Applied Energy 190 (2017) 902–910

Contents lists available at ScienceDirect

Applied Energy

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

Output power variation of different PV array configurations during irradiance transitions caused by moving clouds

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HIGHLIGHTS

- Output power variation of PV arrays during irradiance transitions was studied.
- The average rate of change of PV output power was around 3%/s.
- The maximum instantaneous rates of change of the output power were around 75%/s.

ARTICLE INFO

Article history:
Received 9 November 2016
Received in revised form 5 January 2017
Accepted 6 January 2017
Available online 13 January 2017

Keywords:
Photovoltaic power generation
Power variation
Partial shading
Irradiance transition
PV array

ABSTRACT

This paper presents a study of the output power variation of different photovoltaic (PV) array configurations during irradiance transitions caused by moving clouds. The study was based on velocity and other characteristics of roughly 27,000 irradiance transitions identified in measured irradiance data and conducted using a mathematical model of irradiance transitions and an experimentally verified simulation model of a PV module. The studied electrical PV array configurations were series-parallel, total-cross-tied and multi-string. The different PV array orientations and layouts (physical shapes) of the configurations were also studied.

The average rate of change of the power of these studied PV array configurations during the irradiance transitions was around 3%/s and the maximum instantaneous rates of change of the power were around 75%/s. Half of the time during the studied transitions, the rate of change in the power was over 1.2%/s, and most of the time during the transitions, it exceeded typical PV power ramp rate limits set by grid operators. The average rate of change of PV array power decreased with an increasing maximum array dimension and it was observed to be the largest when the shorter dimension of the array was parallel to the dominant movement direction of the shadow edges. The results of this study are relevant especially in terms of PV array design, maximum power point tracking algorithm development and energy storage systems sizing.

1. Introduction

Photovoltaic (PV) systems are prone to irradiance fluctuations caused by overpassing cloud shadows that are the main cause of fluctuating PV power production. As the share of PV power production increases, there is a growing potential for PV output power variability having a negative effect on both power quality and reliability of the grid. Thus, with the fast growth of PV power production, technical requirements, such as ramp rate control, voltage ride-through capability and reactive power capability, are now being mandated to accommodate large amounts of PV power production in the power systems [1,2]. The average diameter of cloud shadows has been found to be around 800 m [3] meaning that even the largest PV power plants are widely affected by them. The geographic dispersion of PV power production has been reported to dampen the effects of irradiance fluctuations [4–6]. However, this issue is of special importance locally and in weak grids with high PV penetration levels. Further, partial shading caused by moving clouds is the main cause of mismatch losses of PV systems, which are the difference between the sum of the global maximum power point (MPP) powers of individual PV modules and the global MPP power of the PV system. Also, partial shading can lead to failures in MPP tracking causing extra losses.

Solar radiation variability caused by overpassing cloud shadows has been studied by several researchers at several specific locations previously: 1 and 5 min resolution irradiance data at four sites

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http://dx.doi.org/10.1016/j.apenergy.2017.01.013
0306-2619/

Nomenclature

a	change of irradiance during an irradiance transition (W/m^2)
A	ideality factor
A_{bypass}	ideality factor of a bypass diode
b	steepness related parameter in the mathematical model of irradiance transitions (s)
c	minimum irradiance during an irradiance transition (W/m^2)
G	irradiance (W/m^2)
G_s	irradiance under full shading (W/m^2)
G_{us}	irradiance of an unshaded situation (W/m^2)
I	current (A)
I_o	dark saturation current (A)
$I_{o,bypass}$	dark saturation current of a bypass diode (A)
I_{ph}	light-generated current (A)
k	Boltzmann constant (J/K)
q	elementary charge (C)
R_s	series resistance (Ω)
$R_{s,bypass}$	series resistance of a bypass diode (Ω)
R_{sh}	shunt resistance (Ω)
t	time (s)
t_0	duration related parameter in the mathematical model of irradiance transitions (s)
T	temperature (K)
U	voltage (V)
U_T	thermal voltage (V)

Abbreviations

BL	bridge-link
HC	honey-comb
MPP	maximum power point
MS	multi-string
OC	open-circuit
PV	photovoltaic
SC	short-circuit
SS	shading strength
SP	series-parallel
STC	standard test conditions
TCT	total-cross-tied
TUT	Tampere University of Technology

across Colorado was used in [7]; 1–30 s irradiance data from 10 locations in the United States was used in [8]; 1 s data from six PV plants in Spain was used in [9]; from 20 s to 1 min data at 24 sites in the United States was used in [10]; 1 s resolution irradiance data from Estonia and Hawaii were used in [11,12], respectively; and 0.1 s measured irradiance data from Finland was used in [3]. The characteristics and identification of irradiance transitions caused by the edges of cloud shadows have also been studied in several papers [13–16]. In [13], a comprehensive analysis and a mathematical model of irradiance transitions caused by overpassing cloud shadows have been presented. It has been found that the shading strength of irradiance transitions varies from very thin shadings up to 90%, and irradiance can change over 300 W/m^2 in 0.1 s, meaning that irradiance transitions caused by overpassing cloud shadows can be very large and steep. The duration of irradiance transitions can also vary a lot from a second up to several minutes. In [3], a comprehensive analysis of shading periods caused by moving clouds has been presented and their duration has been found to vary from a few seconds up to almost 1.5 h; the speed of cloud shadows also varied considerably with an average value of around 13 m/s.

When a cloud shadow is covering a PV array, the apparent speed of the shadow edge, i.e., the component of shadow speed normal to that shadow edge, actually defines how fast the PV array is becoming shaded. Thus, the apparent velocity of a linear shadow edge is a vital quantity in any analyses of the effects of overpassing cloud shadows on the operation of small PV systems and the PV arrays of large PV power plants. Still, the assumption of linearity for the shadow edge might not be valid with large power plants as a whole [14]. In [14], a comprehensive study of the apparent velocity of shadow edges caused by moving clouds has been presented. It has been found that the average apparent speed of shadow edges is close to 9 m/s and that the length of irradiance transitions on the edges of cloud shadows is typically around 100 m, which is the order of the diameter of the largest PV arrays feeding a utility scale PV inverter. The characteristics of the edges of cloud shadows have not been found to have any annual trends [13,14].

The operation of PV generators under static partial shading conditions has been studied in several papers: the power production of different PV array configurations, such as series-parallel (SP), total-cross-tied (TCT), bridge-link (BL) and honey-comb (HC) configuration, has been studied in [17–20] and the MPP characteristics of series connected PV modules and the SP configuration in [21,22], respectively. In [23], a model to study the effects of partial shading on PV array characteristics has been presented. The operation of PV generators under partial shading conditions that are caused by moving clouds has also been studied e.g. in [24–27]. Several studies have been presented as well regarding the output power fluctuations of PV systems [9,27–30]. For example, up to 70% per minute variations have been recorded at a 9.5 MWp PV plant [9].

In [27], the effects of irradiance transition characteristics on the variation of the output power of traditional SP, TCT and multi-string (MS) PV array configurations of 32 kWp nominal power and 41 m maximum dimension have been studied using simulations by changing the value of the studied variable while keeping the values of the other variables fixed at their typical, experimentally observed values. Those values and the applied variable value ranges were based on measured irradiance transitions. The mean rate of change of output power while a typical shadow edge moved over the studied PV generators was found to be around 4%/s. However, the maximum observed instantaneous rate of change was almost 50%/s. That high variation in the power fed to an electric grid can have considerable negative effects on the power quality and reliability of the grid.

From a practical point of view, the most important finding of [27] is that the variation of PV array power during irradiance transitions caused by moving clouds was practically the same for the studied electrical PV array configurations. The reason is that the length of a typical irradiance transition region is much longer than the diameter of PV arrays, thus causing only minor irradiance differences between adjacent PV modules. However, it has been found in [27] that deep and steep irradiance transitions, which lead to the largest PV output power variations, bring about certain differences between electrical PV array configurations. Thus, sharp shadows, which are caused by nearby objects, can be considered the worst-case scenarios. However, a fully comprehensive research on the output power variation of different PV array configurations during irradiance transitions caused by moving clouds based on irradiance measurements is still missing.

In this paper, the output power variation of different PV array configurations during irradiance transitions caused by moving