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ScienceDirect

Solar Energy 131 (2016) 30–38

SOLAR ENERGY

www.elsevier.com/locate/solener

Statistical analysis of I–V curve parameters from photovoltaic modules

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Received 4 September 2015; received in revised form 12 January 2016; accepted 19 January 2016

Communicated by: Associate Editor Arnulf Jaeger-Waldau

Abstract

The performance of a photovoltaic (PV) system depends on several factors, such as the solar radiation availability and its spectral distribution, the PV module temperature, soiling, cable losses, PV power degradation over time and so forth. An important factor that also affects the PV array power is the mismatch loss due to the differences between single modules, since is inherent to the manufacturing process certain variability in the I–V curve parameters. The manufacturing technology of PV modules has improved considerably, resulting in higher efficiencies and better quality control process, which enabled a lower maximum power tolerance range of PV modules available in the market. The actual shape of the statistical distribution of the main electrical parameters is necessary to evaluate the mismatch losses using simulation software, and also to verify if a new selection of PV modules besides the one performed by the manufacturer is relevant. In order to analyze these topics, a statistical study was carried out based on data obtained from I–V curve measurements of 105 multicrystalline PV modules with the same nominal characteristics. The measurements were performed in a pulsed solar simulator in standard test conditions. The descriptive statistics were obtained for each main electrical parameter and the best probability density function that describes the parameters dispersion was determined. The results show that the maximum power, the maximum power voltage and the open circuit voltage are preferably represented by a Burr probability density function, however a normal distribution is adequate as well. The short circuit current, the maximum power current and the fill factor are actually described by a two parameter Weibull distribution. In order to analyze the effects of the mismatch losses in arrays, several I–V curves of strings with 10 PV modules randomly selected from the sample were synthesized and compared to strings of modules sorted by the maximum power current value. The advantage of performing a new selection of PV modules with better current match was not relevant in comparison to random strings. The selection performed at the factory for a PV module with the same nominal power is sufficient to prevent considerably mismatch losses considering that the PV modules were sorted using standard procedures.

Keywords: Photovoltaic module; I–V curve parameters; Statistical analysis

1. Introduction

The photovoltaic (PV) solar energy has increased its share in the electricity mix in a consistent way over the last few years, contributing to achieve higher levels of low carbon electricity production. The global photovoltaic

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http://dx.doi.org/10.1016/j.solener.2016.01.061
0038-092X/

industry chain is well established, making the PV solar energy at the edge of being competitive with traditional sources of electricity due to considerable price reduction.

The PV solar energy is an intermittent way of producing electricity and its performance is affected by several factors that should be considered, including the solar radiation availability and its spectral distribution, the PV module technology, the PV module operating temperature, the mismatch losses due to non identical *I–V* (current–voltage) curves, the long term effects such as soiling and power degradation. The nominal characteristics of PV modules are determined in standard test conditions (STC) comprising solar irradiance of 1000 W/m^2, cell temperature of 25 °C and radiation spectral distribution AM 1.5, standardized by IEC 60904-3 (2008). The field operation conditions differ substantially from STC, so the parameter NOCT (nominal operating cell temperature) is useful, since it is the temperature reached by the PV module under irradiance of 800 W/m^2, wind speed of 1 m/s and open rack mounted PV module. The main electrical characteristics of a PV module are obtained from the *I–V* curve, including the maximum power (P_m), maximum power voltage (V_{mp}), maximum power current (I_{mp}), open circuit voltage (V_{oc}), short circuit current (I_{sc}) and the fill factor (FF). The efficiency is also an important parameter related to the area of the PV module.

In order to reach the voltage and the current compatible to the inverters, the PV modules are connected in series, making strings and then in parallel, forming arrays. The array power is not necessarily the sum of individual PV module power, since *I–V* curves of single modules are not identical. The manufacturing process of a PV module results in variation of the *I–V* curve parameters and so the manufacturer selects and classifies the PV modules according to its maximum power in STC within a certain range. The current of the string is limited by the PV module with the lowest current at the string polarization voltage. In parallel connection of strings, the array voltage is limited by the lowest string voltage. Mismatch losses are considered in PV systems performance simulation and dimensioning software, where a value around 2% is usually assigned as default.

The PV modules manufacturing technology has improved substantially, reaching efficiencies around 17–18% for conventional monocrystalline silicon PV modules and around 16% for multicrystalline PV modules. The power tolerance for the PV modules has decreased considerably as well. It used to be ±10%, but tolerance values of ±3% are currently assured by the factory. Currently, manufacturers produce PV modules with positive tolerance and in 5 W class intervals, which corresponds to approximately +2%. A typical 60 cell multicrystalline PV module is made with 156 mm × 156 mm cells, with power ranging from 235 W to 265 W. Photovoltaic modules with 72 cells are sorted in 5 W models with positive tolerance too, which would correspond to +1.6%. There are cases where the PV modules are binned in 5 W intervals and the tolerance is stated as +3%, which theoretically would result in power superposition between models.

Although the mismatch losses should be considered in the performance of a PV system, it has been found low by several authors. Lorente et al. (2014) concluded by studies of PV arrays performance simulation that mismatch losses are quite low and so a new selection of PV modules, after the manufacturer one, to reduce the mismatch is not justified. According to Herrmann et al. (2013), instead of performing a new selection in order to match the maximum power current, the employment of modules with the same power class and low tolerance ($\leqslant$2%) would be an enough practice to reach negligible mismatch losses. Spertino and Akilimali (2009) also concluded that mismatch losses in PV systems are unimportant, considering the current status of power tolerance assured by reliable PV module manufacturers.

Despite the fact that some authors have found low mismatch losses for PV systems, it is inevitable that PV modules with the same class power have dispersion in the *I–V* curve parameters. The dispersion of P_m values is expected due to random variation in the manufacturing process. However it is not possible to predict the shape of the probability density function of all *I–V* parameters from a sample without suitable measurements and statistical analysis. The PV module has several manufacturing steps and the ultimate selection by P_m defines the nominal PV module power. Shirzadi et al. (2014) performed a mismatch losses minimization study using genetic algorithms considering a normal distribution for I_{sc}, although the findings of Zilles and Lorenzo (1991), based on several *I–V* curve measurements of PV modules, concluded that P_m, V_{oc} and V_{mp} follow a normal distribution whereas I_{sc} follows a Weibull distribution. The statistical distributions were achieved based on PV modules available that time. Considering the technological advancements that occurred in the PV industry, current data about the statistical distribution of the *I–V* curve parameter dispersion are scarce.

Chamberlin et al. (1995) found mismatch losses around 0.1% on average and never exceeding 0.53% in arrays with random selection of modules with the same nominal power. The economic advantage of a further selection of PV modules was found minimum according to Webber and Riley (2013) on a study based on Monte Carlo technique to generate artificial random arrays and evaluate the mismatch using the methodology proposed by Bucciarelli (1979), a methodology to calculate mismatch losses that is sensible to the statistical distribution of I_{mp}.

Iannone et al. (1998) used Monte Carlo techniques to study mismatch losses, however, the assumption was that I_{sc} and I_{mp} were normally distributed within the tolerance range. Independently of the chosen method to assess the mismatch losses, the statistical distribution of the *I–V* curve parameters is necessary in order to reach reliable results.

The main objective of this study is to determine the statistical distribution of the electrical parameters obtained