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A novel approximate explicit double-diode model of solar cells for use in simulation studies

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ABSTRACT

In this paper a novel explicit model is proposed to represent I-V expression of conventional double-diode model for photovoltaic (PV) cells. This model is based on two rules in electronics: first, Thevenin's theorem to describe the linear components of equivalent circuit of PV cells, and second piecewise linear (PWL) model to approximate the behavior of remained nonlinear part. Defining a new parameter (a), an approximate explicit solution for I-V curve of PV model is extracted which surpasses conventional implicit model due to its high computational efficiency particularly in repetitive simulation of PV fields. Dispensing any need to change the concept and consequently the values of conventional double-diode parameters, only single new translation equation is developed for the parameter (a) in wide environmental conditions, which reduces the model complexity in comparison with other reported double-diode explicit solutions. The suitability of the proposed model would be thoroughly accredited by circuit analysis, experimental data and extensive simulation studies.

1. Introduction

Modeling of PV cells is inevitable for engineers in order to debug repeatedly the design and configuration of PV arrays within PV power plants in order to acquire the optimal operation. In fact, fast and accurate models empower the designers to conveniently simulate PV fields to predict the expected power under vast illumination and temperature degrees and also mismatch conditions like partial shading [1–3].

There are two widely used models for solar cells: the single-diode model and the double-diode model; both of which may be accompanied with series and parallel resistances corresponding to the power dissipation of the parasitic resistive non-idealities [4,5]. Fundamentally, these two models are implicit and nonlinear, which means they require numerical iterative methods for simulation studies, such as the Gaussian, Newton–Raphson or particle swarm optimization methods [6–9]. In practice, these iterative methods are often undesirable since they need initial values and probably fail to converge even with good initial guess values. As well, numerical iterations impose large volumes of computational load that destroys the calculation efficiency especially when the model is to be used repeatedly. Hence, if available, equivalent explicit models are the appropriate solution because of their easier and faster computation and also lack of need for initial values. Moreover, explicit models benefit from direct derivations to analytically obtain and track the maximum power point [10,11]. Also the existence of the explicit equations is favorable among researchers for their convenience in parameter extraction of solar cell [12–15].

Generally, there are two approaches to convert implicit models to explicit ones: exact and approximate approaches. Both are entirely investigated in multiple reports for single-diode models [16]. The exact explicit methods usually employ Lambert W-function to extract pure current or voltage terms encountering mathematical expressions like $W(x)\exp[W(x)]$ [17–21]. Alternatively, approximate explicit methods consider simple model such as cubic polynomias for a particular solar cell and estimate the model regulating parameters using curve fitting algorithms [22–25]. Moreover, there are lots of mathematical tools such as Taylor's series expansion, rational function, Pade approximation, Chebyshev polynomial and power law function to transform the inherently implicit single-diode model to explicit expression [26–30]. While these approximations have lost model accuracy to some extent,

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they do provide much simpler expressions and faster computation process.

Although some reports state that single-diode model exceeds double-diode one considering both of the antagonistic factors, accuracy and simplicity [31,32], it might fail to represent several conduction phenomena that significantly contribute to the total current of the cell p-n junction especially at low irradiance [33]. Despite numerous reports in literature which exactly and approximately introduce explicit expressions for single-diode models, explicit solutions for double-diode models have not been exactly investigated except for two exclusive cases: firstly, the case of double-diode model without parallel resistance in which the ideality factor of one of the diodes is twice of another; no explicit expression is found for cell current but terminal voltage is obtained explicitly without any need for Lambert W-function [34]. Secondly, the case of double-diode model with both series and parallel resistances in which the ideality factors of both diodes are equal, although this substantial constraint is not clearly mentioned in the source paper of [35].

In this paper, a novel approximate explicit model is presented for PV cell models consisting of two main types of exponential current transport mechanisms along with both series and parallel parasitic resistive losses. In Section 2, Thevenin's theorem is used for the linear elements of PV model circuit, and Thevenin equivalent resistance and voltage are computed. Then defining a regulating parameter (a) and using Lambert W-function, the methodology to obtain the explicit expression for I-V curve of PV model is explained. In Section 3, considering piecewise linear model of diodes, the capability of the regulating parameter (a) to convert conventional implicit model to approximate explicit one is proved by circuit analysis. In Section 4, the proposed model is verified with real data of a polycrystalline PV cell and a monocrystalline PV module at standard test condition (STC). Using synthetic data generated by a conventional model of a polycrystalline PV cell, an extensive simulation study is done in Section 5 for the proposed model assessment in wide range of temperature and irradiation, and eventually, a novel translation equation is developed in Section 6. The paper comes to a conclusion in Section 7.

2. Proposed model

The double-diode equivalent circuit of solar cells is represented in Fig. 1. Additional to two diodes reflecting the physical behavior of the p-n junction, this circuit consists of an ideal current source I_{ph} as photoelectric phenomena, series resistance R_s to replicate current circulation throughout the cell and parallel resistance R_p as current leakage of the p-n junction [4]. Also I is the current flowing through the PV cell, V is the terminal voltage, I_{s1} and I_{s2} are the dark saturation currents of two diodes, V_T is the thermal voltage and eventually, n_1 and n_2 are the ideality factors corresponding to first and second diodes that choose the values between 1 and 2 in silicon based PV cells. The output current of this model is described as:

$$I = I_{ph} - G_p V_D - I_D \tag{1}$$

where G_p is parallel parasitic conductance used instead of $1/R_p$ for mathematical convenience. Also I_D is the total current of two diodes and V_D is the voltage across them. To express (1) explicitly in terms of PV cell parameters, the separation of linear and nonlinear components for PV cell model is demonstrated in Fig. 1. Then employing Thevenin's theorem, the equivalent circuit containing the nonlinear part and Thevenin equivalent of linear part can be represented as Fig. 2. This idea allows to deliberately make the five parameters of I, V, I_{ph}, R_s and R_p of linear part concise in two Thevenin equivalent parameters of V_{Th} and R_{Th}. These two parameters are described as:

$$R_{Th} = \frac{R_s}{1 + G_p R_s} \tag{2}$$

$$V_{Th} = \left(\frac{V}{R_s} + I_{ph}\right) R_{Th} \tag{3}$$

As [36] presented, if particular factors of R_{Th} are substituted at each branch in series with each diode, I_D can be approximately evaluated in explicit form. This hypothesis will be clarified with a circuit analysis in Section 3. In this paper, the factor (a) of R_{Th} and identical R_{Th} are considered respectively for first and second diode as shown in Fig. 3. The Shockley diode equation for first diode can then be described as:

$$I'_{D1} + I_{s1} = I_{s1} e^{\frac{V_{Th} - I'_{D1} a R_{Th}}{n_1 V_T}} \tag{4}$$

Multiplying the both sides of (4) by $\frac{aR_{Th}}{n_1 V_T} e^{\frac{aR_{Th}(I'_{D1}+I_{s1})}{n_1 V_T}}$, it can be rewritten as:

$$\frac{aR_{Th}(I'_{D1}+I_{s1})}{n_1 V_T} e^{\frac{aR_{Th}(I'_{D1}+I_{s1})}{n_1 V_T}} = \frac{I_{s1} a R_{Th}}{n_1 V_T} e^{\frac{V_{Th}+I_{s1} a R_{Th}}{n_1 V_T}} \tag{5}$$

On the other hand, it is well known that the Lambert W function of the variable x is the inverse function of [37]:

$$f(x) = xe^x \tag{6}$$

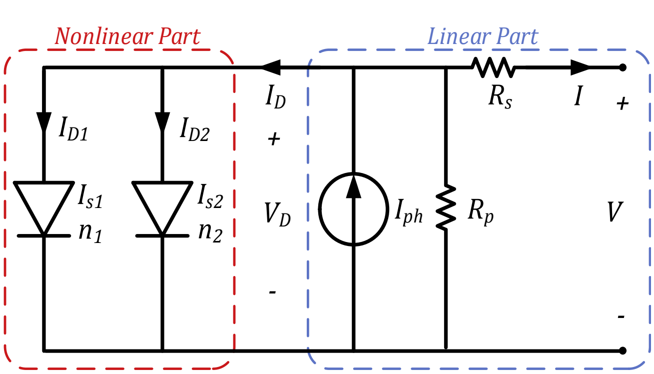

Fig. 1. Equivalent circuit for PV cell including two diodes, photo-generated current source, and also series and parallel resistive losses; Linear and nonlinear elements are distinctly obvious.

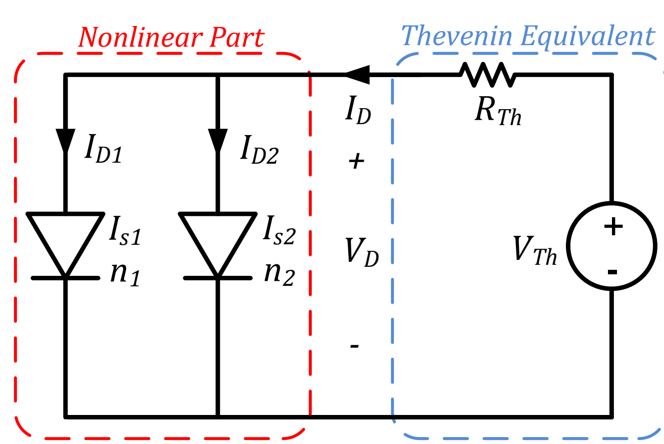

Fig. 2. Nonlinear part and Thevenin equivalent of the linear part of double-diode model for PV cell with the series and parallel resistive losses.

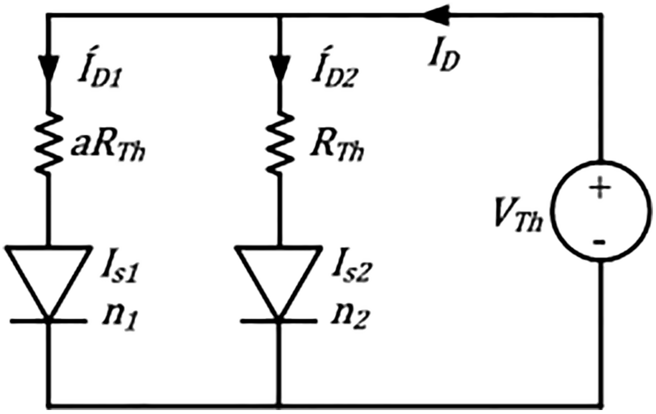

Fig. 3. Individual resistances are substituted for Thevenin equivalent resistance.

Hence using (6), the current passing through first diode is extracted from (5) as:

$$I'_{D1} = \frac{n_1 V_T}{aR_{Th}} Lambert\ \ w\left(\frac{I_{s1} aR_{Th}}{n_1 V_T} e^{\frac{V_{Th}+I_{s1} aR_{Th}}{n_1 V_T}}\right) - I_{s1} \tag{7}$$

Subsequently, the similar process of equation (4) up to (7) can be separately repeated for second diode which yields the current through the second branch:

$$I'_{D2} = \frac{n_2 V_T}{R_{Th}} Lambert\ \ w\left(\frac{I_{s2} R_{Th}}{n_2 V_T} e^{\frac{V_{Th}+I_{s2} R_{Th}}{n_2 V_T}}\right) - I_{s2} \tag{8}$$

As Fig. 3 shows, I_D is the summation of the both solutions of (7) and (8):

$$I_D = I'_{D1} + I'_{D2} \tag{9}$$

Moreover, the voltage across diodes can be expressed by (10) based on the equivalent circuit of Fig. 2:

$$V_D = V_{Th} - I_D R_{Th} \tag{10}$$

So if we substitute (9) in (10) and subsequently (10) in (1), equation (11) will be concluded for describing the I-V characteristic curve of the PV cell. Mathematically this equation is in an explicit form of $I = f(V)$ that is suitable for analytic computation in PV cells research and applications. In next sections, qualification of the model is examined with theoretical analysis, real data and also simulation studies.

$$I = \frac{I_{ph} + I_{s1} + I_{s2} - G_p V}{1 + R_s G_p} - \frac{n_1 V_T}{aR_s} Lambert\ w\left[\frac{I_{s1} aR_s}{n_1 V_T (1 + R_s G_p)} exp\left(\frac{V + I_{ph} R_s + I_{s1} aR_s}{n_1 V_T (1 + R_s G_p)}\right)\right] - \frac{n_2 V_T}{R_s} Lambert\ w\left[\frac{I_{s2} R_s}{n_2 V_T (1 + R_s G_p)} exp\left(\frac{V + I_{ph} R_s + I_{s2} R_s}{n_2 V_T (1 + R_s G_p)}\right)\right] \tag{11}$$

3. Clarification of R_{Th} replacement

In the previous section, we hypothesized that R_{Th} of Fig. 2 can be substituted with individual resistances in series with two diodes. It helped us to solve independently the current passing through each diode. In this section, this idea is clarified with a circuit analysis. Since, nonlinearity complicates calculations in circuits involving diodes, piecewise linear (PWL) models are employed here for illustrative purposes.

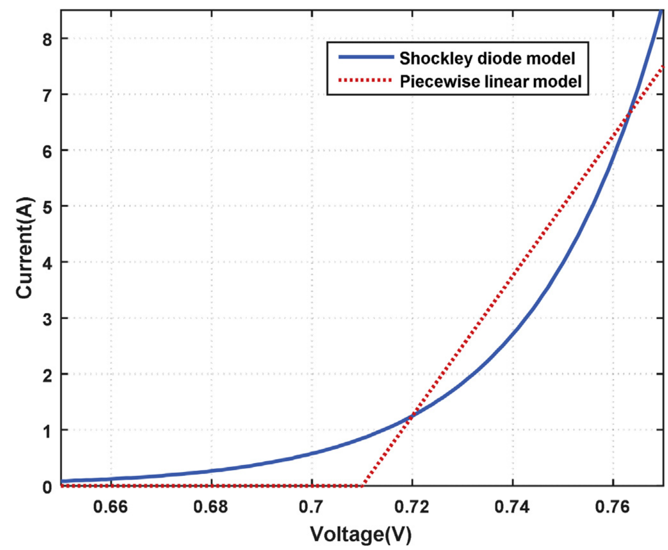

Fig. 4. I-V characteristics of Shockley-diode and PWL models: The diode parameters are supposed as $I_s = 10^{-12}$, $n = 1$ and $V_T = 0.0258$.

As Fig. 4 demonstrates, PWL model is a linearized model for nonlinear I-V characteristic of Shockley diode. This method is used to approximate the diode characteristic curve as a series of linear segments. As Fig. 5 and Fig. 6 show, the PWL models of both diodes are replaced with their associated non-ideal models of Figs. 2 and 3. Generally the PWL model has three components: D_1 and D_2 are ideal diodes, V_{t1} and V_{t2} are voltage sources and, R_{D1} and R_{D2} are resistors. Exclusively, if V_{t1} and V_{t2} are supposed equal, the points of A and B will be equipotential, and since the same power injected from V_{Th}, the equivalent resistances between the positive and negative poles of V_{Th} in both circuits of Figs. 5 and 6 are equal and described by (12):

$$R_{Th} + (R_{D1} \parallel R_{D2}) = (aR_{Th} + R_{D1}) \parallel (R_{Th} + R_{D2}) \tag{12}$$

where the regulating parameter (a) can be extracted as:

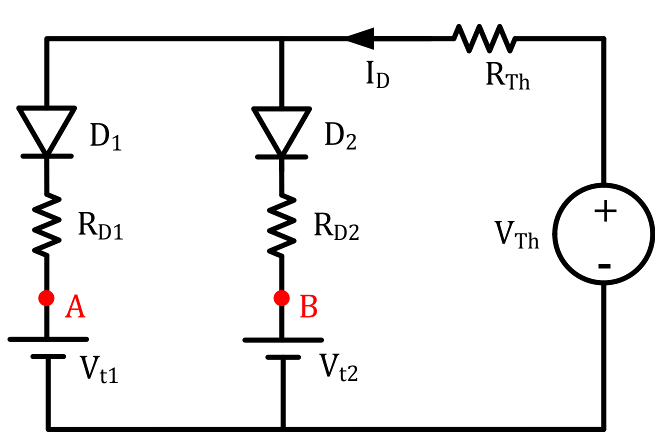

Fig. 5. Implicit PV cell model containing PWL model of the diodes; the indicated points are supposed equipotential.

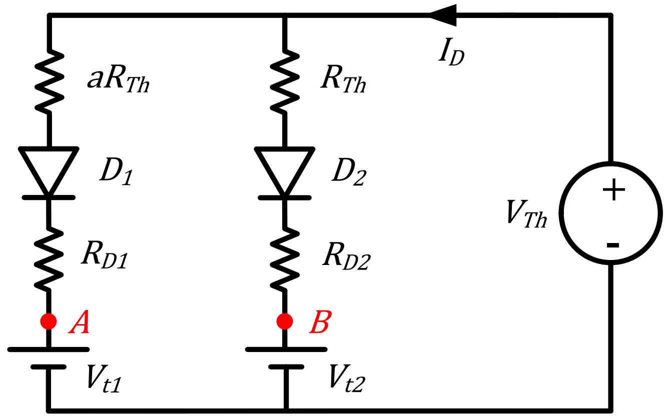

Fig. 6. Proposed explicit model containing PWL model of the diodes in series with individual resistances; the indicated points are supposed equipotential.

$$a = 1 + \frac{R_{D1}(R_{Th} + R_{D2}) + R_{D2}(R_{Th} + R_{D1})}{R_{D2}^2} \tag{13}$$

Equation (13) yields (a) analytically for a specific case; for other cases there exists a value for (a) but it cannot be generally defined by a mathematic function, however it can be estimated by curve fitting methods used in next sections.

4. Model verification with real data

The classical double-diode mathematical equation reflecting the current-voltage behavior of PV cell is extensively elaborated in Refs. [38–40]. The general conventional I-V expression for double-diode model is described in (14). In this section, the suitability of the proposed model is verified with real data of a polycrystalline (P-Si) PV cell and a monocrystalline (Mono-Si) PV module reported respectively in Refs. [38] and [41]. They obtained double-diode model parameters of the mentioned P-Si PV cell and Mono-Si PV module at standard test condition (STC) which are listed in Table 1. STC signifies nominal temperature and irradiation defined as $T_0 = 25^{\circ}$C and $G_0 = 1000\ W/m^2$.

$$I = I_{ph} - I_{s1}\left(e^{\frac{V+IR_s}{n_1 V_T}} - 1\right) - I_{s2}\left(e^{\frac{V+IR_s}{n_2 V_T}} - 1\right) - \frac{(V + IR_s)}{R_p} \tag{14}$$

With no change in the concept and consequently in the values of the PV cell conventional parameters in (14), (a) is estimated that is shown in Table 1 with a grey background. Also, the suitability of the proposed model to represent the I-V curve of conventional implicit model is demonstrated in Fig. 7. To compare the two models, sum of squared errors (SSE) are calculated with the values of 8.22×10^{-7} and 1.43×10^{-5} respectively for the P-Si PV cell and the Mono-Si PV module. The result shows the capability of the proposed model to resemble the behavior of the conventional model.

Table 1
Double-diode parameters of a P-Si PV cell and a Mono-Si PV module at STC used for the proposed model verification.

PV cell or module parameters	P-Si cell	Mono-Si module
Common in the conventional and proposed models		
Proposed model parameter		
$I_{ph}(A)$	4.69×10^{-2}	5.55
$I_{s1}(A)$	6.11×10^{-10}	6.45×10^{-9}
$I_{s2}(A)$	9.15×10^{-7}	3.62×10^{-5}
$R_s(\Omega)$	4.88×10^{-1}	11.7×10^{-3}
$R_p(\Omega)$	$3.23 \times 10^{+2}$	$6.34 \times 10^{+1}$
n_1	1	1.21
n_2	2	2.72
a	1.39	1.46

5. Model verification with simulation

Equation (14) consists of five parameters I_{ph}, I_{s1}, I_{s2}, R_s and R_p that naturally depends on temperature and irradiation. These values are not practically available in a wide range of environmental conditions. To examine the accuracy of the proposed model outside of STC, the translation equations (15)–(19) are used for updating PV cell parameters to simulate changes in temperature and irradiation. These equations belong to a P-Si PV cell which is comprehensively analyzed in Ref. [42].

$$I_{ph}(T,G) = \frac{G}{G_0} I_{ph}(T_0, G_0)\left[1 + k_{ph}(T - T_0)\right] \tag{15}$$

$$I_{si}(T) = I_{si}(T_0)\left(\frac{T}{T_0}\right)^{\frac{3}{n_i}} exp\left(\frac{E_g(T)}{n_i V_T} - \frac{E_g(T_0)}{n_i V_{T_0}}\right),\ i = 1,\ 2 \tag{16}$$

$$E_g(T) = 1.17 - 4.37 \times 10^{-4}\frac{T^2}{T + 636} \tag{17}$$

$$R_s(T,G) = R_s(T_0, G_0) + \phi_G\left(\frac{1}{G} - \frac{1}{G_0}\right) + \nu_T(T - T_0) \tag{18}$$

$$R_p(T) = R_p(T_0) exp(\psi_T(T - T_0)) \tag{19}$$

where k_{ph}, ν_T, ϕ_G and ψ_T are thermal and irradiation coefficients. E_g is band gap energy. The values of $I_{ph}(T_0, G_0)$, $I_{si}(T_0)$, $R_s(T_0, G_0)$ and $R_p(T_0)$ are calculated at STC with data presented by manufacturers, including open circuit voltage V_{oc}, short circuit current I_{sc}, maximum power point voltage V_{mp} and maximum power point current I_{mp}. The specifications of the P-Si PV cell under study in this paper are listed in Table 2 [42]:

5.1. Changing of temperature

Implicit model of (14) and updating equations (15)–(19) are employed to generate I-V data at G_0 and the example temperatures of 20, 30, 40 and 50 °C. Then using curve fitting algorithms in each temperature, the corresponding (a) of the proposed model is extracted in order to obtain most conformity with conventional model. Fig. 8 shows the original data produced by the conventional double-diode model and the curves fit by the proposed model. To evaluate the accuracy, the error values between currents in (11) and (14) are calculated during voltage values from short circuit up to open circuit. The error curves are depicted in Fig. 9 at the considered temperatures that show the error increases around open circuit voltage by increasing temperature. Although the maximum absolute error value is 0.05 that signifies suitability of the proposed model to represent the I-V characteristic behavior of the conventional model.

5.2. Changing of irradiation

The proposed model is also verified with irradiation changes. Hence, the data generated by conventional double-diode model is fit with the proposed model at T_0 and irradiations 50 up to

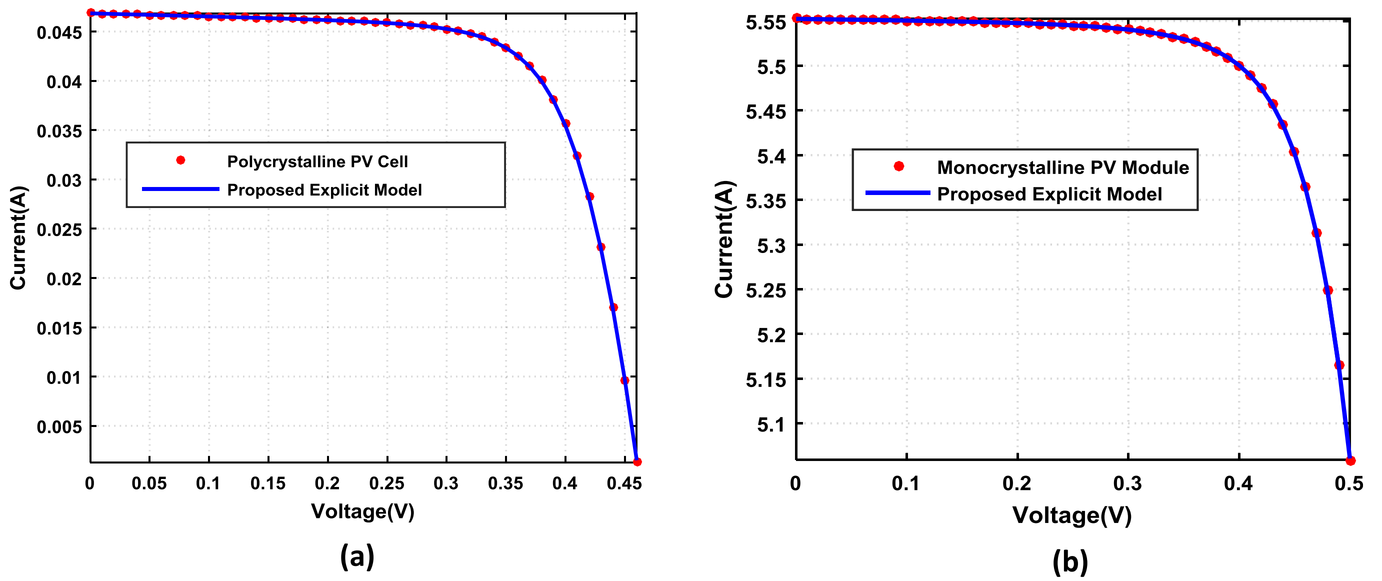

Fig. 7. I-V characteristic curve of implicit double-diode model (dots) and its corresponding proposed explicit one (solid line) at STC; (a): P-Si PV cell, (b): Mono-Si PV module.

Table 2
P-Si PV cell specifications used in the simulation [42].

Specification	Value
V_{oc}	0.569 V
I_{sc}	2.98 A
$R_s(T_0.G_0)$	0.03 Ω
$R_p(T_0)$	6 Ω
k_{ph}	$1.7\times10^{-3}1/^{\circ}K$
ν_T	$2\times10^{-3}1/^{\circ}K$
ϕ_G	500 Ω.W
ψ_T	$-8.5\times10^{-3}1/^{\circ}K$

1100 W/m^2 with the moving step of 150 W/m^2. Fig. 10 shows both models in the mentioned irradiations. To examine the proposed model fitness, the error between both currents in (11) and (14) are calculated in whole applicable voltages. As Fig. 11 demonstrates, the error increases in vicinity of open circuit voltage. Moreover absolute value of the error increases in high illumination; however the error value is less than 0.02 even in the worst case scenario which indicates that the proposed model is acceptable approximation of the conventional implicit model of the (14).

5.3. SSE evaluation

The accuracy of the proposed model is also evaluated by SSE values calculated in whole aforementioned temperatures and irradiations. As Fig. 12 illustrates, it is observable that the value of SSE increases by increasing the temperature and irradiation intensity. However, the maximum SSE is the acceptable value of 0.013 that occurred in temperature 50 °C and irradiation 1100 W/m^2. This faithfully guarantees the performance of the proposed model to fit the conventional model.

The inherent implicit form of conventional models needs numerical iteration for being used in repetitive simulation or parameter extraction procedure. However, the proposed model reduces computational efforts because of its explicit nature. As reported in Ref. [33], typically, explicit models enhance the computation efficiency by a factor of 10 to recreate the I-V behavior of PV cells. Additionally, this work improves what resulted in the paper [33] in two aspects; first only one regulating parameter (a) is introduced to propose explicit model in comparison of two parameters in Ref. [33] which definitely reduces the complexity of the model and then computational effort, and secondly, all of the conventional parameters preserve their original physical definitions and values. In fact, the parameters I_{ph}, I_{s1}, I_{s2}, R_s and R_p are updated with their conventional translation equations in changing of environmental conditions. It is substantial improvement with respect to results of [33] where new translation equations shall be developed for all of the conventional parameters. Moreover, in comparison with explicit models of [34,35] that presented double-diode models in two exclusive conditions of $n_1 = n_2$ and $n_1 = 2n_2$, the proposed model in this paper can cover a much larger family of PV cells with any values of ideality factors.

It is worth to mention that the open circuit voltage of the PV cell is violated at low irradiations in Fig. 10. The amount of such a voltage drop is severely dependent to the value of R_p that is discovered in Ref. [43]. Furthermore, the terminal current of the PV cell has to be positive regarding its direction in Fig. 1. In fact, the negative currents in Figs. 8 and 10 are impractical and investigated only for mathematical purposes.

6. Analysis of the parameter (a)

Since (a) is estimated in adequate numbers of environmental conditions in the previous section, its behavior then can be sought comprehensively with temperature and irradiation change. Fig. 13 demonstrates (a) in G_0 and temperatures between 20 and 55 °C with the step of 5 °C.Apparently, a linear behavior can be deduced with respect to temperature. Hence the linear function of (20) describes (a) corresponding to temperature at G_0:

$$a = \mathrm{a}(T_0, G_0) + 0.025(T - T_0), \quad \mathrm{a}(T_0, G_0) = 6.352 \tag{20}$$

The behavior of (a) is also analyzed in all the operating irradiations and the previously linear behavior is observed in irradiations from 70 up to 1100 W/m^2. Thus, the general equation (21) can be resulted to determine (a) with respect to temperature and irradiation.

$$a(T, G) = \mathrm{m}(G)\,(T - T_0) + b(G) \tag{21}$$

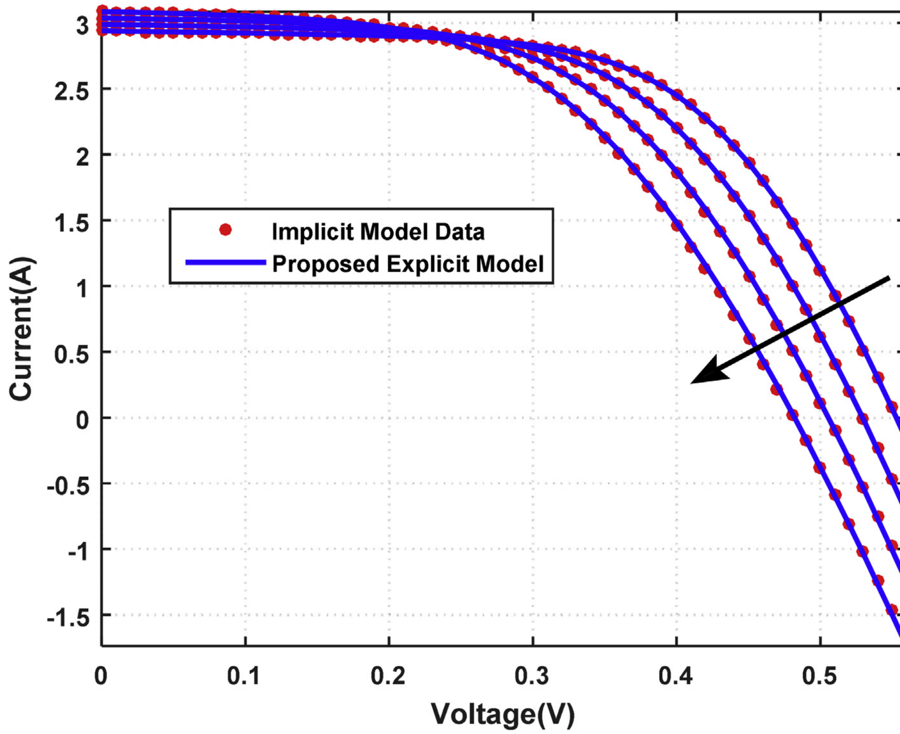

Fig. 8. I-V curves of the conventional model (dots) and proposed model (solid line) of the PV cell at G_0 and temperatures 20, 30, 40 and 50 °C. The arrow direction indicates temperature increase.

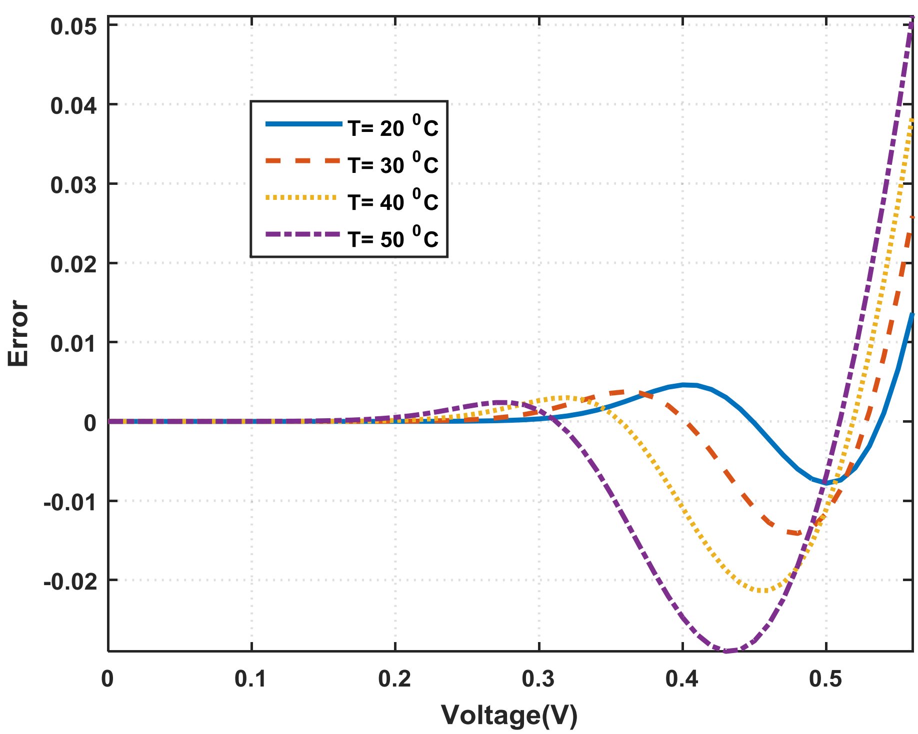

Fig. 9. The error between the currents of conventional and proposed models at G_0 and example temperatures of 20, 30, 40 and 50 °C.

where $m(G)$ is the slope of (a) and $b(G)$ is the point at which the linear function intercept virtual line of $T = T_0$. The argument G denotes that both of m and b are absolutely dependent on irradiation.

The variation of m versus irradiation obviously shows three behavioral areas. In fact, m is fit with the best possible function distinctly in irradiations of $70:80\ \text{W/m}^2$, $80:400\ \text{W/m}^2$ and $400:1100\ \text{W/m}^2$ that can be seen in Fig. 14. Quadratic polynomial, double exponential and linear functions of (22)–(24) are developed for m in the respective areas. The notation $\tilde{G}$ is normalized value of

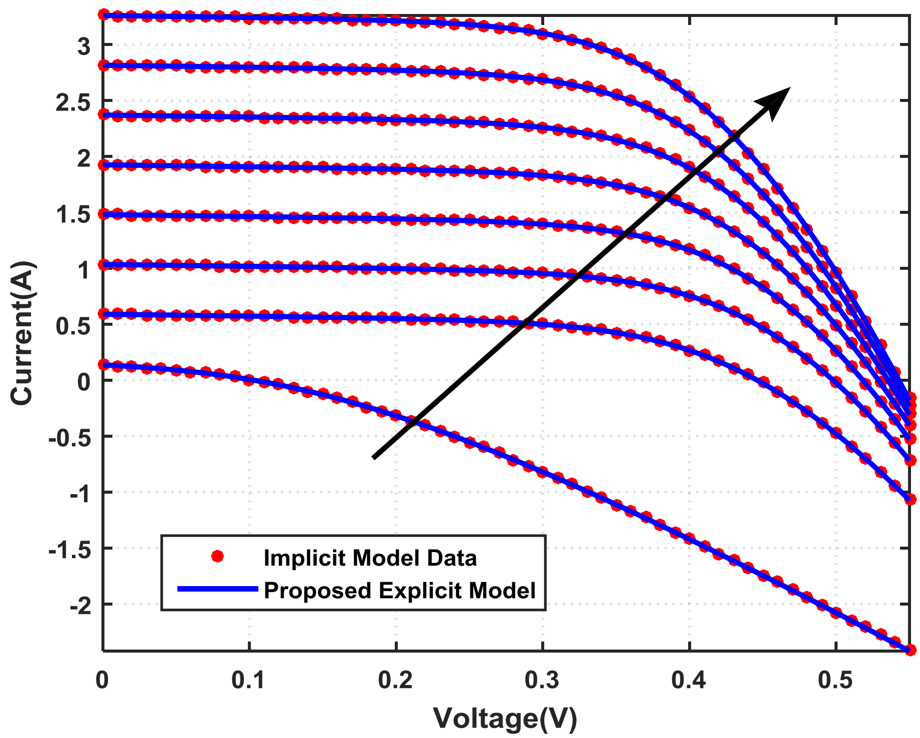

Fig. 10. I-V curves of the conventional model (dots) and proposed model (solid line) of the PV cell at T_0 and irradiation between 50 and 1100W/m^2 with moving step of 150 W/m^2. The arrow direction indicates irradiation increase.

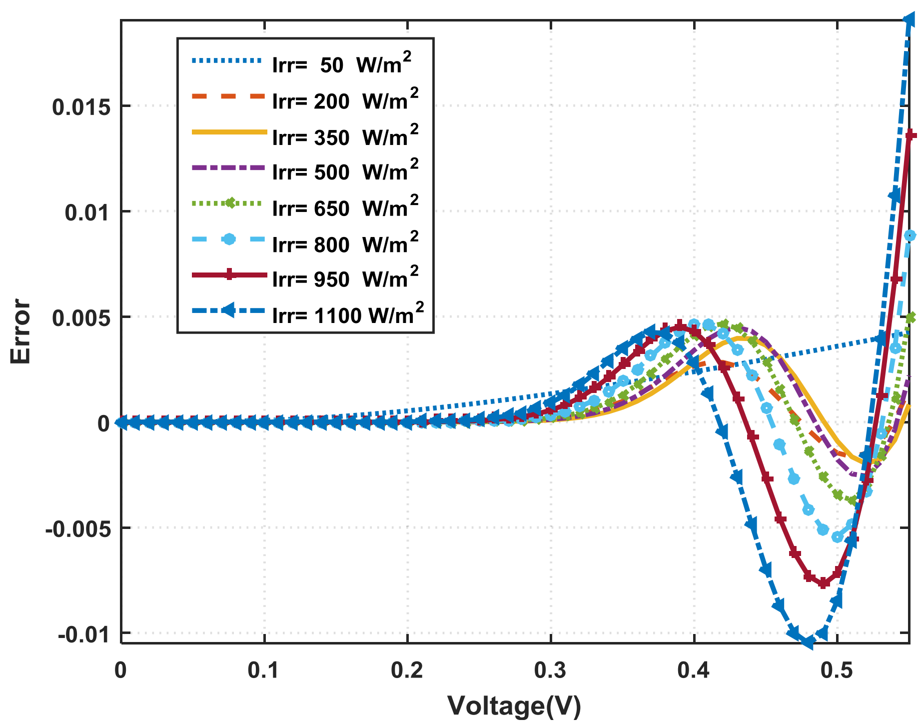

Fig. 11. The error between the currents of conventional and proposed models at T_0 and in example irradiations between 50 and 1100 W/m^2 with moving step of 150 W/m^2.

G that is equal to G/G_0.

Moreover the variation of b is explored corresponding to G. The behavior of b implies three mathematical characteristic; two distinct power law functions are considered for the strictly descending areas in irradiations $70:100$ W/m^2 and $100:400$ W/m^2 shown in Fig. 15 (a and b). Also a double exponential function results the best fit for b in the third area respect to irradiations $400:1100$ W/m^2 shown in Fig. 15 (c). The

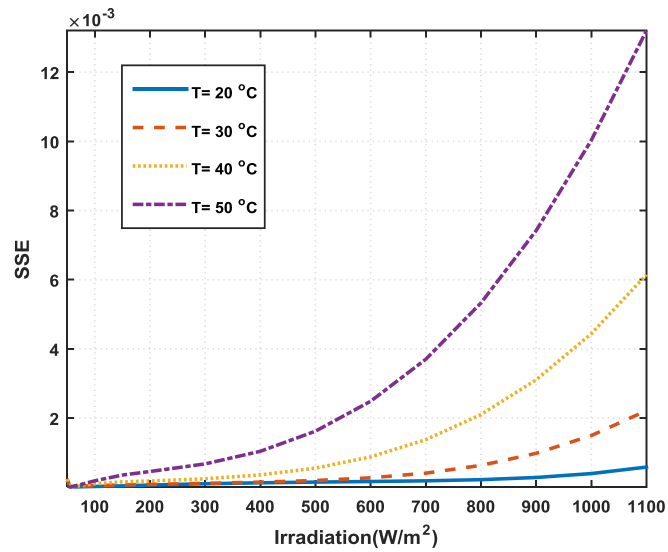

Fig. 12. The proposed explicit model accuracy in term of SSE corresponding to irradiation in example temperatures of 20, 30, 40 and 50 °C.

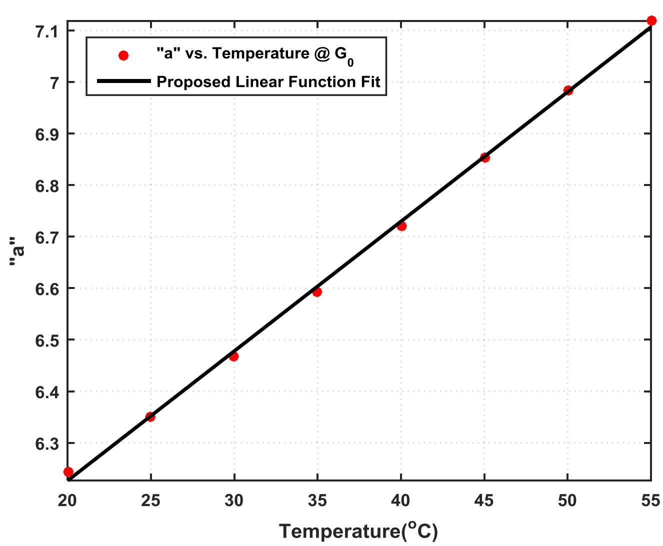

Fig. 13. (**a**) versus temperature (dots) and proposed linear function as translational equation (solid line) at $\mathbf{G}_0$.

corresponding functions are defined with (25)–(27).

$$m|_{G=70:80} = -40.444\tilde{G}^2 + 6.693\tilde{G} + 0.253 \tag{22}$$

$$m|_{G=80:400} = 0.05\exp\left(-13.528\tilde{G}\right) + 0.008\exp(1.2659) \tag{23}$$

$$m|_{G=400:1100} = 0.019\tilde{G} + 0.005 \tag{24}$$

$$b|_{G=70:100} = 0.019\tilde{G} + 11.424 \tag{25}$$

$$b|_{G=100:400} = 0.045\tilde{G}^{-2.59} + 5.977 \tag{26}$$

$$b|_{G=400:1100} = 7.559\exp\left(-5.683\tilde{G}\right) + 5.17\exp\left(0.202\tilde{G}\right) \tag{27}$$

As mentioned above, (a) is a linear function of temperature. The slope of the function is m that is dependent on irradiation. As Fig. 14 illustrates, the maximum value of m is 0.026 which means (a) increases as 0.026 in one increment in the PV cell temperature; On the other hand, as Fig. 15 signifies, the parameter b is strictly sensitive to irradiation in the range of $70:400\ \text{W/m}^2$. Thus it can be inferred that (a) is absolutely more dependent on the value of irradiation than temperature in irradiations between 70 up to $400\ \text{W/m}^2$.

7. Conclusion

A circuit analysis has been done for PV cell double-diode model using Thevenin's theorem. Then the Thevenin's equivalent resistance has been approximated with individual resistances in diodes branches which leads to a novel explicit I-V expression for double-diode model of PV cells. The accuracy of the proposed model has been verified at STC by experimental parameters and outside of STC by simulation study. The error between the proposed explicit and conventional implicit model in both experimental and simulation analysis demonstrates acceptable performance of the proposed model to recreate I-V behavior of PV cells.

The proposed model would be a better model to do extensive simulation study in power electronics integrated by PV panels because of its superior computational efficiency. The explicit expression of $I = f(V)$ allows straightforward derivation for MPP calculation, and consequently can be used for other MPPT algorithms verification. In comparison with explicit models reported in

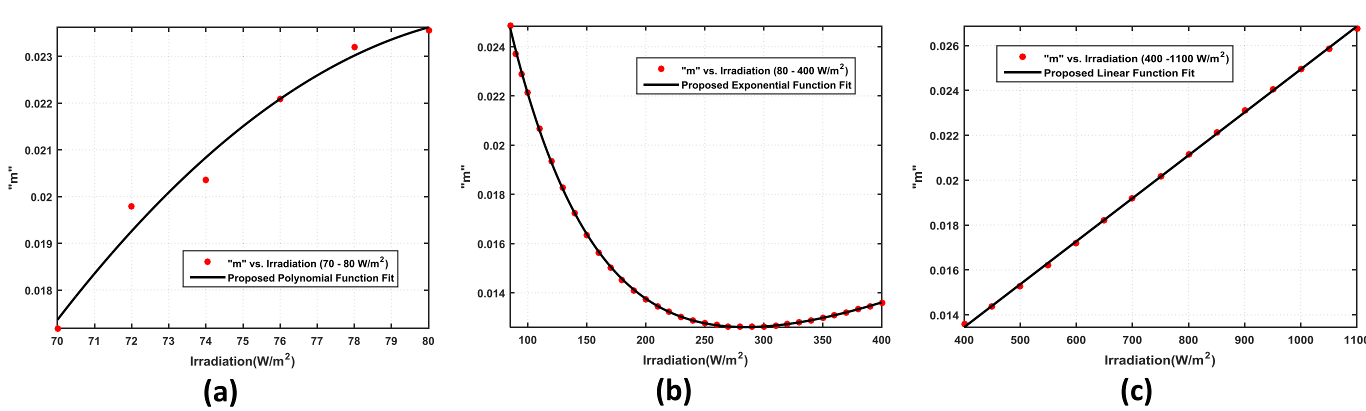

Fig. 14. $\boldsymbol{m}$ versus irradiation (dots) and proposed fit functions (solid line); (a): Polynomial function for $\boldsymbol{G} = 70:80\ \text{W/m}^2$, (b): Exponential function for $\boldsymbol{G} = 80:400\ \text{W/m}^2$ and (c): Linear function for $\boldsymbol{G} = 400:1100\ \text{W/m}^2$.

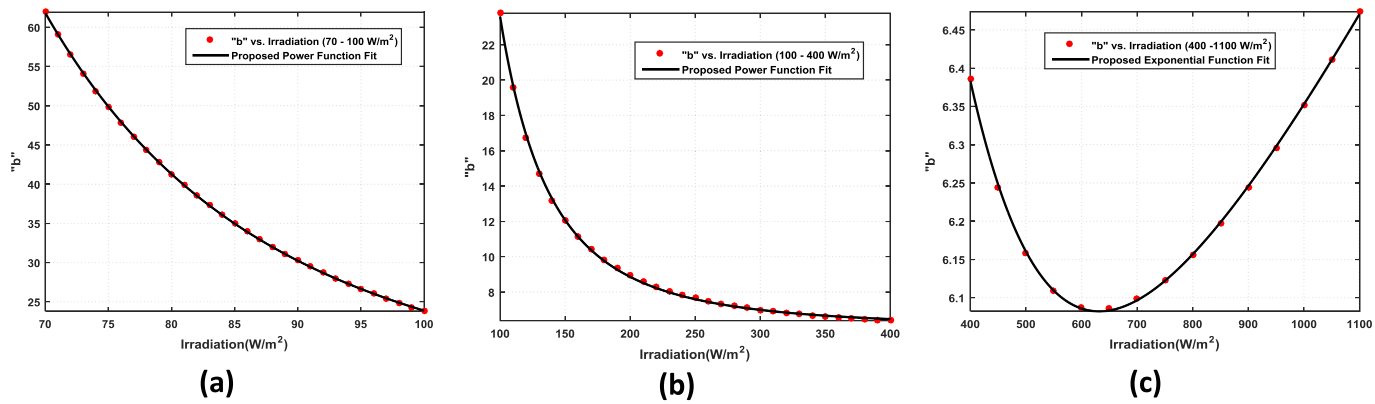

Fig. 15. ***b*** versus irradiation (dots) and proposed fit functions (solid line); (a): Power function for $\boldsymbol{G} = 70:100\ \mathrm{W/m^2}$, (b): Power function for $\boldsymbol{G} = 100:400\ \mathrm{W/m^2}$ and (c): Exponential function for $\boldsymbol{G} = 400:1100\ \mathrm{W/m^2}$.

some exclusive conditions, the proposed model can represent PV cells behavior with any inherent arbitrary values of ideality factors. Moreover, since single regulating parameter is engaged, the model complexity has been reduced compared with two parameters previously presented.

A significant result of this paper is the fact that in spite of the existing double-diode explicit model, the proposed model does not contradict the physical concepts and values of conventional parameters. Consequently, new single translation equation is required for updating currently presented parameter (a) that has been fully developed in this paper. It has been concluded that (a) behaves linearly with temperature and almost exponentially dependent on irradiation.

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