Received: 25 October 2020 | Revised: 24 January 2021 | Accepted: 28 February 2021

The Journal of Engineering

DOI: 10.1049/tje2.12032

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH PAPER

Simple and Fast Dynamic Photovoltaic Emulator based on a Physical Equivalent PV-cell Model

Habes A. Khawaldeh[1,2] | **Mohammad Al-soeidat**[1] | **Dylan Dah-Chuan Lu**[1] | **Li Li**[1]

[1] School of Electrical and Data Engineering, University of Technology Sydney, Sydney, Australia

[2] Department of Renewable and Sustainable Energy Engineering, Al al-Bayt University, Mafraq, Jordan

Correspondence
Habes A. Khawaldeh, School of Electrical and Data Engineering, University of Technology Sydney, Sydney, Australia.
Email: habes.a.khawaldeh@student.uts.edu.au

Funding information
al-Bayt University, Grant/Award Number: Ref.: 4/2/2/10383; Australian Research Council, Grant/Award Number: Discovery Project No. DP180100129

Abstract

Photovoltaic emulators are a specific type of power electronics system to mimic the behaviour of a photovoltaic (PV) panel or array and facilitate the testing of energy systems. Existing solutions usually require sophisticated hardware design and fast computing. This paper presents a simple, reliable, and effective circuit-based photovoltaic (PV) emulator based on the equivalent PV stacked cells. The PV emulator can be used for solar system testing and analysis, such as maximum power point tracking (MPPT) and partial shading effect. The I–V and P–V characteristic curves of the emulator have been generated by using an LTspice simulator. It is experimentally investigated and compared with a real PV panel and existing emulator products. The experiment results show good agreement with the mimicked actual PV panel. The proposed PV emulator shows a better dynamic response and shorter settling time than several benchmarked commercial products. The enhancement in the time response is due to the simplicity of the emulator, where a few power diodes and some resisters are used. In addition to simplicity, the PV emulator is very cost-effective.

1 | INTRODUCTION

Recently, owing to the increase in energy demand, environmental issues and scarcity of traditional energy sources, the world is moving towards using renewable energy sources such as wind energy and solar power. Power electronic systems are the enabling technology to interface with these sources and integrate them into the electricity grid. To facilitate the testing of these power electronic systems, energy emulators based on the power electronics system are developed. Solar photovoltaic (PV) emulators have been useful for indoor testing to provide a convenient tool to develop solar PV power systems and related products.

The PV emulator is used to produce the non-linear electrical characteristics of PV cells or panels [1, 2]. The majority of the reported PV emulators use a power supply, either a switching power converter or a linear regulator. Many studies have been done in the literature on PV source emulators, most of them are based on the switched-mode power supply (SMPS) because SMPS is more effective than a linear regulator [3, 4].

In [1], the authors used a two-switch non-inverting buck–boost DC/DC converter topology as a PV emulator to mimic the real PV behaviour. The key idea is to use multiple linear equations to perform curve fitting of the actual I–V curve. The authors in [2] proposed a boost–buck DC/DC converter with dual-loop proportional-integral (PI) current control to mimic the PV system characteristic of series and parallel combinations and under dynamic operating conditions. The authors in [5] proposed a PV emulator by using a microcontroller and switched-mode buck DC/DC converter. A feedback compensator is designed in order to improve the speed response, and system stability, also to reduce the steady-state error. The proposed controller has been experimentally verified for a 115 W solar panel (Shell S115). In [4], a DC/DC push–pull forward (PPF) converter topology is used as a PV simulator. The feedback Takagi–Sugeno fuzzy PI controller based on the MATLAB/Simulink interface is used to achieve an acceptable dynamic and steady-state performance. The DC/DC buck converter based on the two-stage LC filter is proposed in [6] to extend the control bandwidth of the PV emulator. Nevertheless, the dynamic responses of these converter-based PV emulators with better control are still significantly slower than the real PV panel. Empirical model-based emulators with the assistance of more advanced and expensive digital controllers have also been introduced in [7] and [8]. The reconfigurable simulator for checking the partial shading effect was provided in [9]. The dual-mode controller was also introduced in [2, 10], which works in both the current source and voltage source regions. However, it needs additional electronic hardware in addition to the basic converter and associated circuitry.

The authors in [11], proposed a low-cost PV emulator. It is used to test the maximum power point tracking (MPPT) for a PV system. However, it has an inaccurate P–V and I–V characteristic curves. PV emulators in the market are generally costly due to complex hardware design and implementation costs to reach high level of accuracy, mimic different environmental conditions, high power level and high efficiency [12]. Many MPPT techniques have been reported in recent years, such as fraction open-circuit voltage (FOC), hill climbing (HC), fraction short-circuit current (FSC), perturb and observe (P&O), incremental conductance (InC), feedback voltage/current, and current sweep [13–15].

Based on the previous literature review, the PV emulator is even very hard to implement and required a high-performance controller or simple structure with inaccurate performance and slow dynamic response. Therefore, a simple structure based on a physical PV-cell model is used in this study. Since the electro-thermal property of the diode is similar to the PV cell, the PV emulators based on this type of circuit achieve better performance, both in the steady state and transient state. The authors in [16] have briefly described the aforementioned method; however, it is unclear how the diode string is designed to mimic the electrical characteristics of a commercial PV panel. In addition, the dynamic response, partial shading condition, and the electro-thermal property of the circuit have not been studied.

Here, first, a PV emulator using the physical PV-cell model has been built based on the key design equations. In addition to the work presented in [16], the thermal issue related to the diode string has been investigated and solved by adding a cooling system (variable speed fan). Second, the study includes investigating the effects of the partial shading (PS) of series combinations of PV cells and compare their maximum power points (MPPs). A boost DC/DC converter loaded with a perturbing and observe (P&O) algorithm is used to evaluate the proposed PV emulator platform [15, 17]. The performance of the proposed emulator is also compared with a commercial 10 W PV panel and several commercial PV emulator products.

This work is organized as follows: The photovoltaic mathematical model and equivalent circuit design based on a one-diode photovoltaic representation are presented in Section 2. Section 3 illustrates and discusses the simulation and experimental results. Finally, Section 4 concludes the paper.

2 | PHOTOVOLTAIC MATHEMATICAL MODEL AND EQUIVALENT CIRCUIT DESIGN BASED ON A ONE-DIODE PHOTOVOLTAIC REPRESENTATION

For the sake of simplicity and acceptable accuracy, the one-diode PV model, as shown in Figure 1 [18, 19] is used in this paper. The PV model is built by using DC current source, diode, series resistance (R_s), and parallel resistance (R_p). The DC current source I_{ph} is used to represent the cell photo-current generated by the PV cell. I_{ph} is a function of both solar radiation and cell temperature. The series resistance (R_s) is used to represent the total of several structural and contact resistance of the PV model. Last, the equivalent parallel resistance (R_p) is used to present the leakage current during the p–n junction that depends on the fabrication technology of the PV cell itself.

The mathematical representation for the series-connected PV cells shown in Figure 2 shows can be derived as follows [15, 20]:

$$I_{pv} = I_{ph} - \frac{V_d}{R_{peq}} - I_d, \tag{1}$$

where V_d is the forward diode voltage (V), and I_d is the diode forward current (A).

$$\begin{aligned} I_d &= I_o \times \left[exp\left(\frac{V_d}{a \times V_t} \right) - 1 \right] \\ &= I_o \times \left[exp\left(\frac{(V_{pv} + I_{pv} \times R_{seq})}{a \times V_t} \right) - 1 \right], \end{aligned} \tag{2}$$

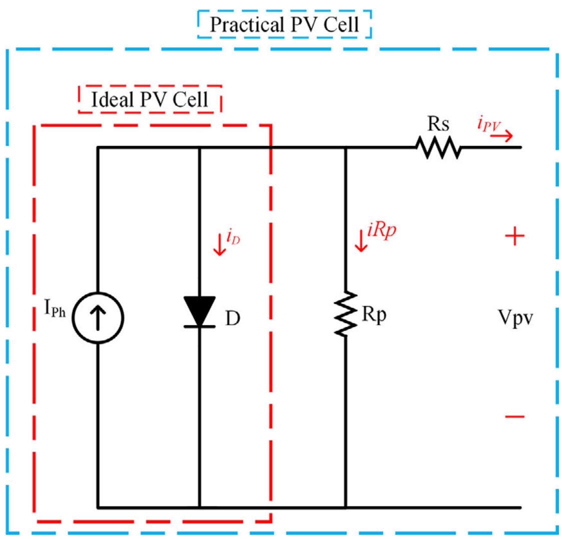

FIGURE 1 One-diode model of the theoretical PV cell and equivalent circuit of a practical PV system, including both the series and parallel resistances

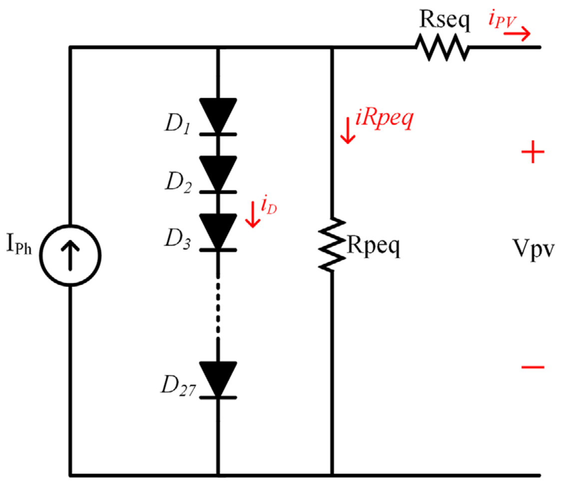

FIGURE 2 A simple PV emulator using the idea of the one-diode equivalent circuit of a PV cell with series resistance and shunt resistance. A diode string is used to create a similar effect of stacking multiple PV cells to develop a PV panel

$$I_{pv} = I_{ph} - I_o \times \left[exp\left(\frac{(V_{pv} + I_{pv} \times R_{seq})}{a \times V_t} \right) - 1 \right] - \frac{(V_{pv} + I_{pv} \times R_{seq})}{R_{peq}}, \tag{3}$$

where I_{pv} is the output current of PV (A). I_{ph} and I_o are the photovoltaic and saturation currents of the PV array, respectively. V_{pv} is the output voltage of PV (V). V_t is the thermal voltage of the PV system with several cells connected in series. R_{seq} is the equivalent series resistance (Ω), and R_{peq} is the equivalent parallel resistance (Ω). a is the diode ideality factor.

$$V_t = \frac{NKT}{q}, \tag{4}$$

where K is the Boltzmann constant, and it is equal to $1.3806503 \times 10^{-}23$ ($\frac{J}{K}$). T is the actual temperature of the p–n junction (Kelvin). q is the electron charge and it is equal to $1.60217646 \times 10^{-}19$ C. N is the number of cells connected in series to increase the output voltage of the PV panel.

Here, a p–n junction power diode, resistors, and a constant current source are used to build a simple PV panel emulator as an equivalent physical PV cell/panel model, as shown in Figure 2. I_{ph} of the PV emulator is represented by using a DC voltage source which operates at constant current mode. In order to clarify the proposed circuit clearly, Equation (1) is presented graphically in Figure 3.

In general, the manufacturers of PV panels supply limited information about electrical and thermal behaviour at the standard test conditions (STC). Usually, the photovoltaic datasheet contains details about the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), the current and voltage at MPP (I_{mpp} and V_{mpp}) [21]. This paper uses the datasheet of commercially available PV panel to work out the circuit parameters for the emulator. By using three operating points, namely, short circuit, MPP, and open circuit, we are able to develop the model with four boundary conditions [22]. However, mathematically it is not sufficient to find the values of the five parameters of the PV emulator (R_{seq}, R_{peq}, N, I_{Ph}, and diode ideality factor a) based on the four boundary conditions.

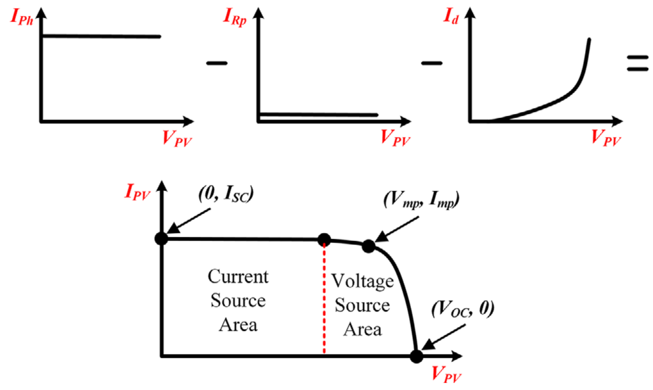

FIGURE 3 The characteristic I–V curve of the photovoltaic cell. The net cell current I_{pv} is composed of the light-generated current I_{ph}, I_{Rpeq}, and the diode current I_d

According to the semiconductor material used to fabricate diodes, the ideality factor is between 1 and 2 [22, 23]. The diode ideality factor is estimated to be 1.85, according to the diode datasheet (1n5400) and (V_{oc}–I_{sc}) curve method [24]. By using boundary conditions, the following equations can be produced [25].

By considering the value at short-circuit operation condition and substitute the value of the voltage and current $(0, I_{sc})$, Equation (3) can be express as (5).

$$I_{sc} = I_{ph} - I_o \times \left[exp\left(\frac{q \times (I_{sc} \times R_{seq})}{a \times N \times K \times T} \right) - 1 \right] - \frac{(I_{sc} \times R_{seq})}{R_{peq}}. \tag{5}$$

By substituting the voltage and current values at open-circuit condition $(V_{oc}, 0)$ in Equation (3), it can be re-written as:

$$0 = I_{ph} - I_o \times \left[exp\left(\frac{(q \times V_{oc}}{a \times N \times K \times T} \right) - 1 \right] - \frac{V_{oc}}{R_{peq}}. \tag{6}$$

By considering the value at MPP operation condition and substitute the value of the voltage and current (V_{mpp}, I_{mpp}), Equation (3) can be express as (7).

$$I_{mp} = I_{ph} - I_o \times \left[exp\left(\frac{q \times (V_{mp} + I_{mp} \times R_{seq})}{a \times N \times K \times T} \right) - 1 \right] - \frac{(V_{mp} + I_{mp} \times R_{seq})}{R_{peq}}. \tag{7}$$

The derivative of (7) with respect to V_{mp} at MPP is given by:

$$\frac{-I_{mp}}{V_{mp}} = \left(\frac{-I_o}{a \times V_t}\right) \times \left(1 - \frac{I_{mp}}{V_{mp}} \times R_{seq}\right) \times \left[exp\left(\frac{(V_{mp} + I_{mp} \times R_{seq})}{a \times V_t}\right)\right] - \frac{1}{R_{peq}} \times \left(1 - \frac{I_{mp}}{V_{mp}} \times R_{seq}\right). \tag{8}$$

Equation (8) can be simplified to find the values of the four parameters, as shown below:

$$N = \frac{(q \times V_{oc})}{\left(a \times K \times T \times ln\left(\frac{I_{sc}}{I_o} + 1\right)\right)}, \tag{9}$$

where N is the number of diodes required to build a PV emulator.

$$R_{seq} = A \times (W_{-1}(B \times exp(C)) - (D + C)), \tag{10}$$

where:

$$A = \frac{a \times V_t}{I_{mp}}, \tag{11}$$

$$B = -\frac{V_{mp} \times (2 \times I_{mp} - I_{sc})}{(V_{mp} \times I_{sc} + V_{oc} \times (I_{mp} - I_{sc}))}, \tag{12}$$

$$C = \frac{-(2 \times V_{mp} - V_{oc})}{a \times V_t} + \frac{(V_{mp} \times I_{sc} - V_{oc} \times I_{mp})}{(V_{mp} \times I_{sc} + V_{oc} \times (I_{mp} - I_{sc}))}, \tag{13}$$

$$D = \frac{(V_{mp} - V_{oc})}{a \times V_t}, \tag{14}$$

and W_{-1} is the negative branch of the lambert W function.

$$R_{peq} = \frac{(V_{mp} - I_{mp}R_{seq})(V_{mp} - R_{seq}(I_{sc} - I_{mp}) - aV_t)}{((V_{mp} - I_{mp} \times R_{seq}) \times (I_{sc} - I_{mp}) - aV_t I_{mp})}, \tag{15}$$

$$I_{ph} = \frac{(R_{peq} + R_{seq})}{R_{peq}} \times I_{sc}. \tag{16}$$

TABLE 1 PV emulator parameters calculated by MATLAB

Parameter name	MATLAB simulation value
R_{seq}	1.870488 (Ω)
R_{peq}	362.1797 (Ω)
N	27
I_{ph}	0.6533569 (A)

TABLE 2 Product information of the selected PV panel

POWERTECH	
Model	**ZM9054**
Maximum power (P_{max})	10 W(±5%)
Open-circuit Voltage (V_{oc})	21.5 V
Short-circuit Current (I_{sc})	0.65 A
Rated voltage (V_{mp})	17.5 V
Rated current (I_{mp})	0.57 A
Maximum system voltage	1000 V
Test condition	AM 1.5, 1000 W/m^2, 25°C

3 | SIMULATION AND EXPERIMENTAL RESULTS

3.1 | Experimental circuit setup

In this study, the Powertech PV panel (ZM9054) is selected as the reference PV panel to be mimicked. The PV emulator consists of a DC voltage source (operating at constant current mode), a diode string, and two of the electrical resistance, as shown in Figure 2. The PV emulator components, such as R_s, R_p, N, and I_{ph}, are selected based on MATLAB calculation of the mentioned mathematical equation of the real PV panel. The design component values are shown in Table 1. Equations (9), (10), (15), and (16) are used to calculate parameters required to build the emulator circuit. A selected power diode (1n5400), with reverse saturation current (5×10^{-6}), is used with I_{sc}, V_{oc}, I_{mp}, and V_{mp} values from the commercial datasheet, as shown in Table 2.

The number of power diodes (N) needed to mimic the real PV panel is different from one PV panel to another, and it can be calculated by using (9). The number of diodes for the proposed PV emulator is found below by considering the maximum operating temperature of the selected diode, which is equal to 150°C based on its datasheet.

$$N = \frac{((1.60217646 \times 10^{-19}) \times (21.5))}{((1.85) \times (1.3806503 \times 10{-}23) \times (273 + 150) \times ln(\frac{0.65}{(5 \times 10^{-6})} + 1))}$$

$N = 27$, where T equals 273 + 150.

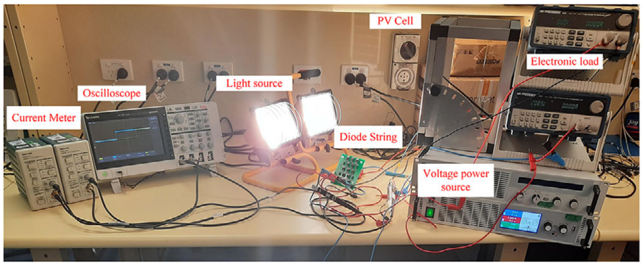

FIGURE 4 Experimental PV emulator in the lab

The PV emulator circuit has been built and tested, as shown in Figure 4. There are 27 power diodes, and a DC voltage source (constant current mode) has been adjusted based on the open-circuit voltage and short-circuit current of the mimicked PV panel, the voltage and current of the DC voltage source (constant current mode). A programmable DC load (model: B&K Precision 8500, 300 W) is used to vary the output resistor to generate the I–V and P–V characteristics curves.

3.2 | Steady-state response

The experiment results agree with the simulation results, as shown in Figure 5. Figure 5a shows the experimental I–V curve of the commercial programmable PV emulator device (PPVE, model: EA-PSI 9360-15 2U), PVE LTspice simulation, proposed PV emulator (based on diode string), and real PV panel (Powertech-ZM9054). Whereas Figure 5b shows the P–V curve for the same setup. It is clear from the real PV panel curve that the I_{sc} equals 0.65 A and the open-circuit voltage equals 21.5 V at 990 W/m^2, and 26°C. To simulate the same electrical characteristic, the DC power supply (constant current mode) is limited to 0.65 A and the voltage is set at 21.5 V. The actual PV panel voltage and current are measured again at different irradiation levels (760 W/m^2 at 27°C). The short-circuit current drops to 0.513 A, and the open-circuit voltage reduces to 20.4 V. The voltage and current values are used as input for the PV emulator. The I–V and P–V curves for the used commercial programmable PV emulator, PVE LTspice simulation, proposed PV emulator, and real PV panel are plotted in Figure 6. The proposed PV emulator shows high performance, where the output voltage and current match the one generated from the real PV panel and commercial programmable PV emulator device.

3.3 | Thermal behaviour based on cooling system

In order to evaluate the impact of using a variable speed cooling system (12 VDC 0.24 A 3 pin cooling fan PVA092G12M), the different speed scenarios starting from 0 up to full speed have been used. The fan speed is controlled by using a simple switching circuit and variable duty cycle.

Figure the thermal behaviour and the issues associated with using a single diode model to mimic the PV panel. The x-axis

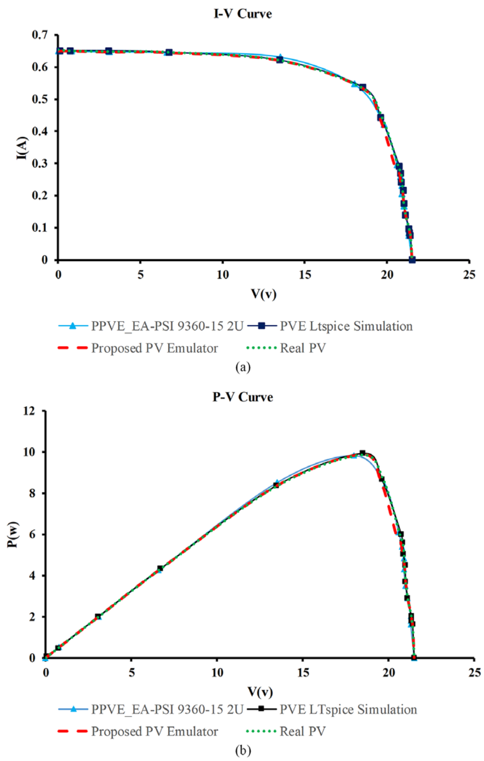

FIGURE 5 Experimental and simulation results at I_{pv} = 0.650 A, and V_{oc} = 21.5 V: (a) I–V and (b) P–V characteristic curves

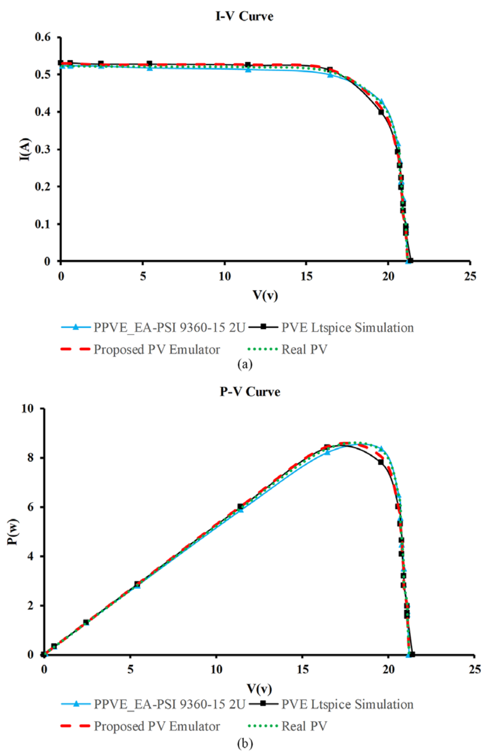

FIGURE 6 Experimental and simulation results at I_{pv} = 0.513 A, and V_{oc} = 20.4 V: (a) I–V and (b) P–V characteristic curves

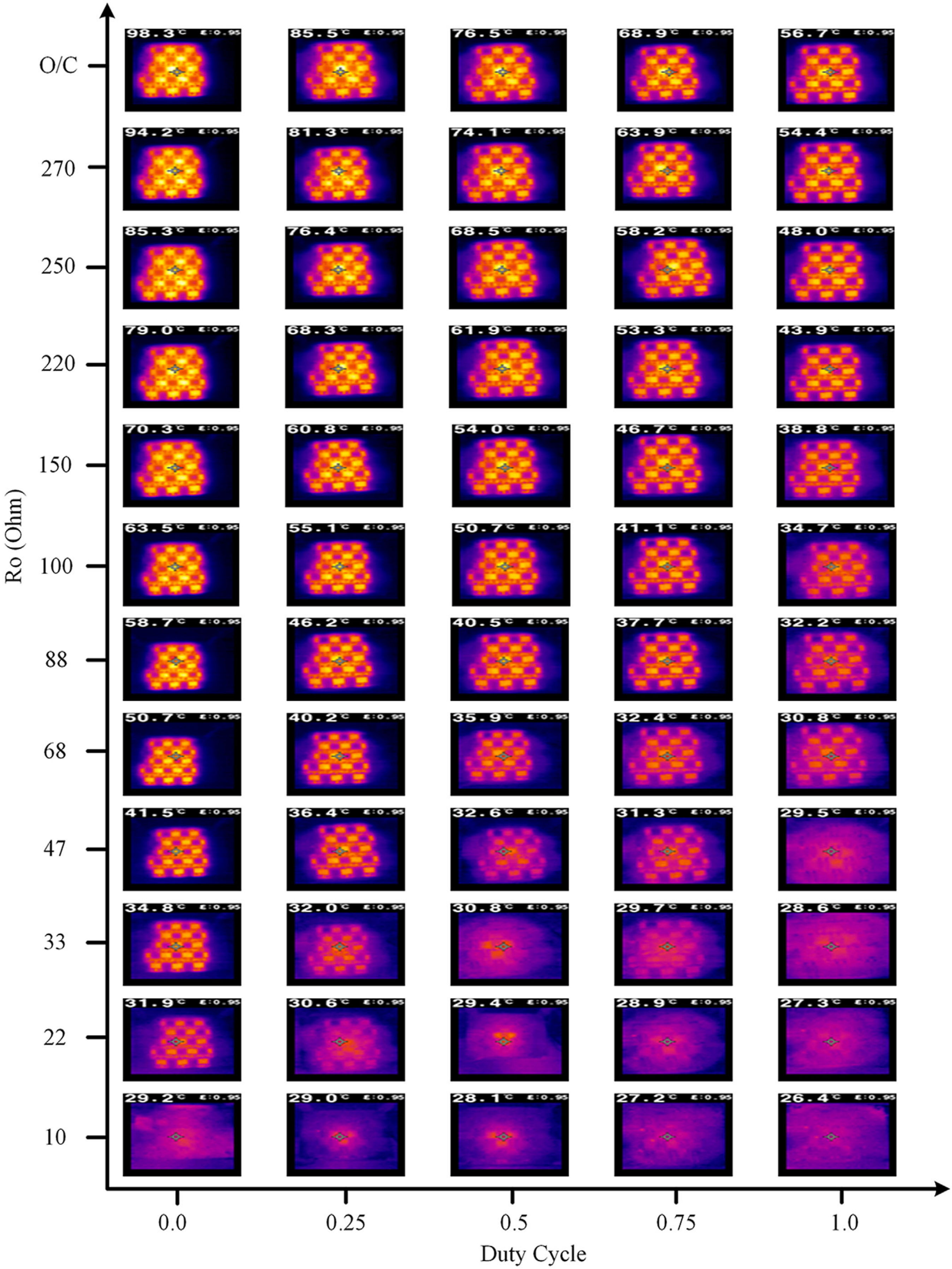

FIGURE 7 Thermal behaviour of diode string at different operating conditions

presents the duty cycle that controls the speed of the fan, where the y-axis shows the output resistive load connected with the PV emulator. In Figure 7, when moving from the left- to right-hand side, the speed of the fan is increasing by increasing the duty cycle. When moving from bottom to top, the resistive load is increasing up to the point that the emulator reaches open-circuit operating condition. A thermal imaging camera (FLIR TG 167) is used to capture the temperature change once the current increases.

It is notable from the figure that the diode string temperature increases from 29.2 to 98.3°C, without any cooling system (first column on the left). After that, the cooling system (fan) used at duty cycle $D = 0.25$, the diode string temperature increases from 29 to 85.5°C. At D= 0.5, the diode string temperature increases from 28.1 to 76.5°C. At $D = 0.75$, the diode string temperature increases from 27.2 to 68.9°C, and finally, at $D = 1.0$, the diode string temperature increases from 26.4 to 56.7°C. The cooling system is used to keep the diode string temperature at an acceptable value to minimize the high-temperature effects on the PV emulator characteristics.

3.4 | Partial shading response

The series connection of the two groups of diode string by using a bypass diode to mimic the electric characteristic of the PV cell under PS condition is shown in Figure 8. Each diode string has its own current source (irradiation level), and the two current sources have different values. The first current source value is based on the current of the real PV panel under a certain irradiation level, where the other current source is based on the value of the generated current of the actual PV panel after partial shading.

Figures 9 and 10 show a comparison between the I–V and P–V characteristic curves based on experiment and simulation results for the real PV panel, proposed PV emulator, and

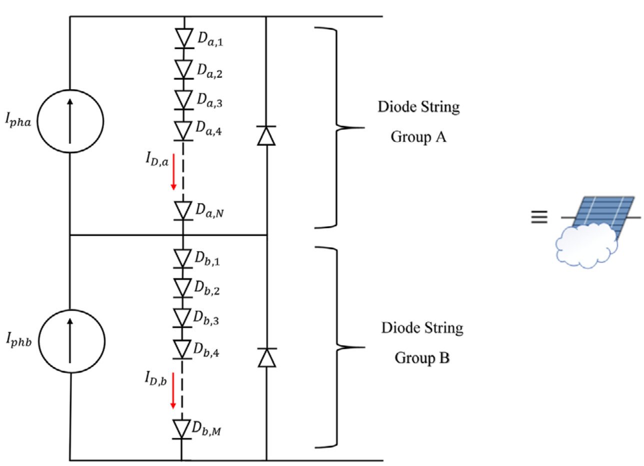

FIGURE 8 The series connection of the two groups of diode string with different irradiation (various current) in order to mimic PV cell behaviour under PS and PVE cell under PS condition by using bypass diodes where $I_{D,a} \neq I_{D,b}$

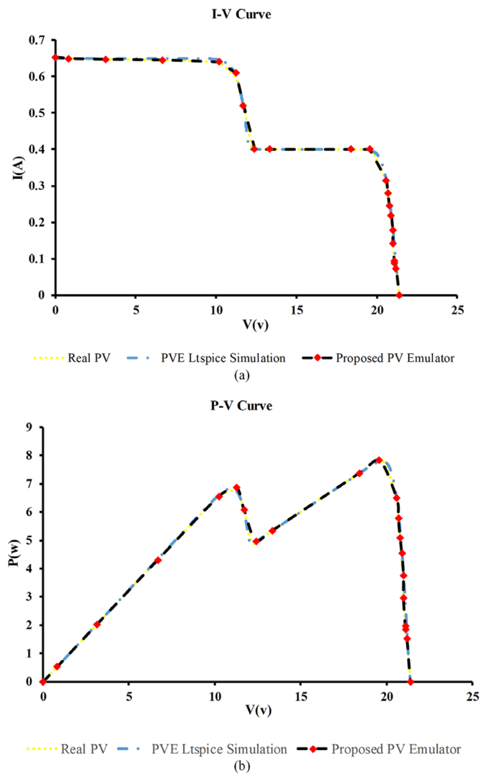

FIGURE 9 Experimental and simulation characteristic curve under PS effect: (a) I–V curve, and (b) P–V curve. Scenario 1

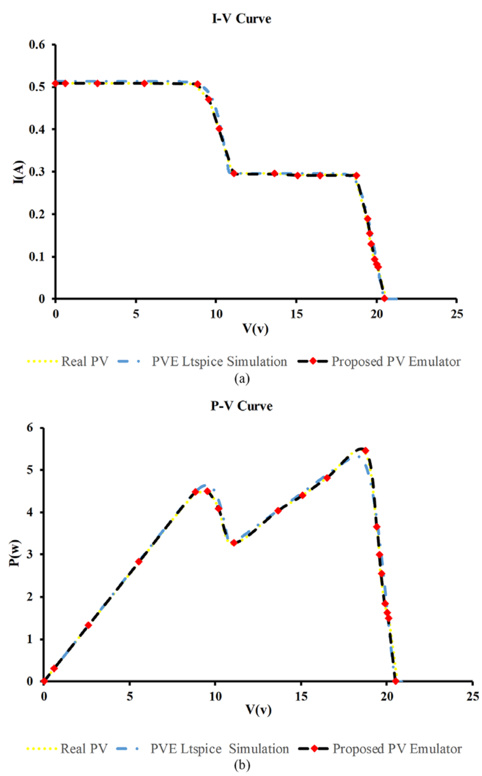

FIGURE 10 Experimental and simulation characteristic curve under PS effect: (a) I–V curve, and (b) P–V curve. Scenario 2

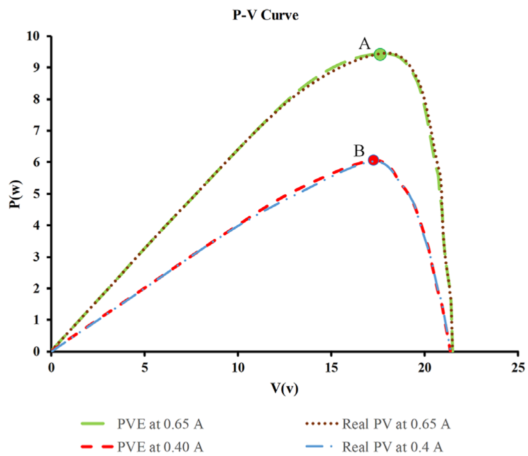

FIGURE 11 MPPT points based on a boost DC/DC converter

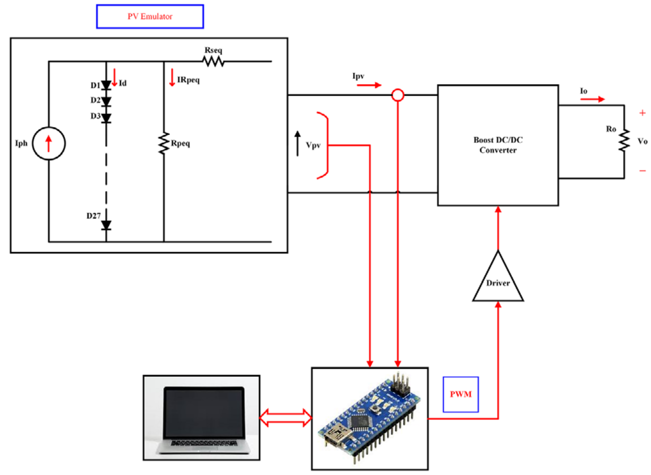

FIGURE 12 MPPT experiment setup

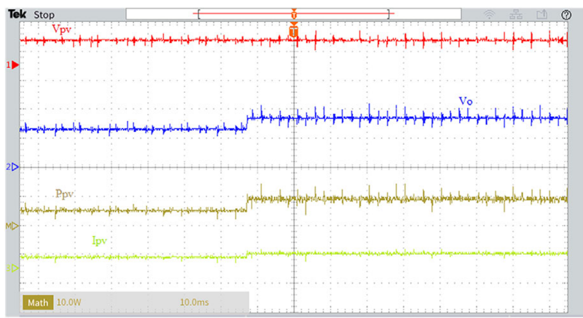

FIGURE 13 The dynamic response of the output power. Time base: 10 ms. I_{PV}: 1 A/div. V_{PV} and V_o: 20 V/div. P_{PV}: 10 W/div

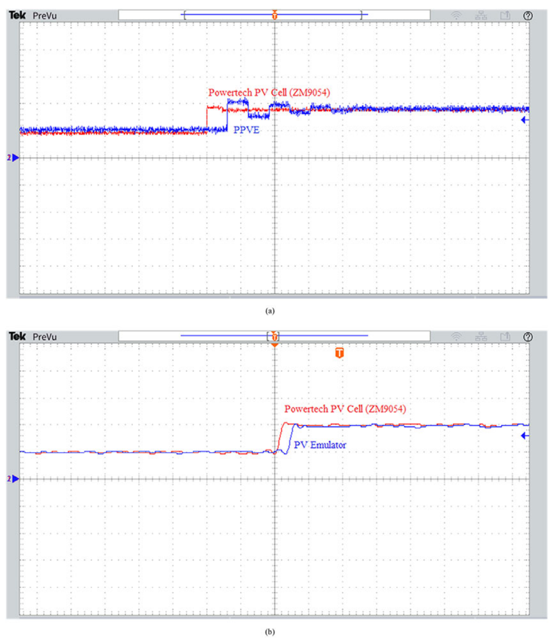

FIGURE 14 The dynamic PV characteristic when I_{pv} converted from 0.185 to 0.385 A based on load variation: (a) Real PV compared with programmable PV emulator device (PPVE, model: EA-PSI 9360-15 2U). (b) Real PV compared with PV emulator based on diode string. Time base (a): 200 ms. Time base (b): 10 ms. I_{pv}: 200 mA/div

LTspice simulation under PS effect, respectively. It is clear from Figure 9 that the real PV panel will have two MPPs under partial shading conditions, that is, local value (6.7380 W) and global value (7.8721 W). Another shading scenario (irradiation level 760 W/m^2 at 27°C) is shown in Figure 10. It is clear from the two figures that the proposed PV emulator mimics the real PV panel perfectly even under partial shading effect.

3.5 | MPPT test using a boost DC/DC converter

In this section, another experimental work has been conducted to test and validate the proposed PV emulator during the dynamic MPPT test. Figure 11 shows the P–V curves for the proposed PV emulator and the real PV panel under two different irradiation levels, where the performance of the proposed emulator and real PV panel are identical. It is clear from the figure that the PV emulator will have two MPPs (points A and B). The voltage and current at the first MPP (point A) equal 17.6 V and 0.55 A, respectively. Whereas the voltage and current at the second MPP (point B) equal 17.3 V and 0.36 A, respectively.

A boost DC/DC converter with a P&O algorithm is used to test the proposed PV emulator. The experimental setup is shown in Figure 12. Figure 13 shows the performance of the proposed PV emulator during MPPT test. The top waveform presents the output voltage of the PVE side, followed by the output voltage of the boost converter side, followed by the output power, then the current of the PVE side. It is clear from the figure that the performance of the proposed PV emulator is not effected by the used MPPT system. On the other hand, the tracking system is able to track the MPPs, where the tracked current and voltage match with the one in Figure 11 at the same irradiation levels.

3.6 | Dynamic characteristics

In Figure 14, the comparison of the dynamic behaviour between Powertech PV panel (ZM9054), PV emulator based on diode

TABLE 3 Dynamic response comparison for an existing platform with the proposed PV emulator

No.	Author\s (Ref.)	Converter used	Structural and control complexity	Dynamic response (ms)
1	Cirrincione et al. [26]	Buck	Complex	160
2	EA-PSI 9360-15 2U [27]	SMPSU	Complex	120
3	Ayop and Tan [28]	Buck	Complex	21.25
4	Remache et al. [29]	Boost	Complex	18
5	Koran et al. [6]	Buck	Complex	3.8
6	Proposed PV emulator	Diode string	Simple	3

string, and programmable PV emulator device (PPVE, model: EA-PSI 9360-15 2U) is shown. The programmable electronic load is used to change the load resistance where the current changes from 0.185 to 0.385 A. According to Figure 14b, the PV emulator dynamic response lags around 3 ms with respect to the real Powertech PV panel (ZM9054). In addition, the programmable PV emulator (PPVE, model: EA-PSI 9360-15 2U) lags around 120 ms with respect to the real Powertech PV panel (ZM9054), as shown in Figure 14a. The PV emulator based on the diode string is simple, but it is very effective, and it has fast dynamic behaviour compare to both real PV panel and commercial PV emulator. The dynamic response of the proposed PV emulator also compared with some of the existing PV emulator platforms, as shown in Table 3. The proposed emulator shows the best response time compare with the existing solutions.

4 | CONCLUSION

This paper presents a simple and cost-effective method to develop a PV emulator that can mimic a real PV panel by using a few power diodes and some resistors. The main problem of this design is the increase of diode string temperature, specifically at the open-circuit condition (i.e. maximum power dissipation), where the diode string temperature increases from 29.2 to 98.3°C without any cooling system. This problem has been solved by adding a variable speed fan.

The electro-thermal performances of series-connected PV cells have been studied. LTspice simulation program is used to build the electrical model of the solar panel. In addition to simulation work, a thermal camera is used to investigate and capture the effect of temperature on the diode string. The proposed PV emulator shows high performance, where the generated power was identical with a real PV panel and a commercial PV emulator. Furthermore, the dynamic response of the proposed PV emulator shows improvement by 117 *ms* compared to the commercial PV emulator device. To sum up, the proposed emulator has been tested by using one of the well-known MPPT methods (P&O), where the result was closed to the result when the real PV panel is used.

ORCID

Habes A. Khawaldeh https://orcid.org/0000-0002-8340-9076

REFERENCES

1. Lu, D.D., Nguyen, Q.N.: A photovoltaic panel emulator using a buck-boost dc/dc converter and a low cost micro-controller. Sol. Energy 86(5), 1477–1484 (2012)
2. Zhang, W., Kimball, J.W.: Dc–dc converter based photovoltaic simulator with a double current mode controller. IEEE Trans. Power Syst. 33(7), 5860–5868 (2017)
3. Alaoui, M., et al.: Photovoltaic emulator of different solar array configurations under partial shading conditions using damping injection controller. Int. J. Power Electron. Drive Systems 11(2), 1019 (2020)
4. Zhang, J., et al.: Design and realization of a digital PV simulator with a push-pull forward circuit. J. Power Electron. 14(3), 444–457 (2014)
5. Vijayakumari, A., Devarajan, A., Devarajan, N.: Design and development of a model-based hardware simulator for photovoltaic array. Int. J. Electr. Power Energy Syst. 43(1), 40–46 (2012)
6. Koran, A., et al.: Design of a photovoltaic simulator with a novel reference signal generator and two-stage LC output filter. IEEE Trans. Power Syst. 25(5), 1331–1338 (2009)
7. Balato, M., et al.: Design and implementation of a dynamic FPAA based photovoltaic emulator. Sol. Energy 123, 102–115 (2016)
8. Azharuddin, M., et al.: A nearly accurate solar photovoltaic emulator using a dSPACE controller for real-time control. Electr. Power Compon. Syst. 44(7), 774–782 (2016)
9. Mai, T.D., et al.: Reconfigurable emulator for photovoltaic modules under static partial shading conditions. Sol. Energy 141, 256–265 (2017)
10. Kim, Y., et al.: Dual-mode power regulator for photovoltaic module emulation. Appl. Energy 101, 730–739 (2013)
11. Mukerjee, A., Dasgupta, N.: DC power supply used as photovoltaic simulator for testing MPPT algorithms. Renew. Energy 32(4), 587–592 (2007)
12. Ram, J.P., et al.: Analysis on solar pv emulators: A review. Renewable Sustainable Energy Rev. 81, 149–160 (2018)
13. Al.Soeidat, M., Lu, D.D.C., Zhu, J.: An analog BJT-tuned maximum power point tracking technique for PV systems. IEEE Trans. Circuits Systems II: Express Briefs 66(4), 637–641 (2018)
14. Priyadarshi, N., et al.: An extensive practical investigation of FPSO-based MPPT for grid integrated PV system under variable operating conditions with anti-islanding protection. IEEE Syst. J. 13(2), 1861–1871 (2018)
15. Priyadarshi, N., et al.: An experimental estimation of hybrid ANFIS-PSO-based MPPT for PV grid integration under fluctuating sun irradiance. IEEE Syst. J. 14(1), 1218–1229 (2019)
16. Ünlü, M., Çamur, S.: A simple photovoltaic simulator based on a one-diode equivalent circuit model. In: 2017 4th International Conference on Electrical and Electronic Engineering (ICEEE), pp. 33–36.IEEE (2017)
17. Padmanaban, S., et al.: A novel modified sine-cosine optimized MPPT algorithm for grid integrated PV system under real operating conditions. IEEE Access 7, 10467–10477 (2019)
18. Khawaldeh, H.A., et al.: Performance investigation of a PV emulator using current source and diode string. In: 2018 26th International Conference on Systems Engineering (ICSEng), pp. 1–5 (2018)
19. Priyadarshi, N., Sharma, A.K., Azam, F.: A hybrid firefly-asymmetrical fuzzy logic controller based MPPT for PV-wind-fuel grid integration. Int. J. Renew. Energy Res. (IJRER) 7(4), 1546–1560 (2017)
20. Priyadarshi, N., et al.: Fuzzy SVPWM-based inverter control realisation of grid integrated photovoltaic-wind system with fuzzy particle swarm optimisation maximum power point tracking algorithm for a grid-connected pv/wind power generation system: Hardware implementation. IET Electr. Power App. 12(7), 962–971 (2018)
21. Villalva, M.G., Gazoli, J.R., Ruppert-Filho, E.: Modeling and circuit-based simulation of photovoltaic arrays. In: 2009 Brazilian Power Electronics Conference, pp. 1244–1254.IEEE (2009)
22. Laudani, A., Fulginei, F.R., Salvini, A.: High performing extraction procedure for the one-diode model of a photovoltaic panel from

experimental I–V curves by using reduced forms. Sol. Energy 103, 316–326 (2014)

23. Villalva, M.G., Gazoli, J.R., Ruppert-Filho, E.: Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Syst. 24(5), 1198–1208 (2009)
24. Carrero, C., Amador, J., Arnaltes, S.: A single procedure for helping PV designers to select silicon PV modules and evaluate the loss resistances. Renew. Energy 32(15), 2579–2589 (2007)
25. Cubas, J., Pindado, S., Victoria, M.: On the analytical approach for modeling photovoltaic systems behavior. J. Power Sources 247, 467–474 (2014)
26. Cirrincione, M., et al.: Real-time simulation of photovoltaic arrays by growing neural gas controlled dc-dc converter. In: 2008 IEEE Power Electronics Specialists Conference, pp. 2004–2010.IEEE (2008)
27. EA.Elektro.AutomatikGmbH. 'Ea-psi 9360-15 2u'. may, 2015. shorturl.at/hlCMN
28. Ayop, R., Tan, C.W.: Rapid prototyping of photovoltaic emulator using buck converter based on fast convergence resistance feedback method. IEEE Trans. Power Syst. 34(9), 8715–8723 (2019)
29. Remache, S.E.I., Cherif, A.Y., Barra, K.: Optimal cascaded predictive control for photovoltaic systems: Application based on predictive emulator. IET Renew. Power Gener. 13(15), 2740–2751 (2019)

How to cite this article: Khawaldeh HA, Al-soeidat M, Lu DD-C, Li L. Simple and fast dynamic photovoltaic emulator based on a physical equivalent PV-cell model. J. Eng. 2021;2021:276–285. https://doi.org/10.1049/tje2.12032