Fast I-V Curve Approximation Technique for Photovoltaic Panels using Superellipse

Tofopefun Nifise Olayiwola* · Sung-Jin Choi**

[1,2]Department of Electrical, Electronic and Computer Engineering, University of Ulsan, Ulsan, 44610, South Korea

*tofopefungraduate@gmail.com, **sjchoi@ulsan.ac.kr

Abstract

A solar array simulator (SAS) is a DC/DC power supply used in the industry which gives an output similar to real PV panels. However, due to the implicitness of the I-V characteristic equation, enumeration of the I-V curve is not straightforward. Various approximated models have been proposed in the past to obtain numerical solutions across the full range of the curve. A major drawback of these techniques is the execution time required. For a high-performance implementation of SAS in real-time, a very fast execution time is required. In this paper, a novel approximation method based on the principle of the superellipse is proposed. In its first quadrant, the proposed method has an execution time that is 32 times faster than the conventional fixed-point iterative method.

1 Introduction

The three main components of SAS are the controller circuit, a DC/DC converter, and a reference generator. The reference generator is responsible for the fast and accurate enumeration of the I-V curve. Most SAS reference generators are often embedded with either a look-up table or a set of transcendental equations used in approximating the basic I-V characteristic equation.

Approximate I-V equations proffer an easy way to obtain instantaneous enumeration across the full range of the I-V curve. The most commonly used transcendental equations are based on the Lambert-W function and the Newton-Raphson method due to their easy fit to the basic I-V characteristic equation [1]. Other proposed methods in the literature are based on the Chebyshev polynomials, Padé approximants, sine-cosine function, and datasheet transforming curves [2].

However, obtaining the solution to these equations is quite difficult requiring long iterations, and in some rare cases, this results in a non-convergence due to infinite iterations [3]. This high iteration count leads to a corresponding slow execution time as observed in most SAS. Hence, this paper proposes a novel method for achieving a fast and accurate enumeration of the I-V curve using the mathematical principle of a superellipse.

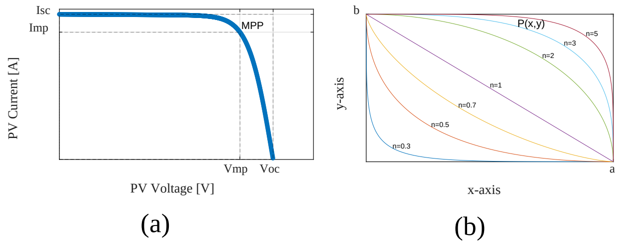

Fig. 1 A plot of a (a) typical I-V curve for PV panels (b) superellipse with a varying n

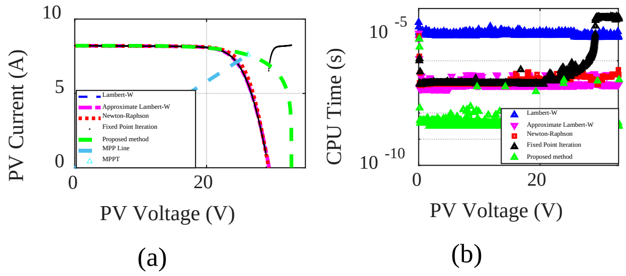

Fig. 2 Comparison using 5 different methods (a) I-V curve approximation (b) execution time

2 Proposed Method

The single-diode model of the photovoltaic (PV) panel is the most widely used equivalent circuit model for its modeling and simulation. The characteristic equation describing a typical I-V curve in Fig. 1a with its four key points (open circuit voltage V_{oc}, short circuit current I_{sc}, current at the maximum power point I_{mp}, and voltage at the maximum power point V_{mp}) can be written as

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_s)}{A_q kT}} - 1\right) - \frac{(V+IR_s)}{R_p} \qquad (1)$$

where I is the PV terminal current, V is the PV terminal voltage, k is the Boltzman constant $(1.38\times10^{-23}J/K)$, q is the electronic charge $(1.6\times10^{-19}\,C)$, T is the PV cell temperature, while I_s and I_{ph} is the saturation current and the photo-generated current respectively. The limitation of the exponential equation in (1) is that the parameters are not directly related to the key points.

On the contrary, a superellipse is an ellipse that retains its fixed points irrespective of distortion in shape as shown in Fig. 1b. A closer look at Fig. 1 shows that both curves share some similar characteristics, especially at the fixed

Table 1 Enumeration performance for 5 different approximation methods using KC200GT PV panel

Method	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	Error Vmp (%)	Error Imp (%)	Error Voc (%)	Error Isc (%)	Fill Factor (%)	Execution Time (ns)**	Relative Execution Time
Manufacturer	26.3000	7.6100	32.9000	8.2100					0.7410		
Proposed (n≅3.6)	25.8485	7.4644	32.9000	8.2100	-1.7167	-1.9130	0	0	0.7143	4	1
Newton-Raphson	24.8644	7.0978	29.4400	8.2096	-5.4586	-5.3970	-10.5167	-0.0055	0.7407	117	29
Fixed-point iteration	24.5680	7.0978	29.0800	8.2096	-6.5856	-6.7300	-11.6109	-0.0045	0.7304	127	32
Approximate Lambert-W	24.5350	7.1916	29.5070	8.2093	-6.7110	-5.4980	-10.3131	-0.0083	0.7284	138	35
Lambert-W	24.5680	7.1993	29.440	8.2096	-6.5856	-6.7305	-10.5167	-0.0055	0.7215	9830	2458

** Enumeration was evaluated in an 11th Gen Intel(R) Core(TM) i9-11900K @ 3.50GHz, 3504 Mhz, 8 Core(s), 16 Logical Processor(s) CPU

points. In its Cartesian coordinate, the equation describing a given point $P(x, y)$ in Fig. 1b is given as

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1 \quad (2)$$

where n, a, and b are the fitting parameter and fixed-points of the major and minor axes, respectively.

The exponent can therefore be determined by considering the maximum power point $MPP(V_{mp}, I_{mp})$ for the I-V curve, while the fixed-points (a, b) as the (V_{oc}, I_{sc}). The new mathematical equation to be used in approximating the I-V curve is now

$$\left(\frac{V_{mp}}{V_{oc}}\right)^n + \left(\frac{I_{mp}}{I_{sc}}\right)^n = 1. \quad (3)$$

$\left(\frac{V_{mp}}{V_{oc}}\right)$ and $\left(\frac{I_{mp}}{I_{sc}}\right)$ are the voltage and current ratios that have been used in literature for the effective approximation of MPP using MPP tracking algorithms [4]. Hence, using (3), the full range of the I-V curve can be easily enumerated. To simplify (3), let's take $A = \frac{V_{mp}}{V_{oc}}$ and $B = \frac{I_{mp}}{I_{sc}}$, then the simplified equation now becomes

$$A^n + B^n = 1. \quad (4)$$

To obtain n, a simple iteration is performed after introducing an error margin (ERM) into (4) such that

$$|(A^n + B^n) - 1| \leq ERM. \quad (5)$$

3 Simulation Results

The KC200GT PV panel is the most widely used panel for evaluating the performance of the I-V curve approximation method. The proposed method and four other methods are therefore implemented using its panel specification in MATLAB R2021b.

Similar to the iteration performed in the four conventional methods, the proposed method is also dependent on its ERM as shown in (5). A higher ERM reduces the number of iterations required while downgrading its accuracy. The 4 conventional methods failed to obtain the exact MPP as specified by the manufacturer datasheet with an average percentage error of roughly -7%.

With an optimum value of $n \approx 3.6$, the proposed method generates an approximate I-V curve with a percentage error that is about one-third of the conventional methods as shown in Table 1.

Furthermore, the fill factor of the proposed method is close to the value obtained from the manufacturer datasheet as shown in Table 1. In addition, the execution time of the proposed method is relatively 32 times faster than the conventional methods as shown in Fig. 2b.

These results meet the specific requirement for high-performance SAS as discussed in Section 1. Also, the simulation results in Fig. 2 validated that the ratios in (4) and (5) can be used to eliminate the need for solving the long equations often required in conventional methods for the full-range enumeration of the I-V curve.

4 Conclusion

This paper presents a novel method for approximating the I-V curve. By obtaining the optimum value of n, the proposed method can be used for both the accurate and rapid generation of the I-V curve. In the future, this proposed method will also be used for the enumeration of the I-V curve under partial shading conditions.

5 Acknowledgments

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF – 2020R1A2C2009303).

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2022 Power Electronics Conference

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*tofopefungraduate@gmail.com **zerotics@gmail.com

Department of Electrical, Electronic and Computer Engineering, University of Ulsan, Ulsan, 44610, South Korea

1. Introduction

- A **solar array simulator (SAS)** as shown in Fig. 1 is a DC power supply that gives the **exact output characteristics** as a photovoltaic (PV) panel in real time.

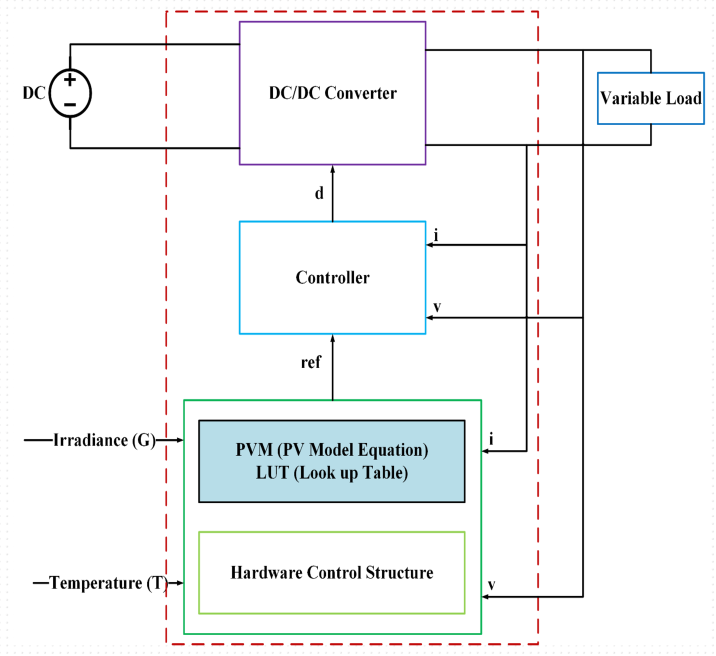

Fig. 1. A block diagram of the internal structure of a typical SAS.

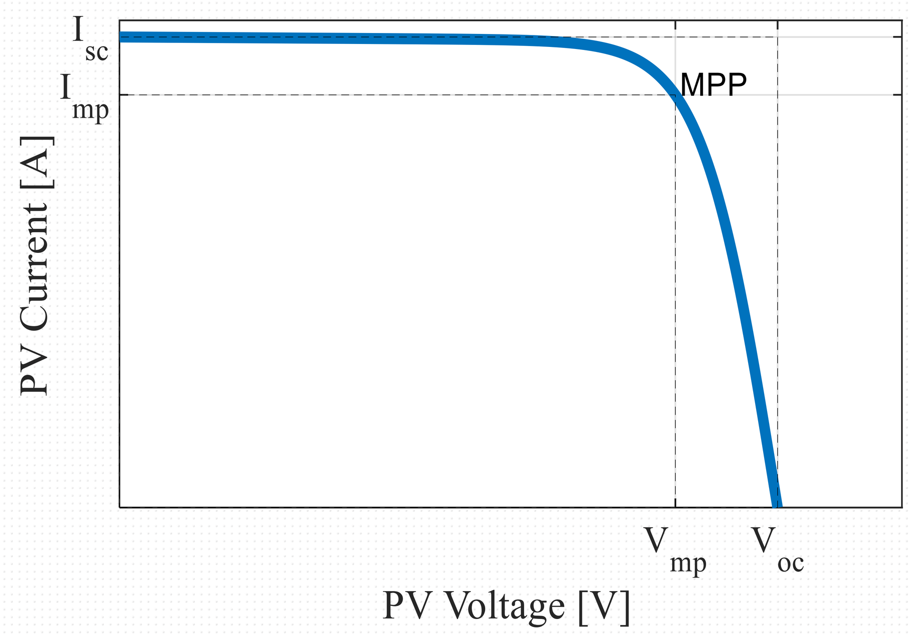

Fig. 2. A typical I-V curve with its four key points under standard test conditions as defined in any manufacturer's datasheet.

$$i_{pv} = I_{ph} - I_s\left[e^{\left(\frac{v_{pv}+i_{pv}R_s}{ANV_t}\right)} - 1\right] - \frac{v_{pv} + i_{pv}R_s}{R_{sh}} \quad (1)$$

- Due to the **exponential function** in (1), the full range enumeration of the I-V curve as shown in Fig. 2 is quite **complex**.
- The **reference generator** is usually embedded with **approximate PV model (PVM) equations** for the full implementation of SAS.
- This paper proposes a **new PVM equation** for the **fast and accurate approximation** of the I-V curve using the reference generator.

2. Motivation

- The **choice of PVM equation** affects both the **static and dynamic performance** of a SAS.
- The **long iteration or non-convergence** often associated with the conventional PVM equations **compromises the performance and execution time** of the SAS.
- To address this challenge, a PVM equation which is based on the **mathematical principle of an nth-shaped superellipse** is proposed.

3. Proposed Method

- An **nth-shaped superellipse** is an ellipse that **retains its geometric points** at both its **semi-major and semi-minor axes** respectively as shown in Fig. 3.
- Due to the unique similarities in Figs. 2 and 3, the exponent in (1) can be **parameterized** such that

$$\left(\frac{V_{mp}}{V_{oc}}\right)^n + \left(\frac{I_{mp}}{I_{sc}}\right)^n = 1. \quad (2)$$

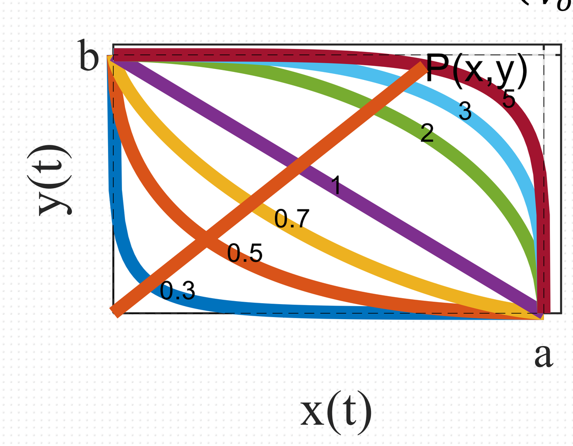

Fig. 3. A plot of an nth-shaped superellipse.

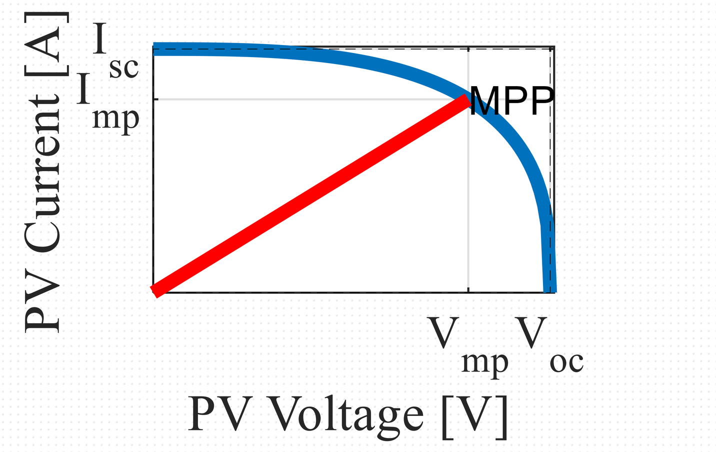

Fig. 4. A plot of an nth-shaped superellipse describin g the four key points of the I-V curve.

- The ratios $\frac{V_{mp}}{V_{oc}}$ and $\frac{I_{mp}}{I_{sc}}$ in (2) are the **voltage and current ratios** of a typical I-V curve in Fig. 2 which can be obtained directly from any **manufacturer's datasheet**.
- Taking $A = \frac{V_{mp}}{V_{oc}}$ and $B = \frac{I_{mp}}{I_{sc}}$, the simplified equation describing Fig. 4 can therefore be defined as

$$A^n + B^n = 1. \quad (3)$$

- To obtain the **optimum value for n**, a **simple iteration** is performed after introducing an **error margin (ERM)** into (3) as described in Fig. 5.

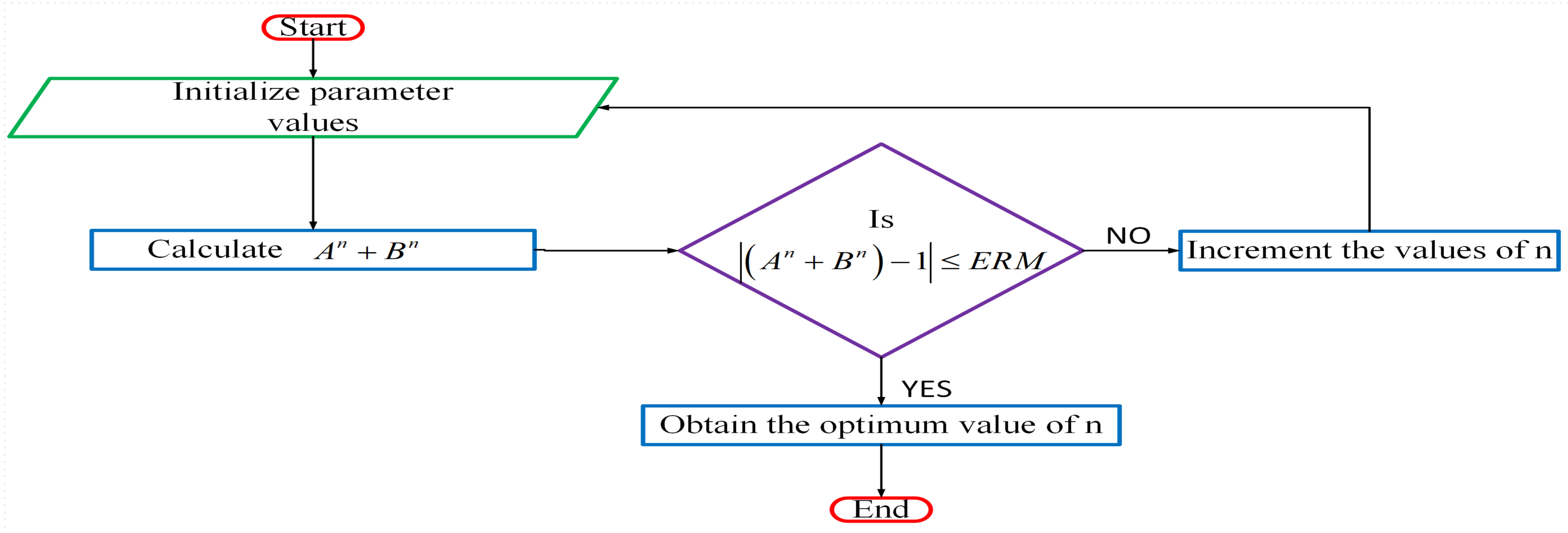

Fig. 5. A simple fixed-point iteration used for obtaining the optimum value for an nth-shaped superellipse.

4. Simulation Results

Table 1. Enumeration performance for 5 different I-V curve approximation methods using KC200GT PV panel.

Method	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	Error Vmp (%)	Error Imp (%)	Error Voc (%)	Error Isc (%)	Fill Factor (%)	Execution Time (ns)**	Relative Execution Time
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****Enumeration was evaluated in an 11th Gen Intel(R) Core(TM) i9-11900K @ 3.50GHz, 3504 Mhz, 8 Core(s), 16 Logical Processor(s) CPU**

- The four conventional methods **failed** to obtain the **maximum power point** as specified in the manufacturer's datasheet with a percentage error of about -7%.
- With an **optimum value of $n \approx 3.6$**, the proposed method generates an I-V curve with a percentage error that is roughly **one-third of the conventional method**.
- Simulation results in Fig. 6 therefore validates that the newly proposed PVM equations in (3) **eliminates the need for solving complex equation** often associated with the conventional methods.

Electrical and Physical Specifications of the KC200GT PV panel under Standard Test Conductions (STC)**

Maximum Power (P_{max})	200 W (+10% /−5%)	Number of cells per module	54
Maximum Power Voltage (V_{mpp})	**$26.3\ V$**	Weight	$18.5kg$
Maximum Power Current (I_{mpp})	**$7.61\ A$**	Length Width Depth	$1425mm \times 990mm \times 36mm$
Open Circuit Voltage (V_{oc})	**$32.9\ V$**	IP Code	$IP65$
Short Circuit Current (I_{sc})	**$8.21\ A$**	Reduction in Efficiency under Low Irradiance	7.8%
Temperature Coefficient of V_{oc}	$-1.23 \times 10^{-1}\ V/℃$	**Manufacturer**	**KYOCERA Corporation**
Temperature Coefficient of I_{sc}	$3.18 \times 10^{-3}\ A/℃$	****STC**	$1000\frac{W}{m^2}$ $AM1.5, 25℃$

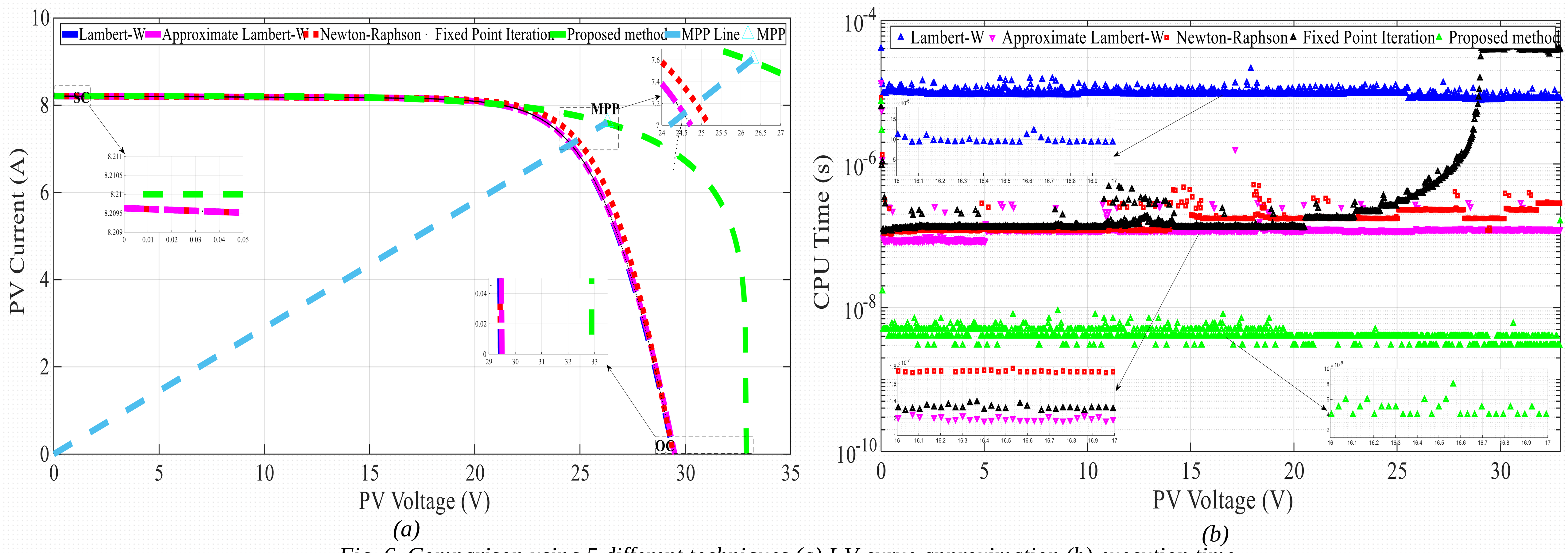

Fig. 6. Comparison using 5 different techniques (a) I-V curve approximation (b) execution time.

5. Conclusions

- A **simple and easy to use** approximate PVM equation based on the **mathematical principle of the superellipse** is proposed.
- Performance indices show that the proposed method gives an **accurate enumeration of the key points of the I-V curve** across its full range with minimal error.
- The **average CPU execution time** of the proposed method is roughly **32 times faster than the conventional methods**.

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