Photovoltaic modules transient response analysis and correction under a fast characterization system

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ABSTRACT

Failures of single photovoltaic (PV) modules lead to significant power losses in large PV systems. Individual and periodic monitoring of each PV module is a powerful way to detect these losses. Recently, a novel monitoring method, named Module to Module Monitoring System (M3S), has been proposed. This monitoring method, without disconnecting the PV module from the rest of the system, is able to produce and measure small variations around the operating point of the PV module. The entire measurement is performed in less than 5 ms, using only low-power components. For current high-efficiency PV modules, these short measurement times generate a hysteresis effect in the current–voltage (I-V) curve during the transient-state, which makes it difficult to directly estimate the static I-V characteristics of the PV module. In this work, the transient response of the PV module is analyzed and a methodology to correct the hysteresis effect and estimate the I-V characteristics of the PV module around the operating point with a mean squared error below 0.8%.

1. Introduction

Solar photovoltaic (PV) is currently one of the fastest growing energy source. By 2019, installed PV capacity increased to more than 600 GW (Louwen and van Sark, 2020) and it is expected to grow by more than 140 GW in 2020. Most of this new PV capacity will be installed in large PV systems with hundreds of thousands of PV modules. Thermal losses, DC/AC conversion losses, wiring losses and failures in PV modules and in the rest of the system, among others, result in power losses of approximately 15–20% of the performance ratio (Khalid et al., 2016; Matsumoto et al., 2016).

PV module power losses due to degradation typically increase by around 0.6% per year (Jordan et al., 2016). In addition, PV modules failures (Buerhop et al., 2018; Cristaldi et al., 2015; Dhimish et al., 2018; Silverman et al., 2016; Sinha et al., 2018), may increase power losses and speed up this degradation rate (Köntges et al., 2016). Extreme weather conditions such as hailstorms (Muehleisen et al., 2018) or hurricanes (Hotchkiss and Walker, 2020) also have a severe impact on PV system performance. Moreover, a failure on a single module may lead to a higher power loss since PV modules are connected to each other. Thus, the automatic and periodic monitoring of PV systems is of major importance.

Several monitoring methods have been proposed to detect these failures. Some of these approaches measure electrical data at string level or at the inverter entry (Bright et al., 2018; Silvestre et al., 2016; Wang et al., 2018). However, it is not clear if this methods are able of detecting failures on single PV modules (Jones et al., 2018; Ortega et al., 2017) since these failures may be diluted among the entire system. At module level, some methods measure the operating voltage of the module (Jones et al., 2018; Kilper et al., 2015) or the output power (Han et al., 2015; Samara and Natsheh, 2019). However, with these methods its not always possible to detect the fault or to indentify which is the failing module. For that, better access to the current–voltage (I-V) curve of each module is required. I-V curve tracers measure the full I-V curve of the PV module (Belmili et al., 2010; Duran et al., 2007; Sperzini et al., 2015), characterizing the PV module. These methods require to disconnect the PV module from the rest of the system, long measuring times and power electronics components and large capacitors.

Due to these limitations, in (Ortega et al., 2019) a new methodology named Module to Module Monitoring System (M3S) was proposed. M3S, without power electronics components and with capacitors in the range of tens of microfarads, is able to take partial measurements of the I-V curve. These measurements are taken in a few milliseconds without disconnecting the PV module under measurement from the rest of the...
This proposal was evaluated in a low-capacitance 25 W PV module, and an accuracy of between 1 and 3% was achieved when recomposing the I-V characteristics for the region close to the maximum power. However, the I-V characteristic estimation of a state-of-the-art PV module, with higher minority carrier lifetimes, connected in a string is not as straightforward. Due to the dynamic response of the PV modules and the interaction with the rest of the system, further processing is required to estimate the I-V characteristics. The aim of this work is to analyze the dynamic response of PV modules when measured using the M3S, a fast characterization system, and to present a correction method for the dynamic effects caused by internal associated capacitances.

2. Description of the system

This monitoring methodology, which has been explained in detail in previous work (Ortega et al., 2019) can be implemented on any system size. However, it is intended for central inverter systems, where there are hundreds of PV modules for each inverter and there is little information about each PV module. The monitoring methodology is based on two different circuits, one control unit (CU) for the entire PV system and a monitoring circuit (MC) connected in parallel to each PV module. Fig. 1 shows the proposed monitoring system for an entire PV system. Each MC is able to measure its PV module automatically and remotely and send the measurement data to the CU, which performs the further processing.

The simplified scheme of the MC is shown in Fig. 2. The MC is a low cost electronic circuit that uses only low-power components and is able to disturb the operating point of the PV module by modifying its output current. The MC is based on two 22 μF capacitors controlled by six switches: four switches (transistors: Q1, Q2, SW1 and SW2) controlled by an 8-bit microcontroller and another two (diodes) controlled by the direction of the current.

The MC, has four operating modes: standby, T1, T2 and T3. Most of the time, the MC is in standby mode and no current is extracted from the PV module. During T1, the first step of the monitoring sequence, capacitors C1 and C2 are charged in a slow process (50 ms) to the module voltage, draining little current from it. In T2, capacitor C1 is discharged towards the PV module, increasing the output current of the module with a step-like function limited to 0.3 A. This way, the operating point is displaced towards short-circuit. This movement is done outside the static I-V characteristics since, due to the intrinsic capacitance of PV modules, the dynamic behavior is not able to follow the PV module I-V characteristics. Once the capacitor is discharged, it returns to the initial operating point with values similar to those of the static I-V characteristics, since the movement is much slower. During T3 the operating point is displaced to higher voltages through capacitors C1 and C2, decreasing...
the output current in 0.3 A and moving it to open-circuit with a similar behavior to T2. Once the operating point returns again to equilibrium, the MC switches back to standby mode. During T2 and T3, which are completed in a few milliseconds, the MC takes pairs of current and voltage values with a 35 μs sampling period and sends them to the CU.

The MC has been previously evaluated with a 25 W Isofotón bifacial PV module following the described setup in (Ortega et al., 2019). The results obtained are shown in Fig. 3. The green line shows the movement of the operating point to short-circuit (T2) and the yellow line indicates the movement to open-circuit (T3). The T2 and T3 sequences take only 3 ms each to be completed. From these data, based on the methodology explained on the previous paper, it is possible to recompose the I-V characteristics of the 25 W PV module with an accuracy between 1 and 3% for the region close to the maximum power. A final version of the MC could be integrated, except for the two capacitors, on a single integrated circuit including in that the communications system, which could be done through Power Line Communications (PLC) or other communication system. The MC could be integrated in each PV module with a cost in the dollar range.

Fig. 3. Measurement with the MC in a 25 W PV module. Static I-V characteristics (dashed blue line), displacement towards short-circuit (SC) (green line, T2) and displacement towards open-circuit (OC) (yellow line, T3).

Fig. 4. 3.42 kW PV system setup. The figure shows the MC connected to three of the PV modules and the CU connected to them. At the bottom left, the 12 modules are shown.
3. Dynamic considerations

As stated in the introduction section, in low-capacitance PV modules it is easy to directly estimate the I-V characteristic with this method and it has been already demonstrated. However, in PV modules with higher minority carriers lifetimes is not as straightforward. This section intends to address this aspect. For that, the monitoring methodology has also been evaluated in a state-of-the-art high efficiency PV module, with longer response times. For that purpose, the setup shown in Fig. 4 has been implemented on the roof of the Faculty of Engineering in Bilbao (Spain). The 3.42 kW PV system is composed of 12 monocrystalline Jinko JKMS285M-60 PV modules (Jinko Solar, Shanghai, China) connected in series and a SMA-Sunny Boy 3000TL-21 inverter (SMA, Niestetal, Germany). The inverter is connected to a variable load and to an SMA-Sunny Home Manager, which allows controlling the injected power to the grid and thus, adjusting the operating point of the system, testing the monitoring methodology at different operating points. These 285 W modules have, under standard test conditions (STC), $V_{oc} = 38.7\,\text{V}, I_{sc} = 9.51\,\text{A}$ and an efficiency of 17.41% (19.5% at the cell level). The MC is connected in parallel to the PV module and strapped to the rear side of the PV module as shown in Fig. 5. In (Ortega et al., 2019) preliminary results with this PV system were presented, obtaining a dynamic I-V curve equivalent to the previous curve obtained with the 25 W module.

Fig. 6 shows the dynamic I-V characteristics (yellow line) obtained with the MC in the 285 W module during normal operation, without disconnecting it from the rest of the system, and the static I-V curve (dashed blue line).

The measured points were fitted to the I-V curve using the Multiv software (Martínez and Jimeno, 1998). Dynamic I-V data, on the other hand, was measured with the methodology explained in Section 2, during PV modules normal operation, with the MC connected in parallel to the PV module as shown in Fig. 5. In the subsequent analyses, static I-V curve is used as a reference to determine the accuracy of the dynamic data.
In this experiment, the MC is able to move the operating point, for the current operating point, 3 V to short-circuit and 2 V to open-circuit, but always the voltage sweep is limited by the 0.3 A current step. Fig. 6 also shows a zoom of the operating point area with the sample points of the acquired data. These points show how the rate of change of the operating point is not constant during the measurement. The measurement shows a high sample density near the operating point and maximum deviation points and a lower sample density in intermediate areas. In Figs. 7 and 8 a detailed zoom of the displacement of the operating point towards short-circuit and open-circuit is shown. Similar to the results obtained with the 25 W module (Ortega et al., 2019), in both measurements three sections can be identified: the shift of the operating point (Section 1) with a sudden current increase or decrease as a function of the displacement direction, the discharge of the capacitor (Section 2) and the return to the operating point (Section 3). However, there are some differences with the 25 W PV module. For the 285 W PV module, the return path (Section 3) is not close to the static I-V characteristics of the PV module. This result is due to the higher efficiency of state-of-the-art PV modules (in this experiment, the 285 W PV modules) than the efficiency of the 1980s small PV module such as the Isofoton’s

![Fig. 7. Displacement towards short-circuit with the MC in a 285 W PV module. Static I-V characteristics (dashed blue line) and dynamic I-V characteristics (green line). Three sections can be identified: one, shift of the operating point; two, discharge of the capacitor; and 3, return to equilibrium.](image1)

![Fig. 8. Displacement towards open-circuit with the MC in a Jinko JKMS285-60 PV module. Static I-V characteristics (dashed blue line) and dynamic I-V characteristics (yellow line). Three sections can be identified: one, shift of the operating point; two, discharge of the capacitor; and 3, return to equilibrium.](image2)
Fig. 9. Model of the 3.42 kW PV system with 12 Jinko JKMS285M-60 PV modules developed with LTspice IV.

Fig. 10. Simulation transient-states for three different PV cell response times: 5 μs (red), 180 μs (purple) and 500 μs (brown). The static I-V curve (blue) matches the 5 μs response time, and the 285 W PV module dynamic I-V curve (green) matches the 180 μs response time.
enables the modification of its parameters. One of the diodes is a dy
cmodeled with the double-diode model and the simulation environment
LTspice IV (Linear Technology, California, United States). Each PV cell is
rest of the modules.

if; in addition, there is an interaction with the MC dynamic and with the
hysteresis loop is only due to the dynamic behavior of the PV module or
is composed of 12 PV modules, one of them with a current source con
namic diode, through their internal transit-time parameter, enables to
simulate several minority carrier lifetimes. The model of the PV system
dynamic curve, it is possible to directly estimate the static I-V curve,
with an error below 3%. For longer response times (180 μs), a more
severe hysteresis effect is observed due to higher internal associated
 capacitances. This finding is in line with the experimental results ob-
tained on the 285 W PV modules (green). For these response times, the
FW path is far from the static I-V curve, and it is not possible to directly
estimate it. For longer response times (500 μs), the hysteresis effect is
even larger. This effect has also been experimentally confirmed adding
an external capacitance to the 25 W module (Ortega et al., 2018),
obtaining a larger hysteresis loop. These results confirm that the hys-
teresis effect observed during fast measurement of PV modules with the
MC, depends on the PV cell response times and it is not significantly
affected by the MC dynamic behavior or by its interaction with the rest
of the system.

This hysteresis effect during fast I-V curve measurement of PV
modules is a well known problem and appears for two main reasons: the
I-V curve scanning speed and the scanning direction. Several methods
have been proposed to minimize the occurrence of the hysteresis effect
using different voltage profiles (Ferretti et al., 2013; Monokroussos
et al., 2012; Virtuani and Rigamonti, 2013) or multi-flash (Sinton et al., 2005) or
long pulse (Hu et al., 2011) in the case of use of flash measurements. A
minimum of 500 ms flash pulses are used in many cases to measure PV
modules (Hishikawa et al., 2013; Ramspeck et al., 2014). Accordingly,
different parameters optimization approaches have been proposed to
determine the optimum scanning time or the minimum number of
points, among others, to minimize the hysteresis effect (Gao et al., 2018;
Herman et al., 2012). Other approaches propose a correction method for
fast I-V curve measurements based on a slow measurement of the dark I-
V curve (Kojima et al., 2014; Virtuani and Rigamonti, 2013).

Recently, a new approach was proposed (Sinton et al., 2017) to
correct the hysteresis effect in PV cells or modules. This method is based
on estimating the dynamic capacitance of the PV module from a
weighted sum of the forward and reverse currents and then determining
the capacitive current of the PV module. By adding this current to the
forward or reverse current, it is possible to approximate the I-V char-
acteristics of the PV module. This proposal has already been imple-
mented for PV cell I-V measurements, using solar simulators (Vahlman
et al., 2018), with a minimum sweep time between 20 and 30 ms.

According to the PV module equivalent circuit in Fig. 11, the total
current of the PV module (I_m) can be given as the sum of the steady-state
current and dynamic current, as in Eq. (1). Steady-state currents
comprise the photogeneration current (I_p) and the recombination cur-
rent (I_r). The dynamic or capacitive current (I_c) is due to the charge and
discharge of PV module solar cells during voltage sweeps.

\[ I_m = I_p - I_r - I_c. \]  

(1)

During steady-state conditions, while there is no voltage variation,  
I_p
is zero and the module current depends only on $I_c$ and $I_o$. Variations from steady-state current during the transient-state are due to changes in the capacitive current (Kerr et al., 2002), which according to Eq. (2) depends on the voltage and its rate of change:

$$I_c = C(V_j) \frac{dV_j}{dt}.$$  

(2)

where $V_j$ is the junction voltage and can be computed as:

$$V_j = R_s \cdot I_m + V_m.$$  

(3)

From there, the FW and REV currents can be subtracted, and the capacitance of the PV module can be estimated as:

$$C(V_j) = \frac{I_{m,REV}(V_j) - I_{m,FW}(V_j)}{\frac{dV_j}{dt}|_{FW} - \frac{dV_j}{dt}|_{REV}}.$$  

(4)

Knowing the PV module capacitance, the module current can be corrected as:

$$I_m(V_j) = I_{m,FW}(V_j) + C(V_j) \frac{dV_j}{dt}|_{FW}.$$  

(5)

Even if this method is able to estimate the steady-state I-V

Fig. 12. Forward (green line) and reverse (red line) sweeps for the movement towards short-circuit given at junction voltage. Yellow squares (FW points), green circles (REV points), purple triangles (corrected points) and black arrows depict the correction process. From $I_{FW}$, adding $I_{c,FW}$, $I_m$ is obtained from Eq. (5).

Fig. 13. Static I-V characteristic (blue), corrected points from the short-circuit sweep (purple) and corrected points from the open-circuit sweep (orange).
characteristics of the PV module from two dynamic measures, it has two general constraints (Vahlman et al., 2018): at least 20 characteristics of the PV module from two dynamic measures, it has two possible noise sources. At cell level, the correction method would be very sensitive to the series resistance determination accuracy, especially with short voltage sweeps. In addition, the time derivative of the junction voltage is very sensitive to measurement data error.

When applied to the data acquired from the MC, there are other specific limitations: first, with M3S, only a small section of the I-V curve (around the operating point) is known. I-V curve tracers, typically measure the full I-V curve two times: from $V_{oc}$ to $I_{sc}$ and from $I_{sc}$ to $V_{oc}$. M3S, however, only measures a small segment of the I-V characteristics around the operating point in each direction (steps T2 and T3 of the monitoring sequence). Each measurement is divide into two parts: the movement from the operating point to the maximum deviation point, and the return to the operating point. In this way, if we consider the measurement towards short-circuit (step T2), the movement from the operating point towards short-circuit would be the REV sweep and, the return to the operating point would be the FW sweep.

Second, the measurement is very fast, an order of magnitude shorter than the advised time. Step T2, taking into account the REV and FW sweeps, takes only 3 ms to be completed (Ortega et al., 2019). Finally, the FW and REV sweeps are typically made with known voltage profiles, obtaining current values at the same voltage in the forward and reverse directions, which are necessary to estimate the capacitance value according to Eq. (4). In this proposal, because the movement is generated by a current injection with the charge and discharge of a capacitor, as explained in Section 2, and data are acquired with an 8-bit microcontroller, the sampling frequency is constant; however, since the rate of change of the voltage is not constant, samples are obtained at different voltages in the FW and REV directions. Therefore, before implementing this method, the FW and REV samples require to be synchronized, which adds an additional error to the process.

The displacement towards short-circuit (Fig. 7) is chosen to implement this correction method with M3S, with Sections 1 and 2 being the REV direction and Section 3 being the FW direction. From these data, the forward and reverse points are changed from module voltage to junction voltage using Eq. (3), with $R_s = 0.165 \Omega$. $R_s$ was estimated from the three-parameter model of the PV module, where from $I_{sc}, V_{oc}$ and $FF$ manufacturer data there is only one $R_s$ value that fits the model. Small variations in $R_s$ value have no influence on the method accuracy. Fig. 12 shows the reverse (red) and forward (green) sweeps. For both sweeps, the $V_j$ derivative is computed and, since there are very few samples and any acquisition error could lead to a much higher derivative error, the derivative is fitted to a second order polynomial expression. From Eq. (4) the module mean capacitance is determined, obtaining a value of 32 $\mu$F. With this value, from Eq. (5), the adjusted module current for the movement towards short-circuit (T2) is computed by adding the FW and capacitance currents. This way, as shown in Fig. 12, for each FW point the corrected current of the module ($I_{MC}$) can be estimated by adding to the FW current ($I_{FW}$) at that point the capacitance current ($I_{CMFW}$). The process show in Fig. 12 is repeated for the entire sweep. Similarly, the same process is repeated for the movement towards open-circuit (step T3, Fig. 8, Section 3), correcting the I-V curve by adding the capacitance and REV currents.

Fig. 13 shows the fitting between the steady-state I-V curve and the adjusted I-V points in both directions: short-circuit (purple points) and open-circuit (orange points). The proposed correction methodology shows good fitting with the steady-state I-V curve around the operating point. A mean squared error (MSE) of 0.33% is obtained between the corrected points and the static I-V curve points. Observed deviations between tests can be due to small variations on the operating point. For several tests have been performed on the same module, in a short period of time, following the same process. Fig. 14 shows the fitting between the corrected points and the static I-V curve for four tests, after applying the proposed methodology. As it can be seen, the corrected points show good fitting with the static I-V curve. Observed deviations between tests can be due to small variations on the operating point.
Towards short-circuit (purple) and corrected points from sweep towards open circuit (orange).

An error below 0.8%.

the I-V characteristic of the PV module around the operating point with measures are performed for each PV module and dynamic data is corrected in times as short as 5 ms for both directions and some error is added even if some error is added due to operating conditions variation while the MPP is estimated with a maximum error below 2.1%. These results are obtained even though the measures are performed addition, when estimating the MPP, the error remains below the 2.1%.

The proposed methodology shows good results in order to estimate the static I-V characteristic around MPP and to estimate the MPP of the module. However, there is no information of the rest of the I-V characteristic. For that, mathematical processing must be expanded to obtain a better recomposition of the full I-V characteristic of the PV module, estimate its parameters ($I_{sc}$, $V_{oc}$, $I_{th}$ ...) and determine the failure causes.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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