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MODELING OF PHOTOVOLTAIC PANELS USING MATLAB/SIMULINK

MATLAB/SİMULİNK İLE FOTOVOLTAİK PANELLERİNİN MODELLENMESİ

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ÖZET

Bu yayındaki amaç bir fotovoltaik (PV) hücresinin 4 bilinmeyen parametre (I_{ph}, I_0, R_s, R_{sh}) kullanarak bir modelini oluşturmak ve bu modelin güneş ışınımı ve sıcaklık değişimlerine karşı davranışını hem simulasyon hemde deneysel ortamda göstermektir. PV hücresinin model parametrelerinin bulunmasında daha önce yapılmış çalışmalardan yararlanılmış, simulasyon çalışması ise Matlab/Simulink kullanılarak kendimizce geliştirilmiştir. Modelleme için hem seri hem de paralel dirençli ve tek diyotlu hücre biçimi seçilmiştir. Panel davranışının ışınım ve sıcaklıkla değişimi MATLAB / Simulink ile simüle edilmiş ve simulasyon sonuçları biri 10 W'lık ve 36 adet seri bağlı hücrelerden oluşan bir panel üzerinde diğeri ise 250 W'lık ve 60 adet seri bağlı hücreler içeren bir panel üzerinde test edilmiştir. Her iki panel içinde simulasyon ile elde edilen veriler panel üreticisi firmalar tarafından sağlanan datasheet'lerindeki verilerle karşılaştırılarak modellemelerin doğrulukları teyid edilmiştir. Ayrıca elde edilen modeller kullanılarak panellerin standart test koşulundan farklı sıcaklık ve ışınımlardaki I-V ve P-V eğrileri oluşturularak grafik olarak gösterilmiştir.

Anahtar Kelimeler: Fotovoltaik, radyasyon, sıcaklık, simulink.

ABSTRACT

The goal of this paper is to create a PV cell model using 4 unknown parameters (I_{ph}, I_0, R_s, R_{sh}) and show the behavior of this model against solar radiation and temperature changes in both simulation and experimental. Previous studies have been used to find the model parameters of the PV cell, while the simulation programs have been developed by us using Matlab / Simulink. The chosen model for a PV cell is the single diode model with both series and parallel resistors. Simulation results were tested on two PV panels. The first one is a 10W panel consisting of 36 series connected cells. While the other one is a 250W panel consisting of 60 series connected cells. The accuracy of models has been confirmed by comparing the data obtained by simulation for both panels with the data in datasheets provided by panel manufacturers. In addition to that, obtained models are used to generate the I-V and P-V curves graphically at temperatures and irradiances other than the standard test condition (STC).

Keywords: Photovoltaic, irradiance, temperature, simulink.

INTRODUCTION

Renewable resources, such as PV systems and wind turbines are being used in many places nowadays and their usage is expected to increase in the future. In particular, the PV panels are in use for over a decade and are proven to be reliable source of energy. They have relatively small installation budget and require minimum maintenance fees compared to those of similar other sources. Some other reasons behind their widespread usage are:

• PV panels are clean and nature friendly source of energy compared to petroleum and coil related energy sources and does not possess any danger in its use as in nuclear power.

• PV panels could practically be mounted anywhere so that power could be provided to even remote locations at no additional cost

• PV panel life exceeds over 20 to 30 years with manufacturer warranties.

There are many studies conducted on PV systems. We briefly summarize 3 of them below. İşler and Salihmuhsin (İşler Y. S., Salihmuhsin M., 2016) performed a study on several software tools and packages which are available commercially to be used for different purposes in the analysis of PV related systems. The available software packages are categorized under 4 broad categories. These are tools used for pre-feasibility analysis, tolls used for placement, sizing and scalability analysis, software used for simulation purposes and software packages that are called as open architecture. The open architecture software packages are used to perform all necessary analysis such modeling, simulation, cost analysis and sizing in one program. Several tools and software for each category were specified in their study along with brief information regarding their usage.

İşler (İşler Y. S., Yılmaz Ş., Salihmuhsin M., 2016) conducted another study on cost analysis of a 10 KWp fresnel parabolic type solar collector. The study was performed utilizing the weather data of city of Istanbul, Turkey. Modeling and cost analysis of the system was performed by CPV CAD software. They had shown that the modeled system would provide an annual income of 1720.3 $ per year and would return it's total investment cost back in 7.8 years.

Cubas (Cubas J., Pindado S., Victoria M.,2014) suggested simple and accurate method to model PV panels. Their method was based on analytical determination of 4 parameters, namely I_{ph}, I_0, R_s and R_{sh} of a PV cell. They had shown that their method could successfully generate a model for any given PV panel by obtaining models of several commercially available panels. The values of the cell parameters for each model are compared with the values of those found by other researchers for the same commercial panels. It's shown that cell models found by their algorithms are accurate for all cases. They also stated that the developed method would work under variations at different temperatures and irradiations.

In this study, a model of a PV cell consisting of one diode and two resistors is constructed. An analytical determination method of cell parameters is chosen to be implemented. The generated cell model is used to form a general I-V formulation for a panel containing both series and parallel cell connections. A program in Matlab/Simulink is developed to apply generated results to 2 different PV panels consists of series connected cells for experimental part of the study. For both panels, I-V and P-V curves are generated by Matlab/Simulink in order to be compared with similar curves in manufacturer datasheets.

CHARACTERISTIC OF A SOLAR CELL

PV cells are semiconductor devices which have input output characteristics similar to that of a diode. A cell can generate a voltage and current at its output when it's put under sunlight and could feed an electrical load. A PV cell can be made of several different materials. The most widely used ones are monocrystalline and multi-crystalline silicon, thin film etc.

An ideal PV cell is modeled as a current source connected with a diode in parallel. The current source represents the photocurrent generated by the cell when it is exposed to sunlight. The diode represents the pn junction of the solar cell. The ideal solar cell model is rarely used in practice due to several causes of power loses when the cell (or panel composed of cells) is put into practical use. In order to incorporate these loses into the cell model, a series resistance and a parallel resistance should be added to the cell model.

Series resistance R_s represents power loses due to factors such as resistivty of the p and n layer, metal contacts, current collecting busses and metal grid of the cell. The fill factor of the cell largely depends on R_s. The shunt resistance, R_{sh}, represents mainly non-idealities and non-accuracies due to cell fabrication. Some examples of these non-idealities are localized short currents at the emitter layer of the cell and along cell borders (Büyükgüzel, 2011). The effect of R_{sh} is large at low illumination and low operating voltage conditions (Cubas, 2014). The Figure 1 shows an equivalent circuit model of an ideal PV cell and which that contains both series and parallel resistances.
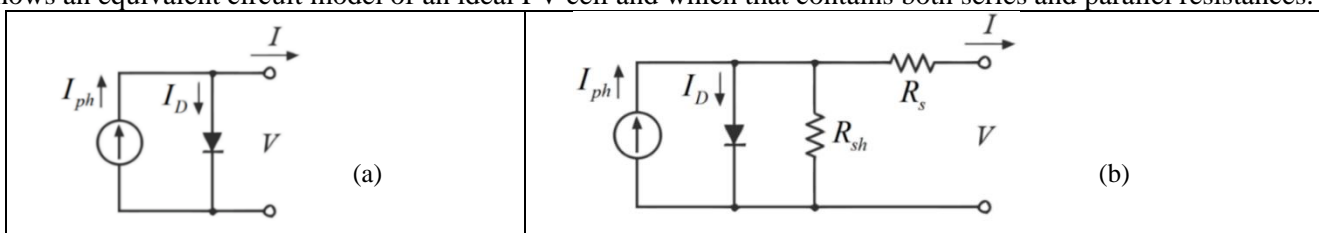

Figure 1. Different Circuit Models to Study the Behavior of Solar Cells, **(a)** 1-diode; **(b)** l-diode/2-resistors.

In panel datasheets, characteristics of a PV cell are generally described in terms of three operating points called open circuit condition, short circuit condition and maximum power point condition. When a cell is exposed to sunlight but it's terminals are not connected to a load, the voltage across cell terminals is called as Open Circuit Voltage V_{oc}. When a load is connected in between cell terminals, a current begins to flow through the load and the voltage across the cell begins to drop. The maximum current to pass through the cell can be obtained when the load is replaced with a short circuit. This current is named as Short Circuit Current I_{sc}. The third characteristic is described as the operating point where the power obtained from the cell is maximum. The current and the voltage values corresponding to this case are generally named as I_{mp} and V_{mp}.

MODELLING OF A PHOTOVOLTAIC PANEL

In general, the l-diode/2-resistors circuit is commonly used to study the behavior and features of a PV cell. In order to find relationship between electric current, I, and voltage V, the node equation for the top node of the circuit in the Figure 1(b) is written as:

$$I = I_{ph} - I_0 \left[exp\left(\frac{V + IR_s}{\alpha V_T}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where, I_{ph} : Photo current delivered by a constant current source.

$\quad\quad I_0$: Is the reverse saturation current of the diode.

$\quad\quad R_s$: Is the series resistance, R_{sh}: Is the shunt resistance.

$\quad\quad \alpha$: The ideality factor for the diode.

$\quad\quad V_T$: The thermal voltage of the diode that depends on temperature of the cell T in kelvin, the charge of an electron q, the Boltzmann constant k. $V_T = \frac{kT}{q}$

The model of the cell is obtained by determining 5 unknown parameters of the above equation, namely $I_{ph}, I_0, R_s \ and \ R_{sh}$. The value of the fifth unknown parameter α is closely related to the material type of the cell and could be chosen as an approximate constant accordingly. One way of determining unknown parameters is to utilize above mentioned 3 operating points of the cell.

Short Circuit Condition

The short circuit condition states that the current through short circuited terminals of the cell is I_{sc} which brings the voltage at the terminals to zero. By substituting these values into the equation 1, the equation 2 is obtained.

$$I_{sc} = I_{ph} - I_0 \left[exp\left(\frac{I_{sc}R_s}{\alpha V_T}\right) - 1 \right] - \frac{I_{sc}R_s}{R_{sh}} \tag{2}$$

Experimental studies show that at the short circuit condition, the value of the second term at the right hand side of the above equation is negligibly small compared to values of other two terms and consequently could be omitted (Cubas, 2014). As a result, the equation is put into the form as:

$$I_{ph} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} \ , Rsh >> Rs \ so \ Iph$$
$$\cong \ Isc \tag{3}$$

Open Circuit Condition

The operation point for this case is $(I, V) = (0, V_{oc})$. Substituting this into equation 1 results in:

$$0 = I_{ph} - I_0 \left[exp\left(\frac{V_{oc}}{\alpha V_T}\right) - 1 \right] - \frac{V_{oc}}{R_{sh}} \tag{4}$$

It is again shown by experimental studies that the -1 in the second term at the right hand side of the above equation can be neglected. After substituting the expression found for I_{ph} into the equation (15), the following expression for I_0 is obtained.

$$I_0 = \frac{GI_{sc,T_r} - \frac{V_{oc}}{R_{sh}}}{G_{ref} exp\left(\frac{V_{oc}}{\alpha V_T}\right)} \tag{5}$$

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Maximum Power Point Condition

The operation point for this case is $(I, V) = (I_{mp}, V_{mp})$. Substituting it into equation 1 gives:

$$I_{mp} = I_{ph} - I_0 \left[exp\left(\frac{V_{mp} + I_{mp}R_s}{\alpha V_T} \right) - 1 \right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{6}$$

Again similar approach as mentioned above allows us to neglect the -1 in the second term of the right hand side. By substituting values of I_{ph} and I_0 into the equation (6), the equation (7) is obtained.

$$I_{sc} - \left(I_{sc} - \frac{V_{oc} - R_s I_{sc}}{R_{sh}} \right) \left[exp\left(\frac{V_{mp} + I_{mp}R_s - V_{oc}}{\alpha V_T} \right) \right] - \frac{V_{mp} + I_{mp}R_s - R_s I_{sc}}{R_{sh}} = I_{mp} \tag{7}$$

However, one more equation is needed to solve equations containin 4 unknowns. Cubas et al. suggested that by examining derivativae of power equation $P = V * I$ and applying several stages of mathematical manipulations, one could get an explicit expression for R_{sh} and implicit expression for R_s. Combined with equations (2) and (3), four unknown parameters of the cell model could now be determined. Formulations suggested by Cubas for R_{sh} and R_s are given below.

$$\frac{\alpha V_T V_{mp}(2I_{mp} - I_{sc})}{\left(V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc}) \right)\left(V_{mp} - I_{mp}R_s \right) - \alpha V_T(V_{mp}I_{sc} - V_{oc}I_{mp})} = \left[exp\left(\frac{V_{mp} + I_{mp}R_s - V_{oc}}{\alpha V_T} \right) \right] \tag{8}$$

$$R_{sh} = \frac{(V_{mp} - I_{mp}R_s)(V_{mp} - R_s(I_{sc} - I_{mp}) - \alpha V_T)}{(V_{mp} - I_{mp}R_s)(I_{sc} - I_{mp}) - \alpha V_T I_{mp}} \tag{9}$$

PV panels are made of interconnecting PV cells. When modeling a panel, the equation 1 needs to be modified according to series and/or parallel placement of individual cells in the panel. Certain type of PV panels consists of only series combination of cells. For such panels, the equation 1 is modified as below in order to obtain input/output relationship of the panel where N_s represents number of cells connected in series.

$$I = I_{ph} - I_0 \left[exp\left(\frac{V + IN_s R_s}{\alpha N_s V_T} \right) - 1 \right] - \frac{V + IN_s R_s}{N_s R_{sh}} \tag{10}$$

Another type of PV panels consists of both series and parallel combination of cells as shown in the figure 2. A typical placement of cells for these type of panels is given below where N_s represents number of cells in series for each vertical array of cells and N_p represents number of vertical arrays.
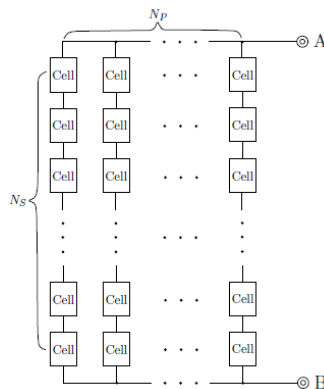

Figure 2. Physical Configiration of Series and Parallel Cells in a PV Module.

In This case, the I-V relationship of the panel is obtained by modifying the equation 1 in the following manner.

$$I = N_p I_{ph} - N_p I_0 \left[exp\left(\frac{V + I\frac{N_s}{N_p}R_s}{\alpha N_s V_T} \right) - 1 \right] - \frac{V + I\frac{N_s}{N_p}R_s}{\frac{N_s}{N_p}R_{sh}} \tag{11}$$

The Effects of Solar Irradiance and Temperature

Environmental conditions, such as temperature and irradiation variations effect the behavior of solar cells. Both current and voltage at the output of cell are decreased with increase in the temperature. The equations that describe changes in the open circuit voltage and the short circuit current of the cell are given below. Changes in the maximum power point voltage and current are described with the same corresponding equations. More information on this subject could be obtained from (Cubas , 2014).

$$V_{oc,T} = V_{oc,T_r}\left(1 + \frac{\beta V_{oc}(T - T_r)}{100}\right) \tag{12}$$

$$I_{sc,T} = I_{sc,T_r}\left(1 + \frac{\alpha I_{sc}(T - T_r)}{100}\right) \tag{13}$$

where, $V_{oc,T_r}, V_{oc,T}$: are respectively the open circuit voltage at $25^o C$ and input temperature.

βV_{oc}: The percentage variation of the open circuit voltages when the temperature increases one degree.

T_r, T : are respectively the temperature at STC and input temperature.

$I_{sc,T_r}, I_{sc,T}$: are respectively the short circuit current at $25^o C$ and input temperature.

αI_{sc} : The percentage variation of the short circuit current when the temperature increases one degree.

Change in the photo current of the cell I_{ph} in the case of illumination and temperature variations is described in the following equation:

$$I_{ph} = I_{ph.ref}\left(\frac{G}{G_{ref}}\right) \tag{14}$$

In the above equation, $I_{ph.ref}$ is the photo current at STC which is $I_{ph.ref} \cong I_{sc,T_r}$. Subsitution of this into the equation (14) results in:

$$I_{ph} = I_{sc,T_r}\left(\frac{G}{G_{ref}}\right) \tag{15}$$

where, I_{ph} : the photocurrent delivered by the current source of the equivalent circuit.

G_{ref}, G : are respectively the reference value of the irradiance and the irradiance on the cell/solar panel.

The Effects of Ideality factor

Changing the temperature of a PV cell is one of the most important factors affecting the ideality factor α while this factor does not depend on radiation. The ideality factor value may be arbitrarily selected at a given temperature of a PV cell. The correct estimate value of this factor have been discussed in many methods by many researchers and authors (C. Carrero, 2007; G. Walker, 2001). Usually, $1 \leq \alpha \leq 1.5$ for silicon PV cells and other parameters of the I-V model help determine the correct value of this factor (M. G. Villalva , 2009).

Basing on the empirical analysis, some values of α are found in (W. De Soto, 2006). The curvature of the I-V curve Affected by changing the value of α, while the value of the I_{sc} (short circuit current) remains unchanged. Because α Specifies the amount of ideality of the diode and it is totally experimental, any initial value of α can be chosen in order to adjust the model at a given manufacturer's data. In order to improve the model fitting to the experimental values the value of ideality factor α must be readjusted.

Table 1: Idelaity Factor (α) (Huan-Liang Tsai., 2008).

Technology	Ideality factor
Si-mono	1.2
Si-poly	1.3
a-Si-H	1.8
a-Si-H Tandem	3.3
a-Si-H triple	5
cdTe	1.5
CTs	1.5
AsGa	1.3

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SIMULATION RESULTS

Experimental part of this study is conducted by developing a Matlab/Simulink program in order to calculate 4 unknown parameters of a cell model described in the section 2. The cell model is then used to construct the model of the related PV panel. The developed program is a general purpose program and could be used to generate cell model for any given PV panel. The program consists of several sub modules. The Figure 3 shows a picture of the top module (the main sub system) of the program.
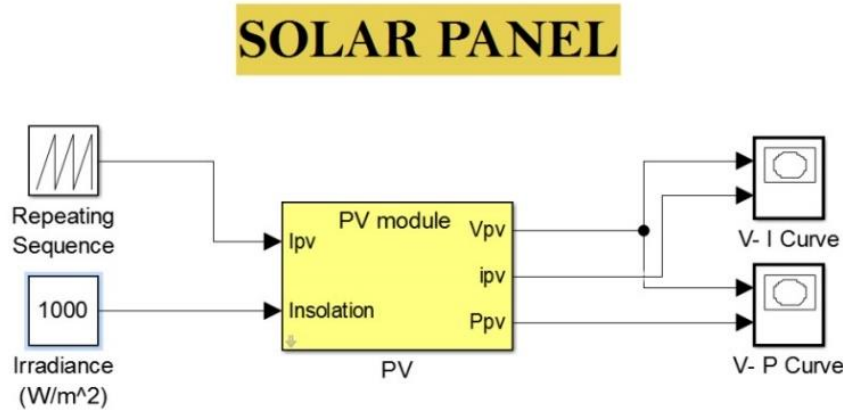
Figure 3. The Front Page of the Developed Simulink Program.

When clicked on the PV Module sub system, a mask shows up on the screen. The user has to input necessary information related to the panel using manufacturer datasheets such as values of V_{oc}, I_{sc}, V_{mp} etc. Once all values are entered, the program calculates values of 4 unknown parameters I_{ph}, I_0, R_s and R_{sh} and displays on the screen. The obtained parameter values are put into equation (10) to get I-V relationship of the panel. Upon appropriate manipulation of the I-V equation, I-V and P-V curves of the panel for desired illumination and temperature conditions are constructed. The Figure 4 shows a snapshot of the mask for the PV module sub system and a picture of the PV Module sub system from the developed program.
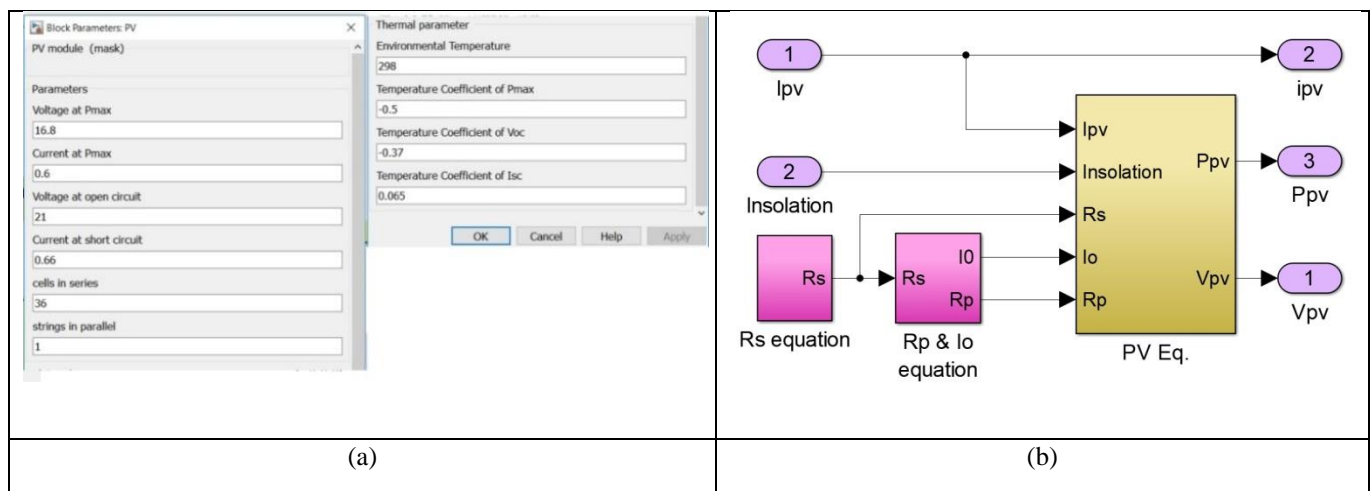

(a)	(b)

Figure 4. (a) A Snapshot of the Mask. **(b)** a Picture of PV Module Subsystem.

In order to verify theoretical formulations given in the section 2 and 3, two actual panels are used to perform experiments. For each panel, the cell model, I-V characteristics and P-V characteristics are obtained by the developed program and compared with the corresponding curves and values provided by the manufacturers for the standard test condition.

The first panel used for verification purpose is TPS-105 Mono crystalline solar panel. It is a 10W panel which has 36 individual cells connected in series. The second PV panel is CWT250-60P 250W poly-crystalline PV panel. It has 60 individual cells connected in series. For both panels, some important specifications from manufacturer datasheets are given in the Table 2.

Table 2: Specifications of PV Panels

Parameters of Module	TPS-105 Mono-crystalline solar panel specifications	CWT250-60P poly-crystalline solar panel specifications
Maximum Power (Pmax)	10.0 W	250.0 W
Open Circuit Voltage (Voc)	21.0 V	36.3 V
Short Circuit Current (Isc)	0.66 A	8.71 A
Maximum Power Voltage (Vmp)	16.8 V	30.6 V
Maximum Power Current (Imp)	0.60 A	8.17 A
Cells in series	36	60
Temperature Coefficient of Pmax	-0.5%	-0.5%
Temperature Coefficient of Voc	-0.37%	-0.35%
Temperature Coefficient of Isc	0.065%	0.060%

The Figure 5(a) gives I-V and P-V curves of the TPS-105 Mono crystalline solar panel generated by the developed program at standard test conditions (STC). The Figure 5(b) shows the corresponding I-V curve provided by the manufacturer in the datasheet. As seen from figures, the program successfully models the panel and generates I-V curve as close approximate to that provided by the manufacturer. The Figure 6(a) and 6(b) display I-V and P-V curves of the TPS-105 Mono crystalline solar panel generated by the developed program for various illumination and temperature conditions. These curves are not provided in the manufacturer datasheet.
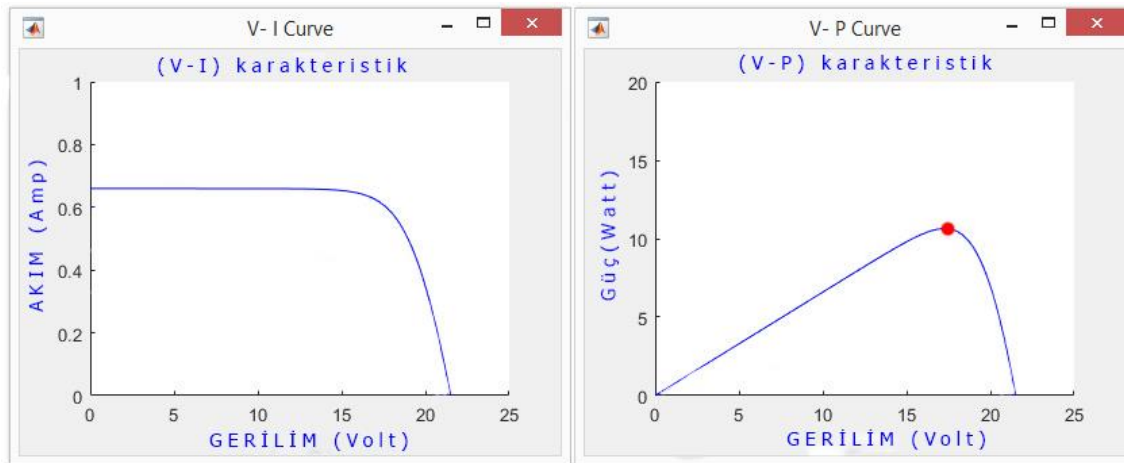

Figure 5. (a): I-V Curve and P-V Curve of the TPS-105 Mono Crystalline Solar Panel Generated by the Developed Program at STC.
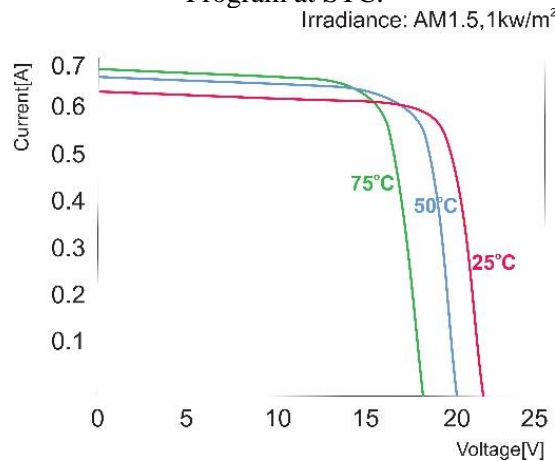

Figure 5(b): I-V Curves of the TPS-105 Mono Crystalline Solar Panel Provided by the Manufacturer.
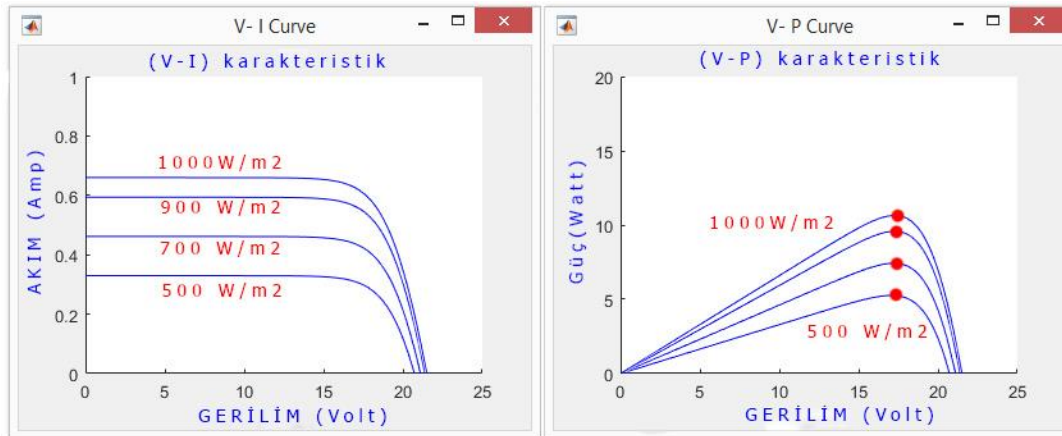
Figure 6(a): I-V Curve and P-V Curve of the TPS-105 Mono Crystalline Solar Panel Generated by the Developed Program for Different Levels of Solar Irradiances.
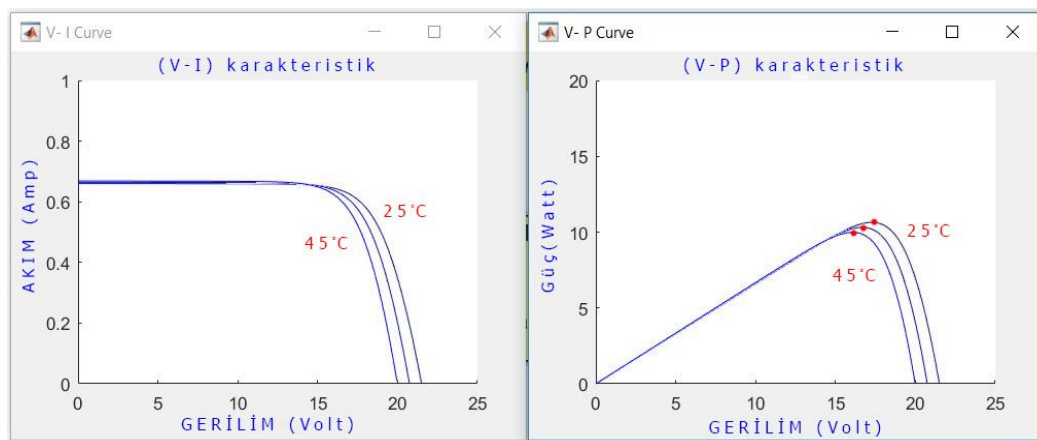

Figure 6(b): I-V Curve and P-V Curve of the TPS-105 Mono Crystalline Solar Panel Generated by the Developed Program for Different Values of Temperatures.

Similarly for 250 W CWT250-60P poly crystalline solar panel, the Figure 7(a) shows I-V and P-V curves obtained by the developed program at STC and the Figure 7(b) shows the corresponding curves given by the manufacturer in the datasheet. Again, it is seen that calculations obtained from simulations closely represent corresponding curves in the datasheet. The Figure 8(a) and 8(b) display I-V and P-V curves of the CWT250-60P poly crystalline solar panel generated by our program for various illumination and temperature conditions. These curves again are not provided in the manufacturer datasheet.
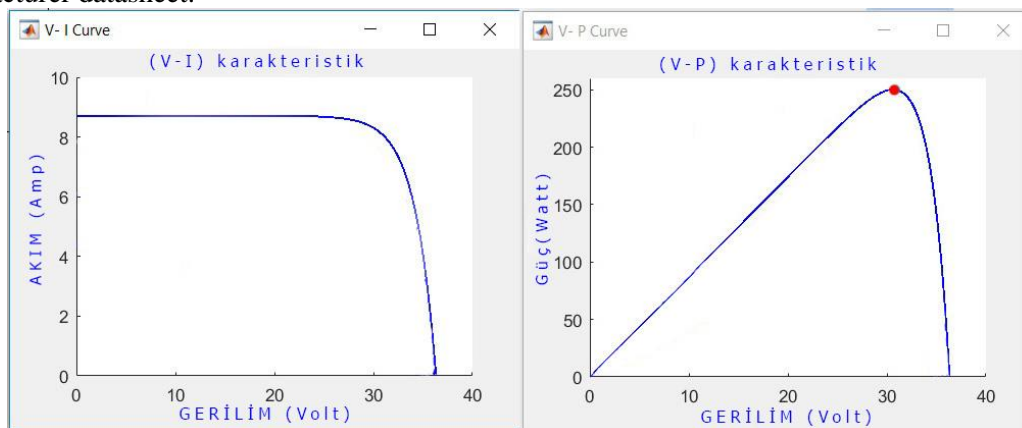

Figure 7(a): I-V Curve and P-V Curve of the CWT250-60P Poly Crystalline Solar Panel Generated by the Developed Program at STC.

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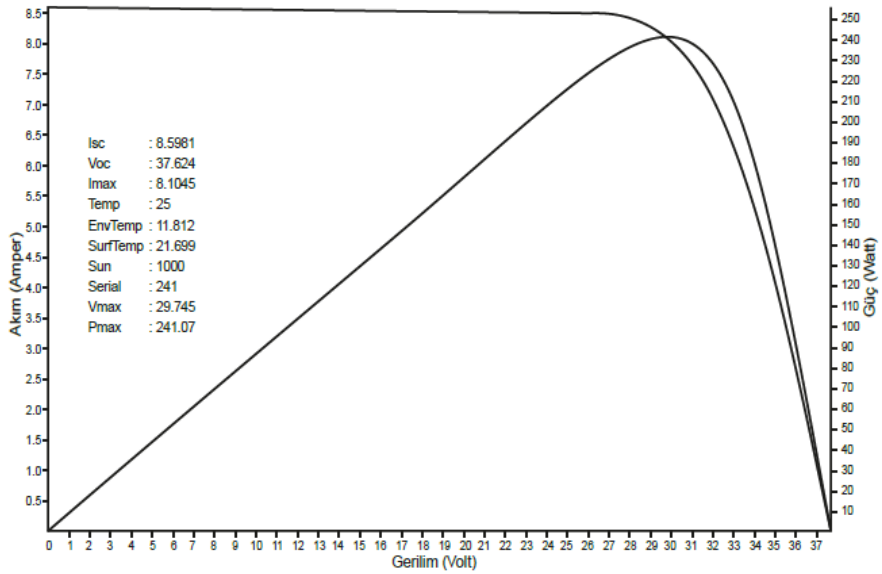*B. A. Aldwıhı, M. Salihmuhsin*

Figure 7(b): I-V Curve and P-V Curve of the CWT250-60P Poly Crystalline Solar Panel Provided by the Manufacturer in the Datasheet at STC.
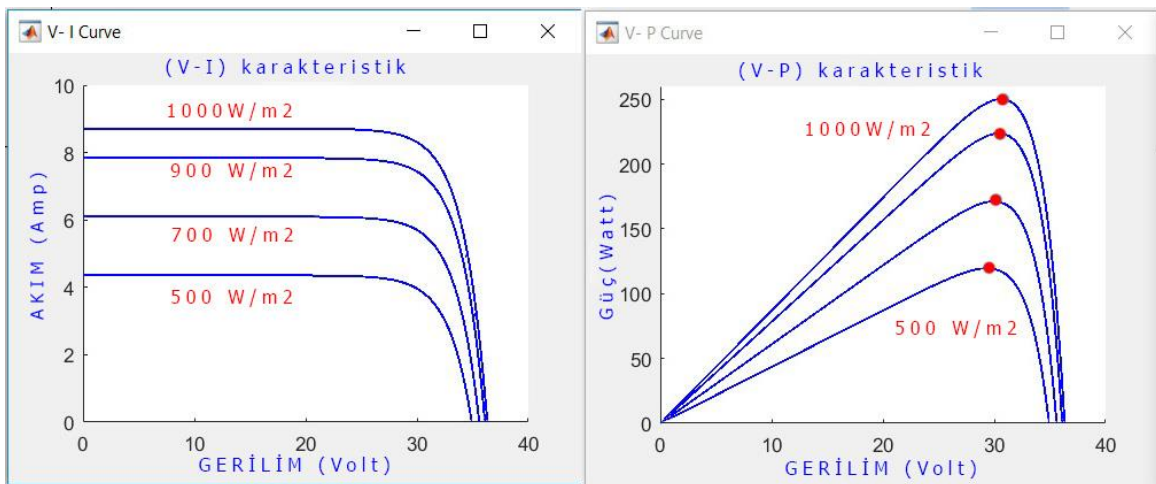

Figure 8(a): I-V Curve and P-V Curve of the CWT250-60P Poly Crystalline Solar Panel Generated by the Developed Program for Diffferent Levels of Solar Irradiances.
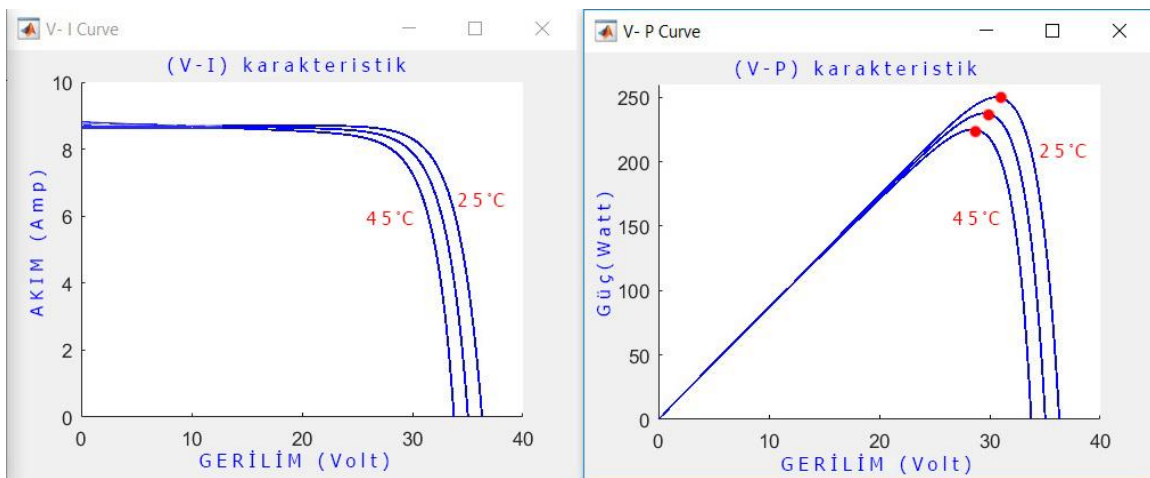

Figure 8(b): I-V Curve and P-V Curve of the CWT250-60P Poly Crystalline Solar Panel Generated by the Developed Program for Various Temprature Values.

CONCLUSIONS

In this study, a cell model consisting of 4 unknown parameters is presented. A Matlab/Simulink program that implements the obtained equations for the cell model is developed. In order to present accuracy of the parameter calculation and success of the developed program, two actual PV panels are used to perform an experimental study. Simulation results showed that the developed Matlab/Simulink program successfully obtained panel model for the PV panels used in experiments and generated related I-V and P-V curves for any desired illumination and temperature condition.

REFERENCES

Büyükgüzel B. (2011). Microcontroller Based Maximum Power Point Tracker for Solar Panels, M. Sc. Thesis, Çukurova University, Institute of Natural and Applied Sciences, Department of Electrical and Electronics Engineering.

Cubas J., Pindado S., Victoria M. (2014). On the Analytical Approach for Modeling Photovoltaic Systems Behavior, Journal of Power Sources, Vol 247, pg 467–474.

İşler Y. S., Salihmuhsin M. (2016).Yenilenebilir Enerji Kaynakları İçin Yazılım Araçlarının Sınıflandırılması, International Conference on Natural Science and Engineering (ICNASE'16), sy 2419-2426, Mart 19-20 Kilis, Türkiye.

İşler Y. S., Yılmaz Ş., Salihmuhsin M. (2016).İstanbul Şartlarında 10 kWp Optimum verimli Fresnel Parabolik Oluk Tipi Güneş Kolektörü tasarımı ve Maliyet Analizi, International Conference on Renewable Energy Technologies and Applications (RETA'16), sy 1-9, Mart 5-6 İstanbul, Türkiye.

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