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# SOLAR CELL INTERNAL PARAMETERS EXTRACTION: MATLAB BASED APPROACH

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**Abstract:** In this paper, a technique based on numerical method is proposed for improving the accuracy of solar cell parameters extraction. The extraction is carried out by programming in MATLAB environment using Newton Raphson iterative technique based on single diode model to determine the internal series and shunt resistances of the photovoltaic module. The method under consideration aims to find a pair of values of series and shunt internal resistances that makes the maximum power point coincides with the experimental maximum power point at standard test conditions $(\mathrm{STC})$. The simulation results obtained, compared with points taken directly from the data sheet and curves published by the manufacturers, were found to have good agreement. The effect of internal resistances on the performance of photovoltaic module was also investigated and discussed.
**Keywords:** MATLAB, Photovoltaic module, Simulation, Single diode model, Standard Test Conditions

## INTRODUCTION

The behaviour of photovoltaic cell/module is generally described by its current-voltage characteristics in which their shapes are greatly dependent on the values of the five parameters$\mathrm{I_{ph}}$, $\mathrm{I_0}$, $\mathrm{A}$, $\mathrm{R_s}$, $\mathrm{R_{sh}}$ besides their dependence on solar irradiance and module temperature. The determination of these parameters at any solar irradiance and module temperature conditions makes easy to apply the model for predicting the energy production of photovoltaic module.

The accuracy of commercially available software for PV module or system simulation mainly depends on the accuracy of the solar cell/modules models and the extraction method being used to determine model`s parameters (Yetayew and Jyothsna, 2013). Generally, there are two possible approaches to extract the solar module parameters: (1) the analytical and (2) the numerical extraction techniques. The former requires information on several key points of the $\mathrm{I-V}$ characteristic curve, i.e the current and voltage at the maximum power point$(\mathrm{MPP})$, short circuit current $\mathrm{I_{sc}}$, open circuit voltage $\mathrm{V_{oc}}$ and shapes of the $\mathrm{I-V}$ characteristics at the axis intersections. Accuracy-wise, the approach relies heavily on the correctness of the selected points on the $\mathrm{I-V}$ curve. It has to be noted that the $\mathrm{I-V}$ curve is highly non-linear and any wrongly selected points may results into significant errors in the computed parameters (Dominique, Zacharie and Donatien, 2013).

On the other hand, the numerical extraction technique is based on a certain mathematical algorithm to fit all the points on the $\mathrm{I-V}$ curve. More accurate results can be obtained because all the points on the $\mathrm{I-V}$ curve are utilized. In this work, a MATLAB-based program for solar cell internal parameters extraction using Newton Raphson method is presented.

## RESEARCH METHODOLOGY

Single diode model was adopted and the implementation was carried out in MATLAB/Simulink. The determination of internal series and shunt resistances ($\mathrm{R_s}$ and $\mathrm{R_{sh}}$) among the unknown parameters was carried out by programming in MATLAB environment using Newton Raphson iterative method.

Table 1.0: Electrical Characteristics Data of KC200GT PV Module (www.kyocera.com)

| Electrical Performance under Standard Test Conditions(STC) | |
|---|---|
| Maximum Power ($\mathrm{P_{max}}$) | 200W (+10%/−5%) |
| Maximum Power Voltage ($\mathrm{V_{mpp}}$) | 26.3V |
| Maximum Power Current ($\mathrm{I_{mpp}}$) | 7.61A |
| Open Circuit Voltage ($\mathrm{V_{oc}}$) | 32.9V |
| Short Circuit Current ($\mathrm{I_{sc}}$) | 8.21A |
| Max System Voltage | 600V |
| Temperature Coefficient of $\mathrm{V_{oc}}$ | $-1.23 \times 10^{-1}\mathrm{V/°C}$ |
| Temperature Coefficient of $\mathrm{I_{sc}}$ | $3.18 \times 10^{-3}\mathrm{A/°C}$ |
| *STC: Irradiance $1000\mathrm{W/m^2}$,AM 1.5 spectrum, module Temperature $25°\mathrm{C}$ | |
| Electrical Performance at $800\mathrm{W/m^2}$,NOCT,AM 1.5 | |
| Maximum Power ($\mathrm{P_{max}}$) | 142W |
| Maximum Power Voltage ($\mathrm{V_{mpp}}$) | 23.2V |
| Maximum Power Current ($\mathrm{I_{mpp}}$) | 6.13A |
| Open Circuit Voltage ($\mathrm{V_{oc}}$) | 29.9V |
| Short Circuit Current ($\mathrm{I_{sc}}$) | 6.62A |
| Number of Cells Per Module | 54 |

KC200GT 200 W PV module was taken as the reference photovoltaic module for the simulation and the name plate details are given in Table 1 (kyocera KC200GT).

### Single Diode Model

Photovoltaic cell is usually represented by the single diode model. The equivalent circuit of single diode model, which represents a photovoltaic cell, shown in Figure 1.0 is considered appropriate and the simplest form of representing the electrical circuitry layout of a photovoltaic module, Selmi, Abdul-Niby and Alameen, (2014); Rekioua and Matagne, (2012). Primarily, it consists of a diode that represents p-n junction of the photovoltaic cell and a current source that generates photo-current ($I_{ph}$) which is a function of incident irradiance and cell temperature. In practical photovoltaic cells, voltage loss is observed on the path to the external terminals. This voltage loss depends on the internal series resistance $R_s$ of the photovoltaic cell. In addition, leakage current is also observed which depends on shunt resistance $R_{sh}$, Pandiarajan and Ranganath, (2011).

The single-diode model of photovoltaic module is formulated through the extension of diode law to account for internal series resistance and shunt resistance as well as various equations which appropriately describe irradiance and temperature effects on photo-current. The voltage-current characteristic equation of a photovoltaic cell, Jay and Gaurag, (2013) is given in eqn. (1). Equation (1) is a nonlinear mathematical equation, where $I_{ph}$ is photocurrent, $I_s$ is diode saturation current, $q$ is charge of an electron, $K$ is Boltzmann's constant, $A$ is ideality factor, $v$ is output voltage in volt, $T_a$ is cell`s working temperature, $R_s^c$ is cell series resistance, $R_{sh}$ is shunt resistance and $I_{pv}$ is the output current of the photovoltaic cell. The photo-current $I_{ph}$ depends basically on the solar irradiance and cell`s operating temperature, which is described in eqn. (2).

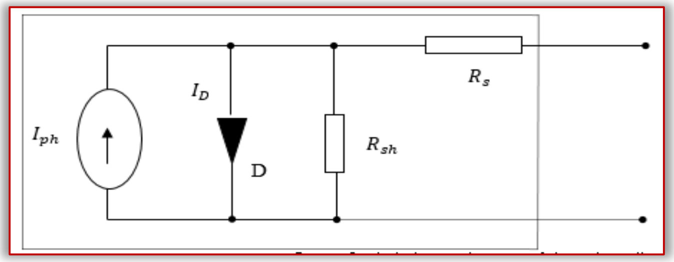


Figure 1. Single diode equivalent circuit of photovoltaic cell.

$$I_{pv} = I_{Ph} - I_s\left[\exp\left(\frac{q[V+IR_s^c]}{KAT_a}\right) - 1\right] - \frac{v+IR_s^c}{R_{sh}} \qquad (1)$$

$$I_{Ph} = [I_{sc} + k_i(T_a - T_r)]\frac{G}{1000} \qquad (2)$$

where $I_{sc}$ is the short-circuit current at standard test conditions, $K_i$ is the temperature coefficient of short circuit current, $T_a$ is the cell`s operating temperature, $T_r$ is the reference temperature, and $G$ is the irradiance.

Furthermore, the cell`s saturation current $I_s$ varies with the operating temperature of the cell, as given in eqn. (3).

$$I_s = I_{rs}\left(\frac{T_a}{T_r}\right)^3 \exp\left[\frac{qE_g\left(\frac{1}{T_r}-\frac{1}{T_a}\right)}{KA}\right] \qquad (3)$$

where $I_{rs}$ is the cell`s reverse saturation current at a reference temperature, and $E_g$ is the band energy gap of the semiconductor material used in making the photovoltaic cell as given in eqn. (4) (Singh et al., 2014).

$$E_g = E_{go} - \frac{\alpha {T_a}^2}{T_a+\beta} \qquad (4)$$

where $E_{go}$ represents band gap energy in $ev$, at $T = 0K$,

$T_a$ represents Cell working temperature,

$\alpha, \beta$ are parameters that define Band energy gap of the semiconductor ($^{eV}/_{K^2}$ ,K)

The reverse saturation current $I_{rs}$ is given in eqn. (5).

$$I_{rs} = \frac{I_{sc}}{\exp\left[\left(\frac{qV_{oc}}{KAT_a}\right)-1\right]} \qquad (5)$$

Practically, the power output of a single photovoltaic cell is not sufficient for almost any application. Therefore, photovoltaic cells must be connected in series-parallel configuration to form an array in order to generate the required power as a typical photovoltaic cell produces less than 2 W at 0.5 V approximately. Equations (2) , (3) and (5) can be modified by including the number of parallel connected cells $N_p$ and the number of series connected cells $N_s$ to get new equations for $I_{ph}$, $I_s$, and $I_{rs}$ as shown in eqns. (6),(7) & (9) respectively. This results in a new equation for the current output, $I$ of the photovoltaic module as given in eqn (10).

$$I_{ph}^T = N_p I_{ph} \qquad (6)$$

$$I_s^T = N_p I_s \qquad (7)$$

$$R_s = \frac{N_s}{N_p} R_s^c \qquad (8)$$

where $I_{ph}^T$ , $I_s^T$ and $R_s$ represent the total photo-current, total diode saturation current and total series resistance of photovoltaic module respectively. Hence, the reverse saturation current $I_{rs}$ and the current output $I$ of a photovoltaic module with $N_s$ number of series cells and $N_p$

number of parallel cells are as given in eqns. (9) and (10) respectively.

$$I_{rs} = \frac{I_{sc}}{\left[\exp\left(\frac{qV_{oc}}{N_s KAT_a}\right)-1\right]} \quad (9)$$

$$I = N_p I_{ph} - N_p I_s \left[\exp\left(\frac{q(V+IR_s)}{N_s KAT_a}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (10)$$

where $R_s$ is series resistance of the photovoltaic module in Ohms and V is voltage output of the photovoltaic module in volts.

### Solution for Internal Series Resistance and Shunt Resistance

The aim is to find the values of the pair $(R_s, R_{sh})$ that make the maximum power point $(V_{mp}, I_{mp})$ that coincide with the experimental maximum power point $(V_{mp,e}, I_{mp,e})$. In other words, one search for the pair $(R_s, R_{sh})$ that makes the peak of the mathematical power-voltage curve that coincide with the experimental peak power point at $(V_{mp,e}, I_{mp,e})$.

This requires an iterative process until $V_{mp} = V_{mp,e}$ and $I_{mp,e} = I_{mp,e}$ or $P_{max,m} = P_{max,e}$. The iterative process was carried out using MATLAB-based Newton Raphson program. Newton Raphson iterative method was adopted because of its fast convergence. This involves increasing the series resistance Rs slowly starting from Rs=0. The flowchart of Newton Raphson iterative method is illustrated in Figure 2.0.

The general Newton Raphson`s method in eqn. (11) was applied to solve eqn. (10).

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (11)$$

where $f'(x_n)$ is the derivative of the function, $f(x_n) = 0$, $x_n$ is a present value and $x_{n+1}$ is a next value. Rewriting eqn. (10) gives eqn. (12) with its first derivative given in eqn. (14)

$$f(I_n) = N_p I_{ph} - I_n - N_p I_s \left[\exp\left(\frac{q(V+I_n R_s)}{N_s KAT_a}\right) - 1\right] - \frac{V+I_n R_s}{R_{sh}} = 0 \quad (12)$$

$$f'(I_n) = -1 - \frac{qR_s I_s}{N_s KAT_a}\left(\exp^{\frac{q(V+I_n R_s)}{N_s KAT_a}}\right) - \frac{R_s}{R_{sh}} \quad (13)$$

Substituting eqns. (12) and (13) into eqn. (11) gives eqn. (14)

$$I_{n+1} = I_n - \frac{N_p I_{ph} - I_n - N_p I_s\left[\exp\left(\frac{q(V+I_n R_s)}{N_s KAT_a}\right)-1\right] - \frac{V+I_n R_s}{R_{sh}}}{-1 - \frac{qR_s I_s}{N_s KAT_a}\left(\exp^{\frac{q(V+I_n R_s)}{N_s KAT_a}}\right) - \frac{R_s}{R_{sh}}} \quad (14)$$

In the iterative process, $R_s$ must be slowly incremented starting from $R_s = 0$. Adjusting the P-V curve to match the experimental data requires finding the curve for several values of $R_s$ and $R_{sh}$. Plotting the curve is not compulsory, as only the peak power is required.

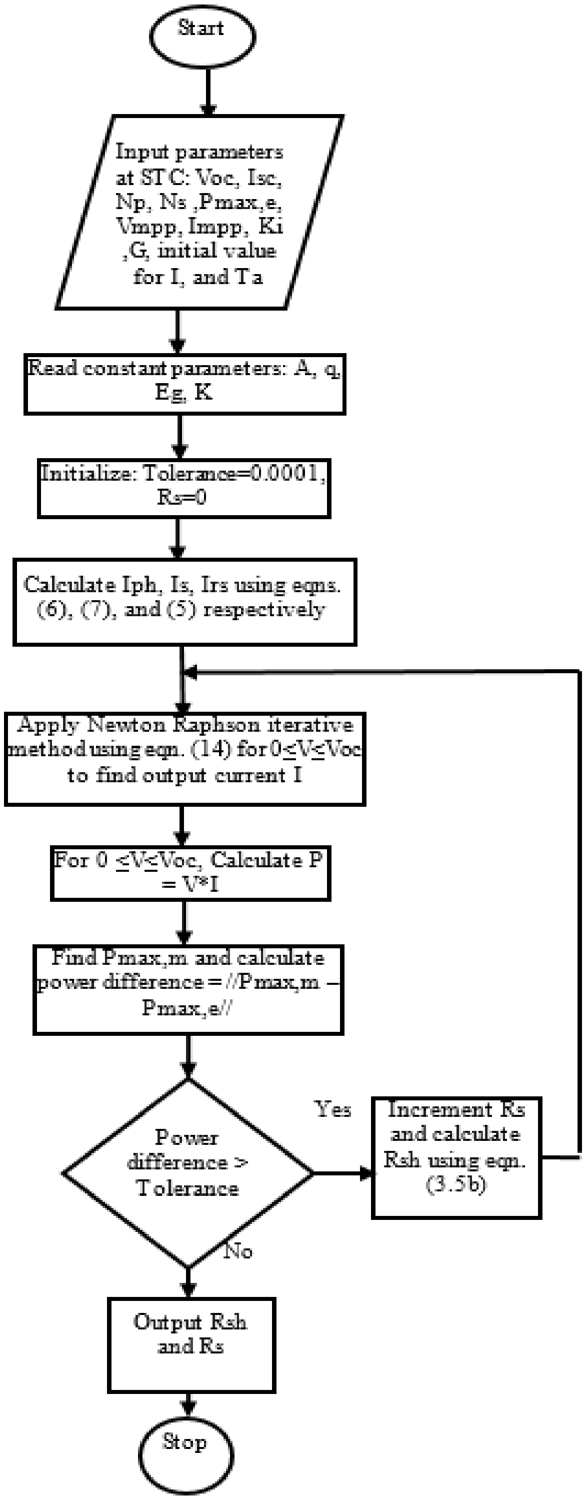


Figure 2. Flowchart for Newton Raphson iterative process.

The plotting the P-V and I-V curves requires solving the fundamental mathematical equations of single diode model for $I \in [0, I_{sc,n}]$ and $\in [0, V_{oc,n}]$. The fundamental equation of single diode model does not have a direct solution because $I = f(V, I)$ and $V = f(I, V)$. This transcendental equation must be solved by a numerical method. The $I - V$ points are easily obtained by numerically solving $g(V, I) = I - f(V, I) = 0$ for a set of V values and obtaining the corresponding set of I points. Obtaining the P-V points is straightforward by calculating output power $P$.

An iterative method is used to adjust $R_s$ and $R_{sh}$ concurrently based on the fact that there is only a pair $\{R_s,R_{sh}\}$ that warranties that the maximum power of the model equals to the experimental power at the maximum power point. In other words, the maximum power calculated by the I-V model, $P_{max,m}$, must be equal to the maximum experimental power from the datasheet, $P_{max,e}$, at the maximum power point (MPP).

The relation between series resistance and shunt resistance, among the unknowns of eqn. (10) could be found by making maximum power of the model equals to the experimental maximum power from the data sheet and solving the resulting equation for $R_s$ and $R_{sh}$, as shown in eqns (15), (16) and (17).

$$P_{max,m} = V_{mp}\left\{N_pI_{ph} - N_pI_s\left[\exp\left(\frac{(V_{mp}+R_sI_{mp})q}{AN_sKT}\right) - 1\right] - \frac{V_{mp}+I_{mp}R_s}{R_{sh}}\right\} = P_{max,e} \quad (15)$$

when

$$R_{s_{n+1}} = R_{s_n} + 0.01 \quad (16)(a)$$

$$R_{sh} = \frac{V_{mp}(V_{mp}+I_{mp}R_s)}{\left\{V_{mp}N_pI_{ph} - V_{mp}N_pI_s\exp\left[\frac{(V_{mp}+R_sI_{mp})q}{aKTN_s}\right] + V_{mp}I_s - P_{max,e}\right\}} \quad (16)(b)$$

At $n = 1$, $R_s = 0$, then the corresponding minimum shunt resistance, $R_{sh,min}$ is given in eqn (17).

$$R_{sh,min} = \frac{V_{mp}}{I_{sc,n}-I_{mp}} - \frac{V_{oc,n}-V_{mp}}{I_{mp}} \quad (17)$$

Equations (16) (a) and (b) could be interpreted that for any value of series resistance, there will be a value of shunt resistance that makes the mathematical current-voltage output curve crosses the experimental $(V_{mp}, I_{mp})$ point.

## RESULTS AND DISCUSSION

### Simulation Results for Newton Raphson Iterative Solution of shunt and series Resistance

The Newton Raphson iterative method adopted gives the solution of internal series $R_s$ as $0.23\Omega$ and shunt resistance $R_{sh}$ as $597.75\Omega$ for KC200GT PV module. Figure 3 shows a plot of power difference as a function of internal series resistance for $I = I_{mp}$ and $V = V_{mp}$. This plot shows that $R_s = 0.23\Omega$ is the desired solution as indicated in Figure 4.

Figures 5 and 6 show plots of power and current as a function of voltage output respectively for $I = I_{mp}$ and $V = V_{mp}$. As internal series resistance, $R_s$ increases the P-V curve moves to the left and the peak power, $P_{max,m}$ goes towards the experimental maximum power point (MPP). The plots show the contour drawn by the peaks of the power curves for several values of internal series resistance $R_s$. For every P-V curve in Figure 5 there is a corresponding I-V curve as shown in Figure 6.

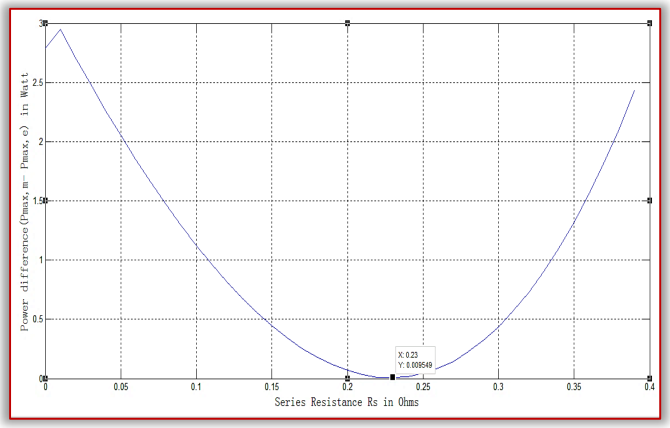


Figure 3. Power difference against internal series resistance

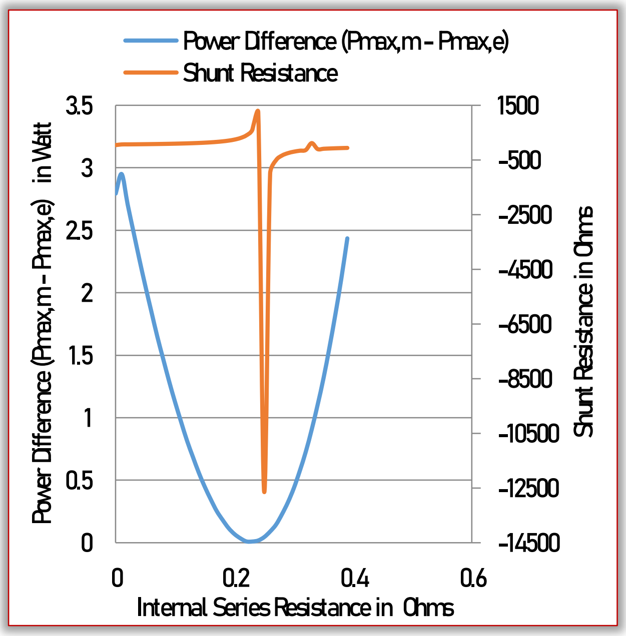


Figure 4. Power differences and shunt resistance against internal series resistance (KC200GT).

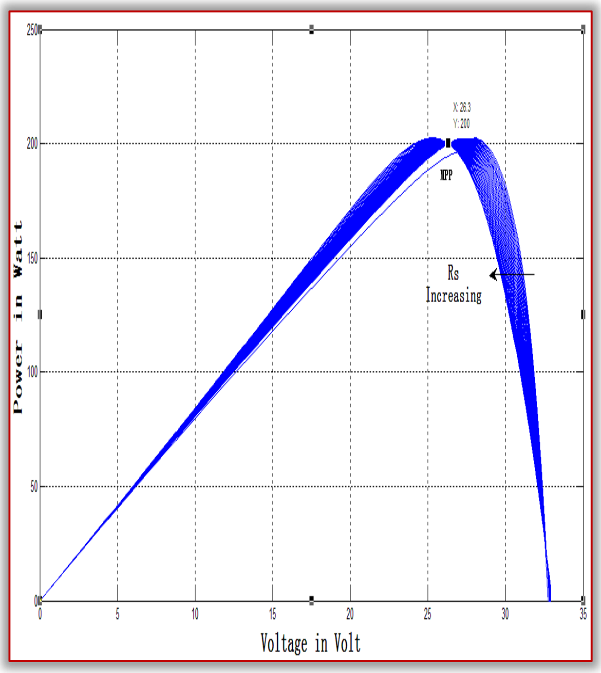


Figure 5. P–V curves for different values of series resistance $R_s$ and $R_{sh}$ at STC.

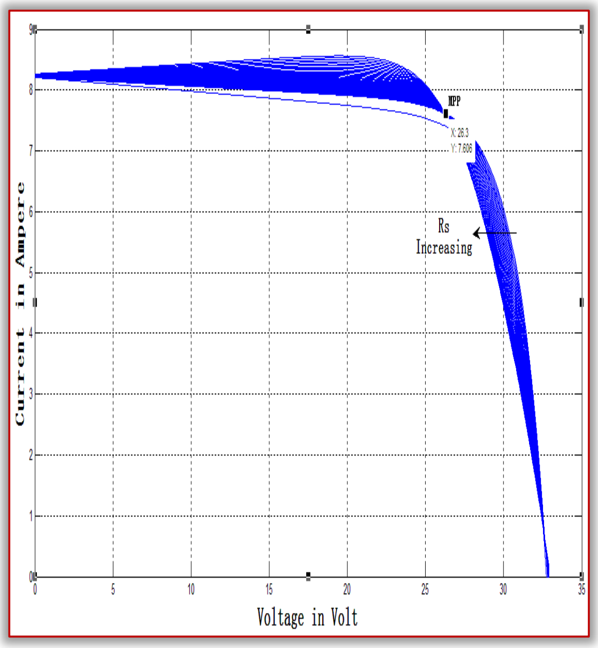


Figure 6. I–V curves for different values of $R_s$ and $R_{sh}$ at standard test conditions.

## CONCLUSION

In this work, a simple but accurate method to determine internal resistances of photovoltaic module is presented. The method is based on single diode model using Newton Raphson iterative technique. Using the presented methodology, it is possible to construct a realistic model of a solar panel that reproduces the experimental data provided by the manufacturer in the data sheet, including variations at different temperatures and irradiations.

Finally, an interesting application of this method is to construct realistic model of solar panels that can be used in simulations of MPPT algorithm.

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