Analysis of Measurement Reproducibility for Photovoltaic Modules Under Outdoor Test Conditions

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Abstract. Reproducibility of measurement for photovoltaic modules under outdoor test conditions is critical for performance evaluation of photovoltaic modules in the field. However, the literature related to measurement reproducibility for photovoltaic modules in outdoor test is still scarce. In this paper, measurement reproducibility of electrical parameters corrected to standard test conditions of photovoltaic modules is investigated for the first time. The results indicate that the value of measurement reproducibility in outdoor test is generally higher compared with that in indoor test. Moreover, it is found that the reproducibility value of maximum power voltage is the largest, followed by short circuit current, open circuit voltage and maximum power current, and reproducibility value of maximum power is the smallest. The obtained results in this paper provides a preliminary insight into on-site performance degradation determination for photovoltaic modules.

Keywords: Photovoltaic Modules, Measurement Reproducibility

1. Introduction

Performance evaluation of photovoltaic (PV) modules is important for reliability analysis and payback period determination for PV plants. The indoor test is the most accurate approach to obtain the current-voltage characteristic of solar modules. Much of the literature has studied the measurement uncertainties under indoor test conditions using solar simulators [1-3]. Nevertheless, as the installed capacity of PV plants is increased exponentially, it is increasingly critical to evaluate performance of PV modules in the field. This is because transporting a large number of modules from plants to indoor test laboratories not only incurs significant transportation costs, but also involves the cumbersome process of dismantling, handling, reinstallation, and increases the risk of microcracks. Also, with the scarcity of urban land resources, more and more modules are situated in remote areas such as deserts or mountains. In outdoor testing, reproducibility is a core aspect to correctly describe the measured results and evaluate module performance. Whitfield et al. [4] proposed an uncertainty estimation procedure for measuring the electrical performance of PV modules using natural sunlight and calibrated secondary reference cells. Carrillo et al. [5] shared the experience of IES-UPM in outdoor characterization of PV modules. A relatively simple device composed of a thermally insulated wooden box can measure the STC (Standard Test Conditions) characteristics of PV

modules with a lower uncertainty. Raina et al. [6] studied the error estimation of corrections to electrical parameters under different irradiance and temperature ranges. Atmaram et al. [7] discussed general procedures for estimating measurement uncertainty and the specific application in assessing the rated power of modules in the field. However, to our knowledge, measurement reproducibility for PV modules under outdoor conditions has not been reported. In this study, measurement reproducibility of electrical parameters is investigated for the first time. The current-voltage data of PV modules under arbitrary conditions is corrected to STC by using correction procedure 4 in IEC 60891:2021. The results indicate that the value of measurement reproducibility in outdoor test is generally higher compared with that in indoor test. Moreover, it is found that reproducibility value of maximum power voltage is the largest, followed by short circuit current, open circuit voltage and maximum power current, and reproducibility value of maximum power is the smallest. The obtained results in this paper provide a preliminary insight into on-site performance degradation determination for photovoltaic modules.

2. Experimental details

In this study, a monocrystalline silicon solar module was selected as the test sample. The PV module is composed of 60 series-connected passivated emitter and rear cells, each with dimensions of 156 mm × 156 mm. PV200 portable I-V curve tester and Survey200 solar irradiance tester were used to obtain the real-time I-V curves of modules and plane of array irradiance on modules, respectively. Performance tests of modules were conducted on sunny days. Throughout the test, the module angle was fixed to ensure a relatively constant irradiance over a short period. To minimize temperature uncertainty and reduce the impact of wind speed on the uniformity and stability of module temperature, measurements were taken with wind speeds less than 2 m/s. Additionally, data recording was performed when the temperature difference between the highest and lowest points on the backsheet of the photovoltaic module was within $3°\text{C}$ at the same moment.

3. Results and discussion

3.1 Mathematical model for STC correction

We have established a mathematical model for the voltage and current values of the tested module under standard test conditions (STC), following Procedure 4 of IEC 60891-2021.The initial model can be expressed by Equation (1).

$$I_{G,C} = I_{TEST} + I_{SC,TEST} \times (G^* / G_{TEST} - 1)$$

$$V_{G,C} = V_{TEST} - R_S \times (I_{G,C} - I_{TEST})$$

$$I^* = I_{G,C} + \alpha_{rel} \times I_{sc}^* \times (T^* - T_{TEST,C})$$

$$V^* = V_{G,C} + (T^* - T_{TEST,C}) \times \frac{1}{T_{TEST,C}} \times (V_{G,C} - n_s \times \varepsilon)$$

(1)

In this initial model, I_{TEST} and V_{TEST} represent the current and voltage values at the tested characteristic point at an irradiance G_{TEST} and temperature T_{TEST}. $I_{G,C}$ and $V_{G,C}$ represent the current and voltage values corrected for irradiance. I^* and V^* signify the current and voltage values further corrected for both irradiance and temperature. G_{TEST} is the irradiance measured by the reference device, and G^* is the target irradiance for the tested module. $T_{TEST,C}$ is the corrected temperature of the tested module, obtained by adding $2.5°\text{C}$ to the measured backsheet temperature, T_{TEST}. T^* is the target temperature.

$I_{SC, TEST}$ is the measured short-circuit current of the tested module at G_{TEST}, $T_{TEST,C}$, and $I_{SC}*$ is the short-circuit current of the tested module at standard test conditions. The parameter α_{rel} represents the relative current-temperature coefficient of the tested module measured at an irradiance of 1000 W/m². Due to the limited temperature range at this irradiance level during outdoor testing, the accuracy of the temperature coefficient calculation is compromised, and a value of 0.00045°C^{-1} is applied in this case. R_S represents the internal series resistance of the Device Under Test (DUT); ns is the number of cells connected in series, and ε is a device-specific constant, typically around 1.232V for crystalline silicon (c-Si).

Where $I_{SC}*$ can be obtained by Equation (2).

$$I_{SC}^{*} = \frac{1000\,{}^{W}\!/_{m^2}}{G_{TEST}} \times \frac{I_{SC,TEST}}{\left[1 + \alpha_{rel} \times \left(T_{TEST,C} - 25℃\right)\right]}$$

(2)

Using a set of data from outdoor testing for $I_{SC}*$ calculation, with an irradiance of 1001 W/m² and a backsheet temperature of 46.56 °C, the short-circuit current is 8.838A. The value of $I_{SC}*$ is calculated as 8.735A.
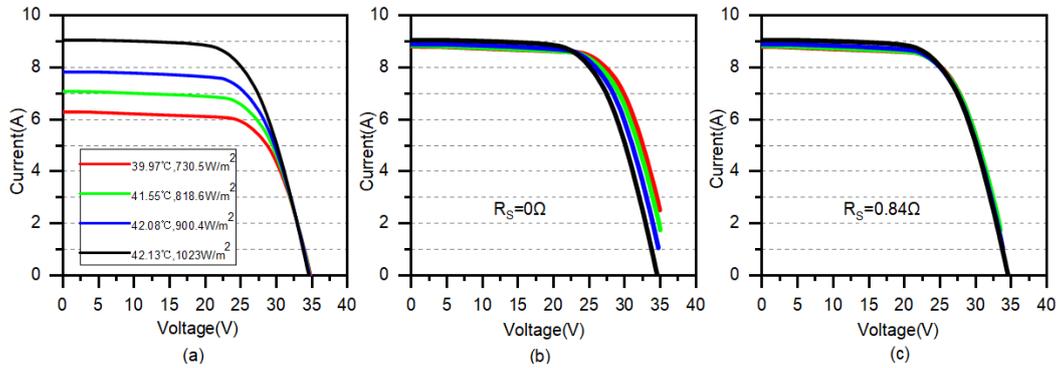
Figure 1. *I-V curves of the sample module: (a) during outdoor testing, (b) after correction with R_S = 0, and (c) after correction with R_S = 0.84 Ω.*

The determination of the series resistance involves maintaining a constant temperature, with the backsheet temperature within the range of 41.05±1.1℃. Setting R_S to 0, the correction procedure is utilized to individually correct the I-V curves obtained at lower irradiance levels in Figure 1(a) to the highest irradiance level, resulting in the corrected I-V curves shown in Figure 1(b). After correction, the curves do not completely overlap. Therefore, the R_S value needs to be adjusted, and the correction process is repeated. Through iterative refinement, it is determined that R_S equals 0.84 Ω provides the optimal correction, ensuring the maximum power deviation is within 0.5%. Consequently, the STC correction model can be established.

3.2 Reproducibility analysis of outdoor testing correction results
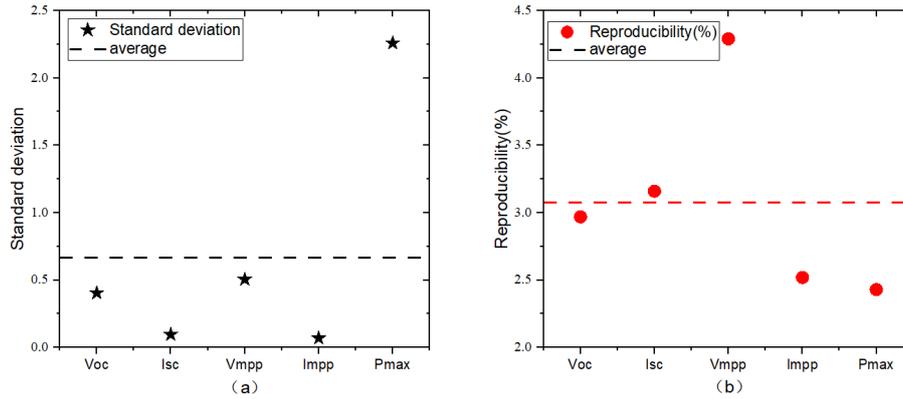
Figure 2. *(a) Standard deviation and (b) reproducibility of V_{OC}, I_{SC}, Impp, Vmpp and Pmax for the sample module*

Since the converted results of power testing for photovoltaic modules follow a normal distribution, and both test results under reproducibility conditions adhere to the overall distribution of laboratory power test results. When outdoor testing yields power test results for this photovoltaic module, which follow a normal distribution $A \sim N(\mu, \sigma)$, where μ is the average value and σ is the standard deviation, the reproducibility limit for the test results is represented by r. The expression of r can be expressed as Equation (3).

$$r = \frac{2\sqrt{2}\sigma}{\mu} \times 100\%$$

(3)

Figure 2 presents the standard deviation and reproducibility of the V_{OC}, I_{SC}, I_{mpp}, V_{mpp}, and P_{max} parameters of the photovoltaic modules after correction, based on ten sets of data. From the Figure 2, it can be found that the standard deviation of V_{OC} is smaller than that of V_{mpp}, so the reproducibility of V_{OC} is better. The standard deviation of I_{SC} is slightly larger than that of I_{mpp}, so the reproducibility of I_{SC} is poor. Parameters of different units cannot be directly compared. For instance, P_{max} has the largest standard deviation but the best reproducibility, which is due to its larger average value. The standard deviation of the maximum power is only 2.259 W (0.86%), which is relatively small in comparison to the maximum power. This suggests that the study demonstrates a relatively high level of reliability.

4. Conclusions

This study explores the reproducibility of outdoor testing results for photovoltaic modules for the first time. Electrical performance parameters of photovoltaic modules were tested outdoors using the PV200 I-V curve tracer and Survey200 solar irradiance meter. Subsequently, a model was developed based on Procedure 4 of the IEC60891 international standard for correction, converting the test data to standard test conditions, and the reproducibility of the converted electrical performance parameters was studied. The study of reproducibility for the converted results indicates that Vmpp exhibits the highest reproducibility, followed by Isc and Voc, Whereas Impp and Pmax show the lowest reproducibility. The research reveals a relatively high reliability in outdoor testing conditions and methodologies. This work provides a comprehensive understanding of the reproducibility of photovoltaic modules during outdoor testing, quantifying the consistency of outdoor measurement results.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Author contributions

Conceptualization: Baojie Lv and Hong Yang; Methodology: Baojie Lv and Hong Yang; Validation: Baojie Lv; Formal Analysis: Baojie Lv; Resources: Hong Yang; Data Curation: Qian Yang; Writing – Original Draft Preparation: Baojie Lv; Writing – Review & Editing: Xixiang Xu, Ting Lei, Wei Li, Chan Liu; Visualization: Baojie Lv; Supervision: Hong Yang; Project Administration: Hong Yang; Funding Acquisition: Hong Yang.

Competing interests

The authors declare no conflict of interest.

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References

[1] Emery K. Uncertainty analysis of certified photovoltaic measurements at the national renewable energy laboratory[R]. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.

[2] Dirnberger D, Kräling U. Uncertainty in PV module measurement—Part I: Calibration of crystalline and thin-film modules[J]. IEEE Journal of Photovoltaics, 2013, 3(3): 1016-1026.

[3] Chandel R. Uncertainty analysis of photovoltaic power measurements using solar simulators[J]. Energy Technology, 2013, 1(12): 763-769.

[4] Carrillo J M, Martínez-Moreno F, Lorenzo C, et al. Uncertainties on the outdoor characterization of PV modules and the calibration of reference modules[J]. Solar Energy, 2017, 155: 880-892.

[5] Raina G, Vijay R, Sinha S. Assessing the suitability of I-V curve translation at varying irradiance and temperature range[J]. Sustainable Energy Technologies and Assessments, 2022, 51: 101925.

[6] Atmaram G H. Uncertainty estimate of photovoltaic module power rating for outdoor testing[C]//2006 IEEE 4th World Conference on Photovoltaic Energy Conference. IEEE, 2006, 2: 2124-2128.

[7] Carrillo J M, Martínez-Moreno F, Lorenzo C, et al. Uncertainties on the outdoor characterization of PV modules and the calibration of reference modules[J]. Solar Energy, 2017, 155: 880-892.