

Improvement of the MATLAB/Simulink Photovoltaic System Simulator Based on a Two-Diode Model

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Abstract— This paper presents modeling and simulation for the PV cells, modules, and array, and building of blocks based on MATLAB / Simulink software package. The main aim of this work is the improvement of the PV solar cell simulator based on a two-diode model. This model is more accurate than the single diode model especially at low insolation levels; therefore this will give more accurate prediction of the performance of the solar cell system. Most of the inputs to the simulator are given in the PV module datasheet, and the other (i.e. R_p and R_s) are estimated by an iteration method. The simulation model makes use of the two-diode model basic circuit equations of PV solar cell, taking the effect of sunlight irradiance and cell temperature into consideration on the output current V-I and output power V-P characteristics. The output current and power characteristics of PV module and PV array are simulated using the proposed model. The simulator is verified by applying the model to Kyocera Solar KC200GT and Solarex MSX-64 PV Modules.

Index Terms— Modeling, PV module/ Array, Simulation, MATLAB/Simulink

I. INTRODUCTION

A photovoltaic (PV) power generation has an increasing importance in the renewable energy market place due to this ability to quietly produce emission free power at the load. PV cells generate electric power by directly converting solar energy to electrical energy with no pollutant emission. Since the voltage and current output of a single PV cell is too small for practical usage, PV generation systems usually consist of series- parallel combinations of PV cells in order to obtain the required voltage and current output. These combinations, known as PV modules (or panels) and arrays, generate DC power that has to be converted to AC at standard power frequency in order to feed the loads.

The output characteristics of PV module depend on the solar insolation, the cell temperature and the output voltage of PV module. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications. The mathematical PV models used in computer simulation have been built for over the past four decades [1]-[3]. The most important contribution of this work is the execution of a generalized PV model for the modules and arrays using MATLAB/ Simulink based on the two- diode PV cell model.

The most important component that affects the accuracy of a simulation is the PV cell modeling, which primarily involves the estimation of the non-linear I-V and P-V characteristics curves. The simplest model is the single- diode model i.e. a single diode connected in parallel with a photocurrent source I_{pv} , a shunt resistor R_p expressing a leakage current, and series resistor R_s describing an internal resistance to the current flow [4] as shown in Figure (1). It requires five parameters, namely the short-circuit current (I_{sc}), the open circuit voltage (V_{oc}), the diode ideality factor (A), the shunt resistor (R_p), and the series resistor (R_s). This model has a significant improvement in comparison with the old models, but it demands significant computational effort.

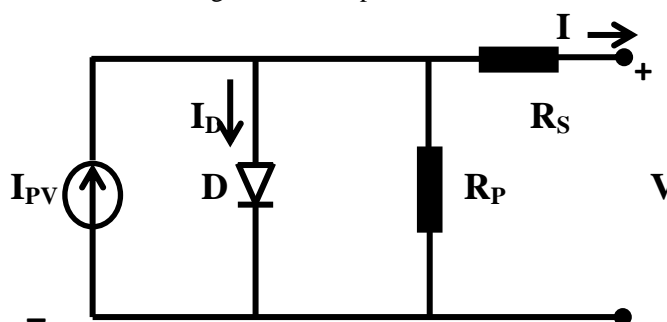


Figure (1) Single-diode model with R_s and R_p of PV solar cell

The single diode equation assumes a constant value for the ideality factor A . In reality the ideality factor is a function of voltage across the device. At high voltage, when the recombination in the device is dominated by the surfaces and the bulk regions the ideality factor is close to one. However at lower voltages, recombination in the junction dominates and the ideality factor approaches two. In fact, this cannot be perfectly modeled by a single-diode. The junction recombination is modeled by adding a second diode in parallel with the first one of Figure (1), this will lead to a more perfect model known as the two-diode model [5]. The inclusion of an additional diode increases the model parameters (i.e. I_{pv} , I_{o1} , I_{o2} , R_p , R_s , A_1 , and A_2). The main aim now is how to reducing the model parameters, and that is done by calculating the values of some parameters (i.e. R_p and R_s) and assuming the values of some parameters like (A_1 , and A_2).

In this paper, an improved modeling technique for the two-diode model is proposed. This model is known to have better accuracy, especially at low irradiance levels. However, previous researchers have avoided the use of this model in their PV simulators; this

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is because of the increasing in computational time. The input to the simulator is information available in a standard PV module datasheet. The performances of the model are compared against the single- diode model [6] including R_s and R_p (Figure (1)) and validated with references KC200GT and MXS-64 PV Modules. A PV model simulator is built using MATLAB/ Simulink to illustrate and verify the nonlinear V-I and V-P characteristics of the PV systems. Section II presents the equivalent circuit models of the PV solar cell device, equations for (I) the output current from the PV module based on a two-diode model and the numerical calculation of the PV cell parameter specifications using Newton Raphson method. Kyocera Solar KC200GT and Solarex MSX-64 PV Modules are taken as the reference models for simulation, the building blocks for the PV module and array, simulation results for different temperature T and irradiance λ conditions, and discussion are presented in Section III. Finally conclusion of the modeling process is presented in section IV.

II. MODELING OF PHOTOVOLTAIC CELLS BASED ON TWO-DIODE MODEL

The cell two- diode model equivalent circuit is shown in Figure (2). For a given incident light intensity, at a given temperature, the implicit V-I relationship is given by [7]

$$I = I_{pv} - I_{D1} - I_{D2} - \left(\frac{V + IR_s}{R_p} \right) \quad (1)$$

Where,

$$I_{D1} = I_{o1} \left[\exp\left(\frac{q(V + IR_s)}{A_1 kT} \right) - 1 \right] \quad (2)$$

And,

$$I_{D2} = I_{o2} \left[\exp\left(\frac{q(V + IR_s)}{A_2 kT} \right) - 1 \right] \quad (3)$$

where I_{o1} and I_{o2} are the reverse saturation currents of diode 1 and diode 2 (A), I_{pv} is the light- generated current at nominal condition (25oC and 1000W/ m2), q is the electron charge (1.602x10-19C), V is the voltage across the diode (V), k is Boltzmann's constant (1.3805x10-23J/K), T is the junction temperature (K), A_1 and A_2 are the diode 1 and diode 2 ideality factors, R_s is the series resistance of diode (Ω), and R_p is the shunt resistance of diode (Ω). The I_{o2} term in (3), compensate the recombination loss in the depletion region [8].

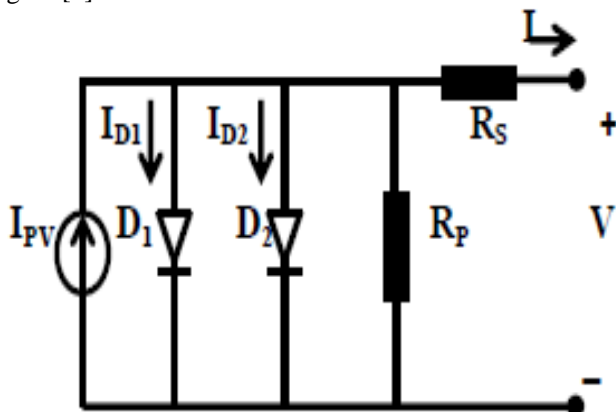


Figure (2) Two-diode model of PV solar cell.

The use of double- diode model make the simulation results more accurate than with a single- diode model, but the difficulties and the simulation time will increase during the computation of seven parameters, namely I_{pv} , I_{o1} , I_{o2} , R_p , R_s , A_1 , and A_2 . For simplicity, we assumed that $A_1= 1$ and $A_2= 2$. This assumption is widely used but not always true [3]. The equation for PV current as a function of temperature and irradiance can be written as

$$I_{pv} = [I_{scr} + K_i(T_k - T_{refk})] \times \lambda / 1000 \quad (4)$$

where K_i is the short- circuit current/ temperature coefficient (A/ K), normally provided by the manufacturer, T_k and T_{refk} are, respectively, the actual and reference temperature in Kelvin ($T_{refk}=298K$), λ is the PV device illumination (W/ m2) = 1000W/ m2, I_{scr} is the PV device short- circuit current at 25oC and 1000W/ m2, and the nominal irradiation is 1000W/m2.

The cell revers saturation current, I_{rs} , is given by:

$$I_{rs} = I_{scr} / [\exp(qV_{oc} / AkT) - 1] \quad (5)$$

where V_{oc} is the open- circuit voltage (V).

The cell saturation currents I_{o1} and I_{o2} vary with the temperature, for simplicity we take I_{o1} and I_{o2} are equal, and given by:

$$I_{o1} = I_{o2} = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp\left[\frac{q \times E_{go}}{Ak} \left\{ \frac{1}{T_r} - \frac{1}{T} \right\} \right] \quad (6)$$

Where, E_{go} is the band gab energy of the semiconductor ($E_{go} \approx 1.1eV$ for the polycrystalline Si at 25oC).

The values of R_p and R_s are calculated by numerical iteration. In this paper, R_p and R_s are calculated simultaneously, similar to the procedure produced in [3]. The idea is to maximize the power point (P_{mp}) matching; i.e. to match the calculated peak power ($P_{mp,C}$) and the experimental peak power ($P_{mp,E}$) by iteratively increasing the value of R_s while simultaneously calculating the value of R_p . At maximum power point condition, equation (1) can be rewritten as:

$$R_p = \frac{V_{mp} (V_{mp} + I_m R_s)}{[V_{mp} \{ I_{pv} - I_{D1} - I_{D2} \} - P_{max,E}]} \quad (7)$$

Substituting the open- and short- circuit conditions to find initial conditions for both resistances and that are given below:

$$R_{so} = 0; \quad R_{po} = \frac{V_{mp}}{I_{scn} - I_{mp}} - \frac{V_{ocn} - V_{mp}}{I_{mp}} \quad (8)$$

KC200GT [4] and Solarex MSX-64 [6] PV modules are chosen for illustration to obtain the correct value of R_s . R_s is increased until $P_{max;C}$ becomes exactly equal to $P_{max;E}$ and the value of R_p is calculated simultaneously using equation (7). Moreover substituting the maximum power point (MPP) conditions we can get the values of (I_{PV} Eq. (4), I_{O1} & I_{O2} Eq. (6).) This mechanism is shown in Figure (3). Now, by using

Newton-Raphson method, the output current of the PV cell can be determined (using eq. (1)).

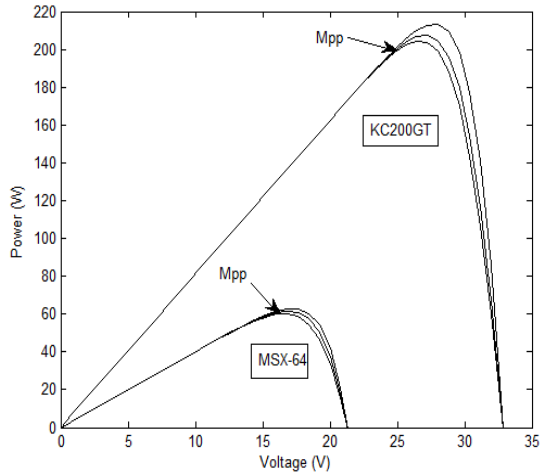


Figure (3) Matching V-P curves methodology for two PV modules

The PV cells are connected in series ($N_s \times N_p$ cells, where $N_p = 1$) to produce the PV module. Basic equation that describes the current output of PV module (I of the two-diode model presented in Figure (2) is given by equation (9)), the PV cell voltage-current relationship in equation (1) is modified for PV module and it is given by:

$$I = N_p \times I_{pv} - N_p \times I_{o1} \left[\exp\left\{ \frac{q \times (V + I R_s)}{N_s A_1 k T} \right\} - 1 \right] - N_p I_{o2} \left[\exp\left\{ \frac{q \times (V + I R_s)}{N_s A_2 k T} \right\} - 1 \right] - \left(\frac{V + I R_s}{R_p} \right) \quad (9)$$

And in a typical installation of a large PV power generation system, the modules are configured in a series parallel structure with any number of PV modules ($N_{ss} \times N_{pp}$ modules) to produce the PV array, as shown in Figure (4), the PV module voltage-current relationship in equation (9) is modified for PV array and it is given by:

$$I = N_{pp} \times I_{pv} - N_{pp} \times I_{o1} \left[\exp\left\{ \frac{q \times (V + I R_s \left(\frac{N_{ss}}{N_{pp}} \right))}{N_{ss} A_1 k T} \right\} - 1 \right] - N_{pp} I_{o2} \left[\exp\left\{ \frac{q \times (V + I R_s \left(\frac{N_{ss}}{N_{pp}} \right))}{N_{ss} A_2 k T} \right\} - 1 \right] - \left(\frac{V + I R_s \left(\frac{N_{ss}}{N_{pp}} \right)}{R_p \left(\frac{N_{ss}}{N_{pp}} \right)} \right) \quad (10)$$

where I_{pv} , I_{o1} , I_{o2} , R_s , R_p , A_1 , and A_2 are the parameters of the individual modules, N_s and N_p are the number of cells connected in series and parallel, respectively, N_{ss} and N_{pp} are the number of modules connected in series and parallel, respectively.

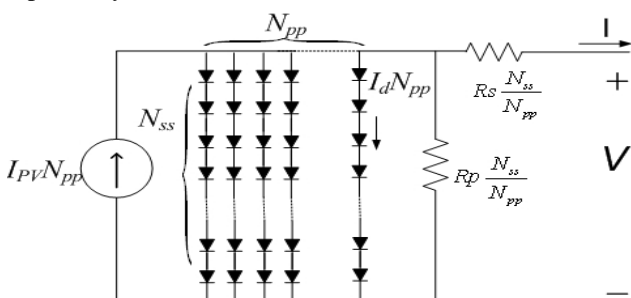


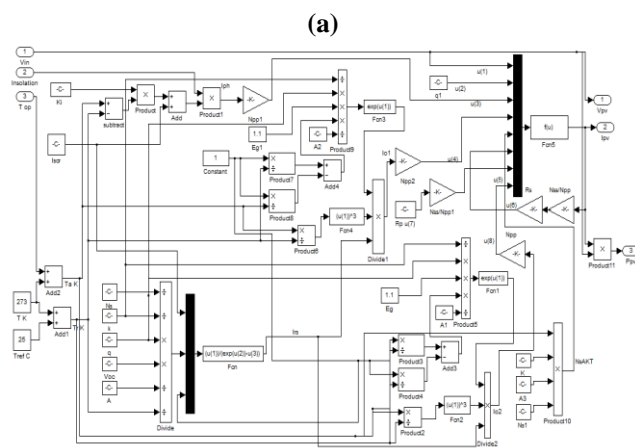
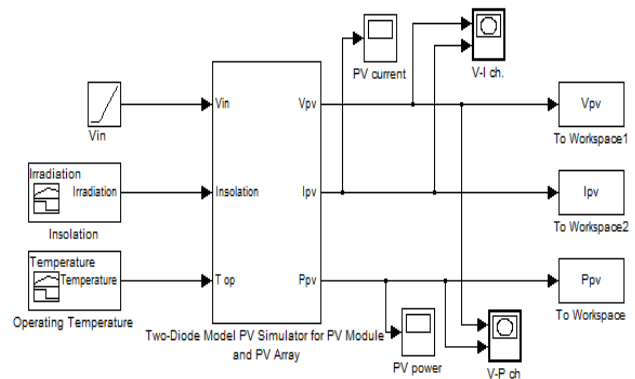
Figure (4) Series parallel connection of modules in a PV array.

III. SIMULINK MODELING FOR PV SYSTEM

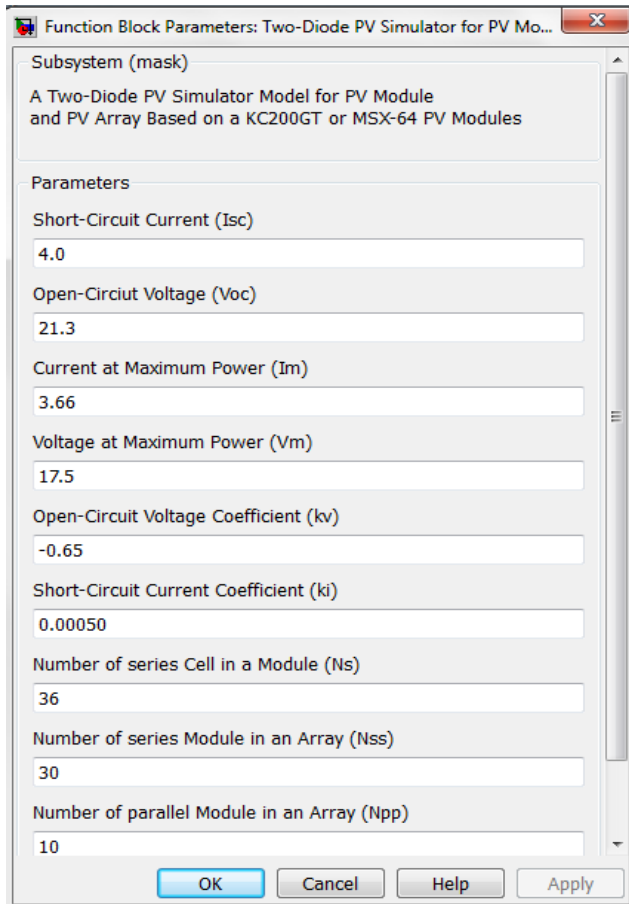
A. Building Of Pv Module And Array

A model of PV module with moderate complexity which includes the temperature independence of the photocurrent source, the ideality-factor A , series resistance R_s , and shunt resistance R_p are considered based on the Shockley diode equation. It is important to build a generalized model suitable for all of the PV module and array, which is used to design and analyze a maximum power point. Being illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity with both V-I and V-P output characteristics.

Figure (5a) shows a building block of a PV Module for any number of series connections of PV cells based on a two-diode model of solar cell. Figure (5b) shows the circuit under the building block based on equation (9). In order to make the PV model easier to use, a mask model for the proposed simulator model is designed to have a dialog box as shown in Figure (5c), in which the parameters of PV module can be configured in the same way for the MATLAB/ Simulink. The simulator of Figure (5) can be modified according to equation (10) to simulate a large PV array for any number of series and parallel connections of PV modules based on a two-diode model of solar cell, by increasing the values of N_{ss} and N_{pp} from one to any number in order to obtain the desired voltage and current. These models take irradiation, operating temperature, and model voltage as input and give the output current I_{pv} , output voltage V_{pv} , and output power P_{pv} . All of the parameters for the inputs are available from the manufacturer's datasheet.



(b)



(c)

Figure (5) (a) Building block of a PV module. (b) Circuit under the building block. (c) Dialog box of the Simulator PV Model (MSX-64).

B. THE SIMULATION RESULTS AND DISCUSSION

1- Pv Cell And Pv Module Simulation

In this paper, the two-diode model is described and validated with Multi- Crystalline Kyocera Solar KC200GT and Solarex MSX-64. The specifications of the modules are summarized in Table I. Table II shows the computational parameter specifications of the proposed two-diode model circuit of Figure (2) that are obtained by the numerical iteration as mentioned above. The computational results are compared with a single diode model circuit of Figure (1). Figures (6 & 7) shows the V-I and V-P characteristics of single- and two-diode models for KC200GT module with different levels of illumination ($\lambda = 200, 400, 600, 800,$ and 1000W/m^2) and constant temperature ($T = 25\text{oC}$). The current is increase with increasing insolation, but the voltage is almost constant, this indicates that the current is proportional to incident sunlight. Therefore the output power also increases when the solar insolation increase as displayed in Figure (7). The proposed two-diode model and the single-diode with R_s and R_p model give similar results. More accurate results are obtained from the two-diode model at low irradiance levels, especially in the neighborhood of the open circuit voltage (V_{oc}). At open circuit voltage, the single-diode model shows a departure from the standard experimental data sheet in [4 & 6]; this suggests that the single-diode model is inappropriate when dealing with low irradiance levels

Description	Multi- Crystalline Kyocera Solar KC200GT	Solarex MSX-64
Maximum voltage (V_m)	26.3V	17.5V
Current at maximum power (I_m)	7.61A	3.66A
Open circuit voltage (V_{oc})	32.9V	21.3V
Short circuit current (I_{sc})	8.21A	4A
Total No. of cells in series (N_s)	54	36
Total No. of cells in parallel (N_p)	1	1
Temperature coefficient of V_{oc} (K_v)	-123mV/°C	-(80±10)mV/°C
Temperature coefficient of I_{sc} (K_i)	3.18mA/°C	(0.065±0.015)%/°C

Table (1) KC200GT and MXS 64 PV modules parameter specifications

Descriptio n	Multi- Crystalline Kyocera Solar KC200GT	Solarex MSX-64
V_m	26.3V	17.5V
I_m	7.61A	3.66A
V_{oc}	32.9V	21.3V
I_{sc}	8.21A	4A
$I_{o1}=I_{o2}$	$1.045 \times 10^{-9}\text{A}$	$2.266 \times 10^{-9}\text{A}$
I_{pv}	8.21A	4A
R_p	158.26Ω	166.13Ω
R_s	0.29Ω	0.34Ω

Table (2) The proposed two- diode PV module Parameter specifications

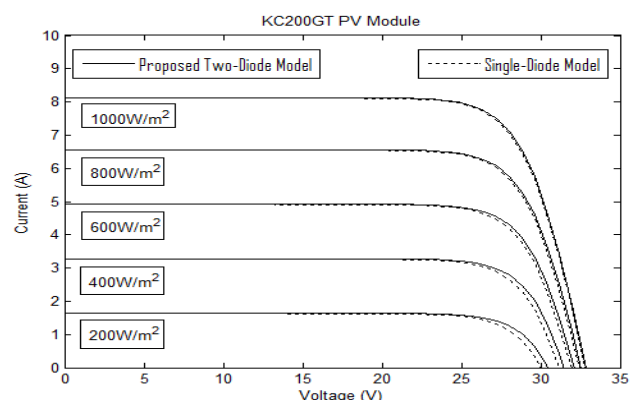


Figure (6) Single- and proposed two-diode model V-I output characteristics of the KC200GT PV module with different λ - constant T .

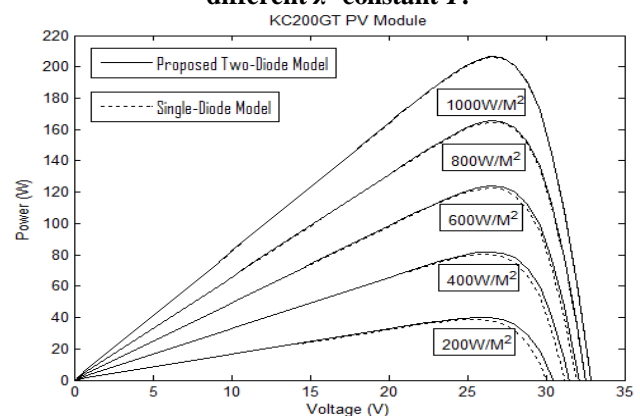


Figure (7) Single- and proposed two-diode model V-P output characteristics of the KC200GT PV module with different λ - constant T .

Figures (8 & 9) shows the V-I characteristics of single- and two-diode models for KC200GT and MSX-64 PV modules, respectively, with different levels of temperature ($T= 0, 25, 50, 75,$ and 100°C) and constant insolation ($\lambda=1000\text{W}/\text{m}^2$). The varying of temperature of the PV module will affects the photo generated and the saturation currents. The diode reverse saturation current of the PV module will increase with increases in temperature and this will reduces the open circuit voltage of the PV module as shown in Figures (8 & 9). As can be seen in Figures (8 & 9), respectively, the V-I curves computed by the two-diode model accurately match the experimental data in [4 & 6]; for all temperature conditions. On the other hand, at higher temperature, the results from the single-diode model depart from the measured values quite significantly.

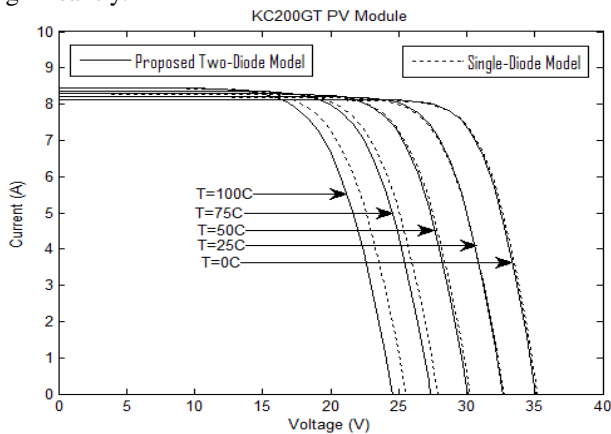


Figure (8) Single- and proposed two-diode model V-I output characteristics of the KC200GT PV module with different T -constant λ .

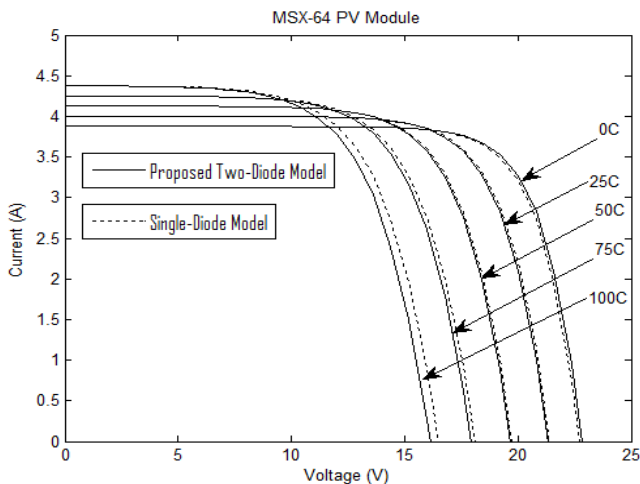


Figure (9) Single- and proposed two-diode model V-I output characteristics of the MSX-64 PV module with different T -constant λ .

2 - PV ARRAY SIMULATION

The Simulink of Figure (5) can be used to simulate a large PV array configuration by defining the inputs N_{ss} and N_{pp} to the number of modules in series and parallel, respectively. Figures (10 & 11) shows the V-I and V-P curves generated for ($N_{ss}= 30 \times N_{pp}=10$) using KC200GT modules with different levels of illumination ($\lambda= 200, 400, 600, 800,$ and $1000\text{W}/\text{m}^2$) and constant temperature ($T=25^{\circ}\text{C}$). As can be seen from the figures, the output current and output power are increases with increasing the sunlight intensity and the number of modules connected in parallel. The voltage is

constant with increasing illumination but it is increases with increasing the number of modules connected in series.

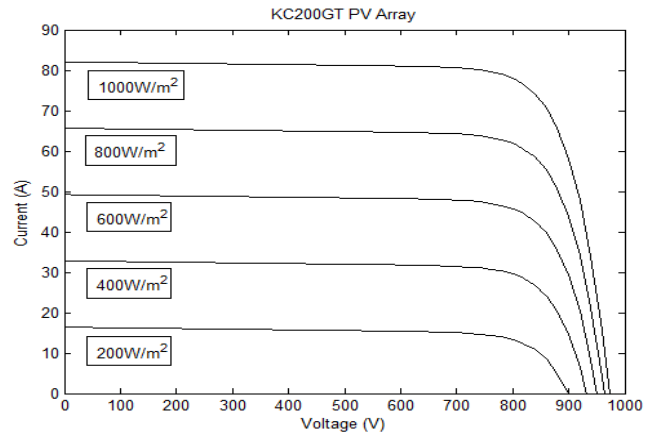


Figure (10) PV array V-I output characteristics for KC200GT module of 30×10 configuration with different constant T .

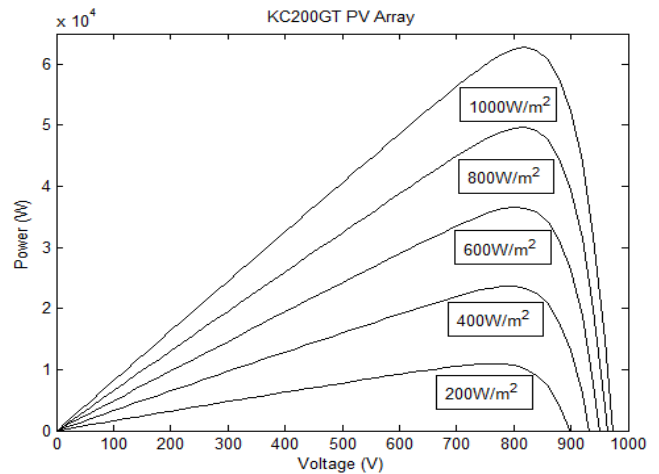


Figure (11) PV array V-P output characteristics for KC200GT module of 30×10 configuration with different λ -constant T .

The effects of temperature variations (for $T= 25, 50, 75,$ and 100°C) on the V-I and V-P curves of the PV array ($N_{ss}=30 \times N_{pp}=10$) using KC200GT module are shown in Figures (12 & 13).

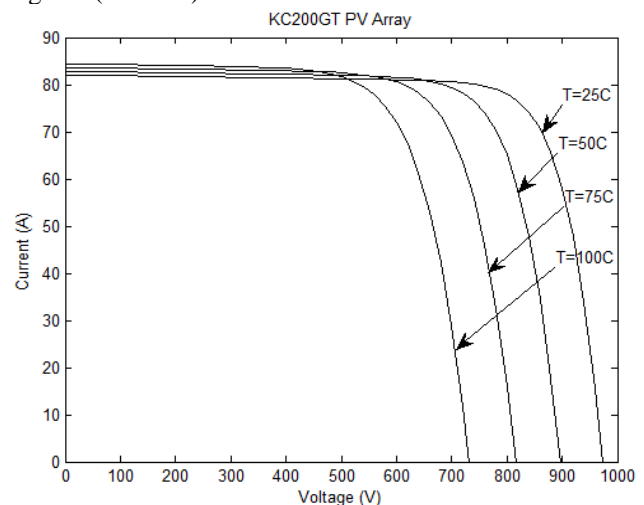


Figure (12) PV array V-I output characteristics for KC200GT module of 30×10

configuration with different T - constant λ .

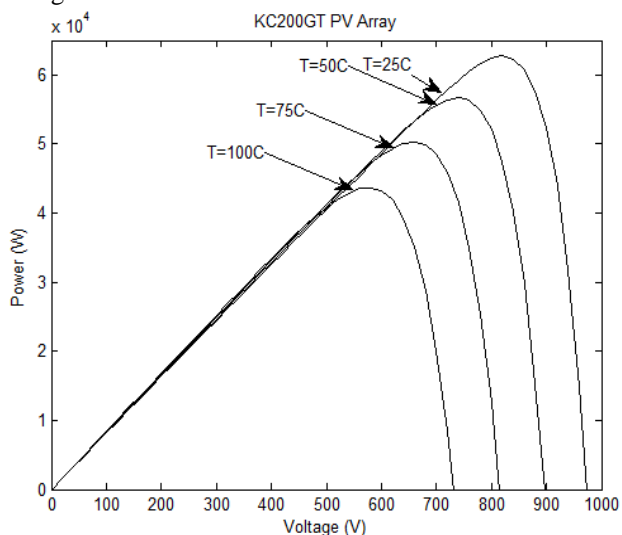


Figure (13) PV array V-P output characteristics for KC200GT module of 30x10 configuration with different T - constant λ .

IV. CONCLUSION

A MATLAB/ SIMULINK simulator for the PV system based on the basic equations of a two-diode model has been improved in this paper. The input parameters such as V_m , I_m , V_{oc} , I_{sc} , k_i , and k_v are taken from the manufacturer's datasheet, and the values of I_{PV} , I_{O1} , I_{O2} , R_p , and R_s are calculated by using Newton-Raphson method, that is to reduce the number of input parameters. The proposed model outputs the V-I and V-P characteristics of the PV module and array as a function of the external parameters (input parameters) such as sunlight irradiance and temperature. The mask icon makes the block model more user-friendly and a dialog box lets the users easily configure the PV model. The accurateness of the simulator is verified with KC200GT and MSX-64 PV modules. As a result of the study, it is observed that the two-diode circuit model has been shown to be more accurate representation of solar cell behavior than the single-diode (with and without R_p and R_s) model, but the analysis is more complex and need more simulation time. Finally, the proposed model presented here facilitates a rapid determination of the solar cells circuit model parameters that are need by researchers and designers.

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