An Improved Oblique Asymptote Method for Parameter Identification of PV Panels

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***Abstract* — A single-diode model is the most important and broadly used tool for PV module design and analysis. The model has 5 parameters to be identified from the I-V characteristics curves. However, due to the lack of explicit form of I or V with the unknown 5 parameters, parameter identification is very difficult. Recent progress in PV model identification are discussed in this paper with the simulation of MATLAB against the measured data from a real PV module. An improved Oblique Asymptote Method is then proposed and compared with existing identification methods. Test results show that the proposed method achieves lower RMSE with less knowledge of *I-V* data points.**

***Index Terms* — single-diode model, parameter identification, oblique asymptote method.**

I. Introduction

A single-diode model for a PV module with N_p cells in parallel and N_s cells in series is governed by [1]

$$I = N_p I_{ph} - N_p I_s \left(\exp\left(\frac{1}{nV_T} \left(\frac{V}{N_s} + \frac{R_s I}{N_p} \right) \right) - 1 \right) - \frac{N_p}{R_{sh}} \left(\frac{V}{N_s} + \frac{R_s I}{N_p} \right) \tag{1}$$

where I_{ph} is the photocurrent proportional to the irradiance, I_s is the reverse saturation current of the diode, R_s and R_{sh} are the resistance in the series and parallel, respectively, n is the diode ideality factor and $V_T = kT_c/q$, where T_c is the cell temperature (K), $k = 1.3806488\times10^{-23}$ is the Boltzmann's constant (J/K) and $q = 1.60217653\times10^{-19}$ is the electronic charge (C).

To solve the 5 unknown parameters I_{ph}, I_s, n, R_s and R_{sh}, conditions at open-circuit, short-circuit and MPP are considered. At short-circuit, $N_p I_{ph} \approx I_{sc}$, so

$$I_{ph} = \frac{I_{sc}}{N_p}. \tag{2}$$

At open-circuit,

$$I_{sc} - \frac{N_p V_{oc}}{N_s R_{sh}} = N_p I_s \left(\exp\left(\frac{V_{oc}}{nV_T N_s} \right) - 1 \right) \approx N_p I_s \exp\left(\frac{V_{oc}}{nV_T N_s} \right).$$

So

$$I_s = \frac{I_{sc} - \dfrac{N_p V_{oc}}{N_s R_{sh}}}{N_p \exp\left(\dfrac{V_{oc}}{nV_T N_s} \right)}. \tag{3}$$

R_s and R_{sh} are respectively approximated by

$$R_s = -\frac{1}{N_s} \frac{dV}{dI}\bigg|_{V=V_{oc}}, \tag{4}$$

$$R_{sh} = -N_p \frac{dV}{dI}\bigg|_{V=0}, \tag{5}$$

n is then derived from the following MPP condition

$$I_{mpp} = I_{sc} - N_p I_s \left(\exp\left(\frac{1}{nV_T} \left(\frac{V_{mpp}}{N_s} + \frac{R_s I_{mpp}}{N_p} \right) \right) - 1 \right) - \frac{N_p}{R_{sh}} \left(\frac{V_{mpp}}{N_s} + \frac{R_s I_{mpp}}{N_p} \right). \tag{6}$$

The analytical five point method (5PM) solves (2) to (6) directly, which is not very accurate as approximations have to be made. Over the years, more accurate methods were proposed and the majority of them require a large number of data points on the *I-V* curve. These methods include genetic algorithm (GA) [2]-[4], differential evolution (DE) [5]-[7], particle swarm optimization (PSO) [8]-[9], many more [10]-[11]. However, due to the degree of complexity in their implementation and complicated computations involved, most of them are not suitable for online calculation.

This paper presents an improved Oblique Asymptote Method (OAM) based on the work in [12]. In recent publications related to OAM, an analytical quasi-explicit method is proposed in [13], which requires four data points that are arbitrarily located along the *I-V* curve and utilizes the same approximation in OAM on the slope of the *I-V* curve at the short circuit point. This was further extended in [14] which presents a two-step procedure for parameter identification. The linear least squares method was used, which was previously proposed in [15]-[16].

Section II provides the principle of OAM and its improvements are shown in Section III. Test results and comparison with the existing methods are presented in Section IV and the conclusions are drawn in Section V.

II. Oblique Asymptote Method

Defining $A := N_p I_{ph} R_{sh}/(R_{sh} + R_s)$, $B := N_p I_s R_{sh}/(R_{sh} + R_s)$, $C := \exp(1/(nV_T N_s))$, $D := \exp(R_s/(nV_T N_p))$, $E := N_p/(N_s(R_{sh} + R_s))$, (1) then becomes

$$I = A - B\left(C^V D^I - 1\right) - EV. \tag{7}$$

Since I_{ph}, I_s, R_{sh}, R_s, n are all positive, the following condition is satisfied: $A > 0$, $B > 0$, $C > 1$, $D > 1$, and $E > 0$. The five unknowns can then be retrieved in the form of

$$I_{ph} = \frac{1}{N_p}\frac{A\ln C}{\ln C - E\ln D}, \tag{8}$$

$$I_s = \frac{1}{N_p}\frac{B\ln C}{\ln C - E\ln D}, \tag{9}$$

$$n = \frac{1}{N_s V_T \ln C}, \tag{10}$$

$$R_s = \frac{N_p}{N_s}\frac{\ln D}{\ln C}, \tag{11}$$

$$R_{sh} = \frac{N_p}{N_s}\left(\frac{1}{E} - \frac{\ln D}{\ln C}\right). \tag{12}$$

Now five unknown A, B, C, D, E need to be identified.

To apply OAM, the following conditions are required: (1) The short circuit current, I_{sc}; (2) The slope of the I-V curve in the proximity region of the short circuit point, I'_{sc}; (3) Three independent data points on the I-V curve: (V_1, I_1), (V_2, I_2) and (V_3, I_3). With the application of the last condition, the three data points have to be preferably selected with a voltage level of greater than the MPP and distributed in a uniformed manner. The main advantage of OAM over 5PM is that knowledge of the slope at V_{oc} is not required. However, this also results in the inaccuracy of R_s.

Considering the short-circuit condition where $V = 0$ and $I = I_{sc}$. It follows from (7) that $A + B \approx I_{sc}$ and $E = -I'_{sc}$. From the second condition, the oblique asymptote of the single-diode model is then $I_{sc} + I'_{sc}V$. From the third condition, we still need other three different points of the I-V curve (V_1, I_1), (V_2, I_2), (V_3, I_3). From (7),

$$BC^V D^I = A + B - EV - I. \tag{13}$$

Taking logarithms on both sides of (13),

$$\ln B + V\ln C + I\ln D = f(V, I),$$

where $f(V, I) := \ln(A + B - EV - I)$.

Noting that the theoretical curve has to pass through the points (V_k, I_k), $k = 1, 2, 3$, the following function must be satisfied

$$\ln B + V_k \ln C + I_k \ln D = f(V_k, I_k). \tag{14}$$

From (14), it is easy to solve

$$D = \exp\left(\frac{\left(f(V_1,I_1) - f(V_2,I_2)\right)(V_2 - V_3) - \left(f(V_2,I_2) - f(V_3,I_3)\right)(V_1 - V_2)}{(I_1 - I_2)(V_2 - V_3) - (I_2 - I_3)(V_1 - V_2)}\right), \tag{15}$$

$$C = \exp\left(\frac{f(V_2,I_2) - f(V_3,I_3) - (I_2 - I_3)\ln D}{V_2 - V_3}\right), \tag{16}$$

$$B = \exp\left(f(V_1,I_1) - V_1\ln C - I_1\ln D\right). \tag{17}$$

Finally, $A = I_{sc} - B$ and $E = -I'_{sc}$.

The five unknown parameters can now be extracted from (8) – (12). The main advantage

III. Improvements

Further improvements to the OAM in Section II is on the lowering the number of data points on the I-V curve for solving B, C and D. In [16], R_s is determined independently through a binary search. If R_s is known, from (11),

$$\ln C = \frac{N_p}{N_s R_s}\ln D. \tag{18}$$

Substituting (18) into (14),

$$\ln B + \left(V_k\frac{N_p}{N_s R_s} + I_k\right)\ln D = f(V_k, I_k). \tag{19}$$

There are two unknowns in (19), so only two data points are required to solve B and D as

$$D = \exp\left(\frac{f(V_2,I_2) - f(V_1,I_1)}{\frac{N_p}{N_s R_s}(V_2 - V_1) + I_2 - I_1}\right). \tag{20}$$

$$B = \exp\left(f(V_1,I_1) - \left(V_1\frac{N_p}{N_s R_s} + I_1\right)\ln D\right). \tag{21}$$

Once B and D are determined, the values can then be used to derive the five unknown parameters. Subsequently, an error, ERR can be computed.

By evaluating the sign of the change in error, R_s can be adjusted accordingly to update B and D in an iterative manner till $RMSE$ converges to $\pm 1\%$.

The detailed steps are as follows:

Step 1: Arbitrarily choose R_s from $[R_s^{low}, R_s^{upp}]$, where $R_s^{low} = 0$ and $R_s^{upp} = -1/\left.\frac{dI}{dV}\right|_{oc}$ and calculate $\hat{A}$, $\hat{B}$, $\hat{C}$, $\hat{D}$ and $\hat{E}$ from (20) and (21).

Step 2: Calculate from (7) that $\hat{I} = \hat{A} - \hat{B}\left(\hat{C}^v \hat{D}^I - 1\right) - \hat{E}V$, and $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2}$.

Step 3: Calculate $ERR = \sum_i^N \left(\hat{I}(t_i) - I(t_i)\right)$

and, $$Rs = \begin{cases} \frac{R_s + R_s^{low}}{2} & if\ ERR > 0 \\ \frac{R_s + R_s^{upp}}{2} & otherwise \end{cases}$$

Step 4: Update R_s^{low} and R_s^{upp} accordingly. If *ERR*>0, $R_s^{upp} = R_s$, otherwise $R_s^{low} = R_s$.

A flowchart illustrating the process is shown in Figure 1.

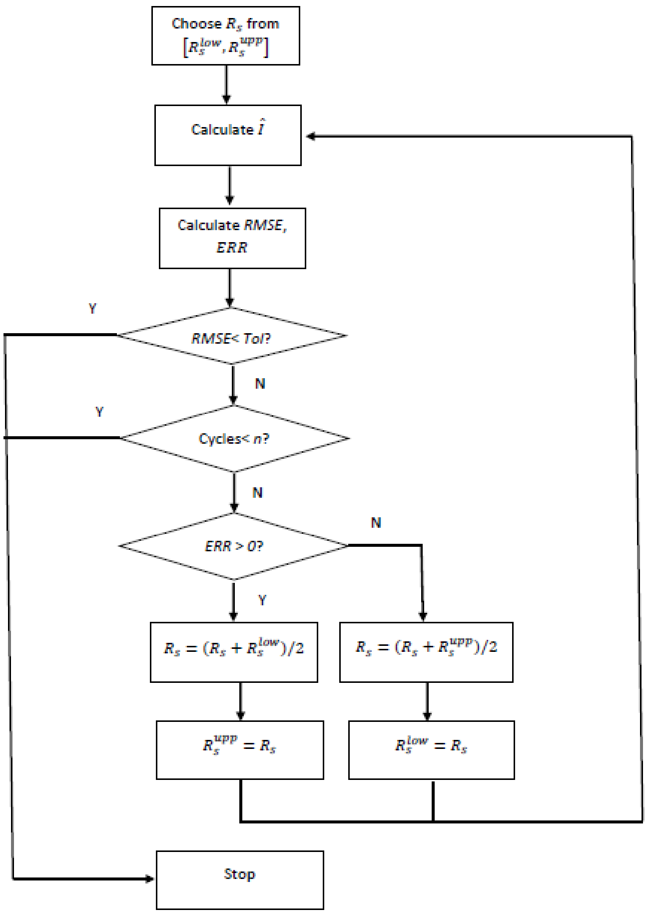

Fig. 1. Flowchart illustrating the iterative update.

IV. Results

Figures 2 to 4 show the results of the proposed improved OAM using different sets of two data points on the real *I-V* curve. It is shown that the identified *I-V* curve is very close to the real curve, even for data points far away from V_{oc}, which is one of the conditions applied for the theoretical 5PM method.

The *RMSE* for these three cases are listed in Table I. The *RMSE* are very low and the identified *I-V* curve is close to the real curve, as shown in Figures 2 – 4.

TABLE I

RMSE OF IMPROVED OAM

Case	(V_1, I_1)	(V_2, I_2)	RMSE (×10^{-2})
I	(35.91, 6.08)	(40.4, 4.28)	3.816
II	(35.91, 6.08)	(42.7, 2.51)	3.838
III	(35.91, 6.08)	(45.0, 0.29)	3.809

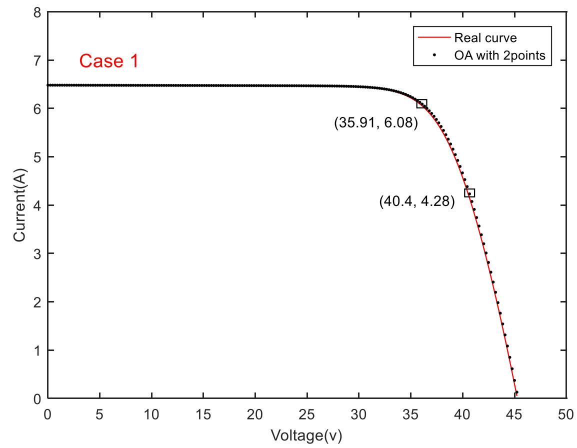

Fig. 2. Results from improved OAM for Case 1.

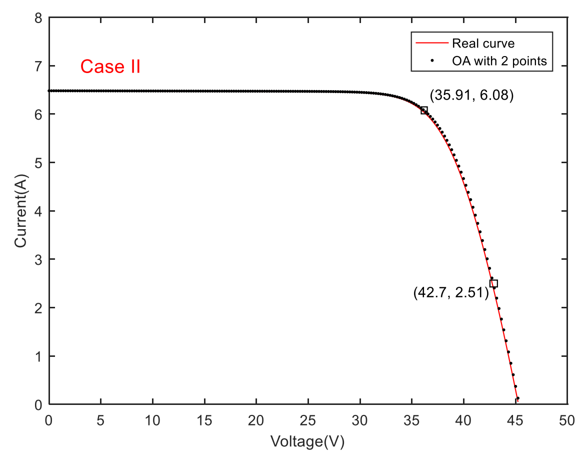

Fig. 3. Results from improved OAM for Case II.

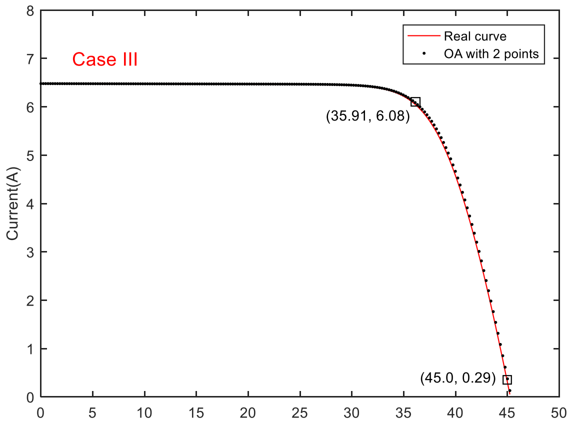

Fig. 4. Results from improved OAM for Case III.

A comparison with the analytical five-point method and original OAM is shown in Table II. It is observed that the proposed method is superior to the OAM and the 5PM in terms of accuracy.

TABLE II
COMPARISON WITH OTHER METHODS

Method	I_{ph} (A)	nV_T (V)	R_s (Ω)	R_{sh} (Ω)	I_s (10^{-10} A)	RMSE (×10^{-2})
5PM	6.482	1.85	0.658	2.27	1.56	5.68
OAM	6.48	1.946	0.633	2.27	5.08	3.98
Proposed	6.482	1.947	0.633	2.27	5.16	3.82

V. CONCLUSION

This paper proposed an improved OAM to identify a single-diode PV model with two data points only. Different data points were selected to evaluate the robustness of the method. The test results on a real *I-V* curve illustrate the effectiveness and accuracy over the existing method.

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