Parameter Extraction of Two Diode Photovoltaic Model Using An Analytical Approach

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***Abstract*—In this study, a Two-Diode Model is implemented for photovoltaic modules to accurately derive photovoltaic parameters. A noteworthy contribution of this work is the introduction of a simplified current equation, necessitating the estimation of only seven parameters. Additionally, we present an effective modeling approach for the Photovoltaic module based on the Two-Diode Model. The extraction of Two-Diode Model parameters is accomplished using the suggested analytical method. Case studies are conducted on the PWP-201 module and the R.T.C. France Solar Cell module to showcase the accuracy of the analytical method. Results from an experimental setup comprising two 40 W Poly-crystalline Photovoltaic panels are also reported. The performance of the proposed analytical method for the Two-Diode Model is assessed, and its consistency with experimental I-V curves and other methods is established.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8542

***Index Terms*—Analytical method, Parameter extraction methods, Photovoltaic, Single Diode Model, and Two Diode Model.**

I. INTRODUCTION

The most accessible energy sources for meeting the world's energy demands still revolve around fossil fuels such as coal, oil, and natural gas. However, these energy sources are not only scarce and exhaustible but also rapidly depleted. Consequently, their use contributes significantly to the release of harmful gases like carbon dioxide into the global environment, posing various challenges to the economy, climate, and human health [1]. The imperative to reduce CO_2 emissions has prompted a shift towards exploring alternative, clean, renewable, and abundantly available sources over the past few decades. Among the most promising energy sources today is solar power, attracting attention from experts worldwide who are focused on enhancing its efficiency [2]. Photovoltaic energy systems, with their substantial potential as practical and clean energy solutions for future needs, have become a focal point of research in recent decades [3]. The escalating interest in solar energy has propelled the accelerated and widespread adoption of solar-powered systems.

Solar cells come in various types, including thin-film, mono-crystalline, and poly-crystalline modules. The mono-crystalline cell is the most expensive of the three types. Among the three types, mono-crystalline cells tend to be more expensive. Thin-film technology generally exhibits lower efficiency compared to poly-crystalline solar cells. While ideality factors in solar cells typically vary between 1 and 4 [4], of all unknown parameters, it is not feasible for the ideality factor to exceed a value of 4, which is observed in thin-film solar cells. Therefore, it is essential to prioritize the development of efficient poly-crystalline solar cells. Analyses of solar cells include considerations of irradiation, temperature, and output voltage, all of which play a significant role in determining the output characteristics of a photovoltaic (PV) module. The output of a PV cell, structured with a P-N junction resembling that of a diode, exhibits a strong nonlinear feature [5]. To gain a deeper understanding of their performance, various literature provides mathematical representations and simulations of different PV system components [6]. The rapid increase in global energy requirements, driven by both technological advancements and the expanding world population, necessitates close attention to these developments.

There has been a notable advancement in technology for modeling PV systems through efficient methods. Beyond mere modeling, it is crucial to predict the internal physical effects that influence the performance of PV systems operating under various temperatures and levels of irradiance [7]. To implement the model for a PV module, several circuit characteristics must be determined. A Single Diode Model (SDM) comprises R_{S} and R_{P} models, each with four and five parameters, respectively [8]. The transcendental equation describing the voltage-current relationship in the R_{P} model involves five unknown parameters. Equivalent circuits, such as the SDM and Two diode Model (TDM), are commonly employed for this purpose [9]. The unknown parameters in PV equivalent circuits introduce a complex nature, necessitating approximations and assumptions to mitigate non-linearity and obtain an analytically determined set of unknown parameter values.

The SDM represents the most fundamental among various mathematical representations of a PV module. Both the five-parameter SDM and seven-parameter TDM are widely used, featuring non-linear representations. PV device models play a crucial role in determining the I-V and P-V properties of these devices, as well as estimating the output power under diverse application scenarios. Numerous researchers employ sophisticated algorithms for parameter extraction, such as the genetic algorithm [10], the bacterial foraging algorithm [11], and the pattern search algorithm [12]. However, intelligent algorithms have inherent drawbacks, including the need for

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an initial value, a complex calculation process, potential early convergence, increased computational resource requirements, and susceptibility to getting trapped in local optima. In recent literature, the estimation of PV module parameters has been explored using innovative algorithms like the Lambert W function and the Co-content method [13], the Flow Direction Algorithm [14], Systems Engineering Methodology [15], and the Combined Analytical and Genetic Algorithm [16].

Numerous methodologies have been explored in the existing literature for determining model parameters. These techniques can be classified into three primary categories: firstly, those dedicated to deriving parameters from manufacturer datasheets; secondly, those centered around acquiring parameters through a series of experimental current-voltage data points; and lastly, those that integrate both datasheet information and experimental data. Among these approaches, specific techniques have been developed to represent parameters as functions of irradiance and temperature. An enhanced TDM for the PV system was suggested to further increase accuracy [17]. The use of analytical methods in real-time applications, such as predicting PV module performance, effective load scheduling, and providing a means to extract hydrogen for making steel and other purposes, aligns with sustainable development goals. To achieve these sustainable goals, effective modeling of PV modules is necessary for assessing efficiency, performance, and, consequently, the lifetime (utilizing the life cycle assessment method [18]) of the modules. Estimation of PV parameters is essential to increase the lifetime of the PV module. Since recombination losses are incorporated in the TDM, proper modeling is necessary.

This paper is organized as follows: section II addresses unknown parameters and the mathematical modeling of the TDM. In Section III, the implementation of the analytical method for the TDM is discussed in detail. The objective of Section IV is to assess the precision of the proposed method using various test systems involving PV cells and modules. Finally, Section V presents the conclusions drawn from this work.

II. MATHEMATICAL MODELING OF TWO DIODE MODEL

It is apparent from the literature that the majority of studies are focused on the SDM due to its simplicity and a lower number of unknown factors, making it easier to analyze and extrapolate unknown parameters. The advantage of TDM lies in its ability to capture the behavior of a PV cell, accounting for recombination losses and potential-induced degradation, and considering the temperature effect on diode voltage and series resistance. In addition to the factors addressed in the SDM, the TDM incorporates the impact of recombination current loss within the space charge region by introducing a second diode connected in parallel to the first within the equivalent circuit model. This results in a notable enhancement in accuracy. The inclusion of the I_{02} term compensates for compound losses within the depleted area, demonstrating improved accuracy, particularly in instances of low irradiance [19]–[22].

The parameter estimation problem is recognized to be challenging due to the non-linearity and implicit nature of the governing equations of the models. The key features of this model encompass the ideality factors (a_1 and a_2) of the two diodes, their respective reverse saturation currents (I_{01} and I_{02}), series parasitic resistance (R_S), parallel parasitic resistance (R_P), and light-produced current (I_{ph}) [23]. Consequently, various methods for parameter estimation have been introduced in the scientific literature [24]. However, this model requires the computation of seven parameters and can offer higher precision. Modeling serves to convey graphical representations, design information, simulate real-world behavior, or specify the processes of a system. The equivalent circuit for the TDM is depicted in Fig. 1 [25]. The equation for the TDM is given by [25] –

$$I_{ph} = I_{D_1} + I_{D_2} + I_P + I \tag{1}$$

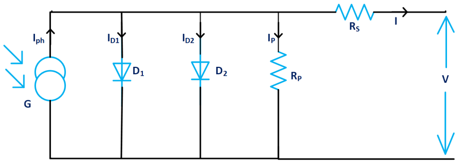

Fig. 1. Equivalent Circuit for Two Diode PV module.

where

$$I_P = \frac{V + IR_S}{R_P}$$

By substituting I_P value in Eq. (1), we obtain the below equation as -

$$I_{ph} = I_{D_1} + I_{D_2} + \left(\frac{V + IR_S}{R_P}\right) + I$$

Rearranging the above equation as -

$$I_{ph}R_P = I_{D_1}R_P + I_{D_2}R_P + (V + IR_S) + IR_P$$

$$\frac{I_{\mathrm{ph}}R_P}{R_S + R_P} = \frac{I_{D_1}R_P}{R_S + R_P} + \frac{I_{D_2}R_P}{R_S + R_P} + \frac{V}{R_S + R_P} + I$$

where

$$I_{D1} = I_{01}\left[e^{(V+IR_S)/a_1V_T} - 1\right]$$

and

$$I_{D2} = I_{02}\left[e^{(V+IR_S)/a_2V_T} - 1\right]$$

By substituting I_{D1} and I_{D2} values in above equation, we obtain the equation as -

$$I = \frac{I_{ph}R_P}{R_S+R_P} - \frac{I_{D_1}R_P}{R_S+R_P} - \frac{I_{D_2}R_P}{R_S+R_P} - \frac{V}{R_S+R_P} \tag{2}$$

where

$$V_T = \frac{k * T}{q}$$

Eq. (2) involves the temperature (T) and irradiance in the form of photon generated current (I_{ph}). The proposed Eq. (2) involves the TDM parameter extraction analysis with inputs as temperature and irradiance. Few terms in Eq. (2) are considered as constant and they are -

$$M = I_{ph}\left(\frac{R_P}{R_P + R_S}\right)$$
$$F = \frac{1}{R_P + R_S}$$
$$B = I_{01}\left(\frac{R_P}{R_P + R_S}\right)$$
$$C = e^{\frac{1}{a_1 V_T}}$$
$$D = e^{\frac{R_S}{a_1 V_T}}$$
$$E = I_{02}\left(\frac{R_P}{R_P + R_S}\right)$$
$$g = \frac{a_1}{a_2}$$

Therefore Eq. (2) can be rewritten as –

$$I = (M) - B\left(C^I D^V - 1\right) - E\left(C^{Ig} D^{Vg} - 1\right) - VF$$
$$I = (M + B + E - VF) - \left(BC^I D^V\right) - \left(EC^{Ig} D^{Vg}\right) \quad (3)$$

Since M, B, E are constants, K=(M+B+E) is also a constant. Considering ‘g’ as ratio of ideality factors reduces the number of parameters to be estimated to seven. Now Eq. (3) changes to –

$$I = (K - VF) - \left(BC^I D^V\right) - \left(EC^{Ig} D^{Vg}\right) \quad (4)$$

The seven unknowns in Eq. (4) are K, F, B, C, D, E and g and solved using a three-step process. First step is linear part and other two parts are exponential part 1 and exponential part 2. As there are a total of ‘n’ data points on the I-V curve of PV module, among all the existing data points, n_1 to m_1 (where n_1=1 and m_1=n_1+1) are considered in the first step. In the second step the data points from n_2 to m_2 (where n_2=n_1+1 and m_2=n_2+2) are considered. Furthermore, data points from n_3 to m_3 (where n_3=n_1+1 and m_3=n_3+1) are considered in the third step.

III. IMPLEMENTATION OF PROPOSED ANALYTICAL METHOD

In this paper, the analytical method is employed to obtain accurate PV model parameters. The three-step procedure for TDM is as follows -

A. STEP 1: Linear Part

In this step, only the linear part is considered for calculating the K and F unknowns.

$$I = K - VF \quad (5)$$

The objective function (O.F.) for Eq. (5) is given by

$$O.F. = \min\{[K - VF - I]^2\} \quad (6)$$

Partial derivative of Eq. (6) w.r.to K and F, and equating to zero result in Eq. (7) and Eq. (8).

$$\frac{\partial}{\partial K}(O.F.) = 0 \Rightarrow 2 * [K - VF - I] = 0$$
$$\Rightarrow K\sum_{i=n_1}^{m_1} 1 - F\sum_{i=n_1}^{m_1} V_i = \sum_{i=n_1}^{m_1} I_i \quad (7)$$

$$\frac{\partial}{\partial F}(O.F.) = 0 \Rightarrow 2 * [K - VF - I] * [-V] = 0$$
$$\Rightarrow (-K)\sum_{i=n_1}^{m_1} V_i + F\sum_{i=n_1}^{m_1} (V_i)^2 = -\sum_{i=n_1}^{m_1} I_i V_i \quad (8)$$

Rewriting Eq. (7) and Eq. (8) in the matrix form –

$$\begin{bmatrix} \sum_{i=n_1}^{m_1} 1 & -\sum_{i=n_1}^{m_1} V_i \\ -\sum_{i=n_1}^{m_1} V_i & \sum_{i=n_1}^{m_1} (V_i)^2 \end{bmatrix} \begin{bmatrix} K \\ F \end{bmatrix} = \begin{bmatrix} \sum_{i=n_1}^{m_1} I_i \\ -\sum_{i=n_1}^{m_1} I_i V_i \end{bmatrix}$$

$$\begin{bmatrix} K \\ F \end{bmatrix} = \begin{bmatrix} \sum_{i=n_1}^{m_1} 1 & -\sum_{i=n_1}^{m_1} V_i \\ -\sum_{i=n_1}^{m_1} V_i & \sum_{i=n_1}^{m_1} (V_i)^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=n_1}^{m_1} I_i \\ -\sum_{i=n_1}^{m_1} I_i V_i \end{bmatrix} \quad (9)$$

Obtain the values of K and F by solving Eq. (9).

B. STEP 2: Exponential Part 1

For obtaining the values of B, C, and D, Eq. (4) can be considered as –

$$I = (K - VF) - BC^I D^V \quad (10)$$
$$BC^I D^V = (K - VF) - I \quad (11)$$

Apply logarithm on both sides of Eq. (11)

$$\ln(B) + I\ln(C) + V\ln(D) = \ln(K - VF - I) \quad (12)$$

The objective function (O.F.) for Eq. (12) is given by

$$O.F. = \min\{[\ln(B) + I\ln(C) + V\ln(D) - \ln(K - VF - I)]^2\} \quad (13)$$

As there are three unknowns (B, C and D) in Eq. (13), three gradients are possible.

$$\frac{\partial}{\partial B}(O.F.) = 0$$
$$\Rightarrow \ln(B)\sum_{i=n_2}^{m_2} 1 + \ln(C)\sum_{i=n_2}^{m_2} I_i$$
$$+ \ln(D)\sum_{i=n_2}^{m_2} V_i = \sum_{i=n_2}^{m_2} \ln\left(K - V_i F - I_i\right) \quad (14)$$

$$\frac{\partial}{\partial C}(O.F.) = 0$$
$$\Rightarrow \ln(B)\sum_{i=n_2}^{m_2} I_i + \ln(C)\sum_{i=n_2}^{m_2} (I_i)^2$$
$$+ \ln(D)\sum_{i=n_2}^{m_2} (V_i I_i) = \sum_{i=n_2}^{m_2} I_i \ln\left(K - V_i F - I_i\right) \quad (15)$$

$$\frac{\partial}{\partial D}(O.F.) = 0$$
$$\Rightarrow \ln(B)\sum_{i=n_2}^{m_2} V_i + \ln(C)\sum_{i=n_2}^{m_2} (V_i I_i)$$
$$+ \ln(D)\sum_{i=n_2}^{m_2} (V_i)^2 = \sum_{i=n_2}^{m_2} V_i \ln\left(K - V_i F - I_i\right) \quad (16)$$

Eq. (14), Eq. (15), and Eq. (16) in matrix form –

$$A_2 X_2 = B_2 \Rightarrow X_2 = (A_2)^{-1} B_2 \quad (17)$$

where

$$A_2 = \begin{bmatrix} \sum\limits_{i=n_2}^{m_2} 1 & \sum\limits_{i=n_2}^{m_2} I_i & \sum\limits_{i=n_2}^{m_2} V_i \\ \sum\limits_{i=n_2}^{m_2} I_i & \sum\limits_{i=n_2}^{m_2} (I_i)^2 & \sum\limits_{i=n_2}^{m_2} (V_i I_i) \\ \sum\limits_{i=n_2}^{m_2} V_i & \sum\limits_{i=n_2}^{m_2} (V_i I_i) & \sum\limits_{i=n_2}^{m_2} (V_i)^2 \end{bmatrix}$$

$$X_2 = \begin{bmatrix} \ln(B) \\ \ln(C) \\ \ln(D) \end{bmatrix}$$

$$B_2 = \begin{bmatrix} \sum\limits_{i=n_2}^{m_2} \ln(K - V_i F - I_i) \\ \sum\limits_{i=n_2}^{m_2} I_i * \ln(K - V_i F - I_i) \\ \sum\limits_{i=n_2}^{m_2} V_i * \ln(K - V_i F - I_i) \end{bmatrix}$$

B, C, and D values are obtained from ln(B), ln(C) and ln(D) using Eq. (17).

C. STEP 3: Exponential Part 2

Last two unknowns i.e, E and g can be attained using Eq. (4) with consideration of all ramp and exponential parts.

$$I = (K - VF) - \left(BC^I D^V\right) - \left(EC^{Ig} D^{Vg}\right)$$

$$\left(EC^{Ig} D^{Vg}\right) = (K - VF) - \left(BC^I D^V\right) - I \tag{18}$$

Applying logarithm on both sides of Eq. (18) -

$$\begin{aligned} &\ln(E) + g\left\{I \ln(C) + V \ln(D)\right\} \\ &= \ln\left\{(K - VF) - \left(BC^I D^V\right) - I\right\} \end{aligned} \tag{19}$$

The objective function for the above equation can be written as –

$$\begin{aligned} O.F. = \min\{[&\ln(E) + g\{I \ln(C) + V \ln(D)\} - \\ &\ln\{(K - VF) - (BC^I D^V) - I\}]^2\} \end{aligned} \tag{20}$$

Two unknowns in Eq. (20) can be obtained from two gradients:

$$\frac{\partial}{\partial E}(O.F.) = 0 \Rightarrow \ln(E) \sum_{i=n_3}^{m_3} 1 + g \sum_{i=n_3}^{m_3} O_1 = \sum_{i=n_3}^{m_3} N_1 \tag{21}$$

$$\frac{\partial}{\partial g}(O.F.) = 0$$

The Eq. (22) is related to objective function when the gradient w.r.to ‘g’ is zero.

$$\Rightarrow \ln(E) \sum_{i=n_3}^{m_3} \{\mathrm{O}_1\} + g \sum_{i=n_3}^{m_3} [\mathrm{O}_1]^2 = \sum_{i=n_3}^{m_3} [\mathrm{O}_1 * \mathrm{N}_1] \tag{22}$$

Representing Eq. (21) and Eq. (22) in matrix form –

$$A_1 X_1 = B_1 \Rightarrow X_1 = (A_1)^{-1} B_1 \tag{23}$$

where,

$$\mathrm{A_1} = \begin{bmatrix} \sum\limits_{\mathrm{i=n_3}}^{\mathrm{m_3}} 1 & \sum\limits_{\mathrm{i=n_3}}^{\mathrm{m_3}} \{\mathrm{I_i \ln(C) + V_i \ln(D)}\} \\ \sum\limits_{\mathrm{i=n_3}}^{\mathrm{m_3}} \{\mathrm{I_i \ln(C) + V_i \ln(D)}\} & \sum\limits_{\mathrm{i=n_3}}^{\mathrm{m_3}} [\mathrm{I_i \ln(C) + V_i \ln(D)}]^2 \end{bmatrix}$$

$$\mathrm{X_1} = \begin{bmatrix} \mathrm{\ln(E)} \\ \mathrm{g} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \sum\limits_{i=n_3}^{m_3} N_1 \\ \sum\limits_{i=n_3}^{m_3} O_1 * N_1 \end{bmatrix}$$

$$N_1 = \ln\left\{(K - V_i F) - \left(BC^{I_i} D^{V_i}\right) - I_i\right\}$$

$$O_1 = \{I_i \ln(C) + V_i \ln(D)\}$$

Values of E and g can be obtained from Eq. (23). Based on Eq. (9), Eq. (17), and Eq. (23) we obtain the values of seven (I_{ph}, I_{01}, I_{02}, R_S, R_P, a_1, and a_2) unknown parameters.

$$a_1 = \frac{1}{V_T * \log(C)}$$

$$a_2 = \frac{a_1}{g}$$

$$R_S = a_1 * V_T * \log(D)$$

$$R_P = \frac{1}{F} - R_S$$

$$I_{ph} = \left(\frac{M}{R_P}\right) * (R_P + R_S)$$

$$I_{01} = \left(\frac{B}{R_P}\right) * (R_P + R_S)$$

$$I_{02} = \left(\frac{E}{R_P}\right) * (R_P + R_S)$$

To validate the analytical technique for extracting the parameters of PV modules, four case studies are considered. The first two case studies, i.e., PWP-201 and R.T.C. France solar cell, involve experimental data collected from [25] and [26]. For the PWP-201 case study, the temperature and the number of cells in series were considered as 51°C and 36, respectively. Additionally, for the R.T.C. France solar cell, a temperature of 33°C and a single cell were considered. Case studies 3 and 4 are conducted using a PV panel hardware setup of 40 W (Poly-crystalline).

IV. RESULTS AND DISCUSSION

The proposed method is validated through various case studies. The performance indicator, Root-Mean-Square-Error (RMSE), is assessed by –

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{N} \left(I_{\exp(i)} - I_{est(i)}\right)^2}{N}}$$

where $I_{\text{exp (i)}}$ and $I_{\text{est (i)}}$ are currents obtained using experimentation and proposed method. $I_{\text{est (i)}}$ is obtained using two-diode equation which involves linear part (n_1, m_1), exponential part 1 (n_2, m_2) and exponential part 2 (n_3, m_3). With these three parts, many combinations of n_1 to m_3 values are obtained using analytical method. To ensure the reliability of these data points, all these values are simulated using a MATLAB simulation circuit to obtain better performance index. The results obtained by the MATLAB circuit are treated as the estimated current using the proposed method. The performance index (RMSE) is evaluated using both the measured current and the estimated current. The specifications of PWP-201, R.T.C. France and PV hardware experimental setup are presented in Table I.

TABLE I
SPECIFICATIONS OF PWP 201, RTC FRANCE AND PV PANEL EXPERIMENTAL SETUP

Electrical Quantity	Ratings PWP-201 [25]	RTC France [26]	Experimental
Rated Maximum Power	11.5 W	0.31 W	40 W
Open Circuit Voltage	16.788 V	0.57270 V	21.9 V
Short Circuit Current	1.030 A	0.76050 A	2.45 A
Rated Voltage	12.649 V	0.4590 V	17.4 V
Rated Current	0.9120 A	0.67550 A	2.3 A

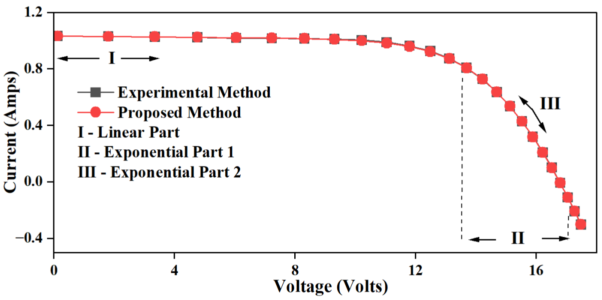

Fig. 2. Linear and Exponential parts indication for PWP-201 PV module.

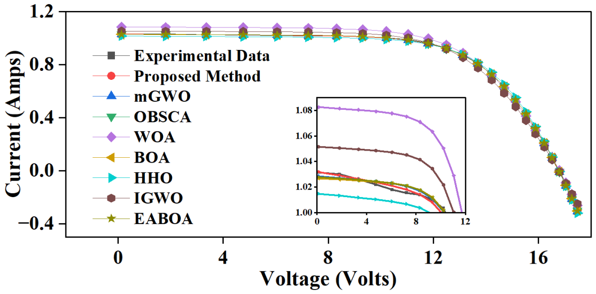

Fig. 3. Comparison of I-V characteristics obtained using proposed method for PWP-201 test system.

A. Case Study 1: Implementation of Proposed Method on PWP-201 Test System

Experimental current and voltage data for the PWP-201 system were extracted from [25] and are listed in Table II. The I-V characteristics, obtained using both experimental and proposed methods for PWP-201 at a temperature of 51°C, are illustrated in Fig. 2. Fig. 3 presents a comparison of various I-V curves using different methods. Observing the results, it is evident that the analytical method accurately reflects the experimental data, supporting the assertion that the proposed analytical method minimizes the RMSE. Fig. 2 provides an analysis of linear and exponential values at which the RMSE is minimum. Table III presents the unknown parameters and RMSE values obtained by the proposed analytical method in comparison with other algorithms such as mGWO [25], OBSCA [25], WOA [25], BOA [25], HHO [25], IGWO [25], and EABOA [25].

TABLE II
COMPARISON OF CURRENT VALUES FOR THE PWP-201 SOLAR CELL

Experimental Data		Current Obtained Using Proposed Method: I (Amp)							
Voltage (V) [25]	Current (A) [25]	Proposed Analytical Method	mGWO [25]	OBSCA [25]	WOA [25]	BOA [25]	HHO [25]	IGWO [25]	EABOA [25]
0.1248	1.0315	1.0319	1.02844598	1.02752089	1.08249	1.02689	1.0148202	1.05141531	1.02784541
1.8093	1.03	1.0291	1.0271365	1.02650624	1.08139	1.026017	1.0132686	1.05044832	1.02674284
3.3511	1.026	1.0264	1.02587528	1.02551516	1.08032	1.025154	1.0118101	1.04950948	1.0256708
4.7622	1.022	1.0238	1.02456196	1.02444948	1.07914	1.024205	1.0103719	1.04849971	1.02453007
6.0538	1.018	1.0212	1.02299226	1.02310668	1.07758	1.022967	1.0088045	1.04719281	1.02311703
7.2364	1.0155	1.0182	1.02077499	1.02109621	1.07516	1.021048	1.0068108	1.04511891	1.02104031
8.3189	1.014	1.0142	1.01721849	1.01772462	1.07094	1.017753	1.0038428	1.04137392	1.01760666
9.3097	1.01	1.008	1.01119512	1.01185861	1.06343	1.01195	0.9989654	1.03439128	1.01168507
10.2163	1.0035	0.9982	1.00102855	1.00181056	1.05042	1.00195	0.9907176	1.02175596	1.0015937
11.0449	0.988	0.9825	0.98448874	0.98533372	1.02905	0.98551	0.977043	1.0002764	0.98509557
11.8018	0.963	0.9579	0.95894331	0.95977668	0.99627	0.959981	0.9553515	0.96650354	0.95955159
12.4929	0.9255	0.9217	0.92177036	0.92250464	0.9495	0.922737	0.9228276	0.91774667	0.92233678
13.1231	0.8725	0.8716	0.87099445	0.87154496	0.88756	0.871807	0.8770272	0.8531907	0.87147933
13.693	0.8075	0.8065	0.80569725	0.80600291	0.81095	0.806297	0.8163838	0.77408148	0.80607223
14.2221	0.7265	0.7271	0.72661426	0.72665491	0.72203	0.726978	0.740965	0.6836048	0.72686784
14.6995	0.6345	0.6355	0.6355888	0.63538863	0.62393	0.63573	0.6521459	0.58543005	0.63572651
15.1346	0.5345	0.5345	0.53535329	0.53497251	0.52005	0.535312	0.5524632	0.48316886	0.53539393
15.5311	0.4275	0.4275	0.42895805	0.42847779	0.41355	0.428792	0.4450254	0.37987262	0.42892797
15.8929	0.3185	0.3174	0.31916366	0.31867106	0.30684	0.318935	0.3328133	0.27773502	0.31909148
16.2229	0.2085	0.2067	0.20853146	0.20810881	0.20198	0.208298	0.218682	0.178472	0.20844438
16.5241	0.101	0.0976	0.09902477	0.09874314	0.10033	0.098838	0.1048905	0.08315036	0.09894649
16.7987	-0.008	-0.0084	-0.0076736	-0.0077572	0.00299	-0.00777	-0.006606	-0.007407	-0.0077238
17.0499	-0.111	-0.1106	-0.110796	-0.1106378	-0.0897	-0.11077	-0.114837	-0.0930971	-0.1108029
17.2793	-0.209	-0.208	-0.2093889	-0.2089582	-0.1773	-0.20922	-0.218669	-0.1735806	-0.2093415
17.4885	-0.303	-0.302	-0.302829	-0.3021065	-0.2595	-0.30251	-0.317339	-0.248725	-0.3027197
RMSE		0.0024185	0.0024632	0.00244732	0.0372324	0.0024712	0.0118626	0.0308180	0.0024462

B. Case Study 2: Implementation of Proposed Method on R.T.C. France Cell

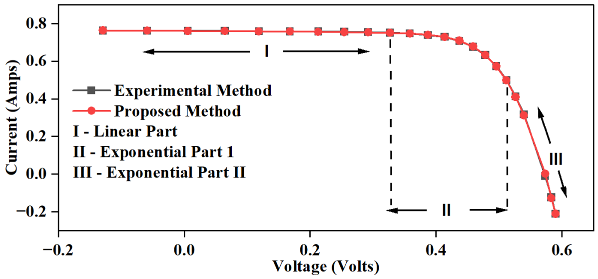

Fig. 4. Linear and Exponential parts indication for R.T.C. France Solar Cell.

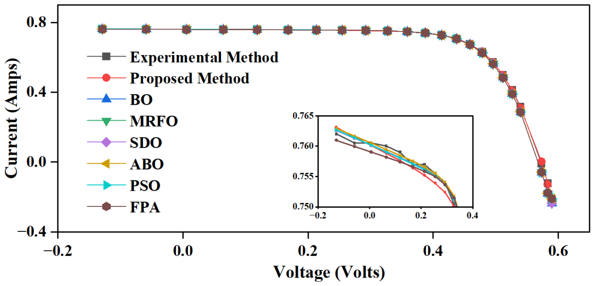

Fig. 5. Comparison of I-V characteristics obtained using Proposed method for R.T.C. France Test System

In this case study, the proposed analytical method is implemented on the R.T.C. France Cell with temperature of 33°C and the corresponding current-voltage data points that were considered from [26]. Fig. 4 illustrates the comparison of current-voltage characteristics between the experimental and proposed analytical methods, providing a clear indication of both linear and exponential parts.

The performance index, RMSE, is evaluated for the proposed analytical method and compared with existing methods, as listed in Table IV. Observing Table IV reveals that the RMSE for the proposed analytical method is 0.003254, the minimum among all methods. Fig. 4 illustrates the analysis of linear and exponential values, identifying the minimum RMSE value. Based on the currents obtained from the experimental and proposed methods (Table III), various I-V curves are plotted, as shown in Fig. 5. Table V presents the RMSE and seven unknown parameter values obtained by the proposed analytical method, comparing them with other techniques such as BO [26], MRFO [26], SDO [26], ABO [26], PSO [26], and FPA [26].

C. Case Study 3: Irradiance of 115 W/m^2

Case studies 3 and 4 involve PV panel hardware that is considered and tested for two different irradiances, i.e., 115 W/m^2, and 450 W/m^2. The PV hardware and devices utilized, including a voltmeter, ammeter (in-built), connecting wires, and irradiance meter, are shown in Fig. 6. The methodology for the hardware setup is as follows:

1) Set the irradiance value (115 W/m^2, and 450 W/m^2 for case studies 3 and 4).
2) Vary the resistance and note the readings of voltage and current.
3) Apply the proposed analytical method to the obtained voltage and current readings, with a performance index (RMSE) attained as 0.00605 (case study 3) and 0.00917 (case study 4).

Fig. 6. PV Panel Experimental Setup.

In this case study, the proposed method is implemented for an irradiance and temperature of 115 W/m^2 and 26.7°C. The current and voltage data points obtained from experimental data and the proposed analytical method are tabulated in Table VI. Fig. 7 displays the I-V characteristics of the experimental and proposed method. The resulting RMSE error and the parameters are shown in Table VII. An RMSE of 0.00605 is achieved with proposed analytical method.

TABLE III

COMPARISON OF PWP-201 SOLAR CELL TWO DIODE MODEL PARAMETERS

	I_{ph} (A)	I_{01} (A)	R_S (Ω)	R_P (Ω)	a_1	I_{02} (A)	a_2	RMSE
mGWO [25]	0.678596	4.16E-05	0.000898	2686.39	1.76928	2.31E-05	3.11592	0.0024632
OBSCA [25]	0.684616	5.50E-05	0	3737.32	2.29433	6.52E-05	1	0.00244732
WOA [25]	0.676977	2.19E-06	0.000402	4999.95	1.67466	1.53E-07	3.56683	0.0372324
BOA [25]	0.683641	2.91E-05	1.85E-10	1595.88	2.13525	6.87E-05	1.08945	0.0024712
HHO [25]	0.679146	3.87E-05	0	193.902	1.75828	2.44E-05	3.70627	0.0118626
IGWO [25]	0.683612	1.43E-05	0	1546.58	1.97835	8.59E-05	2.52658	0.030818
EABOA [25]	0.691508	1.48E-07	0.007947	12.4673	1.38154	5.16E-05	1.38882	0.0024462
Analytical Method	1.0343193	2.4421906e-06	1.2419901	589.70077	1.2912055	3.157e-10	1.1047247	0.0024185

TABLE IV
COMPARISON OF CURRENT VALUES FOR R.T.C. FRANCE SOLAR CELL

Experimental Data			Current Obtained Using Proposed Method: I (Amp)					
Voltage (V) [26]	Current (A) [26]	Proposed Analytical Method	BO [26]	MRFO [26]	SDO [26]	ABO [26]	PSO [26]	FPA [26]
-0.2057	0.764	0.7647	0.7644892	0.7644892	0.7645101	0.7648214	0.7646393	0.7624956
-0.1291	0.762	0.7631	0.7626024	0.7626024	0.7626083	0.7629463	0.7626811	0.7609835
-0.0588	0.7605	0.7615	0.7613363	0.7613363	0.761331	0.7616757	0.7613644	0.7599652
0.0057	0.7605	0.7601	0.7601733	0.7601733	0.7601581	0.7605091	0.7601555	0.7590301
0.0646	0.76	0.7588	0.7591076	0.7591076	0.7590842	0.7594413	0.7590495	0.758174
0.1185	0.759	0.7576	0.7581214	0.7581214	0.7580921	0.7584553	0.7580297	0.7573823
0.1678	0.757	0.7564	0.7571879	0.7571879	0.7571564	0.7575256	0.7570721	0.7566319
0.2132	0.757	0.7552	0.7562436	0.7562436	0.7562151	0.7565888	0.7561173	0.7558641
0.2545	0.7555	0.7539	0.7551766	0.7551766	0.755158	0.7555303	0.7550583	0.7549673
0.2924	0.754	0.7524	0.7537203	0.7537203	0.7537193	0.7540747	0.7536324	0.7536744
0.3269	0.7505	0.7501	0.7513882	0.7513882	0.7514109	0.7517181	0.7513525	0.7514881
0.3585	0.7465	0.7463	0.7472689	0.7472689	0.747317	0.7475238	0.7473	0.7474783
0.3873	0.7385	0.7396	0.7398967	0.7398967	0.7399649	0.7400034	0.7399934	0.7401517
0.4137	0.728	0.7278	0.7269549	0.7269549	0.72703	0.7268356	0.7270954	0.7271653
0.4373	0.7065	0.7081	0.7059596	0.7059596	0.7060247	0.7055864	0.7061055	0.7060315
0.459	0.6755	0.6769	0.6729697	0.6729697	0.6730124	0.6724117	0.673084	0.6728371
0.4784	0.632	0.6321	0.6259944	0.6259944	0.6260168	0.6254587	0.6260643	0.6256682
0.496	0.573	0.572	0.5627924	0.5627924	0.5628134	0.5625816	0.5628435	0.5623725
0.5119	0.499	0.4974	0.4840904	0.4840904	0.484137	0.4844714	0.4841741	0.4837394
0.5265	0.413	0.4092	0.3902978	0.3902978	0.3903938	0.3914176	0.3904696	0.3901971
0.5398	0.3165	0.3111	0.2862293	0.2862293	0.2863767	0.2879671	0.2865062	0.2864963
0.5736	-0.01	0.0026	-0.0593831	-0.0593831	-0.0591741	-0.057430	-0.058909	-0.057865
0.5833	-0.123	-0.1282	-0.1799648	-0.1799648	-0.1797837	-0.178575	-0.179508	-0.178115
0.59	-0.21	-0.2107	-0.2360522	-0.2360522	-0.2361043	-0.21	-0.21	-0.21
RMSE		0.003254	0.0184521	0.0184521	0.0183913	0.0170795	0.0175188	0.0172737

TABLE V
COMPARISON OF R.T.C. FRANCE SOLAR CELL TWO DIODE MODEL PARAMETERS

	I_{ph} (A)	I_{01} (A)	R_S (Ω)	R_P (Ω)	a_1	I_{02} (A)	a_2	RMSE
BO [26]	0.760781089	2.258E-07	0.03674105	55.48760306	1.450969113	7.504E-07	2	0.0184521
MRFO [26]	0.760769105	2.333E-07	0.036601704	54.99425215	1.455616277	3.357E-07	1.823701869	0.0184521
SDO [26]	0.760774368	2.277E-07	0.036639868	54.83458992	1.453532535	0.000000367	1.832083757	0.0183913
ABO [26]	0.760720472	0	0.035591653	58.37873514	2	3.859E-07	1.499268441	0.0170795
PSO [26]	0.76079885	6.947E-07	0.036785973	54.79121514	2	2.279E-07	1.451480929	0.0175188
FPA [26]	0.760294548	5.723E-07	0.034119253	97.08923363	1.540625296	0	1.350173077	0.0172737
Proposed Analytical Method	0.76093	8.7289e-08	0.041802	46.607	1.3604	4.1456e-05	3.9677	0.003254

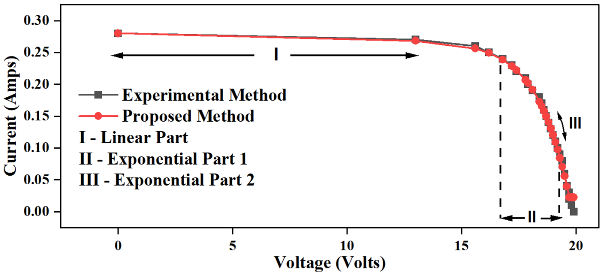

Fig. 7. Linear and Exponential parts indication for Irradiance of 115 W/m^2.

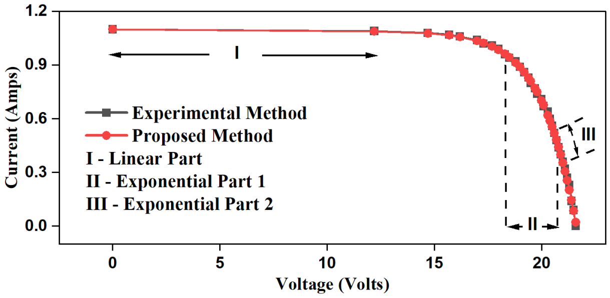

Fig. 8. Linear and Exponential parts indication for Irradiance of 450 W/m^2.

D. Case Study 4: Irradiance of 450 W/m^2

This case study evaluates for temperature and irradiance of 26.7°C and 450 W/m^2, using the experimental data points as shown in Table VIII. Fig. 8 displays the Current-Voltage characteristics of the experimental and proposed method data and attains the RMSE value of 0.00917 with corresponding TDM parameters are tabulated in Table IX. The results of the proposed analytical method for TDM are compared with one diode model for PWP-201 (1000 W/m^2) and R.T.C. France solar cell (1000 W/m^2) are tabulated in Table X and Table XI.

Generally, irradiance exhibits variability over time, and this variability can be predicted. Case studies 3 and 4 involve experimentation on a photovoltaic (PV) hardware setup. However, in these cases, irradiance was intentionally held constant by adjusting the variable knob, allowing for the attainment of corresponding stable temperatures. Both irradiation and temperature remained constant throughout the analysis of case studies 3 and 4. The selected irradiance levels were 115 W/m^2

TABLE VI

COMPARISON OF PROPOSED METHOD CURRENT WITH EXPERIMENTAL CURRENT AT IRRADIANCE OF 115 W/m^2

	Experimental Data		Proposed Analytical Method		Experimental Data		Proposed Analytical Method
Data Point	Voltage (V)	Current (A)	Current (A)	Data Point	Voltage (V)	Current (A)	Current (A)
1	0	0.28	0.279999895	15	18.8	0.14	0.140458526
2	13	0.27	0.268310203	16	18.9	0.13	0.13080725
3	15.6	0.26	0.25633132	17	19	0.12	0.12042954
4	16.2	0.25	0.249317629	18	19.1	0.11	0.10927129
5	16.8	0.24	0.238631173	19	19.2	0.1	0.097274528
6	17.2	0.23	0.22849525	20	19.3	0.09	0.084377155
7	17.4	0.22	0.222222355	21	19.4	0.08	0.070512683
8	17.8	0.21	0.206596558	22	19.5	0.06	0.055609959
9	17.9	0.2	0.201929394	23	19.6	0.04	0.039592875
10	18.1	0.19	0.191514257	24	19.7	0.03	0.022380061
11	18.4	0.18	0.17275895	25	19.7	0.02	0.022380061
12	18.5	0.17	0.165541663	26	19.8	0.01	0.022380061
13	18.6	0.16	0.157780259	27	19.9	0	0.022380061
14	18.7	0.15	0.14943384	RMSE			0.00605

TABLE VII

TWO DIODE MODEL PARAMETERS FOR IRRADIANCE OF 115 W/m^2

	I_{ph} (A)	I_{01} (A)	R_S (Ω)	R_P (Ω)	a_1	I_{02} (A)	a_2	RMSE
Proposed Analytical Method	0.28002	1.0405e-07	0.082329	1299.9	1.447	1.4632e-09	1.4247	0.00605

TABLE VIII

COMPARISON OF PROPOSED METHOD CURRENT WITH EXPERIMENTAL CURRENT AT IRRADIANCE OF 450 W/m^2

	Experimental Data		Proposed Analytical Method		Experimental Data		Proposed Analytical Method
Data Point	Voltage (V)	Current (A)	Current (A)	Data Point	Voltage (V)	Current (A)	Current (A)
1	0	1.1	1.1	18	19.8	0.74	0.7494
2	12.2	1.09	1.088	19	20	0.71	0.7021
3	14.7	1.08	1.0772	20	20.1	0.67	0.6762
4	15.7	1.07	1.0659	21	20.3	0.64	0.6191
5	16.2	1.06	1.057	22	20.4	0.6	0.5878
6	17	1.04	1.035	23	20.5	0.56	0.5545
7	17.3	1.02	1.0233	24	20.6	0.52	0.5191
8	17.7	1.01	1.0035	25	20.7	0.48	0.4815
9	18	0.99	0.9849	26	20.8	0.44	0.4415
10	18.3	0.96	0.9622	27	20.9	0.4	0.399
11	18.5	0.94	0.9443	28	21	0.36	0.3539
12	18.8	0.92	0.9127	29	21.1	0.32	0.3061
13	19	0.89	0.8879	30	21.2	0.27	0.2554
14	19.2	0.86	0.8597	31	21.3	0.23	0.2017
15	19.4	0.83	0.8275	32	21.4	0.14	0.1448
16	19.5	0.8	0.8098	33	21.5	0.09	0.0846
17	19.7	0.77	0.7708	34	21.6	0	0.0208
RMSE							0.00917

TABLE IX

TWO DIODE MODEL PARAMETERS FOR IRRADIANCE OF 450 W/m^2

	I_{ph} (A)	I_{01} (A)	R_S (Ω)	R_P (Ω)	a_1	I_{02} (A)	a_2	RMSE
Proposed Analytical Method	1.1001	4.0058e-07	0.14938	1219.9	1.5714	1.3389e-06	2.93	0.00917

TABLE X

TWO DIODE MODEL PARAMETERS COMPARISON WITH ONE DIODE FOR PWP-201

	2 Diode	1 Diode [27]	FA [28]	MPA [29]
I_{ph} (A)	1.0343193	1.0327	1.0452	1.0352
I_{01} (A)	2.44E-06	4.27E-06	4.68E-05	6.72E-05
R_S (Ω)	1.2419901	1.1896	0.85464	0.83191
R_P (Ω)	589.70077	1121.8	222.2	413.85
a_1	1.2912055	1.3737	1.7106	1.7707
I_{02} (A)	3.16E-10	-	-	-
a_2	1.1047247	-	-	-
RMSE	0.0024185	0.023	0.4024	0.3636

TABLE XI

TWO DIODE MODEL PARAMETERS COMPARISON WITH ONE DIODE FOR R.T.C. FRANCE

	2 Diode	1 Diode [30]	FA [28]	MPA [29]
I_{ph} (A)	0.76093	0.7362	0.76681	0.76769
I_{01} (A)	8.73E-08	3.47E-07	1.54E-06	3.08E-07
R_S (Ω)	0.041802	0.0365	0.01801	0.021365
R_P (Ω)	46.607	43.0829	2.7461	2.1967
a_1	1.3604	1.4909	1.692	1.511
I_{02} (A)	4.15E-05	-	-	-
a_2	3.9677	-	-	-
RMSE	0.003254	0.00368	0.0346	0.0419

(case study 3) and 450 W/m^2 (case study 4), resulting in a maximum power of 4.056 W (data point 3 in Table VI) and 17.877 W (data point 8 in Table VIII), respectively. These values were obtained under static conditions. Future investigations could explore the impact of varying irradiance levels on the system.

V. CONCLUSION

This paper introduces the TDM, to address the limitations inherent in the SDM. In the current study, an analytical method is employed to extract the PV module parameters. This method is applied by solving three parts of I-V characteristics separately: the linear part (n_1), exponential part 1 (n_2), and exponential part 2 (n_3). Various combinations of available data points are explored using n_1, n_2, and n_3. Among these combinations, the one yielding the best performance index (Root Mean Square Error - RMSE) is identified, and the corresponding PV module parameters are recorded. The RMSE value obtained by proposed method shows improvement by 98.87% and 19.01% over optimization methods for PV-TDM in PWP - 201 and R.T.C. France solar cell. The RMSE values obtained for PWP – 201 indicate an improvement of 10.6% and 0.7% over the SDM when utilizing analytical and heuristic methods, respectively. Similarly, for R.T.C. France, the performance index shows improvements of 9.41% and 88.43% over the SDM through the application of heuristic and analytical methods. The proposed analytical method for parameter extraction in the TDM demonstrates enhanced accuracy. Future work will aim to develop a hybrid analytical method to reduce the computational time needed to achieve the lowest RMSE value, as the current approach is time-intensive.

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