Improving Accuracy of Solar Cells Parameters Extraction by Minimum Root Mean Square Error

Abdulhamid Atia
School of Engineering
Cardiff University
Cardiff, United Kingdom
atiaam@cardiff.ac.uk

Fatih Anayi
School of Engineering
Cardiff University
Cardiff, United Kingdom
anayi@cardiff.ac.uk

Gao Min
School of Engineering
Cardiff University
Cardiff, United Kingdom
min@cardiff.ac.uk

***Abstract*— This paper presents a technique for enhancing the accuracy of parameters extraction of photovoltaic (PV) cells from experimental current-voltage (I-V) curve. This technique is based on entering nearly all the possible points of an I-V curve to extract the slopes near the open circuit voltage and short circuit current to determine approximate values of the series and shunt resistance, respectively. These values are utilised to find accurate values of the five parameters of the single diode model based on an analytical method from the literature. The calculated I-V curves from all groups of points are then compared with the experimental one and the curve that provides the minimum root mean square error (RMSE) is selected as the best fit. Experimental results are provided in this paper to validate the approach. The results show that the analytical method can become more accurate than iterative/numerical methods if the points used to calculate the slopes are properly selected.**

Keywords—photovoltaic (PV) cells, single diode model, analytical parameters extraction.

I. INTRODUCTION

Photovoltaic (PV) technology is one of the most attractive renewable energy sources that directly converts sunlight into electricity without any moving mechanical parts, which leads to lower maintenance requirement. Over the past few decades, the use of photovoltaics as an alternative energy source to fossil fuels has increased significantly thanks to the huge efforts of research and development [1].

In a variety of PV research and applications, it is desirable to model PV systems accurately and reliably. Several models exist in the literature to simulate the behaviour of a PV device. The single and double diode models are the basic models that are commonly used. The single-diode model that has five parameters, which is depicted in Fig. 1, takes into account the electrical losses in a real PV device and it provides a compromise between accuracy and simplicity [2].

The current-voltage (I-V) relationship of a solar cell using the model in Fig.1 is represented by the following equation [1]:

$$I = I_{ph} - I_s \left(\exp\left(\frac{IR_s+V}{V_{th}n}\right) - 1\right) - \frac{IR_s+V}{R_{sh}} \tag{1}$$

where: I is the output current , I_{ph} is photo-generated current, I_s is the reverse saturation current of the diode, V is the output voltage, n is the ideality factor of the diode, which is typically between 1 and 2, R_s is the series resistance, R_{sh} is the shunt resistance and V_{th} is the thermal voltage and it is given by [1]:

$$V_{th} = \frac{kT}{q} \tag{2}$$

where: q is the electron charge ($1.60217657 \times 10^{-19}$C), k is Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K) and T is the cell temperature in Kelvin.

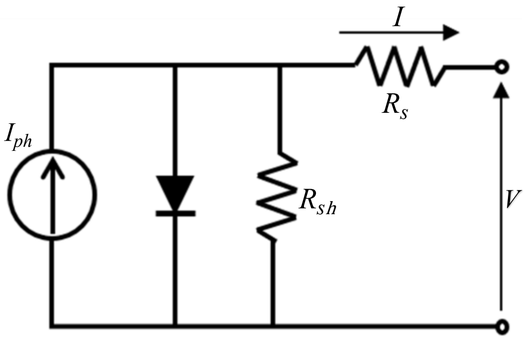

Fig. 1. The equivalent circuit of the single diode five-parameter model [1].

In order to produce the output characteristics of a PV device using this model, five parameters have to be obtained. These parameters are the series resistance (R_s), the shunt resistance (R_{sh}), the photo-generated current (I_{ph}), the ideality factor (n) and the reverse saturation current (I_s) [2]. Most of the existing parameters extraction methods in the literature can be generally classified into three categories. Namely, the analytical methods [3], [4], the iterative/numerical methods [2], [5], [6] and the evolutionary computing algorithms [7], [8].

The analytical methods are simple and do not suffer from convergence issues compared with the other methods. However, their main drawback is the poor accuracy [9]. The iterative/numerical methods are based on solving a set of equations by a numerical solver [2], [6] or by an iterative process [5]. They are generally more accurate than the analytical methods. However, they suffer from convergence issues, higher computational time and complexity. In addition, the evolutionary computing algorithms provide a very high accuracy but at the cost of increased complexity [9]. Thus, it will be advantageous to develop a simple but accurate parameters extraction method. In this paper, a hybrid method that employs a MATLAB algorithm to improve the accuracy of an analytical method is reported.

II. SELECTING THE BEST VALUES OF THE SLOPES

Some of the analytical and iterative methods rely on calculating the slopes at the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) points. These slopes represent approximate values of the series (R_{s0}) and shunt resistances (R_{sh0}), respectively [1]. These values are then used to extract the other parameters as in [3], [5].

When the I-V curve data is available, selecting proper points to calculate the slopes can significantly affect the solution [9]. Benghanem and Alamri [10] suggested that the best selection of R_{s0} is to calculate the slope between the V_{oc} point and the point located at 50 % of the I_{sc}. Also, the best solution of R_{sh0} is suggested to be the slope between the I_{sc} point and 95 % of I_{sc}. Orioli and Gangi [11] used approximate procedure to select the best points to find the slopes of crystalline silicon PV modules. They calculated R_{s0} from the slope between V_{oc} and 20 % of I_{sc}, whereas R_{sh0} was calculated from the slope between I_{sc} and 20 % of V_{oc}. In addition, the authors proposed two empirical equations to determine R_{s0} and R_{sh0} from the information provided in the data sheet. Similar approach is proposed in [12], in which the authors used many points to calculate the slopes and then found the optimum values of R_{s0} and R_{sh0}. Further, they proposed empirical equations to calculate R_{s0} and R_{sh0} from data sheet and then they are entered in a numerical algorithm to extract the five parameters. However, it was not shown in [12] whether all the possible points to calculate R_{s0} and R_{sh0} are used and how they are entered or indexed.

This paper presents an algorithm that can be used when the I-V experimental data is available. It uses many points to calculate the slopes and selects the pair that produces the best fit between the theoretical and experimental I-V curves. The analytical method proposed by Phang *et al.* [3] is used with the developed algorithm. An illustration of Phang's model equations is given in the following.

The slopes of the tangent lines at I_{sc} and V_{oc} are given by (3) and (4), respectively [1]:

$$R_{sh0} = -\frac{\Delta v}{\Delta I} \ (\text{at } \ I=I_{sc}) \tag{3}$$

$$R_{s0} = -\frac{\Delta v}{\Delta I} \ (\text{at } \ V=V_{oc}) \tag{4}$$

Once R_{s0} and R_{sh0} are determined, the five parameters are extracted subsequently using the following five equations [3]:

$$R_{sh} = R_{sh0} \tag{5}$$

$$n = \frac{(V_m + I_m R_{s0} - V_{oc})}{V_{th}\left[\text{Ln}\left(I_{sc} - \frac{V_m}{R_{sh}} - I_m\right) + \frac{I_m}{I_{sc} - \frac{V_{oc}}{R_{sh}}} - \text{Ln}\left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right)\right]} \tag{6}$$

$$I_s = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) \exp\left(-\frac{V_{oc}}{V_{th} n}\right) \tag{7}$$

$$R_s = R_{s0} - \frac{V_{th} n}{I_s} \exp\left(-\frac{V_{oc}}{V_{th} n}\right) \tag{8}$$

$$I_{ph} = I_{sc}\left(1+\frac{R_s}{R_{sh}}\right) + I_s\left(\exp\left(\frac{R_s I_{sc}}{V_{th} n}\right) - 1\right) \tag{9}$$

where: V_m and I_m are the voltage and current at the maximum power point (MPP), respectively.

The program code was written in MATLAB. Fig. 2 shows a flow chart illustrating the algorithm steps. At first, the I-V data is entered alongside with the temperature value. To Determine R_{sh0}, an iterative loop is created in the program that takes every point starting from a point near the I_{sc} point and ending by 50 % of V_{oc}. For every point, all the possible points to calculate R_{s0} are tested starting from a point near the V_{oc} and ending by 50 % of I_{sc}. The 50 % was selected as a limit of both ranges used, i.e. taking only the linear part until just before the knee of the MPP starts as shown in Fig. 3. Thereby testing all the possible pairs of R_{s0} and R_{sh0} within these ranges except the points very near to V_{oc}, which in some I-V curves that have large number of data points, gives unrealistic negative value of R_s. In every case, (3) to (9) are executed to calculate the five parameters. Subsequently, the I-V curve is produced by solving (1) using the Newton Raphson method.

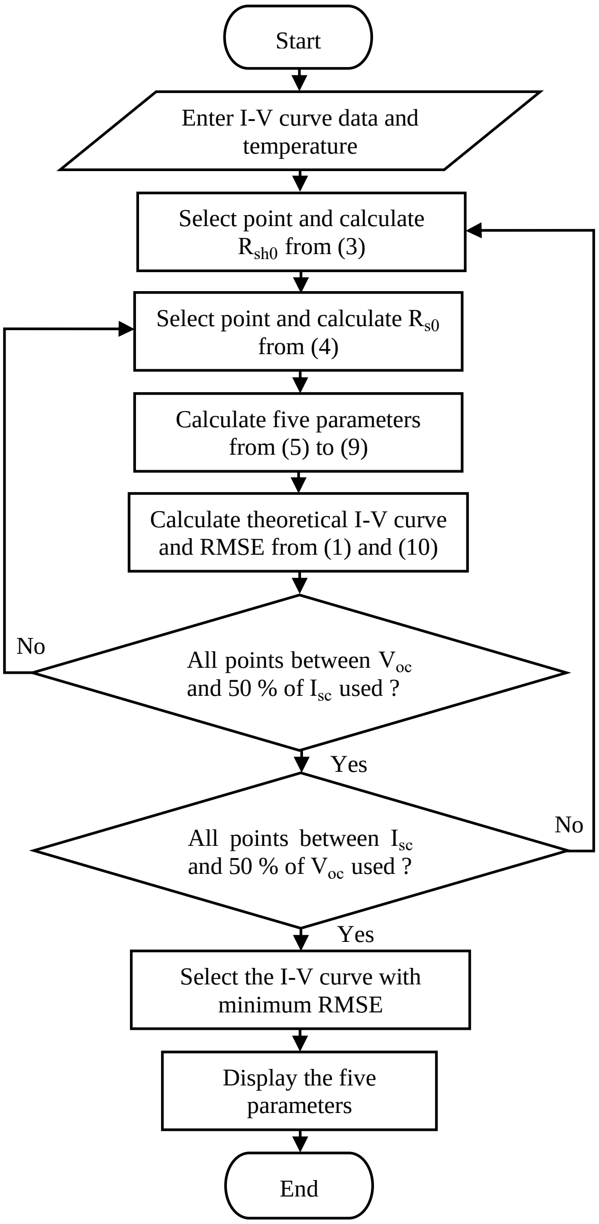

Fig. 2. The flow chart of the proposed algorithm combined with the model of Phang *et al.* [3].

An illustration of how the pairs of points is indexed is depicted in Fig. 3. For instance, the first pair constitutes the first index near I_{sc} with the first index near V_{oc}. The second pair constitutes the first index near I_{sc} with the second index near V_{oc}. This process in continued until all the points between V_{oc} and 50 % of I_{sc} are used. Then, the process in transferred to the second index near I_{sc} to be used with all points between V_{oc} and 50 % of I_{sc} and so on until all the points between I_{sc} and 50 % of V_{oc} are utilised.

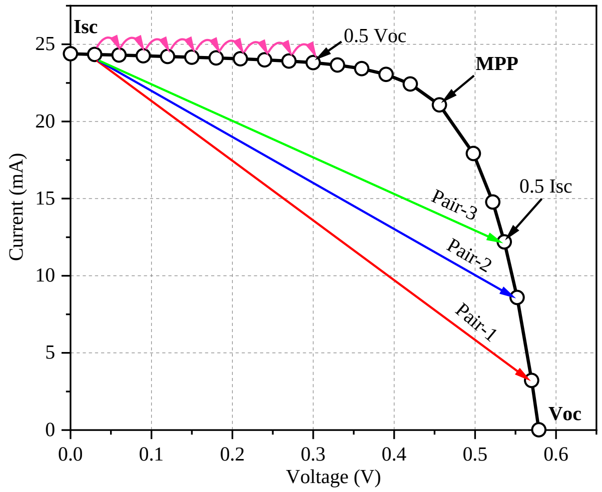

Fig. 3. An illustration of how the points used to calculate R_{sh0} and R_{s0} are indexed.

After all the I-V curves are stored, they are compared with the experimental I-V curve in terms of the Root Mean Square Error (RMSE). Finally, the curve that gives the minimum RMSE is selected as the best fit and its five parameters are displayed. The RMSE between theoretical and experimental I-V curves is determined from [13]:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(I_{i,exp} - I_{i,cal})^2}{N}} \qquad (10)$$

where: N is the number of data points, $I_{i,exp}$ and $I_{i,cal}$ are the experimental and theoretical values of the current of the i_{th} point in the I-V curves, respectively.

III. RESULTS AND DISCUSSION

A set of experiments were carried-out in order to validate the designed algorithm in terms of accuracy and computational time. In order to test this analytical method with I-V curves of different shapes, a mono-crystalline silicon (mono-Si) cell and an amorphous silicon (a-Si) module were characterised under Class BCA calibrated light source. The temperature of the cells was measured using a thermocouple and was kept fixed during the I-V curve sweep using a water circulator and a copper heat exchanger placed underneath the PV device. The I-V curves were obtained using Keithley 2601 I-V tracer with Test Script Builder (TSB) software.

A. *Results of Mono-crystalline Silicon Solar Cell*

The active area of the mono-Si cell is 0.78 cm². The cell was soldered on a printed circuit board (PCB). The specifications of this solar cell were obtained at standard test conditions (STC). The I_{sc} is 24.308 mA, the V_{oc} is 0.578 V, and the maximum power is 9.713 mW. The parameters were extracted using the proposed approach, an iterative method proposed by De Blas *et al.* [5] and an iterative/numerical method proposed by Villalva *et al.* [2]. The method of De Blas uses the slopes and hence it was implemented with two approaches to find them proposed by [10] and [11]. The program code of De Blas model was written in MATLAB based on the illustrations given in [5], [14]. Besides, the program code of Villalva model was also written in MATLAB according to the web page provided by the authors in [2], which provides a sample code for this model.

The RMSE, the mean absolute percentage error (MAPE) and the absolute percentage error (APE) were used as a measure of accuracy for comparison. The RMSE is determined from (10), whereas the MAPE is calculated from [13]:

$$\mathrm{MAPE} = \frac{\sum_{i=1}^{N}(|I_{i,exp} - I_{i,cal}|\,(100/I_{i,exp}))}{N} \qquad (11)$$

These two error values result in a single value for a complete I-V curve data. In order to assess the error at each point in the I-V curves, the APE is determined for every point as follows [13]:

$$\mathrm{APE} = |I_{i,exp} - I_{i,cal}|\,\frac{100}{I_{i,exp}} \qquad (12)$$

It is important to point out that the MAPE and the APE will result in undefined value when they are calculated for the V_{oc} point. This is because the current equals zero at this point and it is in the denominator. Hence, only this point is eliminated from the calculations.

The I-V curves at three different irradiance levels and fixed temperature of 25 °C are given in Fig. 4. The I-V curves at two different temperatures and fixed irradiance of 1000 W/m² are shown in Fig. 5.

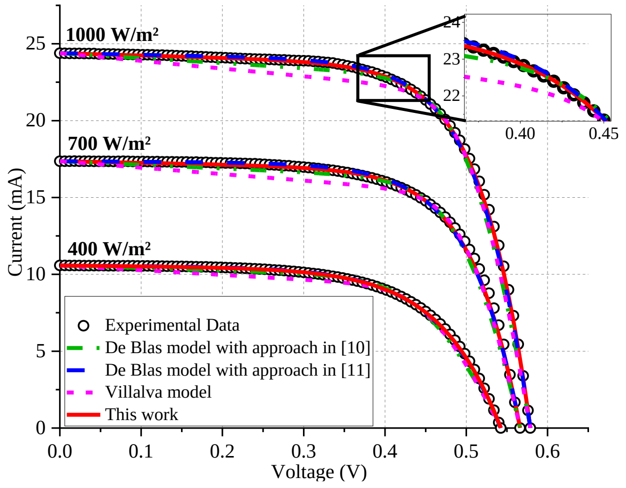

Fig. 4. Comparison between experimental and calculated I-V curves of the mono-Si solar cell using the four methods (three irradiance levels and fixed temperature of 25 °C).

It can be observed from the results in Figs. 4 and 5 that when using the proposed method, there is a good agreement between the experimental and theoretical results. The proposed method is even more accurate than iterative and numerical methods included in this comparison. This also can be seen from the results in Tables I and II, which compare the parameters calculated by the four methods, the RMSE and the MAPE. Tables I and II correspond to the I-V curves shown in Figs. 4 and 5, respectively.

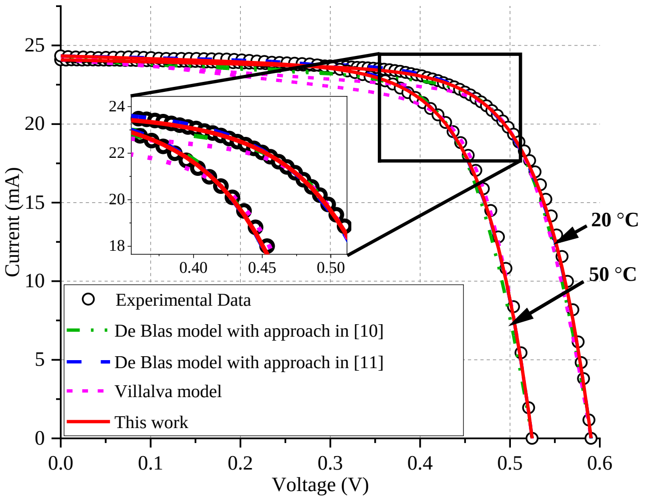

Fig. 5. Comparison between experimental and calculated I-V curves of the mono-Si solar cell using the four methods (two temperatures and fixed irradiance of 1000 W/m²).

As can be seen in Tables I and II, the proposed approach provided the minimum error. In some cases, such as under irradiance of 1000 W/m² and temperature of 50 °C shown in Table II, the method of De Blas using the approach in [11] became close to the proposed approach in terms of accuracy. The larger diversion between the measured and calculated data was noticed for Villalva model. This might be attributed to the fact that this model does not provide a method for calculating the ideality factor and hence a fixed value of 1 was assumed [2].

The APE was evaluated under irradiance of 1000 W/m² and temperature of 25 °C. It was calculated at each point in the I-V curve for all methods included in this study. The results are shown in Fig. 6, demonstrating the effectiveness of the proposed approach. It can be seen that the APE obtained from this work is generally small over the whole range compared to the other approaches, with a significant difference near V_{oc}. It is also interesting to see that the deviation at the MPP appears to be very small for all techniques.

TABLE I. Parameters Values and Errors Between Experimental and Calculated I-V Curves of the Mono-si Solar Cell Using the Four Methods (Three Irradiance Levels and Fixed Temperature of 25 °C)

Extraction Method	**Irradiance = 1000 W/m²**						
	***R_s* (Ω)**	***R_{sh}* (kΩ)**	***n***	***I_s* (μA)**	***I_{ph}* (mA)**	***RMSE (A)***	***MAPE (%)***
De Blas model with approach in [10]	1.829	0.309	1.271	0.00046	24.532	5.114×10^{-4}	2.772
De Blas model with approach in [11]	0.504	1.015	2.058	0.420	24.399	2.303×10^{-4}	1.094
Villalva model	2.133	0.198	1	3.575×10^{-6}	24.650	7.199×10^{-4}	3.756
This work	0.344	0.687	2.060	0.418	24.448	1.444×10^{-4}	0.694
	Irradiance = 700 W/m²						
De Blas model with approach in [10]	2.233	0.420	1.337	0.00112	17.452	4.168×10^{-4}	2.761
De Blas model with approach in [11]	0.191	3.574	2.266	1.027	17.359	2.207×10^{-4}	1.231
Villalva model	2.532	0.237	1	4.071×10^{-6}	17.545	5.972×10^{-4}	3.784
This work	0.396	0.962	2.073	0.405	17.367	1.956×10^{-4}	1.165
	Irradiance = 400 W/m²						
De Blas model with approach in [10]	5.968	0.590	1.363	0.00182	10.682	2.349×10^{-4}	3.283
De Blas model with approach in [11]	1.391	3.353	2.540	2.558	10.577	7.751×10^{-5}	1.032
Villalva model	6.741	0.321	1	6.157×10^{-6}	10.797	3.597×10^{-4}	4.523
This work	0.922	2.163	2.584	2.913	10.580	4.545×10^{-5}	0.605

TABLE II. Parameters Values and Errors Between Experimental and Calculated I-V Curves of the Mono-si Solar Cell Using the Four Methods (Two Temperatures and Fixed Irradiance of 1000 W/m²)

Extraction Method	**Temperature = 20°C**						
	***R_s* (Ω)**	***R_{sh}* (kΩ)**	***n***	***I_s* (μA)**	***I_{ph}* (mA)**	***RMSE (A)***	***MAPE (%)***
De Blas model with approach in [10]	1.390	0.337	1.259	0.00019	24.185	5.340×10^{-4}	2.969
De Blas model with approach in [11]	0.079	1.602	2.073	0.301	24.086	2.446×10^{-4}	1.180
Villalva model	1.807	0.242	1	1.545×10^{-6}	24.265	7.196×10^{-4}	3.937
This work	0.209	0.754	1.914	0.116	24.095	2.072×10^{-4}	1.050
	Temperature = 50°C						
De Blas model with approach in [10]	1.577	0.281	1.101	0.00084	24.469	6.069×10^{-4}	3.189
De Blas model with approach in [11]	0.066	0.909	1.877	1.035	24.334	2.493×10^{-4}	1.213
Villalva model	1.041	0.155	1	0.00014	24.497	7.504×10^{-4}	3.195
This work	0.136	0.573	1.786	0.613	24.339	2.320×10^{-4}	1.201

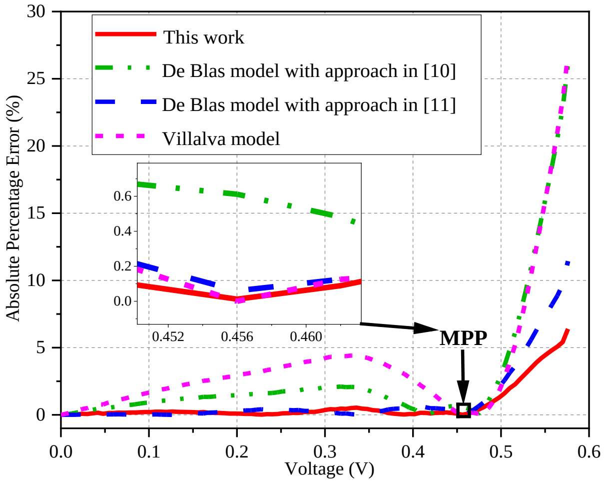

Fig. 6. Absolute percentage error (APE) for each voltage of the mono-Si solar cell using the four methods (irradiance of 1000 W/m² and temperature of 25 °C).

B. *Results of Amorphous Silicon Solar Module*

An a-Si solar module (SANYO AM-8701) with an area of 28.78 cm² was used. This module consists of 7 solar cells connected in series. The maximum power of the module given in the data sheet under STC is 190 mW. The current and voltage at the maximum power are 41.2 mA and 4.6 V, respectively. The method of De Blas using both approaches of [10] and [11] was also applied to extract the parameters of the experimental I-V curves. As the method of Villalva [2] did not provide a reasonable solution and has convergence issues with this module, it has not been included in the comparison. Shown in Fig. 7 are the I-V curves at three different irradiance levels and fixed temperature of 25 °C. Fig. 8 depicts the I-V curves at two temperatures and fixed irradiance of 1000 W/m².

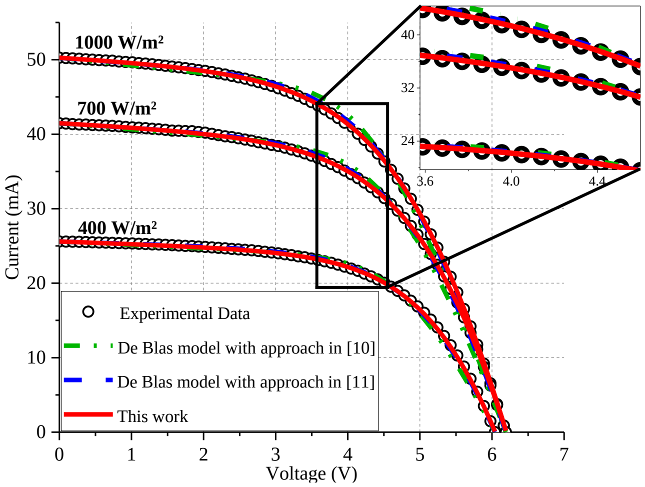

Fig. 7. Comparison between experimental and calculated I-V curves of the a-Si solar module using the three methods (three irradiance levels and fixed temperature of 25 °C).

As can be seen from Figs. 7 and 8, the enhanced analytical method of Phang is also capable of producing accurate parameters for a-Si modules. The agreement between the theoretical and measured I-V curves is satisfactory. In addition, this approach provided more accurate results than the other iterative methods compared herein.

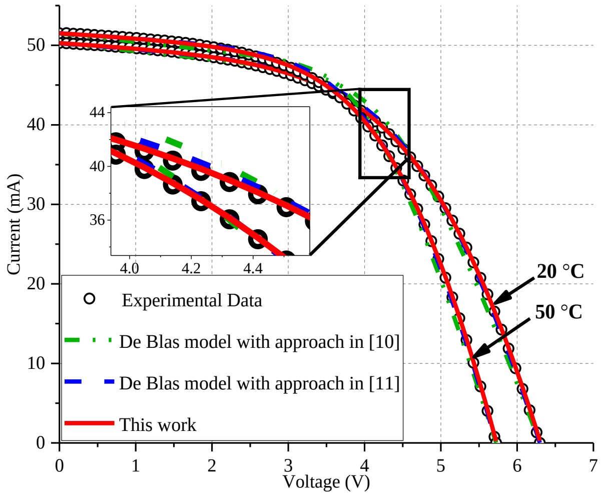

Fig. 8. Comparison between experimental and calculated I-V curves of the a-Si solar module using the three methods (two temperatures and fixed irradiance of 1000 W/m²).

The MAPE of the proposed approach was calculated and found to be less than 1 % in all cases in Figs. 7 and 8, even though the shape of the I-V curve is greatly different from the normal crystalline silicon curves. Fig 9. illustrates the APE at each point in the I-V curve for the three methods in the case of irradiance of 1000 W/m² and temperature of 25 °C.

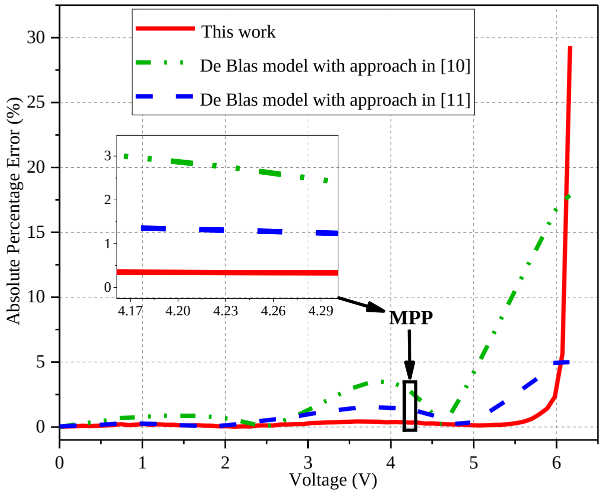

Fig. 9. Absolute percentage error (APE) for each voltage of the a-Si solar module using the three methods (irradiance of 1000 W/m² and temperature of 25 °C).

As shown in Fig. 9, the algorithm developed in this work led to a very small APE except at the vicinity of V_{oc}. By contrast, the other two approaches showed a fluctuating APE throughout the I-V curve. At the MPP in particular, which is at 4.232 V, this work has much lower APE as highlighted in Fig. 9. Overall, the algorithm of this work shows a better accuracy compared with the other methods.

It is worth mentioning that in both PV devices used in this work, it has been found that the best point for calculating R_{s0} (in the range between V_{oc} and 50 % of I_{sc}) is the nearest point to V_{oc}. The best point for calculating R_{sh0} (in the range between I_{sc} and 50 % of V_{oc}), however, is different from one I-V curve to another.

C. Computational Time Evaluation

The computational time of Phang's model combined with the proposed algorithm highly depends on the number of data points processed. In order to assess the computational time and compare it with the other methods, the time of calculating the parameters of both devices used in the previous sections was computed. The time was assessed for the working condition of 1000 W/m² irradiance and 25 °C temperature. All the algorithms were run on a core-i5 processor computer, which has a RAM of 8 GB. Computing the time was accomplished using the MATLAB command (tic-toc) and the results are given in Table III.

TABLE III. COMPUTATIONAL TIME OF CALCULATING THE PARAMETERS USING THE FOUR METHODS APPLIED TO BOTH MONO-SI AND A-SI PV DEVICES

Extraction method	**Computational time (seconds)**	
	Mono-Si cell	***a-Si module***
De Blas model with approach in [10]	0.0124	0.0130
De Blas model with approach in [11]	0.0121	0.0124
Villalva model	16.8328	/
This work	0.0770	0.0872

The computational time of De Blas model with the two approaches of [10] and [11] is almost equal. The time of the proposed technique, on the other hand, is quite longer resulting in about 0.08 and 0.09 second for the mono-Si and a-Si, respectively. However, Villalva model has shown a higher computational time mainly because of involving both iterative and numerical processes in this method. In general, although the computational time of the proposed approach is larger than that of De Blas model, it is still very low compared to other methods, e.g. Villalva model. This is basically due to the simplicity of the added iterative process by the proposed technique. Moreover, the number of points pairs (Fig. 3) in the I-V curves processed by the proposed approach was 288 and 340 pairs for the mono-Si and a-Si, respectively. Despite this large number of theoretical I-V curves processed, the time taken to compute the final parameters is very short and less than 0.1 second.

IV. CONCLUSION

It has been shown in this work that the accuracy of analytical parameters extraction methods based on calculating the slopes can exceed the iterative/numerical methods if proper points are selected. The analytical method of Phang was enhanced by designing a MATLAB program that selects the best points from an I-V curve to find the slopes at the short circuit current and open circuit voltage points. This method has become more accurate than iterative/numerical methods in the literature included in this paper. This algorithm can be used as a useful tool to investigate the location of the best points to find the slopes with any type of solar cells, thereby allowing to extract the parameters from data sheet information only. Further, it can be useful when it is desired to extract the parameters from experimental I-V curves, e.g. in solar cells characterisation research. The proposed algorithm might be effectively used with any other parameters extraction method that depends on finding the slopes providing an optimum accuracy. The accuracy is verified with two I-V curves of different shapes and the results are satisfactory. Although the computational time of the analytical method is increased when adding the designed program, a low level of complexity is maintained and a high level of accuracy is achieved.

It is also to be noted that the technique reported in this paper has been proved to be valid for a single cell and multiple cells connected in series without bypass diodes. However, the validity of the technique for large panels and arrays, which consist of several tens or hundreds of cells with bypass diodes, needs to be investigated in future. In addition, the computational time of the technique applied to I-V curves with large number of experimental data points needs to be investigated.

ACKNOWLEDGMENT

Abdulhamid Atia acknowledges the sponsorship from the Ministry of Education in Libya. The solar cell characterisation facilities were developed under the projects EP/K029142/1 and EPK022156/1 supported by EPSRC.

REFERENCES

[1] K. Mertens, *Photovoltaics Fundamentals, Technology and Practice*. Chichester: Wiley, 2014.

[2] M. Gradella Villalva, J. Rafael Gazoli, and E. Ruppert Filho, "Comprehensive approach to Modeling and Simulation of Photovoltaic Arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, 2009.

[3] J. C. H. Phang, D. S. H. Chan, and J. R. Phillips, "Accurate analytical method for the extraction of solar cell model parameters," *Electron. Lett.*, vol. 20, no. 10, pp. 406–408, 1984.

[4] E. I. Batzelis and S. A. Papathanassiou, "A Method for the Analytical Extraction of the Single-Diode PV Model Parameters," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 504–512, 2016.

[5] M. A. De Blas, J. L. Torres, E. Prieto, and A. García, "Selecting a suitable model for characterizing photovoltaic devices," *Renew. Energy*, vol. 25, no. 3, pp. 371–380, 2002.

[6] P. Rodriguez, D. Sera, R. Teodorescu, and P. Rodriguez, "PV Panel Model Based on Datasheet Values," in *2007 IEEE International Symposium on Industrial Electronics*, 2007, pp. 2392–2396.

[7] D. Mathew, C. Rani, M. R. Kumar, Y. Wang, R. Binns, and K. Busawon, "Wind-driven optimization technique for estimation of solar photovoltaic parameters," *IEEE J. Photovoltaics*, vol. 8, no. 1, pp. 248–256, 2018.

[8] X. Chen, B. Xu, C. Mei, Y. Ding, and K. Li, "Teaching–learning–based artificial bee colony for solar photovoltaic parameter estimation," *Appl. Energy*, vol. 212, no. December 2017, pp. 1578–1588, 2018.

[9] E. Batzelis, "Non-iterative methods for the extraction of the single-diode model parameters of photovoltaic modules: A review and comparative assessment," *Energies*, vol. 12, no. 3, pp. 14–28, 2019.

[10] M. S. Benghanem and S. N. Alamri, "Modeling of photovoltaic module and experimental determination of serial resistance," *J. Taibah Univ. Sci.*, vol. 2, no. 1, pp. 94–105, 2009.

[11] A. Orioli and A. Di Gangi, "A procedure to calculate the five-parameter model of crystalline silicon photovoltaic modules on the basis of the tabular performance data," *Appl. Energy*, vol. 102, pp. 1160–1177, 2013.

[12] O. Mares, M. Paulescu, and V. Badescu, "A simple but accurate procedure for solving the five-parameter model," *Energy Convers. Manag.*, vol. 105, pp. 139–148, 2015, doi: 10.1016/j.enconman.2015.07.046.

[13] N. Nehaoua, Y. Chergui, and D. E. Mekki, "Determination of organic solar cell parameters based on single or multiple pin structures," *Vacuum*, vol. 84, no. 2, pp. 326–329, 2009.

[14] G. Ciulla, V. Lo Brano, V. Di Dio, and G. Cipriani, "A comparison of different one-diode models for the representation of I-V characteristic of a PV cell," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 684–696, 2014.