



Optimal parameters estimation and modelling of photovoltaic modules using analytical method



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ABSTRACT

This paper introduces a proposed approach to estimate the optimal parameters of the photovoltaic (PV) modules using in-field outdoor measurements and manufacturers' datasheet as well as employing the nonlinear least-squares fitting algorithm. The main goal is to determine the optimal parameter values of the implemented model which are: series resistance, reverse saturation current, photocurrent, ideality factor and shunt resistance in case of the five parameters model. A Microsoft Excel spreadsheet is developed in order to perform modeling and analysis of the parameters analytical initial values using manufacturer datasheet specifications regarding to the changing in solar irradiance and ambient temperature. Then, the sum of the squared residuals between in-field measured and simulated data are calculated and minimized using Excel solver in order to obtain the optimal values of the parameters simultaneously, to describe the best fit for the outdoor measured data. The proposed approach is used to find the optimal parameters of the PV module TRINA TSM-295 using an array tester. The convergence confidences of the estimated parameters are presented and assessed in an easy way. This approach allows all parameters to be optimized, simultaneously. The results are verified and compared with other research studies for different PV cell technologies. The obtained results are useful for the tested PV module manufacturer and assess the performance of the products in different weather conditions.

1. Introduction

Appropriate circuit modeling and optimal parameters estimation of the photovoltaic (PV) modules are critical topics for different activities such as: simulation, design, assessing efficiency computations, performance evaluation under various conditions and control of PV systems [1, 2, 3]. Also, it is useful for monitoring operation of PV systems, forecasting produced power, developing fault detection methods, calculating losses, developing and testing maximum power point tracking (MPPT) algorithms [4] and reproducing the references of PV simulators as a function of real time variation of irradiance and temperature values to test the commercial PV inverters [5].

The PV cells are usually characterized using current-voltage (I-V) and power-voltage (P-V) curves. The manufacturers present the datasheet specifications at the standard test conditions (STC) for open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power point (mpp) i.e. current (I_{mpp}) voltage (V_{mpp}) and power (P_{mpp}) [6]. For some manufacturers, the values of the temperature coefficients for open circuit voltage (β_{oc}) and short circuit current (α_{sc}) are also tabulated. The PV cell

equivalent circuit is conventionally represented using current source and one diode without any hint to series resistance (R_s) and parallel resistance (R_p) in the ideal PV cell model. Various studies have been presented for development the PV cell models. However, these models have different levels of the complexity. The differences between these models are based on the employed diodes numbers, finite or infinite shunt resistance, fixed or variable ideality factor and the utilized algorithms to find required parameters. So far, a comparison between the presented PV cell models is an important topic in the scientific community [7].

The model of the PV cell characteristic is obtained based on physical principles. The equivalent model of single diode parameters is based on the employed circuit, such as photocurrent current (I_{ph}), saturation current (I_0), diode ideality factor (n), R_s and R_p resistances. However, these parameters are neither always explicitly nor completely provided by the manufacturers of PV modules. Consequently, choice of electrical PV cells model and the method of parameters extraction are based on different principles such as estimation speed, PV technology, complexity and accuracy [8]. In [8], the authors discussed five PV cells mathematical models of varying complexity, such as lumped four parameters (L4P) and

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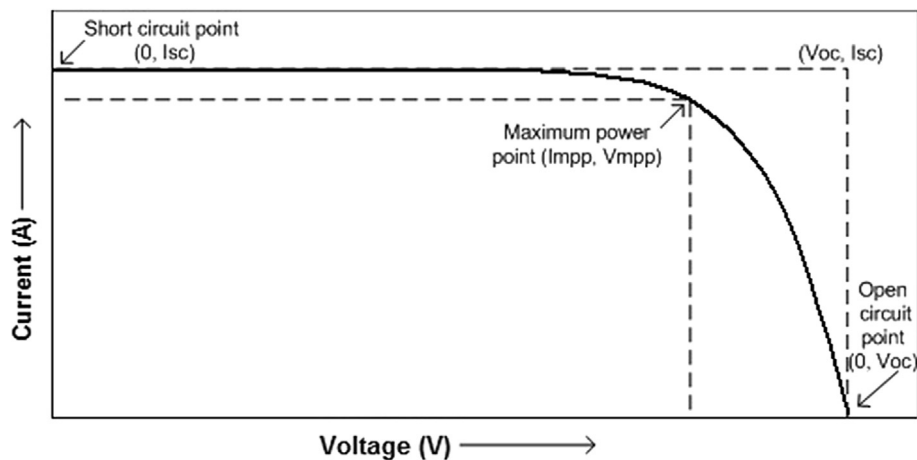


Fig. 1. I-V characteristic curve of a PV cell.

lumped five parameters (L5P) methods in order to investigate the long term performance of direct coupled PV systems. The authors concluded that, the L4P model of the multicrystalline PV module presented the best match to the experimental measured data, at low irradiance of 200 W/m^2 [9].

Authors in [10] referred to an iterative method proposed by [11] based on fitting the theoretical curve to the experimental points (the voltage and slope at the open circuit point, the maximum power point (V_{mpp} , I_{mpp}), the current and slope at the short circuit point) as 5-points method. This method did not fit the model to every point of the curve, but achieved good fitting with experimental measured data. However, there are practical difficulties in measuring the slopes, specially the short circuit slope. Authors in [12] presented a direct analytical extraction of 5-points method using experimental data based on least square technique. The authors employed an iterative procedure in order to determine the equation of a silicon solar array from empirical data measured at 21 points, where all points were considered. Finally, the authors in [10], presented a comparison between curve-fitting, iterative 5-points and analytical 5-points methods for estimating the parameters of the single-diode model.

As stated in [13], there is a need for analytical expression to determine the parameters I_{ph} , n , I_0 , R_s and R_p , directly. A comparison between an analytical expression and an iterative method for parameters estimation was presented in [13]. Analytical methods are derived for simple and fast procedures by simplifying the assumptions without sacrificing accuracy [13, 14, 15]. Numerical methods employ a set of equations and find a solution using iterative algorithms [16, 17]. Several techniques have been presented to find the optimal parameters of the PV modules using analytical or iterative techniques based on the manufacturers data sheet information only [18, 19, 20, 21, 22]. In [14], six prevalent analytical methods for modeling and extracting parameters of the PV modules were evaluated. The authors concluded that, the analytical methods can compete in terms of accuracy with the numerical methods. In [23], the authors presented a set of analytical solutions, which can be used as initial values for estimating L5P double-diode model for numerical solutions based on Newton–Raphson method.

There are many databases of research publications under the topic of PV modelling and the parameter estimation. A review on the important research works on modelling and parameters estimation of the PV cells can be found in [24]. The authors discussed three PV cell models, namely the single diode R_s , R_p and the two diodes. Also, the authors covered both the analytical and the soft computing approaches for parameters estimation. Finally, the review in [24] recommended hybrid approach between soft computing and analytical methods. Most of the used PV cell parameters extraction methods are graphical, analytical, numerical, heuristics or from artificial intelligence as presented in [9].

As stated in a review can be found in [2] that, the PV cell parameters can be evaluated using manufacturer data sheet information and experimentally measured I-V curves. Also, the author classified the PV cell parameters estimation methodologies into three main approaches as: analytical, metaheuristic optimisation and hybrids of analytical and metaheuristic. The nonlinear least square fitting is widely used to find parameters of PV modules. The nonlinear least squares approach extracts parameters of PV cells by reducing least squared error between simulated target variables and experimentally measured data. However, the current and voltage in PV cell equation (I_{pv} , V_{pv}) takes the form of an implicit function, which includes dependent and independent variables in both sides of the equation at the same time. Such implicit nature of the PV module equation increases the complexity and the difficulty of parameters extraction [25].

A modified non-linear least error square optimization approach was presented in [26] based on Newton's method to extract five illuminated PV cell parameters using the experimentally measured data. The authors introduced an initialization routine of two parameters in order to overcome the difficulty in initializing the parameters. In [27], the authors presented an analytical solution technique based on Co-content function, which was expressed in terms of the Lambert W function to extract the PV cell parameters by numerical fitting of the equations. Similar analytical solution methods were presented in [28, 29, 30]. In [31, 32, 33, 34], the authors employed the pattern search optimization technique [31], Bacterial Foraging Algorithm [32], harmony search-based algorithms [33] and bird mating optimizer [34] for extracting the parameters of different PV cell models.

In [35], an approach to determine the required parameters of the PV cell using a single I-V curve under constant illumination value was presented. The authors used Lambert W function and reduced the estimated parameters, so that, the expression for I_{pv} was depending only on n , R_s , and R_p . Then, the PV cell parameters were directly extracted by fitting the analytical expression with the experimentally measured data. In [36], the authors presented a technique for determining the PV cell parameters using the light generated I-V curve based on an assumption for different technologies of the PV cells. This technique neither involved an initial approximations nor included an iteration processes. This approach was programmed and implemented on C platform.

The determination of PV module parameters using experimentally measured data is important for designing and sizing of PV systems [10]. An accurate model of PV cells is useful to predict performance of the system [6]. The PV systems designers select between different PV modules. The optimization of such systems is the main goal for designers in order to select PV module with the best performance based on available information. But, the manufacturers do not provide sufficient data in order to get an accurate analysis [37]. The objectives of this paper are

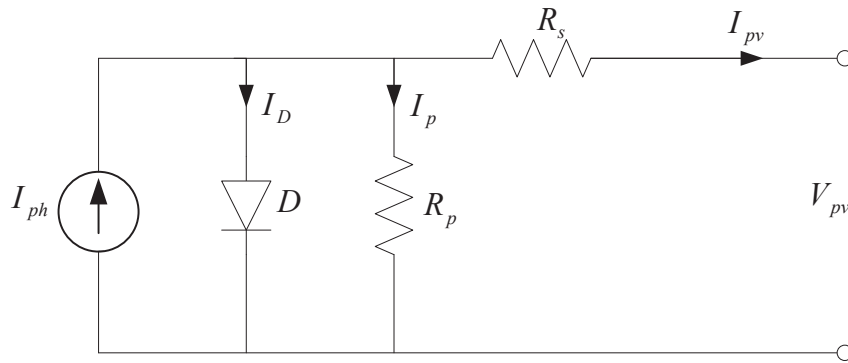


Fig. 2. Equivalent circuit for a single diode model.

modeling and estimating the optimal parameters of PV modules using the proposed approach. A Microsoft Excel spreadsheet is employed to simulate the I-V curve of the PV modules and determine the initial values of parameters based on analytical expressions and finally to estimate the optimal values of parameters based on the curve fitting to measured data using the Excel solver. This paper proposes an approach to estimate the PV module parameters using outdoor test data and simulated data. A simple and rapid procedure is proposed to find the optimal parameters of the PV module. The paper is organized as follows: Section 2 discusses the mathematical model of PV modules and reviews the different approaches of analytical initial conditions and parameter estimation studies. Section 3 presents the proposed approach to estimate the optimal parameters of the PV modules. Section 4 contains the experimental measurements data of the case studied and the implementation of least squares data fitting using the Excel solver. Section 5 affirms on the proposed approach validation and its accuracy. Results and discussions are declared in section 6. Finally, the conclusions can be found in Section 7.

2. Background

2.1. Background of the solar cell mathematical modeling

There are different approaches for modeling and simulating the PV cells. In [38], the authors used artificial neural network and Lambert W function for modeling the PV cells characteristics and estimating the model parameters using real experimentally measured data. Most common approaches are employing the equivalent electrical circuit model of PV cells [2]. However, Authors in [39], focused on multi-junction PV cells to improve the conversion efficiency based on an electrical equivalent circuit of the multi-junction cells. The electrical characteristics of the PV modules are defined by I-V characteristic curves as shown in Fig. 1. The manufacturer's data sheet presents information about the PV module such as open circuit voltage (V_{oc}), short circuit current (I_{sc}), peak power (P_{max}), voltage and current at maximum peak point (V_{mpp} , I_{mpp}) at different indoor conditions such as the standard test condition (STC) as well as the nominal operating cell temperature (NOCT). The different weather conditions, types of the used materials and manufacturing technologies are the main items which affect on the PV module parameters. The PV systems installations environment are different from the STCs. Parameters determination using only the manufacturers data sheet leads to an inaccurate result of the estimated parameters.

The equivalent circuit of the single diode LSP is shown in Fig. 2 [1].

$$I_{pv} = I_{ph} - I_D - I_p \tag{1}$$

where, I_{pv} is the generated current by the PV cell, I_D is the Shockley diode current and I_p is parallel resistance current.

The Shockley diode (I_D) equation can be expressed as follows [40]:

Table 1
Different approaches of the parameters estimation studies.

Additional information	Iteration	Initial parameters
Single diode LSP model		
[22] Slope at OC and SC	No	No
[43] points	No	Yes (I_{ph} , I_0 , R_s , R_p and a)
[21]	Yes, for the convergence of R_s	Yes (R_s)
[16] None	Yes to compute R_p and R_s	Yes (a)
[46] None	Optimization algorithm to solve for all parameters	Yes (I_{ph} , I_0 , R_s , R_p and a)
[17] M (Air mass modifier)	Nonlinear equation solver	Yes (I_{ph} , I_0 , R_s , R_p and a)
[31] I-V curve	non-linear least error	Yes (R_p , a)
[52]	A piecewise curve-fitting method	Yes (I_{ph} , I_0 , R_s , R_p and a)
[53]	Optimization algorithm to solve for R_s and R_p	Yes (a)
[54]	Nonlinear equation solver	Yes (I_{ph} , I_0 , R_s , R_p and a)
[55]	non-linear least error to solve for I_{ph} , I_0 and R_p	Yes (R_s , R_p , a)

$$I_D = I_0 \left(\exp \left[\frac{q(V_{pv} + R_s I_{pv})}{nKT_c} \right] - 1 \right) \tag{2}$$

where; I_0 is the dark saturation current (A),

- n is the diode ideality factor (unitless),
- K is the Boltzmann's constant (1.38066×10^{-23} J/K),
- q is the elementary charge (1.60218×10^{-19} coulomb),
- R_s is the series resistance (Ω),
- T_c is the module temperature ($^{\circ}C$)

Finally, by developing the terms I_D , I_p and I_{ph} , the I-V characteristic can be calculated using Eq. (3), which presents the single diode R_p model [2, 40]:

$$I_{pv} = I_{ph} - I_0 \left[\exp \left[\frac{q(V_{pv} + R_s I_{pv})}{nKT_c} \right] - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_p} \tag{3}$$

The single diode LSP model seeks about five parameters values, i.e. I_{ph} , I_0 , n , R_s and R_p . There are different methods to solve Eq. (3) using the different approximation mathematical models. The different models generally employ the manufacturers data sheet information. The L4P model assumes that the shunt resistance has infinite value and can be neglected. Eq. (3) can be rewritten using the following equation:

$$I_{pv} = I_{ph} - I_o \left[\exp \left[\frac{(V_{pv} + R_s I_{pv})}{nV_t} \right] - 1 \right] \quad (4)$$

where, V_t is the thermal voltage of a cell given by the following approximation [37]:

$$V_t = \frac{KT_c}{q}$$

Authors in [40] identified the product of n^*V_t in Eq. (4) as a single parameter denoted as (a). So, Eq. (4) can be written using the following equation.

$$I_{pv} = I_{ph} - I_o \left[\exp \left[\frac{(V_{pv} + R_s I_{pv})}{a} \right] - 1 \right] \quad (5)$$

The L4P model needs the calculation of four parameters values, i.e. I_{ph} , I_o , a and R_s .

The one diode model is widely used within specific software toolboxes for estimating and predicting the produced power by PV systems and the algorithms of MPPT [41]. Different approaches of the single diode L5P model estimation studies are presented in Table 1. Several research studies presented different equations or approaches in order to be used for estimating L5P using manufacturer data sheet information [20, 21, 22, 42, 43, 44]. It can be found that, the L5P model demands extra information due to its complexity as presented in the second column of Table 1, in addition to the data presented by the manufacturers datasheet at STC, i.e. $P_{max,STC}$, $V_{oc,STC}$, $I_{sc,STC}$, $V_{mpp,STC}$, $I_{mpp,STC}$, α_{sc} and β_{oc} . Additional information about slopes at short circuit and open circuit points are needed as in [21, 22, 42, 43]. In the context of the PV simulator and array tester devices, this can be considered as a disadvantage because the PV module manufacturers do not provide these data readily. When the I-V curve and the slopes information are obtained, its passage to the simulator is not convenient.

Extraction of PV module parameters using analytical methods can be achieved using data in manufacturers datasheet. In [45], the authors employed an empirical model of PV array based on an initial value of the Shockley diode ideality factor equal 2. Many authors discussed ways to estimate the correct value for this constant, but usually it is selected as $1 < a < 1.5$ according to [16, 37, 46]. There are other perspectives for estimating ideality factor because of the higher values are affecting on the curvature of I-V characteristics and values of resistances. According to [37], the most accurate value is near to operating point and provides good agreement with the experimental measured values. In [16], the authors used the manufacturer data sheet in order to estimate R_s and R_p initial values to fit the maximum power point of theoretical and experimental measured curves.

Many approaches of optimization techniques have been presented in order to extract five parameters of the PV model using experimentally measured I-V curves only [31, 32, 33, 34, 47]. This approaches in general, execute the fitting methods to the experimental measured data without taking into account any theoretical values of the manufacturer data sheet. In the resolution of this uncertainty, several computing techniques have been presented recently. Authors in [48, 49], presented adaptive differential evolution algorithm for the extraction of L5P using synthetic and the experimentally measured I-V curve. In [50], an analytical method for the parameters extraction based on the manufacturers data sheet only was presented. In [51], the authors modified the four parameters model in order to fit the I-V curve by employing an equation to describe the V_{oc} . The author in [52] proposed complex method to find the L5P of the PV model. The author presented an analytical method to estimate the L4P using the manufacturer data sheet. Then, piecewise fitting algorithm and L4P have been used in order to obtain two differential values for short circuit and open circuit points at

STC. Finally, an explicit method was used to extract L5P at STC and to revise the five parameters with the experimentally measured data at the in-field operating conditions.

Authors in [53] employed an analytical method to calculate the initial values of series resistance and shunt resistances using manufactures data sheet. Then, R_s and R_p were estimated by means of fitting to measured I-V characteristic using MATLAB based on Newton Raphson method optimization technique. By this way, the author avoided the negative values of R_s and R_p . It can be noticed that R_s and R_p were not affected by the irradiance and temperature. The author used the LabVIEW software to acquire the environmental conditions which affect on the photocurrent by means of sensors which measure the irradiance and temperature of the PV panel surface. Only I_{ph} and I_o were estimated considering the environmental conditions, while a, R_s , and R_p , were counted as constants for different weather conditions. To obtain accurate results, the effects of the various environmental conditions should be considered [24].

In [36], the authors presented analytical technique in order to estimate all parameters without any initial approximations or iterations. Also, this analytical technique was employed for estimating parameters of different PV cells technologies. This technique was programmed and implemented using C platform. The author in [54], presented hybrid approach of numerical and analytical methods. The obtained values of the analytical approach were used as an initial values for solving the nonlinear equations of the parameters in MATLAB. The author validated this approach using indoor and outdoor experimental measurements. A hybrid approach of numerical and analytical solution was presented by [55]. The author estimated R_s and the ideality factor n using analytical formulations based on the available data in the manufacturer's datasheet. The other three parameters of I_{ph} , I_o and R_p were extracted using measured I-V curves of PV module using the linear least squares method. But, the author appended the ideality factor equal to 1.3. Other model as in [17] required additional information such as air mass modifier. Authors in [19] presented analytical equations to estimate the initial values of R_p , R_s and n using the available data in the manufacturer datasheet. Then, the model parameters were computed by solving the equations in the MATLAB environment by using the Newton Raphson method. The author highlighted that, the use of proper initial values leads to decrease the maximum number of iterations to 12.

2.1.1. Parameters for real outdoor weather conditions

Generally, the PV modules are operating in different weather conditions consequently the required parameters are dependent on the environmental conditions such as solar radiation and temperature. Therefore, it is necessary to relate all parameters to outdoor conditions [2, 9, 40, 54].

The I_{ph} values depend on the cell temperature and the irradiance. I_{ph} can be calculated as the following equation [2, 52, 54]:

$$I_{ph} = \frac{G}{G_{STC}} (I_{ph,STC} + \alpha_{sc}(T_c - T_{STC})) \quad (6)$$

where, G_{STC} , $I_{ph,STC}$, and T_{STC} are solar irradiance, photocurrent and cell temperature at STC conditions, respectively. G , I_{ph} , and T_c are the relevant parameters at the real outdoor conditions, α_{sc} is the current temperature coefficient of the PV module.

Reverse saturation current (I_o) changes with PV cell temperature and can be computed using the following equation [52, 54]:

$$I_o = I_{o,STC} \left[\frac{T_c}{T_{STC}} \right]^3 \exp \left(\frac{q}{Ka} \left[\frac{E_{g,STC}}{T_{STC}} - \frac{E_g}{T_c} \right] \right) \quad (7)$$

where, $I_{o,STC}$ and T_{STC} are the reverse saturation current and the PV cell temperature at STC conditions, respectively. I_o and T_c are dependent on parameters at real outdoor condition. $E_{g,STC}$ is the material band gap energy and equal to 1.121 eV for silicon PV cell at STC.

The band gap energy (E_g) is slightly dependent on the PV cell

temperature at outdoor conditions and can be expressed as follows [9, 52]:

$$E_g = E_{g,STC}(1 - 0.0002677(T_c - T_{STC})) \tag{8}$$

Also, authors in [9] presented the formula of E_g as in Eq. (9), which is suitable for the silicon cells technology and the two diode model.

$$E_g = 1.17 - 0.000473 \frac{T_c^2}{T_c + 636} \tag{9}$$

The factor (a) can be estimated using the following equation [43, 52, 56]:

$$a = a_{STC} \left(T_c / T_{STC} \right) \tag{10}$$

The influence of R_s parameter cannot be neglected because it is responsible about the shape of I-V curve at maximum power point and depends on PV cell temperature and solar irradiance [52]. So, It is rational to determine R_s and R_p values corresponding to thermal parameters of the material. The formula of R_s can be described as follows [2, 9, 52, 54, 56, 57]:

$$R_s = R_{s,STC} \frac{T_c}{T_{STC}} \left[1 - \beta_{oc} \ln \left(\frac{G}{G_{STC}} \right) \right] \tag{11}$$

where, $R_{s,STC}$ is the series resistance at STC conditions and R_s is the resistance value at the real outdoor weather condition. The value of β_{oc} approaches 0.217.

Concerning the parallel resistance, the high values of R_p lead to flat slope of the short circuit point [52]. Authors in [9, 17, 56, 57] reported that, the R_p value is inversely proportional to the solar irradiance as follows:

$$R_p = R_{p,STC} \frac{G_{STC}}{G} \tag{12}$$

where $R_{p,STC}$ is the parallel resistance at STC conditions. R_p is the parameter values at the real outdoor weather condition.

It can be noticed that the PV cell temperature T_c has significant value for estimating other parameters at outdoor conditions. T_c can be represented as a function of ambient temperature T_a and G using the following expression [9, 52]:

$$T_c = T_a + \frac{G}{800} (T_{NOCT} + 293.15) \tag{13}$$

where, T_{NOCT} is the nominal temperature of the PV cells at 800 W/m², an ambient temperature of 20 °C and a wind speed of 1 ms⁻¹.

The PV module L4P can be obtained at the operating temperature and solar irradiance using Eq. (14) [40]:

$$\begin{cases} I_{ph} = \frac{G}{G_{ref}} * [I_{ph,STC} + \alpha_{sc} * (T_c - T_{c,STC})] \\ I_o = I_{o,STC} * \exp \left[\left(\frac{E_g}{a} \right) \left(1 - \frac{T_{c,STC}}{T_c} \right) \right] * \left(\frac{T_c}{T_{c,STC}} \right)^3 \\ R_s = R_{s,STC} \\ a = a_{STC} * \left(T_c / T_{c,STC} \right) \end{cases} \tag{14}$$

These four parameters (I_{ph} , I_o , R_s , a) are corrected to the environmental conditions changes using Eq. (14) to be used in Eq. (5)

2.1.2. Analytical initial conditions of parameters extraction

An unsuitable choice of bad initial parameters leads to increase the iteration number and sometimes leads to a divergence of the optimal solution [9, 36, 54]. In this section, literature on the analytical solutions

are discussed to obtain the initial values for the numerical employed algorithm. The photocurrent ($I_{ph,STC}$) was estimated as the short circuit current in many research studies. This assumption was considered as the best initial point in various refined iterative algorithms [9]. But, authors in [54] presented the following equation to obtain $I_{ph,STC}$ at the standard test conditions:

$$I_{ph,STC} = I_{o,STC} * \left[\exp \left(\frac{q(V_{oc,STC})}{N_s a_{STC} K T_c} \right) - 1 \right] + \frac{V_{oc,STC}}{R_{p,STC}} \tag{15}$$

where, $I_{o,STC}$ is the dark saturation current at standard test conditions, a_{STC} is the diode ideality factor at standard test conditions and N_s is the number of series cells.

Many authors as in [16] set the diode ideality equals 1. These values are accepted only for the ideal cell and cannot be accurate for a real diode. As reported and adopted by [9], real solar cells present high values of ideality factor ($1 \leq n \leq 2$). Consequently, authors in [54] presented the following equation at the standard test conditions:

$$a_{STC} = \frac{q(2V_{mpp,STC} - V_{oc,STC})}{N_s K T \left[\ln \left(1 - \frac{I_{mpp,STC}}{I_{sc,STC}} \right) + \frac{I_{mpp,STC}}{(I_{sc,STC} - I_{mpp,STC})} \right]} \tag{16}$$

The saturation current is dependent on the cell temperature rise and it is a function of cell temperature, short circuit current and open circuit voltage. According to [53] and [9], the initial value of the saturation current can be expressed as follow:

$$I_{o,STC} = \frac{I_{sc,STC}}{\exp \left(- \frac{q(V_{oc,STC})}{N_s a_{STC} K T_c} \right)} \tag{17}$$

Consequently, in [54], the authors used Eq. (18) in the final calculations, but it can be noted that the equation is function in $R_{s,STC}$, a_{STC} and $R_{p,STC}$. So, the authors used Eq. (17) firstly to calculate the series and shunt resistances in order to avoid the rotating references. The main idea is that, the values of $I_{ph,STC}$ and $I_{o,STC}$ can be calculated, if the values of $R_{s,STC}$, a_{STC} and $R_{p,STC}$ are known.

$$I_{o,STC} = \frac{I_{sc,STC} (R_{p,STC} + R_{s,STC}) - V_{oc,STC}}{R_{p,STC} \left[\exp \left(\frac{q(V_{oc,STC})}{N_s a_{STC} K T} \right) - \exp \left(\frac{q(I_{sc,STC} R_{s,STC})}{N_s a_{STC} K T} \right) \right]} \tag{18}$$

When the $R_{s,STC}$ value is set to a very low, this parameter can be neglected sometimes. However, many researchers assumed that the initial value of the $R_{s,STC}$ is fixed to zero. Authors in [9], used the following expression to compute $R_{s,STC}$:

$$R_{s,STC} = n_o * \frac{V_2}{I_2 - I_1} * \log \left(\frac{I_{ph} - I_2}{I_{ph} - I_1} \right) - \frac{V_2 - V_1}{I_2 - I_1} \tag{19}$$

where, (V_2 , I_2) and (V_1 , I_1) are two points on measured I-V curve, which are closed to the open circuit voltage point. Concerning the shunt resistance, the following formula can be used to calculate initial value of $R_{p,STC}$ as:

$$R_{p,STC} = \frac{V_{mpp,STC}}{I_{sc,STC} - I_{mpp,STC}} - \frac{V_{oc,STC} - V_{mpp,STC}}{I_{mpp,STC}} \tag{20}$$

On the other hand in [54], The authors presented the following equation to calculate $R_{s,STC}$ and $R_{p,STC}$ as:

$$R_{s,STC} = \frac{V_{mpp,STC}}{I_{mpp,STC}} - \frac{2V_{mpp,STC} - V_{oc,STC}}{(I_{sc,STC} - I_{mpp,STC}) \left[\ln \left(1 - \frac{I_{mpp,STC}}{I_{sc,STC}} \right) + \frac{I_{mpp,STC}}{(I_{sc,STC} - I_{mpp,STC})} \right]} \tag{21}$$

$$R_{p,STC} = \sqrt{\frac{R_{s,STC}}{\frac{qI_{o,STC}}{N_s k T_c a_{STC}} \exp\left(\frac{q(I_{sc,STC} R_{s,STC})}{N_s k T_c a_{STC}}\right)}} \quad (22)$$

In [19], the authors presented the following equations in order to calculate $R_{s,STC}$ and $R_{p,STC}$ as:

$$R_{s,STC} = \frac{V_{oc,STC} - \left[\ln\left(\frac{I_{ph,STC} - I_{mpp,STC}}{I_{o,STC}}\right) N_s V_t \right]}{I_{mpp,STC}} \quad (23)$$

$$R_{p,STC} = \frac{V_{mpp,STC} + R_{s,STC} I_{mpp,STC}}{I_{ph,STC} - I_{o,STC} \left[\exp\left(\frac{V_{mpp,STC} + R_{s,STC} I_{mpp,STC}}{N_s V_t a_{STC}}\right) - 1 \right] - I_{mpp,STC}} \quad (24)$$

Authors in [20], presented a procedure to estimate the L5P of one diode model using performance tabular data that have the minimal data provided by PV manufacturers data sheet. The resistances $R_{s,STC}$ and $R_{p,STC}$ are extracted using the graphical data given by the manufacturers. Also, three analytical correlations are defined based on the performance data for more than one hundred PV modules. Reciprocal for slope of I-V curve is dependent on the short circuit and the open circuit points corresponding to $R_{p,STC}$ and $R_{s,STC}$, respectively. Finally, The authors represented $R_{s,STC}$ and $R_{p,STC}$ using the following empirical equation:

$$R_{s,STC} = C_s \frac{V_{oc}}{I_{sc}}; R_{p,STC} = C_p \frac{V_{oc}}{I_{sc}} \quad (25)$$

where, $C_s = 0.11175$ and $C_p = 34.49692$.

The following analytical expressions are used as a start point for a numerical solution. The following approximations as in Eq. (26) are used to determine the initial values of the L4P at the standard test conditions as [40]:

$$\begin{cases} I_{ph,STC} = I_{sc,STC} \\ a_{STC} = \frac{\beta_{oc} * T_{c,STC} - V_{oc,STC} + E_g}{(T_{c,STC} * \alpha_{sc} / I_{ph,STC}) - 3} \\ I_{o,STC} = \frac{I_{ph,STC}}{\exp[(V_{oc,STC} / a_{STC}) - 1]} \\ R_{s,STC} = \frac{a_{STC} * \ln[1 - (I_{mpp,STC} / I_{ph,STC})] - V_{mpp,STC} + V_{oc,STC}}{I_{mpp,STC}} \end{cases} \quad (26)$$

3. Methodology

3.1. Methodology of the proposed approach

To estimate the performance of PV systems, reliable and effective predictive tools are important and must be sensitive to all the physical parameters. Predictive performance tools are used by designers of the PV systems to optimize the system performance and to maximize the cost effectiveness of the systems. It is better to use less accurate predictive tool that is suitable to represent the electrical behavior of PV cell by means of minimum technical data which is provided by the manufacturer data sheet [20]. An accurate performance estimation is dependent on the accurate estimation of the PV cell parameters.

In [17], the authors presented a model to predict the energy production and compared with the developed model by Sandia National Laboratory. The author used an external computational (commercial) software i.e. the engineering equation solver (EES). The integration of this software to stand-alone PV simulator, which is coded in LabView and C, may leads to incompatibility issues. The computational speed of this simulator is expected to be compromised in case of more data points on the I-V curve, which are utilized [24]. The authors in [36] presented an analytical technique which was programmed and implemented using C platform. Authors in [20] presented a simple BASIC routine to determine

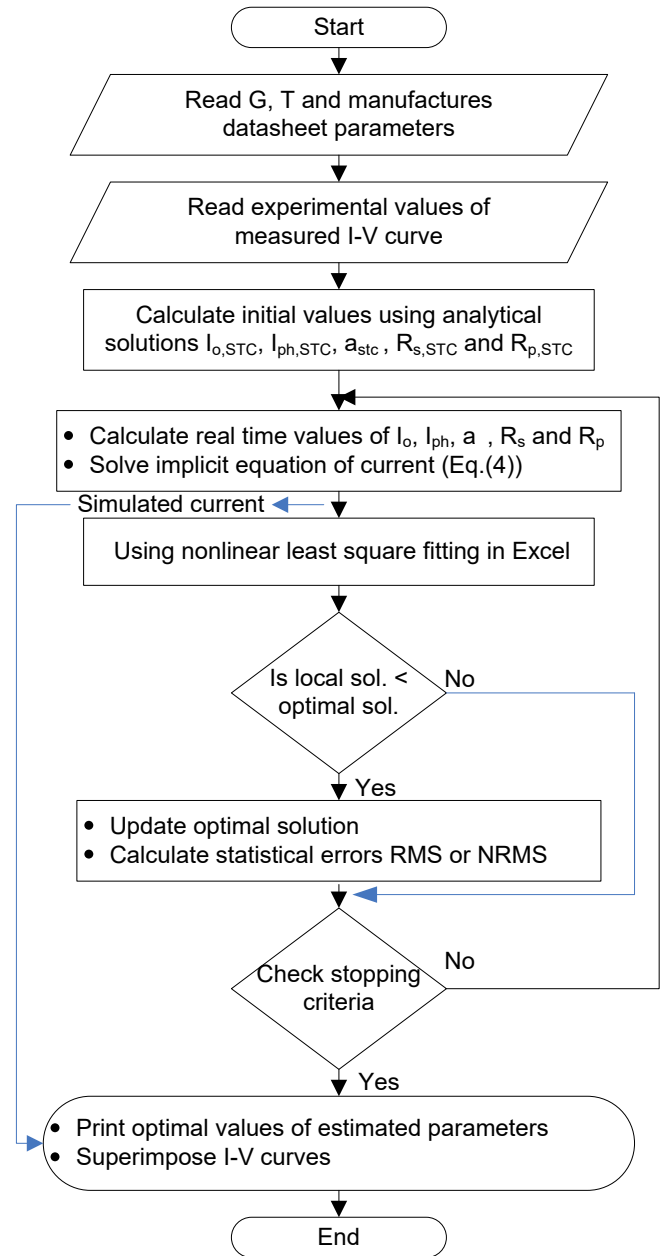


Fig. 3. Parameters' estimation flow chart using the proposed approach.

the parameters. This routine was easily used, like Visual Basic (VB) macros in Microsoft Excel.

Complex mathematical software packages such as SPICE, Mathematica and Matlab can carry out the nonlinear least squares fitting (NLSF). These programs have built in additional features such as the statistical tests to determine the confidence of the best fit and the advanced procedures such as the automated global fits [58]. Although such tools are used in the power electronics and for engineering applications, it might be beneficial to use Microsoft Excel, which is widely used for diverse calculations. Excel solver has been used in numerous and different applications. The authors in [58], introduced and described all details about the Excel solver.

Using Excel, a wider class of students can be enabled to become more interested in studying PV systems. Thus, this work presents a proposed approach using Microsoft Excel, where Microsoft Excel is used to model and estimate the optimal parameters of PV modules. Output values of solar simulator and array tester devices are used as input to the developed Excel worksheet. It is noted that, Eq. (5) is implicit and involves the

Table 2
Electrical data of TSM-295 PV module at standard test conditions.

Parameters	Values
I_{sc} (A)	8.55
V_{oc} (V)	45.2
V_{mpp} (V)	36.6
I_{mpp} (A)	8.07
β_{oc} (%/K)	-0.33
α_{sc} (%/K)	0.046

overall output current generated by the PV module in both sides at the same time. Furthermore, the parameters I_{ph} , I_o , R_s , a and R_p are varied with the solar irradiance and ambient temperature depending on the manufacturing tolerance [31].

The presented approach, to extract the optimal parameters of the PV module, is based on the least-squares fitting (LSF), i.e. by minimizing the difference between measured data point ($I_{measured}$) and its calculated counterpart (I_{model}). The evaluation is going on all data points which are considered in the regression analysis. This evaluation is used to guarantee the accuracy of the model using the real data [59]. Many references used the standard error analysis like the root mean squared error (RMSE) and mean absolute error (MAE) to determine the accuracy of their methods [24]. The employed objective function is to minimize the sum squared residuals between the measured data and simulation results and employ the relative weighting based on the measured data. The percentage RMS errors are presented as follows [51]:

$$RMS(\%) = \frac{\left[\frac{1}{n} \sum_{i=1}^n (I_{i,measured} - I_{i,model})^2 \right]^{\frac{1}{2}}}{\sum_{i=1}^n I_{i,measured}} \times 100 \tag{27}$$

Statistical analysis was performed to represent the accuracy using the normalized root mean square error (NRMSE), given by [55]:

$$NRMSE = \frac{\left[\frac{1}{n} \sum_{i=1}^n (I_{i,measured} - I_{i,model})^2 \right]^{\frac{1}{2}}}{\frac{1}{n} \sum_{i=1}^n I_{i,measured}} \tag{28}$$

This approach is practically straightforward and applicable whenever the error scales employ the measured variable as relative weight. The implementation of the proposed approach to find the optimal parameters of the PV modules using the measured data and the simulated data is shown in the flow chart as in Fig. 3. The simplicity of this approach makes it handy for power electronics engineers, assists the designers with an effective tool for accurate analysis and simulation of the PV modules.

4. Experimental

4.1. Experimental measurements of the studied case

4.1.1. Characteristics of PV module

In order to validate the PV model using in-field measurements, an experimental setup using the PV module TRINA-295 PC14 (Polycrystalline cells) and the array tester is established for detailed modeling. The PV module provides 295 W of nominal power and consists of 72 cells connected in series. The measurements of the I-V and P-V characteristic

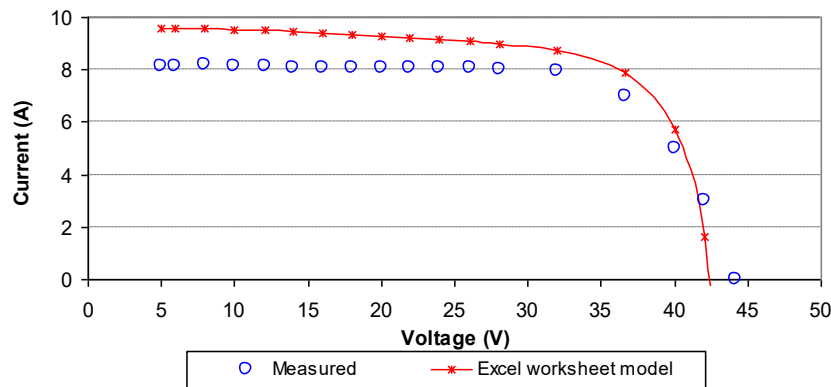


Fig. 4. PV module TSM-295 I-V curves for the experimental measurements and the L4P Excel worksheet model.

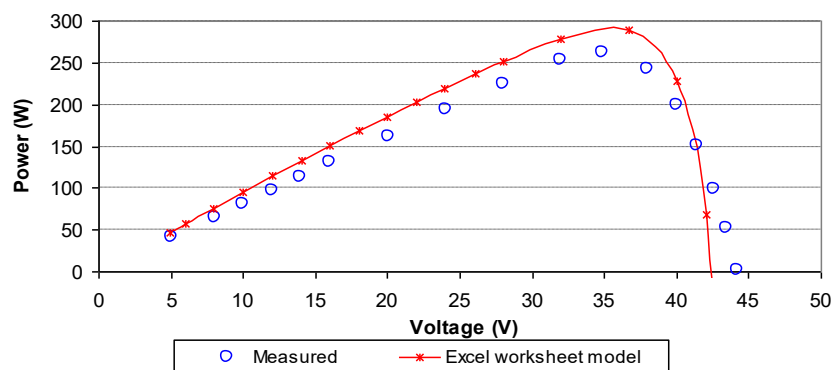


Fig. 5. PV module TSM-295 P-V curves for the experimental measurements and the L4P Excel worksheet model.

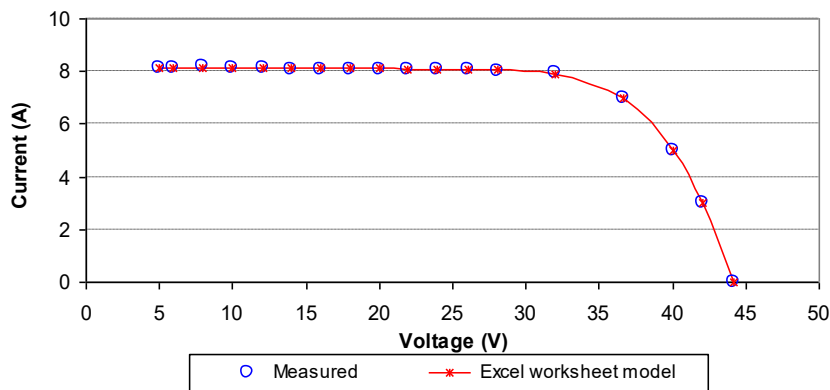


Fig. 6. PV module TSM-295 I-V curves for the experimental measurements and the fitted L4P model using Excel worksheet at 999.5 W/m² and 29 °C.

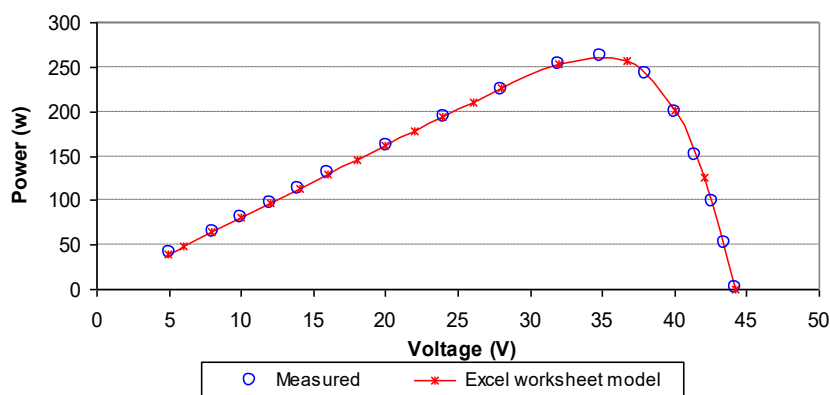


Fig. 7. PV module TSM-295 P-V curves for the experimental measurements and the fitted L4P model using Excel worksheet model at 999.5 W/m² and 29 °C.

curves of the considered PV module technology are performed with the array tester 550 at the Electronics Research Institute, Egypt. Experimental evaluation and characterization for power quality parameters of 8 kW grid connected system and all details about the considered field location in this paper can be found in [60, 61]. The solar irradiance and the ambient temperature as well as the I-V, P-V curves are all measured by the array tester 550, which is a reference cell and array tester. The tester contains a data acquisition card connected to a personal computer, and the output data can be collected using LabVIEW software. The manufacturer specifications of the PV module at the standard test conditions are presented in Table 2.

The importance of parameters estimation are presented using the measured actual data at the real outdoor conditions rather than the information given by the datasheet only. Developed Excel worksheet is constructed using the parameters given in the datasheet at the STC for PV module TRINA TSM-295 PC14. Firstly, by using Eq. (26) and the manufacture template data, the analytical solution of the four parameters initial values at STC conditions can be calculated. Then, the four parameters of the L4P model (I_{ph} , I_0 , R_s , a) are corrected to the real time measurement values of solar irradiance and ambient temperature using Eq. (14) and to be used in Eq. (5).

The simulation results of the I-V and P-V curves are compared to the

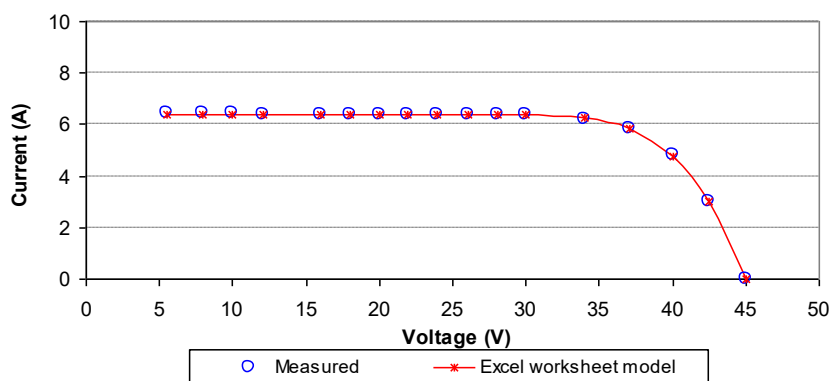


Fig. 8. PV module TSM-295 I-V curve for the experimental measurements and the fitted L4P model using Excel worksheet at 801.8 W/m² and 30 °C.

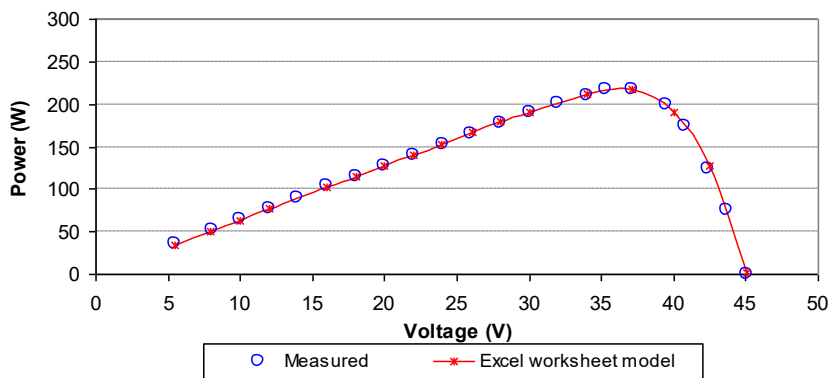


Fig. 9. PV module TSM-295 P-V curves for the experimental measurements and the fitted L4P model using Excel worksheet model at 801.8 W/m² and 30 °C.

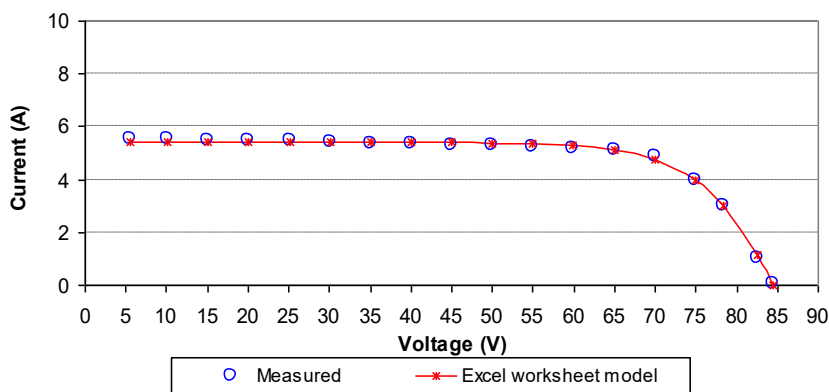


Fig. 10. Two series TSM-295 modules I-V curve for experimental measurements and Excel worksheet model at 694 W/m² and 31 °C.

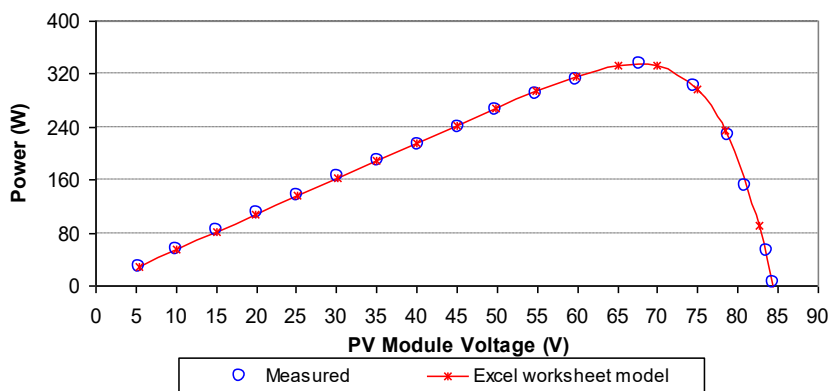


Fig. 11. Two series TSM-295 module P-V curve for experimental measurements and Excel worksheet model at 694 W/m² and 31 °C.

measurement results as provided in Figs. 4 and 5. These results show the difference between the analytical solution output obtained from the datasheet values at STC and the outdoor measured data. These results confirm that, estimated parameters which are dependent on the information given by the manufacturer data sheet only, have drawbacks and not more accurate to be applied for performance analysis.

4.1.2. Implementation of least squares data fitting

The importance of the algorithm is to fit the PV module current as in Eq. (3) for each measured I-V points. For each I-V curve, set of parameter

values (i.e., I_{ph} , I_0 , R_s , R_p , a) are obtained. Parameter values of the PV model are estimated by fitting the simulated I-V curve at the irradiance and temperature conditions with the measured I-V curve. The implementation of the nonlinear least-squares technique, to find the parameters of the PV module is shown in details in flow chart presented in Fig. 3. To relieve the effects of cabling connections on the calculated values of R_s , currents and voltages measurements are obtained at the PV module terminals.

The proposed approach of data fitting with the aid of Excel worksheet and solver can be divided into the following steps: (i) The RMS or NRMSE

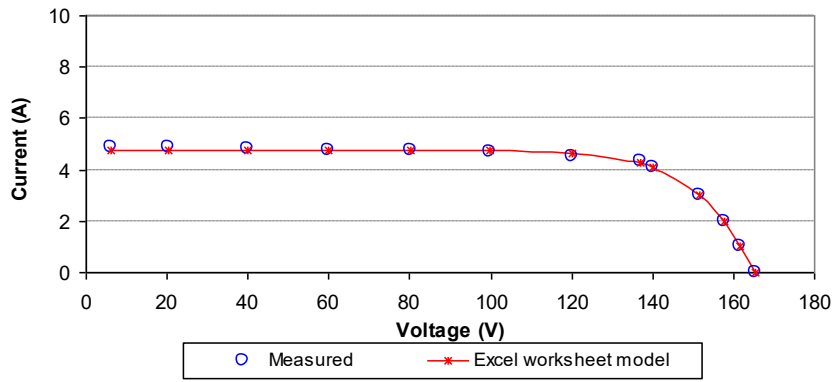


Fig. 12. Four series TSM-295 modules I-V curve for experimental measurements and Excel worksheet model at 653.8 W/m² and 30 °C.

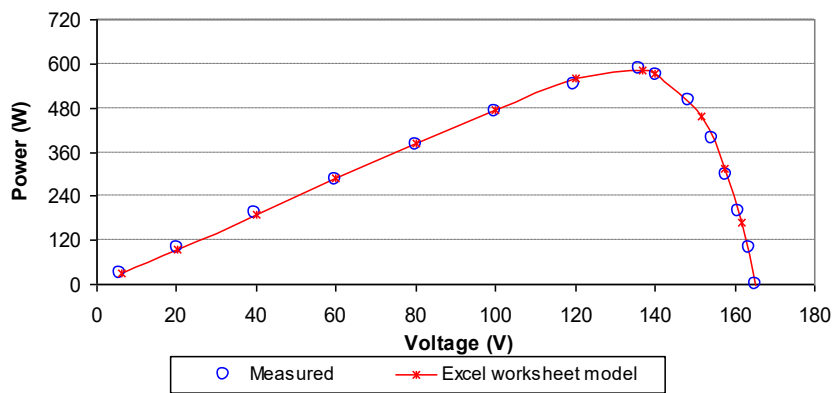


Fig. 13. Four series TSM-295modules P-V curve for experimental measurements and Excel worksheet model. 653.8 W/m² and 30 °C.

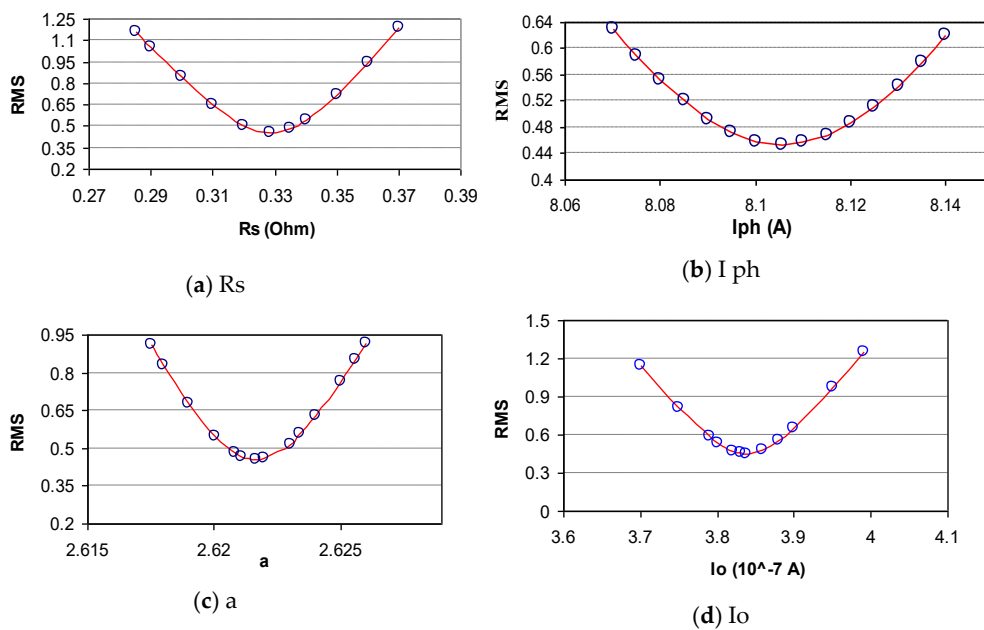


Fig. 14. Convergence characteristics L4P.

Table 3
PV module TSM-295 estimated four parameters.

Parameters	One Module		Two series modules	Four series modules
	999.5 W/m ² 29 °C	800 W/m ² 31 °C	694.6 W/m ² 29 °C	653.8W/m ² 30 °C
I _{ph} (A)	8.10563	6.39638	5.40645	4.78159
I _o (μA)	0.3838	0.0412	1.4277	2.0224
R _s (Ω)	0.32828	0.36944	0.5137	0.753788
a	2.62166	2.39017	2.785	2.8136
RMS	0.45409	0.47955	1.46412	1.31754

Table 4
PV module TSM-295 estimated five parameters.

Parameters	One Module		Two series modules	Four series modules
	999.5 W/m ² 29 °C	800 W/m ² 31 °C	694.6 W/m ² 29 °C	653.8W/m ² 30 °C
I _{ph} (A)	8.17229	6.48199	5.57698	4.89626
I _o (A)	9.626*10 ⁻⁰⁸	5.2983*10 ⁻⁰⁹	2.9813*10 ⁻⁰⁹	3.61186E-08
R _s (Ω)	0.35709	0.417502	0.89404	1.31563
R _p (Ω)	275.394	246.5277	204.15651	519.56788
a	2.42461	2.15729	3.96764	8.8544
RMS	0.36762	0.35286	0.63126	0.69288

between the measured and calculated data are computed using an Excel worksheet. (ii) The Solver add-in is adopted with the help of visual basic. The objective function is to minimize RMS or NRMSE. Excel worksheet cells, which contain the values of the required parameters are specified. (iii) The fitting procedure is repeated many times using the estimated

Table 5
Estimated parameters of different PV modules.

Estimated parameters	SST 230 Polycrystalline		Shell SP75 Monocrystalline		Shell SQ150 Monocrystalline		Shell ST40 Thin-film	
	[51]	Proposed Method	[51]	Proposed Method	[51]	Proposed Method	[51]	Proposed Method
Estimated parameters of L4P								
I _{ph} (A)	8.52	8.53589	4.8	4.80384	4.8	4.79774	2.68	2.64875
I _o (μA)	3.6230	2.7625	1.4356	1.26706	1.4356	1.25554	0.44734	0.81055
R _s (Ω)	0.1293	0.15548	0.2524	0.28763	0.5048	0.52452	1.3582	1.29649
a	1.6230	2.46294	1.5619	1.43433	1.5619	2.86493	1.6144	1.55947
Estimated parameters of L5P								
I _{ph} (A)	8.52	8.53831	4.8	4.84726	4.8	4.85293	2.68	2.72079
I _o (μA)	0.094629	1.56212	0.06957	1.44837	0.06975	1.4953	0.010264	1.0189
R _s (Ω)	0.2	0.16864	0.33	0.25283	0.67	0.50448	1.52	1.28792
R _p (Ω)	152.6382	2029.069	236.768	200.9878	466.46	402.153	284.1	373.1949
a	1.3	1.5382	1.3	1.5635	1.3	1.567	1.3	1.7078

values of the adjustable parameters at each step. (iv) The confidence of the estimated parameter value is assessed by fixing the investigated parameter at a value, which is slightly different from the optimal one.

Figs. 6 and 7 show the PV module I-V and P-V characteristics obtained using the implemented model after the curve fitting with the obtained experimentally measured curve at solar radiation 999.5 W/m² and ambient temperature 29 °C. These figures illustrate an excellent agreement between the measurements and the developed model output. Further, as shown in Figs. 8 and 9, the developed Excel worksheet model of I-V and P-V characteristics show excellent agreement with the similar measurements of solar radiation value 801.8 W/m² and ambient temperature value 30 °C. These figures show the capability, efficiently and accurately of the estimated parameters using the proposed approach.

5. Analysis

5.1. Analysis of the proposed approach validation

The characteristics of two and four series connected PV modules are simulated using the proposed approach and their response are fitted to the experimental measurements as shown in Figs. 10, 11, 12, and 13. The proposed Excel worksheet approach for I-V and P-V curves show excellent agreement with the experimental measurements of various PV modules connections at different weather conditions. In case of double series modules, as shown in Figs. 10 and 11, the solar radiation value is 694 W/m² and the ambient temperature value is 31 °C. Finally, in the case of four series modules as shown in Figs. 12 and 13, the solar radiation value is 653.8 W/m² and the ambient temperature value is 30 °C. The confidence of the estimated parameter values are assessed by fixing the parameter to be inspected at a value which is somewhat different from the optimal one. The convergence characteristics of the estimated L4P parameters of polycrystalline PV module TSM-295 are presented in

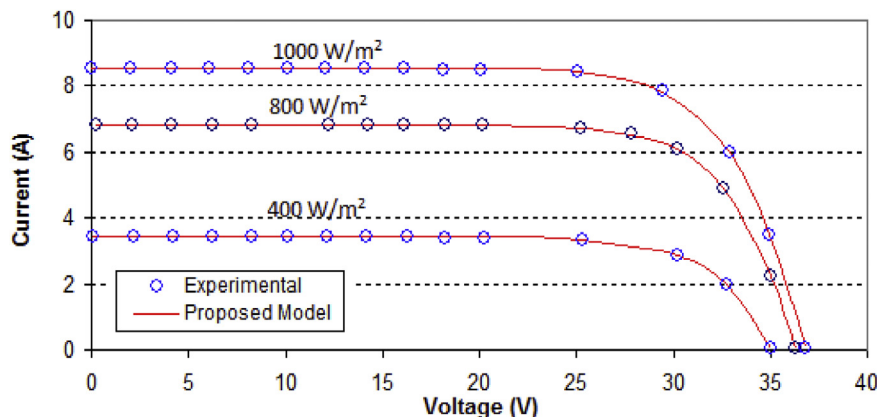


Fig. 15. Polycrystalline module SST230 I-V characteristics using the proposed approach.

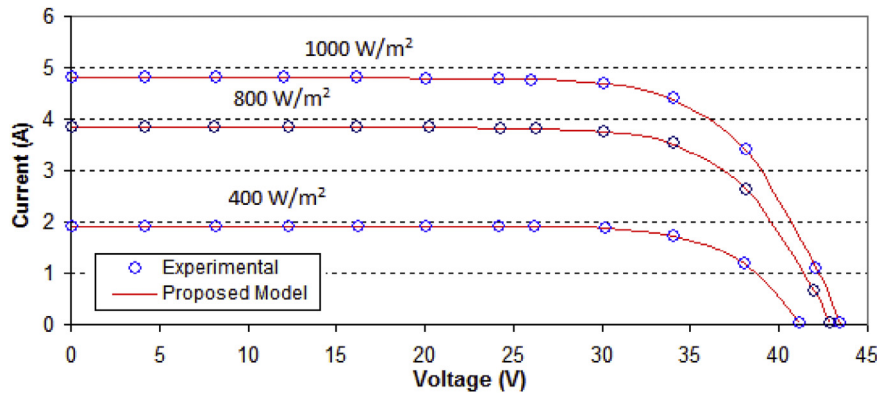


Fig. 16. Monocrystalline module SQ150 I-V characteristics using the proposed approach.

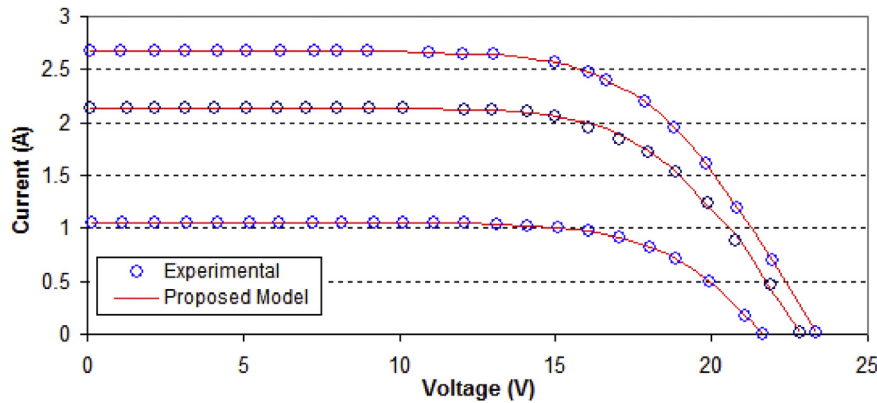


Fig. 17. Thin-film module ST40 I-V characteristics using the proposed approach.

Table 6
RMS Errors four parameter model calculated for SQ150, ST40 and SST230 modules (at T = 25 °C).

Irradiance (W/m ²)	SST 230		SQ150		ST40	
	[51]	Proposed Method	[51]	Proposed Method	[51]	Proposed Method
RMS error four parameter model (%)						
1000	0.1082	0.13706	0.3125	0.30373	1.7421	1.43279
800	1.6553	0.2455	0.3005	0.25849	1.8300	1.03668
400	0.9864	0.1494	0.3827	0.21219	1.6951	1.43343
RMS error five parameter model (%)						
1000	0.3313	0.07695	0.3313	0.50679	2.2239	0.96499
800	0.8523	0.20318	0.8523	0.73614	2.1550	1.11751
400	1.5111	0.17984	1.5111	1.35779	2.2515	0.87807

Fig. 14. The estimated L4Ps are obtained and listed in Table 3. Firstly, by using $I_{ph,STC} = I_{sc,STC}$ and a_{STC} as in Eq. (26) as well as Eqs. (17), (19), and (20) and the manufacture template data, the parameters, $I_{o,STC}$, $R_{s,STC}$, $R_{p,STC}$ at STC conditions are determined, correspondingly. According to the real-time measurement values of solar irradiance and ambient temperature, the five parameters of the L5P model are calculated using Eqs.

(6), (7), and (11) of I_{ph} , I_o , R_s corresponding, $R_p = R_{p,STC}$ and $a = a_{STC}$. Also, E_g can be calculated using Eq. (8), While $E_{g,STC} = 1.17$. The estimated parameters are obtained and listed in Table 4 as method 1.

Table 7
PV module KC-200GT estimated parameters.

Calculated parameters	Kyocera KC-200GT						
	[16]	Proposed Method	[50]	[19]	[14]	[55]	[41]
I_{ph} (A)	8.214	8.1542	8.2132	-	8.2119	8.211	8.2252
I_o (μ A)	0.09825	1.9113	0.097631	-	0.17097	0.00212	0.0076324
R_s (Ω)	0.221	0.0759	0.221	0.2198	0.2172	0.233	0.1958
R_p (Ω)	415.405	750.2459	597.3855	991.5159	951.3267	132.88	106.0344
a	1.3	1.551	1.3	1.3370	1.3405	1.0758	1.1833
NRMSE	0.0251	0.00808	0.0269	-	-	0.0086	0.0124

6. Results and discussion

In this section, the estimated L4P and L5P are compared with other research studies. The estimated L4P and L5P described in this paper are validated by estimating the parameters of three different modules such as polycrystalline, amorphous, and thin film as presented in Table 5. The identified parameters are compared with previously reported study given in [51]. The $I_{ph,STC}$ and $I_{o,STC}$ can be computed after obtaining the values of a_{STC} , $R_{s,STC}$ and $R_{p,STC}$ using Eqs. (15), (18), (16), (21), and (22) for L5P of the single diode PV model. $I_{o,STC}$ is computed firstly using Eq. (17) in order to facilitate the calculations of $R_{s,STC}$ and $R_{p,STC}$, then $I_{ph,STC}$ can be computed using $I_{o,STC}$ as in Eq. (18) to avoid the rotating references. According to real-time measurement values of solar irradiance and ambient temperature, the five parameters of L5P are calculated dependent on Eqs. (6), (7), (11), and (12) of I_{ph} , I_o , R_s and R_p , respectively, and $a = a_{STC}$. E_g can be calculated using Eq. (8), while $E_{g,STC} = 1.17$. Finally, The estimated parameters are obtained and listed in Table 5 as method 2.

Figs. 15, 16, and 17 present comparison for some of the results that are obtained at different operating conditions using the proposed L5P approach. The obvious conclusion from these figures is that the I-V curves generated by the L5P model are accurate in fitting with the measured data which are given by the corresponding module manufacturers for different PV cell technologies.

Table 6 exhibits the RMS errors that are obtained using the proposed approach of L4P and L5P for three types of PV cells with different technologies. It can be noticed that, the proposed approach provides the best match with the experimental data compared with the results by [51]. Also, the proposed approach can be integrated into the sun simulator and array tester devices.

The extracted five parameters of Kyocera KC-200 GT PV module are shown in Table 7. The identified model parameters and NRMSE percentage of the proposed method of Kyocera KC-200 GT PV module are compared with [16, 41, 50, 55]. The authors in [55], presented an analytical expression for estimating the series resistance and the ideality factor using datasheet information and employed the least squares method for solving the three equations of saturation current, photocurrent and shunt resistance. Authors in [41, 55] presented lower than expected values of the ideality factor and the saturation current and consequently, led to the low value of the shunt resistance. The differences between these parameter values using these researches and the proposed approach are due to the lack of accurate initial conditions. The proposed approach using Excel worksheet employs five analytical equations to estimate initial values and solves for the optimal values of five parameters, simultaneously, based on the least squares method. The authors in [14], reviewed and evaluated six analytical methods for modeling and extracting circuit parameters of KC200GT PV module. The authors compared the results with an iterative method as in [19] and the Numerical method, Newton-Raphson as in [16]. Also, the authors in [14], concluded that the analytical methods can compete in terms of accuracy with their numerical counterparts. In [19], the authors used Newton Raphson method in order to solve the equations of R_s , R_p and ideality factor by starting from the presented analytical initial values. Results in [14] were presented based on the presented method by [19]. It can be noticed that the difference between results of Kyocera KC-200 GT PV module are due to the impact of initial values as well as the main effect of the employed formula for the ideality factor and the saturation current.

7. Conclusions

This paper presents a proposed approach to estimate the parameters of PV module using the experimental measurements based on the nonlinear least-squares algorithm. This approach has been implemented to estimate parameters of 295W polycrystalline TRINA TSM-295 PC14 PV module using the single diode models. Good agreement has been obtained between the simulation output with the calculated parameters and the experimental measurements at different environmental

conditions. The developed Excel worksheet can facilitate to study PV system performance, design and analysis of various technologies of PV cells. In this way, the proposed approach is expected to be useful in the development of the solar cells simulator, degradation analysis and for development of MPP tracking algorithms, employing few steps and few milliseconds execution times using a simple notebook. Finally, It is concluded that the proposed approach can be employed as an easy tool for the PV power converter designers and the circuit simulator developers. In the future work, the impact of different operating conditions such as the dynamic shading of PV modules can be studied. Finally, the proposed Excel worksheet approach for PV module modeling can be implemented in an optimization toolbox with the aid of visual basic and presented handy method for power electronics engineers and designers.

Declarations

Author contribution statement

A. Elkholy: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

A. A. Abou El-Ela: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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