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Modeling and Simulation of PV Systems

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Abstract: *Photovoltaic(PV)systems are used for obtaining electrical energy directly from the sun. In this paper, a solar cell unit, which is the most basic unit of PV systems, is mathematically modeled and its behavior is simulated in detail by using Matlab/Simulink. The effects of solar irradiation, ambient temperature, series resistance and shunt resistance on the output characteristics of the PV cell are investigated. The PV cell open-circuit voltage and short-circuit current equations that are the two of important parameters of a PV cell are extracted. The obtained equations are simulated by using Matlab/Simulink. The change in PV cell's open-circuit voltage and short-circuit current under changing solar irradiation and ambient temperature conditions are also investigated. The PV module is formed by using several solar cells. The output characteristic of PV module under changing environmental conditions is investigated by adapting the PV cell model attained by Matlab/Simulink to PV module model. Finally, an electrical PV array is formed by using multiple PV modules. The Voltage-Current and the Voltage–Power characteristics of PV array are examined by exposing them to partial shade.*
Keywords*: PV cell, PV module, PV string, PV array, Partial shading.*

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I. Introduction

As PV systems are considered as reliable and promising renewable energy sources, they are expected to play the key role in the future among power generation systems. Thus, PV systems are popular research areas. A solar cell is the most basic unit of a PV system. Several solar cells are interconnected in series and/or parallel to compose a PV module. PV modules are connected in series to form a PV string. PV strings are also connected in parallel to form a PV array [1-4].

The output characteristics of PV array(V-I characteristics and V-P characteristics)are not linear and are also highly dependent on environmental conditions. Environmental conditions are identified by some factors such as solar irradiation(G), ambient temperature (T) and partial shading condition of PV array. Since the output characteristics of a PV array aren't linear, it is complicated to understand them. That is why there are a variety of methods developed for performance analysis of a PV array. In the literature these methods are generally seen as analytical equations which are used to model the equivalent circuit of a PV cell [5-15]. Preferred option for performance analysis of a PV array is the use of an equivalent circuit. A good equivalent circuit should be as simple as possible. The results obtained in the modeling of equivalent circuit and the electrical characteristic provided by manufacturer data sheet should show a good agreement. The model of equivalent circuit should also accurately be able to simulate the changes in environmental conditions.

In this paper, a solar cell unit is mathematically modeled, and its behavior is simulated in detail by using Matlab/Simulink. The effects of the environmental conditions, series resistance and shunt resistance on the output characteristics of the cell are investigated. The equations of open-circuit voltageV_{oc} and short-circuit currentI_{sc} of the solar cell are acquired and these equations are used for simulations. The open circuit voltage and short-circuit current parameters' sensitivity to environmental changes are analyzed through simulation. The PV module equations are designed based on the PV cell standard equations. Then, an electrical PV array is developed by using electrical PV modules for simulating partially shaded conditions. Section 2 presents an elaborate mathematical modeling and simulation study of a PV cell. Section 3 analyses the open-circuit voltage and short-circuit current of a PV cell. Section 4 shows the procedure for modelling a PV module, an electrical PV source and partial shading conditions. Finally, the obtained results are evaluated.

II. PV Cell

In this section, an elaborate mathematical modeling and simulation study of a PV cell are presented. The solar cell is the most basically a semiconductor diode disposed to irradiance. The solar cells are made up of semiconductor by using the different procedure of production [16]. Solar irradiance consists of photons containing different levels of energy, some of which are absorbed in the p-n junction. The photons with the energy less than the bandgap of the solar cell are useless. Those photons can't generate the voltage and the electrical current. The photons, which have much more energy than the bandgap, generate energy but the energy is only used at a level equal to the bandgap. The remaining energy is dissipated as heat in the body of the PV cell [17-18].

The equivalent circuits commonly used for modelling of a PV cell are known as single-diode and two-diode models. The single-diode and two-diode models of a PV cell are as shown in Fig.1 and Fig.2 respectively. The two-diode equivalent circuit has a more complex structure and exhibits more nonlinear characteristics than the single-diode equivalent circuit. Therefore two-diode models are rarely used. Single-diode models are commonly used models as a good trade-off between accuracy and simplicity[4,19,20].

In this paper, single-diode equivalent circuit model is preferred, and DS-100 M PV module is taken as reference model for practical comparison. The DS-100 M PV module datasheet parameters are given as rated power 100W, voltage at maximum power point (MPP) 18V, current at MPP 5.55A, open circuit voltage 21.6V, short circuit current 6.11A, the number of cells in series $(\mathrm{N_s})$ 36, the number of cells in parallel $(\mathrm{N_p})$ 1, maximum system voltage 1000V, the short circuit current/temperature coefficient $(\mathrm{K_i})$ 0.002 and range of operation temperature-40°C - 80°C. The datasheet parameters of a PV module are given at standard test conditions (STK; $25℃$ and$1000\ \mathrm{W/m^2}$) [18].

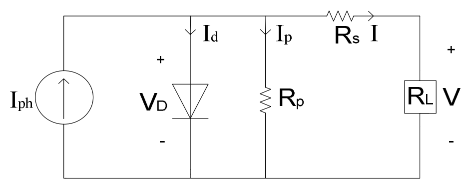


Fig.1 The single diode equivalent circuit model of a solar cell.

The basic equations expressing the single diode PV cell:

$$I = I_{ph} - I_d - I_p \tag{1}$$

$$I_{ph} = \left(I_{pho} + K_i(T - T_o)\right)\frac{G}{G_o} \tag{2}$$

$$I_d = I_s\left(e^{\frac{V_D}{AV_t}} - 1\right) \tag{3}$$

$$I_s = I_{so}\left(\frac{T}{T_o}\right)^3 e^{\frac{qE_g}{Ak}\left(\frac{1}{T_o}-\frac{1}{T}\right)} \tag{4}$$

$$V_D = IR_s + V \tag{5}$$

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

$$I_p = \frac{IR_s + V}{R_p} \tag{7}$$

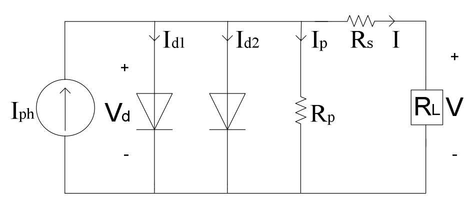


Fig.2 The two diode equivalent circuit model of a solar cell.

The characteristic equation for two diode model is as given in the Eq.(8).

$$I = I_{ph} - I_{d1} - I_{d2} - I_p \tag{8}$$

Where,

$$I_{d1} = I_{s1}\left(e^{\frac{V_D}{A_1V_t}} - 1\right) \tag{9}$$

$$I_{d2} = I_{s2}\left(e^{\frac{V_D}{A_2V_t}} - 1\right) \tag{10}$$

Adding one more diode to the single diode model improves the accuracy of the model but it makes the equation more complex and more nonlinear and also increases the computational time required [4].

I_{ph}: Photon current

I_d, V_D: diode current and diode voltage

V_t: Diode thermal voltage

I_p: leakage current flowing through the shunt resistance
R_p: Shunt resistance
R_s: Series resistance
I: Output current of the PV cell (A)
V: Output voltage of the PV cell (V)
I_{sc}: short circuit current (A)
V_{oc}: open circuit voltage (V)
G: Solar irradiation (W/m^2)
T: Operating cell temperature (K)
K_i: the short circuit current/temperature coefficient
I_s: Diode saturation current(A)
q: Electron charge ($1{,}6 * 10^{-19}$Coulomb)
k: Boltzman constant ($1{,}38 * 10^{-23}$J/K)
E_g: Band gap energy of the semiconductor (1.1eV)
A: The ideality factor of the diode (used for convergence to the actual diode characterictics.)
The subscript "0" stands for the value in STC of the variable.

Before the behavior of a PV cell is simulated, its open circuit condition and short circuit condition should be investigated. The short circuit model of a PV cell at STC is as shown in the Fig.3. According to the analysis of Fig.3 photo current in STC I_{pho} is approximately equal to short circuit current in STC(Eq.(11)),because the series resistance $R_s$given in the Fig.3 is very low.

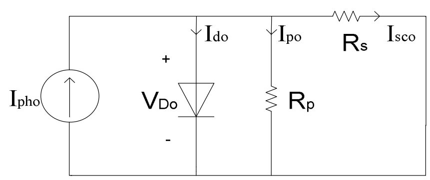


Fig.3 The short circuit model of a solar cell in STC.

$$I_{pho} \cong I_{sco} \tag{11}$$

Eq.(12) is obtained by replacing$\mathrm{I_{pho}}$ in Eq.(2) with $\mathrm{I_{sco}}$ in Eq.(11).

$$I_{ph} = [I_{sco} + K_i(T - T_o)]\frac{G}{G_o} \tag{12}$$

The open circuit model of a PV cell at STC is as shown in the Fig. 4. According to this model, the open circuit voltage in STC V_{oco} is equal to the diode voltage ($V_{oco} = V_{Do} = 0.6$ V(the diode threshold voltage)). As written in Eq.(13) almost all photon current flows through the diode and the current flowing through the shunt resistance is zero ($I_{po} \cong 0$).

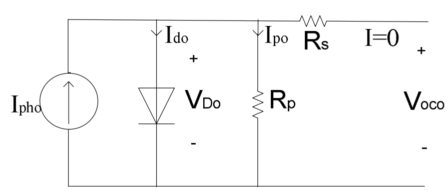


Fig.4 The open circuit model of a solar cell in STC.

$$I_{pho} \cong I_{do} \tag{13}$$

The equation of short circuit current ($\mathrm{I_{sco}}$) can be written by interconnecting Eq.(3), Eq.(11) and Eq.(13) as the following. The expression for calculating the diode saturation current in STC (Eq.(14)) can be obtained from the equation of $\mathrm{I_{sco}}$.

$$I_{sco} \cong I_{do}$$

$$I_{do} = I_{so}\left(e^{\frac{V_{Do}}{AV_{to}}} - 1\right)$$

$$I_{sco} = I_{so}\left(e^{\frac{\mathrm{V_{Do}}}{AV_{to}}} - 1\right)$$

$$I_{so} = \frac{I_{sco}}{\left(e^{\frac{V_{oco}}{AV_{to}}} - 1\right)} \tag{14}$$

Finally, the expression for calculating the diode saturation current (Eq.(15)) is acquired by replacing I_{so} in Eq.(4) by Eq.(14).

$$I_s = \frac{I_{sco}}{e^{\frac{V_{oco}}{AV_{to}}} - 1}\left(\frac{T}{T_o}\right)^3 e^{\frac{qE_g}{Ak}\left(\frac{1}{T_o}-\frac{1}{T}\right)} \tag{15}$$

In this way mathematical modelling of a PV cell can be achieved by using only datasheet information provided by manufacturers. Fig.5, Fig.6 and Fig.7 are the simulation models of a PV cell made of Eq.(1), (3), (5), (6), (7), (12) and (15) by using Matlab/Simulink. A resistive load has been connected to the cell terminals in Fig.5. So, the output voltage of the cell can be expressed as $V = I * R_{load}$. The value of R_{load} in the Fig.5 is made of repeating sequence block in the Simulink to obtain characteristics of V-I and V-P. Under normal operation conditions, $R_{load}$is made of the constant block in the Simulink.

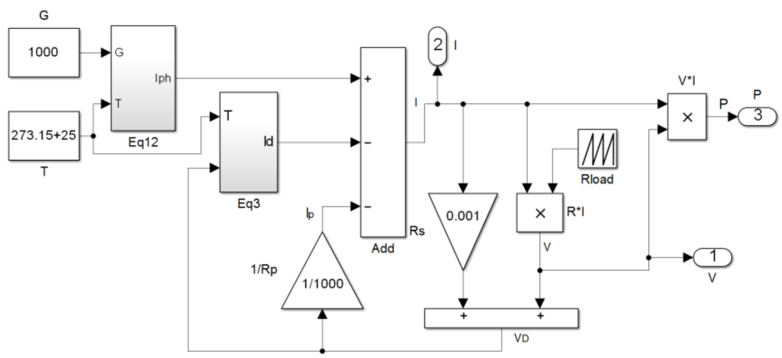


Fig.5 The Matlab model of the PV cell.

The sub blocks of the Eq3 block and the Eq12 block in the Fig.5 are as shown in Fig.6 and Fig.7, respectively.

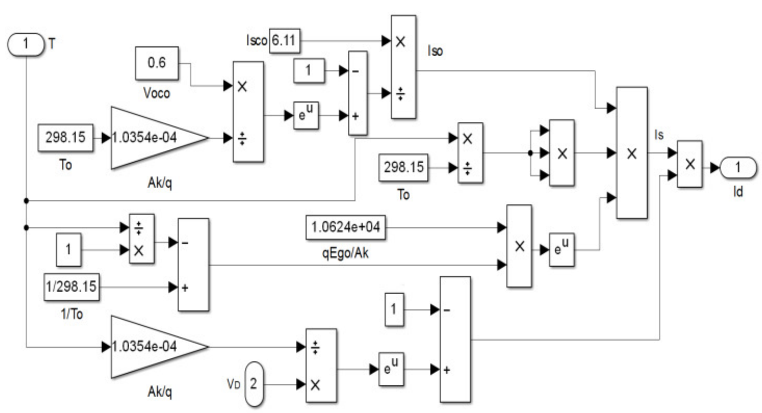


Fig.6 The sub blocks of the Eq3 block.

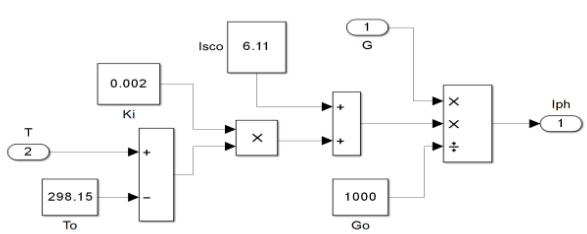
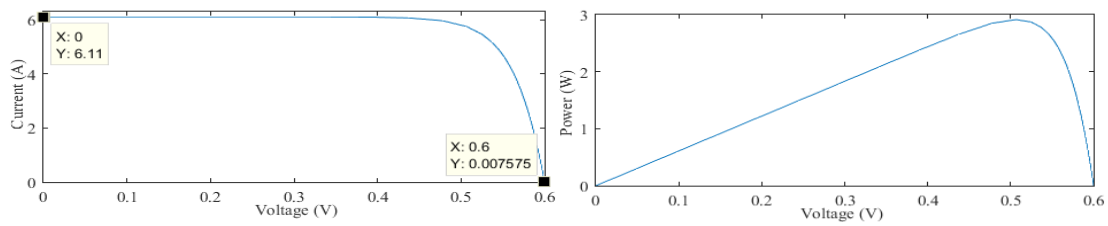


Fig.7 The sub blocks of the Eq12 block.

The characteristics of V-I and V-P of the PV cell in STC are obtained by using the model given in the Fig.5 above and are shown in the Fig.8(a) and (b), respectively. The open-circuit voltage value and the short-circuit current value of the PV cell are respectively 0.6V and 6.11A, as shown in Fig.8(a). Those values coincide with the datasheet parameters. The effect of the change in parameters like solar irradiation(G), temperature(T), series resistance(R_s)and shunt resistance(R_p)on the characteristics of V-I and V-P of the PV cell is given in Fig.9.



(a) (b)

Fig.8 Output characteristics of the PV cell; (a)V-I characteristic and(b) V-P characteristic.

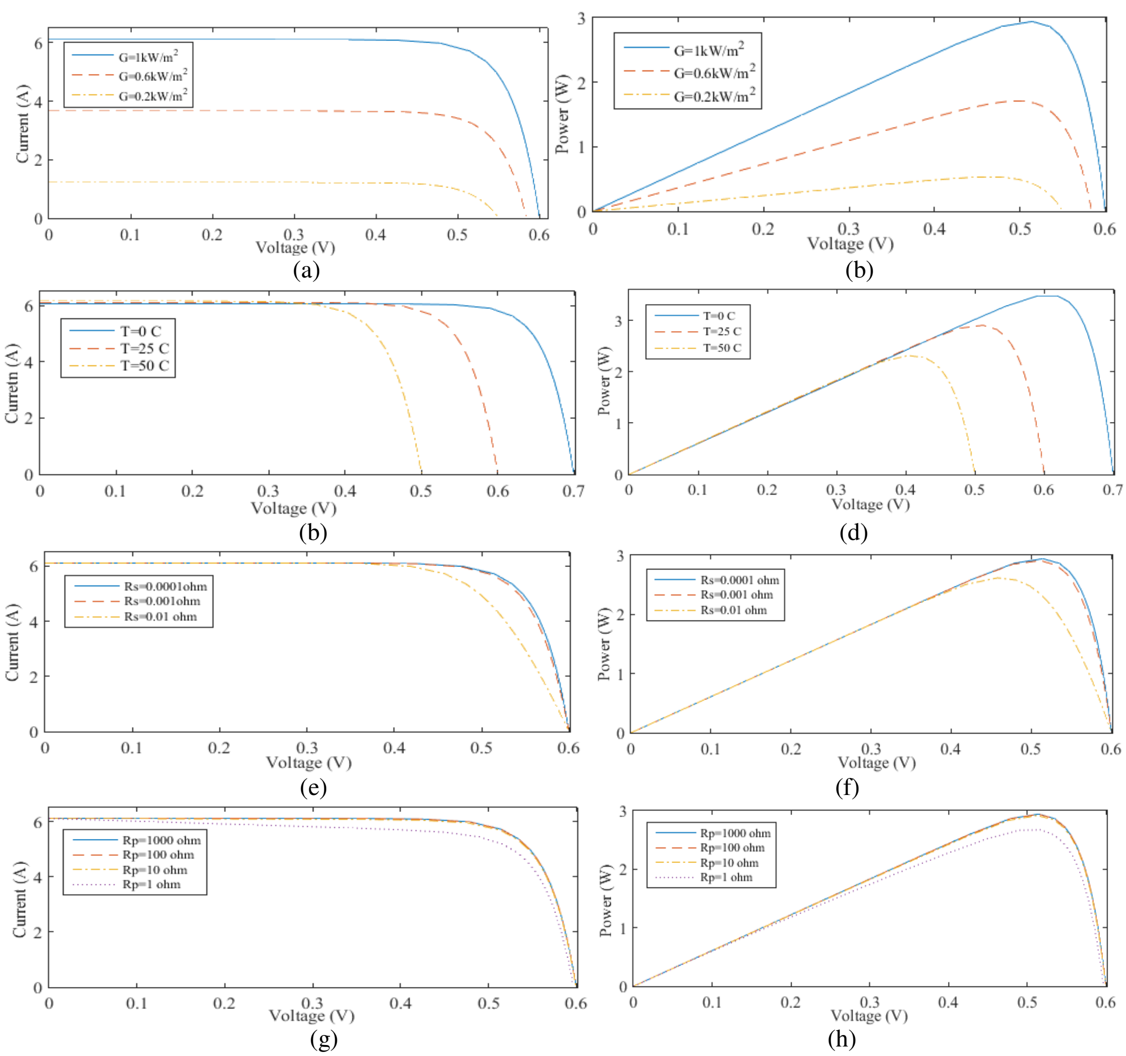


Fig.9 The effects of the change in the parameters like Solar irradiation, temperature , series resistance and shunt resistance on the characteristics of V-I and V-P of the PV cell; (a)V-I characteristic with changing solar irradiation, (b) V-P characteristic with changing solar irradiation, (c)V-I characteristic with changing temperature,(d)V-P characteristic with changing temperature, (e) V-I characteristic with changing series resistance,(f)V-P characteristic with changing series resistance,(g)V-I characteristic with changing shunt resistance and(h) V-P characteristic with changing shunt resistance.

It can be seen from Fig.9(a) and (b) that the amount of current, voltage and power increase is in proportion to the solar irradiation increase. If there is an increase in ambient temperature, the values of voltage and power will decrease. For that case given by Fig.9(c) and (d), there is a slight increase in the current value. As shown Fig.9(e) and (f), the output power of the cell increases when the series resistance value is decreased, and in Fig.9(g) and (h), the output power of the cell decreases when the shunt resistance value is decreased. To illustrate the changes in the graph numerically; when R_s is increased by 100 times, the power is decreased by 11percent and when R_p is decreased by 1000 times, the power is also decreased by 9 percent.

III. Analysis Of Open Circuit Voltage And Short Circuit Current In A PV Cell

The models of open circuit and short circuit of a PV cell in STC were given in section 2. In this section, the influences of solar irradiance and temperature on the value of the open circuit voltage(V_{oc}) and the value of the short circuit current(I_{sc}) are analyzed. The Eq.(11) can be rewritten by generalizing the expression given in STC for any short circuit conditions given in Eq.(16)

$$I_{ph} \cong I_{sc} \tag{16}$$

Eq. (17) can be obtained by replacing the photon current (I_{ph}) in Eq.(12) with the short circuit current (I_{sc}) in Eq.(16).

$$I_{sc} = [I_{sco} + K_i(T - T_o)]\frac{G}{G_o} \tag{17}$$

When solar radiation and temperature change, the new short-circuit current value can be found using Eq.(17). When the solar irradiation is changed between 0 to 1500 W/m^2 and temperature is changed between 270 – 350 K, the change of the short-circuit current $I_{sc}$is shown in Fig.10(a) and (b), respectively. According to Fig.10(a), the short-circuit current is directly proportional to solar irradiation. In the case of temperature change, the change in the short-circuit current is quite small as shown in Fig.10(b).

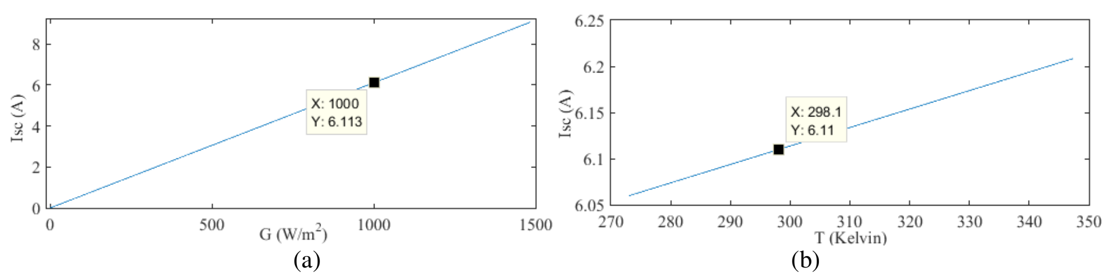


Fig.10 The influence of solar irradiation and temperature on the value of the short-circuit current; (a) the influence of solar irradiation, (b) the influence of temperature.

Eq.(13) can be rewritten for any open-circuit conditions as given Eq.(18).

$$I_{ph} \cong I_d \tag{18}$$

The diode voltage (Eq.(20) can be obtained from Eq.(19)occurred when the photon current in Eq.(18) is written instead of the diode current in Eq.(3)

$$I_{ph} = I_s\left(e^{\frac{V_D}{AV_t}} - 1\right) \tag{19}$$

$$\frac{I_{ph} + I_s}{I_s} = e^{\frac{V_D}{AV_t}}$$

$$\ln\left(\frac{I_{ph} + I_s}{I_s}\right) = \frac{V_D}{AV_t}$$

$$V_D = \frac{AkT}{q}\ln\left(\frac{I_{ph}}{I_s} + 1\right) \tag{20}$$

When the cell is open circuit,$\mathrm{V_D} = \mathrm{V_{oc}}$.

$$V_{oc} = \frac{AkT}{q}\ln\left(\frac{I_{ph}}{I_s} + 1\right) \tag{21}$$

When solar radiation and temperature change, the new open-circuit voltage V_{oc}value can be found using Eq.(21). When the solar irradiation and temperature are changed, the change of the open-circuit voltage is shown in Fig.11(a) and (b), respectively. It can be seen from Fig.11 that in the case of solar irradiance change, the change in the open circuit voltage is quite small but in the case of temperature change, the open-circuit voltage changes in reverse proportion.

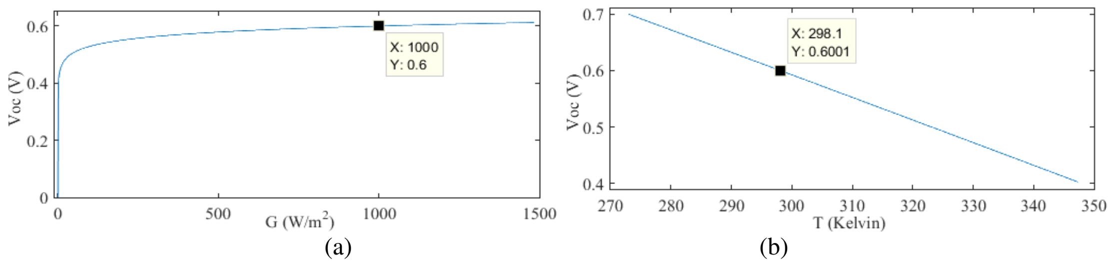


Fig.11 The influence of solar irradiation and temperature on the value of the open circuit voltage; (a) the influence of solar irradiation, (b) the influence of temperature.

In the maximum power point tracking (MPPT) methods based on open circuit voltage and/or short circuit current, the modules must be open-circuited and/or short-circuited to measure V_{oc} and/or I_{sc} in a certain period of time. Those causes serious power losses at the output. Moreover, these methods are not efficient in changing atmospheric conditions. Due to these drawbacks, MPPT methods based on open circuit voltage and/or short circuit current are not preferred [4,22,23].When Eq.(17) and Eq.(21) are used, both current and voltage sensors will not be used, V_{oc}andI_{sc}can be measured without cell short circuit or open circuit, and new open circuit voltage and short circuit current values can be easily calculated under the changing atmospheric conditions. Therefore, the maximum power point tracking cost and power losses will be reduced and the efficiency will be increased.

IV. PV Module, PV String and PV Array

The cells are connected in series and parallel in order to increase the output current and voltage. The output current is increased by connecting the cells in parallel or the cell surface area is increased, and the output voltage is increased by connecting the cells in series [20].PV cells are connected in series and parallel to form PV module. PV modules are connected in series to form PV string. PV strings are connected in parallel to form a higher power rated PV array. In this way, a PV generator can be created at the desired power level (cell, module, string, and array). In a PV module; The following equations can be written if N_s is taken as the number of series connected cells in a one arm, N_p is the number of parallel connected arms, V_M is the module voltage, I_M is the module current, V_{DM} is the total diode voltage in one arm and I_{pM} is the total leakage current.

$$V_M = N_s V \tag{22}$$
$$I_M = N_p I \tag{23}$$
$$V_{DM} = N_s V_D \tag{24}$$
$$V_{DM} = \frac{N_s}{N_p} R_s I_M + V_M \tag{25}$$
$$I_{pM} = N_p I_p \tag{26}$$
$$I_{pM} = \frac{\frac{N_s}{N_p} R_s I_M + V_M}{\frac{N_s}{N_p} R_p} \tag{27}$$

When a cell is enlarged to a module, the module current and voltage values are expressed by the equations given above. In that case, the equivalent circuit for the PV module can be represented as in Fig12.

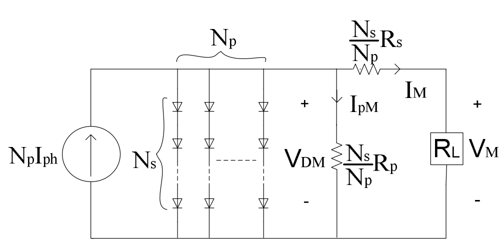


Fig.12 Equivalent circuit of a PV module.

The simulation model of the PV module given in Fig.13 was created by adding the above equations to the simulation model of a cell given in Fig.4. The module model has been tested with the cell numbers in PV referenced in this work (N_s=36 andN_p=1).In Fig.14, the V-I characteristic obtained from the module simulation is given and it is seen that the parameter values (I_{sc}=6.11A andV_{oc}=21.6V) matches with the datasheet. In the next step, the module was created using N_s=36 and *Np*=2. In this case, the change of the output characteristic of the PV module with solar radiation and temperature was examined and the results are given in Fig.15. As seen in

Fig.15 when a cell is expanded to a module, the output characteristics of the cell change in proportion to N_s andN_p.With this simulation method, a PV module with the desired output characteristic can be composed.

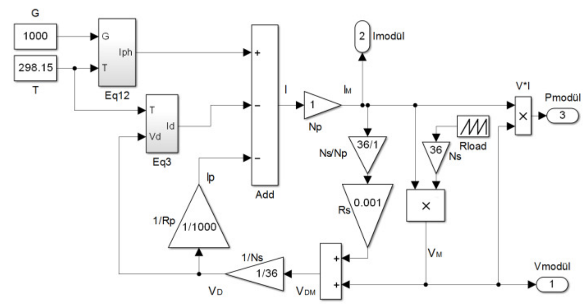


Fig.13 The Matlab model of a PV module.

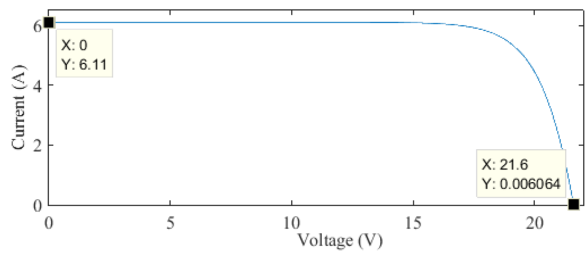


Fig.14 The V-I characteristics of the PV module (for N_s=36 andN_p=1).

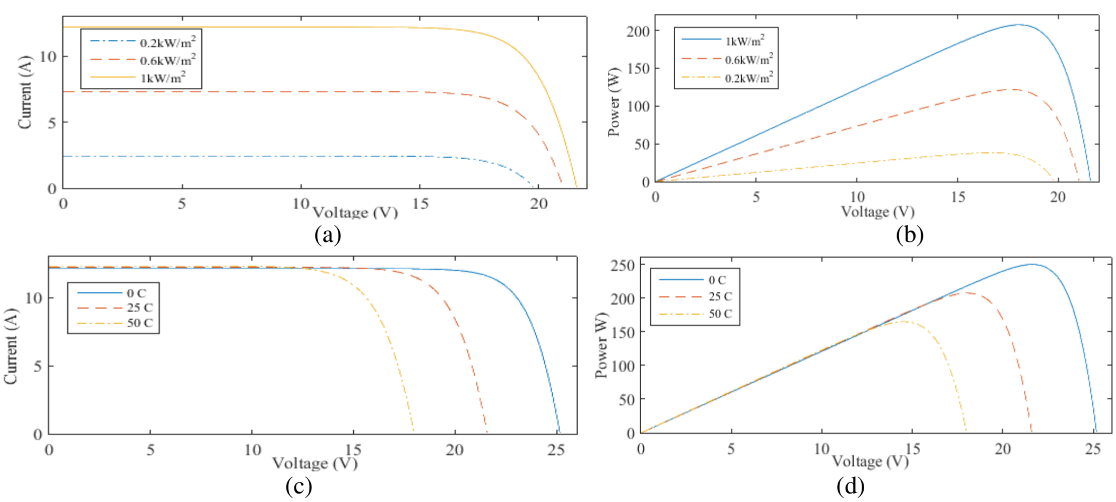


Fig.15 The V-I and V-P characteristics of the PV module under the changing solar irradiation and temperature(for N_s=36 and N_p=2)(a) and(b) the effect of the solar cell and (c) and(d)the effect of the temperature.

The models shown in Fig.5 and Fig.13 are designed to obtain V-I and V-P characteristics with general Simulink blocks. Unlike these models, the electrical model given in Fig.16 has been created in order to be able to carry out analysis of multi-cell and multi-module usage situations. The module current obtained in the designed model is converted to an electrical signal by applying it to a controlled current source input. In addition, a parallel bypass diode is added to the PV module. In this way, the PV modules modeled as blocks are connected in series and parallel to obtain the PV array unit. In Fig.17, a PV array is obtained by connecting two strings in parallel. These strings are made up of three PV modules connected in series. As shown in Fig.17 each string has a diode connected in series. These diodes are blocking diodes. Blocking diodes are used to protect PV modules from the potential difference between strings [1,2, 26].Higher-level analyses can be made by connecting load resistor or different power converter circuits to the terminals of the PV array. In this study, a controlled voltage source representative of the varying voltage on the resistor is connected to the terminals of the array to obtain the V-I and V-P curves of the PV array.

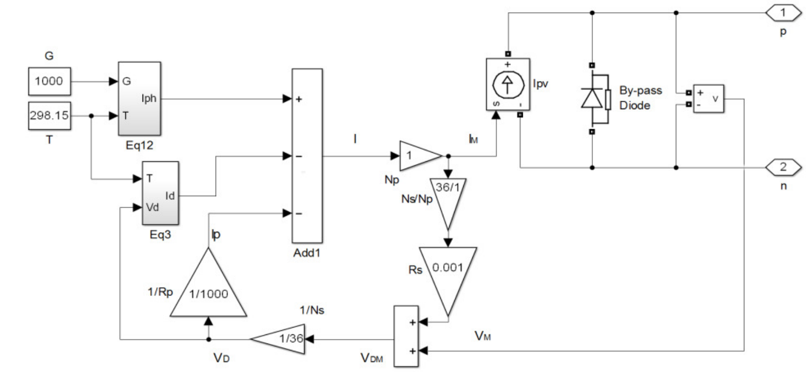


Fig.16 The electrical Matlab model of a PV module.

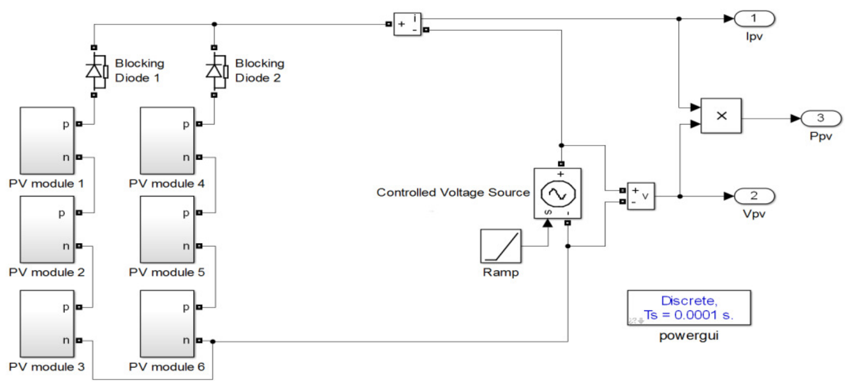
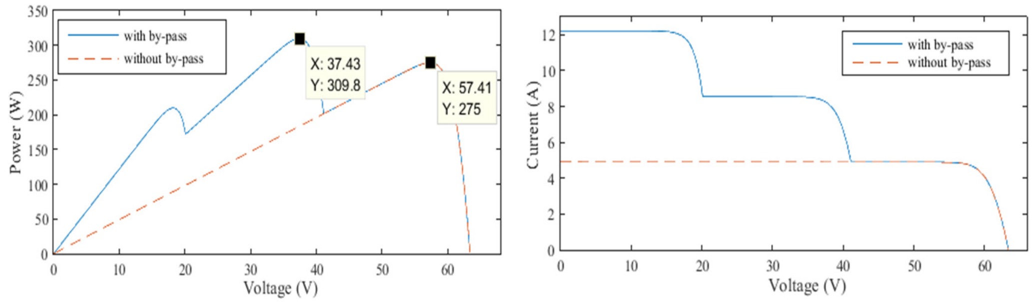


Fig.17 PV array model.

Some modules of a PV array can sometimes not receive the same solar irradiation as other modules due to several reasons such as the clouds passing over them and the shading of nearby trees and buildings. This is called partial shading. When a module is shaded, it generates less current than other modules. So, the shaded module behaves like a load to the array. Normally, the current of all series connected modules (the current of single string) will only cause a voltage drop across the total series resistances (3**Rs*). If a module is shaded, the shaded module also causes a voltage drop across the shunt resistance (*Rp*). Because the Rp value is too large, an excessive voltage drop and power loss will occur in the shaded module. This causes the module to overheat and reduce its efficiency. This problem is called hot spot problem. If the temperature exceeds a certain limit, it permanently damages the module. The module is always in a load state after that. This problem can be solved by adding a bypass diode to each module end. On series-connected modules, the current on the shaded module will flow through the bypass diode [3,24,25].The model shown in Fig.17 is used to examine with and without the by-pass diode output characteristics of a partially shaded PV array. In both of the strings in the model; In STC, a partial shading condition has been established in which the first module is under 400 $\mathrm{W/m^2}$ solar irradiation, the second is 700 $\mathrm{W/m^2}$ solar irradiation, and the third is under 1000 $\mathrm{W/m^2}$ solar irradiation.The simulation results are given in Fig.18. When bypass diodes are used, the characteristic of V-P shows multiple maxima (as shown Fig.18(a)) and the characteristic of V-I shows step downs (as shown Fig.18(b)).Looking at the V-P curve in the Fig.18(a)), it can be seen that the MPP with the by-pass diode (309.8 W) is larger than the MPP without bypass diodes (275 W).Accordingly, it can be said that the use of bypass diodes removes the hot spot problem in the case of partial shading as well as increases maximum power, which can be obtained from the PV array. It can also be said from Fig.18(b) that the open circuit voltage and the short circuit current of the array do not change in the case of partial shading. The disadvantage of the peaks in the V-P curve when bypass diodes are used is that the maximum power point tracking methods are difficult to work with. The methods used should not be trapped at any local peaks; they have to find the global peak.



(a) (b)

Fig.18 The characteristics of PV array under partial shading conditions(a) V-P characteristic, (b) V-I characteristic.

V. Conclusion

In this paper, the mathematical model of the single diode PV cell is obtained by only using information provided by the manufacturer datasheet and its behavior is simulated by using the Matlab/Simulink. The effects of the change of solar irradiation, temperature, the series resistance and the shunt resistance on the characteristics of the PV cell are investigated. The equations of open-circuit voltage and short-circuit current of the solar cell are acquired and these equations are used for simulations. The open circuit voltage and short-circuit current parameters' sensitivity to environmental changes are analyzed through simulation. The results obtained from the simulation model and the results provided by manufacturer data sheet show a good agreement. PV cells are connected in series and parallel to form PV module. PV modules are connected in series to form PV string. PV strings are connected in parallel to form a higher power rated PV array .In this way, how to achieve the desired power level(module, string, array) from cellular power level is shown. The results of PV module simulation match with its data sheet information. Moreover, a partial shading condition of a PV array is simulated and its output characteristics are investigated in detail.

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