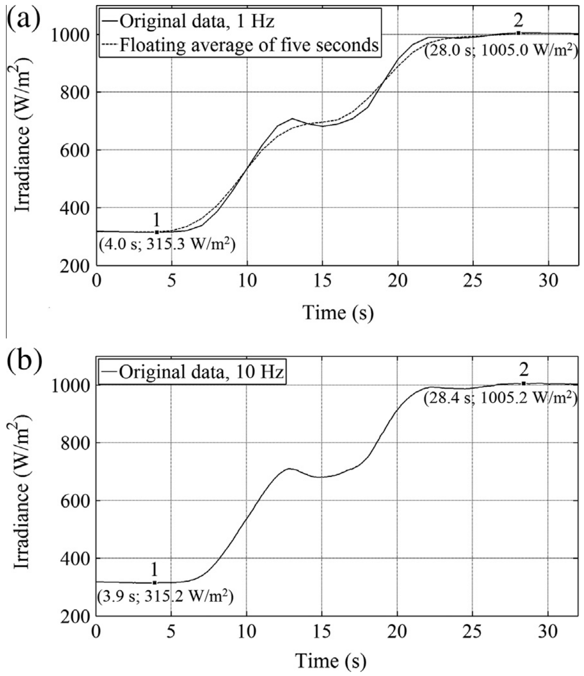

Fig. 1. (a) Measured irradiance during an irradiance rise down-sampled to sampling frequency of 1 Hz (solid line) and the moving average of five seconds (dotted line) as a function of time. (b) The original irradiance data at sampling frequency of 10 Hz as a function of time. The recognized rough and final minimum and maximum points are marked with dots in figures (a) and (b), respectively.