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PV MODULE SINGLE–DIODE MODEL, PARAMETER EXTRACTION OF POLYCRYSTALLINE AND AMORPHOUS SOLAR PANEL

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ABSTRACT
Solar energy is a good option to replace the fossil driven energy market. Research is still ongoing to make solar technologies more efficient and affordable. Modeling is key in this area. Parameter extraction of PV modules enables easier simulation and accurate modeling of various PV cells/modules. The parameters are namely: (I) the photo generated current, I_{ph}, (II) the reverse saturation current, I_s, (III) ideality factor, n, (IV) the series resistance, R_s and (V) the shunt resistance, R_{sh}. This research work extracted the equivalent circuit parameters of polycrystalline and amorphous solar panels. An 11 V polycrystalline and 6 V amorphous solar panels were illuminated with a 500 W halogen lamp to generate I-V characteristics with the aid of a data capture device. A Matlab/Simulink model was modified using the single diode equation to model the two test solar panels. The Orthogonal Distance Regression (ODR) method from the origin lab was adopted to solve the nonlinear/transcendental equation of the solar cell/module with the single diode model to determine the parameters of a polycrystalline and amorphous solar panel. The results show a variation in the parameters of the two test solar panels. The polycrystalline indicates a higher R_{sh} and I_{ph} with low R_s and n values, which result to high efficiency. The amorphous panel shows higher n and R_s values, which makes it have low efficiency. The polycrystalline solar panel has smaller residual sum of square (RSS) which makes it a better retrieval while the amorphous solar panel has a higher residual sum of square (RSS), the ODR method for polycrystalline was more accurate than the amorphous solar panel as observed from the validation results of the two test panels.

Keywords: Single diode model, I-V characteristics, Matlab Simulink, Photovoltaic module, ODR.

INTRODUCTION
The world is faced with an energy crisis resulting from population growth and diminishing deposits of non- renewable energy resources including coal, natural gas, and fossil fuels. The usage of energy from non-renewable sources has led to increasing global warming, and damage to environment and ecosystem (Ansari et al, 2017). A sustainable source of energy without negative effects on the environment requires renewable energy sources development (Sabzpooshani and Mohammadi, 2014). Solar energy is a renewable source with a capacity to fulfill numerous energy needs of the world (Kachhiya et al., 2011). Solar energy can be used for electricity generation through solar photovoltaic (PV) effect. The PV panels convert sunlight directly into DC electricity. Manufacturers of solar cells or PV panels usually publish the current-voltage (I-V) curves at only a few operating conditions. However, a solar cell can be represented by a model, which is composed of a few electrical components (Carrero et al., 2007). Parameters for the model may be extracted from that limited information. Then the I-V relation at other operating conditions and/or operating loads can be estimated. There have been many studies on solar cell models (and parameter extraction) in recent years (Chin et al., 2015; Cotfas et al., 2013 and Humada et al., 2016), but only a few models are widely accepted. The single-diode model with relevant simple equations is suitable for most commercial PV panels, and almost as accurate as the double diode (two diodes in parallel) or the triple model (three diodes in parallel). Single diode model can be used to predict model parameters with special physical meaning and the relationship between the physical parameters and varying operating conditions (Zhang et al., 2017).
Several works have reported single diode models including a MATLAB Simulink script file program, which uses Newton Raphson's method to compute the five parameters of the single diode model of illuminated solar cells obtained by simulation. This shows consistency between the data and obtained parameters given by the manufacturer, short circuit current (Isc); open circuit voltage (Voc); and maximum power point (Pmpp). The parameters can be used for quality control during production or to provide insights into the operation of the devices, thereby leading to improvements in devices (Bonkoungou et al., 2013). Anani and Ibrahim (2020) reported the use of MATLAB-based software with reference values where the STC parameters and the parameter adjustment methods were deployed to calculate the modified parameters of the single diode model under various operating conditions of temperature and irradiance. Several authors have proposed different methods for extracting the parameters that describe the non-linear electrical model of solar cells (Khalis et al., 2011). El- Tayyan (2013), reported a simple method of modeling and simulation of PV systems to find the parameters (*Iph*, *Io*, R_s, R_{sh} and *n*) of the single diode model by adjusting the P-V curve and/or I-V curve at parameters provided by the manufacturer specification sheets (*Isc*, *Voc*, *Imp*, and *Vmp*). Estimation of the optimal parameters of PV modules using in-field outdoor measurements, manufacturers' datasheet and employing the nonlinear least squares fitting algorithm to determine the optimal parameter values of the implemented model which are series resistance, reverse saturation current, photocurrent, ideality factor and shunt resistance in case of the five parameters model was proposed by Elkholy and Abou (2019). In this work, we proposed a method for improved parameter extraction by constructing a data capture device to aid the characterization of the solar panel where I-V characteristics were obtained by connecting the solar panels across the varying resistance. The single diode model was used to model the behavior of the two solar panels using Matlab Simulink. The model was designed to allow input of different variables of the various parameters of the single diode model, temperature and

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irradiance level of the solar panels for better parameter extraction and the origin lab was used because it comes with orthogonal distance regression solver for implicit functions to determine the parameters of the test solar modules.

MATERIALS AND METHODS

To measure the I-V characteristics of the polycrystalline and amorphous solar panels, modification of the single diode model and for the method of parameter extraction used. The following materials, hardware (sensors) and software are used. The hardware includes Arduino nano development board, INA219 current and voltage sensor, MLX90614 contactless temperature sensor, TES 132 solar, power meter, Halogen lamp, 11V poly crystalline Test solar panel, 6V amorphous Test solar panel and Laptop. The software includes Microsoft Excel with Plx Daq Macro, Matlab Simulink 2019 and Origin Lab 2016.

The I-V characteristics values of the two test solar panels obtained from the data captured device were transferred to an excel spreadsheet through the serial port of Arduino microcontroller with the help of the PLX-Daq Microsoft excel macro. In this paper, MATLAB Simulink was used to modify and test the model of the polycrystalline and amorphous solar panels. Figure 1, shows the modified Simulink model of the solar panel which is used for parameter extraction. The single diode model equation 1, (Vengatesh and Rajan, 2011) was used to model the behavior of the test solar panels using predefined Simulink blocks, the parameters of the solar model are colored in blue.

$$I = I_{ph} - I_s \left[exp\left(\frac{q(V+IR_S)}{nk_B T_c} \right) - 1 \right] - \frac{V+IR_S}{R_{sh}} \text{ ....1}$$

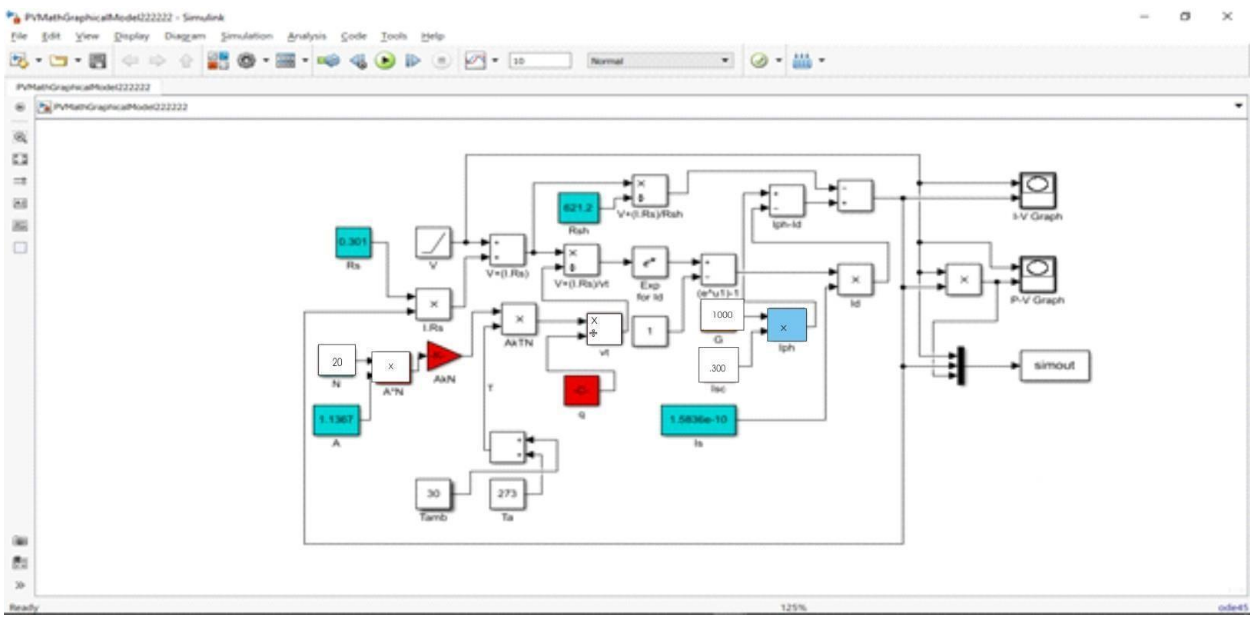

Figure 1. Simulink model of the solar panel

The I-V model was designed to allow input of different variables of the five parameters, which are the Iph, Is, n, Rs & Rsh, temperature and irradiance levels. This allows plotting the various I-V curves from the model. Equation 1, is an implicit nonlinear equation and has been solved by various methods including the Lambda (W) which transforms the implicit function into an explicit function. Others have used Newton Rapson method but the method used for estimation of the parameters in this work is the orthogonal distance regression (ODR) package from Origin Lab software. This requires a function of the model to be defined in a C++ form, the Simulink model is then verified and implemented as a function in the origin lab. These transformed the Simulink model into an origin Lab functional model where regression could now be carried out against the model and the recorded experimental values.
The model was validated for the two-test solar panels (polycrystalline and amorphous) with the aid of the Matlab Simulink. The obtained equivalent circuit parameters and the STC values of temperature and irradiance are simulated and certain values of current and voltage were obtained and the I-V curve plotted which were used to validate the two solar panels.

RESULTS AND DISCUSSION

The results of the PV module characteristics from the designed data capture device and the modified single diode model are shown in Figure 2, 3 & 4. The I-V characteristic curves for the polycrystalline and amorphous, Figure 2 and 3 respectively, are like the I-V characteristics derived from the Simulink model (Figure 4).

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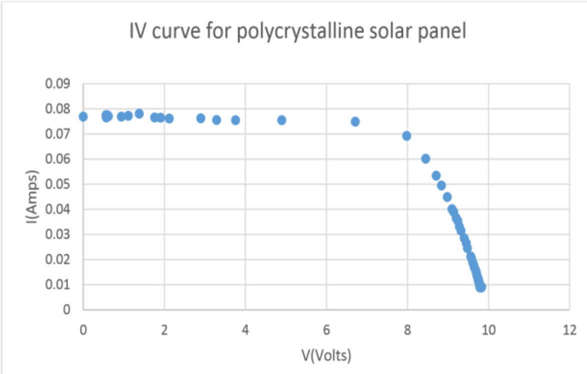

Figure 2. Polycrystalline solar panel at 480W/m^2.

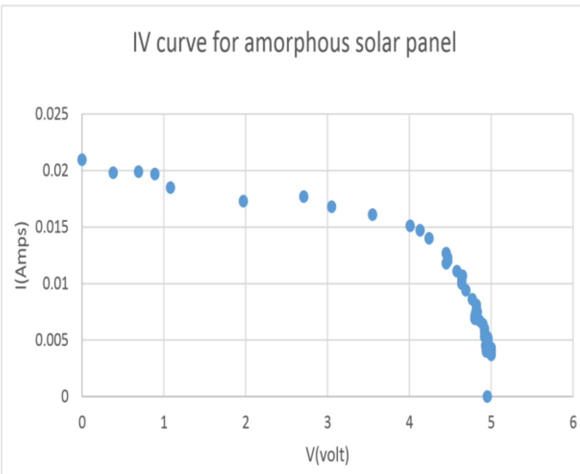

Figure 3. Amorphous solar panel at 300W/m^2

From Figure 2 & 3 we can say that the polycrystalline solar panel gave more data points due to the higher open circuit voltage which makes it have higher efficiency than the amorphous solar panel. The performance of a PV cell or module is generally determined by the current-voltage (*I–V*) characteristics, which provide a key performance parameter, open circuit voltage (*Voc)* and the value of efficiency is dependent on *Voc*, (Khan et al., 2010).
It was also observed that the shape of the curves formed by the test solar panels varies, while the polycrystalline solar panel closely resembles the ideal curve (Yan et al., 2017). The amorphous solar panel does least resemble the ideal curve. This can be due to differences in the parameters of the test solar panels.
The Simulink model that was designed, was simulated and certain values were obtained. To make a successful model, the values of the obtained parameters were initialized. The initial values for the parameter were taken to aid easy and quicker convergence. As shown in Table 1, some default values from the data sheet made modeling of the test solar panel possible. The I-V graph of the Simulink model is given in Figure 4. The model was designed in such a way to allow input of different variables of the various parameters of the single diode model, temperature and irradiance level of the solar panels, the Simulink model once verified, was implemented as a function in the origin lab for better parameter extraction.

Table 1. Initialized values for the design of the Simulink model

Voc (V)	11
Isc (A)	0.143
Pmax (W)	3.6
Vpm (V)	11.5
Ipm (A)	0.28

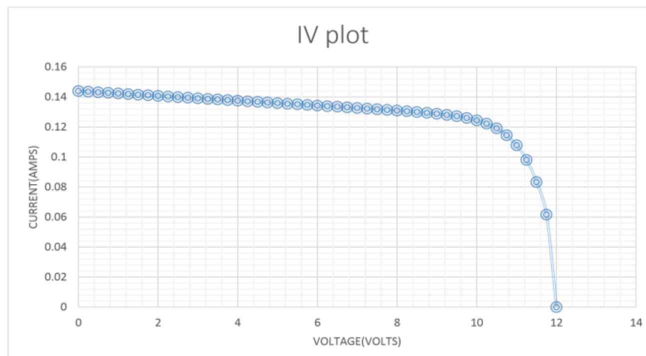

Figure 4. The I-V characteristics derived from the Simulink model

Parameter Extraction
For the regression process, the origin lab enables fitting of experiential values with this function by the ODR method mentioned earlier. One major setback of the ODR method is the initial estimate as to what appropriate initial values of the parameters to be determined must be made (Press et al, 2002). If the choice of the initial values is made properly, then the iteration process will be smooth and convergence achieved very fast. However, if the choice of the initial values is too distant from the real value, the algorithm will not converge (Can and Ickilli, 2014). Different initial values and range (lower and upper bounds) of the unknown parameters for the polycrystalline and amorphous solar panels were made. The range is not compulsory but it aids faster convergence.
The complete results are given in Table 2 and Table 3 for polycrystalline and Table 4 and Table 5 for amorphous solar panel. Figure 5 and 6 are the fitted curves for polycrystalline and amorphous solar panels, respectively.

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Table 2: Parameters for polycrystalline solar panel (480W/m^2)

Parameters

	Value	Standard Error	t-Value	Prob>|t|	Dependency
T	302	0	--	--	0
Is	1E-7	1.3747E-8	0.72743	0.46946	0.99999
Rs	1.00598	0.0695	3.62705	5.49522E-4	0.99016
n	1.31407	0.1591	9.89858	8.21565E-15	0.99999
Rsh	1985.90503	340.41111	5.83384	1.65533E-7	0.95309
Iph	8.07695	0	--	--	0

Table 3. Statistics of polycrystalline solar panel.

Statistics

	V,I
Number of Points	72
Degrees of Freedom	68
Reduced Chi-Sqr	9.69812E-7
Residual Sum of Squares	6.59472E-6
R-Square(COD)	1
Adj. R-Square	1
Fit Status	Succeeded (100)

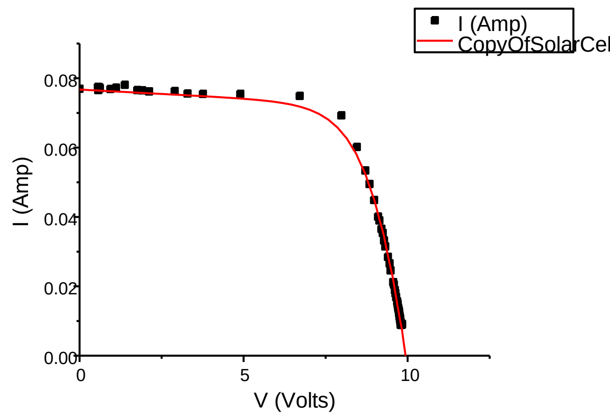

Figure 5. The fitted curve for polycrystalline solar panel

Table 4. Parameters for amorphous solar panel (300W/m^2)

Parameters

	Value	Standard Error	t-Value	Prob>|t|	Dependency
T	307	0	--	--	0
Is	1.40603E-9	1.95215E-10	0.51226	0.61004	0.99998
Rs	1.2491	0.90341	0.1503	0.88095	0.98877
n	1.932	0.21921	6.15699	3.79521E-8	0.99998
Rsh	780.8591	67.06722	11.64293	0	0.97844
Iph	6.02096	0	--	--	0

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Table 5. Statistics for the amorphous solar panel.

Statistics	
	V,I
Number of Points	76
Degrees of Freedom	72
Reduced Chi-Sqr	4.03377E-7
Residual Sum of Squares	2.90431E-5
R-Square(COD)	1
Adj. R-Square	1
Fit Status	Succeeded(100)

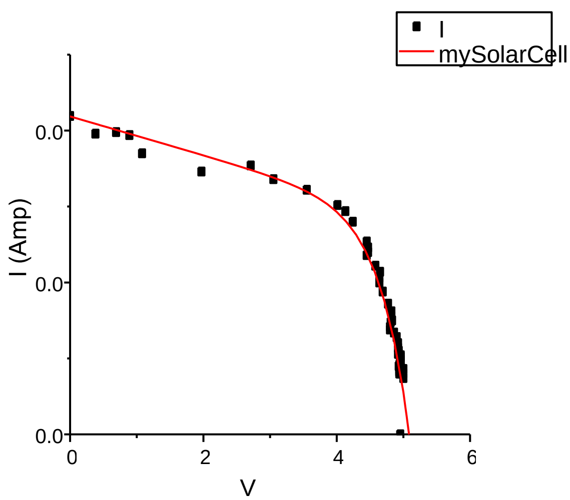

Figure 6. The fitted curve for amorphous solar panel.

As shown from the results of the regression obtained in Table 2 and Table 4, the parameter varies for the two solar panels. The amorphous solar panel has a considerably higher ideality factor (n) and series resistance (R_s) compared to the polycrystalline solar panel. Which results in a gentle slope of the I-V curve and lower efficiency of the amorphous solar panel. The polycrystalline solar panel has a higher shunt resistance(R_{sh}) and photo-generated current (I_{ph}) with lower series resistance (R_s) and ideality factor (n). This results in higher efficiency of the polycrystalline solar panel. The polycrystalline solar panel as presented in Table 3 has smaller residual sum of square (RSS) which makes it a better retrieval than the amorphous solar panel in Table 5. The RSS values are 6.59472E-6 and 2.90431E-5 for polycrystalline and amorphous solar panels respectively. The shape of the curves formed by the two solar panels after regression varies. Hence the difference in the parameters of the test solar panels.

Extracted Parameters Based On Different Approaches In Comparison With Method Employed In This Work

To measure the performance of the proposed method employed for parameter extraction, it is instructive to compare with various reported methods. Table 6 contains the extracted model parameters as reported by other different authors based on different approaches. It is observed that the approach used in this work yields a considerably accurate result compared with other optimizations, as it is observed that it has a high R_{sh} and I_{ph} with low R_s and n values for both the polycrystalline and amorphous solar panels which will result to a better efficiency (Khan et al., 2010).

Table 6. Extracted parameters by the current method and the previous work.

PV System	*Iph* (A)	*Is* (*μ*A)	*Rs* (Ω)	*Rsh* (kΩ)	*n*
Polycrystalline					
Previous work *a*	3.812	6.45E-7	0.2165	274.937	1.277
Previous work *b*	8.53831	1.5621E-6	0.16864	2029.069	1.5382
Previous work *c*	0.7609	0.1912E-7	0.0423	55.75	1.388
This work	8.07695	1E-7	1.00598	1985.90503	1.31407
Amorphous					
Previous work *d*	3.377	9.5 E-7	0.491	125.437	2.81
Previous work *e*	2.72079	1.0189E-6	1.28792	373.1949	1.7078
This work	6.02096	1.40603E-9	1.2491	780.8591	1.932

a See Ref. 12., *b* See Ref. 8., *c* See Ref. 19, *d* See Ref. 18., *e* See Ref. 8.

Validation Of The Model

Wherever a model is used to determine parameters, it is essential to validate such a model by comparing with experimental data. This is usually done at the Standard Test Condition (STC), which is at temperature of 25^{O}C and irradiance of 1000W/m^2. The obtained parameters from the regression and the STC values of temperature and irradiance are simulated and Figure 7 and Figure 8 below are the graphs obtained from Simulink for the validation of model for polycrystalline and amorphous solar panel respectively.

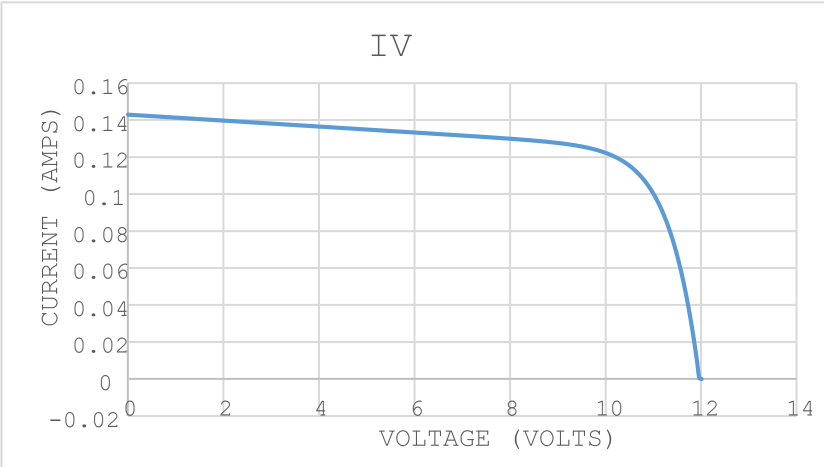

Figure 7. A graph of validated polycrystalline solar panel at 480W/m^2

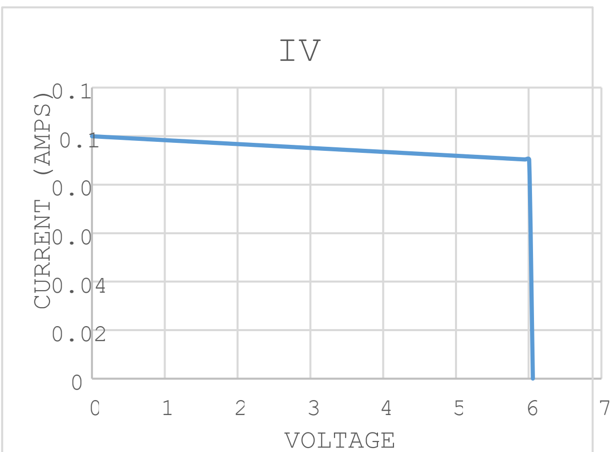

Figure 8. A graph of validated amorphous solar panel at 300W/m^2

The result of the validation (Figure 7 & Figure 8) shows that the ODR method for polycrystalline solar panel parameter extraction was more accurate than the amorphous solar panel as these can be seen when compared with the I-V curves obtained from experimental data (Figure 2 & 3) in which Fig. 2 & 7 considerably agree with each other than Fig. 3 & 8 which shows little agreement (Roberts et al., 2015). However, the model performed excellently well for the two solar panels.

Conclusion

This paper presents the practical measurement of I-V characteristics of PV module, a modified single - diode model with Matlab Simulink and the application of suitable nonlinear regression method for parameter extraction. A solar I-V data capture device was designed purposely for the characterization of solar panel. The logging process was carried out at different irradiances and temperature. The polycrystalline was logged at 820W/m^2, 480W/m^2 and 240W/m^2. It was observed that at an irradiance of 480W/m^2 a good curve was achieved while the amorphous solar panel was logged at 300W/m^2 and 124W/m^2, at an irradiance of 300W/m^2 a good I-V was achieved with temperature gain of not more than 2 degrees. The MATLAB Simulink model was used for the modeling of the solar panels with the aid of the single diode model which was implemented in the origin lab where the ODR from the origin Lab was used as the method of parameter extraction for the two solar panels. The results show the polycrystalline solar panel has a higher R_{sh} and I_{ph} with low R_s and n. This makes it has higher efficiency than the amorphous solar panel which has a considerably higher n and Rs. The polycrystalline solar panel has a smaller RSS which makes it a better retrieval than the amorphous solar panel. It is also found out that ODR method was more accurate for the polycrystalline solar panel than the amorphous.

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