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RESEARCH ARTICLE-PHYSICS

A Simple and Efficient Determination of the Ideality Factor of Solar Cells and Modules from the Knee Point of the Shunt Resistance Curve

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Abstract

In this work, a simple and efficient method is proposed to determine the ideality factor of solar cells and modules using the knee point of the shunt resistance curve. The method was implemented by deriving a nonlinear empirical equation, which is a function of the shunt resistance and ideality factor, from which a peak value of the function is obtained that corresponds to the knee point of the shunt resistance. Researchers can use this simple approach to efficiently determine the ideality factor by either having the datasheet information or experimental current–voltage (I–V) data. Also, the determined ideality factor can be utilized to extract the other parameters of solar cells/modules, thereby modelling the I–V curve of these devices at different conditions. The method was validated on four different PV modules that are available on the market, namely Poly-Si, Mono-Si, thin film and multijunction (hybrid). It was found that the determination of the ideality factor by applying the proposed approach is easier and more efficient than the methods reported in the literature.

Keywords Solar cell · PV module · Parameter extraction · Simple approach · Datasheet information

1 Background and Literature Review

Solar energy has a lot of potential to meet our energy needs in the future as it can be used in various interesting ways. Photovoltaic (PV) technology involves the conversion of solar energy into usable electrical power by means of solar cells or modules [1]. Four solar cell technologies are currently available on the market that utilize monocrystalline, multicrystalline, thin film, and hybrid semiconductors [2–4]. A precise model of the current–voltage (I–V) characteristics of solar cells/modules enables effective quality control and performance analysis of these devices [5–7]. It is also essential for the prediction of energy yield, understanding solar cell defects, and assessing PV modules in different environmental conditions [8–10]. However, to carry out a successful I–V modelling, it is imperative to determine the parameters of solar cell/module devices. These parameters include the ideality factor (n), series resistance (R_s), shunt resistance (R_{sh}), photocurrent (I_{ph}), and saturation current (I_o), which can be described by the single-diode model (SDM) [11].

The ideality factor (n) indicates the degree to which a solar cell resembles the characteristic of an ideal diode (for ideal diodes, $n = 1$). Therefore, the ideality factor is crucial in determining the electrical response and fill factor of solar cell devices [12, 13]. The value of ideality factor for conventional solar cells is typically between one and two; however, it can be greater than two for organic and perovskite solar cells. In addition to the accurate I–V modelling of solar cells and modules, determination of ideality factor is important for the study of recombination mechanisms, solar cells/modules ageing [14–17] and understanding the effects of temperature and illumination energy on the performance of solar cells [18–22]. Furthermore, very recently, researchers used deep-learning approach to monitor the ideality factor, thereby estimating iron concentration in silicon solar cells [23]. Williams et al. revealed the importance of the ideality factor to being a key variable for the design of tandem perovskite-on-silicon solar cells, due to its strong influence over whether tandem sub-cells should be current-matched or intentional current mismatched [24]. Also, investigation of

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ideality factor plays an important role in understanding the electrical and microscopic properties of both light-emitting diodes and normal diodes [25, 26].

A survey of literature revealed the availability of a number of computational and analytical techniques for determining the ideality factor (n) and the four parameters (R_s,R_{sh},I_{ph},I_o) that assist researchers simulate the I–V response of solar cells and modules [27–36]. Analytical methods are not accurate due to neglecting part of the quantities in the manipulation process of equations [37–40]. Computational metaheuristic algorithms were also used to find the ideality factor and other parameters simultaneously, but they are computationally complex and less stable in locating the best value of ideality factor compared to the deterministic computational methods [41–44].

Along this line, several methods were proposed to determine the ideality factor [45, 46]. For instance, Singh et al. used special trans function theory (STFT) to determine the ideality factor of grey and blue solar cells [47]. The advanced STFT was also proposed as an alternative exact analytical approach to determine the ideality factor of solar cells [48]. However, the implementation of these methods is complex and it leads to obtain a less accurate I–V modelling, especially around the maximum power point (MPP). Moreover, Bayhan and Bayhan proposed a simple analytical technique to find the ideality factor of solar cells under illumination, which was less accurate due to considering equal approximate values of the photocurrent (I_{ph}) and short-circuit current (I_{sc}) in the utilized equations [49]. The methods of D.C. and A.C. electro-analytical were also reported to measure the ideality factor [43]. However, they are complex and unable to be implemented when only datasheet information of the solar cell/module is available. On the other hand, the use of analytical methods to find the ideality factor together with the R_s, R_{sh}, I_o and I_{ph} parameters leads to inaccurate estimation because approximations are carried out with all parameters to model the I–V response [50–54]. Noticeably, a trivial uncertainly in the ideality factor results in a high relative error of the I–V model [28]. Therefore, it has been inferred that deterministic computational techniques can perform better to determine the ideality factor if a right optimization algorithm is chosen. In our previous works [27–29], different deterministic approaches were proposed to extract the five parameters of solar cells and modules accurately, thereby modelling the I–V characteristics. However, accurate ideality factor had to be determined by simulating a collection of I–V curves relative to the reference I–V curve, which was relatively a complex and time-consuming operation.

2 Research Gaps

A comprehensive literature review revealed that there has not been a defined approach for determining the ideality factor of solar cells and modules in a simple and efficient manner (trade-off between simplicity and accuracy). Metaheuristic approaches may provide a precise estimate of the ideality factor, albeit at the expense of computational efficiency. In addition, analytical and deterministic methods can provide a straightforward estimation of the ideality factor at the expense of precision.

3 Research Objective

This paper proposes a simple and efficient numerical approach for determining the ideality factor of solar cells and modules. The proposed method is meant to be applicable to all types of solar cells and modules, and the ideality factor can be computed using either the datasheet information or experimental I–V measurements.

4 Research Contribution

The contribution of this work is to aid researchers, engineers, and end-users of solar cells and modules in determining the ideality factor with only the basic datasheet information or measured current–voltage data. This method is novel in that it employs the shunt resistance (R_{sh}) curve at its knee point to find the ideality factor (n) readily and efficiently.

5 Mathematical Formalism

The single-diode model (SDM) equation can be used to model the I–V characteristic of solar cells, which includes the five parameters (n, R_s, R_{sh}, I_o and I_{ph}) [28]:

$$I = I_{ph} - I_o\left[\exp\left(\frac{V + IR_s}{nV_t}\right) - 1\right] - \frac{(V + IR_s)}{R_{sh}} \tag{1}$$

where V_t is the thermal voltage ($k_B T/q$), k_B is Boltzmann's constant, q is the elementary charge, and T is the cell's temperature in Kelvin. The theoretical value of the ideality factor is assumed to be one ($n = 1$), implying that the recombination of charge carriers does not occur in the p–n junction (depletion region) of the cell. However, recombination may occur differently in various regions of the active layer, resulting in a deviation from unity of the ideality factor. Consequently, the ideality factor is a main tool used for determining the type and order of charge recombination in various types of solar cells. For a PV module, which is made from N series of connected cells, the ideality factor (n) in Eq. 1 and the rest of derived formulas should be replaced by $N \times a$, where a is the ideality factor of the PV module.

5.1 Boundary Condition and Manipulation

Taking into account the boundary conditions at the short-circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power (P_{m}) in Eq. 1, it is possible to derive the following equations:

$$0 = I_{\mathrm{ph}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}}} + I_o\left[1 - \exp\left(\frac{V_{\mathrm{oc}}}{nV_t}\right)\right] \tag{2}$$

$$I_{\mathrm{sc}} = I_{\mathrm{ph}} - \frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{R_{\mathrm{sh}}} + I_o\left[1 - \exp\left(\frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{nV_t}\right)\right] \tag{3}$$

$$I_m = I_{\mathrm{ph}} - \frac{R_s I_m}{R_{\mathrm{sh}}} - \frac{V_m}{R_{\mathrm{sh}}} + I_o\left[1 - \exp\left(\frac{V_m + R_s I_m}{nV_t}\right)\right] \tag{4}$$

The simultaneous Eqs. 2 and 3 can be used to solve for the saturation current (I_{o}):

$$I_{\mathrm{o}} = \frac{I_{\mathrm{sc}} + \frac{R_{\mathrm{s}}}{R_{\mathrm{sh}}} I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}}}}{\exp\left(\frac{V_{\mathrm{oc}}}{nV_t}\right) - \exp\left(\frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{nV_t}\right)} \tag{5}$$

The term $\exp\left(\frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{nV_t}\right)$ is small enough to be neglected [55–57], so Eqs. 3 and 5 are rewritten as follows:

$$I_{\mathrm{ph}} = I_{\mathrm{sc}} + \frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{R_{\mathrm{sh}}} - I_{\mathrm{o}} \tag{6}$$

$$I_{\mathrm{o}} = \frac{I_{\mathrm{sc}} + \frac{R_{\mathrm{s}}}{R_{\mathrm{sh}}} I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}}}}{\exp\left(\frac{V_{\mathrm{oc}}}{nV_t}\right)} \tag{7}$$

It is known from the theorem of the maximum power transfer that when the internal impedance (Z_{in}) of a power source is equal to the external impedance of the connected load (Z_{out}), maximum power (P_{m}) is delivered to the load. This can be represented by [28]:

$$\frac{V_{\mathrm{m}}}{I_{\mathrm{m}}} = Z_{\mathrm{out}} = Z_{\mathrm{in}} \tag{8}$$

The internal impedance formula can be derived from the equivalent circuit of the single-diode model and is equated to the external impedance:

$$R_{\mathrm{s}} + \frac{r_d R_{\mathrm{sh}}}{r_d + R_{\mathrm{sh}}} = \frac{V_{\mathrm{m}}}{I_{\mathrm{m}}} \tag{9}$$

where r_{d} is the dynamic non-ohmic resistance of the diode, which is estimated by taking the first derivative of the diode equation as follows:

$$r_d = \left.\frac{\mathrm{d}V_D}{\mathrm{d}I_D}\right|_{P_{\mathrm{m}}} = \frac{nV_t}{I_o \exp\left(\frac{V_{\mathrm{m}} + R_{\mathrm{s}} I_{\mathrm{m}}}{nV_t}\right)} \tag{10}$$

Then, substituting for r_d in Eq. 9, one can get:

$$\frac{nV_t\left(I_{\mathrm{m}} + \frac{R_{\mathrm{s}} I_{\mathrm{m}}}{R_{\mathrm{sh}}} - \frac{V_{\mathrm{m}}}{R_{\mathrm{sh}}}\right)}{V_{\mathrm{m}} - R_{\mathrm{s}} I_{\mathrm{m}}} = I_{\mathrm{o}} \exp\left(\frac{V_{\mathrm{m}} + R_{\mathrm{s}} I_{\mathrm{m}}}{nV_t}\right) \tag{11}$$

Also, subtracting Eq. 2 from 4 yields

$$I_{\mathrm{o}} \exp\left(\frac{V_{\mathrm{m}} + R_{\mathrm{s}} I_{\mathrm{m}}}{nV_t}\right) = I_{\mathrm{sc}} + \frac{R_{\mathrm{s}}}{R_{\mathrm{sh}}}(I_{\mathrm{sc}} - I_{\mathrm{m}}) - \frac{V_{\mathrm{m}}}{R_{\mathrm{sh}}} - I_{\mathrm{m}} \tag{12}$$

Now, the simultaneous Eqs. 11 and 12 can be solved to make R_{sh} subject as follows:

$$R_{\mathrm{sh}} = \frac{R_{\mathrm{s}}^2\left(I_{\mathrm{sc}} I_{\mathrm{m}} - I_{\mathrm{m}}^2\right) + R_{\mathrm{s}}(nV_t I_{\mathrm{m}} - I_{\mathrm{sc}} V_m) + V_{\mathrm{m}}^2 - nV_t V_{\mathrm{m}}}{V_{\mathrm{m}}(I_{\mathrm{sc}} - I_{\mathrm{m}}) + R_{\mathrm{s}}\left(I_{\mathrm{m}}^2 - I_{\mathrm{sc}} I_{\mathrm{m}}\right) - nV_t I_{\mathrm{m}}} \tag{13}$$

Another expression can be achieved from Eq. 6 and 4 as follows:

$$I_{\mathrm{sc}} + \frac{R_{\mathrm{s}} I_{\mathrm{sc}}}{R_{\mathrm{sh}}} = I_{\mathrm{m}} + \frac{R_{\mathrm{s}} I_{\mathrm{m}}}{R_{\mathrm{sh}}} + \frac{V_{\mathrm{m}}}{R_{\mathrm{sh}}} + I_{\mathrm{o}} \exp\left(\frac{V_{\mathrm{m}} + R_{\mathrm{s}} I_{\mathrm{m}}}{nV_t}\right) \tag{14}$$

Substituting for I_{o} in Eq. 14, another formula for the shunt resistance (R_{sh}) can be derived, which is:

$$R_{\mathrm{sh}} = \frac{R_{\mathrm{s}}(I_{\mathrm{sc}} A - I_{\mathrm{sc}} + I_{\mathrm{m}}) + V_{\mathrm{m}} - V_{\mathrm{oc}} A}{I_{\mathrm{sc}}(1 - A) - I_{\mathrm{m}}} \tag{15}$$

where $A = \exp\left(\frac{V_{\mathrm{m}} - V_{\mathrm{oc}} + R_{\mathrm{s}} I_{\mathrm{m}}}{nV_t}\right)$.

Finally, by equating Eqs. 13–15, a relation between the ideality factor (n) and series resistance (R_{s}) can be established:

$$R_{\mathrm{s}} = \frac{\begin{array}{r} nV_t V_{\mathrm{m}}(2I_{\mathrm{m}} - I_{\mathrm{sc}})A^{-1} + nV_t(I_{\mathrm{sc}} V_{\mathrm{m}} - I_{\mathrm{m}} V_{\mathrm{oc}}) \\ + V_{\mathrm{oc}} V_{\mathrm{m}}(I_{\mathrm{sc}} - I_{\mathrm{m}}) - V_{\mathrm{m}}^2 I_{\mathrm{sc}} \end{array}}{I_{\mathrm{sc}} I_{\mathrm{m}}(V_{\mathrm{oc}} - V_{\mathrm{m}}) - I_{\mathrm{m}}^2 V_{\mathrm{oc}}} \tag{16}$$

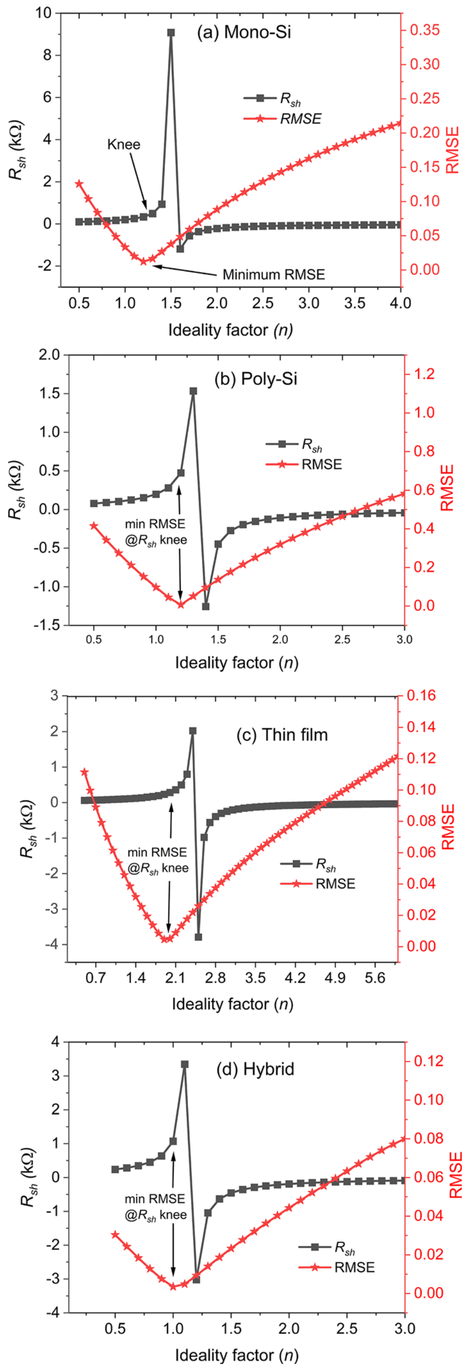


Fig. 1 The relation between ideality factor with shunt resistance and root mean square error for PV modules made from **a** monocrystalline silicon, **b** polycrystalline silicon, **c** thin film, and **d** hybrid active layers

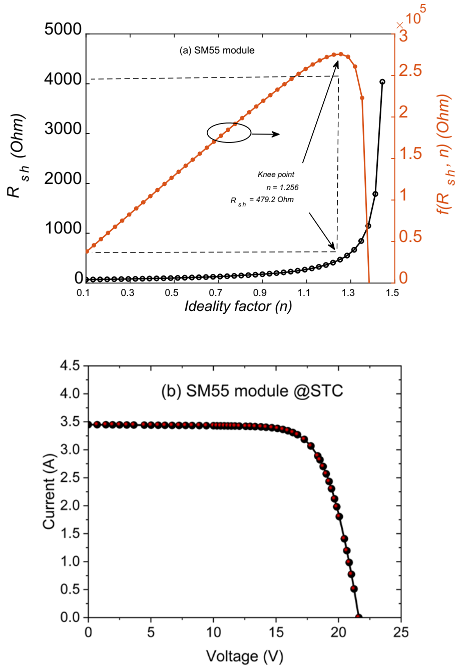


Fig. 2 **a** Determination of the ideality factor where Eq. 17 shows its highest value at the knee point of R_{sh}-n, and **b** the I–V curve of a sample module (SM55) which is opposite to the shape of R_{sh}-n curve

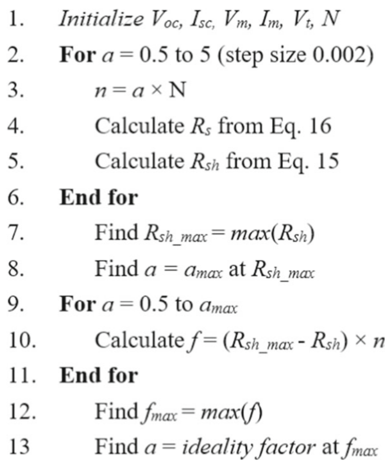
5.2 Proposed Method

This study was inspired by a number of experimental investigations conducted on the modelling of I–V characteristics of solar cells and modules, with the intention of showing an intriguing relationship between shunt resistance (R_{sh}) and ideality factor (n). It was determined that the most accurate I–V model (the one with the minimum error) is obtained when the ideality factor corresponds to the knee point of the nonlinear curve of R_{sh}. Equation 15 can be used to draw this nonlinear curve of R_{sh} as a function of the ideality factor. To justify this finding, plots of R_{sh} versus root mean square error (RMSE) of the I–V modelling were drawn for the four types of solar cell technologies (monocrystalline, polycrystalline, thin film and hybrid), as shown in Fig. 1. As can be seen, the best I–V model is at the knee point of the positive values of R_{sh} curve. Therefore, the ideality factor at the knee point represents the most accurate value.

To develop an algorithm for extracting the ideality factor at the knee point of the R_{sh} curve, we have transformed the curve so that the knee point corresponds to a maximum point (vertex) on the new curve, as shown in Fig. 2a. The new curve was produced as follows; each single value of R_{sh} was subtracted from its maximum value, i.e. $\left(R_{sh\_max} - R_{sh}\right)$, where R_{sh_max} is the maximum value beyond the knee point. Later, the function was multiplied by the ideality factor to obtain:

$$f(R_{sh}, n) = \left(R_{sh\_max} - R_{sh}\right) \times n \tag{17}$$

where $f(R_{sh}, n)$ is the new curve function having a maximum point which corresponding to the knee point of R_{sh}. Figure 3 shows the pseudocode used to execute the algorithm through which the ideality factor was determined at the knee point of the R_{sh} curve.



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Initialize $V_{oc}$, $I_{sc}$, $V_m$, $I_m$, $V_t$, $N$
For $a = 0.5$ to 5 (step size 0.002)
    $n = a \times N$
    Calculate $R_s$ from Eq. 16
    Calculate $R_{sh}$ from Eq. 15
End for
    Find $R_{sh\_max} = max(R_{sh})$
    Find $a = a_{max}$ at $R_{sh\_max}$
For $a = 0.5$ to $a_{max}$
    Calculate $f = (R_{sh\_max} - R_{sh}) \times n$
End for
    Find $f_{max} = max(f)$
    Find $a$ = ideality factor at $f_{max}$
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Fig. 3 The MATLAB coding steps of the proposed method to determine the ideality factor

6 Results and Discussion

The proposed method was validated on four types of PV modules that are available on the market, including monocrystalline-Si (SM55), polycrystalline-Si (KC200GT), thin film (ST40) and hybrid (CTJ30), whose datasheet extracted I–V data can be found elsewhere [27, 58, 59]. The photovoltaic parameters and number of cells of the PV modules at standard test condition (STC), which are reported in the manufacturer's datasheet, are shown in Table 1.

The accuracy of the proposed method to determine the ideality factor was assessed by finding the percentage relative error (RE%) between the calculated I–V and measured I–V data. This is because there are no benchmark ideality factors for the PV modules to be compared with the calculated ones. Consequently, the five intrinsic parameters of the PV modules were determined and utilized to generate the calculated I–V data. Interestingly, the percentage relative error (RE%) was found to be low enough, from 1 to 2.9%, when the proposed method was used to simulate the I–V curve of the PV modules at STC, as shown in Table 2.

As shown in Table 3, the uncertainty of the ideality factor estimated for the PV modules by the proposed method was compared to those determined by other techniques reported in the literature. Notably, the proposed method was found to be more accurate (lower RE%, as shown in bold inside parenthesis) than the previous approaches in determining the ideality factor. In addition, the two approaches developed by Zaimi et al. [60] and El-Achouby et al. [61] exhibited high errors when used to determine the ideality factor and other parameters of the thin film PV modules, but they performed better for the mono-Si and poly-Si modules. It is worth mentioning that despite the higher accuracy of the proposed method, the methodology process is much simpler than the methods reported earlier.

The competence of the proposed method was further demonstrated by estimating the ideality factor of several PV modules at varying temperatures and irradiance levels. Figure 4 shows the effect of temperature and irradiance on the ideality factor of the investigated PV modules using the proposed method. One can notice that for the monocrystalline PV module, the ideality factor was relatively increased and decreased with the increase of temperature and irradiance, respectively. This result was found to be in agreement with the previously reported experimental investigations [18, 50]. However, the ideality factor change for the polycrystalline and thin film PV modules was observed to follow a reverse trend with the increase in temperature and irradiance [28]. Comparably, the change in the ideality factor was found by

Table 1 Photovoltaic parameters of four types of PV modules at STC extracted from their datasheets

PV module	PV parameters				
	V_{oc} (V)	I_{sc} (A)	V_m (V)	I_m (A)	N
Mono-Si (SM55)	21.7	3.45	17.4	3.15	36
Poly-Si (KC200GT)	32.9	8.21	26.3	7.61	54
Thin film (ST40)	23.3	2.68	16.6	2.41	36
Hybrid/Multijunction (CTJ30)	2.610	0.473	2.314	0.452	3

Table 2 Intrinsic parameters of different PV modules extracted by the proposed method at STC

PV module	Module parameters					
	n	R_s (Ω)	R_{sh} (Ω)	I_o (A)	I_{ph} (A)	RE%
Mono-Si (SM55)	1.256	0.381	479.2	2.816E-8	3.453	1.04
Poly-Si (KC200GT)	1.192	0.212	388.6	1.675E-8	8.184	1.87
Thin film (ST40)	1.992	0.899	278.2	6.519E-6	2.687	1.66
Hybrid/multijunction (CTJ30)	1.028	0.055	425.1	2.83E-15	0.473	2.85

Table 3 The determined ideality factor of different PV modules using the proposed method in comparison to those estimated by other researchers

PV module	Ideality factor (n) (RE)		
	This work	Ref. [60–62]	Ref. [63]
Mono-Si (SM55)	1.256 (**1.04%**)	1.036 (1.53%)	1.64 (1.41%)
Poly-Si (KC200GT)	1.192 (**1.87%**)	1.043 (2.34%)	1.22 (2.19%)
Thin film (ST40)	1.992 (**1.66%**)	1.148 (2.21%)	1.38 (1.73%)
Hybrid/Multijunction (CTJ30)	1.028 (2.85%)	NA	NA

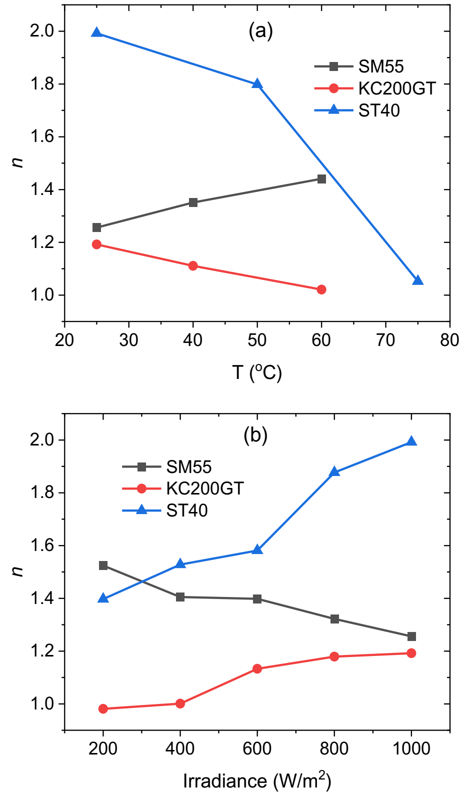

Fig. 4 The simulated I–V curve of thin film (ST40) PV module at **a** different irradiances and **b** temperatures compared to those reported in the datasheet and literature

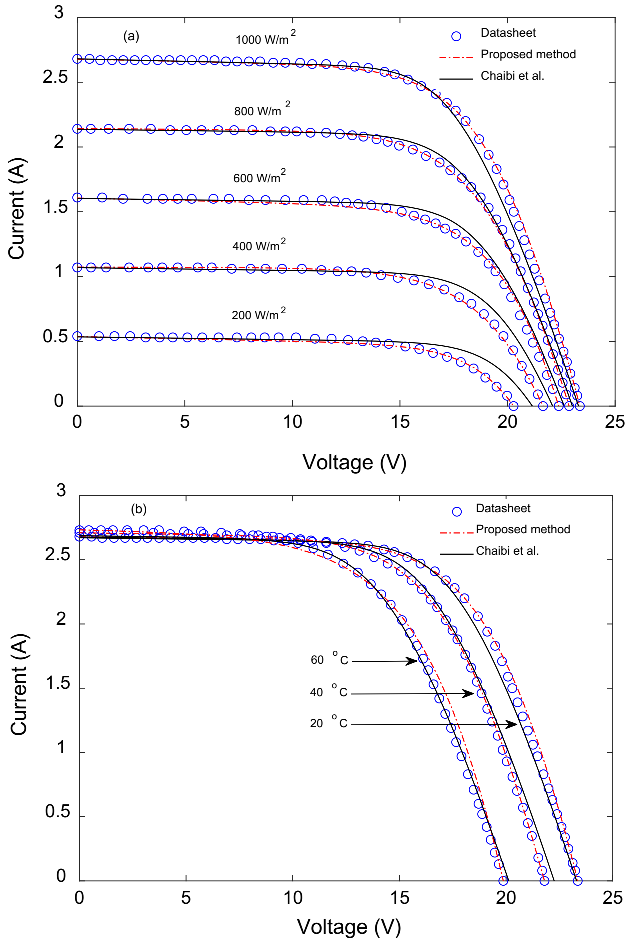

Fig. 5 The simulated I–V curve of thin film (ST40) PV module at **a** different irradiances and **b** temperatures compared to those reported in the datasheet and literature

other researchers to be insignificant with the increase in temperature and irradiance [64].

Additionally, in order to observe the fitness quality of the simulated I–V curves at different irradiances and temperatures, the determined ideality factors were used to calculate the I–V data at each condition. The results of this simulation is shown in Fig. 5 for the thin film (ST40), as a representative PV module. It was found that the proposed method has well fitted the datasheet I–V at different environmental conditions. Noticeably, there has been less deviation of the calculated curves from those of the measured ones at low temperatures and high irradiances, implying an efficient response of the proposed method compared to those reported in the literature. It was observed that the proposed method is more efficient at the maximum power point (MPP) and at the voltages beyond V_{m} (see Fig. 5) compared to that reported by Chaibi's et al. [63].

7 Conclusions

A new simple and efficient numerical method was successfully implemented to extract the ideality factor of solar cells and modules from the knee point of the shunt resistance curve. The ideality factor of mono-Si (SM55) was determined to be 1.256, while that for poly-Si (KC200GT), thin film (ST40) and hybrid (CTJ30) were found to be 1.192, 1.992 and 1.028, respectively. The relative error percentage in the ideality factors estimated by the suggested method was found to be lower than those reported by previous methods. Noteworthy, the relative errors in the ideality factor of mono-Si (SM55), poly-Si (KC200GT), thin film (ST40) and hybrid (CTJ30) were calculated to be 1.04%, 1.87%, 1.66% and 2.85%, respectively. Importantly, the proposed method can use either the datasheet information or experimental current–voltage (I–V) data to extract the ideality factor, through which the other four parameters of solar cells/modules can also be determined. This allows for the correct modelling of I–V characteristics under diverse scenarios. It was determined that the proposed method for obtaining the ideality factor is simpler and more effective than the methods described in the literature. The proposed method can help researchers, engineers, and end-users of solar cells and modules in determining the ideality factor with only the basic datasheet information or measured current–voltage data.

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Data availability The data and material are available within the manuscript.

Declarations

Conflict of interest The author declares that there is no conflict of interest regarding the publication of this paper.

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