

A New Reduced Form for Real-Time Identification of PV Panels Operating Under Arbitrary Conditions

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ABSTRACT

In this work, an efficient solution based on the reducing forms approach is presented to extract the five parameters of the single-diode model of PV generators from their I-V curves. Thus, by reducing the number of the five unknown parameters to two unknowns, the analytical expression of the current based on the LambertW function will then depend only on the ideality factor and the series resistance, as the two unknowns to predict numerically using the non-linear least square technique. The three other parameters are calculated as functions of the two predicted parameters using a linear system of three equations. Two sets of experiments are used for the validation of the proposed approach, which first showed its rapidity and high accuracy compared to the best approaches from the literature. Then, the method was applied for the real-time identification of four PV modules operating outdoors during one reference day at Cocoa (Florida).

KEYWORDS

Experimental Data, I-V Curve, Least Square Method, Modeling, Optimization Method, PV Characteristics, PV Technologies, Real-Time Values of the Five Parameters, Single Diode Model, Solar Cell

INTRODUCTION

Motivation

Given the great technological development of today, the energy needs of countries are also growing more and more. The massive consumption of fossil fuels such as oil, natural gas, bituminous rocks, and coal to produce the needed energy, led to the aggravation of the greenhouse effect by increasing the annual quantity of polluting gases emitted into the atmosphere (Geleta et al., 2019). It also implies the increase in the number of natural disasters and health diseases. Therefore, taking into consideration the natural, health, and economic problems facing the employment of fossil fuels' sources, besides their continuous reduction caused by their massive exploitation makes the production of energy a challenge of great importance (Kandiyoti et al., 2017; & Zaimi et al., 2018). Renewable energies such

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as solar photovoltaic energy, wind energy, hydropower, biomass, and geothermal resources represent an alternative, sustainable, and ecological solutions (Yildiz., 2018; & Humada et al., 2016).

Solar energy is one of the most important renewable energies on which many countries rely as an alternative, it involves converting solar radiation into electricity using photovoltaic converters called cells which represent the basic element in photovoltaic conversion (Kharchenko., 2019; & Zhang et al., 2020). The association of multiple cells in series/parallel gives rise to a photovoltaic module. The identification of the parameters of PV modules or solar cells from their current-voltage experimental characteristics or using the datasheet is an active research topic. The parameters extraction is important for determining the PV generators' performances, simulating their design, and especially for their quality control and improvement (Ciulla et al., 2014). There are different circuit models which are used for modeling the behavior of PV generators. Due to its simplicity and efficacy, the single-diode equivalent circuit with five parameters (the light generated current or the photo-current I_{ph} , reverse saturation current I_s , diode ideality factor n , series parasitic resistance R_s , and shunt resistance R_p) is the most adopted model to describe the experimental current-voltage characteristics (Humada et al., 2016).

BACKGROUND AND LIMITATIONS

According to the literature, several methods have been proposed to extract the different parameters of the single-diode model with various degrees of accuracy and complexity. These methods can be classified into three approaches, namely analytical, numerical, and evolutionary approaches.

- Analytical approaches: These methods are simple, rapid, and use a series of analytical equations based on different remarkable points of the I-V curves (Saleem et al., 2009; Cubas et al., 2014; Louzazni et al., 2015; Maouhoub., 2017; & Batzelis., 2019). But most of these approaches rely on different approximations to reduce the non-linearity degree of the formulas.
- Numerical approaches: These methods either are based on the optimization process that minimizes the error between the theoretical I-V characteristic and the experimental curve (Bouzidi et al., 2007; Villalva et al., 2009; Yadir et al., 2009; Zhang et al., 2011; & Senturk et al., 2017), or the numerical resolution of a set of non-linear equations found using the values of the key-points (Kumar et al., 2017; Tifidat et al., 2021).
- Evolutionary approaches: These approaches are based on the meta-heuristic methods inspired from different natural phenomena. Then, they use various operations to ensure convergence such as crossover and mutation, techniques that can increase the needed calculation time (Awadallah., 2016; Maa et al., 2016; Xiong et al., 2018; & Sharma et al., 2021).
- Hybrid approaches: These kinds of methods are not based only on a single technique to extract the parameters, but they use a combination of more than one approach to identify the PV generator's parameters (Nassar-eddine et al., 2016; Abbassi et al., 2017).

Some of these methods are widely analyzed and reviewed in some review articles (Chin et al., 2015; Boutana et al., 2017; & Peñaranda Chenche et al., 2018).

Laudani et al (Laudani et al., 2013; & Laudani et al., 2014) suggested the extraction of the single-diode electronic circuit model's five parameters from current-voltage curves using the reduction of the search space. Indeed, this technique is based on reduced forms and decreases the dimension of the search space to two unknown parameters, then fitting the experimental I-V curve to get their values. The three other parameters are determined by using three analytical expressions based on preliminary selective data of the I-V curve; the open-circuit voltage (V_{oc}), the short circuit current (I_{sc}), and maximum power point MPP (V_{mp} , I_{mp}). Given that the values of the key-points available on the datasheet can be different from their real-values corresponding to the measured I-V characteristics,

the accuracy of predicting using this technique can be strongly affected by their precision (Benahmida et al., 2020). Angulo Cardenas et al (Angulo Cardenas et al., 2017) proposed another reduced search space approach for the five parameter's estimation from I-V characteristics; this method reduces the number of complexities and does not rely on any additional data from I-V curves. Toledo et al (Toledo et al., 2018) introduced a two-steps linear least squares technique, requiring the coordinates of N point ($N > 5$) of the I-V characteristic. But, the technic relies on many approximations, assuming that the linear effect is minimal for the 2nd zone of the I-V characteristic, and the exponential effect is considered negligible for the first zone. The three proposed methods in works (Laudani et al., 2014; Cardenas et al., 2017; & Toledo et al., 2018) have provided the best solutions for two cases of studies proposed in (Easwarkhanthan et al., 1986), and commonly used in the literature. But, these best solutions were provided by the three methods using a refinement of the results, thing that complicates the automation of such approaches for the real-time prediction and increases their calculation time.

The variation of weather conditions is one of the most items affecting the PV module's parameters (Elkholy et al., 2019). Recently, Zaimi et al (Zaimi et al., 2020) used a tedious calculation based on the key-points values of the I-V curve to reduce the number of the unknown parameters to extract numerically using the "fsolve" from five to three parameters. In this case, all three parameters require a good initialization to guarantee the convergence of the numerical resolution toward the right solutions. Then, mathematical formulas dealing with the transformation of the five parameters from standard test conditions to non-standard test conditions are used. Thus the accuracy of this approach depends on the precision of these key-points as well as the used equations for the prediction for outdoor conditions.

MAIN FOCUS OF THE ARTICLE

The main purpose of the work presented in this paper is to propose a simple, efficient, and fast method based on reduced forms for the identification of the five parameters for outdoor conditions using the experimental I-V characteristics. The proposed approach is based on reducing the search space to two unknown parameters; ideality factor n and series resistance R_s , the three other parameters (I_s , I_{ph} , and R_p) are extracted using three analytical expressions. In the first instance, the new approach was tested for the two most commonly used solar cells and PV modules in the literature (The case of the solar cell RTC and the PV module PWP). The efficacy, as well as the rapidity, were compared to other reduced forms proposed by Laudani et al (Laudani et al., 2014), Angulo Cardenas et al (Angulo Cardenas et al., 2017), and Toledo et al (Toledo et al., 2018). In the second instance, the efficiency of the method's extraction of the five parameters of PV modules operating outdoor under real environmental conditions is tested. This work focuses on real-time meteorological data collected by the National Renewable Energy Laboratory (NREL) (Marion et al., 2014) for two PV modules (the Single-crystalline silicon (x-Si) PV module (xSi12922), the Multi-crystalline silicon (m-Si) PV module (mSi460A8)), operating outdoor at the site of Cocoa-Florida, during almost 13 hours of one reference day (21st, June 2011) starting from 05:55 AM to 7:05 PM with a pitch of 5 minutes. For the two PV panels and every 5 minutes, a couple of (R_s , n) that minimizes the error between the two I-V characteristics; the measured one and the estimated one is calculated. Then, by using three analytical expressions and using the non-linear least-squares method, the three remaining parameters were found. As a result, the current method allows the real-time estimation of the five parameters and the maximum power point using only the measured I-V curves, and the PV module's temperature and without any measuring of irradiance. The proposed method does not use any approximations or any refinement of results. Given that the approach does not require any information about the key-points as well, it can be used for the real-time prediction of the maximum power provided by the PV generator. And it can also be used for the identification of PV generators not only under standard test conditions but also for outdoor conditions.

The organization of the paper is as follows. Section 1 presents the one-diode equivalent circuit model of PV generators, on which this work is based, and gives the analytical solution of non-linear

equation linking the output current to the output voltage and current. In section 2, the authors introduce the procedure to calculate the five parameters from the experimental data based on reduced form. The validation of the proposed method using the two cases of study (RTC solar cell and PWP PV module), as well as the real-time validation for the two PV modules studied by NREL researchers is done in section 3. Finally, the paper is closed by the conclusion of section 4.

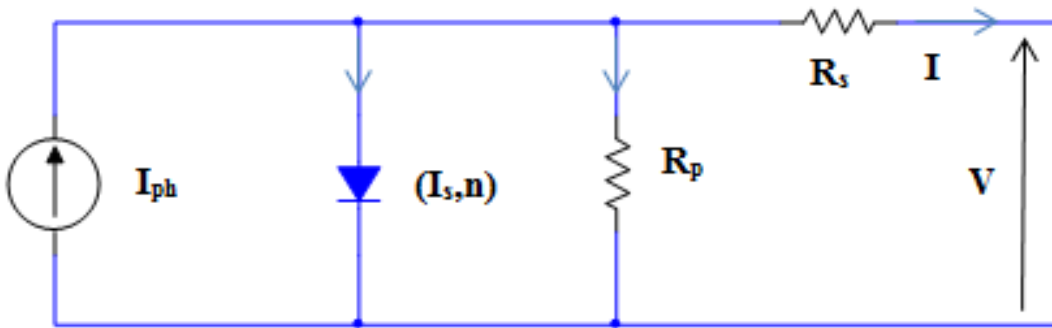
ONE DIODE EQUIVALENT CIRCUIT MODEL

The solar cell or PV module is made up of semiconductor materials that can convert solar irradiance into electrical energy. Based on the electronic theory of semiconductors, the P-N junction inside the PV generator can be modeled by a diode and a current source. The single-diode model equivalent circuit of a PV generator shown in Fig.1 can be described by the equation below linking the current I and the voltage V (Maouhoub., 2017; & Miguel Álvarez et al 2021):

$$I = I_{ph} - I_s \left(\exp \left(\frac{V + IR_s}{nN_s V_{th}} \right) - 1 \right) - \frac{V + IR_s}{R_p} \quad (1)$$

Where I_{ph} is the light-generated current, R_s is the series parasitic resistance, R_p is the parallel parasitic resistance, I_s is the saturation current, N_s is the number of cells connected in series (for a single solar cell $N_s = 1$) and $V_{th} = k_B T / q$ is the thermal voltage, where k_B is the Boltzmann's constant equals to $1.38064852 \times 10^{-23}$ J/K, q is the electron charge equals to $1.60217662 \times 10^{-19}$ C.

Figure 1. Equivalent electrical circuit for a single solar cell



The equation (1) is an implicit expression that cannot be solved analytically. However, with the help of the LambertW function, the solution of $I = f(I, V, (n, R_s, G_p, I_s, I_{ph}))$ is given as follow (Piazza et al., 2017; & Pindado et al 2021):

$$I = f(V, n, R_s, G_p, I_s, I_{ph}) = \frac{I_s + I_{ph}}{1 + R_s G_p} - \frac{G_p}{1 + R_s G_p} V - \frac{n N_s V_{th}}{R_s} \times W \left(\frac{I_s R_s}{n N_s V_{th} (1 + R_s G_p)} \exp \left(\frac{V + R_s (I_s + I_{ph})}{n N_s V_{th} (1 + R_s G_p)} \right) \right) \quad (2)$$

Where $G_p = 1/R_p$.

CALCULATION OF THE FIVE PARAMETERS USING REDUCED FORM TECHNIQUE

This section introduces the theory on which the new technique is based to extract the five parameters' values of the equivalent circuit. In the first subsection, the proposed method to get analytically the values of the three parameters (the photo-current I_{ph} , the reverse saturation current I_s , and the parallel parasitic resistance R_p) as functions of the two parameters (the series resistance R_s and the ideality factor n) is presented. In other words, the details of the research space's reduction from five to two unknown parameters are given. The second subsection is reserved for the suggested numerical method to get the values of R_s and n .

Reduced Form Method

The reduced form is based on the experimental I-V characteristic of the PV generators. In order to reduce the number of parameters to calculate from five to only two unknowns, the equation (1) is rewritten as follow:

$$I_i = I_{ph} - I_s X_i - G_p Y_i = f(I_{i,e}, V_i, C(I_{ph}, I_s, G_p)) \quad (3)$$

Where X_i and Y_i are given by:

$$\begin{cases} X_i = \exp \left(\frac{V_i + R_s I_{i,e}}{n N_s V_{th}} \right) - 1 \\ Y_i = V_i + R_s I_{i,e} \end{cases} \quad (4)$$

And C is defined as vector that groups the three unknown parameters: I_{ph} , I_s , and G_p .

$$C = \begin{pmatrix} I_{ph}(n, R_s) \\ I_s(n, R_s) \\ G_p(n, R_s) \end{pmatrix} \quad (5)$$

To reduce the number of the unknown parameters, the three parameters I_{ph} , I_s , and R_p of equation (3) can be expressed as functions of the other two parameters n and R_s . The things done by exploiting the experimental I-V characteristic to minimize the deviation of squared error between the measured curve and the calculated one, so the problem consists to minimize the following objective function:

$$S = \sum_{i=1}^N \left(f(V_i, C(I_{ph}, I_s, G_p)) - I_{i,e} \right)^2 \quad (6)$$

$I_{i,e}$ and V_i are the measured current and voltage at the i_{th} point, and N is the number of measured data points.

To minimize the function S , the derivation of the squared error of equation (6) with respect to the vector C was done as follow:

$$\frac{\partial S}{\partial C(I_{ph}, I_s, G_p)} = 0 \quad (7)$$

The application of this method can lead to the following system of three equations (Maouhoub., 2018):

$$\begin{cases} I_{ph} N - I_s \sum_{i=1}^N X_i - G_p \sum_{i=1}^N Y_i = \sum_{i=1}^N I_{i,e} \\ -I_{ph} \sum_{i=1}^N X_i + I_s \sum_{i=1}^N X_i^2 + G_p \sum_{i=1}^N Y_i X_i = -\sum_{i=1}^N I_{i,e} X_i \\ -I_{ph} \sum_{i=1}^N Y_i + I_s \sum_{i=1}^N Y_i X_i + G_p \sum_{i=1}^N Y_i^2 = -\sum_{i=1}^N I_{i,e} Y_i \end{cases} \quad (8)$$

For the convenience of representation, the following notation of matrix H is introduced:

$$H = \begin{pmatrix} N & -a & -b \\ -a & d & c \\ -b & c & e \end{pmatrix} \quad (9)$$

Where a , b , c , d , and e depend only on n and R_s , and are given by:

$$a = \sum_{i=1}^N X_i; b = \sum_{i=1}^N Y_i; c = \sum_{i=1}^N Y_i X_i; d = \sum_{i=1}^N X_i^2; e = \sum_{i=1}^N Y_i^2 \quad (10)$$

Another vector λ is introduced as follows:

$$\lambda = \begin{pmatrix} \alpha \\ -\beta \\ -\gamma \end{pmatrix} \quad (11)$$

Where α , β , and γ depend only on n and R_s , and are given by:

$$\alpha = \sum_{i=1}^N I_{i,e}; \beta = \sum_{i=1}^N I_{i,e} X_i; \gamma = \sum_{i=1}^N I_{i,e} Y_i \quad (12)$$

Thus, the system of linear equations in equation (8) can be represented by:

$$H \chi = \lambda \quad (13)$$

The solution of this system is given as:

$$\chi = H^{-1}\lambda \quad (14)$$

The expressions of I_{ph} , I_s , and R_p can be obtained from the equation above only as a function of n and R_s as follows:

$$\begin{cases} I_{ph}(n, R_s) = \frac{\alpha(de - c^2) - \beta(ae - bc) - y(bd - ac)}{\det(H)} \\ I_s(n, R_s) = \frac{\alpha(ae - bc) - \beta(Ne - b^2) - y(ba - Nc)}{\det(H)} \\ G_p(n, R_s) = \frac{\alpha(db - ac) - \beta(ab - Nc) - y(Nd - a^2)}{\det(H)} \end{cases} \quad (15)$$

Where $\det(H)$ refers to the determinant of the matrix H .

Calculation of N and R_s

To extract the two unknown parameters n and R_s , we rewrite the equation (2) by injecting the expressions of G_p , I_s , and I_{ph} as a function of n and R_s obtained in the subsection above. Then the reduced form of the calculated current can be expressed only as a function of n and R_s as follow:

$$I = f(V, n, R_s) \quad (16)$$

The extraction of the two parameters n and R_s is based on minimizing the following Squared Error (SR):

$$SR = \sum_{i=1}^N \left(f(V_i, n, R_s) - I_{i,e} \right)^2 \quad (17)$$

Since the data may be well represented by the model of the current chosen in equation (3), the proposed technique was implemented in MATLAB in order to minimize the value of (SR) of equation (17) using the “lsqnonlin” function of the MATLAB Optimization Toolbox (MathWorks; 2012). This solver deals with the resolution of the non-linear least square curve fitting problems, and does not require any additional assumptions. Moreover, the technic allows not only finding n and R_s but also getting the highest-quality solutions. To start the minimization, the initial values of n and R_s must be chosen. To do this end, the authors choose $n=1$ and $R_s = 0.005 \times (\max(V_i) / \max(I_i))$ as initial guesses (Angulo Cardenas et al., 2017).

Evaluation of the Method's Accuracy

To validate the goodness and accuracy of the fit to the experimental characteristic, some statistical indicators were used in the literature. In this work, the individual absolute error (IAE) and the root mean squared error (RMSE) are selected:

$$IAE = |I_{i,e} - I_{i,c}| \quad (18)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (I_{i,e} - I_{i,c})^2 \right]^{\frac{1}{2}} \quad (19)$$

In order to test the precision of the approach in this work, and especially to compare it to other methods in the literature, another formula giving the Normalized Root Mean Square Error (NRMSE) defined below is used (Zaimi et al., 2020):

$$NRMSE_j (\%) = \frac{\sqrt{\frac{1}{N_j} \sum_{i=1}^{N_j} (I_{i,e}^j - I_{i,c}^j)^2}}{\frac{1}{N_j} \sum_{i=1}^{N_j} I_{i,e}^j} \times 100 \quad (20)$$

Where “j” describes the real-time t, “i” is the subscript that models all (I_i , V_i) couples measured in a specific time “ t_j ”, and “ N_j ” is their number.

To validate the precision of the method for the prediction of the maximum power point and compare it to the literature, the formula of Normalized Error below was selected as well (Zaimi et al., 2020):

$$NE(t_j) = \frac{|P_e(t_j) - P_c(t_j)|}{\text{Max}_j(P_e(t_j))} \quad (21)$$

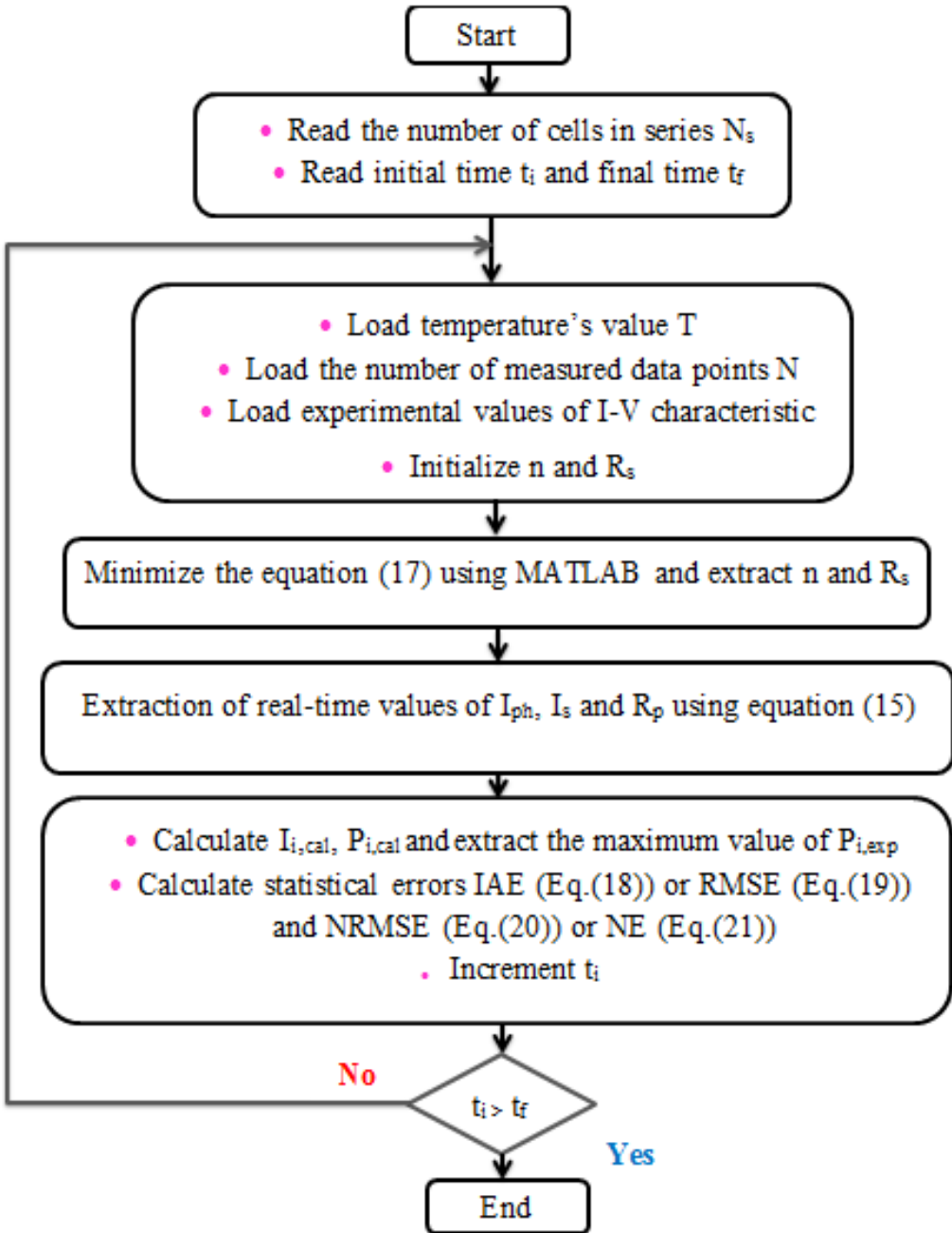
Where $P_e(t_j)$ is the vector of the experimental powers in specific time t_j .

And $P_c(t_j)$ is the vector of the calculated powers for a specific time t_j given as follow:

$$P_c(t_j) = I_c(t_j) \times V(t_j) \quad (22)$$

Figure 2 summarizes the flow chart of different steps of the proposed method.

Figure 2. Flow chart of the proposed method



RESULTS AND DISCUSSION

Validation for the Case of RTC Solar Cell and the PWP PV Module

Intending to validate the efficiency of the proposed approach, two sets of experiments commonly used in the literature were chosen. In the first one, it is applied to the 57 nm diameter commercial

Table 1. Results for case study 1: RTC solar cell

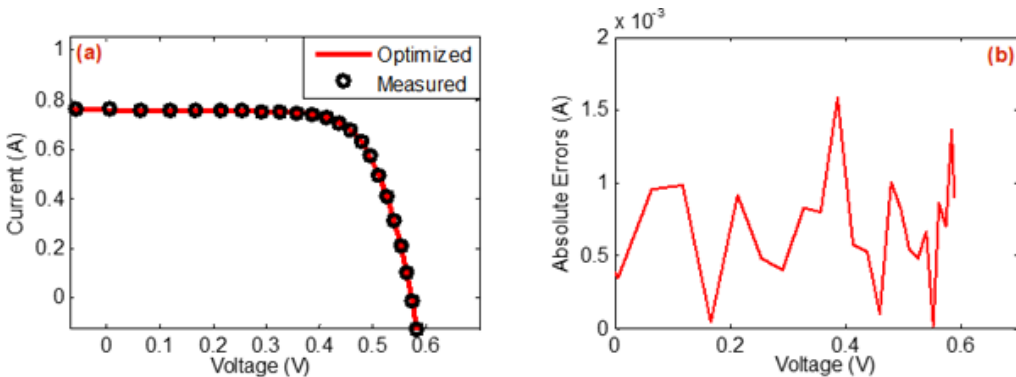
	Laudani et al., 2014	Angulo Cardenas et al., 2017	Toledo et al., 2018	Proposed Method
n	1.476964	1.475956	1.477105	1.477107
$R_s(\Omega)$	0.036553	0.036547	0.036546	0.036546
$R_p(\Omega)$	52.859956	52.890463	52.889804	52.891411
$I_s(A)$	0.310248×10^{-6}	0.31068×10^{-6}	0.310684×10^{-6}	3.106856×10^{-7}
$I_{ph}(A)$	0.760788	0.760788	0.760787	0.760787
RMSE	7.7300939×10^{-4}	7.7300627×10^{-4}	$7.73006272 \times 10^{-4}$	7.730062×10^{-4}
NRMSE (%)	0.14014535	0.14014478	0.14014478	0.14014476
Number of FEs	138	24	24	18
Number of steps	16	7	3	5

silicon solar cell (RTC France) at 33°C and 1000 W/m², and in the second one, to the solar module (Photowatt-PWP 201) at 45 °C and 1000 W/m², in which 36 poly-crystalline cells are connected in series (Laudani et al., 2014; Bai et al., 2014; & Cardenas et al., 2017).

Case 1: RTC Solar Cell

Table 1 shows the estimated five parameters, the values of RMSE, the values of NRMSE, the number of function evaluations (FEs), and the number of steps obtained for silicon solar cell RTC using the proposed method and compared to other reduced form methods of literature (Laudani et al., 2014; Angulo Cardenas et al., 2017; & Toledo et al., 2018). As it can be seen, the proposed method yields the same RMSE and NRMSE without using any refinement of results, unlike Laudani's method based on a refinement of results which implies the difficulty of automating this method in the case of real-time optimization. Moreover, as it can also be seen, the number of steps and the number of function evaluations obtained using the current reduced form are the lowest values as well. The thing proofing its rapidity compared to the other methods. Thus, the real-time identification of PV generators will be faster using the current method, unlike other methods, which can involve a pile-up of the identification time.

Figure 3. (a) Experimental I-V data and the simulated curve for RTC solar cell at 33°C and 1000 W/m². (b) The corresponding Absolute Errors



The calculated I-V curve using the obtained parameters and the experimental characteristic for the first case of study are plotted in Fig.3 (a). Fig.3 (b) represents the curve of absolute errors obtained using the present method. It is readily apparent that the I-V curve in red obtained by the proposed method pass exactly on all measured data represented in black markers. Then, the maximum of individual absolute errors of all measurements is about 1.6 mA. According to this figure, we confirm the choice of the nonlinear least squares approach to find the best fitting model.

Case 2: PWP PV Module

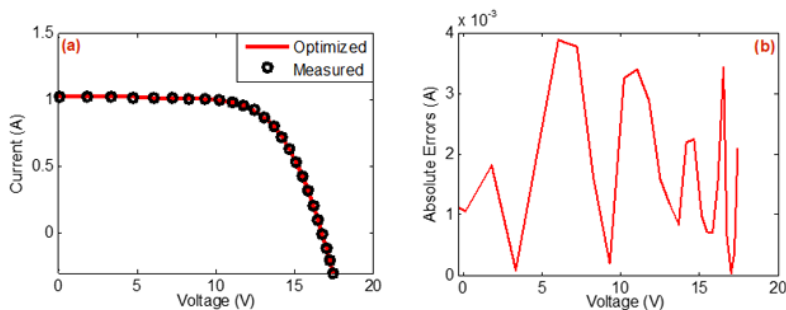
The five parameters obtained, the values of RMSE and NRMSE, the number of function evaluations (FEs), and the number of steps for the PV module PWP are summarized in Tab.2. As it can be seen one more time, the proposed method gives the lower value of RMSE, NRMSE, the number of steps, and the number of FEs.

The simulated I-V curve using the obtained parameters and the experimental characteristic for the PWP module operating under 45 °C and 1000 W/m² are plotted in Fig.4 (a). And the absolute errors obtained which do not exceed 4 mA are shown in Fig.4 (b). Once more, and as Fig.4 shows, for the PV panel PWP, the I-V characteristics obtained using the proposed method cross exactly at all the experimental data points.

Table 2. Results for case study 2: PWP PV module

	Laudani et al., 2014	Angulo Cardenas et al., 2017	Toledo et al., 2018	Proposed Method
n	1.317400	1.316338	1.317159	1.316570
R_s(Ω)	1.239018	1.239060	1.300151	1.240214
R_p(Ω)	745.643	745.712	744.713	751.812
I_s(A)	2.5188841×10 ⁻⁶	2.517957×10 ⁻⁶	2.512905×10 ⁻⁶	2.499002×10 ⁻⁶
I_{ph}(A)	1.032375	1.032377	1.032382	1.032300
RMSE	2.0465409×10 ⁻³	2.0465456×10 ⁻³	2.0465347×10 ⁻³	2.0402614×10 ⁻³
NRMSE (%)	0.310586	0.311508	0.311506	0.310550
Number of FEs	147	141	42	21
Number of steps	19	27	6	6

Figure 4. Experimental I-V data and the simulated curve for PWP solar module at 45 °C and 1000 W/m². (b) The corresponding Absolute Errors



ADVANTAGES OF THE PROPOSED METHODE AND FUTURE RESEARCH DIRECTIONS

The main advantages of the current method are its rapidity and accuracy compared to the other methods. There are no solution refinement and improvement of results, and there is no preliminary remarkable point's selection. On the contrary, according to (Laudani et al., 2014; & Toledo et al., 2018), the extraction of the five parameters is given with solution refinement. Indeed an improvement of results is obtained by using the five parameters returned by the reduced forms as initial guesses for fitting of the data to minimize the RMSE. Furthermore, the reduced form in the work (Laudani et al., 2014) depends on a preliminary selection of three remarkable points; $(0, V_{oc})$, $(I_{sc}, 0)$, (I_{mpp}, V_{mpp}) , so the estimation using this method depends on the availability and precision of the key-points values.

The proposed method can be also implemented to extract the parameters of the other models of the PV generators.

TEMPORAL MONITORING OF THE FIVE PARAMETERS UNDER REAL ENVIRONMENTAL CONDITIONS

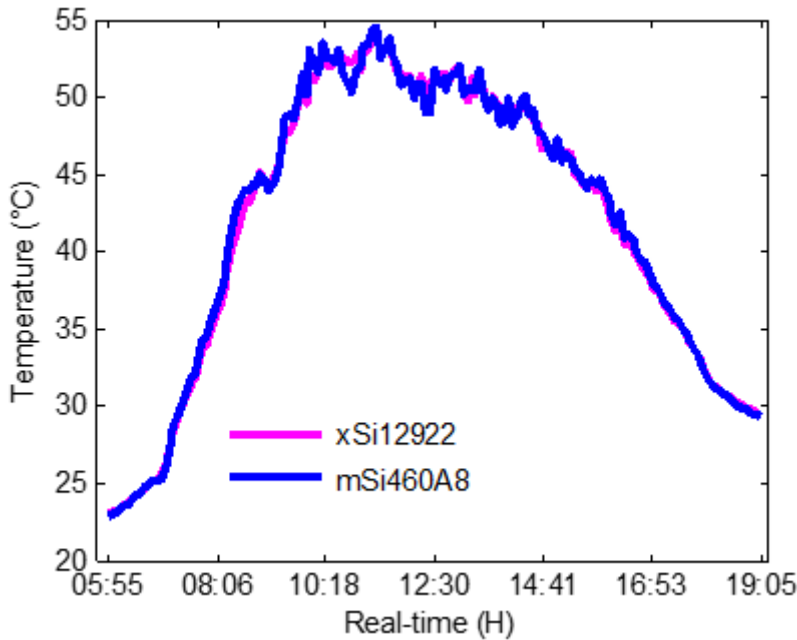
Presentation of NREL Experimental Data

To validate the accuracy of the numerical approach discussed in section 2 under real-time conditions of temperature and irradiance, the publicly available meteorological experimental data collected by NREL's researchers are used (Marion et al., 2014). The data were collected for the four seasons from January 2011 to January 2014 in different locations in the United States of America and included a wide range of irradiance and temperature conditions. But, in this case, we will focus just on the data measured during one reference day (21st June 2011) for almost 13 hours starting from 05:55 AM to 07:05 PM for two PV modules of different technologies (xSi12922 and mSi460A8) operating outdoors at the reference site (Cocoa, Florida). The only necessary specifications of the two PV modules for the present approach are their cell numbers connected in series, which are 36 cells in series for both PV modules xSi12922 and mSi460A8.

The meteorological data collected includes date and time, Plane-of-Array (POA) irradiance, PV modules back-surface temperature, key-points data (Short-circuit current I_{sc} , Open-circuit voltage V_{oc} , voltage of the maximum power V_{mp} and current of maximum power I_{mp}), maximum power of PV modules P_{mp} , fill-factor and other specific parameters of PV generators (Marion et al., 2014). In the current study, only the measured I-V curves and the PV module's temporal back-surface temperature are used.

PV modules' temporal back-surface temperature variations are shown in Fig.5. As it can be seen, the day on which the measurements were taken is generally characterized by a high average temperature, which exceeds the ambient temperature. Second, the instantaneous temperature is more important in the midday hours than in the morning and the afternoon hours, and from the morning it increases faster than its decreases in the afternoon for both PV modules (xSi12922 and mSi460A8).

Figure 5. Temporal variation of back-surface temperature for the two PV modules xSi12922 and mSi460A8 operating outdoors during June 21st 2011 at Cocoa (Florida)



REAL-TIME MEASURED AND OPTIMIZED MAXIMUM POWER OF PV MODULES OPERATING OUTDOOR UNDER REAL ENVIRONMENTAL CONDITIONS

Figures 6-10 represent the obtained real-time values of the five parameters (series resistance R_s , shunt resistance R_p , ideality factor n , saturation current I_s , and photovoltaic current I_{ph}) for the two PV panels (xSi12922 and mSi460A8) operating outdoors at Cocoa (Florida).

The series resistances of the two PV modules decrease when the irradiance's level and PV module's temperature increase, it takes high values for low values of irradiance and temperature. Since the series resistance models the losses by Joule effect caused by all the contacts between every two different materials inside a solar cell, so the movement of carriers in the semiconductor part and the metal contacts strongly influences this parameter. Indeed the increasing of irradiance's level and temperature increases the conductivity of charge carriers that decreases resistivity the thing observed from Fig.6.

The shunt resistances for both PV modules in the study also decrease when the levels of irradiance and temperature increase. This comes from the fact that manufacturing defects and interface states have an increasingly important impact with increasing the level of temperature and the irradiance, with taking into consideration the cells-making structures of each PV module. In addition, low values of this parameter lead to power losses in the PV module.

The reverse saturation current for both PV modules in this study takes the lowest values, and it is highly affected by the irradiation and temperature levels. The increasing of minority carriers causes this parameter.

The photo-generated current increases with the increase of the irradiance level and PV module's temperature, and this is due to the light-generated carriers, which are highly affected by the irradiation level.

The ideality factor for the two PV modules takes the highest values for the lowest values of irradiance and temperature; it takes the lowest values when the irradiance and temperature levels

increase. In addition, since the values taken by this factor describe the recombination phenomenon inside the PN junction of each solar cell, it can be noted that for midday hours the ideality factor tends to take its lowest values, which may be explained by the recombination tending to be limited only by the minority carrier. Then once the irradiance becomes low, more majority carriers are required for the recombination phenomenon.

Figure 6. Real-time variation of series resistances for the two PV modules (xSi12922 and mSi460A8) operating outdoor during June 21st 2011 at Cocoa (Florida)

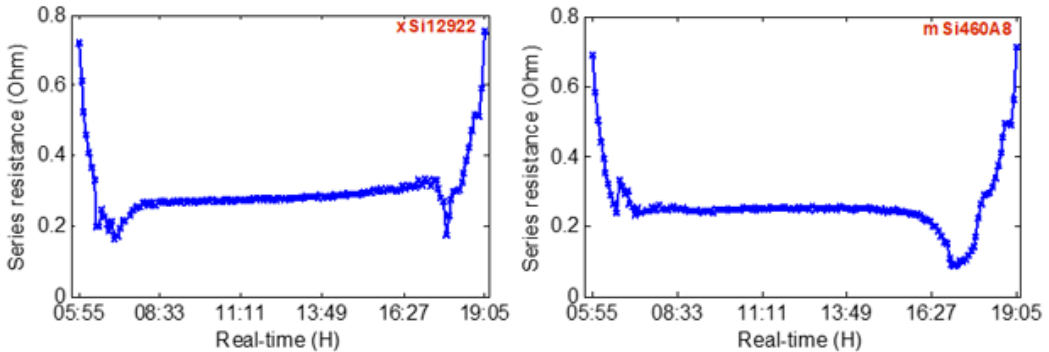


Figure 7. Real-time variation of shunt resistances for the two PV modules (xSi12922 and mSi460A8) operating outdoor during June 21st 2011 at Cocoa (Florida)

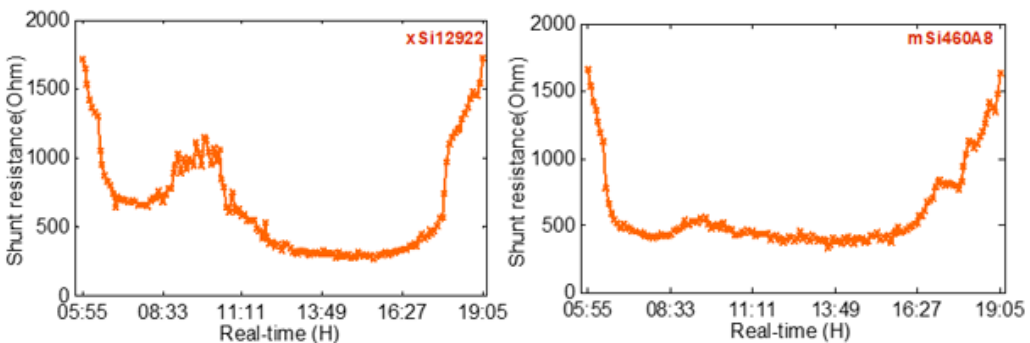


Figure 8. Real-time variation of saturation currents for the two PV modules (xSi12922 and mSi460A8) operating outdoor during June 21st 2011 at Cocoa (Florida)

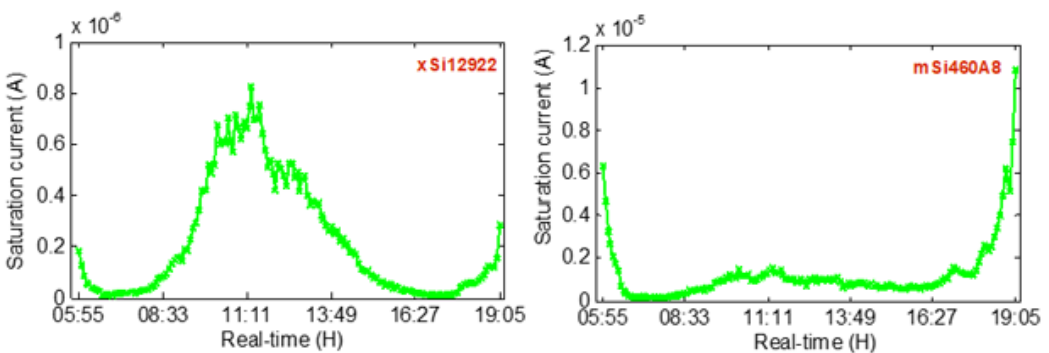


Figure 9. Real-time variation of ideality factors for the two PV modules (xSi12922 and mSi460A8) operating outdoor during June 21st 2011 at Cocoa (Florida)

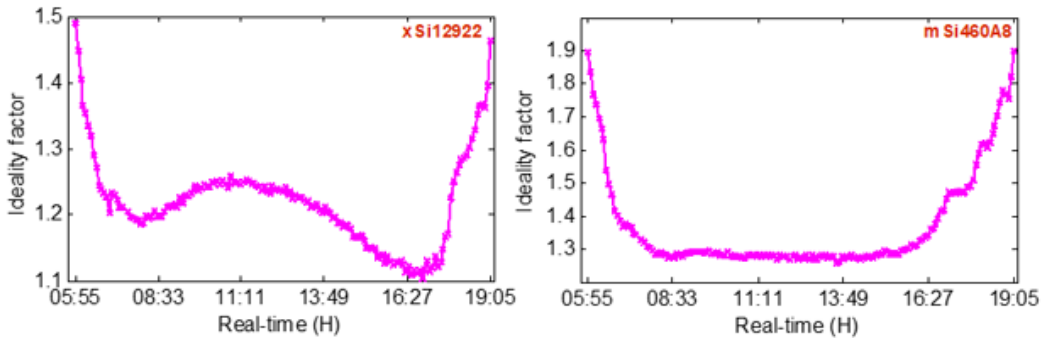
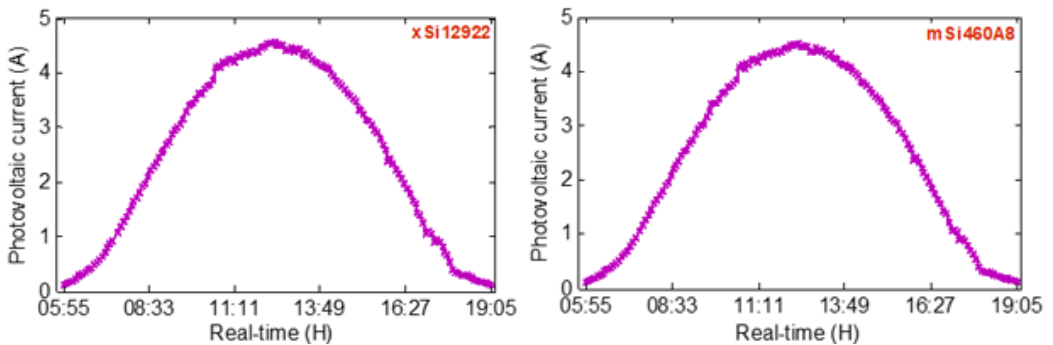


Figure 10. Real-time variation of photovoltaic currents for the two PV modules (xSi12922 and mSi460A8) operating outdoor during June 21st 2011 at Cocoa (Florida)



Experimental and Optimized I-V Curves of PV Modules Operating Outdoors Under Real Environmental Conditions

To check the validity of the extracted values of the five parameters by the present approach, the theoretical currents were calculated for the two PV modules (xSi12922 and mSi460A8) for each hour starting from 05:55 AM to 07:05 PM. The optimized I-V curves for different levels of irradiation and temperature are shown in Fig.11 and Fig.12 in red color, the experimental characteristics measured by NREL researchers for the same external conditions at Cocoa (Florida) are also represented in the same figures by the blue markers.

It is readily apparent that the short-circuit current strongly depends on the irradiance level and has low dependence on the module's back-surface temperature for both modules. The obtained I-V characteristics for the two PV modules (xSi12922 and mSi460A8) operating outdoor conditions at the reference site of Cocoa (Florida) on June 21st 2011 for almost 13 hours starting from 05:55 AM to 07:05 PM cross exactly at all the measured data. To judge the efficacy of the five parameters' extraction using the new approach, the Normalized Root Mean Square Errors (NRMSE) between the optimized values of current and the measured data for the two PV modules from sunrise to sunset have been calculated, and that as defined in section 2. Figures in Fig.13 show the NRMSE calculated in real-time for each PV module.

Figure 11. Experimental and optimized I-V curves for the PV module xSi12922 in the morning (a) and in the afternoon (b) operating outdoors during June 21st 2011 at Cocoa (Florida)

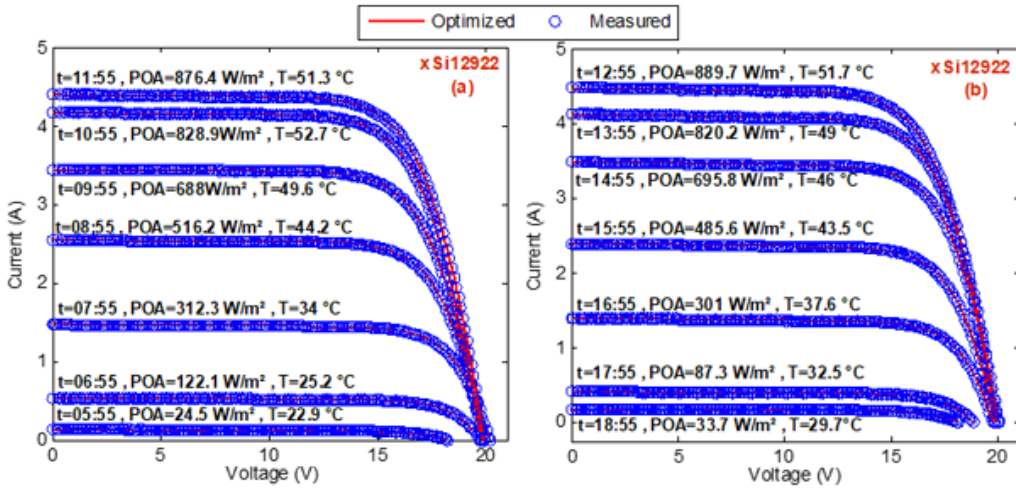
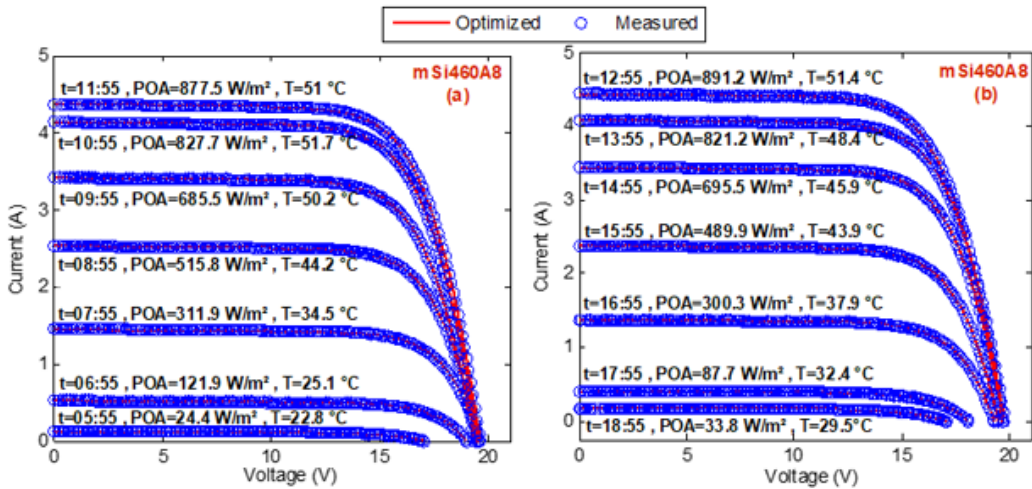
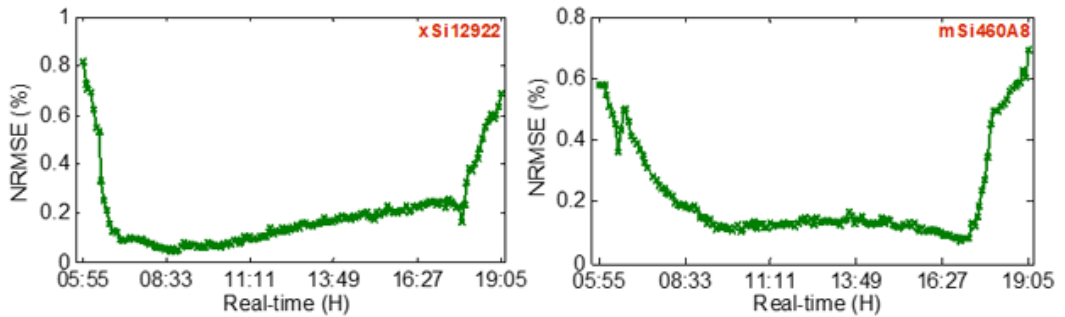


Figure 12. Experimental and optimized I-V curves for the PV module mSi460A8 in the morning (a) and in the afternoon (b) operating outdoors during June 21st 2011 at Cocoa (Florida)



Based on the figures in Fig.13, we can see that the values of the Normalized Root Mean Square Error (NRMSE) obtained using the new method, did not exceed 0.82% for the PV module xSi12922, and 0.7% for mSi460A8. While the values of the Normalized Root Mean Square Error (NRMSE) in the works in (Zaimi et al., 2020) reach 1.2% for the PV module xSi12922 and 1.8% for mSi460A8 which were considered as the best values obtained in the works. Therefore, it can be said that the estimated values of the five parameters using the current method give the best description of the intrinsic parameters of the photovoltaic modules under study.

Figure 13. Real-time variation of NRMSE values for the two PV modules xSi12922 and mSi460A8 operating outdoor during June 21st 2011 at Cocoa (Florida)



Real-Time and Optimized Maximum Power of PV Modules Operating Outdoor Under Real Environmental Conditions

To evaluate the accuracy of the proposed method for predicting the maximum power point, the optimized and the measured values of the peak power for the two PV modules (xSi12922 and mSi460A8) are plotted in Fig.14. Then, the normalized errors for the PV panels were calculated and shown in Fig.15. The optimized peak power values have been extracted by maximizing the optimized P-V curves using the proposed numerical approach.

As it can be seen in Fig.15, the Normalized errors calculated for the peak powers for both PV panels do not exceed 0.09% for the PV module xSi12922 and 0.07% for mSi460A8, when the values obtained by (Zaimi et al., 2020) reach 1% for both PV panels. The results confirm the high efficacy of the new approach in extracting the maximum power points for different weather conditions.

Figure 14. Real-time variation of optimized and measured peak power for the two PV modules xSi12922 and mSi460A8 operating outdoor during June 21st 2011 at Cocoa (Florida)

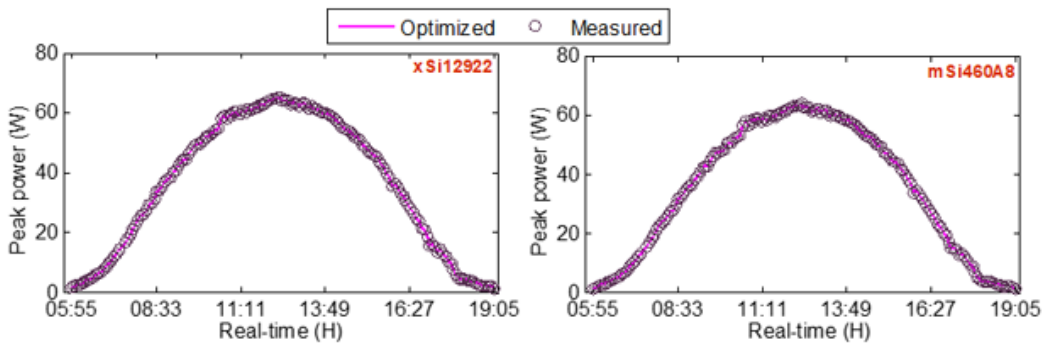
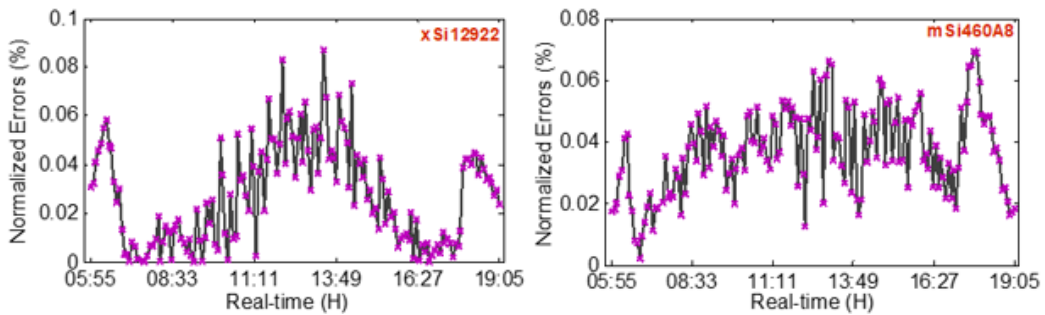


Figure 15. Real-time variation of Normalized Errors (NE) between optimized and measured peak powers for the two PV modules operating outdoor during June 21st 2011 at Cocoa (Florida)



CONCLUSION

An accurate method based on the reducing forms technique to extract the five parameters' values of PV generators has been proposed in this paper. The presented method is based only on the experimental I-V curves to explicit analytically the three parameters (I_{ph} , I_s , and R_p) as functions of the two numerically estimated unknowns (n and R_s). Further, first to validate and evaluate the performances of this method, two important cases of solar cell and PV module were selected, and the results showed a higher order of accuracy compared to other reduced forms of literature. Then, to test the accuracy of the current approach for real-time prediction, the measured data taken by NREL researchers of two PV modules (xSi12922 and mSi460A8) operating outdoor under real-environmental conditions, for almost 13 hours starting from 05:55 AM to 07:05 PM have been used. It has been found that optimized I-V curves are very close to the experimental I-V characteristics, and the NRMSE values have not exceeded 0.82% in the worst case of the study. Measured and optimized maximum power values are also very close, and the NE values have not exceeded 0.09%. The proposed numerical solution showed a higher level of accuracy without any approximation and using only the I-V measured curves and measured PV module's temperature, and without any measurement of irradiation's values. Moreover, the technic does not rely on any refinement of results, which makes it a simple method to be automated for real-time prediction.

CONFLICT OF INTEREST

The authors of this publication declare there is no conflict of interest.

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APPENDIX

Table 3. Nomenclature

Nomenclature	
I_{ph}	Light generated current (A).
I_{sc}	Short circuit current (A).
I_{mp}	Current of maximum power point (A).
I_e	Experimental current (A).
I_c	Calculated current (A).
I_s	Reverse saturation current (A).
P_c	Calculated power (W).
P_e	Experimental power (W)
R_p	Shunt resistance (Ω).
G_p	Shunt admittance (Ω^{-1}).
R_s	Series parasitic resistance (Ω).
V_{mp}	Voltage of maximum power point (V).
V_{oc}	Open circuit voltage (V).
V_{th}	Thermal voltage (V).
n	Ideality factor.
N	Number of measured data points.
N_s	Number of cell connected in series
k_B	Boltzmann constant ($1.38064852 \times 10^{-23}$ J/K).
q	Electron charge ($1.60217662 \times 10^{-19}$ C).
T	PV module Temperature ($^{\circ}\text{K}$).
IAE	Individual Absolute Error.
NRMSE	Normalized Root Mean Square Error.
RMSE	Root Mean Squared Error.
POA	Plane-of-Array Irradiance (W/m^2).
NE	Normalized Error.
NREL	National of Renewable Energy Laboratory.

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