PV Parameter Identification using Reduced I-V Data

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***Abstract*— In this paper, the modelling and parameter identification of a one diode model using reduced *I-V* data are presented. Without scanning the entire *I-V* curve, fewer *I-V* points is used to identify the PV parameters. A linear identification method is then applied to derive the PV parameters. Once the PV parameters are known, the maximum power point can be estimated using the *I-V* and *P-V* characteristics. Using different sets of points on the *I-V* curve, the accuracy of the identified maximum power is validated with the original maximum power. It is shown that accurate curve fitting (low RMSE and MPE) of *I-V* and *P-V* curves and a good estimation of the maximum power point can be achieved using six sets of *I-V* data points.**

Keywords— Linear identification, I-V characteristics, Maximum power point estimation.

I. Introduction

PHOTOVOLTAIC (PV) system installations are growing steadily worldwide [1]. Considering the viable growth in PV systems, it is imperative to understand the factors leading to variability in its performance. Hence, there is a need for reliable modelling and accurate PV parameter identification for PV modules.

There are many driving forces in achieving a reliable PV model. An exact model will guide improved cell designs and increased power output. The well-known Current-Voltage (*I-V)* characteristics of the curve allow a better understanding of the solar cells and modules. However, it is not easy to model the PV cell, as the *I-V* characteristics are non-linear and transcendental in nature. Fig. 1 shows the one diode model, which is commonly used to model a PV module.

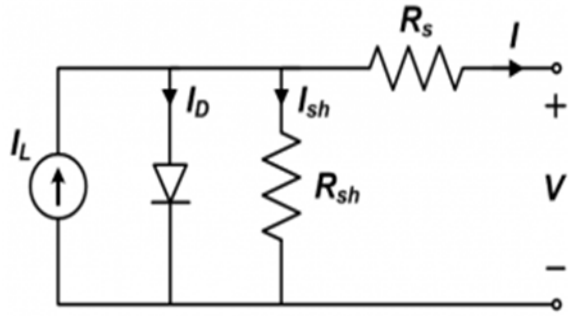

Fig. 1. Circuit model of a one diode mode

Applying the Kirchoff's current law,

$$I = I_L - I_D - I_{sh} = I_L - I_o(\mathrm{e}^{\frac{V+IR_S}{a}} - 1) - \frac{V+IR_S}{R_{sh}}, \qquad (1)$$

where $a = N_s nkT_c/q$ is the modified ideality factor (N_s is the number of cells connected in series, n is the ideality factor, k is Boltzmann's constant, T_c is the cell temperature, and q is the electronic charge [2]. As shown in Equation (1), parameter identification for the five unknown parameters (a, I_L, I_O, R_S, R_{sh}) is not straightforward due to the exponential term which makes it a transcendental equation [3].

Prior studies have reviewed that the one diode model can represent the whole *I-V* curve accurately [4, 5]. The one diode model consists of a single diode for the phenomena of cell separation and two resistors R_S and R_{sh} (series and shunt) for describing the real performance of PV losses. The inclusion of the series and shunt resistances allows for a better representation of the electrical behaviour of a PV system, as it considers the ohmic losses in the system [6, 7]. A typical PV panel can convert about 30% to 40% of solar irradiation into electricity. In practical implementation, PV systems produce less power due to Maximum Power Theorem (MPT), which states that maximum power is dissipated when the load impedance matches the source impedance. Hence, to improve the efficiency of the PV system, a Maximum Power Point Tracking (MPPT) algorithm is required to track the Maximum Power Point (MPP) in real time [8].

In recent publications, only a few *I-V* coordinates are required to solve for four parameters in PV cell model [9, 10]. In a further publication by Toledo et al. [11], six pairs of I-V coordinates near the MPP are used to solve for four parameters, which allowed real-time curve fitting without scanning the entire *I-V* curve from the short-circuit to the open-circuit condition. This application is required mainly for the practical operation of PV panels, especially for the panels used in a satellite in outer space [12]. In that case, a full *I-V* scan of PV panel cannot be easily performed as the PV panels on the satellite must be disconnected, to measure the open-circuit voltage. In addition, the open-circuit voltage cannot be measured accurately in a short time frame. However, the solution for four parameters is less accurate due to the approximation of the slope close to the short-circuit point.

It is also obvious that if real-time curve fitting can be performed without scanning the entire *I-V* curve and the maximum power can be estimated in real time, a maximum power point tracker will not be required [10]. In a recent article by Lim et al. [5]. the non-linear I-V curve is transformed into a linear system output, where the five unknown parameters (a, I_L, I_O, R_S, R_{sh}) are directly obtained from an *I-V* curve. This method reduces the unknown parameter space from five to one and has been proven to be superior and/or comparable to other iterative search methods [5, 12].

This paper considers integrating the concept above-mentioned of using fewer *I-V* data points for parameter identification with the linear identification method published in [5]. The obtained parameters will then be used to plot the Power-Voltage (*P-V*) curve, which is capable of replacing MPPT algorithms. Once the *P-V* curve is obtained, the accuracy of the identified maximum power will be investigated by validating with the actual maximum power from the original *I-V* curve. Additionally, the effect on the data location of each point on the identified maximum power point will be investigated.

The rest of this paper is organized as follows. Section II presents the linear identification method. Section III demonstrates the use of fewer *I-V* data points for parameter identification. The parameters obtained are used to plot the *I-V* and *P-V* curves. The RMSE of the identified *I-V* curve and the maximum power error (MPE) of the identified *P-V* curve are studied in Section IV. Section V presents the conclusions.

II. PARAMETER IDENTIFICATION USING LINEAR IDENTIFICATION METHOD

In this section, the non-linear *I-V* curve is transformed into a linear system output by linking the model parameters with the linear differential equation [5]. Next, the method of integral-based system identification was applied to obtain a reduced form of the five-parameter model. Lastly, the linear least square algorithm was implemented to identify the parameters.

A. Transforming I-V curve into a linear system output

The non-linear *I-V* characteristics are transformed into a linear system output as follows.

Substitute: $y = I$ and $x = V + IR_s$,

$$y = I_L + I_o - I_o\left(e^{\frac{x}{a}}\right) - \frac{x}{R_{sh}}. \tag{2}$$

Differentiating (2) once,

$$\frac{dy}{dx} = -\frac{I_o}{a}\left(e^{\frac{x}{a}}\right) - \frac{1}{R_{sh}}. \tag{3}$$

Eliminating $(e^{\frac{x}{a}})$,

$$-\frac{I_o}{a} = \frac{dy}{dx} + \frac{1}{R_{sh}}. \tag{4}$$

Differentiating (2) twice,

$$\frac{d^2y}{dx^2} = -\frac{I_o}{a^2}(e^{\frac{x}{a}}). \tag{5}$$

Eliminating $(e^{\frac{x}{a}})$,

$$-\frac{I_o}{a} = a\frac{d^2y}{dx^2}. \tag{6}$$

Combining Equation (4) & (6),

$$a\frac{d^2y}{dx^2} - \frac{dy}{dx} = \frac{1}{R_{sh}}. \tag{7}$$

Substitute: $t = x$ and $u(t) = 1$,

$$a\frac{d^2y}{dx^2} - \frac{dy}{dx} = \frac{u(t)}{R_{sh}}. \tag{8}$$

Taking Laplace Transform,

$$a[s^2Y(s) - sy(0) - y'(0)] - [sY(s) - y(0)] = \frac{U(s)}{R_{sh}}$$
(9)

Substituting $su(s) = 1$,

$$a[s^2Y(s) - s^2U(s)y(0) - sU(s)y'(0)] - [sU(s)y(0)] = \frac{1}{R_{sh}}U(s)$$
(10)

Substitute: $y(0) = I_L$ and $y'(0) = -\frac{I_o}{a} - \frac{1}{R_{sh}}$, the transfer function is given by

$$G(s) = \frac{Y(s)}{U(s)} = \frac{aI_Ls^2 - \left(I_o + \frac{a}{R_{sh}} + I_L\right)s + \frac{1}{R_{sh}}}{as^2 - s}. \tag{11}$$

The time domain differential equation is:

$$a\frac{d^2y(t)}{dx^2} - \frac{dy(t)}{dx} = aI_L\frac{d^2y(t)}{dx^2} - \left(I_L + I_o + \frac{a}{R_{sh}}\right)\frac{du(t)}{dx} + \frac{u(t)}{R_{sh}}. \tag{12}$$

B. Integral based linear identification method

Applying integral based linear identification gives

$$\int_{[T_1,T_2]}^{(n)} f(\tau) = \int_{T_1,}^{T_2}\int_{T_1,}^{\tau_n} \dots \int_{T_1,}^{\tau_2} f(\tau_1)d\tau_1 d\tau_2 \dots d\tau_n. \tag{13}$$

For $T_1 = 0, T_2 = t$ and $n = 2$,

$$ay(t) - aI_Lu(t) + \left(I_L + I_o + \frac{a}{Rsh}\right)\int_{[0,t]}^{(1)} u(\tau) - \frac{1}{Rsh}\int_{[0,t]}^{(2)} u(\tau) = \int_{[0,t]}^{(1)} y(\tau). \tag{14}$$

To obtain the reduced form of the five-parameter model, the differential equation is rewritten into the form:

$$\theta = (\phi^T\phi)^{-1}\phi^T\gamma,$$

where γ, θ and ϕ are

$$\gamma(t) = \int_{[0,t]}^{(1)} y(\tau), \quad (15)$$

$$\theta = [a, aI_L, \left(I_L + I_o + \frac{a}{Rsh}\right), \frac{1}{Rsh}]^T, \quad (16)$$

$$\phi(t) = [y(t), -u(t), \int_{[0,t]}^{(1)} u(\tau), \int_{[0,t]}^{(2)} u(\tau)]^T. \quad (17)$$

These three terms were calculated by substituting the *I-V* values as indicated below.

$$\gamma(t) = \int_{[0,t]}^{(1)} y(\tau), \text{ which is the area beneath the curve,} \quad (18)$$

$$\phi(t) = \begin{bmatrix} y \\ 1 \\ t = x \\ -\int_{[0,t]}^{(1)} t\,dt = -\frac{1}{2}t^2 \end{bmatrix}, \quad (19)$$

$$\theta = \begin{bmatrix} a \\ aI_L \\ I_L + I_o + \frac{a}{R_{sh}} \\ \frac{1}{R_{sh}} \end{bmatrix}. \quad (20)$$

C. Linear least square algorithm

The linear least square method gives the best approximation and minimises the sum of squared differences. The term (θ) was calculated using the term (γ) and (ϕ).

After obtaining the term (θ), the four theta values (θ_1, θ_2, θ_3, θ_4) were then derived from the equation (17). The four parameters namely the modified ideality factor (a), photocurrent (I_L), reverse saturation current (I_O) and shunt resistance (R_{sh}) were obtained using the linear least square solution.

$$a = \theta_1, \quad (21)$$

$$I_L = \frac{\theta_1}{\theta_2}, \quad (22)$$

$$I_o = \theta_3 - \frac{\theta_2}{\theta_1} - \theta_1\theta_4, \quad (23)$$

$$R_{sh} = \frac{1}{\theta_4}. \quad (24)$$

A binary search algorithm was implemented to identify the last parameter which is the series resistance, R_s. The algorithm works by updating the value of R_s when compared to the sign of error, as shown in [3].

In the next section, the modified version of the linear identification method by using fewer *I-V* data points will be illustrated to identify PV parameters for *I-V* curve fitting.

III. Parameter Identification with Fewer I-V Data Points

This section illustrates the identification of parameters using fewer *I-V* points.

Six pairs of *I-V* coordinates in two blocks of three coordinates that are relatively close to each other, were chosen near the MPP, as shown in [11]. Thus, the number of *I-V* points used for parameter identification was reduced from the total *I-V* data of one hundred points to only six points, as shown in Fig. 3. Due to the difficulty in obtaining an accurate and stabilized open-circuit voltage in real time implementation, the last data point was chosen to be further away from the actual open-circuit voltage point. as illustrated by Point 6 in Fig. 3.

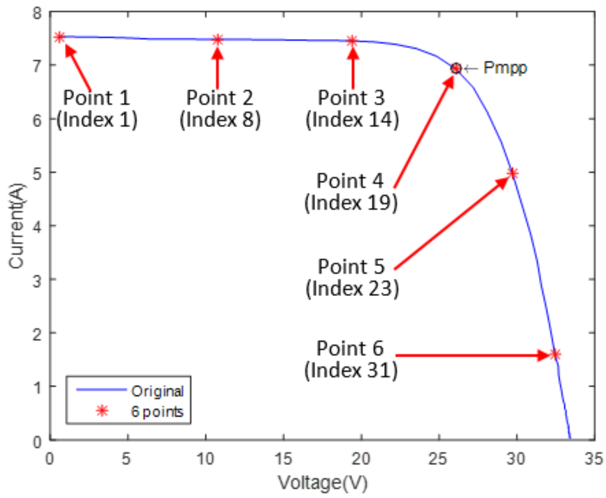

Fig. 3. Position of the six points chosen from the original *I-V* curve

IV. Experimental Results

This section is organized in two parts; a) parameter identification with fewer *I-V* data points, b) identification of the maximum power point based on the estimated *I-V* curve.

A. Parameter identification with fewer I-V data points

This section illustrates the effectiveness of using six points for the parameter identification of PV parameters using the linear identification method aforementioned in Section II.

A comparison of the original and the identified *I-V* curve is as shown in Fig. 4

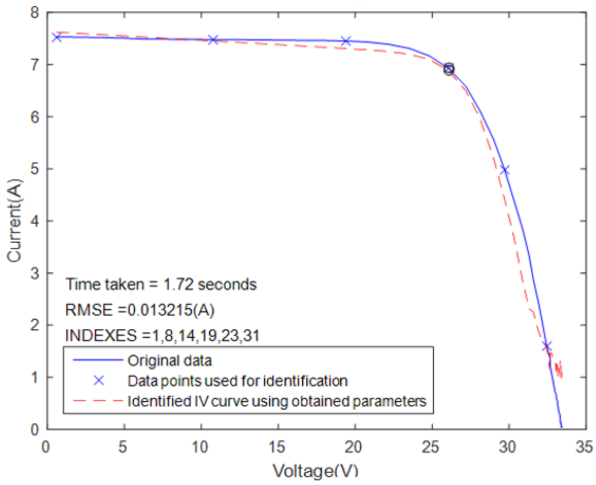

Fig. 4. Identified *I-V* curve using six data points

. By using only six points, the parameters of the one diode model are obtained, as shown in Table I. The identified *I-V* curve is obtained by substituting the identified parameters into the one diode model. The identified *I-V* curve (in red) is close as compared to the original *I-V* curve (in blue), as shown in Fig. 4..

TABLE I
PARAMETERS OBTAINED FROM USING SIX *I-V* DATA POINTS

Parameters	Values
$a\,(V)$	1.18
$I_L(A)$	7.62
$I_O\,(A)$	$1.93e^{-10}$
$R_s\,(\Omega)$	0.56
$R_{sh}(\Omega)$	60.53

In order to determine whether the data location of the six points chosen will affect the accuracy of the *I-V* curve, ten different sets containing different coordinates of six points are tested. The results from using different sets of six points are illustrated in Table II.

For a data size of one hundred indexes, Point 1 belongs to the first index of the I-V data, as index 1 is the starting point on the *I-V* curve. Point 6 belongs to the 31st index which corresponds to the bottom of the *I-V* curve. Subsequently, the rest of the four points in between the first and last points are distributed between these two indexes.

A comparison of the RMSE throughout the range of indexes in Table II, shows that the minimum RMSE of the identified *I-V* curve is 0.0132 and the maximum RMSE is 0.0241.

TABLE II
RMSE OF TEN DIFFERENT SETS OF SIX POINTS

Set	Indexes	*RMSE (A)*
1	1, 8, 14, 19, 23, 31	0.0132
2	1, 8, 15, 19, 23, 29	0.0143
3	1, 8, 15, 19, 23, 30	0.0146
4	1, 8, 15, 19, 23, 31	0.0149
5	1, 9, 16, 20, 23, 31	0.0188
6	1, 9, 16, 19, 23, 31	0.0203
7	1, 9, 16, 20, 25, 31	0.0205
8	1, 9, 16, 20, 25, 31	0.0214
9	1, 9, 15, 19, 23, 31	0.0222
10	1, 9, 15, 19, 24, 31	0.0241

B. *Identification of Maximum Power Point (MPP)*

In this section, ten different sets of indexes are considered to estimate the I-V curve, which is used for maximum power estimation from the identified *P-V* curve, as shown in Table III.

The accuracy of the MPPT is examined by calculating the amount of Maximum Power Error (MPE) compared to the original maximum power. The amount of MPE is studied using the same ten sets of points as before in Table III, where
$MPE = (P_{MPP\_ORIGINAL} - P_{MPP\_IDEN}) \times 100$,
$P_{MPP\_ORIGINAL}$ = Maximum power from original curve,
P_{MPP_IDEN} = Maximum power from original curve.

Table III shows that the amount of MPE produced by using the same configuration for six points modelling is small. All ten sets provided MPE that did not exceed 0.9%, which is comparable to the results in [11]. Therefore, the proposed configuration can provide a good estimate of the MPP with only six points.

TABLE III
COMPARISON OF TEN DIFFERENT SETS OF POWER ERROR AT MPP

Set	Indexes	MPE (%)
1	1, 9, 16, 20, 25, 30	-0.025
2	1, 9, 15, 19, 23, 31	0.126
3	1, 9, 16, 20, 23, 31	0.144
4	1, 9, 16, 20, 25, 31	-0.185
5	1, 9, 16, 19, 23, 31	-0.381
6	1, 9, 15, 19, 24, 31	0.408
7	1, 8, 14, 19, 23, 31	0.611
8	1, 8, 15, 19, 23, 31	0.793
9	1, 8, 15, 19, 23, 30	0.811
10	1, 8, 15, 19, 23, 29	0.848

For the sake of illustration, the original and identified *P-V* curve for Set 1 in Table III is shown in Fig.5. It can be seen that the estimated MPE is around -0.025% and the identified MPP is close to the original MPP, as shown in Fig. 5.

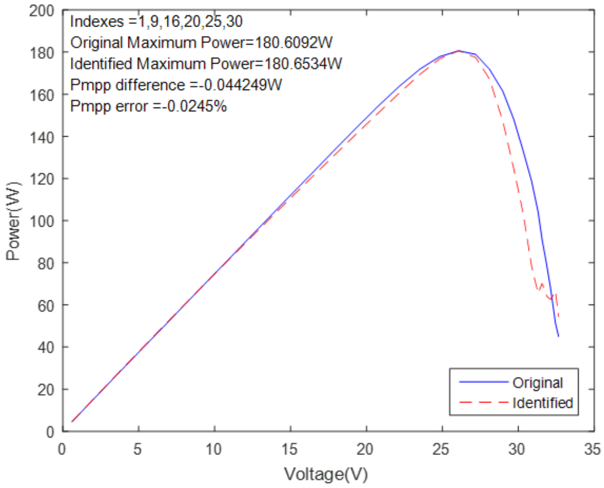

Fig. 5. Original and identified *P-V* curves

By reducing the number of data points used from one hundred to size, the amount of time taken to compute the parameters have been reduced by 2.76 times.

V. Conclusion

In this paper, the number of points used for modelling and simulating of the one diode model for parameter identification is reduced from one hundred to only six points. Utilizing the configuration of six data points demonstrated in Table II, the *I-V* and *P-V* characteristics yielded maximum power points close to that of the original curve For a range of six data points, the RMSE between the original and identified I-V curve is below 3%, which demonstrates the robustness of the approach. Considering ten different sets of data points, it is shown that the range of maximum power error between the original and identified MPP is below 1%. In addition, by decreasing the number of points from hundred to six, the amount of computational time is shortened by 2.76 times.

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