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Photovoltaic mismatch losses caused by moving clouds

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A R T I C L E I N F O

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A B S T R A C T

Mismatch losses is a major issue in the photovoltaic (PV) system and are mainly caused by partial shading; largest mismatch losses are caused by sharp shadows. These shadows are a typical problem for rooftop and residential installations. In large-scale PV plants, partial shading is mostly caused by moving clouds which produce gentle irradiance transitions causing typically only minor irradiance differences between adjacent PV modules.

This paper presents a study of the mismatch losses of PV arrays with various layouts and electrical configurations during around 27,000 irradiance transitions identified in measured irradiance data. The overall effect of the mismatch losses caused by moving clouds on the energy production of PV plants was also studied. The study was conducted using a mathematical model of irradiance transitions and an experimentally verified MATLAB/Simulink model of a PV module.

The relative mismatch losses during the identified irradiance transitions ranged from 1.4% to 4.0% depending on the electrical configuration and layout of the PV array. The overall effect of the mismatch losses caused by moving clouds on the total electricity production of PV arrays was about 0.5% for the PV array with strings of 28 PV modules and substantially smaller for arrays with shorter strings. The proportions of the total mismatch losses caused by very dark or highly transparent clouds were small. About 70% of the total mismatch losses were caused by shadow edges with shading strengths ranging between 40% and 80%. These results indicate that the mismatch losses caused by moving clouds are not a major problem for large-scale PV plants. An interesting finding from a practical point of view is that the mismatch losses increase the rate of power fluctuations compared to the rate of irradiance fluctuations.

1. Introduction

Overpassing cloud shadows are a significant reason for the mismatch losses of large-scale photovoltaic (PV) power plants. Mismatch losses are the difference between the sum of the maximum powers of individual PV cells or modules of a PV system, as if they were operating separately, and the maximum power of the whole PV system. Mismatch losses occur in every PV system when interconnected PV cells have different electrical characteristics at a specific instant. Mismatch losses are mainly caused by partial shading (PS), but they are also caused by other differences in the operation conditions of PV modules, module damages and manufacturing tolerances. PS caused by moving clouds can also lead to failures in maximum power point (MPP) tracking thereby causing additional losses. Moreover, fast irradiance transitions caused by the edges of clouds can lead to fluctuations in the output power of PV systems. While the PS of large-scale PV plants is mainly caused by overpassing cloud shadows, it can also exist due to surrounding objects, snow or soiling.

Solar radiation variability and irradiance transitions caused by the edges of moving cloud shadows have been studied in several papers, e.g. in Lappalainen and Valkealahti (2015, 2016b), Lave et al. (2015), Perez et al. (2011), Tomson (2010) and Tomson and Tamm (2006). In Lappalainen and Valkealahti (2016b), a comprehensive study of the apparent velocity of shadow edges, i.e., the component of shadow velocity normal to the shadow edge, caused by moving clouds has been presented. The apparent speed of the shadow edges has been found to vary considerably and have an average value of around 9 m/s. The length of irradiance transitions on the edges of cloud shadows has also been found to vary considerably with an average of around 150 m. When a cloud shadow is covering a PV array, the apparent speed of the shadow edge defines how rapidly the PV array is becoming shaded. Thus, the apparent velocity of a linear shadow edge is a vital quantity in any analysis 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 for large PV systems as a whole (Lappalainen and Valkealahti, 2016b).

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The mismatch losses of PV generators caused by PS and their mitigation have been studied and reported on in several papers, especially during the past years, e.g. in Picault et al. (2010), Potnuru et al. (2015), Rakesh and Madhavaram (2016), Shams El-Dein et al. (2013a, 2013b), Vijayalekshmy et al. (2016) and Villa et al. (2012). However, these studies are based on static and hypothetical PS conditions and lack the knowledge of real irradiance transitions caused, for example, by moving clouds. Moreover, in these papers, mismatch losses caused by shadings with large irradiance differences between adjacent PV modules, i.e., extremely sharp shadows, have been studied. Mismatch losses under PS conditions caused by moving clouds have been studied using irradiance measurements in Lappalainen and Valkealahti (2017a, 2017b) and Torres Lobera and Valkealahti (2013) and electrical measurements in Rodrigo et al. (2016). Mismatch losses caused by manufacturing tolerances have been studied e.g. in Lorente et al. (2014).

The large lengths of irradiance transitions reported in Lappalainen and Valkealahti (2016b) mean that the shadows of moving clouds cause gentle irradiance transitions, leading typically only minor irradiance differences between adjacent PV modules. The result has been presented in Lappalainen and Valkealahti (2017a) that the mismatch losses of PV arrays decrease with decreasing shadow sharpness. Moreover, the differences between various electrical PV array configurations have been found to decrease with decreasing shadow sharpness. In large-scale PV plants, shading is mostly caused by moving clouds and sharp shadows, which are caused by nearby objects, can be considered as rare worst-case scenarios. In Lappalainen and Valkealahti (2017b) the mismatch losses caused by moving clouds have been estimated to be clearly below 1.0% of the total electricity production of PV arrays. However, a comprehensive study of the total mismatch losses of PV plants caused by moving clouds has not been presented as yet.

In this paper, the mismatch losses of series-parallel (SP), total-cross-tied (TCT) and multi-string (MS) electrical PV array configurations were studied during about 27,000 irradiance transitions identified in measured irradiance data. Moreover, the overall effect of the mismatch losses caused by moving clouds on the energy production of PV plants was determined based on the studied mismatch losses and irradiance measurements. The study was conducted using a mathematical model of irradiance transitions and an experimentally verified MATLAB/Simulink model of a PV module based on the well-known one-diode model of a PV cell. The presented study is based on measurements at a particular location although the characteristics of irradiance transitions may differ regionally. However, the results of this study do provide generally applicable information on the magnitude, range and total amount of the mismatch losses of various PV array layouts and electrical configurations caused by moving clouds. The results of this study are relevant, particularly from the PV array and system design point of view when aiming towards higher overall PV system efficiencies.

2. Methods and data

2.1. Simulation model for the PV modules

The PV modules were modelled by an experimentally verified MATLAB/Simulink model that is based on the model presented by Villalva et al. (2009). This model is based on the well-known one-diode model that provides the following relationship between the current and the voltage of a PV cell:

$$I = I_{ph} - I_o\left(e^{\frac{U+R_sI}{AU_T}}-1\right)-\frac{U+R_sI}{R_{sh}}, \quad (1)$$

where I is the current, I_{ph} the light-generated current, I_o the dark saturation current, U the voltage, R_s the series resistance, A the ideality factor, U_T the thermal voltage and R_{sh} the shunt resistance of the PV cell (Wenham et al., 2007). The thermal voltage of a PV cell can be written as $U_T = kT/q$, where k is the Boltzmann constant, T the temperature of the cell and q the elementary charge. The simulation model for a PV module was obtained by scaling the parameter values used in the model of a PV cell by the number of PV cells in the PV module. Bypass diodes of the PV module were modelled using Eq. (1) by assuming that the light-generated current I_{ph} is zero and the shunt resistance R_{sh} is infinite. The dark saturation current $I_{o,\ bypass}$, the series resistance $R_{s,\ bypass}$ and the ideality factor A_{bypass} of the bypass diodes were determined by using curve fitting to a measured *I–U* curve of a Schottky diode. The temperature of the bypass diodes was assumed to be constant and the same as the temperature of the PV module.

Table 1
The electrical characteristics of the NAPS NP190GKg PV module for short-circuit (SC), open-circuit (OC) and MPP in STC.

Parameter	Value
$I_{SC,\ STC}$	8.02 A
$U_{OC,\ STC}$	33.1 V
$P_{MPP,\ STC}$	190 W
$I_{MPP,\ STC}$	7.33 A
$U_{MPP,\ STC}$	25.9 V

The characteristics of the PV module simulation model were fitted to the characteristics of the NAPS NP190GKg PV module used in the solar PV power station research plant of Tampere University of Technology (TUT) (Torres Lobera et al., 2013). The module is composed of 54 series-connected polycrystalline silicon PV cells and three bypass diodes, each connected in anti-parallel with 18 PV cells. The electrical characteristics of the module, given by the manufacturer, in standard test conditions (STC) are presented in Table 1. The simulation model parameter values for the PV modules and the bypass diodes are presented in Table 2. The results of the simulations could slightly change if different PV modules were used as a reference. However, the basic behavior would not change because the electrical characteristics of crystalline silicon PV modules do not differ essentially. Although the used simulation model contains simplifications and assumptions, it is accurate enough for the analysis of mismatch losses presented in this paper.

2.2. PV array configurations

The electrical connections for the studied SP, TCT and MS PV array configurations are presented in Fig. 1. These configurations were selected since SP and MS are commonly applied in PV array installations, whereas TCT is frequently reported to improve PV array performance under partially shaded conditions when compared to SP (Picault et al., 2010; Rakesh and Madhavaram, 2016; Villa et al., 2012). In the studied configurations, the series-connected PV modules were placed in straight strings of equal length to form a rectangle. The distance between the adjacent strings was 2.0 m, and there were no gaps between the series-connected modules. The east-west orientation of the PV arrays was used in the simulations, i.e., the PV strings were placed from east to west. The PV modules were mounted at a tilt angle of 45° from the horizontal

Table 2
The parameter values of the simulation model for the NAPS NP190GKg PV module and the bypass diodes.

Parameter	Value
A	1.30
R_s	0.329 Ω
R_{sh}	188 Ω
A_{bypass}	1.50
$R_{s,\ bypass}$	0.02 Ω
$I_{o,\ bypass}$	3.20 μA