Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

A High-Resolution Approach for Performance Estimation of Photovoltaics Under Partial Shaded Conditions

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ABSTRACT

Partial shaded conditions (PSC) significantly affect the performance of photovoltaic (PV) systems. Understanding and mitigating PSC effects require an accurate model with the ability to simulate the PV operating in both forward and reverse biased regions. Herein, a high-resolution approach is presented to address this issue. The reversed biased effects of PSC are fully considered at the cell level using an enhanced single diode model. Based on this, the electrical characteristic of the PV module can be accurately calculated. Good agreement is obtained between the simulation and measurement with a maximum relative error of 6.1%. This approach provides a useful tool for comprehensive modeling of the PV system.

Keywords: photovoltaic, reverse biased, partial shaded condition, modeling.

NOMENCLATURE

Abbreviations	
DDM	double-diode model
ECM	equivalent circuit models
PV	photovoltaics
PCE	power conversion efficiency
PSC	partial shaded conditions
SDM	single diode model
Symbols	
a	current fraction in avalanche breakdown
I	current, A
V	Voltage, V
R	Resistance, Ω

1. INTRODUCTION

Photovoltaics (PV) represents a promising alternative to address the global energy dilemma in an eco-friendly way. High power conversion efficiency (PCE) with long-term stability is the eternal pursuit and key challenge of PV research and development. However, both are adversely affected by the partial shaded conditions (PSC), particularly for the modules deployed in the urban context.

PSC has multiple detrimental effects on PV performance. Firstly, the PSC forces the shaded cells to operate in reversed-biased conditions, thus leading to the power mismatch phenomenon within modules or arrays. Secondly, localized hot spots are easily formed when a PV system operates under PSC. Over time, this may permanently damage the PV module and even cause a fire in severe cases. Last but not least, the power-voltage (P-V) characteristics curve will exhibit multiple power peaks under PSC. As a result, the maximum power point tracking task becomes complicated and may significantly reduce the yields.

Understanding and mitigating PSC effects require a scientific and accurate mathematical model. Equivalent circuit models (ECM), e.g., the single-diode model (SDM), and the double-diode model (DDM) have been widely used for performance estimation. Examples includes Villalva et.al [1] and Chaibi et.al [2]. To achieve a better accuracy, some scholars also developed multiphysics models using the thermal model to couple with SDM [3,4]. Although good performance is achieved in these studies, a clear disadvantage is the negligence of the PSC effect. To address this issue, some scholars also tried to include the PSC effect in ECM [5,6]. These methods have been validated using modules operating in some shading conditions. However, most of them neglected the reversed biased effect, thus limiting the applicability in real-world scenarios.

Although the research on PV system modeling is currently advancing at a tremendous pace, accurate estimation of PV systems under PSC remains a big challenge. The objective of this research is to present a complete approach to simulating the PV under PSC. The reversed biased effects of PSC are fully considered using an enhanced single diode model. Based on this, the electrical characteristics of the PV module can be accurately calculated. This approach provides a useful tool for comprehensive modeling of the PV system.

2. METHODOLOGY

The proposed model is based on an extension of the ECM. SDM method is used to achieve a balance between accuracy and efficiency. To consider the reversed biased effect, the traditional SDM is extended.

2.1 Cell modeling

The current-voltage (I-V) characteristics of the solar cell are simulated using Eq. (1) and the *diagram of the ECM is shown in Fig. 1*. Specifically, when the solar cell is forward biased, the traditional SDM (Fig. 1(a)) is solved to obtain the I-V characteristics. When the solar cell is reversed biased, traditional SDM is extended considering the voltage of the avalanche effect (Fig. 1(b)). By solving this model, the I-V characteristics in the reversed biased region can be obtained. Abundant studies have confirmed that the avalanche effect has little effect on the I-V characteristics in the forward-biased region. This switching mode can save unnecessary computational costs, especially when dealing with large PV systems.

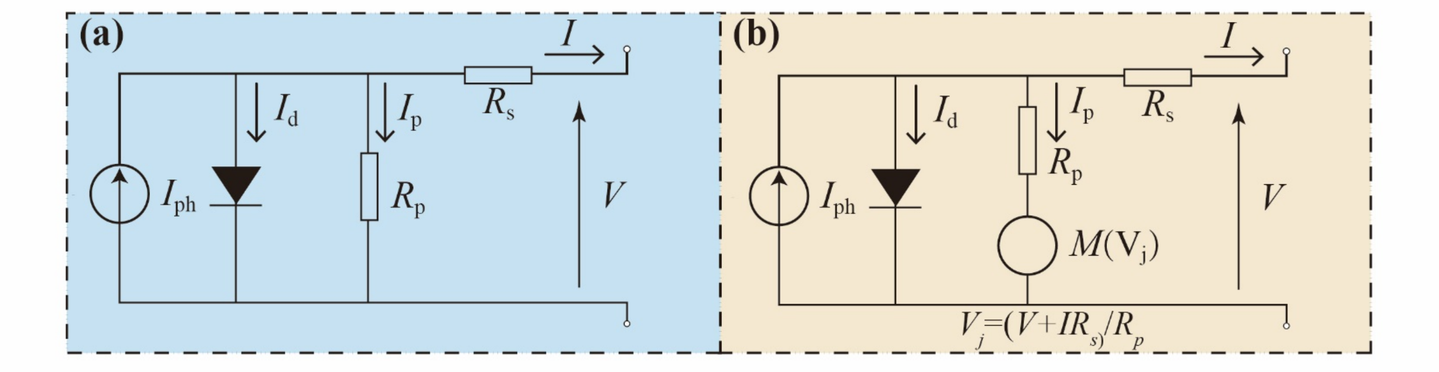

Fig. 1. The diagram of the ECM. (a): Traditional SDM; (b): Extended SDM.

$$I=\begin{cases} I_{ph}-I_o\left[\exp\left(\dfrac{V+IR_s}{V_t}\right)-1\right]-\dfrac{V+IR_s}{R_p} & if\ I\le I_{sc} \\ I_{ph}-I_o\left[\exp\left(\dfrac{V+IR_s}{V_t}\right)-1\right]-\dfrac{V+IR_s}{R_p}\left[1+a\left(1-\dfrac{V+IR_s}{V_{br}}\right)^{-m}\right] & if\ I>I_{sc} \end{cases} \tag{1}$$

where I is the current of the module, A; I_{ph} is the photocurrent, A; I_o is the reverse saturation current, A; V is the output voltage, V; V_t is the thermal voltage, V; R_s and R_p are the series resistance and parallel resistance, respectively; a is the fraction of current involved in avalanche breakdown; V_{br} is the breakdown voltage, V; m is the avalanche breakdown exponent.

2.2 Cells to module

After calculating the I-V characteristics of each solar cell, the module's electrical characteristics can be obtained using the following equations:

$$V_m=\sum_1^i V_{string,i} \tag{2}$$

$$V_{string,i}=\begin{cases} -0.6 & if\ \ \sum_1^n V_{i,n}\le -0.6 \\ \sum_1^n V_{i,n} & else \end{cases} \tag{3}$$

where V_m is the module voltage, V; $V_{string,j}$ is the voltage of the i^{th} string, V; $V_{i,n}$ is the voltage of the n^{th} cell in the i^{th} string, V.

2.3 Numerical treatment

The proposed model is programmed and solved in the MATLAB environment. Due to the transcendental and implicit features of Eq. (1), the Newton-Raphson method is used. The corresponding parameters in Eq. (1) are extracted using the method proposed in [3].

3. VALIDATION SETTINGS

A PV module operating under 8 different shading scenarios from [7] is used to validate the developed model. The module consists of 3 strings with 24 solar cells in each. Table 1 shows the detailed settings of each scenario. Firstly, in scenarios #1-3, 2 cells in string 3 are shaded at 3 different levels. Then, in scenarios #4-6, string 3 is shaded at 3 different levels. Finally, both strings 2 and 3 are shaded in scenarios #7-8. To quantify the accuracy and efficiency of the proposed method, the absolute error and elapsed time are selected as the performance metrics.

Table 1: Shading scenarios settings

Scenarios	***Irradiance (W/m^2)***	***Shading patterns (W/m^2)***		
		String 1	***String 2***	***String 3***
#1	*1276.5*	*Non-shaded*	*Non-shaded*	*8 cells shaded with 570.9*
#2	*1277.1*	*Non-shaded*	*Non-shaded*	*16 cells shaded with 589.1*
#3	*1280.6*	*Non-shaded*	*Non-shaded*	*24 cells shaded with 568.8*
#4	*964.5*	*Non-shaded*	*Non-shaded*	*24 cells shaded with 745.1*
#5	*973.3*	*Non-shaded*	*Non-shaded*	*24 cells shaded with 567.7*
#6	*895.4*	*Non-shaded*	*Non-shaded*	*24 cells shaded with 154.4*
#7	*892.6*	*Non-shaded*	*24 cells shaded with 607.5*	*24 cells shaded with 480.1*
#8	*945.8*	*Non-shaded*	*24 cells shaded with 709.7*	*24 cells shaded with 456.1*

4. RESULTS AND DISCUSSION

4.1 Scenarios #1-3

Fig.2(a-c) shows the simulation results against measurement data of scenarios #1-3. Due to the two shaded cells in the 3rd string, the power-voltage curves show two peaks.

As indicated, good agreement is obtained in each scenario with the absolute errors within 2.07 W and relative errors within 2.1% at the maximum power point (Fig.2(i)). The elapsed time of the proposed model is within 1.478 s (Fig.2(j)), demonstrating the high computational efficiency of the proposed model.

4.2 Scenarios #4-6

Fig.2(d-f) shows the simulation results against measurement data of scenarios #4-6. Since there are two irradiance levels in the module, the power-voltage curves also show two peaks. However, because all the cells in the 3rd string are shaded, the short-circuit current and the maximum power are much lower than that in scenarios #1-3.

As indicated, good agreement is obtained in each scenario with the absolute errors within 3.46 W and relative error within 6.1% at the maximum power point (Fig.2(i)). The elapsed time of the proposed model is within 1.476 s (Fig.2(j)), reconfirming the high computational efficiency of the proposed model.

4.3 Scenarios #7-8

Fig.2(g-h) shows the simulation results against measurement data of scenarios #7-8. Because both the 2nd and 3rd string are fully shaded at different levels, there are three irradiances in the module. As a result, there are three peaks in power-voltage curves.

As indicated, good agreement is obtained in each scenario with the absolute errors within 1.22 W and relative errors within 2.1% at the maximum power point (Fig.2(i)). The elapsed time of the proposed model is within 1.489 s (Fig.2(j)), reconfirming the high computational efficiency of the proposed model.

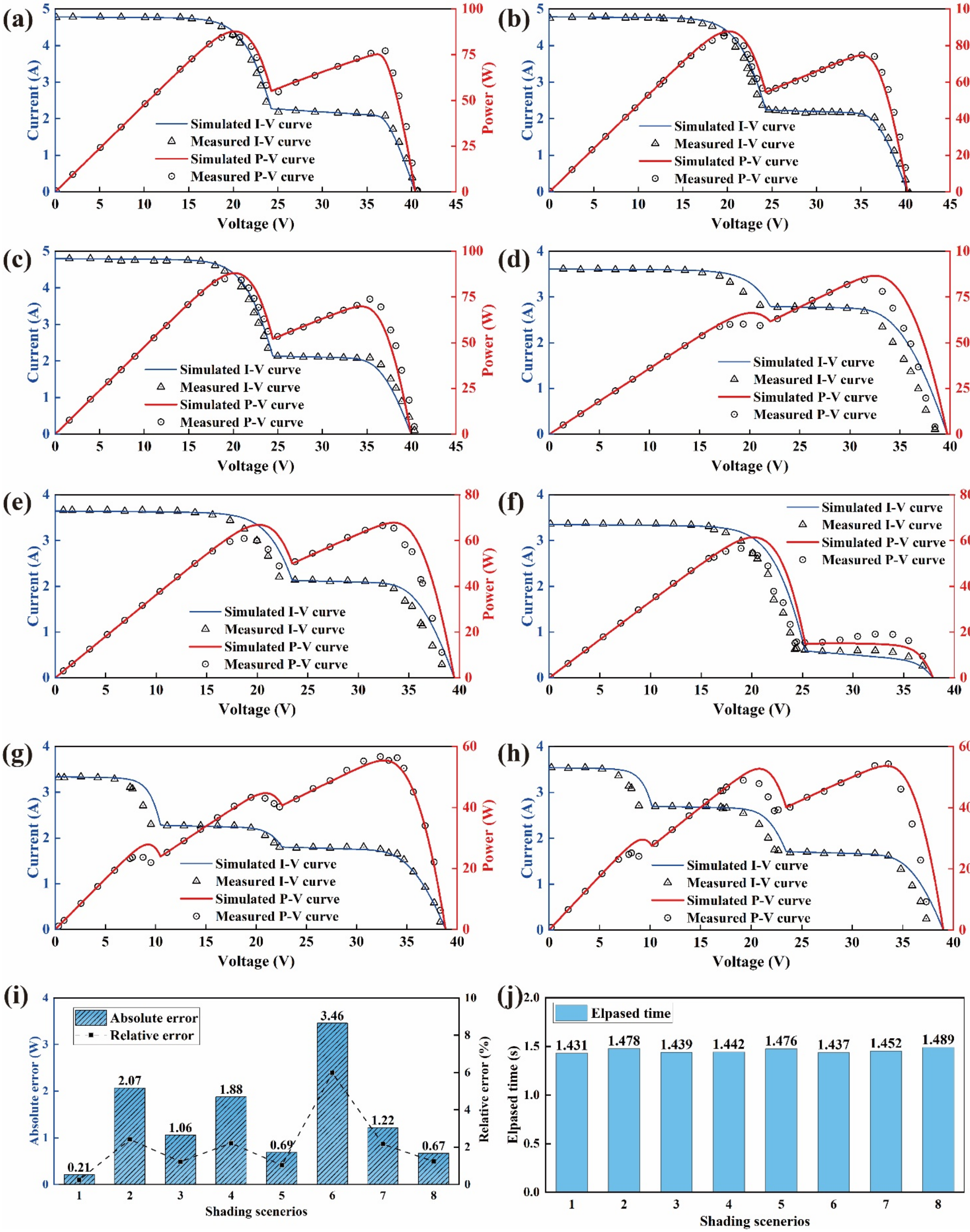

Fig. 2 Validation and performance of the model. (a): Scenario #1; (b): Scenario #2; (c): Scenario #3; (d): Scenario #4; (e): Scenario #5; (f): Scenario #6; (g): Scenario #7; (h): Scenario #8; (i): Error analysis; (j): Elapsed time.

5. CONCLUSIONS

To accurately estimate the performance of PV systems under PSC, this research proposes a complete electrical model considering the reversed biased effects. The models are validated using a PV module operating under 8 different shading scenarios. Outstanding accuracy with high computational efficiency is confirmed by the validation results. This approach provides a useful tool for comprehensive modeling of the PV system.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the supports from the Research Grants Council of Hong Kong (Project number: CityU 11212620, CityU 11215621)

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