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Development software program for extraction of photovoltaic cell equivalent circuit model parameters based on the Newton–Raphson method

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Abstract

Finding the equivalent circuit parameters for photovoltaic (PV) cells is crucial as they are used in the modeling and analysis of PV arrays. PV cells are made of silicon. These materials have a nonlinear characteristic. This distorts the sinusoidal waveform of the current and voltage. As a result, harmonic components are formed in the system. The PV cell is the smallest building block of the PV system and produces voltages between 0.5 V and 0.7 V. It serves as a source of current. The amount of radiation hitting the cell determines how much current it produces. In an ideal case, a diode and a parallel current source make up the equivalent circuit of the PV cell. In practice, the addition of a series and parallel resistor is made to the ideal equivalent circuit. There are many equivalent circuits in the literature on modeling the equivalent circuit of a PV cell. The PV cell single–diode model is the most used model due to its ease of analysis. In this study, the iterative method by Newton–Raphson was used to find the equivalent circuit parameters of a PV cell. This method is one of the most widely used methods for determining the roots of nonlinear equations in numerical analysis. In this study, five unknown parameters (Iph, Io, Rs, Rsh and m) of the PV cell equivalent circuit were quickly discovered with the software program prepared based on the Newton–Raphson method in MATLAB.

Keywords Five unknown parameters · Newton–Raphson method · I–V characteristics of PV cell · PV cell equivalent circuit model · PV cell software program

1 Introduction

The use of renewable energy sources as an alternative to fossil fuel thermal power plants in energy production is becoming increasingly common [1]. It is well known that today, large-scale fossil-based electric power plants are major contributors to environmental pollution. For a cleaner atmosphere and sustainability of human live, the use of fossil fuels must be abandoned and renewable clean energy sources should be utilized instead.

Solar photovoltaics (PVs), which offer many benefits for the future, have gained popularity in the last couple of decades. Thus, it is important to clearly determine the properties of the PV cell. PV sources stand out from other renewable energy sources due to their lower cost and easier applicability.

Photovoltaic energy generators consist of a combination of many cells and convert solar energy into direct current electrical energy. They are extremely simple to install and their efficiency has substantially improved over the years.

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p–n semiconductors are combined to make solar cells in a thin layer. In the dark, the PV cell output I–V characteristic is very similar to the diode characteristic [2]. When it is exposed to light, the current is provided by the movement of electrons with the help of photons. PV cells are made from semiconductor materials that convert sunlight energy into electrical energy. Owing to the semiconductor material in the structure of PV cells, they are nonlinear. When the PV cell is exposed to sunlight, photons fall on it, resulting in a current generation via electron motion.

In reference [3], the unknown parameters of the PV cells were determined by utilizing the I–V characteristics of solar cells. At this stage, five parameters were obtained by using the five points of the I–V characteristics such as short-circuit current of solar cell (Isc), open-circuit voltage of solar cell (Voc), maximum current of solar cell (Imp) and maximum voltage of solar cell (Vmp) in the most efficient operations [2, 4, 5].

The semiconductor substance used in the production of PV cells is silicon which is produced from sand from the ocean. Therefore, there is no shortage of this resource on earth. The PV cell produces a voltage between 0.5 and 0.8 V, depending on the temperature, radiation and the type of semiconductor material from which it is made [6]. Since this voltage level is very low, the PV cells are connected in series to achieve more voltage levels during the design process. PV cells in series are shown in Fig. 1.

The equivalent PV cell circuit is obtained using the analytical equations of the PV cells. To analyze a PV system, analytical models are needed to cover the width from cells to arrays. With these models, which are called electrical equivalent circuits, all kinds of photovoltaic systems can be modeled and analyzed, regardless of their size. The Photovoltaic cell's equivalent circuit parameters are found by using the analytical equations of the PV cells [7, 8]. Although many models have been developed for PV cells, the single-diode model, also known as the five-unknown-parameter model, is the most widely used equivalent circuit model for solar cells in the literature.

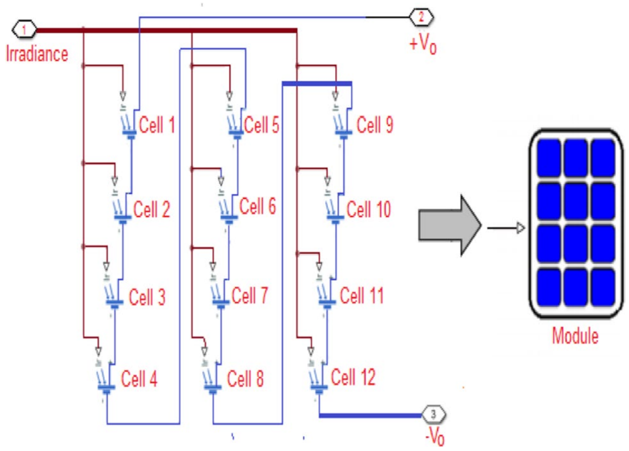

Fig. 1 Photovoltaic module and cells

The five unknown parameters are as follows: Iph is the current produced by the PV cell; Io is the diode reverse saturation current; Rsh is the parallel leakage current resistance; and Rs is the internal resistance in the solar cell and m is the diode ideality factor. In order to define the I–V curve of the solar cell, the specific Io and m parameters of the equivalent circuit parameters must be known [9].

Equivalent circuit parameters of PV cells were found by Newton–Raphson method in [10], while unknown parameters were found by bullet search algorithm in reference [11]. The PV cells act as a source of current that changes according to insolation of the sun. In darkness, the PV cell does not generate energy and instead acts like a diode. In such cases, if it is connected to an external source, Id current passes through the diode. This is called a dark or diode current. This current is illustrated as Id [12].

Numerous factors affect the efficiency of PV solar cell. Therefore, it should be ensured that the panel works with the best efficiency under all conditions. In places where panels are installed, potential efficiency losses due to environmental factors, especially irradiance and temperature, should be identified in advance [13, 14]. Thus, by choosing the most suitable location and direction, it is possible to operate solar power plants with the highest efficiency and profitability. To achieve this, equivalent circuit parameters must be determined.

In the data sheet, information on photovoltaic panels, operating ranges, current and voltage values, short-circuit current and open-circuit voltage that can be provided under the best conditions is given. However, these values assumed for the best conditions cannot be achieved in less optimal conditions. Thus, unforeseen losses in efficiency are encountered. The starting point of this study is to make use of the operating curves of the panels in determining the equivalent circuit parameters. This idea has been presented in some other studies in the literature [15–17]. In [16], equivalent circuit parameters were found by an improved adaptive differential evolution algorithm method. The Newton–Raphson method is used to identify the single-diode equivalent circuit parameters of the PV cell. In this method, the nonlinear diode element is linearized during each iteration step. The solution of the differential equations of the PV cell was developed with this method, and five unknown parameters of the equivalent circuit of the PV cell were then determined [18, 19].

Following the determination of the PV cell's equivalent circuit parameters, the analysis of the PV module becomes quite easy. The output current and voltage of the PV module and the losses are found using the PV cell equivalent circuit parameters. Using these same parameters, the design and analysis of the PV module and PV array can be performed. At the same time, the efficiency and losses of the PV cell can be found using these parameters [20].

2 Photovoltaic cells analysis and modeling

The working principle of PV cells is the same as the working principle of p–n junction diodes. The output I–V characteristic curve of PV cells in the dark is very similar to the characteristic curve of the diode. The single-diode equivalent mode of PV cells consists of photocurrent produced by PV cell, series, a parallel resistor and diode. PV modules are obtained by connecting the produced cells to each other with solders, panels by connecting the modules to each other, and photovoltaic arrays are obtained by connecting the panels to each other.

The PV cell equivalent circuit is nonlinear due to the diode current and additional losses occur in the PV cell. The PV system is very sensitive to changes irradiation intensity and temperature. Solar irradiation and temperature affect some parameters in the PV cell equivalent circuit and change the PV module characteristic.

In addition, I_0 and Isc currents, which are seen as constant in the PV cell equivalent circuit, vary depending on irradiation and temperature. In practice, the five-variable equivalent circuit model for PV cells is extensively used. The equivalent circuit of the PV cell is shown in Fig. 2.

The parameters in this equivalent circuit model are dependent on radiation and temperature. The series resistance (Rs) in the equivalent circuit is a significant parameter that affects the performance of a PV cell. The increase in the short-circuit current density of the PV cell causes an increase in resistance loss.

The case the solar cell is active, Rs acts as the voltage source of the solar cell and Rsh serves as the current source of the cell [21, 22]. Parallel resistance (Rsh), which expresses the leakage currents in the PV cell, is among the parameters affecting the performance of the PV cell [23–25].

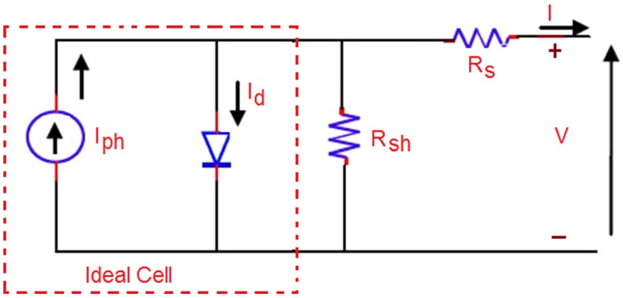

Fig. 2 PV cell single-diode model

The mathematical expressions found as a result of the circuit analysis of the PV cells are given in the equations below.

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

The diode current can be expressed as:

$$I_d = I_0\left(e^{\frac{qV_D}{mkT}} - 1\right) \tag{2}$$

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

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

The load current of PV cell is defined by Eq. (4).

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_s)}{mN_skT>}} - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{4}$$

Here, Iph denotes the photocurrent, Io denotes the reverse saturation diode current, q denotes electron charge, V denotes the PV cell output voltage, I denotes the output of the PV cell current, k denotes the Boltzmann constant, and T indicates the junction temperature. Another parameter used in the modeling of the solar PV cell is m as the ideality factor.

This factor varies depending on the material used in the production of solar cells. It ranges from 1,2 to 6 according to the technology. For example, m = 1,2 for silicon monocrystal and m = 1,5 for cadmium tellurium. Ns is the number of cells connected in series, Rs is the series internal resistance, Rsh is the parallel leakage current resistance, and I_0 is the reverse saturation diode current [24–26]. The short-circuit current of the PV cell is found from the equation given below.

$$I_{sc} = I_{ph} - I_0\left(e^{\frac{I_{sc}R_s}{N_sV_t}} - 1\right) - \frac{I_{sc}R_s}{R_{sh}} \tag{5}$$

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

$$V_t = \frac{mkT}{q} \tag{6}$$

The maximum current of PV cell can be expressed using Eq. (4), (at I = Imp) as,

$$I_{mp} = I_{ph} - I_0\left(e^{\frac{V_{mp}+I_{mp}R_s)}{N_sV_t}} - 1\right) - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{7}$$

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

$$V_{oc} = V_tLn\left(\frac{I_{ph}}{I_0} + 1\right) \tag{8}$$

The single-diode PV cell equivalent circuit model is simple as it only contains an exponential expression in the diode current. Therefore, this model is used extensively in photovoltaic applications. Performance parameters of a PV module are as follows: It consists of maximum output power (PMP), short-circuit current (Isc), open-circuit voltage (Voc), efficiency (η), filling multiplier (FF) and performance ratio (PR).

In order to calculate the performance of the PV cell at a given irradiance value and cell temperature, the characteristic of the I–V curve of the solar cell must be known [27, 28]. I–V and P–V characteristic curves of the PV cell can be drawn using the PV cell equivalent circuit parameters. The photocurrent produced by the PV cell is expressed in the equation given below.

$$I_{ph} = \left[I_{sc} + K_i\left(T - T_{ref}\right)\right]\frac{G}{G_{ref}} \tag{9}$$

If we use the Ki and Tref values in Eq. (9), the photocurrent equation is found as follows.

$$I_{ph} = \left[I_{sc} + 0.0017(T - 298)\right]\frac{G}{1000} \tag{10}$$

The Ki coefficient is a coefficient used to express the change of light flux with temperature. This coefficient takes a different value for each model and it is obtained as a result of experiments carried out in the laboratory environment. The diode saturation current can be determined using Eq. (11) given below:

$$I_0(T) = I_{0(T_{ref})}\left(\frac{T}{T_{ref}}\right)^2 \exp\left[\frac{E_q}{V_t}\left(\frac{T}{T_{ref}} - 1\right)\right] \tag{11}$$

Here, I0 is the reverse saturation diode current, Eq is the band gap energy of the semiconductor material, Tref is the nominal reference temperature and Vt denotes the thermal voltage. Five unknown parameters were found using the single-diode equivalent circuit of the PV cell [29, 30]. The simulation circuit diagram given in Fig. 3 is used to obtain the I–V curve and the P–V curve of the PV cell.

Environmental factors like cell temperature, solar irradiation, clouding and partial shadowing can negatively affect both output power and overall system efficiency. Modeling of single-diode equivalent circuit model was simulated by using MATLAB/Simulink. The I–V and P–V characteristic curves obtained from the simulation model are shown in Fig. 4.

In this study, the single-diode equivalent circuit parameters of the photovoltaic cell were found with the developed software program. After finding the equivalent circuit parameters of the solar cell, the V–I and V–P characteristic curves of the Suntech STP 27,520/Wfw module are plotted.

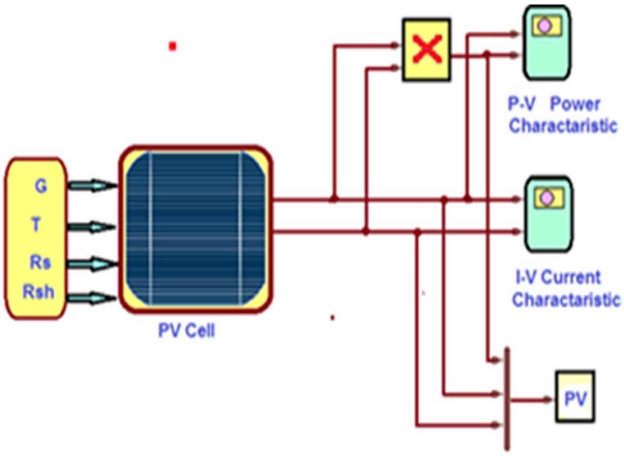

Fig. 3 Obtaining P–V and I–V curves of PV cell

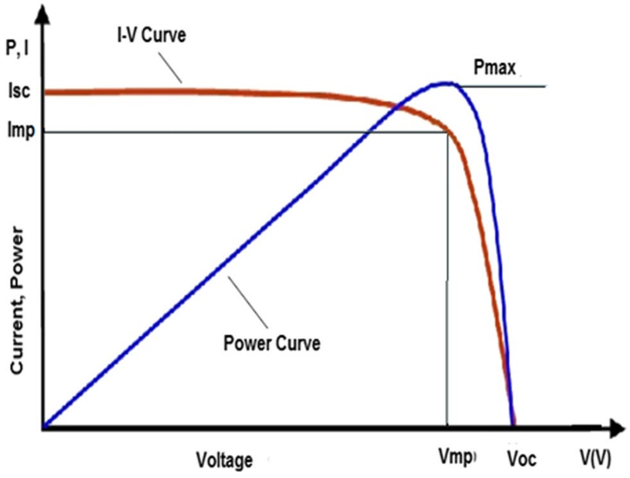

Fig. 4 P–V and I–V curves of the PV cell

2.1 Simulation of the PV cell model

Simulink is used for the analysis and modeling of linear and nonlinear systems. It reduces the need for prototypes. It is modeled in continuous time, discrete time or a combination of both. As is known, PV modules consist of solar cells and are generated by connecting the solar cells in a series. Arrays are obtained when modules come together in a series or parallel. The boundary diagram related to the PV solar cell is shown in Fig. 5.

The most common models used to simulate I–V curves of modules, single- and double-diode, are equivalent circuit models. The dual-diode equivalent circuit model gives better results in shading and low radiation. However, the single-diode equivalent circuit model is still the most widely used model due to its accuracy and ease of calculation. In this study, a single-diode equivalent circuit model was used to

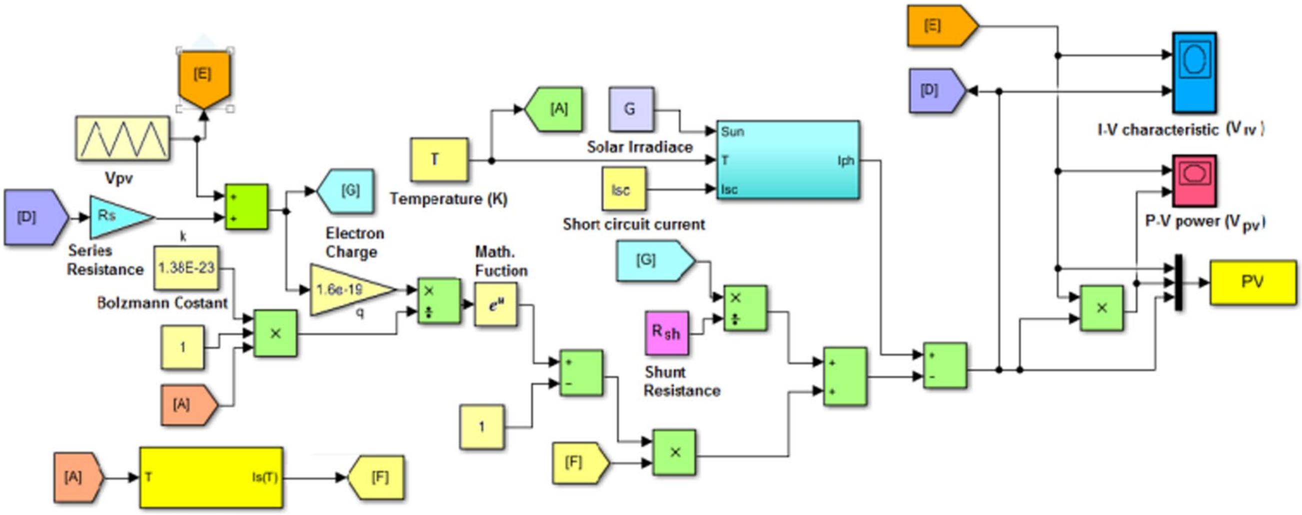

Fig. 5 MATLAB/Simulink of PV Cell

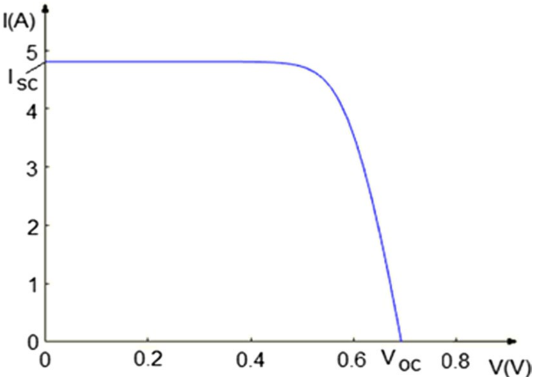

Fig. 6 I–V curve of the PV solar cell

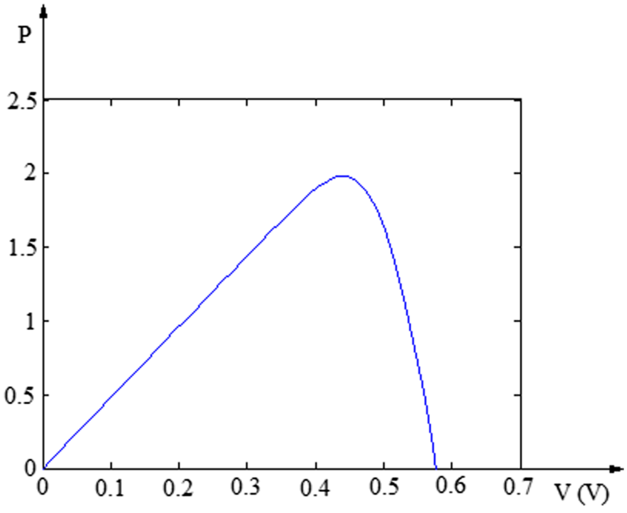

Fig. 7 P–V curve of the simulated PV cell

simulate I–V curves at a given irradiance and module temperature and to find equivalent circuit parameters.

The aim of this study is to model a PV cell close to reality, to obtain characteristic curves and to estimate the necessary parameters for analysis. The I–V characteristic curve for the PV cell is given in Fig. 6.

The output characteristics of the I–V and P–V curves of the PV cell depend on weather conditions. As the weather condition is constantly changing, the properties of I–V and P–V curves of the PV cell are also altered. The Suntech STP275-20/Wfw module was used to find the equivalent circuit parameters of the PV cell. The change of the I–V curve of this PV module is nonlinear. The I–V characteristic of Suntech STP275-20/Wfw module is given in Fig. 7.

The parameter values of diode ideality factor m, parallel resistor Rsh, series resistor Rs, diode saturation current Io and photocurrent Iph, which are not included in the PV panel manufacturer catalog data, were found using the Newton–Raphson method. This method is simple and requires less computation time. At the end of the iteration, reasonable results are obtained. The software program for this method is given in appendix in the article. It is impossible to obtain the equivalent circuit without knowing these parameters. Therefore, simulation of PV cells and panels will not be possible. In this study, five points were determined on the I–V characteristic curve of the PV module. The differential equations of the PV cell were found using Eq. (4).

3 Extraction of the PV cell parameters by iterative Newton–Raphson method

Analysis and modeling of PV systems are difficult due to their nonlinear characteristics. The unknown equivalent circuit parameters of the PV cell were determined by the

Newton–Raphson iterative method. To find the output current and voltage values of the PV module, the equivalent circuit parameters of the PV cell must be known [23]. Five points were selected on the I–V characteristic curve of the PV module. The diode current in the equivalent circuit of the PV cell has a nonlinear characteristic. Therefore, the equivalent circuit is nonlinear as well.

For this reason, the Newton–Raphson iterative method was used to solve nonlinear equations. This method has many advantages. It has the feature of being able to quickly find unknown parameter values. Different methods were used to determine these unknown parameters. The main features of the PV module (Suntech STP275-20/Wfw) are shown in Table 1.

Dusting and shading of the surfaces of PV cells considerably reduce the output power. Therefore, it is necessary to remove objects such as leaves that may fall on the cell surface. These objects not only shade PV cell surfaces, but also damage other cells.

In the application, the Suntech STP275-20/Wfw module was used to find the equivalent circuit parameters of the PV cell. In practice, the I–V characteristic curve of this module is used. The I–V characteristic curve is nonlinear.

Table 1 Parameters of the Suntech STP275-20/Wfw module

PV Module	Suntech STP275—20/Wfw (1000 W/m2, 25 °C)
Short-circuit current (Isc)	9.27 A
Open-circuit voltage (Voc)	38.1 V
Maximum current (Imp)	8.82 A
Maximum voltage (Vmp)	31.2 V
Temperature coefficient of short circuit (Isc)	0.067%/ 0C
PV Module efficiency	16%
Temperature coefficient of open circuit (Voc)	−0,33%/0C
Number of cells connected in series (Ns)	10
Maximum power at STC (Pmax)	275 W

Five points are chosen on this curve to derive the differential equations. The I–V characteristic of the Suntech STP275-20/Wfw PV module is given in Fig. 8.

In this study, an improved parameter identification method was proposed using the iterative method, which is the Newton–Raphson method, for extracting the parameters from the data sheet of the manufacturers by using a code designed according to the flowchart in Fig. 8. Standard panel data are available in panel catalogs produced by companies and give variable values according to individual parameters for each panel or module. The number of cells used in the system is explained separately in each panel catalog. In the standard panel catalogs, there are parameters that determine the full cell and how many cells are used. When the standard panel catalogs are examined, it can be seen that usually 60 to 72 cells are used. The values in Table 2 were obtained from Fig. 1.

The PV cell's single-diode equivalent circuit model has a nonlinear characteristic; there is no direct solution. It is possible to solve systems of nonlinear equations with iterative methods.

We can solve the five nonlinear equations given below with the Newton–Raphson method. The aim of this study is to determine PV cell equivalent circuit parameters (I_{Ph}, I_0, m, R_s and R_{Sh}). At the conclusion of this study, it is aimed to create a PV cell model with five unknown parameters.

General mathematical formulas were created by using the equivalent circuit of the solar cell. The differential equations with nonlinear characteristics given below were found using the numerical data in Table 2.

$$C = \frac{q}{kT} \tag{12}$$

$$f_1 = x_1 - 10^{-6}x_2\left(e^{\frac{C(V_1+I_1X_4)}{36X_3}} - 1\right) - \frac{(V_1+I_1X_4)}{X_5} - I_1 = 0 \tag{13}$$

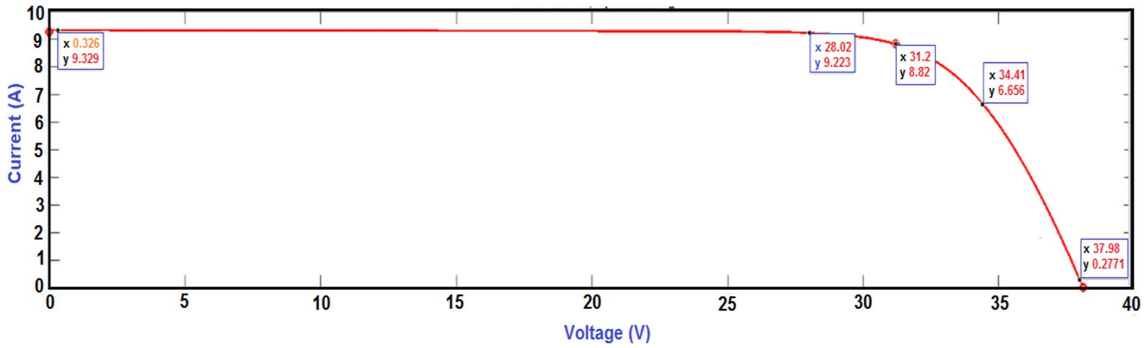

Fig. 8 I–V curves of the PV module (Suntech STP275—20/Wfw)

Table 2 PV cell voltage and current values obtained from the I–V curve (for 200 W/m2)

Points on the I–V curve	Voltage (V)	Current (A)
1	0.326	9.329
2	28.02	9.223
3	31.2	8.82
4	34.41	6.656
5	37.98	0.2771

Table 3 PV cell equivalent circuit parameters

The parameters	PV cell parameter values found from the software program
Iph	9.3006 A
I0	1.0880 × 10–6 A
m	5.8400
Rs	0.2695 Ω
Rsh	600.3101 Ω

$$f_2 = x_1 - 10^{-6}x_2\left(e^{\frac{C(V_2+I_2X_4)}{36X_3}} - 1\right) - \frac{\left(V_2 + I_2X_4\right)}{X_5} - I_2 = 0 \tag{14}$$

$$f_3 = x_1 - 10^{-6}x_2\left(e^{\frac{C(V_3+I_3X_4)}{36X_3}} - 1\right) - \frac{\left(V_3 + I_3X_3\right)}{X_5} - I_3 = 0 \tag{15}$$

$$f_4 = x_1 - 10^{-6}x_2\left(e^{\frac{C(V_4+I_4X_4)}{36X_3}} - 1\right) - \frac{\left(V_4 + I_4X_4\right)}{X_5} - I_4 = 0 \tag{16}$$

$$f_5 = x_1 - 10^{-6}x_2\left(e^{\frac{C(V_5+I_5X_4)}{36X_3}} - 1\right) - \frac{\left(V_5 + I_5X_4\right)}{X_5} - I_5 = 0 \tag{17}$$

In this study, an improved parameter identification method was put forward using the iterative method, which is the Newton–Raphson, for extracting the parameters from the data sheet of the manufacturers by using a code designed according to flowchart in Fig. 8. Standard panel data are available in panel catalogs produced by companies, and they give variable values according to individual parameters for each panel or module.

The iterative methods used in estimation methods of PV cell equivalent circuit parameters are simple and require minimal computation time. In addition, using the methods, accurate results can be obtained with a sufficient number of iterations. Among the analytical methods, the fastest and most useful is the Newton–Raphson method.

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 (Suntech STP275-20/Wfw). The PV cell five unknown equivalent circuit parameters were found with the software program developed in the MATLAB program. The PV cell equivalent circuit parameters are given in Table 3.

The analytical expression of the single-diode equivalent circuit model of the PV cell is nonlinear because the characteristic variation of the diode current in the equivalent circuit is nonlinear. Therefore, at least five independent equations are required to find the values of the five parameters in the equivalent circuit.

These five equations were obtained using specific points on the I–V characteristic curve of the PV cell. These five selected points are shown in Fig. 7 on the I–V characteristic curve. The above equations have nonlinear characteristics and are complex. Furthermore, their solutions are numerical. The Newton–Raphson method, which is among the solution methods of numerical equations, is suitable for simultaneously solving these equation systems.

Many iterative methods have been developed to determine the circuit parameters of the PV cell. These are generally based on iterative and evolutionary algorithms. Owing to these methods, PV cell parameters can be found quickly and accurately. The equivalent circuit parameters of the PV solar cell depend on the amount of radiation and the ambient temperature. Therefore, it is necessary to know the ambient temperature and irradiation levels when calculating the PV cell output current and voltage values.

4 Discussion and conclusion

Five unknown parameters of the solar cell (Rs, Rhs, Io, m and Iph) equivalent circuit parameters, which are not in the manufacturer's catalog. To obtain these five unknown parameters, it is necessary to know the I–V characteristic curve of the PV module. Equivalent circuit parameters of solar cell can be found easily using the software program given in this article in Appendix. The PV cell parameters were found at the end of the twenty-third iteration.

To find the solar cell equivalent circuit parameter, first five points are determined on the I–V characteristic curve. Then the differential equations of the I–V curve were determined. Since these equations have nonlinear characteristic, parameters are found using Newton–Raphson's iterative method.

Suntech STP275-20/Wfw PV module data sheet values were used in the developed software program. After finding the PV cell equivalent circuit parameters, the output current, voltage, filling factor and efficiency of the solar cell can be found easily.

Appendix

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%%% DEVELOPMENT SOFTWARE PROGRAM FOR  FINDING PHOTOVOLTAIC CELL EQUIVALENT CIRCUIT PARAMETERS

%%% GENERAL EXPLANATİONS %%%%%%%
%% 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: V1,I1;V2,I2;V3,I3;V4,I4;V5,I5)
% The state variables for the written program are as follows:
% x1=Iph; x2=Id; x3=m; x4=Rs; x5=Rsh ; 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 ACCORDİNG 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=0.000001; % NR- iteration stop tolerance
max1=10000; % number of maximum iterations
a=0.01;
x0=[3 1 2 0.11 145]; % NR-iteration starting values
q=1.602*1e-19;
T=25+273; %kelvin
K=1.381*1e-23;
C=q/(T*K);
%%%%%%%%%%%%%%%%%%%%%%%% The SUNTECH   STP  275-20/Wfw   CATALOG VALUES WİLL BE USED %%%%%%%%%%%%%%%
%%%%%  5 VALUES OBTAİNED FROM V-I CURVE  of  The SUNTECH STP275-20/Wfw
%%%%%%%%%
I1=9.329;      V1=0.326;  % f(V)=I obtained from the I-V curve (1)
I2=9.223;      V2=28.02;  % f(V)=I obtained from the I-V curve (2)
I3=8.82;      V3=31,2;   % f(V)=I obtained from the I-V curve  (3) MPPT point
I4=6.656;      V4=34.41;  % f(V)=I obtained from the I-V curve  (4)
I5=0.2771;     V5=37.98;  % f(V)=I obtained from the I-V curve  (5)
N=10; % NUMBER OF CELLS IN THE MODULE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%
S=1; % THE NUMBER OF SERIAL-CONNECTED MODULES  INCREASES, THE NUMBER OF "S" ALSO INCREASES. DETERMINE MPPT POINT BY "S" VALUE  %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
b=[3.1 1.11 2.92 2.45 4.09]; % Sensitivity values of state variables
x0=b.*x0;
X=x0;
syms x1 x2 x3 x4 x5
f1= x1-(1e-6)*x2*(exp(C*(V1+I1*x4)/(S*N*x3))-1)-((V1+I1*x4)/x5)-I1;
f2= x1-(1e-6)*x2*(exp(C*(V2+I2*x4)/(S*N*x3))-1)-((V2+I2*x4)/x5)-I2;
f3= x1-(1e-6)*x2*(exp(C*(V3+I3*x4)/(S*N*x3))-1)-((V3+I3*x4)/x5)-I3;
f4= x1-(1e-6)*x2*(exp(C*(V4+I4*x4)/(S*N*x3))-1)-((V4+I4*x4)/x5)-I4;
f5= x1-(1e-6)*x2*(exp(C*(V5+I5*x4)/(S*N*x3))-1)-((V5+I5*x4)/x5)-I5;
Y(1)=subs(f1,{x1,x2,x3,x4,x5},[x0(1) x0(2) x0(3) x0(4) x0(5)]);
Y(2)=subs(f2,{x1,x2,x3,x4,x5},[x0(1) x0(2) x0(3) x0(4) x0(5)]);
Y(3)=subs(f3,{x1,x2,x3,x4,x5},[x0(1) x0(2) x0(3) x0(4) x0(5)]);
Y(4)=subs(f4,{x1,x2,x3,x4,x5},[x0(1) x0(2) x0(3) x0(4) x0(5)]);
Y(5)=subs(f5,{x1,x2,x3,x4,x5},[x0(1) x0(2) x0(3) x0(4) x0(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', '        Id', '        m', '        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
```

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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