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**Modeling and Simulation of Solar Module performance using Five Parameters
Model by using Matlab in Baghdad City**

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ABSTRACT

This work presents the modeling of the electrical response of monocrystalline photovoltaic module by using five parameters model based on manufacture data-sheet of a solar module that measured in stander test conditions (STC) at radiation 1000W/m^2 and cell temperature 25°C . The model takes into account the series and parallel (shunt) resistance of the module. This paper considers the details of Matlab modeling of the solar module by a developed Simulink model using the basic equations, the first approach was to estimate the parameters: photocurrent I_{ph} , saturation current I_s , shunt resistance R_{sh} , series resistance R_s , ideality factor A at stander test condition (STC) by an iteration process. To implement the iteration process, a numerical approach based on the Newton Raphson method has been implemented and programmed in Matlab. The second mathematical model used in Matlab/Simulink using equations for each parameter to determine the parameters at all operating conditions. The Matlab program gives the information about the behavior of the practical PV module, under different atmospheric conditions. The model accuracy was also analyzed through finding out the compatibility between the practical and the theoretical aspects at different solar radiation intensity 500, 750 and 1000W/m^2 by extracting the error ratios. The results show that there is difference between theoretical (modeled) and experimental, the best validation (less error) between five parameters model and experimental maximum power results at radiation 500, 750, 1000W/m^2 and STC was 5.5%, 19%, 18% and 12.3% in January respectively, due to the decreases in ambient temperature and thus decreases in the temperature of solar module in January led to increase in maximum output power and producing best validation between model and experimental in this month.

Key Words: photovoltaic module, simulation, temperature effect

النمذجة والمحاكاة لأداء اللوح الشمسي باستخدام نموذج الخمس عوامل بواسطة الماتلاب في مدينة بغداد

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الخلاصة

يقدم هذا البحث نمذجة الاستجابة الكهربائية لأداء اللوح الشمسي أحادي البلورة باستخدام نموذج الخمس عوامل يستند إلى بيانات ورقة التصنيع للوح الشمسي المقاسة عند الظروف القياسية. يأخذ النموذج في الاعتبار مقاومة التوالي والتوازي للوح الشمسي ويهتم بالبحث

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بنمذجة ماتلاب المفصلة للوحدة الشمسية بواسطة نموذج سيمولينك المتطور الذي يستخدم المعادلات الأساسية، الطريقة الأولى لحساب العوامل: التيار الضوئي، تيار الإشباع، مقاومة التوازي، مقاومة التوالي، عامل الجودة في حالة الظروف القياسية (الإشعاع 1000 واط/متر مربع ودرجة حرارة الخلية 25°C) من خلال عملية التكرار. لتنفيذ عملية التكرار، تم تطبيق نهج رقمي يستند إلى طريقة نيوتن رافسون وبرمجتها في Matlab النموذج الرياضي الثاني المستخدم في ماتلاب / سيمولينك من خلال تكوين المعادلات لكل عامل لاجداد العوامل في جميع الظروف التشغيل. برنامج ماتلاب يعطي المعلومات حول السلوك العملي للوح الكهروضوئي في ظل الظروف الجوية المختلفة. كما تم تحليل دقة النموذج من خلال معرفة التوافق بين العملي والنظري عند شدة الإشعاع الشمسي المختلفة 500, 750, 1000 واط/متر مربع باستخلاص نسب الخطأ. أظهرت النتائج وجود فرق بين نظري (نموذجي) وتجريبي، أفضل تحقيق للطاقة القصوى بين نموذج الخمس العوامل والنتائج التجريبية في الإشعاع 500، 750، 1000 واط/متر مربع و STC هي 5.5% و 19% و 18% و 12.3 في كانون الثاني على التوالي، بسبب الانخفاض في درجة حرارة الجو وبالتالي انخفاض حرارة اللوح الشمسي في كانون الثاني مما يؤدي الي زيادة انتاج الطاقة القصوى وانتاج افضل تحقق بهذا الشهر بين المودل والعملي.
كلمات رئيسية: اللوح الفوتوفولتائي، المحاكاة، تأثير الحرارة.

1. INTRUDUCTION

The increase in population and industrialization leads to the tremendous use of power. Continuous use of fossil fuels, for the power production, leads to the reduction in the fuel deposits and drastically effects the environment and causes to the global warming. The increase of utilization of renewable energy like solar energy, wind energy is growing from last two decades, **Alrikabi, 2014**. A huge attention is towards the conversion and storage of solar energy due to green and environmental friendship, technical improvements, an increase of efficiency. A photovoltaic system (PVs) converts sunlight into electricity. The basic device of a photovoltaic system is the photovoltaic cell. Cells may be grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays as shown in **Fig. 1**. the term array is usually employed to describe a photovoltaic panel (with several cells connected in series and/or parallel) or a group of panels, **Bagher, et al., 2015**. The solar cell is a p-n semiconductor junction exposed to sunlight and generates electrical direct current. PVs have several advantages such as no environmental pollution, high reliability, no noise and low maintenance cost. There are many factors affecting the efficiency and power output of photovoltaic panel such as (radiation, ambient temperature, and wind speed), **Zaoui, et al., 2015**.

In literature, **Wolf, and Rauschenbaer, 1963**, studied three different mathematical methods that are presented in order to estimate the four parameters model (photocurrent I_{ph} , saturation current I_s , series resistance R_s , ideality factor A) and to simulate its current-voltage and power-voltage characteristics, **De Soto, et al., 2006** calculated the panel internal parameters photocurrent, saturation current, series resistance, shunt resistance and ideality factor $I_{ph,r}, I_{s,r}, R_{s,r}, R_{sh,r}, A_r$ respectively of five parameters model at reference conditions ($G=1000W/m^2$ and $T=25^\circ C$) to predict the (current-voltage) curve for four different cells (single crystalline, poly crystalline, silicon thin film, and triple-junction amorphous). The five parameters model agrees with both experimental measurements of the National Institute of Standards and Technology (NIST) and the king model for all four-panel types at different working conditions. **Skoplaki, et al., 2008**, studied the effect of operating temperature upon the performance of free-standing PV panel and the simple semi-empirical explicit correlation was used included the environmental conditions as result the power dependent linearly on panel temperature. **Dongue, et al., 2012**, studied modeling of two different PV modules (mono-crystalline and multi-crystalline) for various working operation by using two models, four parameters model which shunt resistance assuming its value of infinity and five parameters model takes into account series and shunt resistance, concluded both four and five parameters models accurately fit experimental data of both PV panels and the five parameters model more accurate than four parameters model in power and current. **Aoun, et al., 2014**, showed that the five parameters model accurate with experimental data under outdoor weather conditions in three days at different radiation and the error between the maximum power from manufacturer and simulation at STC is 5.63% and the value



of ideality factor obtained at maximum power 250.1 watt is equal 1.5. **Bellia, et al., 2014**, developed an empirical model to produce the current and voltage curve using five located points at the current-voltage curve. However, the method needs empirically coefficients parameters which are typically not available from manufacturer datasheet. The coefficients are provided by the Sandia National Laboratory. This paper presents a study of experimental testing results for the performance of solar module (monocrystalline silicon) under the natural sun and outdoor exposure in Baghdad for two consecutive months (January and February). The data collected were, the open circuit voltage, short circuit current and maximum power output, to investigate the validation of the five parameters model for PV module and compare the (I-V and P-V) curves of PV module at different radiations from model in Matlab/Simulink and experimental results, and take into account the effect of the environmental factors (ambient temperatures, wind speed and solar radiation) on module temperature. The experimental work was presented during the winter to obtain the highest power and efficiency of the solar module and the response was better to the parameters of the module in this period because the ambient temperature is low with good solar radiation make the module temperature in acceptable limits to give better results, while in summer, the ambient temperature high this led to increasing the module temperature which decreases the power output and efficiency.

2. THE CURRENT-VOLTAGE RELATIONSHIP FOR A PHOTOVOLTAIC DEVICE

The most important component that affects the accuracy of a simulation in the PV cell is modeling which primarily involves the estimation of the non-linear I-V and P-V characteristics curves. The simplest model is the single – diode model (five parameter model). **Fig.2** shows the simple equivalent electrical circuit of a solar cell, a single diode connected in parallel with a photocurrent source and the shunt resistance (R_{sh}) expressing a leakage current and series resistance (R_s) describes an internal resistance to the current flow. Applying Kirchoff law, the cell terminal current is expressed by, **Villalva, et al., 2009**:

$$I = I_{ph} - I_D - I_{sh} \tag{1}$$

The diode current is given by Shockley equation, **Lo brano, et al., 2010**:

$$I_D = I_S \left[\exp \left(\frac{q(V+IR_S)}{AKT} \right) - 1 \right] \tag{2}$$

$$\text{Where } V_{sh} = V_D \text{ and } V_D = V + IR_S$$

In which I is the output current and I_{ph} refers to the photo-generated current, I_d represents the diode current, V_D or V_{sh} refers to the diode or shunt voltage (volt), I_s is the saturation current in the diode, V_T is the thermal voltage of the diode, V is the output voltage. **Eq. (3)** is the fundamental basic equation, for the modeling in this study.

$$I = I_{ph} - I_S \left[\exp \left(\frac{(V+IR_S)}{V_T} \right) - 1 \right] - \frac{V+IR_S}{R_{sh}} \tag{3}$$

Measurements of a PV module electrical output traditionally are done at standard test conditions (STC): incident solar radiation of 1000 W/m², module temperature of 25°C as shown in **Table 5**, measurements of I-V curve at reference conditions are commonly available by the manufacturer at three points: open-circuit, short-circuit, and maximum power. In this study, two methods for five parameter model were applied for the modeling of the PV module using Matlab:



- 1- Five parameters model (iterative method) at standard test condition.
- 2- Five parameters model (Simulink method) for another condition.

3.1 The Reference Parameters

Eq. (3) is the basic equation for this model and to evaluate five parameters with less approximation, an iteration process needs to be done. An iteration method was presented by, **villalva, et al; 2009** and others in a similar manner. The method proposes changing R_s and R_{sh} according to the fact of there is only the pair of (R_s, R_{sh}) that achieves the maximum power. The model changes the value of the mentioned resistances until the maximum power determined by **Eq. (3)** equals the experimental maximum power provided in the manufacturer datasheet ($P_m = P_{m,exp}$). The five parameters model calculates the five parameters according to the following points:

- I_{ph} , is the photogenerated current calculated by the advantage of the iteration process for R_s and R_{sh} . each iteration changes R_s and R_{sh} towards the best converging solution of I_{ph} which is given in the following equations: where I_{sc} is the short circuit current at STC from data sheet, **Villalva, et al., 2009**.

$$I_{ph} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} \tag{4}$$

- The shunt resistance R_{sh} is considered to be a function of the series resistance and experimental maximum power and the other parameters. During the iteration, R_s gradually incremented starting from $R_s = 0$ and for each value of R_s . There will be a value of R_{sh} insuring that the modeled I-V curve pass cross the experimental maximum power point. I_m and V_m the maximum current and maximum voltage at STC from data sheet value, **Villalva, et al., 2009**.

$$P_{m,exp} = P_{m,mod} = (V_m I_m)_{Mod} \tag{5}$$

$$= V_m \left\{ I_{ph} - I_s \left[\exp\left(\frac{V_m + I_m R_s}{V_t}\right) - 1 \right] - \frac{V_m + I_m R_s}{V_t} \right\}$$

$$R_{sh} = \frac{V_m(V_m + I_m R_s)}{\left\{ V_m I_{ph} - V_m I_s \left[\exp\left(\frac{V_m + I_m R_s}{V_t}\right) - 1 \right] \right\} - P_{m,exp}} \tag{6}$$

- The reverse saturation current I_s is calculated from the open circuit condition for Eq.(4) **Villalva, et al., 2009**.

$$I_s = \left(I_{ph} - \frac{V_{oc}}{R_{sh}} \right) / \left[\exp\left(\frac{V_{oc}}{V_T}\right) - 1 \right] \tag{7}$$

V_{oc} : Open circuit voltage (V) at STC from data sheet value

- The diode ideality factor (A) equation is shown below, **Villalva, et al., 2009**:



$$A = \left(K_{VOC} - \frac{V_{OC}}{T} \right) / \left(\frac{N_S K T}{q} \left[\frac{K_{ISC}}{I_{ph}} - 3 - \frac{q E_g}{A K T} \right] \right) \tag{8}$$

K_{VOC} : Open circuit temperature coefficient equal -0.07207, **Villalva, et al., 2009.**

K_{ISC} : Short circuit temperature coefficient equal 0.009284, **Villalva, et al., 2009.**

Eg: Band gap energy for the silicon semiconductor which equals 1.124 e, **Villalva, et al., 2009.**

Initial guesses for R_s and R_{sh} are necessary to start the iterative process. R_s tends to be small, therefore many authors take ($R_{s,min} = 0$) as an initial guess. $R_{sh,min}$ estimated from the slope of the straight line between the short circuit current point and the maximum power point, **Bonkougou, et al., 2013.**

$$R_{sh,min} = \frac{V_m - 0}{I_{SC} - I_m}$$

An iterative method is used for simulation resolution of equations 4 – 9 yielding the five reference parameters at STC. Now, there are certain equations for the five parameters except R_s which will be changed until achieving the condition. To execute the iteration process, a numerical approach based on the Newton Raphson’s method will be implemented and programmed in Matlab, **Bellia, et al., 2014.**

$$X_{n+1} = X_n \frac{f(X_n)}{f'(X_n)} \tag{9}$$

Where $X_n = I_n$. Consider $f = f(I, V)$, then $(I_n) = 0$

$$f(I_n) = I_{ph} - I_o \left[\exp \left(\frac{V + I_n R_s}{V_T} \right) - 1 \right] - \frac{V + I_n R_s}{R_p} - I_n$$

$$f'(I_n) = \frac{\partial f(I_n)}{\partial I} = -\frac{I_s R_s}{V_T} \left[\exp \left(\frac{V + I_n R_s}{V_T} \right) \right] - \frac{R_s}{R_{sh}} - 1$$

3.2 Dependence of The parameters on Operating Conditions

The unknown electrical parameters (I_{ph} , I_s , A , R_s , and R_{sh}), were measured under standard test condition (1000 W/m² and 25°C), **Table 1.** In order to use these parameters for any other operating conditions, it is necessary to obtain expressions for their temperature and irradiance dependence. The parameters: photocurrent, saturation current, ideality factor and series and shunt resistance are corrected for new environmental weather using equations (10) to (16) respectively as shown in **Table 2 and 3.** **Eq.(3)** is solved in the Matlab/Simulink as shown in **Fig.8** by using the five parameters at reference condition extracted from the first model in the equations below: **De Soto, et al., 2006.**

$$I_{ph} = [I_{SC} + K_{ISC}(T - T_{ref})] G/G_{ref} \tag{10}$$

where G is the solar radiation at operation conditions (watt), G_{ref} is the solar radiation equal to 1000 W/m², T_{ref} or reference temperature that is equal to 25°C.

$$I_{r,s} = I_{SC} / \exp \left(\frac{q V_{OC}}{N_S T_{ref} K A} - 1 \right) \tag{11}$$



Where $I_{r,s}$ is the reverse saturation current (Amp).

$$I_S = I_{r,s} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{qE_g}{AK} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (12)$$

$$R_{Sh} = R_{Sh,ref} \frac{G_{ref}}{G} \quad (13)$$

Where $R_{Sh,ref}$ the shunt resistance at reference condition which is taken from iterative the method.

$$A = A_{ref} \frac{T}{T_{ref}} \quad (14)$$

Where A_{ref} the ideality factor at reference condition which is taken from iterativthe e method.

$$R_S = R_{S,ref} \quad (15)$$

Where $R_{S,ref}$ the series resistance at reference condition which is taken from iterative the method.

$$V_{OC} = V_{OC,ref} + V_T T_{OP} \ln \left(\frac{G}{G_{ref}} \right) + K_{VOC} (T_{OP} - T_{ref}) \quad (16)$$

3. EXPERIMENTAL SETUP

A mono-crystalline silicon solar PV module is used with electrical specification listed in **Table 5**. The performance of the module is tested at different conditions in the Energy Engineering Department/College of Engineering / University of Baghdad. The module was placed on a steel holding stand fixed to the ground. Firstly, a cleaning operation has to be done for the module, and use a frame with angle 33.3° , installing the PV solar module towards the south in outdoor climate. The time at which the tests were done was on the most from 9:00AM to 1:00PM in the period of two months January and February, 2017, solar power meters were placed at the surface of the PV solar module vertically toward the sky to measure the radiation flux 500, 750 and 1000W/m^2 . The way of obtaining the required solar radiation was waiting for the time of radiation reaching the required value and taking the results without moving the module. The output parameters of the module are measured by Prova 200 solar panel analyzer which is a device used for testing of PV module. When it is used in the installation of solar panel, the Prova 200 solar panel analyzer assists in determining the proper inverter size as well as optimum power output position of the panel and helps identify defective cells or panels that have worn out over time. Solar module analyzer PROVA 200A is used to test the characteristics (I_{sc} , V_{oc} , V_m , I_m and P_m), efficiency and Fill Factor of solar panel, also provides the IV and PV Curves, the PROVA 200A have variable resistance from 0 to ∞ to obtained the parameters of the module. Solar Power Meter TES1333R is used to measure the total incident solar radiation, **Fig.3**. The temperature of the module was measured using digital thermoa meter (TPM-10) attached firmly to the back of the module using weather station vantage pro2 to measure the weather parameters such as ambient temperature, wind speed, solar



radiation in order to study their effects on module temperature and modeling these results in Matlab-Simulink. **Table 6** provides some of the technical specifications of the apparatus used in this study.

4. VALIDATION OF THE FIVE-PARAMETERS MODEL

In the Matlab code, there is a command added specially to export the model results also as an Excel sheet where the experimental and model results are combined together in individual curves at three radiation levels. And to find out the compatibility between the practical and the theoretical by extracting the error ratios because there are differences between the experimental results and theoretical because of the inaccuracy of equipment and environment interactions. Calculation the percentage of error between the practical (Laboratory measurements) and theoretical (Matlab Simulink) is done by **Eq.(17)**.

$$\frac{\text{Matlab Simulink result}-\text{Laboratory measurments}}{\text{Laboratory measurments}} \times 100\% \quad (17)$$

5. RESULTS AND DISCUSSION

At first, the unknown parameters are evaluated by the iterative method in five parameters method using Matlab based on the data provided by the manufacturer in STC, from the results it is possible to estimate the parameters of solar module for different radiation and temperature. To validate the five parameters model, an experimental data extracted from outdoor measured data. The outdoor exposure tests were done in the Energy Engineering Department/College of Engineering / University of Baghdad. Matlab code used for the calculation process of five parameters at STC and the results of the program are tabulated in **Table 1**. Three cases of different solar radiation and temperature were considered and introduced in **Table 2** and **Table 3**. Based on these values of the five parameters, it is possible to plot the I-V and P-V curves at specific conditions

Table 2 and **3** show the theoretical results from the model in two months of the five parameters that change with radiation and cell temperature according to the operation Simulink program. The series resistance is assumed to be constant at all operating conditions ($R_s=R_{s,ref}$). I_s reflects the reverse diffusion current which hardly depends on thermal energy, it is increased when cell temperature increased. I_{ph} depends on solar radiation more than temperature, it is increased when the solar radiation increases, the best value of I_{ph} was 3.106A at $G=1000W/m^2$ and $T_{cell,model}=33.8^\circ C$ on January. R_{sh} depends on solar radiation, it is decreased when the solar radiation increases, shunt resistance R_{sh} equal 209 Ω at radiation flux 1000W/m². The ideality factor increases when cell temperature increases, the best value of A at $G=1000W/m^2$ and $T_{cell,model}=41^\circ C$ was 1.04 in February.

In general, the current-voltage curve is the most informative curve for testing the performance of any PV module. It illustrates the validation percent on the I-V curve for four operation condition for the module. Another important characteristic curve is the P-V curve.

In solar radiation 500W/m² the best theoretical and practical maximum power value is 24.67W and 22.23W respectively in the month of February. The maximum power values at 750W/m² radiation vary over the two months due to the increase in ambient temperature and thus increase the temperature of the solar module, where theoretical and practical maximum power is 38.46W and 32.09W respectively in January and then reduces to 38.08W and 31.92W respectively in February due to increased cell temperature from 28°C to 33.3°C as shown in **Table 4**.



The theoretical value of the $1000\text{W}/\text{m}^2$ solar radiation is almost constant in the two months, with the highest power value of 50.04W in February; the experimental results vary with each month, with the highest power value of 42.39W in January and a decrease of 41.2W in February due to increased cell temperature as shown in **Table 4**. The theoretical maximum power value in STC is considered constant in the two months; equal 50.09W was extracted from the iterative program as shown in **Table 4**, the best value of experimental P_{max} was 44.61W in January.

Fig. 4 and **Fig. 5** represented I-V and P-V curves respectively in January for different levels of irradiance 500 , 750 , $1000\text{W}/\text{m}^2$ and STC, despite the modeling curves do not match experimental data in all points. The error percentage between the experimental measured maximum power and five parameter model (predicted) maximum power at STC was 12.3% , which is considered the best match of the reference condition. At low irradiance of about $500\text{W}/\text{m}^2$ where the five-parameter modeled curve is closer to the experimental data than other radiation. The error at solar radiation $500\text{W}/\text{m}^2$ in January equals 5.5% showing a good agreement this month. The validation percentage error at solar radiation 750 and $1000\text{W}/\text{m}^2$ approximately equal 19% for $750\text{W}/\text{m}^2$ and 18% for $1000\text{W}/\text{m}^2$

Fig. 6 and **Fig. 7** show the I-V and P-V characteristics of PV module in outdoor conditions in February. It can be seen that the I-V and PV curves extracted with the method of this paper are not in agreement with experimental dataset, there is a difference between experimental and calculated values of maximum power for radiation 500 , 750 , $1000\text{W}/\text{m}^2$ and STC equal 10.9% , 19.3% , 21.4% and 17.3% respectively.

6. CONCLUSIONS

In this paper, five-parameters-model was proposed. This approach is based on manufacture data sheet parameters to find and calculate the parameters: A , I_s , I_{ph} , R_s , and R_{sh} at standard test conditions STC (25°C , $1000\text{W}/\text{m}^2$). The model accuracy was also analyzed through comparison between experimental data and simulation results using mono-crystalline PV-module in outdoor climate in Baghdad city. The percentage error of the validation between the experimental measured maximum power and five parameters model (predicted) maximum power at radiation $500\text{W}/\text{m}^2$ was 5.5% at cell temperature 17°C , at radiation of $750\text{W}/\text{m}^2$. The best value of validation was 19% at a cell temperature of 28°C . At radiation $1000\text{W}/\text{m}^2$ the best value of validation was 18% at cell temperature 33°C , at radiation $1000\text{W}/\text{m}^2$ and cell temperature 25 (STC), the best value of validation was 12.3% at cell temperature 25°C . I_{ph} and R_{sh} depend on solar radiation, I_{ph} increases when solar radiation increases while R_{sh} decreases when solar radiation increases and the ideality factor depends on the cell temperature. The error between five parameters model and experimental results was less in January than the other month because the power in January more than February due to the decrease in ambient temperature and increase in wind speed which makes the module temperature low while in February the module temperature increase led to decrease in maximum power and produce more error when comparison is made between theoretical and experimental results.



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NOMENCLATURE

A =diode ideality factor

A_{ref} =ideality factor parameter at SRC

E_g = band gap of the semiconductor. eV

G =solar radiation, W/m^2

$I_{ph,ref}$ =light current at SRC ,A

$I_{s,ref}$ =diode reverse saturation current at SRC ,A

I_{sc} =short circuit Current, A

I_{ph} =photo-generated current, A

I_m =current at maximum power point, A

I_s =reverse Saturation current, A

k =Boltzmann constant = $1.38 \times 10^{-23} J.K^{-1}$

N_s =number of cells

P_m =maximum Power output, W

$P_{m,mod}$ =maximum power output from model,Watt

$P_{m,exp}$ =maximum power output from experimental,Watt

q =Electric charge of electron, [C];

R_s =series resistance, Ω

R_{sh} =shunt resistance, Ω

T_a = the ambient temperature, $^{\circ}C$



T = operating temperature of the module, kelvin, K

V_m =voltage at the maximum power point, v

V_{oc} =open circuit Voltage, v

v = volt

Table 1. Solar module parameters five parameters model of at STC based on the datasheet

Parameters	Calculated Values
I_{ph}	3.1,A
I_s	2.06×10^{-10} ,A
R_{sh}	209.21, Ω
R_s	0.6034, Ω
A	1.02

Table 2. The parameters of mc-Si module extracted by five parameter model at different solar radiation in month January from Matlab Simulink

G,W/m ²	T _{cellmodel} , °C	I _{ph} ,A	I _s ,A	R _{sh} , Ω	R _s , Ω	A
500	17.5	1.549	2.62×10^{-10}	418.4	0.6034	0.99
750	25.7	2.328	6.09×10^{-10}	278.9	0.6034	1.02
1000	33.8	3.106	1.35×10^{-9}	209.2	0.6034	1.04

Table 3. The parameters of mc-Si module extracted by five parameter model at different solar radiation in month February from Matlab Simulink

G,W/m ²	T _{cell model} , °C	I _{ph} ,A	I _s ,A	R _{sh} , Ω	R _s , Ω	A
500	19.0	1.55	4.49×10^{-10}	418.4	0.6034	1.01
750	33.3	2.327	1.21×10^{-10}	278.9	0.6034	1.04
1000	41.0	3.105	3.02×10^{-9}	209.2	0.6034	1.07

Table 4. The validation between experimental result and five parameters model result at solar radiation 500, 750,1000W/m² and STC operating condition for two months.

January 2017							
G,W/m ²	T _{cell,exp.} , °C	P _{m, mod.} ,W	P _{m, exp.} ,W	Error%	η_{sm} %	η_{exp} %	Error%
500	17	23.22	22.00	5.5	10.8	10.2	5.8
750	28	38.46	32.09	19	11.9	9.9	20.2
1000	33	50.03	42.39	18.0	11.6	9.8	18.4



STC	25	50.09	44.61	12.3	11.7	10.4	12.5
February 2017							
500	18.0	24.67	22.23	10.9	11.5	10.3	11.6
750	33.3	38.08	31.92	19.3	11.8	9.8	20.4
1000	41.0	50.04	41.20	21.4	11.6	9.6	21.4
STC	25.0	50.09	42.70	17.3	11.7	9.9	18.2

Table 5. Module specifications at STC as presented by the manufacturer

Rated Power	50W
Voltage At Maximum Power (V_{max})	17.5V
Current At Maximum Power (I_{max})	2.86A
Open Circuit Voltage (V_{oc})	21.6V
Short Circuit Current (I_{sc})	3.1A
Module type	(50)17M800*541
Module weight	5.6Kg
Area	0.43m ²
Ns	36

Table 6. Measurement apparatus range, resolution and accuracy

	Measuring range	Resolution	Accuracy
Solar module analyzer PROVA 200A			
DC voltage measurements	0-60 V	0.001-0.01V	±1%±(1% of Voc±0.09V)
DC current measurements	0-6 A	0.1-1 A	±1%±(1% of Isc±0.9mA)
Solar power meter TES1333R			
Solar Radiation measurement	0-2000W/m ²	0.1W/m ²	±10W/m ² or 5%,higher temperature Induced error of 0.38W/m ² / °C From 25°C
Digital thermometer TPM-10			
Temperature measurement	-50~70°C	p.1°C	±1°C

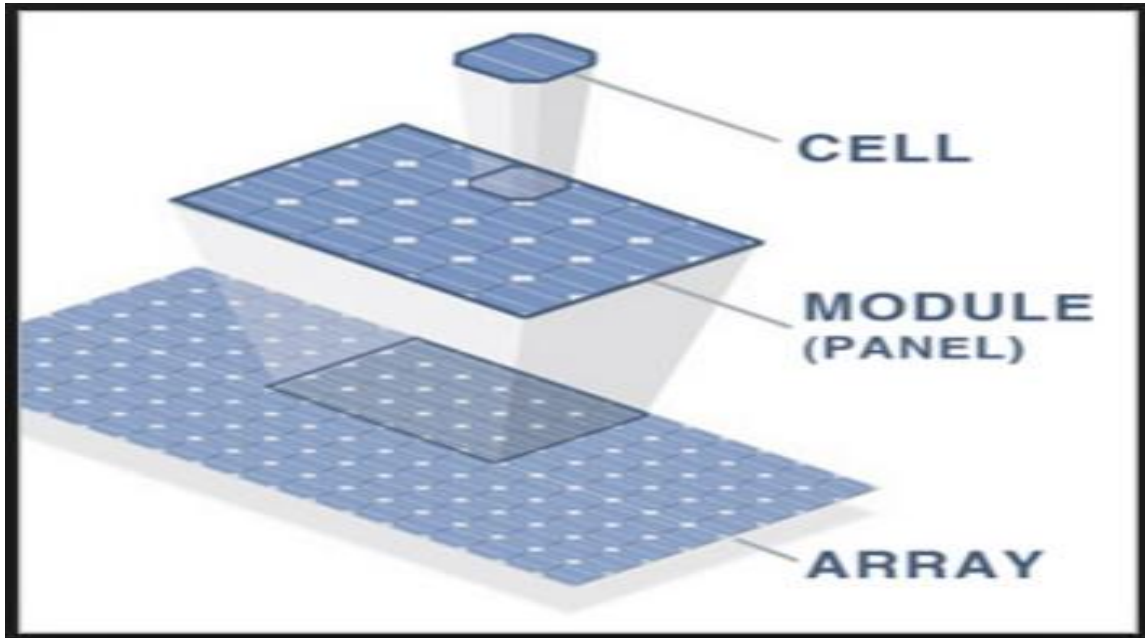


Figure 1. PV hierarchy.

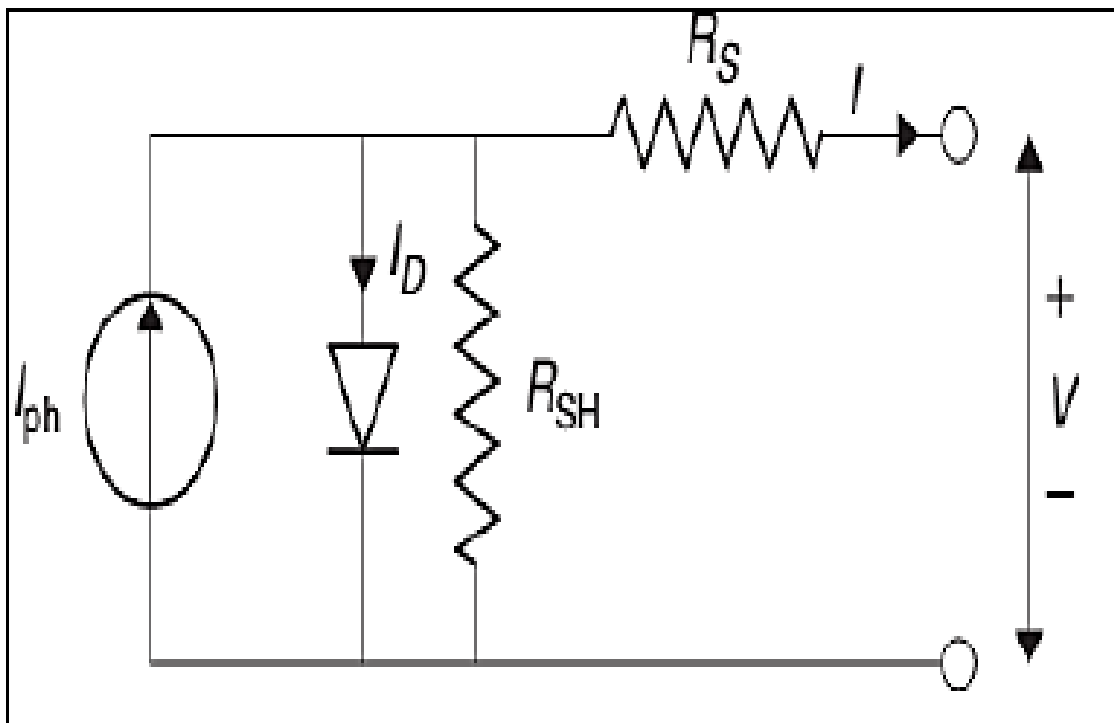


Figure 2. Equivalent electrical circuit of five parameter model.

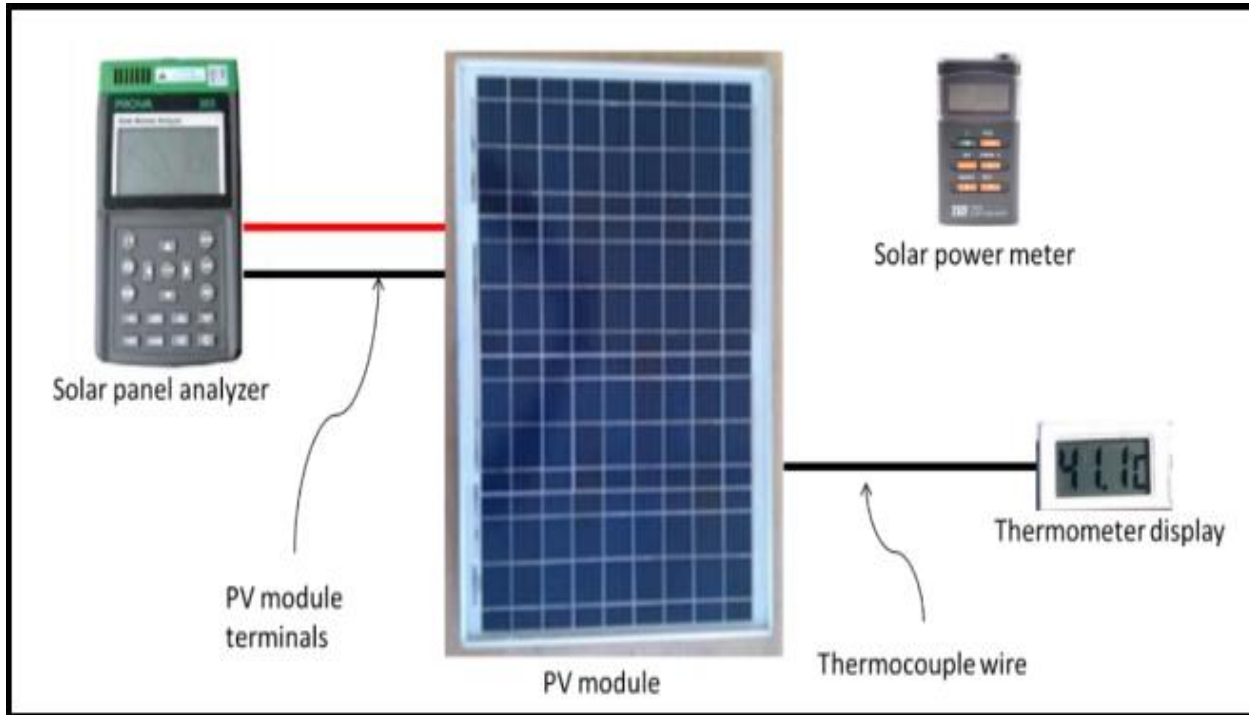


Figure 3. Measurement apparatus (left) PROVA200A solar module analyzer, (right) TES133R solar power meter.

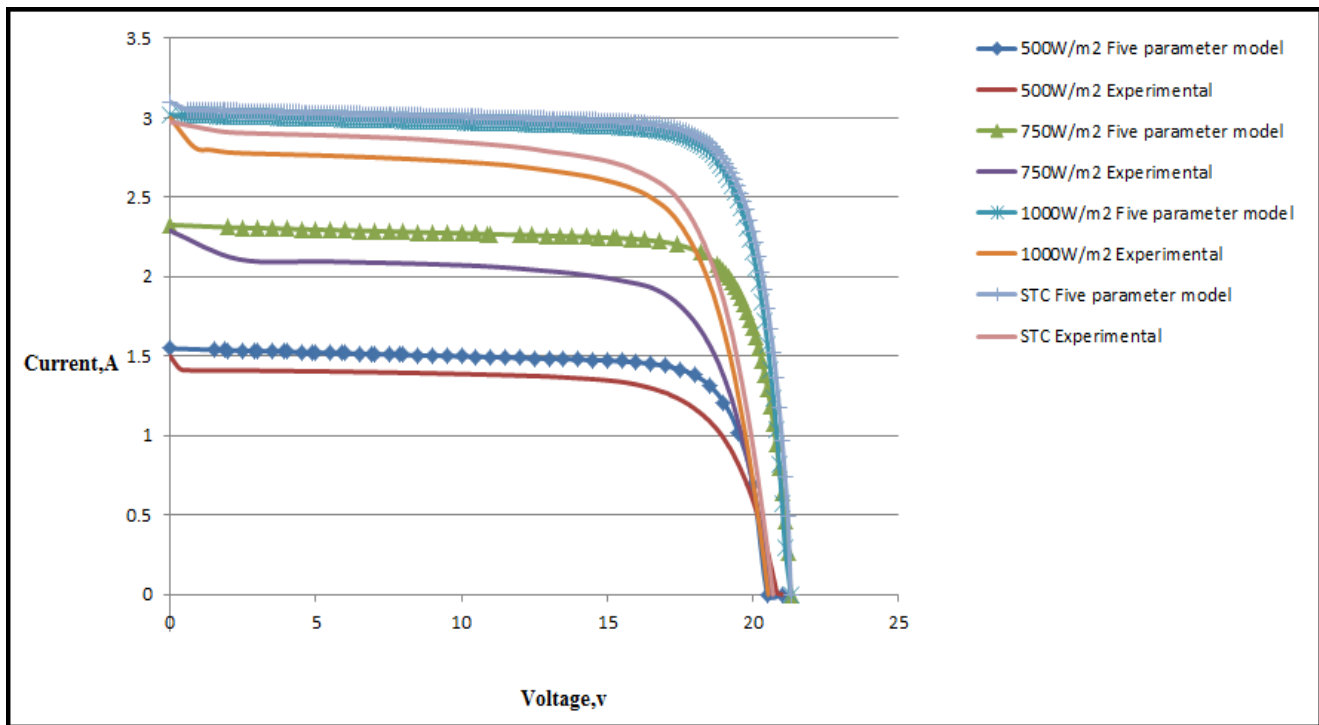


Figure 4. Comparison of current-voltage curves of monocrystalline module predicted by the Five-parameters model and experimentally measured values of radiation flux 500,750,1000W/m² and STC of January month.

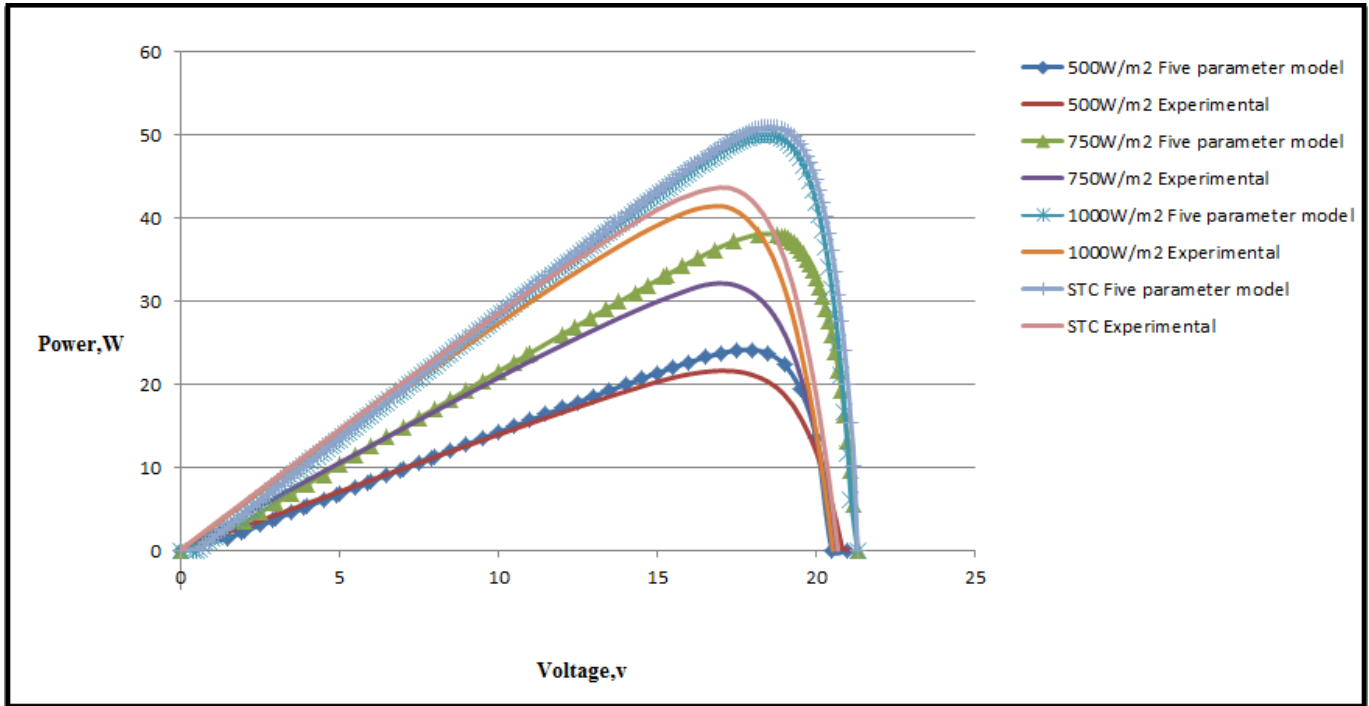


Figure 5. Comparison of current-voltage curves of monocrystalline module predicted by the Five-parameters model and experimentally measured values of radiation flux 500,750,1000W/m² and STC on January month.

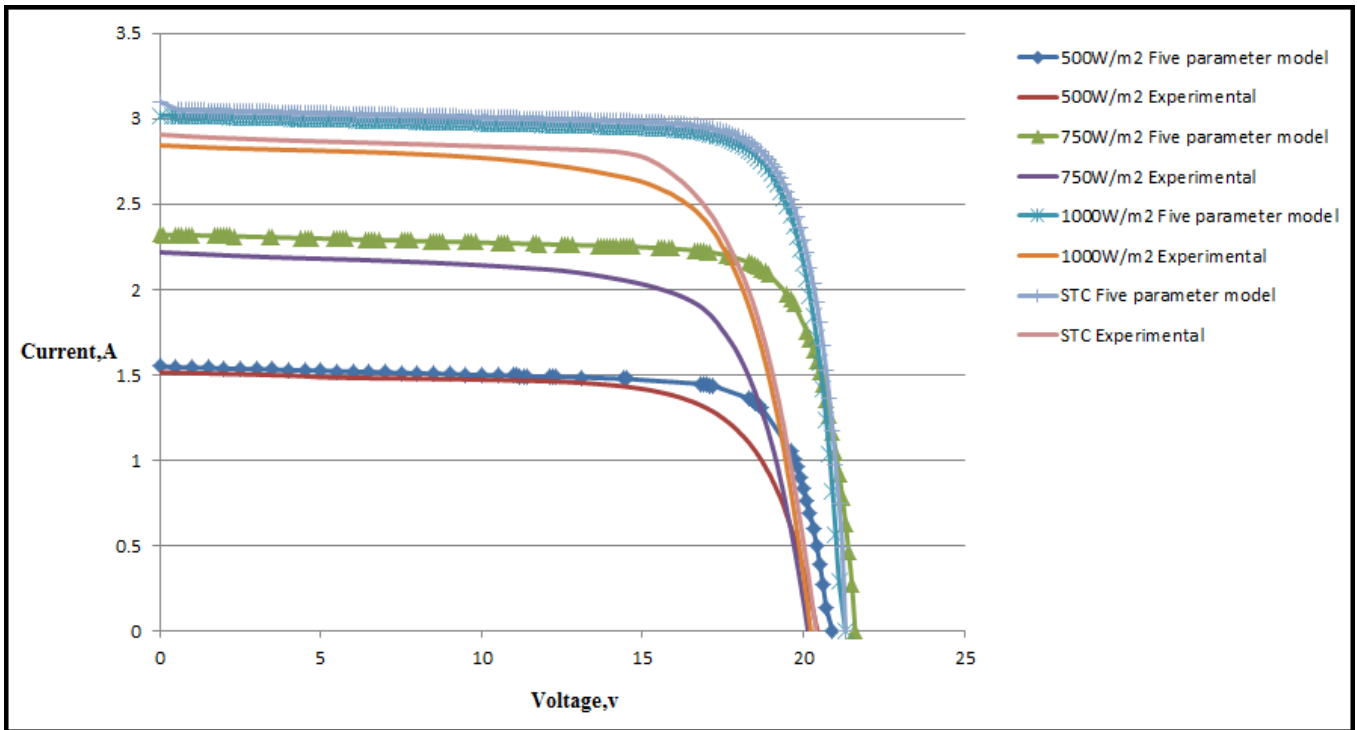


Figure 6. Comparison of current-voltage curves of monocrystalline module predicted by the Five-parameters model and experimentally measured values of radiation flux 500,750,1000W/m² and STC on February month.

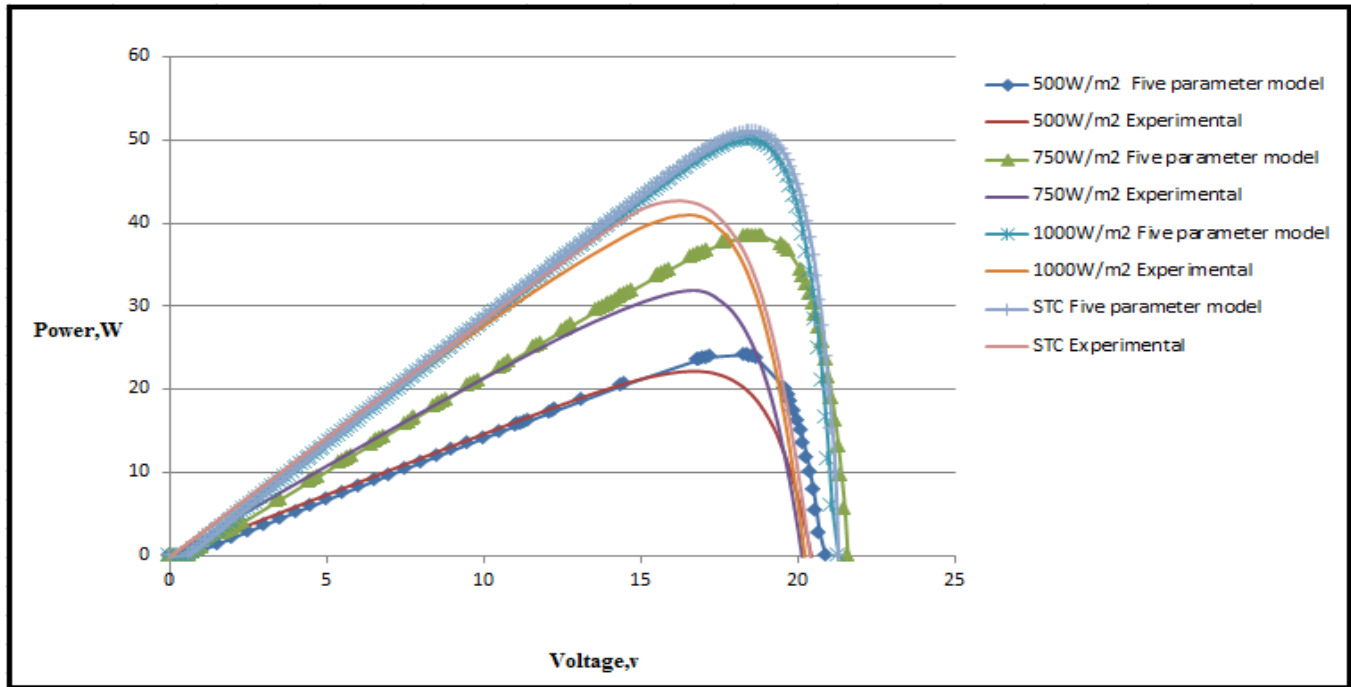
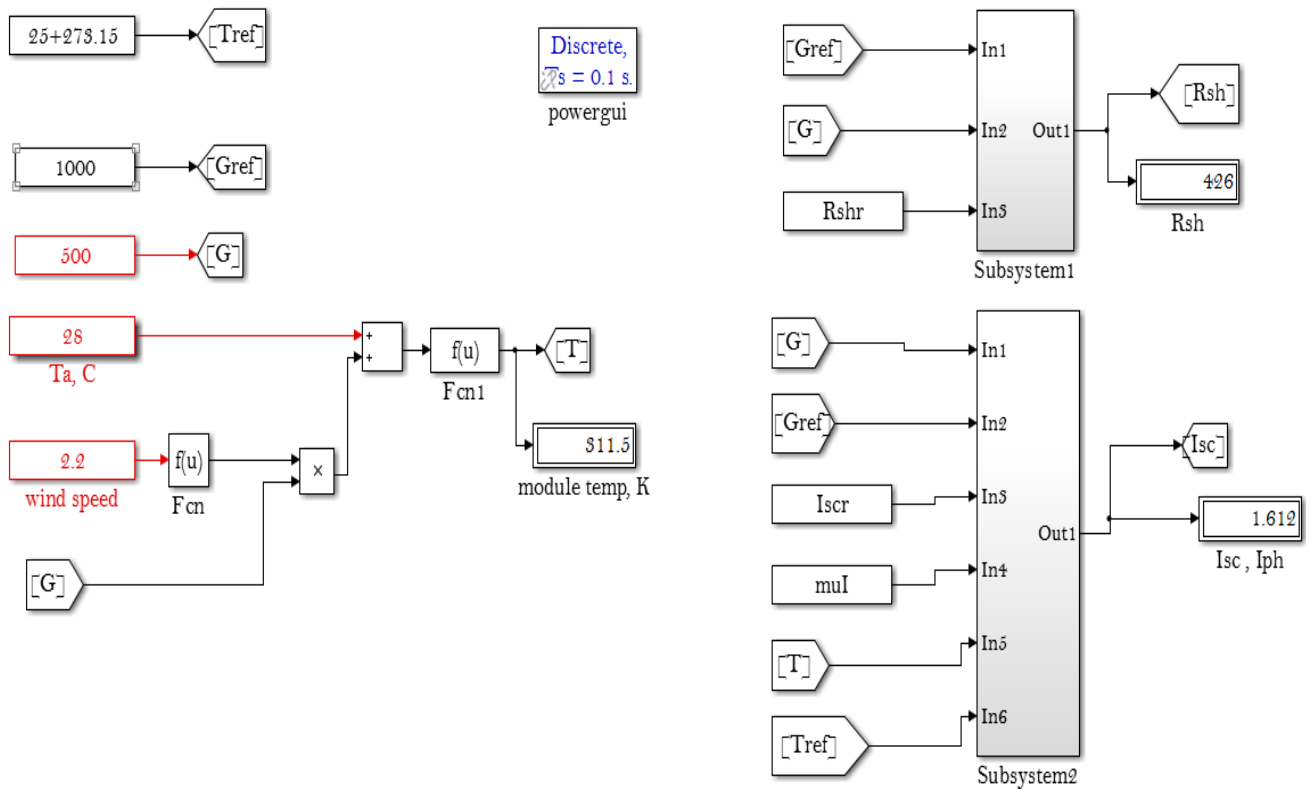


Figure 7. Comparison of current-voltage curves of monocrystalline module predicted by the Five-parameters model and experimentally measured values of radiation flux 500,750,1000W/m² and STC on February month.



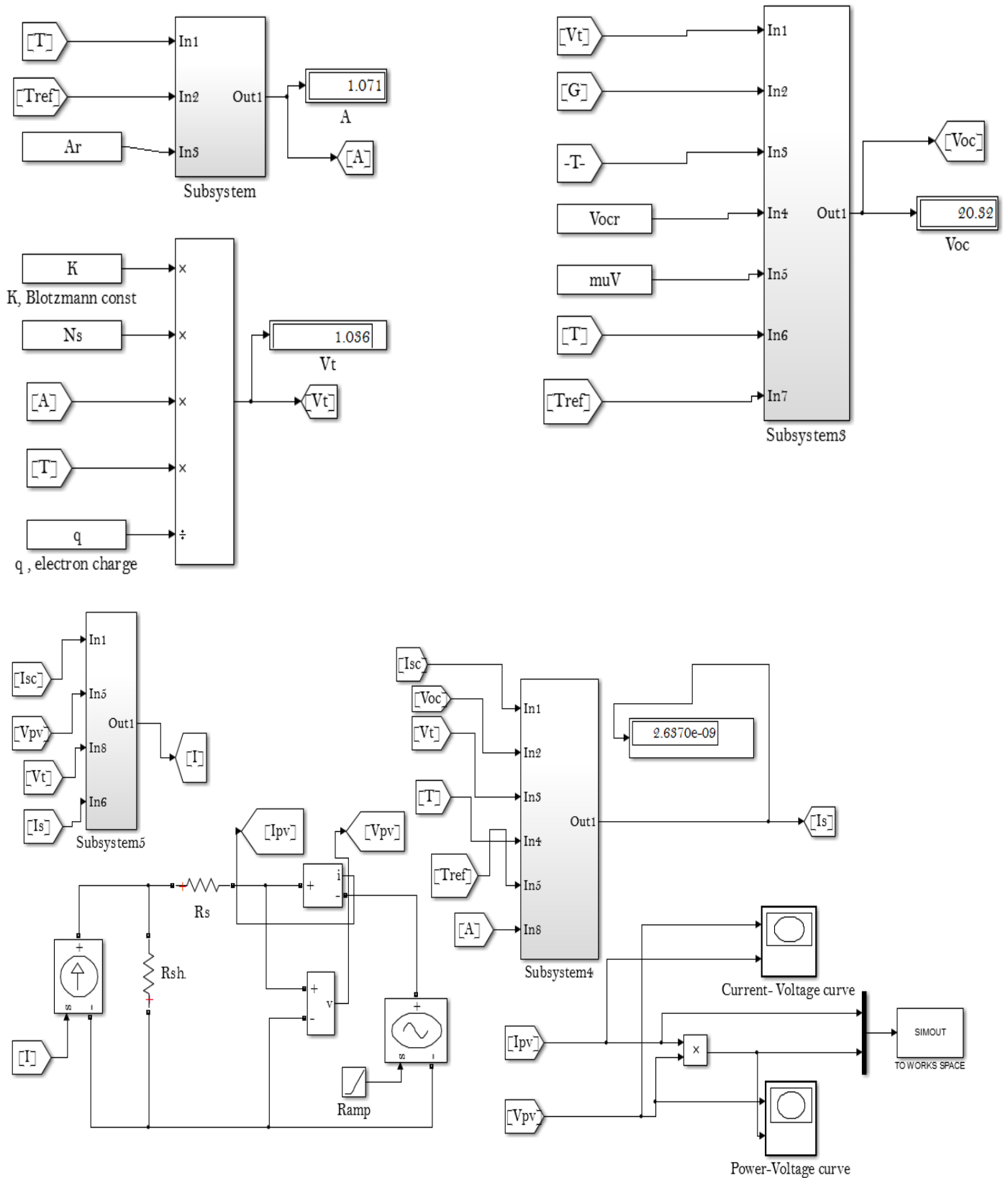


Figure 8. Simulink model for modeling module by five parameter model