Extracting Photovoltaic Panel Parameters for Model and Simulation Purpose

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***Abstract*—The paper proposes an improved method to extract the parameters of a photovoltaic (PV) panel based on the data provided by the manufacturer in technical documents for the purpose of model and simulation. Manufacturers of PV panels, instead of I-V equation, usually provide only a few experimental data about electrical and thermal characteristics. Some of the parameters required for PV panel model cannot be found in manufacturer's datasheets. The two unknown parameters for modeling of a PV panel are series resistance Rs and parallel resistance Rp. Based on a published algorithm, which identifies the parameters of the nonlinear I–V equation by adjusting the curve at three points: open circuit, maximum power, and short circuit, this paper proposed an improved method to increase the accuracy and convergence speed of the previous algorithm by using two loops with golden-section search technique to determine the Rs and Rp.**

Keywords—Array, circuit, equivalent, model, modeling, photovoltaic (PV), simulation, golden-section search

I. INTRODUCTION

Photovoltaic (PV) panels, also known as solar panels, are devices that convert sunlight directly into electricity using the photovoltaic effect. This innovative technology has gained significant attention in recent years due to its potential to harness clean and renewable energy from the sun.

Photovoltaic panels consist of multiple interconnected solar cells, which are typically made of semiconductor materials such as silicon [1]. Since then, advancements in materials science and engineering have led to the development of highly efficient and cost-effective photovoltaic panels [2] [3].

The I-V curve, or current-voltage curve, is a crucial characteristic of a photovoltaic panel that illustrates its electrical behavior under different operating conditions. Understanding the I-V curve is essential for optimizing the performance of a photovoltaic system. The characteristics of the curve can vary based on factors such as temperature, solar irradiance, and the quality of the PV panel.

Usually, the manufacturer of PV panel only provides some experimental electrical and thermal parameters in the datasheets, while the parameters describing the equivalent electrical circuit (PV parameters) are typically unknown, and are directly linked to the performance characteristics provided in the manufacturer's datasheets, under standard test conditions (STC), and are considerably affected by temperature and irradiance [4].

In [5] proposed a method to find the parameters of the I-V curve by adjusting the curve at three points: open circuit, short circuit and maximum power point. Based on these three points, which are provided by all commercially available PV panel manufacturers, the method finds the most matched I-V equation and makes sure that the maximum power of the model coincides with the maximum power point of real PV panel. The algorithm gradually increases series resistance and calculates until the difference between maximum power of the model and the maximum power of real PV panel are smaller than the allowed error. This method requires a very large number of calculation steps if the demand error is very small.

This paper proposes an improved algorithm, which converges faster and more efficiently. The paper will present a model of single PV cell, a model of PV panel, followed by the improved algorithm and the simulation of PV panel.

II. MODEL OF AN PV CELL

Two diode-based PV cell modeling techniques are considered more accurate than single diode-based PV cell modeling techniques [6]. However, for simplicity, the single diode-based is studied in this paper. This model offers a good compromise between simplicity and accuracy [7]. Figure 1 shows the equivalent circuit of a PV cell including a single diode D1 and the series R_{s1} and parallel resistances R_{p1} [8].

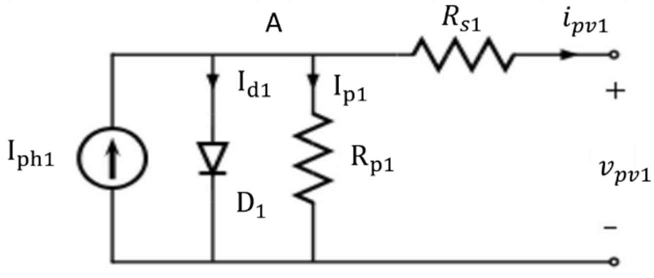

Fig. 1. Equivalent circuit of a PV cell [8]

The mathematical equation of an PV cell is described as following [9]:

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$$i_{ph1} = I_{ph1} - I_{01}\left\{\exp\left(\frac{q\left(v_{pv1}+i_{pv1}R_{s1}\right)}{AkT}\right)-1\right\} - \frac{v_{pv1}+i_{pv1}R_{s1}}{R_{p1}} \quad (1)$$

In which:

- I_{ph1} is the photocurrent from a PV cell, directly proportional to the solar irradiation (A),
- I_{01} is the reverse saturation or leakage current of the diode (A),
- I_{d1} is the current flowing through the diode D1 (A),
- I_{p1} is the current flowing through the parallel resistance R_{p1} (A),
- R_{S1} is the resistance connected in series with the cell (Ω),
- R_{p1} is the resistance connected in parallel with the cell (Ω),
- A is the diode ideality constant
- k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K),
- q is the electron charge ($1.60217646 \times 10^{-19}$ C),
- T is the temperature of PV cell (K),
- i_{pv1} is the output current of a PV cell (A),
- v_{pv1} is the output voltage of a PV cell (V)

The photocurrent I_{ph1} depends on the solar irradiation G and cell's working temperature T

$$I_{ph1} = \left[I_{sc1} + K_i\left(T - T_{STC}\right)\right]\frac{G}{G_{STC}} \quad (2)$$

In which,

- I_{sc1} is the short-circuit current of the cell in standard condition (temperature of 25°C and solar irradiation of 1000W/m2) (A),
- T_{STC} is the standard temperature, equals 25°C (298°K), G_{STC} is the standard solar irradiation, equals 1000W/m^2,
- K_i is temperature coefficient of the short-circuit current, usually provided by the manufacturer.

The saturation current depends on the temperature, described by the following equation [5]:

$$I_{01} = \frac{I_{sc1} + K_i\left(T_{STC} - T\right)}{\exp\left[\frac{q\left(V_{oc1}+K_v\left(T_{STC}-T\right)\right)}{AkT}\right]-1} \quad (3)$$

In which:

- V_{oc1} is the open-circuit voltage of the PV cell in standard condition (V),
- K_i is the short-circuit current/temperature coefficient,
- K_v is the open-circuit voltage/temperature coefficient.

III. Model Of Multiple Cells Connected In Paralel And Serie

A solar panel is a collection of many PV cells connected in parallel and series together. In particular, connecting cells in series will increase the output voltage and connecting cells in parallel will increase the output current. Figure 2 shows the equivalent circuit of a PV panel with Ns x Np PV cells.

The I-V characteristics of a solar panel consisting of N_p in parallel and N_s in series are shown as follows [10]:

$$i_{pv} = N_p I_{ph1} - N_p I_{01}\left\{\exp\left(\frac{q}{AkT}\left(\frac{v_{pv}}{N_s}+\frac{i_{pv}R_{s1}}{N_p}\right)\right)-1\right\} - \frac{v_{pv}\frac{N_p}{N_s}+i_{pv}R_{s1}}{R_{p1}} \quad (4)$$

Where, i_{pv} is the output current of the PV panel (A), v_{pv} is the output voltage of the PV panel (V)

Define $R_s = \frac{N_s}{N_p}R_{s1}$ and $R_p = \frac{N_s}{N_p}R_p$ as the equivalent series resistance and parallel resistance of the PV panel; $I_{ph} = N_p I_{ph1}$ is the photocurrent of the PV panel; $I_0 = N_p I_{01}$ is the saturation current of the PV panel; therefore we can rewrite (4) as following:

$$i_{pv} = I_{ph} - I_0\left\{\exp\left(\frac{q\left(v_{pv}+i_{pv}R_s\right)}{N_s AkT}\right)-1\right\} - \frac{v_{pv}+i_{pv}R_s}{R_p} \quad (5)$$

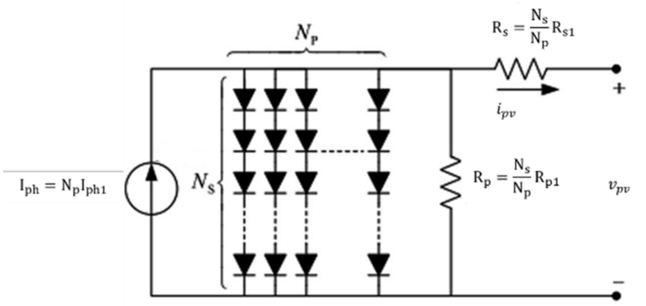

Fig. 2. Equivalent circuit of a PV panel with Ns x Np PV cells [10]

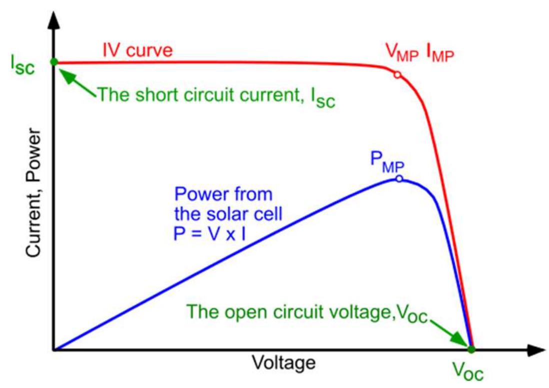

Fig. 3. V-I and P-V characteristics of a PV panel [11]

Equation (5) is the mathematical representation of the I-V curve of the PV panel. To build the I-V curve, let v_{pv} vary from 0 to V_{oc}, find solution for i_{pv} of (5) for each v_{pv}.

The equation can be solved with a numerical method, e.g., Newton-Raphson [12].

PV panel power is calculated according to the formula:

$$P = i_{pv} v_{pv}$$

Figure 3 shows the current-voltage (I-V) and power-voltage (P-V) characteristics of a PV panel. On the I-V characteristic graph, there are the following important points:

- Short-circuit point $(0, I_{sc})$ (intersection of I-V curve with axis I). Short-circuit current is the current when directly connecting the positive and negative poles of the solar panel. This is the largest current that the solar cell can produce when the voltage is zero.

- Open circuit point $(V_{oc}, 0)$ (intersection of line I-V with axis V). Open circuit voltage is the voltage when the PV panel output is open circuit, the output current is 0.

- Maximum power point (V_{mp}, I_{mp}) is the point where the solar panel produces the greatest power: $P_{max} = V_{mp} I_{mp}$. When the solar panel is connected to the load, the operating point will be the intersection of the load line with the I-V characteristic curve of the PV panel. The operating point usually does not fall at the maximum power point. In addition, the maximum power point moves continuously due to frequent changes in solar irradiation and panel temperature. Therefore, it is necessary to ensure that solar panels operate as close to their maximum point as possible. Circuits that perform this function are called maximum power point tracking (MPPT) circuits.

IV. Determine Model's Parameters From PV Specification Provided By Supplier

Model parameters can be determined from the specifications provided by the manufacturer. The typical technical parameters are shown in Table I.

The parameters of the model are determined as follows:

- Short-circuit current of each PV cell: $I_{sc1} = \dfrac{I_{sc}}{N_p}$.
- Open-circuit voltage of each PV cell: $V_{oc1} = \dfrac{V_{oc}}{N_s}$

TABLE I. Technical Specifications of PV panel

Name	Symbol
Rated Power	$P_{max,ds}$
Open-circuit voltage	V_{oc}
Short-circuit current	I_{sc}
Number of series cell	N_s
Number of parallel cell	N_p
Short-circuit current temperature coeffficient	K_i
Open-circuit voltage temperature coeffficient	K_v
Voltage at maximum power point	V_{mp}
Current at maximum power point	I_{mp}

The parameter A is a coefficient that characterizes the ideality of the diode. According to [5] it can be arbitrarily chosen from 1 to 1.5, then adjusted to improve the accuracy of the model if necessary. Other study like [13] proposed a method to extract the ideality factor A from measuring V_{oc} and I_{sc} of PV panel. However, in this paper, for simplicity, A is chosen to be 1.

Two very important parameters in the model are the values of series resistance Rs and parallel resistance Rp, which are often not included in the technical documents of solar panels.

A. Method to find series and parallel resistances

In [5] proposed a method to find R_s and R_p was given by matching the maximum power $P_{max} = V_{mp} I_{mp}$ at the maximum point (V_{mp}, I_{mp}) of the I-V graph built by (5) with the maximum power $P_{max,ds}$ provided by the manufacturer's technical documentation.

To find R_s, R_p so that the maximum power at point (V_{mp}, I_{mp}) of the I-V graph built by (5) with the maximum power P_{max} is equal to $P_{max,ds}$, meaning that:

$$P_{\max} = V_{mp} I_{mp} = P_{max,ds} \tag{6}$$

From (5) and (6), deduce the formula to calculate R_p according to R_s:

$$R_p = \frac{\left(V_{mp} + I_{mp} R_s\right)}{\left(I_{ph} - I_0 \left\{\exp\left(\dfrac{q\left(V_{mp} + I_{mp} R_s\right)}{N_s akT}\right) - 1\right\} - \dfrac{P_{max,ds}}{V_{mp}}\right)} \tag{7}$$

Equation (7) shows that for any R_s there will be a value of R_p such that the I-V curve will pass through the experimental maximum power point (V_{mp}, I_{mp}) (manufacture-provided data).

The goal of the method is to find the value R_s (and R_p according to R_s) that makes the maximum point of the P-V curve coincide with the experimental maximum point (V_{mp}, I_{mp}) in technical documents. The algorithm proposed by is as follows:

1. Let $R_s := 0$ and calculate R_p according to (7)

2. Construct I-V and P-V curves using (5)

3. Find the maximum power P_{max} from the constructed curve

4. Check $\left|P_{max} - P_{max,ds}\right| < \varepsilon$; If the condition is satisfied, end calculation, otherwise, increase R_s and recalculate from step 2.

The algorithm gradually increases R_s and calculates until the difference between $P_{\max}$ and $P_{\max,ds}$ are smaller than the allowed error. This approach is like a *brute force method*, which requires a very large number of calculation steps if the demand error is very small.

B. Proposed improved method

If we let R_s vary and calculate the maximum power P_{max} (by constructing I-V and P-V curve using (5) and find the maximum power point on it), we will obtain a curve that represented by function $P_{max} = f(R_s)$ as on figure 4.

For each Rs, we receive one P-V curve, with one maximum power point that passes through the maximum power point (V_{mp}, I_{mp}) provided by manufacturers. However, this point usually does not match with the maximum power point of this P-V curve. The maximum power point of this P-V curve P_{max} must be higher than or equal to the maximum power provided by manufacturer $P_{max,ds}$. There is not the case that $P_{max} < P_{max,ds}$ because this P-V curve always pass through the (V_{mp}, I_{mp}) point.

Therefore, minimum point of the curve $P_{max} = f(R_s)$is the solution to be found, meaning the minimum point of the curve is the value R_s such that $P_{max} = P_{max,ds}$.

Based on the above characteristics, the author of this paper proposes new algorithm of determining parameters Rs, Rp using the technique of finding extreme points "Golden section search" (GSS) [14].

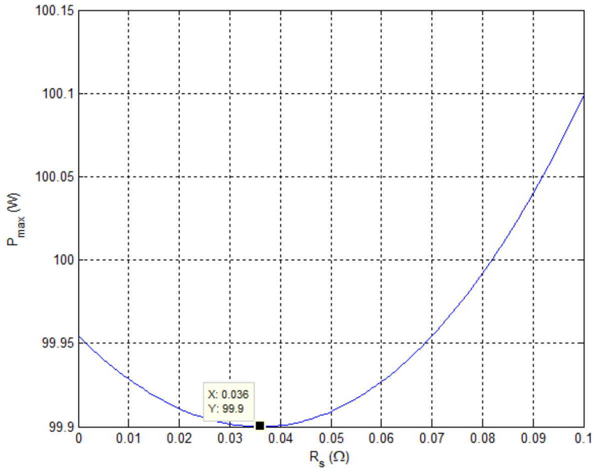

Fig. 4. The curve Pmax=f(Rs)

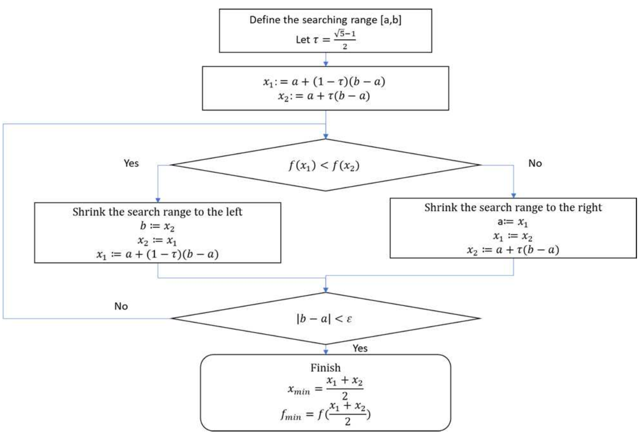

Fig. 5. The Golden section search algorithm for finding the minimum of the function f(x) on the range [a, b]

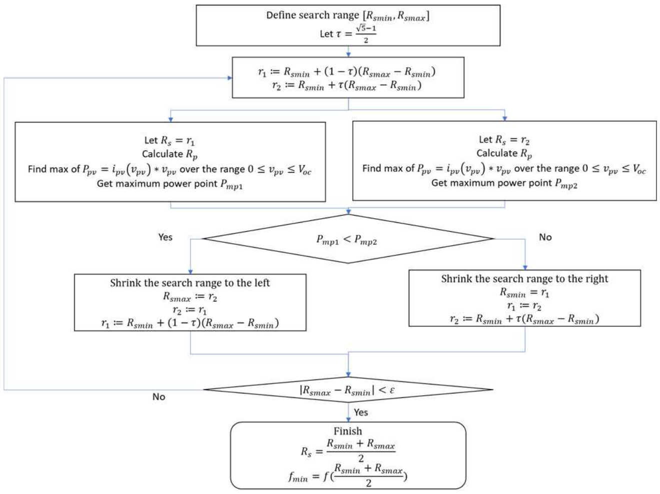

Fig. 6. Proposed algorithm to identify Rs and Rp

The GSS algorithm searches for local extrema on the range [a, b] of the function f(x) shown on figure 5.

The proposed algorithm to determine R_s and R_p uses two GSS loops as following:

- Outer loop to find the minimum of the function $P_{max}(R_s)$
- Inner loop to find the maximum point of the P-V curve (maximum power point) corresponding to a given value of R_s

Proposed algorithm (figure 6) can be described step by step as following:

1. Select a range $\left[R_{smin}, R_{smax}\right]$ to find the extrema of the function $P_{max}(R_s)$
2. Calculate $r_1 := R_{smin} + (1-\tau)(\mathrm{R}_{\mathrm{smax}} - R_{smin})$; $r_2 := R_{smin} + \tau(R_{smax} - R_{smin})$
3. Find the maximum power point corresponding to $R_s = r_1$ and $R_s = r_2$, and calculate R_p using (7):
   - Inner GSS loop 1: Find the maximum power point (V_{mp1}, I_{mp1}) corresponding to $R_s = r_1$: Find the maximum of $P_{pv} = i_{pv}(v_{pv}) \times v_{pv}$ on the range $0 \le v_{pv} \le V_{oc}$ using GSS, where i_{pv} is the function of v_{pv}, retrieved from (5)
   - Inner GSS loop 2: Similarly, find the maximum power point (V_{mp2}, I_{mp2}) corresponding to $R_s = r_2$
4. Compare two maximum power point $P_{mp1} = V_{mp1} I_{mp1}$ and $P_{mp2} = V_{mp2} I_{mp2}$ corresponding to $R_s = r_1$ and $R_s = r_2$:
   - If $P_{mp1} < P_{mp2}$: Shrink the search range to the left, i.e. $R_{smax} := r_2$; $r_2 := r_1$; $r_1 := R_{smin} + (1-\tau)(\mathrm{R}_{\mathrm{smax}} - R_{smin})$

- If $P_{mp1} \geq P_{mp2}$: Collapse the search range to the right, i.e. $R_{smin} := r_1$; $r_1 := r_2$; $r_2 := R_{smin} + \tau(R_{smax} - R_{smin})$

5. Check the termination condition $|R_{smin} - R_{smax}| < \varepsilon$; if it is satisfied, exit, otherwise, go back to step 3.

Instead of finding R_s by increasing it a bit by bit in previous algorithm, the improved algorithm uses GSS to find extrema point of the curve $P_{max} = f(R_s)$, which is the point where $P_{max} = P_{max,ds}$. Since the previous algorithm is like a brute force method, this algorithm is faster. The accuracy should also be better because it trades much less for computation time.

V. SIMULATION OF PV MODEL

A. Building Simulink model

The proposed algorithm was implemented as M-file in MATLAB to determine the model parameters. Equation (5) of I-V curve is rather complicated to be calculated at runtime, so it is pre-calculated and save as a Lookup table. The lookup table has three inputs (output voltage V_{pv}, solar irradiance G and temperature T) and one output (output current I_{pv}).

A lookup table for maximum power point for each value of solar irradiance G and temperature T also created.

A model of PV panel on Simulink uses Lookup Tables to create the panel output current value corresponding to the input values of the panel voltage, solar irradiance G and temperature T is shown on figure 7.

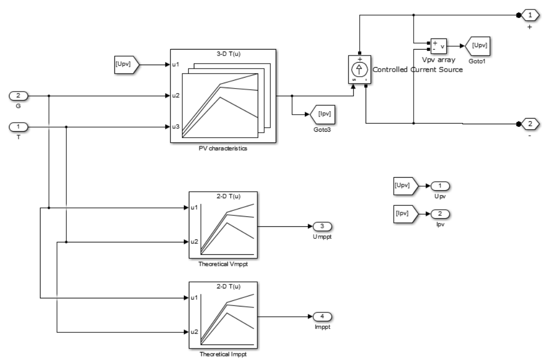

Fig. 7. Simulation of PV Panel on MATLAB/Simulink

B. Simulation results

A real PV panel with the datasheet specified in table II has been simulated.

TABLE II. TECHNICAL SPECIFICATIONS OF PV PANEL

Name	Symbol	Value
Rated Power	$P_{max,ds}$	100 W
Open-circuit voltage	V_{oc}	21.6 V
Short-circuit current	I_{sc}	6.11 A
Number of series cell	N_s	36
Number of parallel cell	N_p	1
Short-circuit current temperature coefficient	K_i	0.05%
Open-circuit voltage temperature coefficient	K_v	-0.35%
Voltage at maximum power point	V_{mp}	18 V
Current at maximum power point	I_{mp}	5.55 A

On figure 8-9, I-V curve and P-V curve of PV panel with different solar irradiance along with maximum power point line (MPPT line on the figure)

On figure 10-11, I-V curve and P-V curve of PV panel with different temperature along with maximum power point line (MPPT line on the figure)

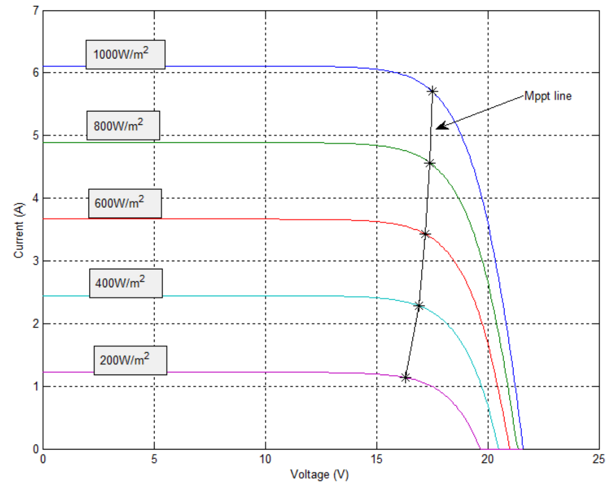

Fig. 8. I-V curve of PV panel with different solar irradiance G

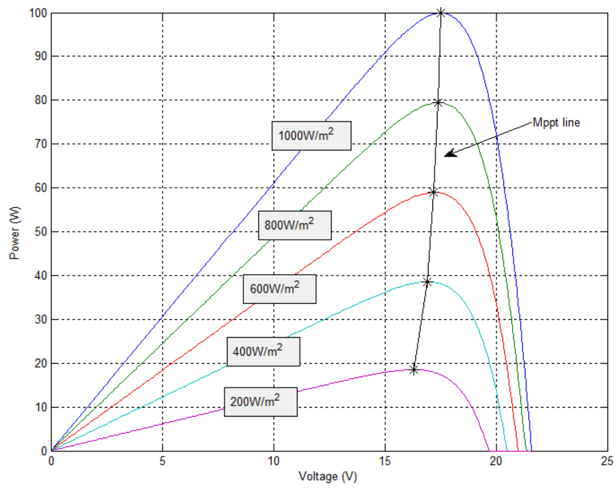

Fig. 9. P-V curve of PV panel with different solar irradiance G

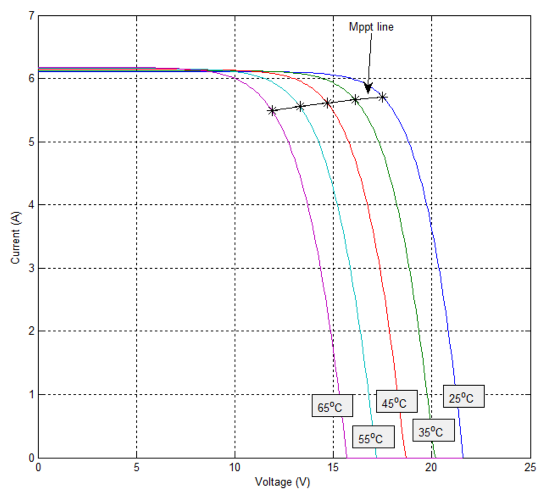

Fig. 10. I-V curve of PV panel with different temperature T

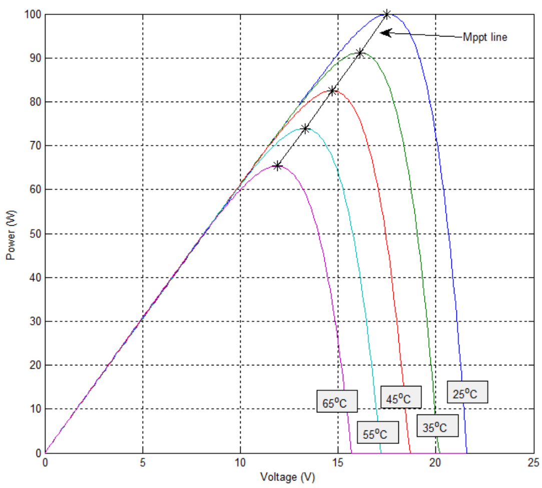

Fig. 11. P-V curve of PV panel with different temperature T

VI. CONCLUSION

A method to identify photovoltaic panel parameters for model and simulation purpose has been presented in the paper. The method uses two loops with golden section search technique to determine the Rs and Rp, the two unknown parameters of PV panel, from the experimental data or data from datasheets provided by PV panel's manufacturer. Compared to the method that it is based on; it is faster and more accurate.

Instead of doing the calculation at runtime of simulation, the author creates the lookup table of the I-V equation. The lookup table can be used in Simulink as a Lookup table Block or can be implemented in microcontroller in PV emulator. This approach is believed to be less computation consuming than direct implementation of the I-V equation.

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