Solar Energy 144 (2017) 548–555

Contents lists available at ScienceDirect

Solar Energy

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

Effects of PV array layout, electrical configuration and geographic orientation on mismatch losses caused by moving clouds

Kari Lappalainen *, Seppo Valkealahti

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

ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 25 January 2017
Accepted 29 January 2017

Keywords:
Photovoltaic power generation
Mismatch losses
Partial shading
Irradiance transition

ABSTRACT

The mismatch losses of photovoltaic (PV) systems are mainly caused by partial shading and the largest mismatch losses are caused by sharp shadows. However, in large scale PV plants majority of shading events is caused by moving clouds which lead to gentle irradiance transitions causing typically only minor irradiance differences between adjacent PV modules. Irradiance transitions caused by the edges of cloud shadows have an average length of almost 150 m meaning that even the largest PV power plants are widely affected by them. In addition of mismatch losses, these irradiance transitions can lead to failures in maximum power point tracking and cause significant fluctuations in the output power of PV systems.

In this paper, the effects of PV array shape, electrical configuration and orientation on mismatch losses caused by moving clouds were studied based on apparent velocity and other measured characteristics of roughly 27,000 irradiance transitions. The study was conducted using a mathematical model and parametrisation method of irradiance transitions and an experimentally verified simulation model of a PV module based on the well-known one-diode model of a PV cell. The studied electrical PV array configurations were series-parallel, total-cross-tied and multi-string.

The results of this study confirmed a prior conclusion, namely, that the mismatch losses decrease with decreasing PV string length. It was also found that the array orientation has a considerable effect on the mismatch losses of the studied array layouts. The mismatch losses were the smallest when the dominant direction of movement of the shadow edges was perpendicular to the PV strings. The differences in the mismatch losses between the studied electrical array configurations were very small. The results indicated that the mismatch losses caused by moving clouds have only a minor effect on the overall efficiency of PV arrays.

1. Introduction

Photovoltaic (PV) systems are affected by irradiance fluctuations, mainly caused by overpassing cloud shadows, suffering from fluctuating output power. With high PV penetration levels, these fluctuations can lead to power system instability and problems in power quality. Although the geographic dispersion of PV power production has been found to dampen the effects of irradiance fluctuations (Lave et al., 2012; Marcos et al., 2011, 2012; Perpiñán et al., 2013), they are of special importance locally and in weak grids with high PV penetration levels. Further, overpassing cloud shadows cause partial shading (PS) which is the main cause of mismatch losses. The mismatch losses of a PV system 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. Moreover, PS can lead to failures in MPP tracking causing extra losses. While PS is mainly caused by overpassing cloud shadows, it can also exist due to, inter alia, surrounding objects, snow or soiling.

Solar radiation variability and irradiance transitions caused by the edges of moving cloud shadows have been studied e.g. in Lappalainen and Valkealahti (2015, 2016b), Lave et al. (2015), Perez et al. (2011), Tomson (2013) and Tomson and Hansen (2011). Lappalainen and Valkealahti (2015) have presented an extensive analysis and a mathematical model of irradiance transitions caused by overpassing cloud shadows. It has been found that the duration of irradiance transitions varies a lot from a second up to several minutes while the shading strength of the transitions varies from very thin shadings up to 90%. In Lappalainen and Valkealahti (2016b), a comprehensive study of the apparent

* Corresponding author.
E-mail addresses: kari.lappalainen@tut.fi (K. Lappalainen), seppo.valkealahti@tut.fi (S. Valkealahti).

http://dx.doi.org/10.1016/j.solener.2017.01.066
0038-092X/

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)
N_s	number of PV cells in a PV module
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
PS	partial shading
PV	photovoltaic
SC	short-circuit
SS	shading strength
SP	series-parallel
STC	standard test conditions
TCT	total-cross-tied
TUT	Tampere University of Technology

velocity of shadow edges, i.e., the component of shadow velocity normal to the shadow edge, caused by moving clouds has been presented. It has been found that the apparent speed of shadow edges varies considerably with an average value of around 9 m/s and that the length of irradiance transitions on the edges of cloud shadows has a median value of around 100 m, which is the order of diameter of the largest PV arrays feeding a utility scale PV inverter. When a moving cloud shadow covers a PV array, the apparent speed of the shadow edge defines how fast the PV array is becoming shaded. Thus, the apparent velocity of a linear shadow edge is a focal quantity in any analyses of the effects of overpassing cloud shadows on the operation of small PV systems or the arrays of large PV power plants, while the supposition of linearity for the cloud edge is not valid with large PV power plants as a whole (Lappalainen and Valkealahti, 2016b).

Mismatch losses, also known as electrical mismatches, occur in every PV system. Mismatch losses exist when interconnected PV cells have different electrical characteristics at a specific instant. Mismatch losses are mainly caused by PS but also by other differences in operation conditions of PV modules, module damages and manufacturing tolerances. The mismatch losses of PV generators have been studied in several papers during the past decades, e.g. in Bishop (1988), Lorente et al. (2014), Mäki and Valkealahti (2012), Mäki et al. (2012), Picault et al. (2010), Rakesh and Madhavaram (2016), Rodrigo et al. (2016), Shams El-Dein et al. (2013a,b), Vijayalekshmy et al. (2016), Villa et al. (2012) and Wang and Hsu (2011). In these papers, the range of studied electrical PV array configurations covers the simple series-parallel (SP) configuration as well as alternative configurations like total-cross-tied (TCT), bridge-link (BL) and honey-comb (HC) with additional connections between PV module strings (Picault et al., 2010; Rakesh and Madhavaram, 2016; Wang and Hsu, 2011). However, the focus of these papers has typically been on static PS conditions, and a comprehensive study of the mismatch losses of different PV array configurations due to irradiance transitions caused by moving clouds is still missing.

Moreover, in Rakesh and Madhavaram (2016), Shams El-Dein et al. (2013a,b), Vijayalekshmy et al. (2016) and Villa et al. (2012) mismatch losses caused by shadings with large irradiance differences between adjacent PV modules, i.e., extremely sharp shadows, have been studied. Sharp shadows are caused by nearby objects while the shadows of moving clouds cause gentle irradiance transitions causing typically only minor irradiance differences between the adjacent modules (Lappalainen and Valkealahti, 2016b). It has been presented in Lappalainen and Valkealahti (2017) that the mismatch losses of SP, TCT and multi-string (MS) PV array configurations increase with increasing shadow sharpness. Moreover, differences between different electrical PV array configurations increase with increasing shadow sharpness. In large scale PV plants, shading is mostly caused by moving clouds and sharp shadows can be considered as rare worst-case scenarios.

It has been noticed in Lappalainen et al. (2013a,b) and Lappalainen and Valkealahti (2017) that the movement direction of shadow edges has a substantial effect on the mismatch losses. The mismatch losses of SP, TCT and MS PV array configurations caused by a moving shadow are the smallest when the shadow edge moves perpendicular to the PV strings. In that case, every string is under uniform irradiance conditions. Thus, no mismatch losses occur in the MS configuration, where every string is controlled individually, and the mismatch losses of the SP and TCT configurations are equal and negligible. When a shadow edge moves parallel to the strings, every configuration behaves like a single series connected PV string, and thus the mismatch losses of all these configurations are equal.

This paper presents a study of the effects of PV array shape, electrical configuration and orientation on mismatch losses caused by moving clouds based on apparent velocity and other characteristics of more than 27,000 irradiance transitions identified in measured irradiance data. The study was conducted by using the mathematical model of irradiance transitions, the parametrisation method of irradiance transitions presented in Lappalainen and Valkealahti (2016a) and an experimentally verified MATLAB Simulink model of a PV module that is based on the well-known one-diode model of a PV cell. Mismatch losses of electrical SP, TCT and MS PV array configurations were studied with respect to the physical shape (PV string length) and geographical orientation of