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Mismatch loss in photovoltaic systems

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Abstract

The effects of current mismatch and shading on the power output of single photovoltaic (PV) modules are well analyzed, but only few investigations address mismatch losses at a PV system level that also limit the annual energy yield. The simple question, what happens if PV strings with different numbers of modules are connected in parallel, has not yet been discussed in detail. In case of strings with unequal module count, the system builder must decide whether to use inverters with multiple maximum power point (MPP) trackers, module-power optimizers, or to shorten all strings for balancing the system. Our findings from this study open a new option. The numerical modeling of PV systems with strings of different length in parallel to several others which have an equal module count renders mismatch losses below 1% for most system configurations. For configurations where one string is one module shorter than the others, the mismatch losses fall below 0.5%. Therefore strings with unequal length may favorably connect to a cost-effective single-MPP inverter without causing significant energy yield losses. Moreover, typical thin film PV modules are less sensitive to mismatch than crystalline silicon based ones.

Keywords: Mismatch; Maximum power point tracking; MPPT; Partial shading; PV system

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1. Introduction

Most common photovoltaic (PV) modules comprise 60 or more solar cells. To maximize the energy yield it is crucial to match the parameters of the cells by binning during module fabrication. Since a standard PV module connects all solar cells within the module electrically in series, the cell current is the most important matching parameter (Bishop, 1988; Woyte et al., 2003). For small PV systems, consisting of just one PV string with a few PV modules connected in series, there is no need for the end user to consider parameter matching since this is done by the module manufacturer. For larger PV systems, however, where several PV strings are connected in parallel to increase the system power, parameter matching becomes an issue. The parallel connection forces all strings to work at the same voltage leading to mismatch losses if a subset of strings would demand a different operating voltage than the others for reaching its maximum power point (MPP) (Woyte et al., 2003). The mismatch effect of the manufacturing tolerances was examined in detail by Chamberlin et al. Chamberlin et al. (1995), Spertino and Akilimali (2009) and there were numerous investigations on the effect of partial shading conditions (Quaschning et al., 1996; Rauschenbach, 1971; Bidram et al., 2012; Kjaer et al., 2005; Rogalla et al., 2010; García et al., 2008). But sometimes there is simply not enough space on a roof to install the same number of PV modules in each string. The possibilities to avoid or reduce the mismatch of strings are manifold. Bidram et al. (2012) gave an over view of the various approaches. The main approaches to overcome mismatch

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losses are to either integrate a maximum power point tracker (MPPT) per PV string into the inverter (Kjaer et al., 2005), or to include power optimizers (Rogalla et al., 2010) in each PV module. While in theory both approaches decrease or cancel the mismatch losses, both raise system cost and reliability issues. Moreover, partial shading conditions were reported where single-MPPT inverters outperform multi-MPPT ones (García et al., 2008).

This contribution focuses on the mismatch losses caused by PV system configurations with unequal strings. The goal is to give an estimation of the losses and thereby to allow a system builder to decide whether an inverter with multiple MPP trackers, multiple inverters or power optimizers are necessary, or to which extent the mismatch losses can be neglected at all. Section 2 introduces the two numerical models and their computational flow implemented for quantifying the mismatch losses of the PV system configurations under investigation. Section 3 presents the results: Section 3.1 analyses one system configuration in detail to elucidate the origin of the mismatch losses, while Section 3.2 presents the calculated mismatch loss caused by varying mismatch conditions. The results show, that for a wide variety of system configurations the mismatch losses of unbalanced PV strings are within the measurement error of ±1% of standard test equipment, and thus can be neglected in practice.

2. Methodology

Two models are used to quantify the mismatch losses originating from the operation of in parallel connected PV strings with different lengths, i.e. different numbers of identical modules per string. First, the ideal one-diode model (ODM) enables the estimation of the *worst case* mismatch losses because the gradient of its I/V characteristics close to the MPP is larger than for real PV modules (Section 2.2 and Fig. 5). Secondly, a numerical method computes PV string performance from measured I/V characteristics of a *Suntechnics* crystalline silicon (c-Si) module and a *Schott* amorphous silicon (a-Si) module (Table 2). The two models allow to compare the real-life mismatch losses with the worst-case ones deduced from the ODM. Both models calculate the I/V curves of PV strings S_n with a length $n = 9$–20 PV modules connected in series and use them to generate the I/V curves of various parallel connections. The comparison of individual string I/V curves and I/V curves of the parallel connections returns the mismatch losses.

Both simulation models assume homogeneous in plane of array irradiance $G = 1000\ \mathrm{W/m^2}$ and temperature $T = 25\ ^\circ\mathrm{C}$ over the whole PV systems. The choice to neglect spatial and temporal variations of the local operating conditions simplifies and focuses our loss calculation, though it is an obvious restriction for comparing results with real-world performance data. Under this approximation, only one operating point serves to compare different system configurations with special regard to our focus on the parallel connection of PV strings of different length. While high resolution data on the temporal variation of irradiance and temperature of PV systems are available (Zinsser et al., 2010), very little is known (Weigl et al., 2012) about spatial irradiance variations up to now. Therefore our approach excludes widely variable and mostly unknown extrinsic factors, like geometry, environment, partial shading and local weather, to provide a general understanding of the mismatch losses in parallel connections of PV strings with unequal length.

2.1. Ideal one-diode model

The equation

$$I = I_{\mathrm{SC}} - I_0\left[\exp\left(\frac{V}{n_1 V_{\mathrm{T}} n_{\mathrm{C}}}\right) - 1\right] \tag{1}$$

describes the I/V characteristics of an ideal one-diode model (ODM) of a crystalline PV module. Table 1 lists the simulation parameters and the resulting module parameters used for this study, namely the saturation current I_0, ideality factor n_1, thermal voltage V_{T}, number of PV cells per module n_{C}, the open circuit and MPP voltages V_{OC}, V_{mpp}, short circuit and MPP currents I_{sc}, I_{mpp}, and MPP power P_{mpp}. The chosen parameters reflect a state of the art crystalline silicon PV module. The ODM implements the basic function of a solar cell. On the one hand, matching its few parameters to the real characteristics of a PV module concludes in inaccurate results, especially for amorphous PV modules. On the other hand, the ideal behavior effects in the highest sensitivity to mismatch conditions, making it a perfect worst-case scenario.

Fig. 1 shows a simplified flow chart of the simulation of the mismatch losses due to the different lengths of the strings. The simulation starts by loading the PV module parameters of Table 1. The string length variable n is set to the minimum string length $n = n_{\mathrm{min}} = 10$. The simulation calculates the I/V curve of the string with a length of n PV modules. To obtain the string I/V curve from the module parameters of Table 1, the simulation uses Eq. (1) but multiplies the number of PV cells per module n_{C}

Table 1
One-diode model (ODM) parameters and the resulting PV module characteristics.

Parameter	Value	Unit
I_0	4.57×10^{-11}	A
n_1	1.00	
V_{T}	0.02569	V
n_{C}	60	
V_{OC}	39.7	V
V_{mpp}	34.8	V
I_{sc}	8.50	A
I_{mpp}	8.10	A
P_{mpp}	283	W
FF	83.3	%