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The effect of manufacturing mismatch on energy production for large-scale photovoltaic plants

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Abstract

In the literature, the effect of the mismatch due to manufacturing tolerances on PV plant productivity has been investigated under the hypothesis of plant operation in Standard Test Conditions (STC). In this paper, mismatch impacts are evaluated in more realistic terms taking into account various possible operating conditions. Results are illustrated through the study case of a 1 MWp solar park for which module datasheets as well as flash test data are available. The plant production is evaluated assuming operating conditions that comply with the European efficiency standards. It is shown how the effect of a given mismatch on the annual productivity estimation can significantly change depending on the operating conditions.

Keywords: Photovoltaic power system; Large-scale photovoltaic plant; Manufacturing mismatch losses; Negative mismatch losses; Performance

1. Introduction

With reference to Fig. 1, the photovoltaic (PV) worldwide market is continuing its exponential growth (Solar energy report, 2014) with a cumulative power with more than 132 GWp at the end of 2013. In 2013, photovoltaics was still the technology exhibiting the highest growth rate in the renewable power sector (REN 21, 2012). In Italy, which is the third worldwide country for PV installations with more than 18 MWp installed (http://www.gse.it), this source guarantees more than 10% of the consumed electricity (http://www.terna.it).

The transition from the era of subsidies (e.g. the Italian policy of incentives has recently ended) to that of grid parity, which has been attained in many locations under a broad range of conditions (Massi Pavan and Lughi, 2012, 2013), represents the passage from childhood to maturity for this solar technology. As the yield of PV plants plays a fundamental role in the determination of grid parity, a more and more accurate calculation of PV plant appears necessary. A phenomenon that must be taken into account for this purpose relates to the power losses that arise due to mismatch, i.e. when modules with different current–voltage characteristics (*I*–*V* characteristics) are interconnected (Luque and Hegedus, 2006). The mismatch effect of the manufacturing tolerances was investigated by Chamberlin et al. (1995); it has been shown that no discernible difference was observed in the maximum output power from parallel string arrays and series block arrays. A statistical approach based on Monte-Carlo technique has been developed in (Iannone et al., 1998) to analyze the electrical mismatch of a 100 kWp PV standard unit

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generator. The manufacturing *I–V* mismatch calculated at Standard Test Conditions (STC) was 0.56% (Spertino and Akilimali, 2009). In (Kaushika and Rai, 2007), the authors showed that with an appropriate series/parallel connection of PV modules, the mismatch losses are in the range [0.4–2.4%]. A comprehensive method for evaluating energy loss due to shading effect of a Grid-Connected Building Integrated PV system is presented by Drif et al. (2012), it has been shown that, the results showed that loss of energy is 1.79 kWh/day, which corresponds to a shading factor of 14.4%. With respect to (Wurster and Schubert, 2014), simulation results demonstrate that photovoltaic systems with strings of different length in parallel to several others which have an equal module count renders mismatch losses below 1% for most configurations. It has been also proven that, for configurations where one string is one module shorter than the others, the mismatch losses fall below 0.5%. As reported in (Lorente et al., 2014) a small array of 40 modules has a negligible loss while 320 modules array has a more significant mismatch loss at about 0.23% of the nominal power. It has been also shown that, module ordering decreases this value to 0.10% and increases the calculated energy.

However, STC represent only a reference needed to rate the power of a PV device, but they hardly occur during the operation of a real PV plant. Furthermore, the purpose of this work is to investigate how the losses due to manufacturing tolerance change depending on environmental conditions. In particular, evaluations are performed for illustrative purposes assuming some plant operating conditions that have a larger probability to happen. Such conditions are identified by the International Electrotechnical Commission in the IEC 61724 Standard in order to define European efficiency values (IEC 61724).

The proposed investigations are conducted on a sample 1 MWp solar plant for which PV module datasheet and flash test data are known. Plant productivity evaluations are based on the empirical model introduced in (Massi Pavan et al., 2014a) and experimentally validated at maximum power point in (Massi Pavan et al., 2014b). In order to calculate the mismatch losses, the yield of the PV plant is calculated in two ways: (i) assuming that all the PV plant modules are identical and share the same electrical parameters provided in the datasheet; (ii) based on the data extrapolated from the flash tests referring to each module. The mismatch losses are then obtained as the difference of the yields computed in the two mentioned ways.

This work is organized as follows: in the next Section, the empirical model of single module is introduced. In Section 3 the model is extended for the purpose of studying a complete field including multiple interconnected modules In Section 4 the case study is introduced, whereas results are discussed in Section 5. Finally, the conclusions are given in Section 6.

2. Empirical model

The advantage of the empirical model presented in (Massi Pavan et al., 2014a) is that the electrical parameters listed in the datasheets or in the flash tests of any PV module are sufficient to describe the behavior of the module itself. For this reason, such empirical model has chosen hereinafter. For a single PV module, the following equations are then used to relate its current I and voltage:

$$I = I_L + z \cdot \Delta T - \frac{e^{m \cdot [V - w \cdot \Delta T]} - 1}{e^m - 1} \tag{1}$$

or, equivalently:

$$V = \log\{[e^m - 1] \cdot [I_L - I + z \cdot \Delta T] + 1\} + w \cdot \Delta T \tag{2}$$

where I (p.u.) is the per unit current referred to the short circuit current I_{SC} (A) at STC, I_L (p.u.) is the per unit irradiance referred to 1.000 W/m^2, T_c (°C) is the solar cell temperature, m () is an exponential factor, V (p.u.) is the per unit voltage referred to the open circuit voltage V_{OC} (V) at STC, z (1/°C) is the current–temperature coefficient referred to the short circuit current at STC ($z = Z/I_{SC}$, where Z (A/°C) is the current–temperature coefficient from the datasheet of the considered PV module) and w (1/°C) is the voltage–temperature coefficient referred to the open circuit voltage at STC ($w = W/V_{OC}$, where W (V/°C) is the voltage–temperature coefficient from the datasheet of the

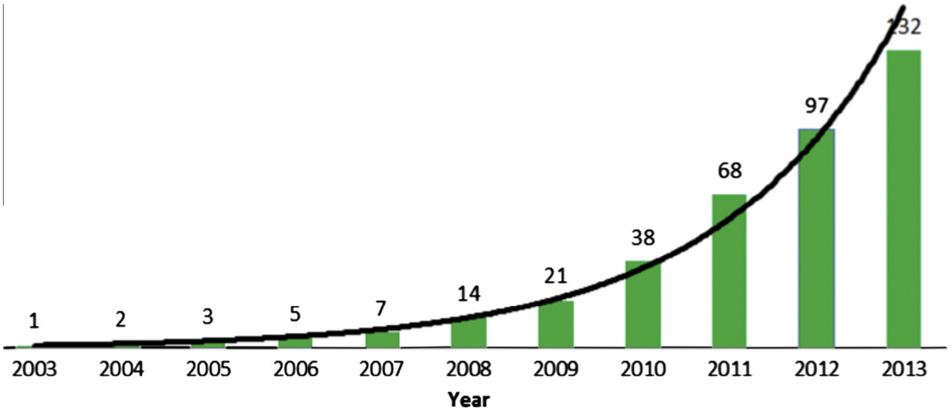

Fig. 1. Worldwide cumulative installed power in GWp.