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Comprehensive modeling of photovoltaic characteristics based on simulation

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Abstract: - Photovoltaics have the characteristic of being an effective representation of the nonlinearity contained in the panels, this is very important in achieving a renewable energy supply system. There have been several models for photovoltaics proposed in several literatures to analyze their characteristics, but a comprehensive analysis still needs to be carried out to obtain a simple model in PV modeling so that manufacturers can easily implement it. Based on empirically derived one, two and three diode circuit modeling. However, an extensive model analysis of the unique characteristics for modeling PV at the maximum power point (MPP) has not been carried out, therefore researchers will conduct a comprehensive review to obtain a model that is suitable for manufacturers. Based on the IEC standard EN 50530, the absolute error around the MPP must be ± 1%. Therefore, this paper proposes an empirically based analysis model regarding the accuracy of PV models to reconstruct the characteristics of PV panels. Limitations of PV modeling were identified based on simulation results obtained with MATLAB and characteristic indices, besides that this paper also provides input for future research directions.

Keywords: comprehensive analysis; photovoltaic modeling; maximum power point.

I. INTRODUCTION

The demand for electrical energy continues to increase for residential needs [1]. Currently the main source of providing electrical energy is fossil energy, but this will result in global warming caused by carbon dioxide and greenhouse gases which will result in climate change and environmental problems [2]. All countries have made laws to protect their citizens from global warming and natural damage, so policies have been made to develop sustainable green energy, such as the development of solar energy plants and so on [3].

Solar power cells (PV) are a model for converting solar radiation energy into electrical energy that is environmentally friendly and almost in tropical areas has a great opportunity to be developed [4], [5]. The basic modeling for PV is one of the interconnection models of several solar cells which are modeled with one, two or three diodes in parallel to achieve the expected maximum energy output. Progress has been made in modeling PV and significant progress has been made towards creating effective PV [6] and [7], with PV efficiency approaching 40% [8]. However manufacturers for PV still have an efficiency of around ± 20% [9].

PV characteristics are a description of the performance of PV modules as an arrangement of solar panel modules in various indoor conditions and are generally available in manufacturers [10]. However, there are still several obstacles, including equipment costs, exact replication of certain environmental conditions required for reconstruction of PV characteristics which is still difficult [11].

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Several alternative methods are used in PV modeling to obtain a representative model of the PV module to obtain accurate and simple characteristics [12]. Mathematically, PV can be modeled simply to get the characteristics of the PV panel and can be simulated to determine the performance of a PV panel and can be applied in manufacturing by predicting the PV model with tools with MATLAB/SIMULINK, etc. The PV approach model used is a model of mathematical, analytical and empirical equations based on diode circuits.

For modeling and to understand the experimental performance of PV panels, the first analysis is an equivalent circuit-based model. The equivalent circuit based on this circuit is several electrical components that are integrated compactly including resistors and diodes [13]. Implement analysis circuit, the implicit characteristic equation can be described in the form of a typical I–V curve which will be derived with complex mathematical variations and is highly dependent on the best estimate of the fitting parameters [14].

An implicit circuit-based model was proposed to model PV decoupled exponential functions in the widely used single diode model [15]. The principle used is a series of equations that are interconnected with each other to change the exponential domain into a simple algebraic equation. Where this PV model discusses the equation between current and voltage explicitly which still depends on the installation parameters of the circuit-based model [16].

Based on empirical modeling has provided another option for effective modeling and simulation of PV panel modules. Empirical modeling often involves fitting curves to unique graphical characteristics of the observed i.e. I–V curves and mathematical equations describing various similar shapes [17]. Comparison of circuit-based and analytical models, where the empirical model fitting parameters are not completely dependent on the real picture of PV panel modules [18].

In PV installation practice, the performance of PV panels, cell materials, can be effectively analyzed and evaluated from their PV characteristics. Based on the IEC standard, EN 50530 informs about the integration of design requirements and provisions for determining the interconnection against the maximum power point (MPP) of typical PV performance curves (i.e., P-V and I–V), incident radiation.

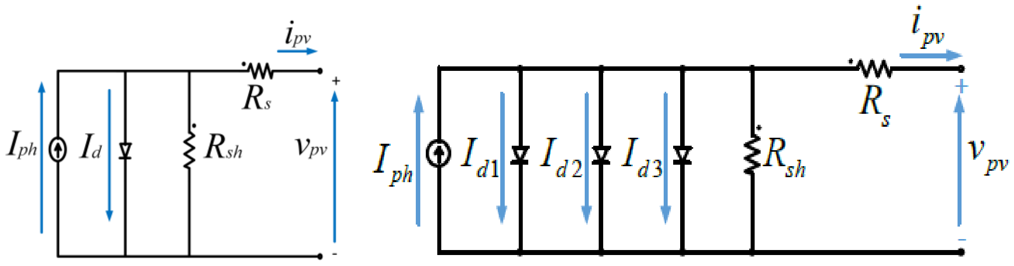
1. PV panels are generally represented in open circuit condition, and short circuit current points. The standard guideline is to determine each PV simulator with a power output that must not deviate more than 1% with a limit of ±10% of the MPP voltage (V_{mp}), against the measured conditions of the specified simulator characteristic curve [19]. Therefore, the aim of this paper is to:
2. Provides a comprehensive summary of several PV models used in the literature.
3. Evaluate the accuracy of the MPP model according to the IEC EN 50530 standard.
4. Identify photovoltaic modeling and proposed potential research directions with the aim of achieving renewable energy.

The next paper is discussed in sub-chapters which discuss the theoretical and mathematical derivation of the PV panel equivalent circuit model. Isolating the exponential terms in the characteristic equations describing single diode models, several approximate PV models have been derived and carefully examined in the next chapter. Furthermore, Part4examines an empirically based model, which is completely independent of PV panel electrical parameters. A comprehensive evaluation of the accuracy of this PV model is carried out in the next section. Based on the results of this simulation, possible directions and conclusions of the research are given in the last Section [20].

This paper presents a new optimization technique which integrates several operators in particle swarm optimization (PSO) to be embedded in the evolutionary programming. This is termed the Embedded Real Swarm Evolutionary Programming (ERSEP). ERSEP is applied to address the intelligent load curtailment strategy for loss control in power systems. The IEEE 30-Bus reliability test system (RTS). In this study, ERSEP is used to solve load curtailment in power system for achieving lower optimal solution through a comparative study conducted between EP and PSO, the effectiveness of ERSEP can be shown. Results from the study managed to reveal the superiority of ERSEP over the traditional PSO and EP when tested on several significant cases.

II. MODELS BASED ON CIRCUITS

Models based on equivalent circuits remain the most widely used approximation models for I–V curve characteristics. This model uses a conversion principle that describes PV panels in general and is classified according to the number of diode components, namely single diode, double diode or triple diode models, as shown in Figure 1**.**



a) Single diode b) triple diode

Figure 1. PV panel circuit approach model

A. Modeling with a single diode

An illustration of PV with a single diode model is depicted in Figure 1.a, consisting of a diode and electrical parameters which is the most basic description of the nonlinear characteristics inherent in PV panels. By applying circuit theory to Figure 1a, an implicit mathematical equation known as the I–V typical characteristic equation has been expressed as equation (1) [13], [14], [21].

$$i_{pv} = I_{ph} - I_0\left[e^{\left(\frac{v_{pv}+i_{pv}R_S}{A_0NV_i}\right)} - 1\right] - \frac{v_{pv}+i_{pv}R_S}{R_{SH}} \quad 1$$

where *Ipv* is the PV output current (A), *vpv* is the PV output voltage (V), iph is the photovoltaic current (A), *I0* is the diode saturation current (A), *A0* is the ideal factor, and *Rs*, *Rsh*, *N* represent the series resistance (Ω), parallel resistance (Ω), and the number of series cells of the panel module. The thermal stress *Vt* is mathematically defined as $V_t = \frac{kT}{q}$, where *k* represents Boltzmann's constant (1.380649×10^{-23}J/K), *q* is the elementary charge, $1.602176634\times10^{-19}$C.

For further circuit analysis, a mathematical correlation can be determined between iph and conditions around the solar cell (irradiation, G, and temperature, T) AS [22].

$$I_{ph} = \frac{G}{G_n}\left(I_{SCn} + \beta_1(T - T_n)\right) \quad 2$$

with all terms of equation (2) expressed in such a way that i_{scn} is the short circuit current at standard test conditions (STC) (T_n=298.14K, G_n=1000W/m^2) when β_1 is the temperature coefficient i_{sc}. Therefore, I_o in (1) can be expressed by [23].

$$I_0 = \frac{I_{SCn} + \beta_1(T - T_n)}{e^{\frac{V_{0cn}+\beta_v(T-T_n)}{A_0V_t}}} \quad 3$$

where V_{ocn} is the open circuit voltage at STC and β_V is the temperature coefficient V_{oc}.

B. Modeling with three diode

A conversion of modeling with three diodes is proposed, as in Figure 1b, based on the third element of the diode which takes into account the effects of recombination in the defect zone of the solar cell [24]. Therefore, the application of circuit analysis and the I–V characteristic equation are obtained [25].

$$I_{pv} = I_{ph} - I_{01}\left[e\left(\frac{v_{pv}+i_{pv}R_S}{A_1NV_i}\right) - 1\right] - I_{02}\left[e^{\frac{v_{pv}+i_{pv}R_S}{A_2NV_i}-1}\right] - I_{03}\left[e^{\frac{v_{pv}+i_{pv}R_S}{A3NV_i}-1}\right] - \frac{v_{pv}+i_{pv}R_S}{R_{SH}} \quad 4$$

where i_{ph}, *R*s, R_{sh} have been defined in the next section.

Numerical solutions to equations (1), (3), and (4) reconstructed with respect to the I–V curves are achieved as shown by the blue curves in Figure 3. Power output instantaneous P_{pv} flows through the circuit in Figure 2 can be defined in a way mathematical as;

$$P_{pv}=i_{pv}.v_{pv} \quad 5$$

The output power (P_{pv}) is illustrated by the red curve in Figure 2. Independent of the conditions surrounding the PV panel, the I–V characteristic curve consists of four main points, namely open circuit voltage (V_{oc}), short circuit current (i_{sc}), voltage at maximum power point (V_{mp}), and current at maximum power point (i_{mp}).

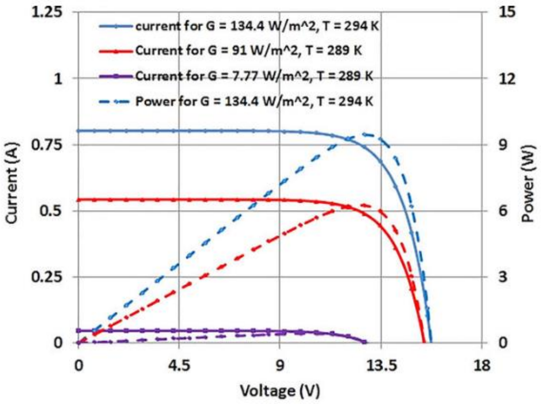


Figure 2. Manufacturer's data PV characteristic curve at standard test conditions (STC).

C. Estimate the PV module model

The numerical solution for calculating the I–V characteristic equation for a single diode model is a challenging task, this is due to its exponential function. Simplifications made to the PVM equation by approximation have been proposed and implemented in the literature.

PVM approach equations consist of two types based on iteration and analytical. The PVM equation based on iteration is expressed as derivative equation (1), obtained after applying datasheet constraints to certain conditions [14], [26]. The analytically based PVM equations are a set of explicit equations obtained after exponential transformation into (1) into a separate domain for performance analysis.

D. Approach Using Asymptotic Formulas

The Lambert function W(W(x)) is a popular method used to estimate (1), because ease of substitution. Basically, this state (1) as an asymptotic formula so that [27].

$$i_{pv} = \left(\frac{R_{sh}(I_{ph}+I_S)-v_{pv}}{R_s+R_{sh}}\right)-\left(\frac{a}{R_s}\right)W\left[\frac{R_sR_{sh}I_s}{a(R_s+R_{sh})}\exp\left(\frac{R_sR_{sh}(I_{ph}+I_s)+R_{sh}v_{pv}}{a(R_s+R_{sh})}\right)\right] \quad 6$$

with

$$W_1(x) = L_1 + \frac{L_2}{L_1} + \frac{L_2(-2+L_2)}{2L_1^2} + \frac{L_2(6-9L_2+2L_2^2)}{6L_1^3} + \frac{L_2(-12+36L_2-22L_2^2+3L_2^2)}{12L_1^4} + \frac{L_2(60-300L_2+350L_2^3-125L_2^3+12L_2^4)}{60L_1^5} + O\left[\left(\frac{L_2}{L_1}\right)^6\right] \quad 7$$

where $a=A_oNV_t$, $L_1=L_n(x)$, $L_2=L_n(L_n(x))$, and $L_n(x)$ are the natural logarithms of x, for the construction of mathematical correlation numerical models for both branches of $W_1(x)$ (positive and negative branches), where Lambert's basic method does not express $W_1(x)$ as a simple basic equation. This is because the data point solution for this equation is challenging and takes a long time.

Modifications and improvements have been proposed in the literature to overcome these challenges. Based on propose to<u>get</u>numerical solution for (7) with<u>utilise</u> Taylor series expansion W(x), as defined as follows.

$$W_2(x) = u + \left(\frac{u}{1+u}\right)p + \left(\frac{(u)}{2(1+u)^3}\right)p^2 - \left(\frac{u(6u^2-8u+1)}{24(1+u)^7}\right)p^4\left[\frac{u}{2(1+u)^3}\right]p^2 - \left[\frac{u(24u^3-58u^2+22u-1)}{120(1+u)^9}\right]p^5$$

$$W_3(x) = L_1 + \frac{L_2}{L_1} + \frac{L_2(-2+L_2)}{2L_1^2} + \frac{L_2(6-9L_2+2L_2^2)}{6L_1^3} + \frac{L_2(-12+36L_2-22L_2^2+3L_2^2)}{12L_1^4} + \frac{L_2(60-300L_2+350L_2^3-125L_2^3+12L_2^4)}{60L_1^5} \quad 8$$

where $u=x/e$, $P=1-(x/e)$, and e=2.7183. Likewise, references [28] also presents a simple analytically based estimate of $W(x)$ based on [29].

$$W_4(x) = (1+\varepsilon)L_n\left[\frac{\left(\frac{6}{5}\right)x}{L_n\left(\frac{\left(\frac{12}{5}\right)x}{L_n\left(1+\left(\frac{12}{5}\right)x\right)}\right)}\right] - \varepsilon.L_n\left[\frac{2x}{L_n(1+2x)}\right] \quad 9$$

where ε = 0.4586887 is a constant whatever the PV module cell material.

A simple and fast approximation technique for W(x) was introduced by [30].

$$W_5(x) = L_n(x)\left[1 - \frac{L_n(L_n(x))}{L_n(x)+1}\right] \quad 10$$

where $L_n(x)$ is the natural logarithm of x. Other methods include using a proper closed form using the devices of t Maple [31], Marine Predator algorithm [32], hybrid analytics [33], and the Hessian function [34].

D. Equations based on Analytics

The fixed point equation of the I–V curve characteristics as stated in Figure 3 and assumed in the PV module, experience $((V_{oc}-i_{sc}R_s)/V_t)>>1$, the three-point model equation is described (1) into the following equation.

$$i_{pv} = I_{sc} - \left(\frac{v_{pv}}{R_{sh}+R_s}\right) - \left(I_{sc} - \frac{V_{oc}}{R_{sh}+R_s}\right)\exp\left(\frac{v_{pv}-V_{oc}+i_{pv}R_s}{V_t}\right) \quad 11$$

To estimate the generally high Rsh value for silicon modules, assuming that $i_{sc}>>v_{pv}/(R_{sh}+R_s)$ and $i_{sc}>>V_{oc}/(R_{sh}+R_s)$, in (11) is declared valid, therefore it can be rewritten the equation as.

$$i_{pv} = I_{sc} - I_{sc.}.\exp\left(\frac{v_{pv}}{V_{oc}} - 1\right)^{\frac{V_{oc}}{V_t}} \quad 12$$

Assumed to be valid for each PV module $-1<(v_{pv}/V_{oc})-1<0$, where the exponent of equation (13) is approximated as $\exp((v_{pv}/V_{oc})-1)\approx(v_{pv}/V_{oc})$. Therefore, The equation is rewritten with a simplified polynomial expression as the coefficient model for the following equation.

$$i_{pv} = c + a.(v_{pv})^b \quad 13$$

where $a = \frac{I_{sc}}{(V_{oc})^b}, b = \frac{V_{oc}}{V_t}, and\ c = I_{sc}$

In another paper suggests the use of the Pade approximation and the Taylor series expansion of exponential functions, proposing a Padé approximation model that defines the approximation of a function

$$f(x) = \sum_{k=0}^{\infty} f_k x^k \text{ as } [m/n](x) = \frac{P_m(x)}{Q_n(x)} \quad 14$$

Where $P_m(x)=\sum_{i=0}^{m} P_i x^i, \quad Q_n(x)\sum_{j=0}^{n} Q_j x^j$ is a polynomial of degree m, n$\in N$, each. With the [m/n]$_{\exp(z)}$ approximation of the exponential function written as

$$[m/n]_{\exp(z)}=\frac{\sum_{i=0}^{n}\left((2n-i)!n!\right)}{(2n)!i!(n-1)!}z^i/(\sum_{i=0}^{n}(2n-i)!n! \Big/ (2n)!i!(n-1)!(-z^i)) \qquad 15$$

where $z=\frac{i_{pv}R_s}{a}$, *and* $a=A_0NV_t$ from equation (1) by taking m=n=2, so [2/2]$_{\exp(z)}$, from equation 1) is obtained as:

$$[2/2]_{\exp(z)}=\frac{12+6z^2}{12-6z+z^2}$$

$$i_{pv}=I_{ph}-I_s.\exp\left(\frac{v_{pv}}{a}\right).\frac{12+6z+z^2}{12-6z+z^2}-1-\frac{v_{pv}-i_{pv}R_s}{R_{sh}} \qquad 16$$

with $p=aR_{sh}+aR_s, q=-16aR_{sh}-I_{ph}R_sR_{sh}-I_sR_sR_{sh}+v_{pv}R_s+I_sR_sR_{sh}\exp(v_{pv}/a)-6aR_s$

$$r=12aR_{sh}+6I_{ph}R_sR_{sh}+6I_sR_sR_{sh}-6v_{pv}R_s+6I_sR_sR_{sh}\exp(v_{pv}/a)+12aR_s$$

$s=-12I_{ph}R_sR_{sh}-12I_sR_sR_{sh}+12v_{pv}R_s+12I_sR_sR_{sh}\exp(v_{pv}/a)$, so it can be rewritten as follows:

$$pz^3+qz^2+rz+s=0 \qquad 17$$

Other references suggest applying the Taylor series expansion in such a way.

$$e^z=1+z+\frac{1}{2!}z^2+\frac{1}{3!}z^3, \qquad 18$$

Where $z=\dfrac{i_{pv}R_s}{a}$, so the equation can be rewritten as:

$$pz^3+qz^2+rz+s=0 \qquad 19$$

$$p=\tfrac{1}{6}I_s\exp(\frac{v_{pv}}{a}),\ q=\tfrac{1}{2}I_s\exp\left(\frac{v_{pv}}{a}\right),\ r=I_s\exp\left(\frac{v_{pv}}{a}\right)+\frac{a}{R_s}+\frac{a}{R_{sh}},$$

Where

$$s=I_s\exp\left(\frac{v_{pv}}{a}\right)+\frac{v_{pv}}{R_s}-I_{ph}-I_s$$

Therefore, to obtain root-root (18) and (20), the Shengjin formula derived from [35] used. Therefore, if we take P=q2-3pr, Q=qr-9qs, R=r2-3qs, and S= Q2-4PR>0, the positive roots can be obtained in such a way, that $z=\dfrac{-q-\sqrt[3]{Y_1}-\sqrt[3]{Y_2}}{3p}$ 20

$$Y_1=pq+\frac{3p(-Q+\sqrt{Q^2-4PR})}{2},\ Y_2=pq+\frac{3p(-Q-\sqrt{Q^2-4PR})}{2},$$

so curve IV is written again as:

$$I_p=a\frac{-q-\sqrt[3]{Y_1}-\sqrt[3]{Y_2}}{3pR_s} \qquad 21$$

where I_P is the current estimated i_{pv}.

The characteristic I–V curve can be calculated via the $_{I}$ approach, based on the i_{PV} value with a known v_{pv} value, and the V approach, based on the v_{pv} value with a known i_{PV} value, where the independent variation of the diode voltage i_{sc} to V_{oc}. Therefore, an improved two-port equivalent circuit-based network is proposed as in Figure 3, explicitly stating the following equation:

$$i_{pv} = I_{ph} - I_s\left[\exp\left(\left(\frac{V_d}{V_t} - 1\right)\right)\right] - \frac{V_d}{R_{sh}} \qquad 22$$
$$V_{pv} = V_d - IR_s$$

where the output current of the 2 port-I network is equal to the input current to the 2 port-II network as in Figure 3, the explicit equation for the I–V curve characteristics is expressed as follows;

$$v_{pv} = \left(1 + \frac{R_s}{R_{sh}}\right)V_d - R_s\left(I_{ph} - \frac{V_{oc}}{R_{sh} + R_s}\right).\left\{\exp\left(\frac{v_{pv}}{V_t}\right) - 1\right\} \qquad 23$$
$$i_{ph} = \frac{V_d - v_{pv}}{R_s}$$

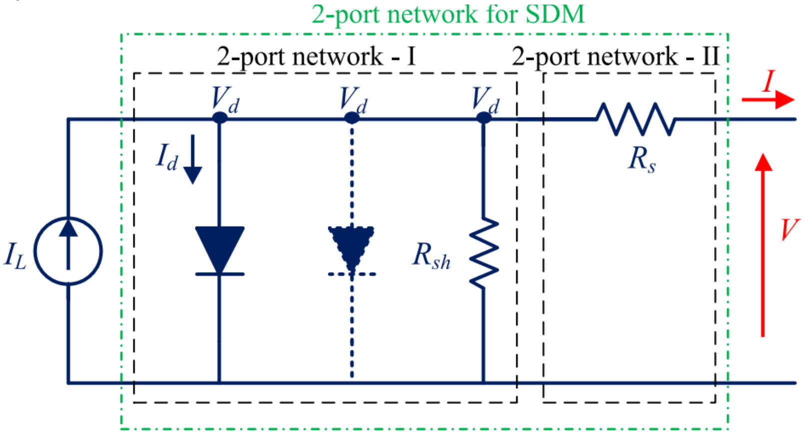


Figure 3. Equivalent circuit of single diode model (SDM)/double diode model (DDM) with two 2 port networks.

For the two-parameter model first introduced by [35], it only requires two pairs of parameters which are derived as follows;

$$i_{pv} = I_{sc} - C_1 \exp\left(-\frac{V_{oc}}{C_2}\right)\left[\exp\left(\frac{v_{pv}}{C_2}\right) - 1\right] \qquad 24$$

where the fitting parameters are calculated using

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right).\exp\left(\frac{-V_{mp}}{C_2 V_{oc}}\right) = \frac{I_{sc}}{1 - \exp\left(\frac{-V_{oc}}{C_2}\right)}$$

$$C_2 = \left(\frac{V_{mp} - V_{oc}}{L_n\left(1 - \frac{I_{mp}}{I_{sc}}\right)}\right). = \frac{V_{mp} - V_{oc}}{W_{-1}\left(1 - \frac{V_{oc}}{V_{mp}}\right).\frac{I_{mp}}{I_{sc}}} \qquad 25$$

where $W_{-1}(z)$ can be solved using the negative branch of the Lambert function W.

E. PV Model Based on Empirics

1. Three diode PV model

For the computational load attributed to PV models based on analytics in the estimation of related parameters, other methods have also been proposed in the literature. Proposed the nonlinear characteristics of the I–V curve reconstructed based on the following model:

$$i_{pv} = \frac{V_{oc} - v_{pv}}{A + B{v^2}_{pv} - Cv_{pv}} \tag{26}$$

where A, B, C are adjusted parameters, with the values of key points of the I–V curve under STC as provided in the manufacturer's data sheet, these coefficients are determined based on the following model:

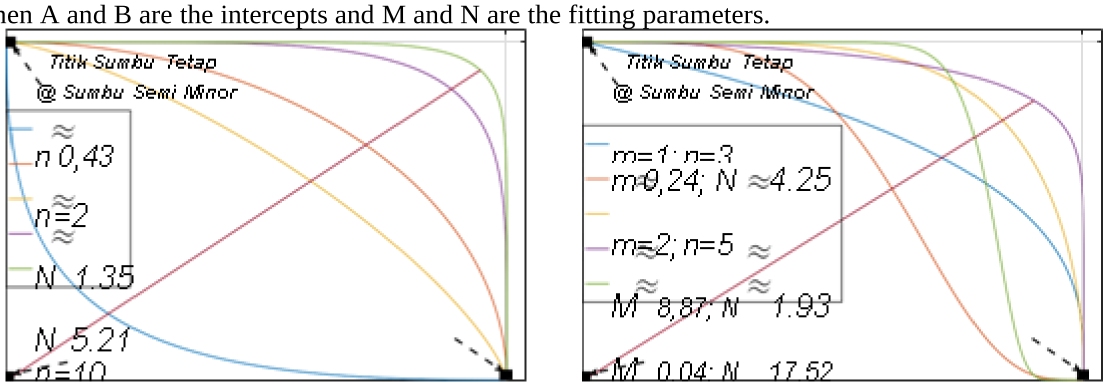
$$A = \frac{V_{oc}}{I_{sc}}$$
$$B = \frac{1}{V_{mp}}\left(\frac{V_{oc}}{I_{sc}V_{mp}} - \frac{1}{I_{mp}}\right) \tag{27}$$
$$C = \frac{V_{oc}}{V_{mp}}\left(2\frac{1}{I_{sc}} - \frac{1}{I_{mp}}\right)$$

2. Super Ellipse Based Model

Super ellipse is a characteristic geometric curve that is close to a Bézier curve and maintains the intercept value at both points without considering the distortion of the overall shape as shown in Figure 4 [36]. The explicit equation describing the curve in Figure 4b is derived as follows;

$$y = B\left(1 - \left(\frac{x}{A}\right)^m\right)^{\frac{1}{n}} \tag{28}$$

when A and B are the intercepts and M and N are the fitting parameters.



a) b)

Figure 4. Superellipse with varying parameter values (a) singular, (b) double

The theoretical and mathematical relationship between Figures 3 and 4 b, an explicit equation that reconstructs the PV characteristic curve has been derived as; [14], [37];

$$i_{pv} = I_{sc}\left[1 - \left(\frac{v_{pv}}{V_{oc}}\right)^m\right]^{\frac{1}{n}}$$
$$\frac{i_{pv}}{I_{sc}} = \frac{1 - \left(\frac{v_{pv}}{V_{oc}}\right)^k}{1 + h\left(\frac{v_{pv}}{V_{oc}}\right)}$$
$$i_{pv} = 1 - (1-\gamma)v_{pv} - \gamma v_{pv}^m \tag{29}$$

with i_{PV} being the output current of the super ellipse model and v_{pv} being the output voltage of the super ellipse model.

Based techniques have been proposed in the literature to extract these suitable parameters. One technique, initially determines the pair's parameters through trial and error. The obtained fit parameters are then adjusted to calculate the correlation coefficient. Based on the estimation of electrical parameters of a single diode model. Based on the data sheet the constraints are entered into Equation (29) for the lower two-dimensional equation. The optimal model fit parameters are obtained by calculating the roots of the equation using a numerical optimization algorithm. Regardless of the method used, these fitting parameters remain constant [38].

3. Comparative and Further Discussion

This section provides a detailed evaluation of the accuracy of several different PVM methods as follows; for MPP based on the IEC EN 50530 standard. Theoretical and mathematical equations describing the IEC EN 50530 standard are discussed. Then, the extracted installation parameters for different PV panel modules are used for analysis in this paper. Finally, the entire range of I–V curves is reconstructed and evaluated around the MPP in the following, while the research trends are outlined in Section 4.

4. Evaluate model accuracy

As explained in the previous section, the IEC EN 50530 standard, published by the European Electrotechnical Standardization Committee, stipulates that the maximum deviation of output power is ≤1%. The accuracy of the PV simulator, has the absolute error between the estimate and the curve on the reference data sheet calculated. Based on conventional numerical analysis [39], the absolute error over the entire range of the I–V curve can be expressed as follows:

$$\left|\frac{i_s(v)-i_r(v)}{i_r(v)}\right| \tag{30}$$

where the subscript S is the measured value of the estimation curve, and r is the data value for the reference model. To calculate the accumulated absolute error within the specified limit of ±10% of V_{mp}, mathematically defined as the area on the I–V curve, with [V_{mp}-0.1V_{mp}, V_{mp}+0.1Vmp], the definite integral [40] is introduced, thus obtaining the model following:

$$\int_{V_{mp}\pm 10\%}\left|\frac{i_s(v)-i_r(v)}{i_r(v)}\right|dv \tag{31}$$

To ensure that, the error calculation is independent of the PV panel behavior, normalized over the entire voltage range, a scaling factor as the total width of the voltage range, i.e. 0.2V_{mp} is introduced, resulting in a simplified equation to calculate the absolute error in MPP for the I–V curve based on the standard IEC EN 50530 and written mathematically as follows; [41], [42].

$$\varepsilon_1(\%)=\frac{1}{0.2V_{mp}}\int_{V_{mp}\pm 10\%}\left|\frac{i_s(v)-i_r(v)}{i_r(v)}\right|dv\ x100. \tag{32}$$

In PV module applications, it has provided actual information about the power output of PV panels, the P–V curve and describes the potential for errors in the voltage source segment on the I–V curve [43]. For this reason, applying a similar theoretical and mathematical derivation process, the absolute error in MPP for the P–V curve is also expressed as follows; [14].

$$\varepsilon_p(\%)=\frac{1}{0.2V_{mp}}\int_{V_{mp}\pm 10\%}\left|\frac{p_s(v)-p_r(v)}{p_r(v)}\right|dv\ x\,100 \tag{33}$$

with the integrals in equations (32) and (33) calculated in this paper using the trapezoidal rule [44].

5. Convergence of PV model parameters

The PV model fitting parameters are extracted by different parameter extraction techniques that have been defined in the relevant literature. For the electrical parameters of a single diode model extracted through existing datasheet information [45], the three parameters of the diode model are extracted with the grasshopper optimization algorithm (GOA) [46], assuming $i_1=i_2$, proposes a simple and fast approach to estimate the parameters dual diode model electricity assuming that $A_1= 1$ and $(A_1+A_2)/P=1$, where $P\geq2.2$.

The PV panels used in this analysis are the same as in the reference paper, so the related electrical parameters are obtained easily, as previously explained. For the analysis carried out at STC, the fit parameters of the PV forecast model and the empirical model are obtained.

6. Comparison of equivalent circuit based models based on IEC Standard EN 50530

Reconstruction of the I–V characteristic curve from Voc to core isc based on the equivalent circuit model can be represented using piecewise circuits or designing implicit equations in MATLAB/Simulink. In this paper, the PV characteristic curve is effectively reconstructed using electrical parameters in MATLAB and designed mathematically in Simulink.

Previously, reconstructing the I–V curve, with the addition of several diode components in the equivalent circuit-based model, the absolute current error (ε_i) around the MPP was reduced. The characteristics of the I–V curve have provided important information about the PV panel (i.e. V_{oc},i_{sc},V_{mp}, and i_{mp}), while the P–V curve provides actual information about the power output of the PV panel..

According to the IEC standard EN 50530, the absolute power error (ε_P) in the reconstructed P–V curve increases with the addition of diode components. The increase in ε_P can be caused by error amplification in the voltage source segment of the I–V curve. The potential factor assumes that ($i_1=i_2$) for the double diode model and the sensitivity of the parameter extraction algorithm applied to the three diode model [47].

F. EMPIRICALLY BASED MODEL COMPARISON

The empirically based PV model is a mathematically explicit equation derived from a unique curve that fits by similarity to the I–V characteristic curve. Applying the fitting parameters extracted from multiple PV panels, to the PVM equations and a complete reconstruction of the I–V characteristic curves is obtained. Regardless of cell or material specifications, empirically based PV models consistently achieve higher model accuracy in the MPP range. This high level of accuracy is expected as these explicit equations are completely independent of the physical meaning or representation of the nonlinear behavior that describes PV panels in general.

III. CONCLUSION

PV modeling is very important to use in research in the field of renewable energy for effective performance evaluation of the static and dynamic characteristics of PV panels in general. Perform a comprehensive analysis of the accuracy of I–V curve reconstruction using various categories of PV models. The accuracy of each model is evaluated on different PV panels, including crystals and thin films, based on the IEC EN 50530 standard.

Although circuit-based models provide a more inclusive representation of the inherent nonlinear characteristics of PV panels, the accuracy of the models, especially dual diode and triple diode models, is highly dependent on parameter extraction techniques and initial conditions or assumptions made before computing. However the simplification of explicit equations describing approximate I–V curves, the accuracy of existing analytically based PV models still depends on accurate estimates of electrical parameters of single diode models.

The empirically based PV model, however, is a curve fitting derivative of the graphical characteristics of the I–V curve and requires fewer fitting parameters to achieve higher accuracy around the MPP. However, this review paper provides insight into the possibility of further research in the field, including conducting hybrid model research, combining two models namely circuit-based and empirical power PV models.

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