



Development software program for finding photovoltaic cell open-circuit voltage and fill factor based on the photovoltaic cell one-diode equivalent circuit model

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Abstract

The photovoltaic (PV) cell is the smallest building block of the PV solar system and produces voltages between 0.5 and 0.7 V. It acts as a current source in the equivalent circuit. The amount of radiation hitting the cell determines how much current it produces. The equivalent circuit of an ideal PV cell consists of a diode and a parallel current source. In order to express losses in applications, series and parallel resistance are added to the ideal equivalent circuit of the PV cell. There are many equivalent circuits in the literature for modeling the equivalent circuit of a PV cell. The single-diode equivalent circuit is the most widely used model because of its simplicity and ease of analysis. There are several methods available to estimate and analyze the parameters of PV cell models, such as Newton Raphson method, Lambert-W function, etc. In this study, the Newton Raphson method was used to find the equivalent circuit parameters of a PV cell. Fill factor is used to determine the quality of electricity generated by the photovoltaic cell. Open-circuit voltage is the maximum voltage value that the PV cell can transmit. The analysis of PV cell fill factor and open-circuit voltage was carried out using the developed software program. Then, the open-circuit voltage and fill factor were found using the software program prepared in MATLAB and given in Appendix.

Keywords PV cell fill factor · PV cell open-circuit voltage · Software program · Five unknown parameters · I–V characteristics of PV cell · PV cell equivalent circuit models · Five unknown parameters

1 Introduction

Today, the use of renewable energy sources is becoming more and more widespread. The use of these resources as an alternative to fossil fuel thermal power plants in energy production is becoming increasingly common. The use of photovoltaic (PV) facilities is increasing day by day due to the decrease in the cost of establishment and the abundance of resources [1–3]. These advantages make the use of PV solar energy an attractive alternative among other renewable energy sources.

It emits twice as much carbon dioxide as thermal power plants. Thus, the carbon dioxide released when coal is burned. The effects of emissions on ecosystems, for example, global warming and climate changes, are significant. For a cleaner atmosphere and sustainability of human life, the use of fossil fuels should be discontinued and replaced with renewable clean energy sources. Maintenance of solar power plants is much easier than other power plants as well as being more cost effective. Operating costs are also low. Therefore, it is important to analyze the PV cell and determine the equivalent circuit parameters [2]. In the dark environment, the I–V characteristic of the PV cell is quite similar to the diode characteristic [4]. When the PV cell is exposed to light, the current is provided by the movement of electrons as a result of the support provided by photons.

PV cells act as a current source that varies according to the amount of irradiation. In the dark, the PV cell does not produce energy and acts like a diode. High ambient temperature reduces the efficiency of PV cells [5, 6], whereas solar radiation change affects the frequency distortions and the energy

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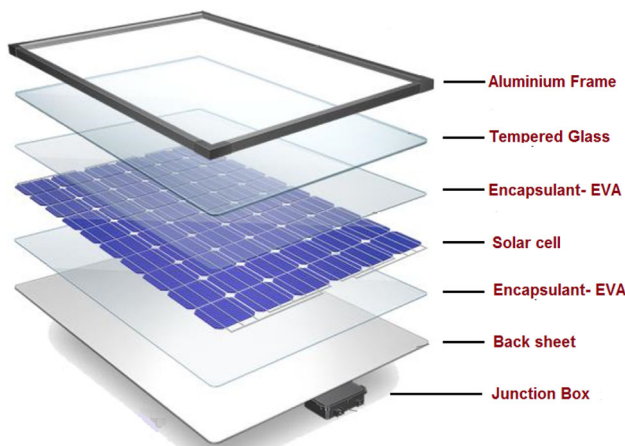


Fig. 1 Structure of the photovoltaic module

produced by the PV. Therefore, the variation of radiation and temperature affects the performance of the solar system. The current flowing by the diode in the dark is denoted as I_d in the equivalent circuit. Factors such as irradiation, temperature and slope angle affect the efficiency of the PV module. It should be ensured that the PV module works with the best efficiency under all conditions (Fig. 1).

In grid-connected systems, systems that provide 24 Volts with 72 cells are the most preferred. The front side of these panels is covered with tempered glass, and the back surface is covered with protective and water-resistant material. Although many models have been developed for PV cell equivalent circuits, the single-diode model is the most frequently used equivalent circuit model in the literature for solar cells.

Depletion of fossil fuels, causing environmental pollution and being unsustainable lead us to renewable energy sources, which are safe and unlimited resources. Solar energy is one of the most significant renewable resources. A photovoltaic module is formed as a result of connecting many cells in a series, parallel with each other and converts solar energy into direct current electrical energy. Their installation is extremely simple and their efficiency has increased considerably over the years.

PV cells are made of silicon-type semiconductor materials. Since power electronics-based devices are made of semiconductor elements, THD₁ is produced [7, 8]. A current with a harmonic component injected from power electronic devices causes the devices in the solar system to malfunction. These materials have a nonlinear character. This distorts the waveform of the current and voltage, which is sinusoidal. As a result, harmonic components are formed in the solar system. In [9], the filling factors for DSSC solar cell at different Irradiations were investigated. PV cells are made of semiconductor materials that convert sunlight energy into electrical

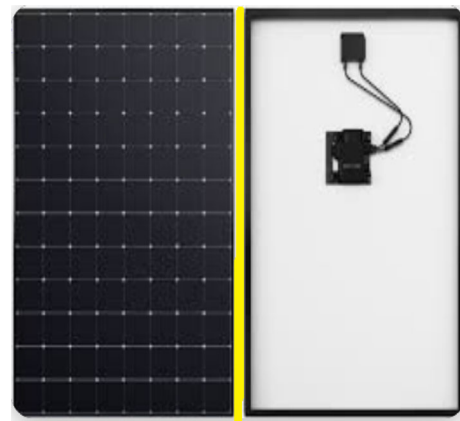


Fig. 2 PV module with 72 cells and bypass diode

energy. Due to the semiconductor materials in the PV cells structure, the I–V change of the PV cells is nonlinear.

In [10, 11], the efficiency and structure of polycrystalline silicon solar cell were examined, while in [12] the performance of monocrystalline PV module under different climatic conditions was investigated. The raw material of PV cells is silicon produced from ocean sands. Therefore, there is no problem in the supply of this resource. In [13], the modeling and analysis of series-connected photovoltaic cells is studied. A PV cell produces a voltage between 0.5 and 0.8 V, depending on temperature and radiation. However, this voltage level is quite low. To achieve high voltage levels, PV cells are connected in series with each other during the design process. The principle diagram of connecting 72 PV cells in series is displayed in Fig. 2.

The basic building block of the photovoltaic system is the solar cell. However, due to their low output power, solar cells are connected in series to form a photovoltaic module. The five unknown parameters in a PV cell single-diode equivalent circuit are listed; I_{ph} is the current produced by the PV cell; I_0 is the diode reverse saturation current; R_{sh} is the parallel leakage current resistance; R_s is the internal resistance in the solar cell and n is the diode ideality factor.

In order to define the I–V characteristic curve of the PV cell, it is necessary to find out the equivalent circuit parameters I_0 and n [14–16]. Efficiency losses due to environmental factors in the place where the panels will be installed should be determined. Thus, the most suitable location and direction should be selected and the PV panel should be operated with the highest efficiency and profitability. The data sheet of photovoltaic panels contain information about current and voltage values, short-circuit current, open-circuit voltage. However, these values are given for standard conditions. These values cannot be obtained when deviating from standard conditions [15–17]. After determining the equivalent circuit parameters of the PV cell, it becomes quite simple to find the open-circuit voltage and fill factor of the PV cell. In

addition, the PV cell equivalent circuit parameters are used to determine the output current, voltage and losses of the PV module [18, 19].

2 Mathematical modeling of the photovoltaic module

The working principle of the PV cell is the same as that of the pn junction diodes. A pn junction diode is formed when a p-type semiconductor is joined to an n-type semiconductor. The output I–V characteristic curve of PV cells in the dark environment is very similar to the characteristic curve of the diode.

The efficiency of solar cells varies depending on parameters such as the internal resistance of the cells, the material from which they are produced, contact structures, light intensity and temperature change. For this reason, an equivalent model for solar cells should be created to achieve correct results in the analyses to be made for solar cells. The single-diode equivalent model of the PV cell consists of the photocurrent produced by the PV cell, a series, parallel resistor and diode [20, 21].

The crystal structures of monocrystalline photovoltaic cells are regular. Therefore, it is difficult to produce and costly. In polycrystalline photovoltaic cells, very small defects in the crystal structure cause the efficiency of this type of cells to decrease slightly. However, the ease of production and lower cost compared to monocrystalline photovoltaic cells lead to an increase in the tendency toward this type of cells in designs. The R_s value in a monocrystalline PV cell is less than the R_s value in a polycrystalline PV cell. On the other hand, n and I_0 parameters are greater than the polycrystalline PV cell values. The wind energy destroys the PV panels' stability.

Due to the diode current in the PV cell equivalent circuit, the circuit has nonlinear characteristics. This causes additional losses in the PV cell. The PV solar system is very sensitive to radiation intensity and temperature change. The change in solar irradiation and temperature affects some parameters in the PV cell equivalent circuit, and, as a result, the PV module characteristic also changes. The equivalent circuit model of the PV cell is shown in Fig. 3.

In [22, 23], the circuit parameters of the PV cell were found using the Grey Wolf Optimizer and Robust Metaheuristic Algorithm, while in [24] they were found using the Salp Swarm algorithm. Parameter values in the PV cell equivalent circuit model depend on radiation and temperature. The series resistance (R_s) in the equivalent circuit is a significant parameter that affects the performance of a PV cell.

In [25, 26], the application of the Trust Region Method and the swarm optimization algorithm are used to find the PV cell equivalent circuit parameters. In [27], open-circuit

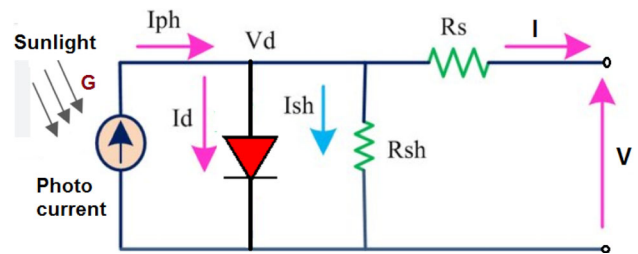


Fig. 3 PV cell single-diode equivalent circuit model

voltage, short-circuit current and fill factor of PV cell were investigated. In [28], the Jaya algorithm was used for estimation of PV cell equivalent circuit parameters. The increase in the short-circuit current density of the PV cell also causes an increase in the resistance loss. Power losses from a shunt resistor result from manufacturing defects [30].

The effect of the shunt resistor is severe at low light levels due to less light current being produced. In addition, the effect of parallel resistance denotes high at low-voltage values where the resistance of the solar cell is high [29–31]. R_s in the equivalent circuit of the PV cell is too small, whereas if R_{sh} is too large, the cell's efficiency is also high. Parallel resistance (R_{sh}), which expresses the leakage currents in the PV cell, is one of the significant parameters that affects the performance of the PV cell [32–34]. To understand and analyze the electrical behavior of a PV solar cell, an electrically equivalent circuit must be built [33]. The differential equations found as a result of the analysis in the equivalent circuit of the PV cell are as follows:

$$I_{ph} - I_d - I_{sh} = 0 \tag{1}$$

The diode current can be expressed as:

$$I_d = I_0 \left[\exp \left(\frac{q(V + IR_s)}{mkT_r N_s} \right) - 1 \right] \tag{2}$$

Resistance of parallel current is defined in Eq. (3).

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{3}$$

PV cell shunt current simulink block diagram is as given below.

The load current of the PV cell is as given in Eq. (4) (Fig. 4).

$$I = I_{ph} - I_0 \left[\exp \left(\frac{q(V + IR_s)}{mkT_r N_s} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{4}$$

where I_0 is the reverse saturation diode current, Eq is the band gap energy of the semiconductor material, T_{ref} is the nominal reference temperature and V_t is the thermal voltage.

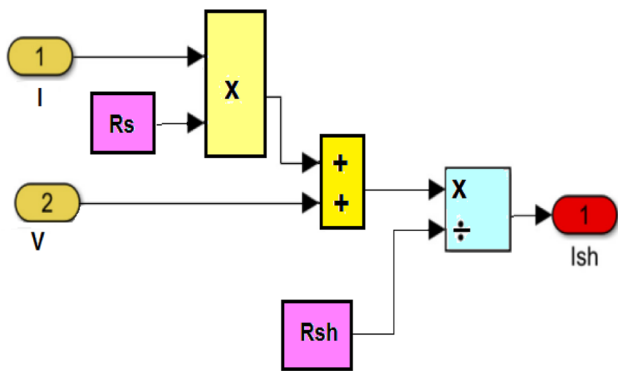


Fig. 4 Simulink block diagram of PV cell shunt current

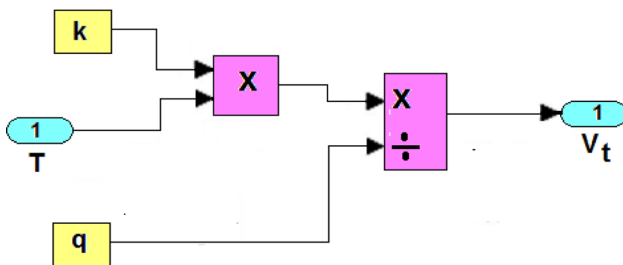


Fig. 5 Simulink model of PV cell thermal voltage

This factor varies according to the type of material used in the manufacture of solar cells. Its value varies between 1.2 and 6. N_s is the number of PV cells connected within a series, R_s is the value of the series internal resistance, R_{sh} is the resistance of parallel leakage currents, I_0 is the reverse saturation current of the diode [34, 35]. The short-circuit current of the PV cell is found using the formula given below:

$$I_{sc} = I_{ph} - I_0 \left[\exp\left(\frac{I_{sc} R_s}{N_s V_t}\right) - 1 \right] - \frac{I_{sc} R_s}{R_{sh}} \quad (5)$$

V_t is defined thermal voltage and given in Eq. 6.

$$V_t = \frac{nkT}{q} \quad (6)$$

where k denotes the Boltzmann constant (J/K), T cell is the hot value of the pn junction in Kelvin and q is the fundamental electron charge (coulomb). The simulink model of the thermal voltage which depends on the cell temperature is as given in Fig. 5.

In order to calculate the performance of a photovoltaic module at a given irradiance and temperature, the current–voltage (I–V) curve of the module must be known. The maximum current of PV cell can be expressed as given in

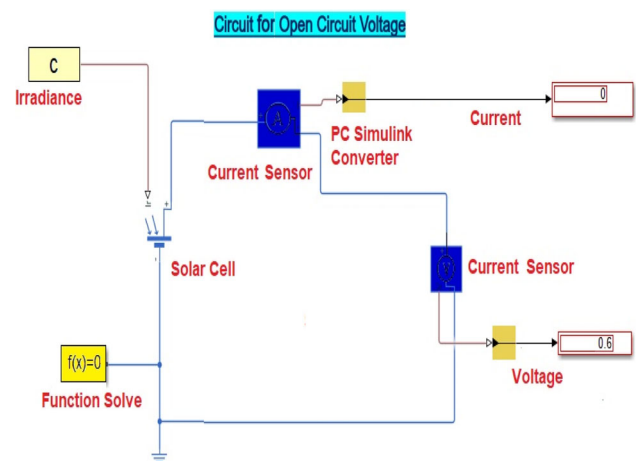


Fig. 6 PV solar cell open-circuit voltage

Eq. (7):

$$I_{mp} = I_{ph} - I_0 \left[\exp\left(\frac{V_{mp} + I_{mp} R_s}{N_s V_t}\right) - 1 \right] - \frac{V_{mp} + I_{mp} R_s}{R_{sh}} \quad (7)$$

The open-circuit voltage of PV cell can be expressed using Eq. (4), (at $I = 0$) as:

$$V_{oc} = \frac{nkT}{q} \text{Ln} \left(\frac{I_{ph}}{I_0} + 1 \right) \quad (8)$$

From the analysis of Eq. (8), it is observed that V_{OC} increases linearly with temperature. The band gap of the material is directly proportional to the open-circuit voltage of the cell. That is, a large band gap is required to achieve a high open-circuit voltage (Fig. 6).

The open-circuit voltage of the PV cell is the maximum voltage that can be obtained from the solar cell. This condition occurs at zero current. The open-circuit voltage changes directly with temperature. The short-circuit current and the open-circuit voltage are the maximum current and voltage rating of a PV Cell, respectively. However, the power transferred from the solar cell is zero at both operating points [36, 37]. The effect of temperature has different effects on complex cell parameters and varies according to PV cell technology. The open-circuit voltage decreases with temperature. As the temperature changes, the I_0 saturation current changes linearly.

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (9)$$

where V_{oc} denotes the open-circuit voltage, I_{sc} is the short-circuit current, FF is fill factor, η is efficiency, and P_{in} is provided to the PV cell. In order to calculate the performance of the PV cell at a given radiation and cell temperature [38,

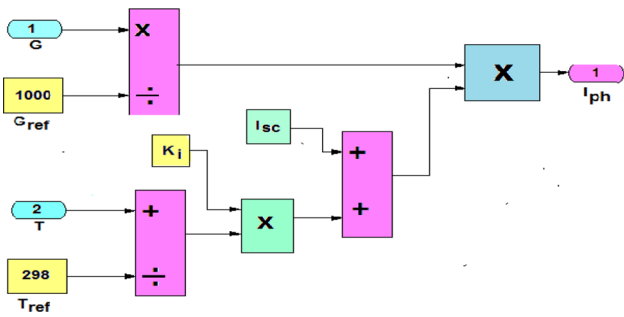


Fig. 7 Photocurrent of PV cell simulink model

39], it is necessary to know the characteristic of the I–V curve of the solar cell. The I–V and PV characteristic curves of the PV cell are plotted using the PV cell equivalent circuit parameters. The photocurrent produced by the PV cell is as given in Eq. (10).

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})] \frac{G}{G_{ref}} \quad (10)$$

PV cell photocurrent simulink block diagram is as given below (Fig. 7).

Ki coefficient is a coefficient used to determine the variation of radiation with temperature. This coefficient takes a different value for each PV cell and is determined in the laboratory environment [40]. The diode saturation current can be determined using Eq. (11).

$$I_0 = I_{0ref} \left(\frac{T}{T_{nom}} \right)^3 \exp \left[\frac{E_g}{V_t} \left(\frac{1}{T_{nom}} - 1 \right) \right] \quad (11)$$

The reference value of the diode current saturation current is given in Eq. (12).

$$I_{0ref} = \frac{I_{sc}(T_{nom})}{\exp\left(\frac{qV_{oc}(T_{nom})}{nkT}\right) - 1} \quad (12)$$

where $I_{sc}(Tr)$ denotes the short-circuit current of the cell at rated temperature, E_g is the band gap voltage, $V_{oc}(Tr)$ is the open-circuit voltage of the PV cell at rated temperature.

The PV cell saturation current simulink block diagram is as given below (Fig. 8).

Equation (12) is used to determine the open-circuit voltage as long as the voltage is lower than the band gap (Fig. 9).

where I_0 is the reverse saturation diode current, E_g is the band gap energy of the semiconductor material, T_{ref} is the nominal reference temperature and V_t is the thermal voltage.

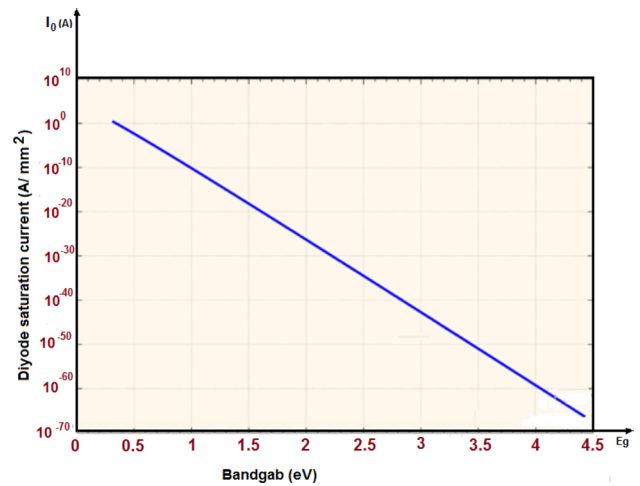


Fig. 8 Variation of the diode saturation current depending on the band gap

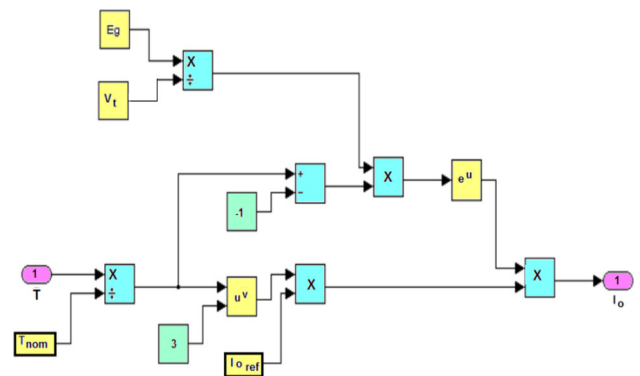


Fig. 9 Simulink model of the reverse saturation diode current

2.1 Analysis of I–V and PV characteristic of photovoltaic module

In general, faults in PV strings can be grouped according to their time characteristics as permanent, initial and intermittent. I–V curve testing is recommended to be performed to detect malfunctions such as cell defects (Fig. 10).

Photovoltaic performance of a photovoltaic module: It is determined by parameters such as maximum output power (PM), short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), efficiency (η) and filling factor (FF). In order to find the photovoltaic performance at any irradiance value, the current–voltage (I–V) curve of the module must be known. The current output of PV module is:

$$I = N_p I_{ph} - N_p I_0 \left[\exp \left(\frac{q \left(\frac{V}{N_s} + \frac{I R_s}{R_{sh}} \right)}{nkT} \right) - 1 \right] - \frac{\frac{V N_p}{N_s} + I R_s}{R_{sh}} \quad (13)$$

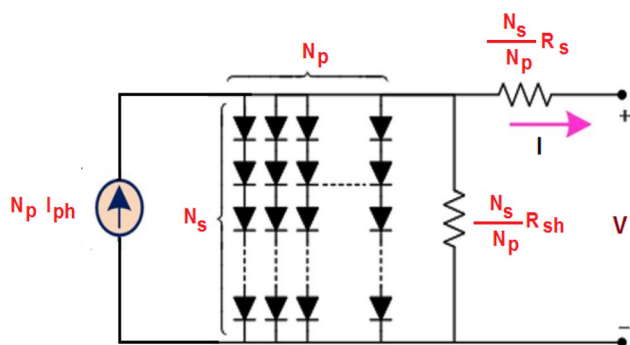


Fig.10 Equivalent circuit of solar PV module

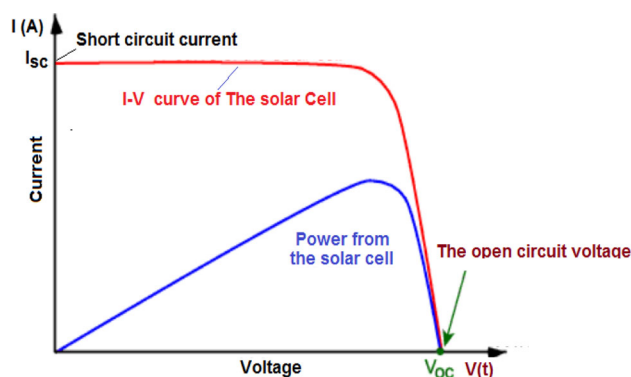


Fig. 12 The I–V and PV curves of the PV cell

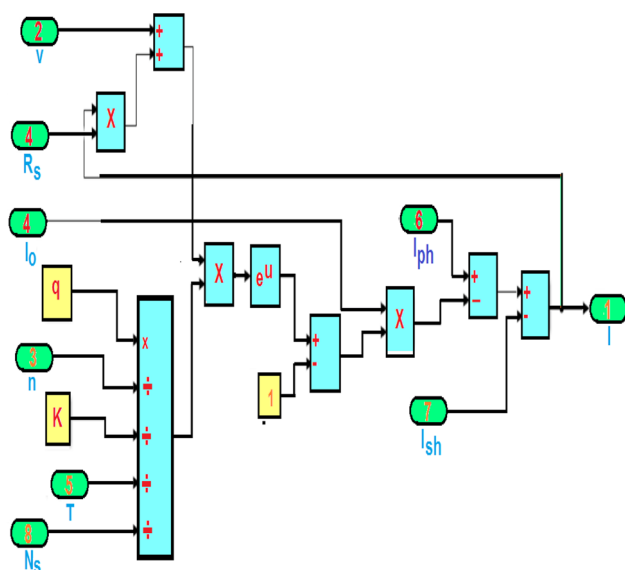


Fig.11 PV output current mode

where I_{ph} denotes the photocurrent, I_0 is the saturation current of the reciprocal diode, q is the electron charge, k is the Boltzmann constant, T is the junction temperature, m is the ideality factor. R_s and R_{sh} are the series and shunt resistors of the PV cell (Fig. 11).

The voltage output of PV module is:

$$V = \frac{N_s n k T}{q} \ln \left[\exp \left(\frac{I_{ph} + I_0 - I + N_p}{I_0 N_p} \right) \right] - \frac{N_s R_s I}{N_p} = 0 \tag{14}$$

where V denotes the voltage across the diode, N_s , number of PV cells connected in series, N_p , number of PV cells connected in parallel and N_s and N_p represent series and parallel resistors. Factors such as ambient temperature, amount of radiation, clouding of the air and partial shading negatively impact both the output power and the efficiency of the PV system. The PV cell I–V and PV characteristic curves are as shown in Fig. 4.

The total DC energy produced from the PV module and the total irradiation values that come to the panel surface are affected by adverse weather conditions. It has been observed that the performance of PV modules decrease in the case of overheating. It has been seen in the experiments that the performance of PV modules decreases by 1% for every 10 °C increase in temperature. In this study, photovoltaic cell equivalent circuit parameters and fill factor were found using the software program given in Appendix. After finding the equivalent circuit parameters of the PV cell, the PV module V–I and V–P characteristic curves were obtained. The open-circuit voltage (V_{oc}) of a photovoltaic (PV) cell is the voltage measured at the cell end terminals when the current running through the cell is zero (Fig. 12).

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The surfaces of PV cells are square, rectangular or circular. Their thickness is between 0.2 cm and 0.4 cm and they each have a square area of 25 cm² and 30 cm². Depending on the PV cell structure, they convert solar energy into electrical energy with an efficiency between 5% and 20%. Since they are used in modeling and analysis of PV systems, it is very important to find equivalent circuit parameters of PV cells. The surfaces of PV cells are square, rectangular or circular. Their thickness is between 0.2 and 0.4 cm, and they each

have a square area of 25–30 cm². Depending on the PV cell structure, they convert solar energy into electrical energy with an efficiency between 5 and 20%. Since they are used in modeling and analysis of PV systems, it is very important to find equivalent circuit parameters of PV cells.

The electrical characteristic of a PV cell is generally represented by the current–voltage (I–V) curve. This curve depends on radiation, temperature and other external environment variables. Single- and double-diode equivalent circuit models are used in the equivalent circuits of PV cells. In practice, the dual-diode equivalent circuit model yields better results in shading and low radiation. However, the single-diode equivalent circuit model is still the most widely used due to its simplicity and ease of calculation. In this study, a single-diode equivalent circuit model is used to find the equivalent circuit parameters and fill factor. Simulink is used for analysis and modeling of linear and nonlinear systems. As a result, the demand for prototypes is reduced.

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Modeling can be performed in continuous time, discrete time, or a combination of both. PV modules are formed by connecting solar cells in series with each other. Sequences are obtained when modules come together in a series. In this study, modeling the PV cell, obtaining the I–V and PV characteristic curves and finding the necessary equivalent circuit parameters is essential in order to conduct analysis. The I–V characteristic curve of the PV cell is as given in Fig. 13.

The output characteristics of the I–V and PV curves of the PV cell depend on weather conditions. Since weather conditions are constantly changing, the I–V and PV characteristic curves also change. Electrical parameters of the PV cell, such as fill factor and efficiency, are determined using the I–V characteristic curve.

The fill factor parameter of the PV cell is a parameter that indicates the solar cell quality. Sunpower SPR-X20-250-BLK module was used to find PV cell equivalent circuit parameters. The change in the I–V curve of this PV module is nonlinear. The I–V characteristic of the Sunpower SPR-X20-250-BLK module is given in Fig. 14.

The diode identity factor n , parallel resistor R_{sh} , series resistor R_s , diode reverse saturation current I_0 and photocurrent I_{ph} parameter values, which are not included in the PV panel manufacturer catalog data, were found using the Newton–Raphson numerical method. This method has many superior features when compared to other methods. It is simple to use and requires less computation time for the solution. The software program for this method is given in Appendix of the article. In this study, five points are determined on the I–V characteristic curve of the PV module. The differential equations of the PV cell were found using Eq. (4).

3 Extracting PV solar cell model parameters using I–V characteristics

The electrical characteristic of a PV cell is usually represented by a current–voltage (I–V) curve. This curve varies depending on the irradiation, temperature and outdoor environment variables. In this study, the Newton–Raphson method, which has many advantages, is used to find the equivalent circuit parameters of the PV cell. In this method, the diode current, which is a nonlinear circuit element, is linearized at each iteration step.

The maximum power point tracker (MPPT) method is used to attain maximum power depending on variable external environmental conditions. In the on-grid network, the amount of electricity production is extremely low when the air is closed or the production is low. In this case, the electricity need is met by transferring electricity from the grid to the load. In order to find the current and voltage values of the PV module, the equivalent circuit parameters of the PV cell must be known. Five points were determined on the I–V characteristic curve of the PV module. The diode current in the equivalent circuit of the PV cell has nonlinear characteristics. Therefore, the equivalent circuit also has nonlinear characteristics. For this reason, the Newton–Raphson iterative method was used in the solution of nonlinear equations. This method quickly detects unknown parameter values. The main features of the PV module (Sunpower SPR-X20-250-BLK) are shown in Table 1.

In this study, photovoltaic cell equivalent, it will be seen that the response time is quite short. In this study, photovoltaic cell equivalent circuit parameters were found using the Newton Rhapsion method.

Shading and dusting of PV cells greatly reduces the output power. Therefore, it is necessary to remove objects such as leaves that may fall on the PV cell surface and to clean the cell surface. Objects falling on the PV surface not only cause PV cell power reduction, but also damage other cells. The data values of the Sunpower SPR-X20-250-BLK module were used to find the equivalent circuit parameters of the PV cell. In practice, the I–V characteristic curve of this module is

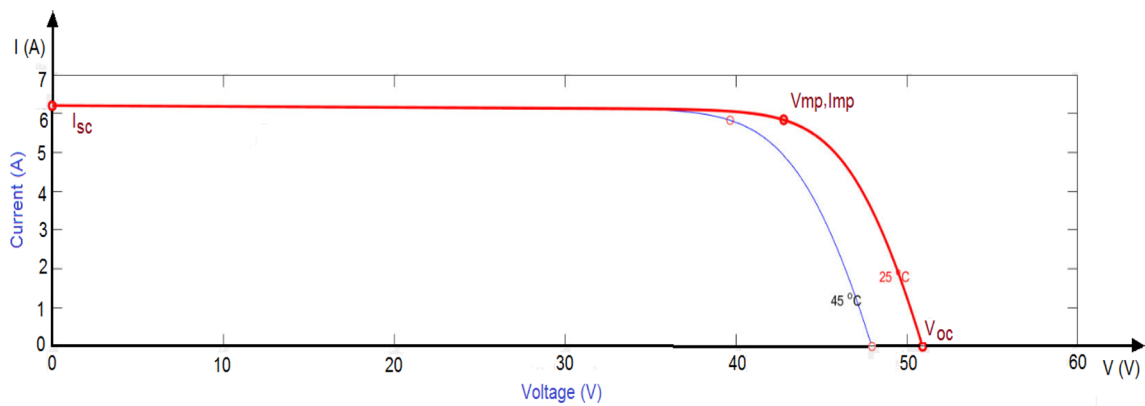


Fig. 13 I–V curve of the SPR-X20-250-BLK PV module

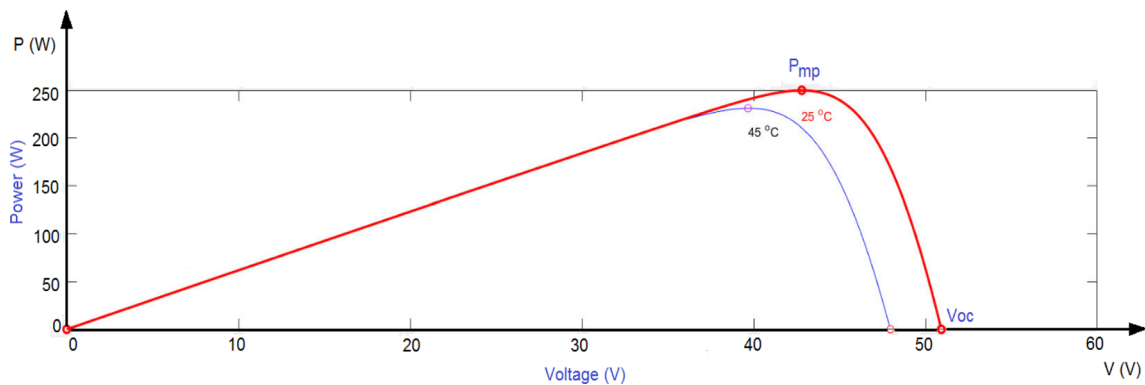


Fig. 14 PV curve of the SPR-X20-250-BLK module

Table 1 Electrical characteristics data the Sunpower SPR-X20-250-BLK module

PV module	The Sunpower SPR-X20-250-BLK (at 1000W/m ² , 25 °C)
Short-circuit current (Isc)	6.2A
Open-circuit voltage (Voc)	50.9 V
Maximum current (Imp)	5.84A
Maximum voltage (Vmp)	42.8 V
Temperature coefficient of short circuit (Isc)	0.06%/K
Peak efficiency of PV module	20.1%
Temperature coefficient of open circuit (Voc)	− 0,127 V/K
Temperature coefficient of power (P)	− 0.3%/K
Number of cells connected in series (Ns)	72
Power rating at STC	250W
Power tolerances	0%/ + 2%
NOCT	45 °C
Power per unit of area (STC)	201.0W/m ²
Maximum system voltage	600 V

nonlinear. Five points required in the solution of differential equations are selected on the I–V curve. The I–V characteristic of the Sunpower SPR-X20-250-BLK PV module is as given in Fig. 15.

Analytical methods are iterative approaches used to estimate equivalent circuit parameters. The most important feature of these methods is that they make quick calculations and find results with minimal errors. In this study, equivalent circuit parameters were found by the Newton Raphson method. The Newton Raphson Method is referred to as one of the most commonly used techniques for finding the roots of given equations. PV cell equivalent circuit parameters were found after 19 iterations with an error of 6.8824e-8.

There are a lot of methods available to estimate and analyze the parameters of PV cell models, such as Newton Raphson method, Lambert-W function, etc. Raphson method, Lambert-W function Raphson method, Lambert-W function Newton Raphson method methods and Lambert-W function are both used to analyze existing literature data, and the results show that these methods not only extract all PV parameters accurately but are also suitable for different types of solar cells. In this paper, we used the Newton Raphson method with MATLAB/Simulink software by excellent programming one of these methods that has not been tried

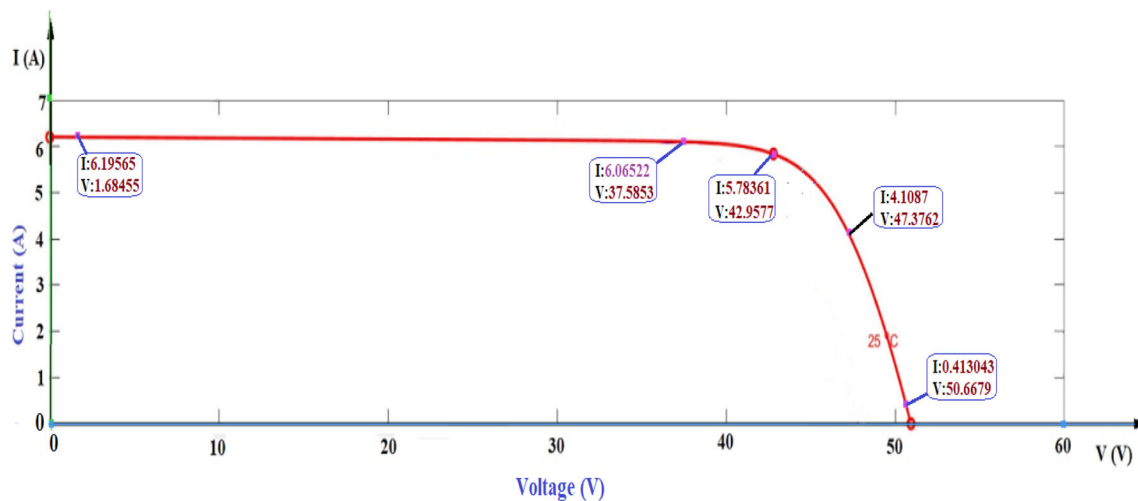


Fig. 15 I–V curves of the PV module (the Sunpower SPR-X20-250-BLK)

before. However, in order to obtain a better result, we compared the performances of this two methods.

Lambert-W function method represents the PV model explicitly, and Newton Raphson method solves the implicit structure of the PV model by iteratively determining the output current. Lambert-W function and Newton Raphson method are classified as indirect approaches to estimating PV parameters and the results obtained showed the same accuracy and reliability when compared. Considering the comparison between Newton Raphson method and Lambert-W function showed very competitive performance in PV parameter estimation, with only slight differences in computational costs.

Silicon, which is abundant in nature, is generally used as the raw material in the production of photovoltaic cells. These cells are called by different names according to their production methods. First generation photovoltaic cells High purity silicon crystals are used as raw material in this type of photovoltaic cells. They are divided into two main groups: monocrystalline and polycrystalline photovoltaic cells. It is a production that requires advanced technology. Their efficiency is higher and their lifespan is longer than cells produced by other methods. The crystal structures of monocrystalline photovoltaic cells are regular. Therefore, it is difficult to produce and costly. In polycrystalline photovoltaic cells, very small defects in the crystal structure cause the efficiency of this type of cells to decrease slightly. However, the ease of production and lower cost compared to monocrystalline photovoltaic cells lead to an increase in the tendency toward this type of cells in designs. The R_s value in a monocrystalline PV cell is less than the R_s value in a polycrystalline PV cell. On the other hand, n and I_0 parameters are greater than the polycrystalline PV cell values. The energy produced in a wind farm is directly proportional to the wind speed. Small changes in wind speed result in large

changes in wind energy. For example, the amount of energy that can be produced by a wind at a speed of 12.6 m/s is twice as much as the energy that can be produced by a wind at a speed of 10 m/s. The efficiency of monocrystalline solar cells is higher than polycrystalline solar cells. While the efficiency of polycrystalline solar panels is around 15%, this value reaches 20% in monocrystalline solar panels.

Due to their different properties, perovskites have been in great demand by researchers, especially in recent years. Its properties may vary depending on the atoms in the perovskite structure. While the band gap is 1.1 in silicon-based solar cells, the band gap can be increased from 1.5 to 3 in perovskite structures. Perovskite solar cells are among the new generation solar energy technologies with their features such as increasing efficiency through integration with silicon panels. In addition to producing high-efficiency perovskite solar cells, ensuring that they are less affected by environmental conditions and have a longer lifespan are the most studied topics. Longer lifespan can be achieved with an encapsulation that will make them less affected by the humidity and oxygen in the environment. Another important issue is that the harmful rays of the sun cause degregation in the perovskite active layer. Encapsulation effectively blocks oxygen and moisture and ensures the stability of the perovskite layer.

In this study, the Newton–Raphson method was used to find the unknown parameters in the PV cell. 72 cells were used in the PV module. The data values in Table 2 were obtained from Fig. 11. The model of the PV cell single-diode equivalent circuit possesses nonlinear characteristics, so there is no direct solution. It is possible to solve nonlinear systems of equations by iterative methods.

Differential equations were created using the equivalent circuit of the solar cell. The nonlinear differential equations given below were found using the data values in Table 2. The nonlinear differential equations given below are solved using

Table 2 PV cell voltage and current values (obtained from the I–V curve of Fig. 15)

Points of voltage and current on the I–V curve	Value of voltage (V)	Value of current (A)
1	1.68455	6.19565
2	37.5853	6.06522
3	42.9577	5.78261
4	47.3762	4.1087
5	50.6679	0.413043

the Newton–Raphson method. The aim of this study is to find PV cell equivalent circuit parameters (I_{ph} , I_0 , n , R_s , R_{sh}) and the fill factor.

$$C = \frac{q}{kT} \quad (15)$$

$$f_1 = x_1 - 10^{-6}x_2 \left(\exp\left(\frac{C(V_1 + I_1X_4)}{36x_3}\right) - 1 \right) - \frac{(V_1 + I_1x_4)}{x_5} - I_1 = 0 \quad (16)$$

$$f_2 = x_1 - 10^{-6}x_2 \left(\exp\left(\frac{C(V_2 + I_2X_4)}{36x_3}\right) - 1 \right) - \frac{(V_2 + I_2x_4)}{x_5} - I_2 = 0 \quad (17)$$

$$f_3 = x_1 - 10^{-6}x_2 \left(\exp\left(\frac{C(V_3 + I_3x_4)}{36x_3}\right) - 1 \right) - \frac{(V_3 + I_3x_4)}{x_5} - I_3 = 0 \quad (18)$$

$$f_4 = x_1 - 10^{-6}x_2 \left(\exp\left(\frac{C(V_4 + I_4x_4)}{36x_3}\right) - 1 \right) - \frac{(V_4 + I_4x_4)}{x_5} - I_4 = 0 \quad (19)$$

$$f_5 = x_1 - 10^{-6}x_2 \left(\exp\left(\frac{C(V_5 + I_5x_4)}{36x_3}\right) - 1 \right) - \frac{(V_5 + I_5x_4)}{x_5} - I_5 = 0 \quad (20)$$

These differential equations exhibit nonlinear characteristics. The Newton–Raphson numerical method was used to find PV cell equivalent circuit parameters. Then, the open-circuit voltage and fill factor were found. The numerical methods used in estimation methods of PV cell equivalent circuit parameters are simple and require minimum calculation time. In addition, using these numerical methods, accurate results can be obtained with a sufficient number of iterations. Among the numerical methods, the Newton–Raphson method can be considered to be the fastest and most useful.

Table 3 PV cell five unknown parameters obtained from the software program is given in Appendix-A

The PV cell parameters	PV cell equivalent circuit parameters
I_{ph}	9.3007 A
I_0	0.0812×10^{-6} A
n	1.8001
R_s	0.0613 Ω
R_{sh}	13.0686 Ω

In this study, PV cell equivalent circuit parameters were found using the Newton–Raphson method and the manufacturer’s catalog data sheet values of the PV module (Sunpower SPR-X20-250-BLK). PV cell equivalent circuit parameters and fill factor were found using the software program developed in MATLAB. In this study, five parameters (I_{ph} , I_0 , n , R_s , R_{sh}) of the PV cell equivalent circuit were found by using the software program and are listed in Table 3.

When the series resistance in the equivalent circuit of the PV cell is very small, the fill factor becomes greater than 0.7. In addition, the maximum power produced by the PV module also increases. The analytical expression of the PV cell equivalent circuit model is nonlinear because the change of diode element current is nonlinear. There are five unknown parameters in the equivalent circuit of the PV cell. Thus, five independent equations are required to find the values of these five parameters.

These five differential equations were obtained by determining certain points on the I–V characteristic curve of the PV module. These five selected points are shown on the I–V characteristic curve given in Fig. 7. The above differential equations have nonlinear properties and are complex. In addition, the solutions of these differential equations are also numerical. The Newton–Raphson method is suitable for solving these differential equation systems simultaneously.

Many numerical methods have been developed to determine the equivalent circuit parameters of the PV cell.

Thanks to these numerical methods, PV cell equivalent circuit parameters can be determined quickly and accurately. The value of these parameters changes with the amount of irradiation and the ambient temperature. Therefore, it is essential to know the ambient temperature and irradiation levels while calculating the PV cell output current and voltage values.

4 Fill factors of a solar cell

The fill factor is often used to indicate the power generation quality of a photovoltaic module. As the series resistance increases, the value of FF decreases (Fig. 16).

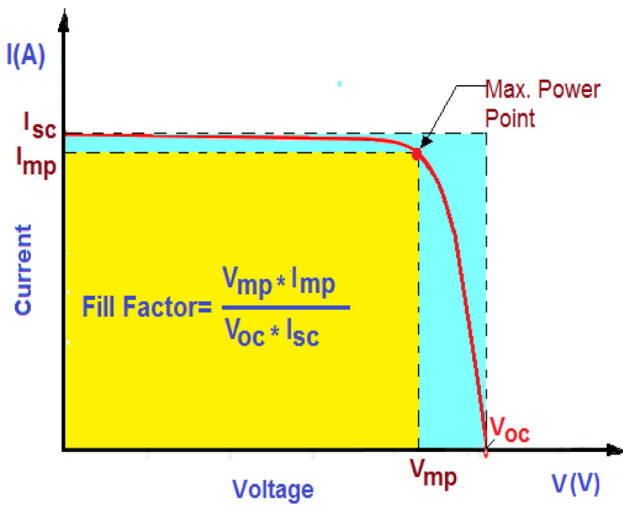


Fig.16 Schematic representation of the fill factor

Graphically, FF is the area of the largest rectangle that will fit on the I–V characteristic curve. The series resistance is of great significance in the PV cell equivalent circuit. It is especially effective in filling factor losses in commercial solar cells. The value of the maximum voltage in the PV cell is determined by Eq. (19).

$$\frac{d(I V)}{d V}=0 \tag{21}$$

The following expression is obtained from the solution of Eq. (21).

$$V_{M P}=V_{o c}-\frac{n k T}{q} \operatorname{Ln}\left(\frac{q V_{M P}}{n k T}+1\right) \tag{22}$$

is found as. The v_{oc} value is the V_{oc} normalized form. It is calculated using the following formula.

$$v_{oc}=\frac{q}{n k T} V_{oc} \tag{23}$$

FF is calculated by the formula below.

$$F F=\frac{v_{oc}-\operatorname{Ln}\left(v_{oc}+0.72\right)}{v_{oc}+1} \tag{24}$$

PV cell FF simulink block diagram is as given below (Fig. 17).

The open-circuit voltage and the fill factor were found with the software program given in Appendix. The open-circuit voltage given in Table 4 and the fill factor was found by running the program in Appendix. The open-circuit voltage given in Table 4 and the fill factor was found by running the program in Appendix.

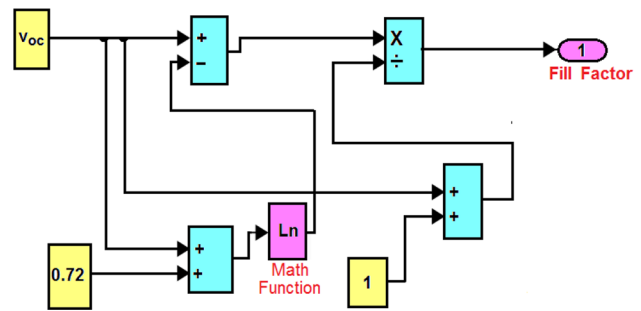


Fig. 17 Simulink model of PV cell fill factor

Table 4 PV cell open-circuit and fill factor (the Sunpower SPR-X20-250-BLK)

The PV cell	PV cell equivalent circuit open circuit and fill factor
v_{oc}	0.6259 V
FF	0.7484 A

5 Discussion and conclusion

Unknown equivalent circuit parameters (R_s , R_{hs} , I_o , n , I_{ph}) of a solar cell are not in the manufacturer’s catalog. The equivalent circuit parameters of the solar cell, the open-circuit voltage and fill factor can be easily found using the softwares program given in Appendix.

Five points were determined on the I–V characteristic curve for finding the PV module (the Sunpower SPR-X20-250-BL) PV cell equivalent circuit parameter. Then the related differential equations were determined. Since these equations have nonlinear properties, Newton–Raphson solution method was used in the solution. In this study, the Sunpower SPR-X20-250-BL PV module datasheet values were used. After the fill factor and open-circuit voltage of the PV cell were found by using Appendix-A- software program given at the end of the article.

Authors’ contribution SA designed the observers and prepared the manuscript. HC tested the observers in simulations and experiments and prepared the figures. Both authors reviewed the manuscript.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval Not applicable.

Appendix

DEVELOPMENT SOFTWARE PROGRAM TO FIND PHOTOVOLTAIC CELL OPEN CIRCUIT VOLTAGE AND FILL FACTOR

GENERAL EXPLANATIONS
 The program is written in general about the known panel system using the $F(V)=I$ curve.

The program is written using 5 points on the $F(V)=I$ curve.

(Ex: $V_1, I_1; V_2, I_2; V_3, I_3; V_4, I_4; V_5, I_5$)

The state variables for the written program are as follows:

$x_1=I_{ph}$; $x_2=I_0$; $x_3=m$; $x_4=R_s$; $x_5=R_{sh}$; taken as

SOLUTION OF NONLINEAR EQUATIONS BY NEWTON-RAPHSON METHOD

tol; It is the tolerance value

max1; The maximum number of iterations that will be allowed.

k; has occurred iteration number.

X; is the vector representing the root values.

error; is the amount of error in iteration convergence.

The initial conditions are included in the X vector.

THE RESULT THAT SHOULD BE ACCORDING TO THE SIMULINK: 9.33 1.0649 5.88 0.2670 599.9994

RESULT iter= 24

Result values of the NR program: 9.33 1.087 5.84 0.2695 593.13

clear all

clc

tol=0.0000001; max1=1000000;

%max1=10000000; % number of maximum iterations

a=0.0008;

$x_0=[3 \ 2 \ 0.11 \ 145]$; % NR-iteration starting values

$q=1.602 \times 10^{-19}$;

$T=25+273$; %kelvin

$K=1.381 \times 10^{-23}$;

$C=q/(T \times K)$;

THE SUNPOWER SPR-X20-250-BLK CATALOG VALUES WILL BE USED

5 VALUES OBTAINED FROM V-I CURVE of The Sunpower SPR-X20-250-BLK

$I_1=6.19565$; $V_1=1.68455$; % $f(V)=I$ obtained from the I-V curve (1)

$I_2=6.06522$; $V_2=37.5853$; % $f(V)=I$ obtained from the I-V curve (2)

$I_3=5.78361$; $V_3=42.9577$; % $f(V)=I$ obtained from the I-V curve (3) MPPT point

$I_4=4.1087$; $V_4=47.3762$; % $f(V)=I$ obtained from the I-V curve (4)

$I_5=0.413043$; $V_5=50.6679$; % $f(V)=I$ obtained from the I-V curve (5)

$N_s=72$; % NUMBER OF CELLS IN THE MODULE

$N_p=1$; % THE NUMBER OF SERIAL-CONNECTED MODULES INCREASES, THE NUMBER OF "Np" ALSO INCREASES. DETERMINE MPPT POINT BY "Np" VALUE

$b=[3.1 \ 0.11 \ 0.92 \ 0.45 \ 0.09]$; % Sensitivity values of state variables

$x_0=b \cdot x_0$;

X=x0;

syms $x_1 \ x_2 \ x_3 \ x_4 \ x_5$

$f_1 = x_1 - (1 - e^{-6}) \cdot x_2 \cdot (\exp(C \cdot (V_1 + I_1 \cdot x_4) / (N_p \cdot N_s \cdot x_3)) - 1) - ((V_1 + I_1 \cdot x_4) / x_5) - I_1$;

$f_2 = x_1 - (1 - e^{-6}) \cdot x_2 \cdot (\exp(C \cdot (V_2 + I_2 \cdot x_4) / (N_p \cdot N_s \cdot x_3)) - 1) - ((V_2 + I_2 \cdot x_4) / x_5) - I_2$;

$f_3 = x_1 - (1 - e^{-6}) \cdot x_2 \cdot (\exp(C \cdot (V_3 + I_3 \cdot x_4) / (N_p \cdot N_s \cdot x_3)) - 1) - ((V_3 + I_3 \cdot x_4) / x_5) - I_3$;

$f_4 = x_1 - (1 - e^{-6}) \cdot x_2 \cdot (\exp(C \cdot (V_4 + I_4 \cdot x_4) / (N_p \cdot N_s \cdot x_3)) - 1) - ((V_4 + I_4 \cdot x_4) / x_5) - I_4$;

$f_5 = x_1 - (1 - e^{-6}) \cdot x_2 \cdot (\exp(C \cdot (V_5 + I_5 \cdot x_4) / (N_p \cdot N_s \cdot x_3)) - 1) - ((V_5 + I_5 \cdot x_4) / x_5) - I_5$;

$Y(1) = \text{subs}(f_1, \{x_1, x_2, x_3, x_4, x_5\}, [x_0(1) \ x_0(2) \ x_0(3) \ x_0(4) \ x_0(5)])$;

$Y(2) = \text{subs}(f_2, \{x_1, x_2, x_3, x_4, x_5\}, [x_0(1) \ x_0(2) \ x_0(3) \ x_0(4) \ x_0(5)])$;

$Y(3) = \text{subs}(f_3, \{x_1, x_2, x_3, x_4, x_5\}, [x_0(1) \ x_0(2) \ x_0(3) \ x_0(4) \ x_0(5)])$;

$Y(4) = \text{subs}(f_4, \{x_1, x_2, x_3, x_4, x_5\}, [x_0(1) \ x_0(2) \ x_0(3) \ x_0(4) \ x_0(5)])$;

$Y(5) = \text{subs}(f_5, \{x_1, x_2, x_3, x_4, x_5\}, [x_0(1) \ x_0(2) \ x_0(3) \ x_0(4) \ x_0(5)])$;

%Y=feval('canki_3_alt_1',X);

for k=1:max1

disp('iter'), disp(k);

The following line calculates the Jacobien matrix for the X values

J=jacobian([f1;f2;f3;f4;f5],[x1 x2 x3 x4 x5]);

J=subs(J, {x1,x2,x3,x4,x5}, [X(1) X(2) X(3) X(4) X(5)]);

J1=double(J);

Q=X-a*(J1\Y');

error=abs(Q-X)

vpa(Q(1),6)

vpa(X(1),6)

if Q(1)-X(1)>0

a=0.5*a;

disp('it started to move away from data values')

%pause

end

```

error =vpa(max(error),5)
if (max(error)<tol)
  disp('number of iterations performed')
  disp(k)
  disp('searched root values ')
  format short
  disp([' Iph', ' Io', ' n', ' Rs', '
Rsh'])
  disp(double(X))
  break
else
  X=Q;
  Z(1)=subs(f1,{x1,x2,x3,x4,x5},[Q(1) Q(2) Q(3) Q(4)
Q(5)]);
  Z(2)=subs(f2,{x1,x2,x3,x4,x5},[Q(1) Q(2) Q(3) Q(4)
Q(5)]);
  Z(3)=subs(f3,{x1,x2,x3,x4,x5},[Q(1) Q(2) Q(3) Q(4)
Q(5)]);
  Z(4)=subs(f4,{x1,x2,x3,x4,x5},[Q(1) Q(2) Q(3) Q(4)
Q(5)]);
  Z(5)=subs(f5,{x1,x2,x3,x4,x5},[Q(1) Q(2) Q(3) Q(4)
Q(5)]);
  Y=double(Z);
  end
end
if k==max1
disp('Iteration stopped because max1 iteration count
has been exceeded')
end
Voc=(double(X(3))*K*T/q)*log( double(X(1))/ 1e-
6*double(X(2))+1)
FF=(q*Voc/( double(X(3))*K*T)-log(q*Voc/(
double(X(3))*K*T)+0.72))/( q*Voc/(
double(X(3))*K*T)+1)

```

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