Datasheet-based Circuit Parameter Extraction Method for Maximum Power Point Simulation of Photovoltaic Array

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***Abstract*-- This paper presents an improved parameter extraction algorithm for photovoltaic (PV) panels based on only datasheet value, which is very useful in the development phase of power conditioning system (PCS). In order to increase the accuracy of PV circuit model especially in the maximum power point (MPP), optimization method with objective function incorporating only the MPP conditions was suggested to obtain the circuit parameters in the single diode model. Pattern search optimization was adopted to implement the algorithm and search region with initial value was also discussed. The measurement data from crystalline PV array showed that the proposed algorithm improved the accuracy near the MPP in comparison with conventional methods. Furthermore, the suggested method provides more uniform and fast way of parameter extraction which is less dependent on power rating of panel and user's skill.**

***Index Terms*—photovoltaic panel, single diode model, optimization method, parameter extraction.**

I. INTRODUCTION

In photovoltaic (PV) generation, output characteristic of a real PV panel is highly non-linear and changes according to ambient temperature and irradiation level of the solar energy source. Therefore, instead of real panels, PV equivalent circuit model is a very powerful tool in the development phase of power conditioning system (PCS). In the performance of a PV model, accuracy near the maximum power point (MPP) is most important because PCS usually adopts maximum power point tracking (MPPT) to maximize the utilization of PV panels during the daytime to increase the overall efficiency of the photovoltaic system [1].

Among various methods to get an PV equivalent circuit, modeling techniques based on only datasheet values are practically valuable, because they can extract the equivalent circuit for a real PV panel without additional measurements and provide rapid performance estimation with good accuracy [3]-[10]. By investigating limitations of conventional works, this paper presents a more effective method for parameter extraction in datasheet-based modeling.

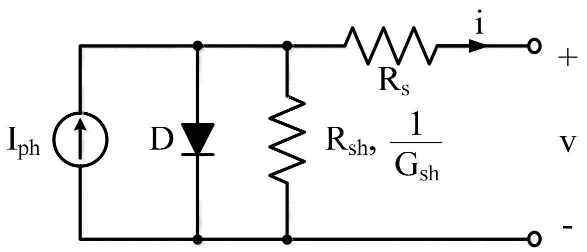


Fig. 1: Single-diode model for PV panel

II. PV CIRCUIT MODEL BASED ON DATASHEET

Usually, PV panel can be described as a single diode model which has a current source paralleled with a diode as shown in Fig. 1. This model accounts for non-linear I-V characteristic of a PV panel [2]. The equation of the I-V characteristic is given by

$$i = I_{ph} - I_o\left(e^{\frac{v+iR_s}{N_S A V_T}} - 1\right) - (v + iR_s)G_{sh} \qquad (1)$$

where V_T is the thermal voltage of diode. In order to represent a PV panel using the single diode model, five circuit parameters - photovoltaic current (I_{ph}), dark saturation current (I_o), series resistance (R_s), shunt conductance (G_{sh}), and diode ideality factor (A) - must be determined only from datasheet values which are the number of cells (N_s), the voltage at the maximum power (V_{mpp}), the current at the maximum power (I_{mpp}), the open circuit voltage (V_{oc}), and the short circuit current (I_{sc}) Some paper also describes the shunt conductance (G_{sh}) as a shunt resistance (R_{sh}). Using these values, proper PV circuit model providing the almost same I-V characteristic as that of the real PV panel can be obtained.

Many researchers have presented parameter extraction methods which make use of four conditions in datasheets:

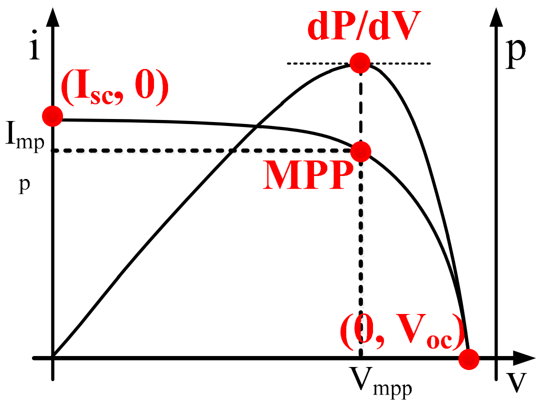


Fig. 2: Critical points in I-V characteristic curve of PV panel

1) I-V curve passes through the MPP.
2) The slope of the P-V curve is null at the MPP.
3) I-V curve starts from (V_{oc}, 0).
4) I-V curve ends with (0, I_{sc}).

and these conditions are shown in Fig. 2. From above conditions, extraction of I_o and I_{ph} is straight forward by the conditions 3) and 4). However, obtaining the other three parameters - R_s, G_{sh}, and A is rather complicated process because there are only two conditions available in spite of three unknown values to extract from them. Furthermore, numerical method is essential to solve the simultaneous equations because of implicit form of the equations.

To solve the under-determined situation, some method just ignores one parameter and extracts remaining two parameters with non-iterative process. For example, R_s is assumed to be very small and thus ignored in [3]. Likewise, R_{sh} is regarded as very large and removed from the equivalent circuit in [4], [5]. As a result, they show poor accuracy inevitably because these methods reduced the number of circuit parameters representing the physical properties of PV panel.

The accuracy of the circuit model can be improved by introducing extra slope condition of I-V curve at the short circuit point [6], [8] or the open circuit point [7] which makes the number of unknown parameters equal to that of conditions. However, these new conditions are derived from the approximation taken at the far ends of the I-V curve and does not always guarantee the accuracy of the model near the MPP.

Fixing one of the unknown parameters can be another possible way. For example, diode ideality factor is set to be constant near 1.5 before proceeding the parameter extraction process in [9], [10]. This method shows good accuracy with less complexity. However, choice of diode ideality factor heavily relies on user's skill and experiences, and thus incorrect assumption of the fixed value may cause inaccuracy of the model.

In order to achieve accuracy near the MPP, optimization method can be viable solution to solve the under-determined nature of parameter extraction without ignoring resistive elements, fixing an ideality constant, or introducing an extra approximate condition. In this paper, PV modeling algorithm using optimization is presented to find all unknown parameters of single diode model at the same time. To suppress the convergence issues common in numerical methods, initial value and search range are also discussed.

III. PROPOSED ALGORITHM

A. Objective Function Definition

In this section, objective function is derived from the MPP conditions. At first, in order to meet the condition 1), the following equation holds.

$$I_{mpp} = I_{ph} - I_o e^{\frac{V_{mpp} + I_{mpp} R_s}{N_S A V_T}} - (V_{mpp} + I_{mpp} R_s) G_{sh} \tag{2}$$

The above equation can be reformulated as a new implicit form in the following.

$$f(R_s, G_{sh}, A) - I_{mpp} = 0 \tag{3}$$

On the other hand, the output power of the solar array can be described as a function of the output voltage as

$$p(v) = iv\,. \tag{4}$$

From above equation, the first derivative of the P-V relation results in

$$\frac{dp}{dv} = \frac{d(iv)}{dv} = i + \frac{di}{dv} v \tag{5}$$

therefore, (6) is obtained by applying condition 2) to (5) and its implicit form is obtained as (7).

$$g(R_s, G_{sh}, A) = 0 \tag{7}$$

In the proposed algorithm, an objection function is defined as (8) and optimal values of R_s, G_{sh}, and A which minimize this function will be found. Optimization algorithm will determine those three parameters which match the conditions 1) and 2) at the same time. In other words, this method can find the R_s, G_{sh}, and A which can provide improved accuracy near the MPP only using MPP conditions.

$$E(R_s, G_{sh}, A) \equiv (f(R_s, G_{sh}, A) - I_{mpp})^2 + g^2(R_s, G_{sh}, A)\,. \tag{8}$$

The remaining parameters, I_o and I_{ph} can be easily obtained as follows. From (1) and conditions 3) and 4), the following two equations are obtained.

$$I_{sc} = I_{ph} - I_o e^{\frac{I_{sc} R_s}{N_S A V_T}} - I_{sc} R_s G_{sh} \tag{9}$$

$$\left.\frac{dp}{dv}\right|_{@mpp} = I_{mpp} - V_{mpp} \frac{G_{sh}\left(\frac{(I_{sc}/G_{sh} - V_{oc} + I_{sc} R_s)}{N_S A V_T} e^{\frac{V_{mpp} + I_{mpp} R_s - V_{oc}}{N_S V_T}} + 1\right)}{1 + R_s G_{sh}\left(\frac{(I_{sc}/G_{sh} - V_{oc} + I_{sc} R_s)}{N_S A V_T} e^{\frac{V_{mpp} + I_{mpp} R_s - V_{oc}}{N_S V_T}} + 1\right)} = 0 \tag{6}$$

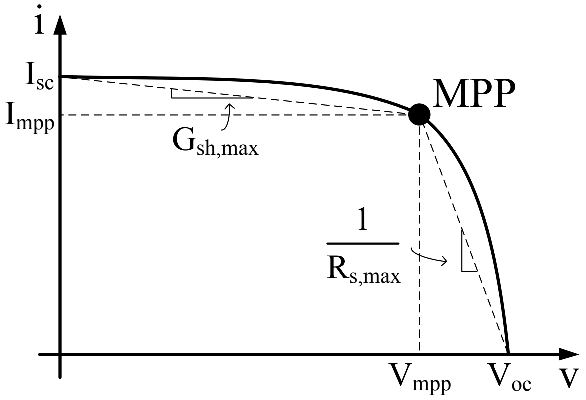


Fig. 3: Graphical method to calculate $R_{s,max}$ and $G_{sh,max}$ for search range

$$I_{ph} = I_o e^{\frac{V_{oc}}{N_S A V_T}} + V_{oc} G_{sh} \tag{10}$$

By eliminating I_{ph} in (9) and (10) with the assumption of $V_{oc} >> I_{sc}R_s$, I_o can be obtained by

$$I_o = \left[I_{sc} - (V_{oc} - I_{sc}R_s)G_{sh}\right] e^{-\frac{V_{oc}}{N_S A V_T}} . \tag{11}$$

B. Parameter Search Region and Initial Condition

Any numerical method to solve non-linear problems needs a proper search region for the parameter variables. In this section, the search range which is not only easily found from datasheet but also physically meaningful is investigated. The series resistance, R_s is ideally zero when there is no series loss and may have maximum value found by a straight line from the short circuit point to MPP as in Fig. 3. Accordingly, search range for R_s is given by

$$0 \le R_s \le \frac{V_{oc} - V_{mpp}}{I_{mpp}} . \tag{12}$$

Likewise, the shunt conductance, G_{sh} has zero value when there is no leakage current in the PV panel and its maximum possible value can be graphically obtained in similar fashion. Therefore, search range for G_{sh} will be given by

$$0 \le G_{sh} \le \frac{I_{sc} - I_{mpp}}{V_{mpp}} . \tag{13}$$

Diode ideality factor, A is inherent from material characteristic. Usually, in silicon PV panel, it falls into the following range.

$$1 \le A \le 2 \tag{14}$$

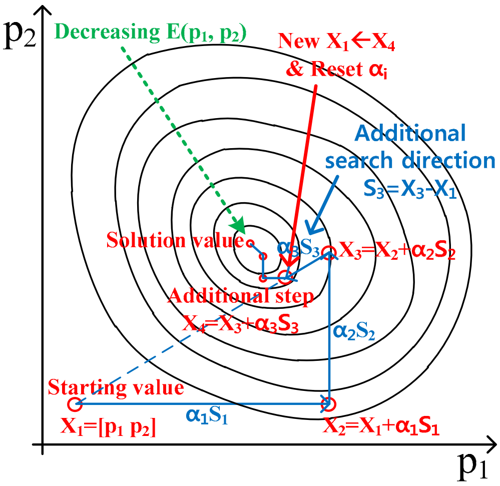


Fig. 4: Pattern search optimization in two variables case

The objective function defined in (8) is non-linear and may cause convergence issue in optimization algorithms. Choosing the initial value for solution should be careful to resolve these problems. In this paper, initial solution vector are suggested as follows.

$$X_1 = [R_{s,1}\ G_{sh,1}\ A_1] = [0, 0, 1] \tag{15}$$

C. Pattern Search Optimization Algorithm

Among various algorithms, pattern search optimization was chosen to minimize the objection function in (8). Because this method does not employ differentiation process of the objective function, it is quite robust as well as simple, and thus can be easily implemented without optimization software. Additionally, it shows good performance at less computation time [11].

In the pattern search algorithm, the solution vector X_i successively reaches the next solution $X_{i+1}=X_i+\alpha_i S_i$ using the search vector, S_i, in the direction of unit vector of each parameter variable, i.e. $S_1=[1,0,0]$ for R_s, $S_2=[0,1,0]$ for G_{sh} and $S_3=[0,0,1]$ for A. The search direction is cycled through the number of variables in an orderly manner executing one additional search direction assembled as the sum of the scalar product of the previous search directions. During this process, the scalar constant α_i is determined to minimize the objective function $E(X_{i+1})$. In this step solving the single variable minimization problem, α_i was found by using golden section algorithm with termination condition with $\varepsilon=1\text{x}10^{-3}$.

A contour plot in Fig. 4 shows the conceptual trajectories of the pattern search algorithm in two variables case. The direction is changing progressively toward the value which minimizes the objective function. Although the initial search vector may be along the wrong direction, the algorithm forces the direction toward the solution in the final stage using α. If the proper initial guesses are set up, speed of the optimization can be further improved.

The flow chart of the proposed algorithm is summarized in Fig. 5. If the termination conditions of algorithm

$$\left|\Delta E\right| \leq \varepsilon_1 \tag{16}$$

$$\Delta X^T \Delta X \leq \varepsilon_2 \tag{17}$$

are met with $\varepsilon_1=1\text{x}10^{-8}$ and $\varepsilon_2=1\text{x}10^{-8}$, algorithm finishes and optimal parameters are extracted. The termination conditions are based on how much the function is decreasing for each cycle and how much change is taking place in the parameter variable itself.

IV. PERFORMANCE RESULT

To evaluate the performance of the proposed algorithm, four crystalline PV samples - Solarland USA's SLP020, THERM Solartechnik's AT50, BP Solar's MSX120, Kyocera's KC200GT - were selected to extract PV circuit models. Datasheet values of each panel are shown in Table 1. Only from the datasheet values, the conventional methods and the proposed algorithm are tested in the following steps.

At first, using I_{sc}, V_{oc}, I_{mpp}, V_{mpp}, and N_s in datasheets, parameters of PV model for each algorithm and panel were extracted using MATLAB m-script. For example, variations in the circuit parameters for KC200GT and the corresponding value of objective function with respect to the iteration steps are shown in Fig. 6. Through the iteration process, the unknown parameter converges within 45 steps of iterations and parameters for PV single diode model are extracted.

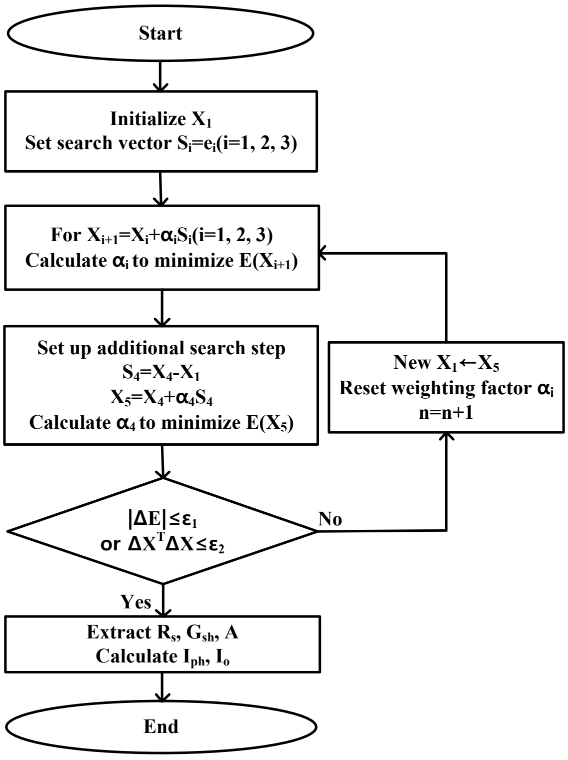
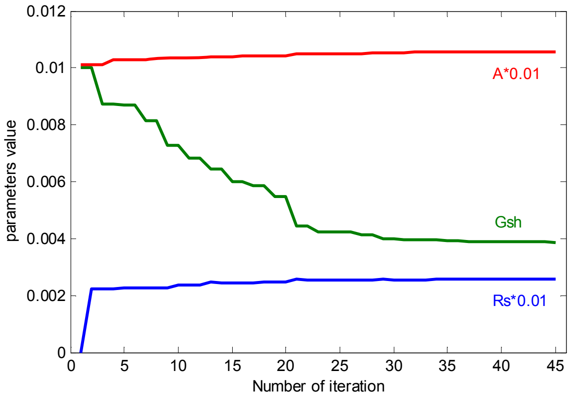


Fig. 5: Algorithm flow chart

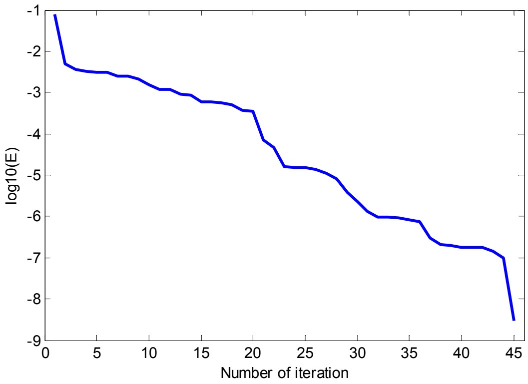
Table 1. Datasheet value of PV panels

value \ Panel	SLP020	AT50	MSX120	KC200GT
I_{sc}(A)	1.31	3.3	3.87	8.21
V_{oc}(V)	21.6	21.5	42.1	32.9
I_{mpp}(A)	1.20	2.86	3.52	7.66
V_{mpp}(V)	18.6	17.5	33.7	26.7
P_{mpp}(W)	22	50	120	200
N_s	36	39	72	54

Secondly, those extracted values were used to obtain the simulated I-V and P-V curve through PSIM circuit blocks in reference to [12] as shown in Fig. 7. Finally, the characteristic curves of the PV model were plotted in Fig. 8 and Fig. 9 together with measured data from real PV panel. The measured data of AT50 panel were reconstructed from [8], and all other measurement curves



(a)



(b)

Fig. 6: Parameter convergence in KC200GT
(a) Unknown parameters (b) Objective function

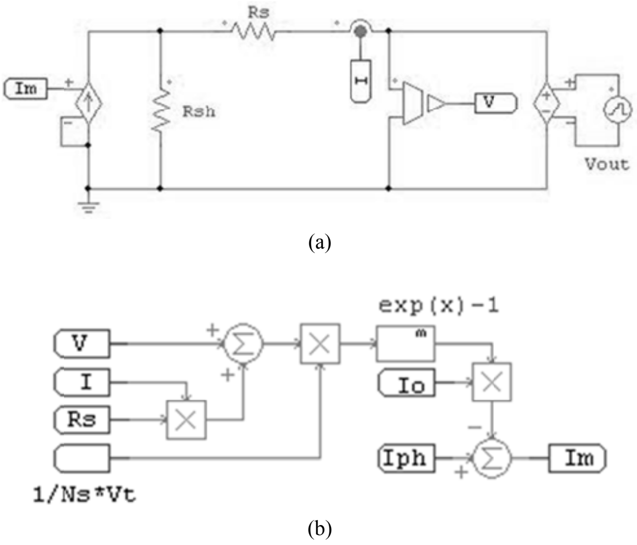
were directly obtained from their datasheets.

Even if each algorithm shows slightly different trends in I-V and P-V curves, it is rather difficult to determine which algorithm is superior to others without criterion.

EN50530 standard states that, the actual I-V characteristic of the PV simulator must not derive more the 1% in the power within the voltage range from $0.9V_{mpp}$ to $1.1V_{mpp}$ (V_{mpp}±10%) related to the predetermined characteristic [13]. To assess the accuracy of each algorithm model according to this standard, current error and power error near MPP were introduced as (18) and (19)

$$\varepsilon_I = \frac{1}{0.2V_{mpp}} \int_{V_{mpp}\pm 10\%} \left| \frac{i_s(v) - i_m(v)}{i_m(v)} \right| dv \qquad (18)$$

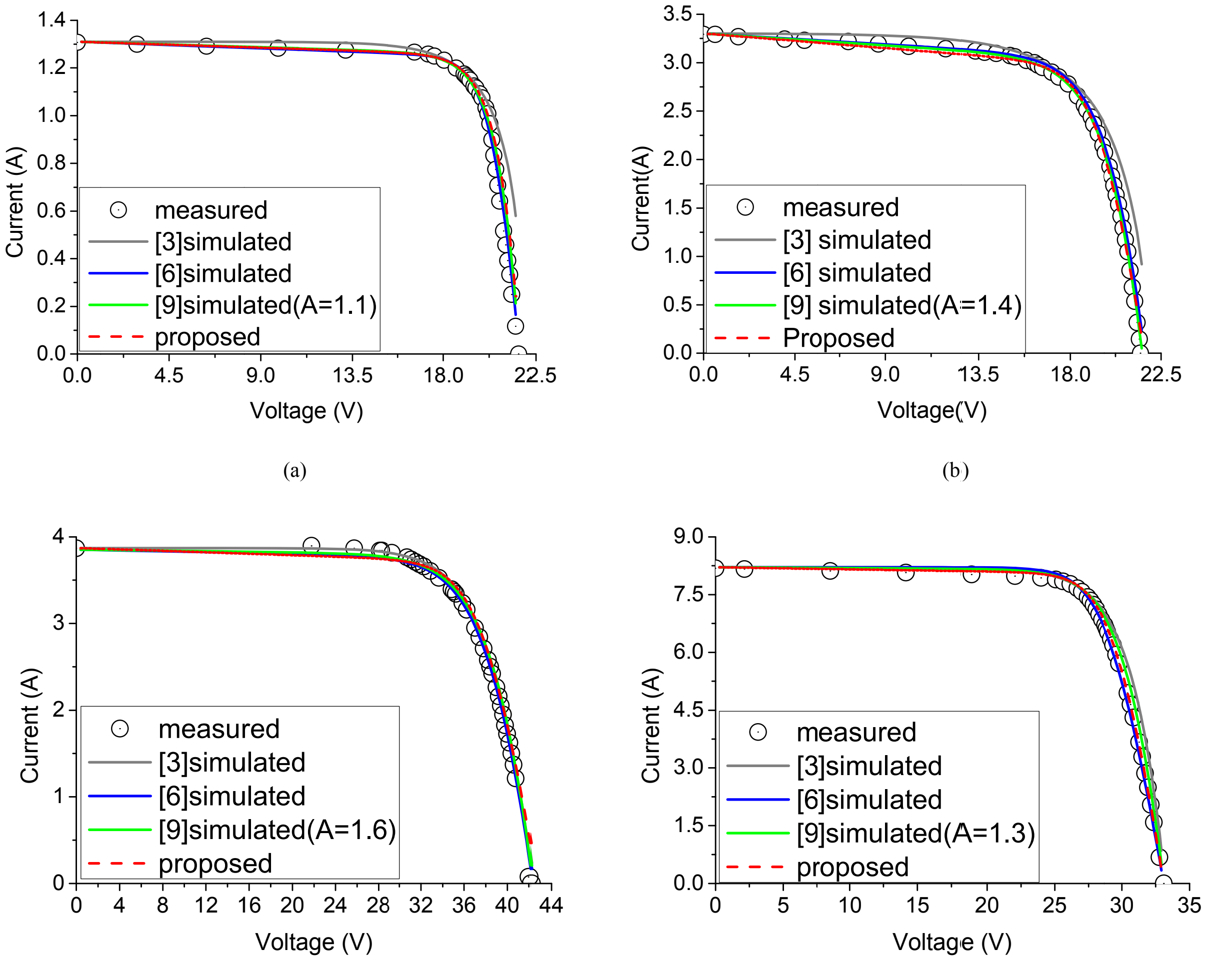
$$\varepsilon_P = \frac{1}{0.2V_{mpp}} \int_{V_{mpp}\pm 10\%} \left| \frac{p_s(v) - p_m(v)}{p_m(v)} \right| dv \, . \qquad (19)$$



(a)

(b)

Fig. 7: PSIM implementation to simulate the characteristic curve
(a) Equivalent circuit (b) Parameter calculation



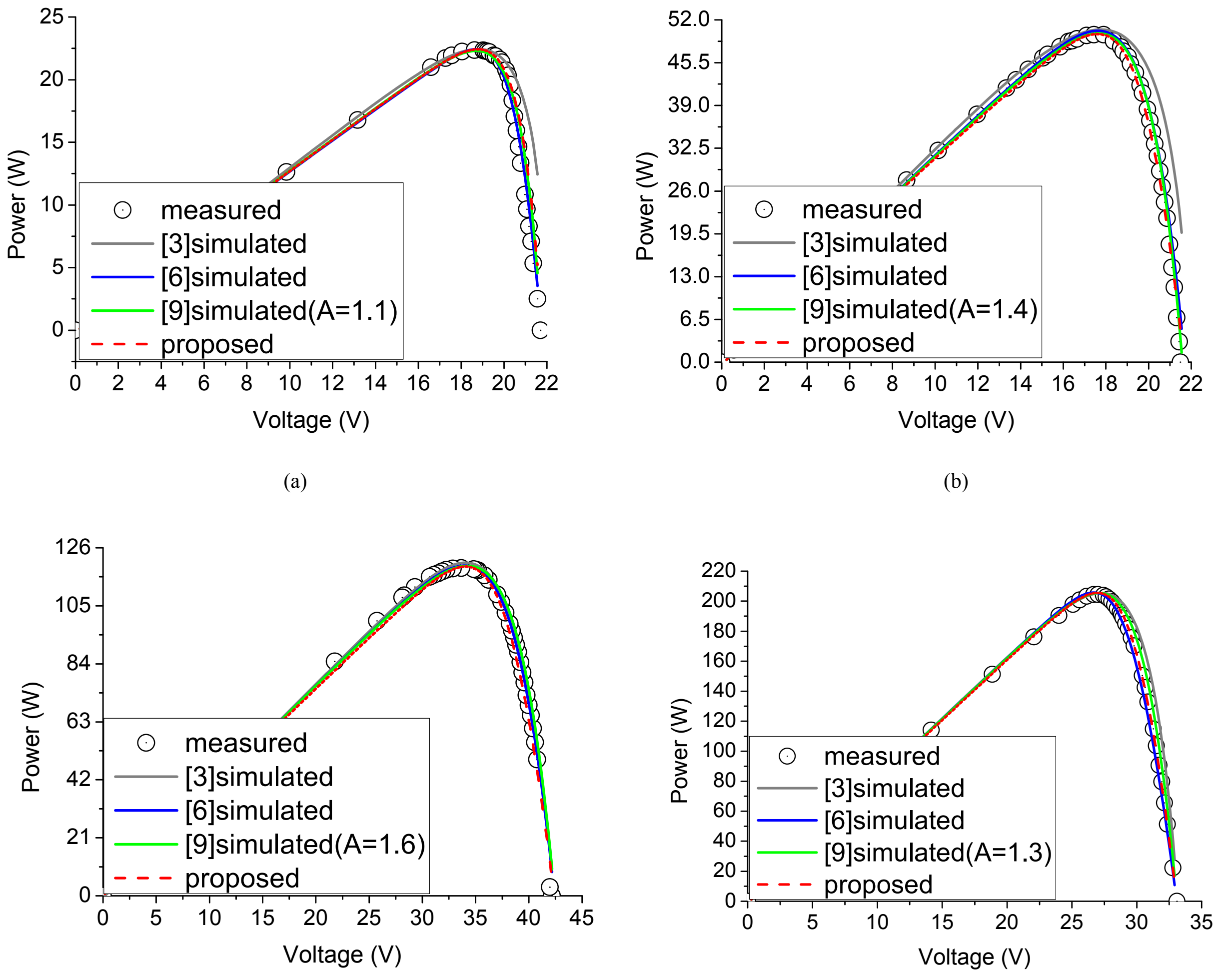
(a)

(b)

(c)

(d)

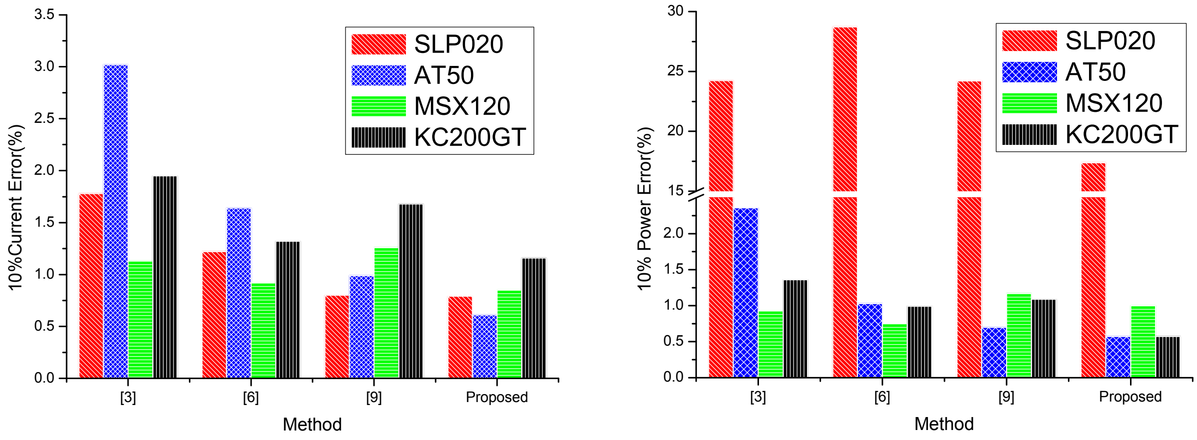
Fig. 8: I-V characteristic curve
(a) SLP020 (b) AT50 (c) MSX120 (d) KC200GT



(a) (b)

(c) (d)

Fig. 9: P-V characteristic curve
(a) SLP020 (b) AT50 (c) MSX120 (d) KC200GT



(a) (b)

Fig. 10: Comparisons of accuracy near MPP
(a) 10% Current error (b) 10% Power error

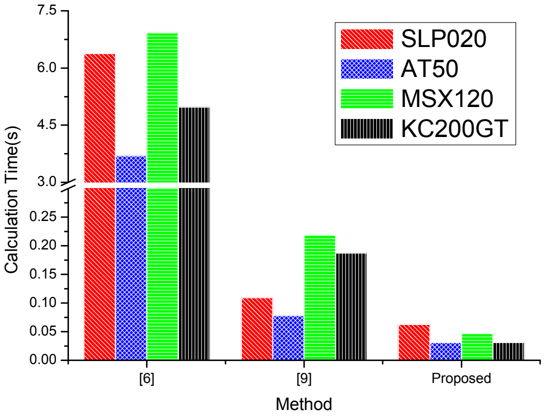


Fig. 11: Comparisons of parameter extraction time

where subscript m and s denote the measured and the simulated value respectively. To implement the numerical integration in (17) and (18), trapezoidal rule was used. Performance comparisons in accuracy of the model and parameter extraction time of algorithms for each panel are summarized in Fig. 10 and Fig. 11 respectively.

While the proposed algorithm provide small error and uniform performance in accuracy regardless of panel type, accuracy of conventional algorithm is not uniform and becomes poor in some panel. Every simulation was performed in Intel i5 760 2.80Hz processor. In plotting the extraction time, method [3] is excluded because that doesn't need iteration process. Consequently, it is obvious that the proposed algorithm provides accurate, uniform, and rapid parameters extraction solution for single diode model of PV panels.

V. CONCLUSION

This paper presented effective parameter extraction method for single diode PV circuit model using only datasheet of PV panel. Instead of ignoring circuit parameters, fixing an ideality constant, or introducing another approximate condition as was done in the conventional algorithms, the proposed method adopts optimization techniques to obtain the circuit parameters from the under-determined set of conditions. The objective function incorporates only MPP conditions and no extra assumption is needed. The performance comparison in view of the current error and the power error near MPP according to EN50530 verifies that this algorithm shows good accuracy irrespective of individual PV panel characteristics. Therefore, the suggested method provides more uniform way of parameter extraction which is less dependent on the panel type and user's skill. Furthermore, the implementation is easy and simple, and the extraction time is very fast.

REFERENCES

[1] H. B. Song, D. H. Baek, and M. T. Cho, "Modeling of PV System and MPPT Control,'' Trans. KIEE., Vol. 59P, No. 4, Dec., 2010.

[2] Z. Ouennoughi and M. Chegaar, "A simpler method for extracting solar cell parameters using the conductance method,'' Solid-State Electronics 43 pp.1985-1988, 1999.

[3] A. Wagner, "Photovoltaik Engineering, Die Methode der Effektiven Solarzellen-Kennlinie," Springer-Verlag, Berlin, Heidelberg, New York, 1999.

[4] W. Xiao, W. G. Dunford, and A. Capel, "A novel modeling method for photovoltaic cells," in Proc. IEEE 35th Annu. Power Electron. Spec. Conf. (PESC), 2004, vol. 3, pp. 1950–1956.

[5] J. Crispim, M. Carreira, and R. Castro, "Validation of Photovoltaic Electrical Models against Manufacturer's Data and Experimental Results,'' POWERENG, April 12-14, 2007.

[6] D. Sera, R. Teodorescu, and P. Rodriguez, "PV Panel Model Based on Datasheet Values," in Proc. On ISIE07, pp. 2392-2396, 2007.

[7] D. Chan and J. Phang, "Analytical methods for the extraction of solar cell single- and double-diode model parameters," Electron devices, IEEE transactions on, vol. 34, no. 2, pp. 286-293, 1987.

[8] H. A. Park and H. S. Kim, "Mathematical Consideration on PV Cell Modeling," The Transactions of Korean Institute of Power Electronics, Vol. 19, No. 1, February 2014.

[9] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive approach to modeling and simulation of Photo voltaic arrays," IEEE Trans. On PE, Vol. 24, No. 5, pp. 1198-1208, 2009, May.

[10] H. A. B. Siddique, P. Xu, and R. W. De Doncker, "Parameter Extraction Algorithm for One-Diode Model of PV Panels based on Datasheet Values,'' ICCEP, International Conference on, 2013.

[11] P. Venkataraman, Applied Optimization with MATLAB Programming, 2nd ed., WILEY, 2009.

[12] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Modeling and Circuit-based Simulation of Photovoltaic Arrays," IEEE Trans. On PE, pp. 1244-1254, 2009, May.

[13] IEC EN50530, Standard for Overall Efficiency of Photovoltaic Inverters, CENELEC, Stassart 35, B-1050 Brussels.