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Comprehensive Modeling of Photovoltaic Array based on Proteus Software

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Abstract

This paper introduces a detailed modeling for the photovoltaic array using mathematical relations that describe all physical and environmental parameters. It is based on Proteus which is easy to use and common software among the electrical and electronics engineers. The aim of this paper is to describe a detailed mathematical model and how can it be implemented to study the different responses of the nonlinear photovoltaic array system behaviour. It offers a comprehensive model to measure the photovoltaic array output under any conditions based on the standard test conditions and the environmental parameters.

Keywords: Array modeling; PV mathematical models; Proteus; Temperature dependence efficiency; Operation temperature; wind speed.

INTRODUCTION

The obvious increase of human population leads to necessary requirements such as clean air and water, sustainable food sources, and the high demands on energy. To get an alternate source of energy without affecting the environment, a renewable and sustainable energy sources would certainly be a good choice [1], [2]. The solar energy is one of the most promising renewable energy sources, it can be converted directly into electrical energy using photovoltaic cells [3].

To deeply understand the PV cells characteristics, mathematics models have been presented by many researchers to describe in details the physical semiconductor characteristics [4], and the environmental parameters, such as temperature [5], [6], wind speed [7], [8],[9] and humidity[10] that affect the performance of the PV cells.

Many researchers discussed the mathematical models of the PV cells in details [11]–[13], and simulate them using MATLAB [14]–[19], but it is rare to find a simulation for the PV cells in details using Proteus software which is a common software well known to electrical and electronic engineers experts [20], [21]. However, both of these papers did not take the temperature, wind speed, and shunt resistors into consideration.

The work to be presented in this paper suggests a detailed procedure to implement and simulate the mathematical model using Proteus software. The model functions perfectly and many graphs will be presented for different outputs of the PV cells under different standard working conditions.

The remaining parts of this paper are organized as follows. In section 2 the cell temperature based on practical environmental factors will be calculated, which will be used later to give more accurate results. In section 0, the array currents are discussed briefly. Section 0 presents equations to calculate the array voltage. An overview of the system is presented in section 0. Results and discussion are presented in section 0, and finally concluding remarks are given in section 0.

PHOTOVOLTAIC CELL TEMPERATURE

The operating temperature of the photovoltaic cell, which directly affects the performance of the PV system, can be calculated based on many environmental factors, such as ambient temperature, wind speed, and solar irradiance.

The proposed sub circuit has five inputs and four outputs, see Figure 1. The inputs include the ambient temperature in degree Celsius (T_a), the solar irradiance in W/m^2 (G), the wind speed in m/s (V_a), the diode ideality factor (A),see

Table **1** and the number of cells that are connected in series (N_s).

$$\begin{bmatrix} T_a \\ G \\ V_a \\ A \\ N_s \end{bmatrix} \rightarrow \begin{bmatrix} Temperature \\ Dependant \\ Simulation \end{bmatrix} \rightarrow \begin{bmatrix} T_c \\ T_{ref} \\ D_T \\ V_T \end{bmatrix}$$

Figure 1. Temperature simulation sub circuit duties

The Outputs of this sub circuit include, the cell temperature in Kelvin (T_c), the cell temperature at the standard test condition in Kelvin (T_{ref}), the difference between T_c and T_{ref} (D_T) and the thermal voltage (V_T).

According to [22], [23], the cell temperature T_c can be calculated based on equation (1).

PV cell Temperature:

$$T_c(K) = 0.943 \times T_a + 0.0195G + 1.528V_a + 273.5029 \quad (1)$$

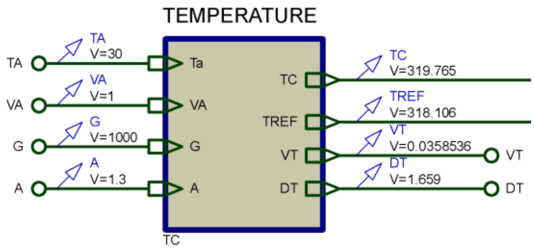
The temperature difference (D_T) is calculated as ($D_T = T_c - T_{ref}$). Finally the thermal voltage V_T is calculated from equation (2) [24], where K is Boltzmann constant ($1.38064852 \times 10^{-23}$) $m^2kgs^{-2}K^{-1}$, and q is the electron charge ($1.6021765 \times 10^{-19}$) coulomb, and A is diode ideality factor, see

Table **1** for more details.

Thermal Voltage:

$$V_T = \frac{KTA}{q} \qquad (2)$$

The temperature dependent sub circuit is simulated using Proteus for typical parameters as depicted in Figure 2.



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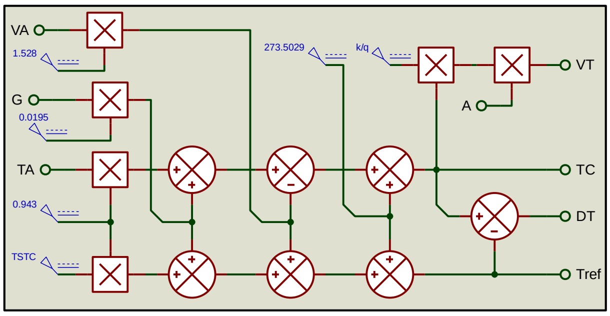

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Figure 2. (a) Block diagram, (b) Simulated circuit for the temperature dependent simulation.

Table 1. Ideality factor (A) [25]

Technology	Ideality factor
Si-mono	1.2
Si-poly	1.3
a-Si-H	1.8
a-Si-H tandem	3.3
a-Si-H triple	5.0
cdTe	1.5
CTs	1.5
AsGa	1.3

ARRAY CURRENT

PV cell main power parameters can be modeled as shown in Figure 3. This model mainly consists of a current source $I_{ph,cell}$, a diode current $I_{d,cell}$, shunt resistor R_p with current $I_{p,cell}$, and main current I_{cell}. By applying Kirchhoff current law on this model, it is clear that the cell current will be calculated according to Eq.(3).

$$I_{cell} = I_{ph,cell} - I_{d,cell} - I_{p,cell} \qquad (3)$$

But most of PV Model have 36 cells connected in series. These PV models also connected in series and/or parallel to make PV array. The number of cells and their connections are a matter of the system design requirements of the voltage, current, and power. To calculate the current produced by a PV array, it is required to model this array. Figure 4 shows the module of the PV array and its effects on the PV cell parameters. These effects are also described mathematically by Eqs. (4-7)[26].

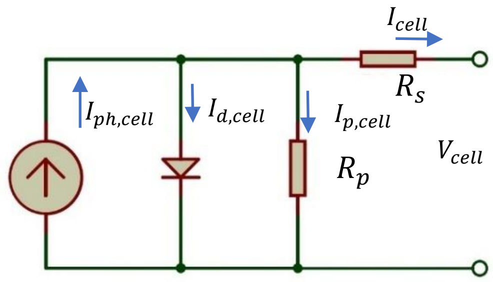


Figure 3. PV Cell Model

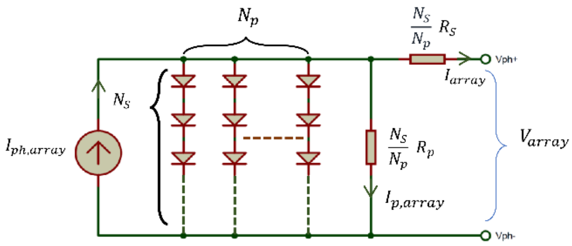


Figure 4. PV array Module circuit[25]

- Series resistance:

$$R_{s,\ array} = \left(\frac{N_s}{N_p}\right) R_{s,cell} \qquad (4)$$

- Shunt resistance:

$$R_{p,\ array} = \left(\frac{N_s}{N_p}\right) R_{p,cell} \qquad (5)$$

- Photocurrent:

$$I_{ph,array} = N_p \times I_{ph,cell} \qquad (6)$$

- Diode current:

$$I_{d,array} = N_p \times I_{d,cell} \qquad (7)$$

The array current can be calculated according to Eq.(8). The parameters of this equation will be discussed briefly in the following subsections.

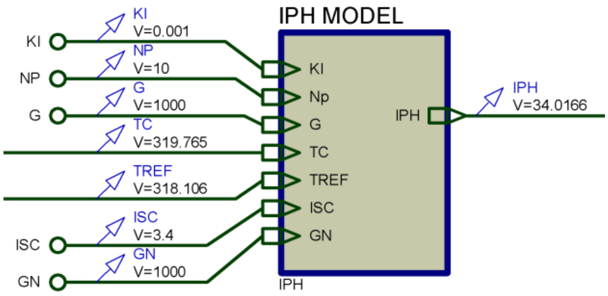
$$I_{array} = I_{ph,array} - I_{d,array} - I_{p,array} \qquad (8)$$

Photocurrent (I_{ph})

The photocurrent or light-generated current is the current that is produced when the PV cell is exposed to light. At the standard test conditions ($G_n = 1000\ W/m^2$, $T_n = 25℃, AM = 1.5$), this current is called (I_{phn}) and it is approximately equal the short circuit current of the PV cell ($I_{phn} \approx I_{sc}$). But under different conditions, it will be calculated according to Eq.(9) [26]. This equation also takes into consideration the temperature effect on the photocurrent as $K_i(T_c - T_{ref})$, where K_i (mA/K) is the current temperature coefficient.

$$I_{ph,cell} = \frac{G}{G_n}\left[I_{phn} + K_i(T_C - T_{ref})\right] \qquad (9)$$

Figure 5 shows the simulated circuit to calculate the photocurrent at any solar irradiance or temperature. This simulated circuit also calculates the photocurrent for the number of cells that are connected in parallel (N_p).



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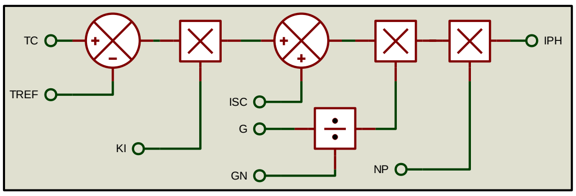

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Figure 5. (a) Block diagram, (b) Simulated circuit for photocurrent simulation

Diode current (I_d)

As in any diode, the photovoltaic diode current increases exponentially when the applied voltage increases according to Eq.(10) [24], where V_d is the diode voltage, V_T is the thermal voltage, and I_{rs} is the dark saturation current. It is obvious that the diode current is a function of the applied voltage, temperature, and reverse saturation current, but the last parameter, according to Eq.(11), also depends on temperature, and other parameters like the intrinsic current I_o, and the energy gap of the depletion region E_g. Further details about E_g and $V_{oc,cell}$ values for different types of semiconductors are shown in Table 2. For PV array, Eq. (12) can be used. Both equation (11) and equation (12) are simulated as shown in Figure 6 and Figure 7 respectively.

Table 2. Some common solar cell materials and their characteristics [27].

Semiconductor	$E_g(eV)$	$V_{oc,cell}(V)$
Si, single crystal	1.10	0.50 – 0.70
Si, poly-crystalline	1.10	0.50 – 0.67
GaAs, single crystal	1.42	1.02
CdTe, thin film	1.50	0.84
InP, single crystal	1.34	0.87

- Diode current for single cell:

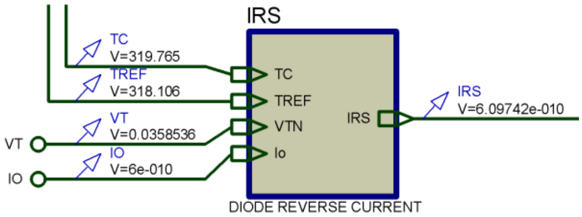
$$I_{d,cell} = I_{rs}\left\{e^{\frac{(V+IR_S)}{V_T}} - 1\right\} \qquad (10)$$

- Diode reverse saturation current:

$$I_{rs} = I_o\left(\frac{T}{T_{ref}}\right)^3 e^{\left(\frac{qE_g\left(\frac{1}{Tref}-\frac{1}{Tc}\right)}{KA}\right)} \qquad (11)$$

- Diode current for array:

$$I_{d,array} = N_p I_{rs}\left\{e^{\frac{1}{V_T}\left(\frac{V}{N_S}+\frac{IR_S}{N_p}\right)} - 1\right\} \qquad (12)$$



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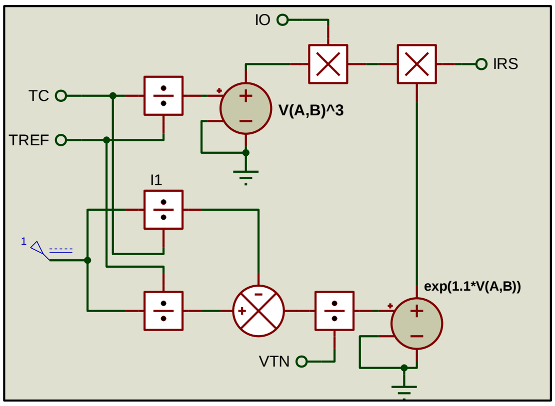

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Figure 6. (a) Block diagram, (b) Simulated circuit for reverse saturation current simulation

Shunt Resistor Current (I_p)

The shunt resistor is a manufacturing defect that causes power losses. Lower shunt resistance means more power loss, since it provides alternate current path for the generated current. At low light levels, the light-generated current will be less, and its loss at the shunt resistor will have a high impact at the solar cell.

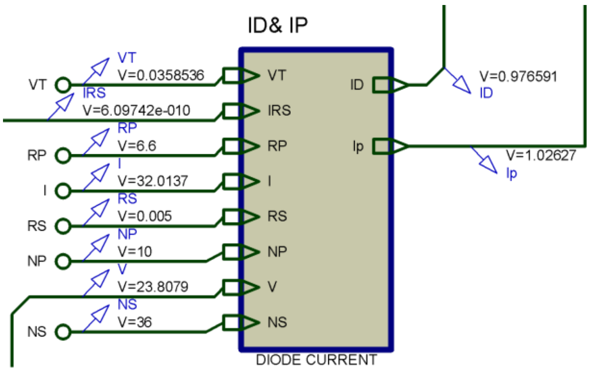
Equation (13) calculates the shunt resistor current $I_{p,cell}$ in a photovoltaic cell, and Eq. (14) calculates the shunt resistor current $I_{p,array}$ in a photovoltaic array. Figure 7 also shows a simulation for this equation.

Shunt Resistor Current for single cell

$$I_{p,cell} = \frac{(V + IR_s)}{R_p} \tag{13}$$

Shunt Resistor Current for array

$$I_{p,array} = \frac{N_p}{R_p}\left(\frac{V}{N_S} + \frac{IR_s}{N_p}\right) \tag{14}$$



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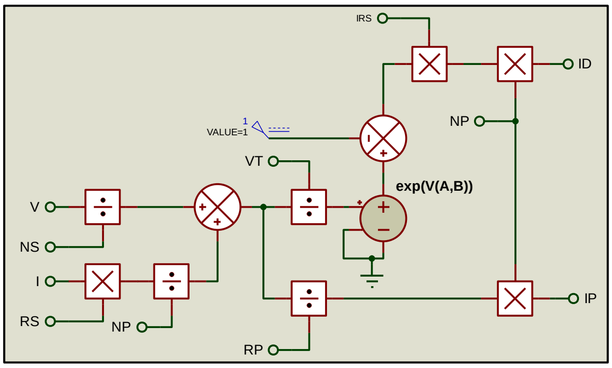

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Figure 7. (a) Block diagram, (b) Simulated circuit for diode and shunt resistor currents

ARRAY VOLTAGE

According to the Kirchhoff voltage law, the output voltage of the PV cell in Figure 3 can be calculated using Eq.(15). It is clear that the output voltage is equal to the diode voltage minus the drop voltage on the series resistor. For the PV module, which consists usually of a number of PV cells (N_s) connected in series, the output voltage is calculated according to Eq.(16).

However, if the temperature effect is taken into consideration, the diode voltage will drop by ($k_v \Delta T$), where k_v is temperature coefficient of voltage, and ΔT is the difference between the operation temperature and the standard temperature. The output voltage will be calculated according to Eq.(17). The PV array consists of several PV modules connected in series or in parallel according to the design requirements. Eq.(18) is used to calculate the PV array output voltage, where N_s is the number of the PV cells connected in series, and N_p is the number of PV modules connected in parallel. Figure 8 presents the simulated circuit to calculate the array output voltage[26].

- PV cell voltage:

$$V_{cell} = V_d - IR_S \tag{15}$$

- PV Module Voltage:

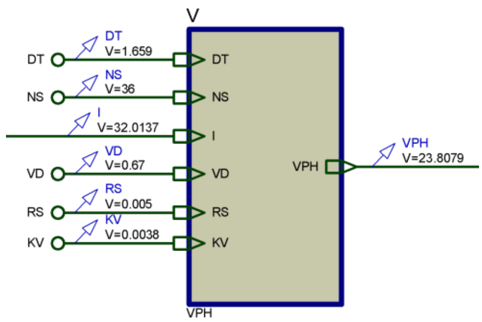
$$V_{module} = N_s(V_d - IR_S) \tag{16}$$

- PV Module Voltage (ΔT):

$$V_{module} = N_s(V_d - k_v \Delta T) - IN_s R_S \tag{17}$$

- PV Array:

$$V_{Array} = V_d\, N_s(1 - k_v \Delta T) - I\frac{R_S Ns}{Np} \tag{18}$$



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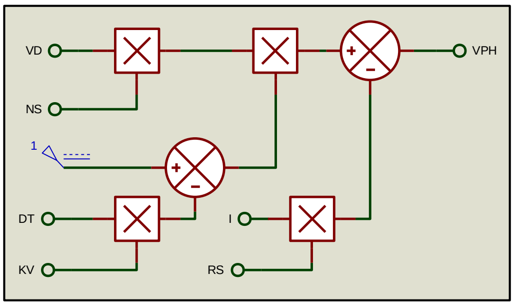


(b)

Figure 8. (a) Block diagram, (b) Simulated circuit for array voltage simulation

MODELING OVERVIEW

All the above sub circuits are combined together to establish the array model. All the three currents are combined to find the main current. The array output voltage is calculated based on the diode voltage and other factors as mentioned before. The drop voltage is also measured and the model becomes a closed loop affecting each other. Feedback voltage is used to measure the parallel current. Note that the produced voltage, current, and power become dependent on the operation temperature.

Figure 9 presents an overall view of the running system. By taking a closer look at this figure, one can see all the values of the inputs and outputs and a complete PV module with a declaration of the used parameters and their values as depicted in Table 3. It is also showing the output voltage, current and the rated maximum power.

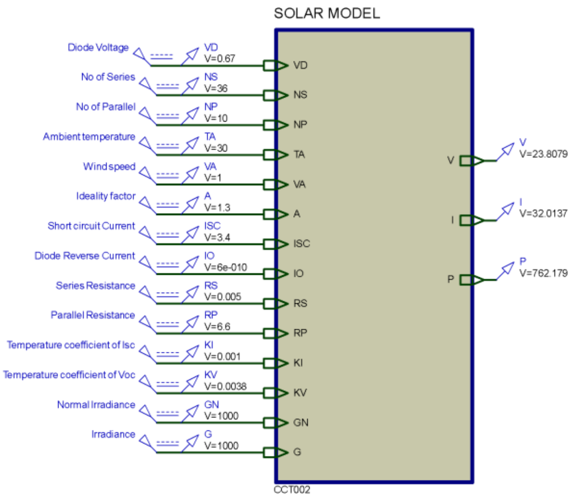


Figure 9. System Overview with parameters declaration

RESULTS AND DISCUSSION

Figure 10 shows the model under typical running conditions and many results can be collected for the internal and the output characteristics as follows:

PV Module Internal characteristics

- Module diode and reverse saturation current are measured at ambient temperature (0 – 50 ℃) and the results are shown in Figure 11a. This graph displays the expected behavior of the diode current which decreases with the increase in ambient temperature. It also shows that the reverse saturation current increases with the increase in the ambient temperature.
- Module photocurrent and parallel current are measured for solar irradiance ($300 - 1300 W/m^2$), the results show the effectiveness of the parallel current at low irradiance ($< 800 W/m^2$) as shown in Figure 11b.
- The cell temperature decreases when the wind speed increase, at fixed ambient temperature ($T_a = 25°C$) and solar irradiance ($1000\ W/m^2$), as shown in Figure 11c.
- Cell Temperature increases when solar irradiance increases, at fixed ambient temperature ($T_a = 25°C$) and wind speed ($1\ m/s$), as shown in Figure 11d.

PV Module Output characteristics

- The array power and voltage are measured for different values of diode voltage ($0 - 795 mV$), and the results are shown in Figure 12a. These results show the maximum power point and how the current dramatically drops after this point.
- Voltage and current are measured for different values of solar irradiance ($300 - 1300 W/m^2$) and the results are shown in Figure 12b. The figure presents a different voltage and current response to the increase in solar irradiance as expected.
- Voltage and current are measured for different values of operation temperature (0 – 50℃), at zero wind speed and solar irradiance ($1000\ W/m^2$) and the results are shown Figure 12c.
- Voltage and current are measured for different values wind speed under the standard test conditions and the results are shown in Figure 12d.

Table 3. Adopted solar array parameters

Parameter	**Abbr.**	**Value**
INPUTS		
Diode voltage	V_d	$0.67V$
Energy Gap (Si, poly-crystalline)	E_g	$1.1eV$
Number of cells in Series	N_S	36
Number of cells in Parallel	N_p	10
Ambient temperature	T_a	$30\ ^oC$
Wind speed	V_a	$1\ m/s$
Ideality factor	A	1.3
Diode reverse saturation current	I_o	$6\times10^{-10}\ A$
Series resistance	R_s	$5m\Omega$

Parallel resistance	R_p	6.6Ω
Current temperature coefficient	K_i	1 mA/K
Voltage temperature coefficient	K_v	-3.8 mV/K
Standard solar Irradiance	G_n	1000 W/m^2
Solar Irradiance	G	1000 W/m^2
OUTPUTS		
Open circuit voltage	V_{oc}	28.6 V
Short Circuit current	I_{sc}	3.4 A
Current at P_{MAX}	I_{mp}	3.12 A
Voltage at P_{MAX}	V_{mp}	24.244 V
Rated maximum power	P_{max}	756.4 W

CONCLUSION

The presented work explains in details the mathematical model for the PV cell, module and array. It was implemented and simulated using Proteus software. Dynamic system simulation studies demonstrate the effectiveness of all the physical and the environmental parameters. Many graphs were presented to describe these effects which means this module can used for any type of PV system.

This model can be used to study the environmental effects on the PV array at any expected installation area, identify the maximum power point tracking for the MPPT, and study the shading effect on the specific PV array.

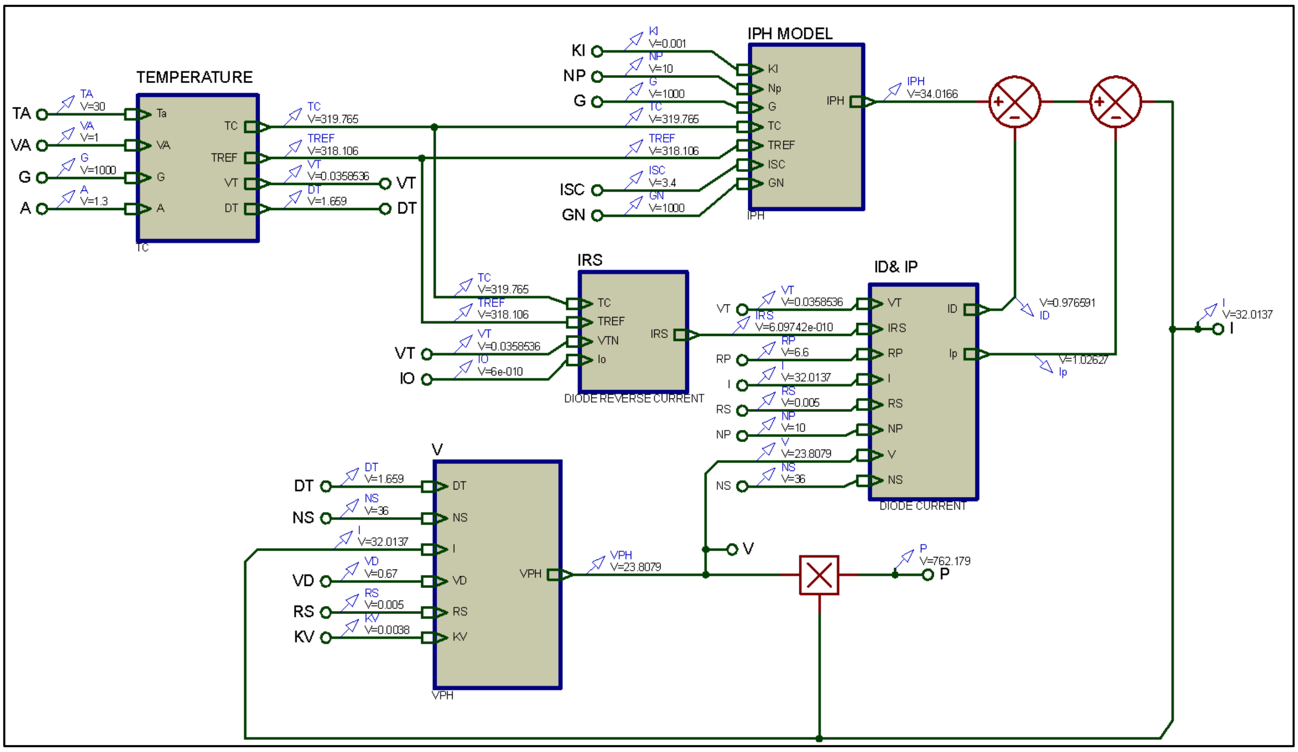
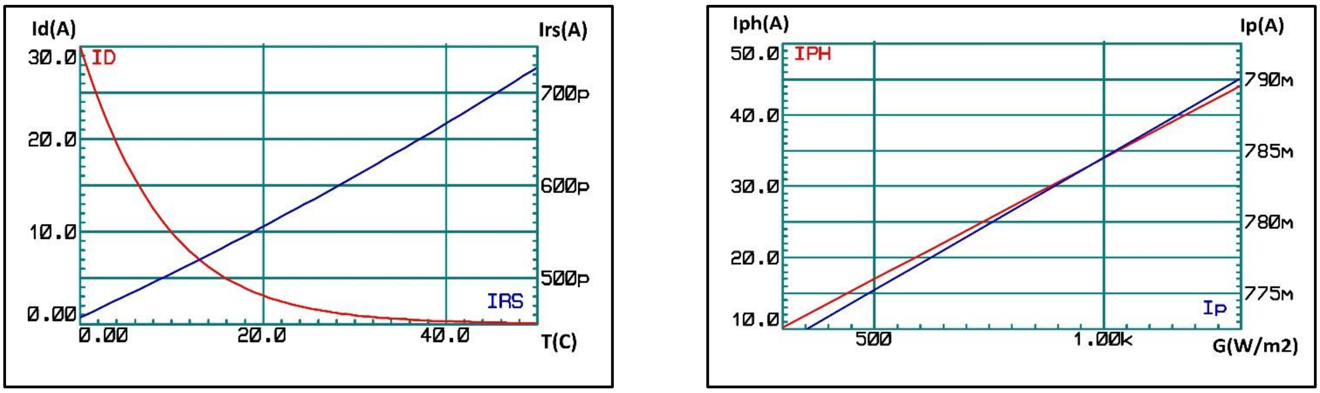


Figure 10. System Simulation



(a) (b)

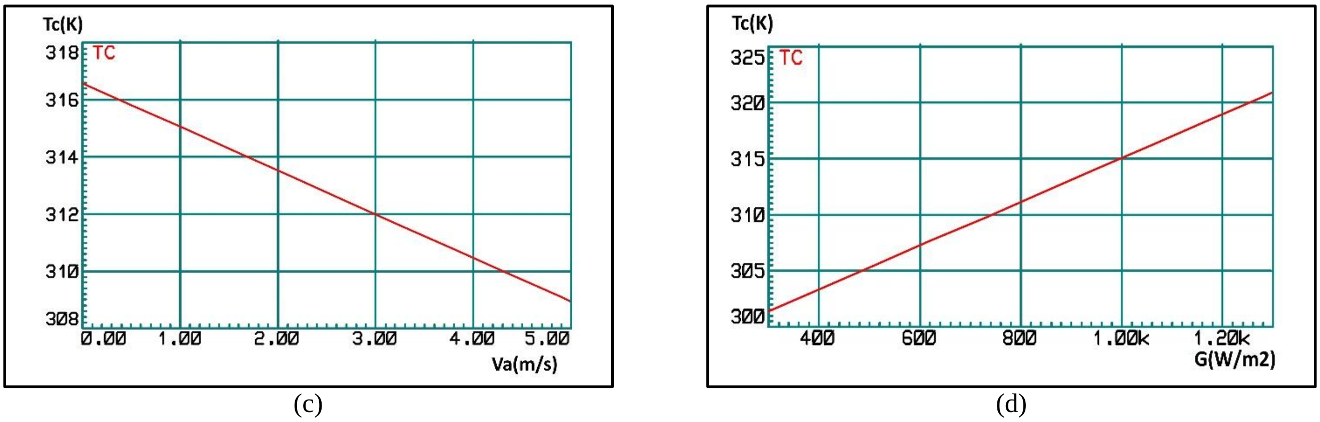


Figure 11. PV Module Internal Characteristics, (a) Module, Diode and Reverse Saturation current versus Ambient Temperature, (b) Module Photocurrent and Parallel current versus Irradiance, (c) Cell Temperature versus Wind Speed, and (d) Cell Temperature versus Irradiance.

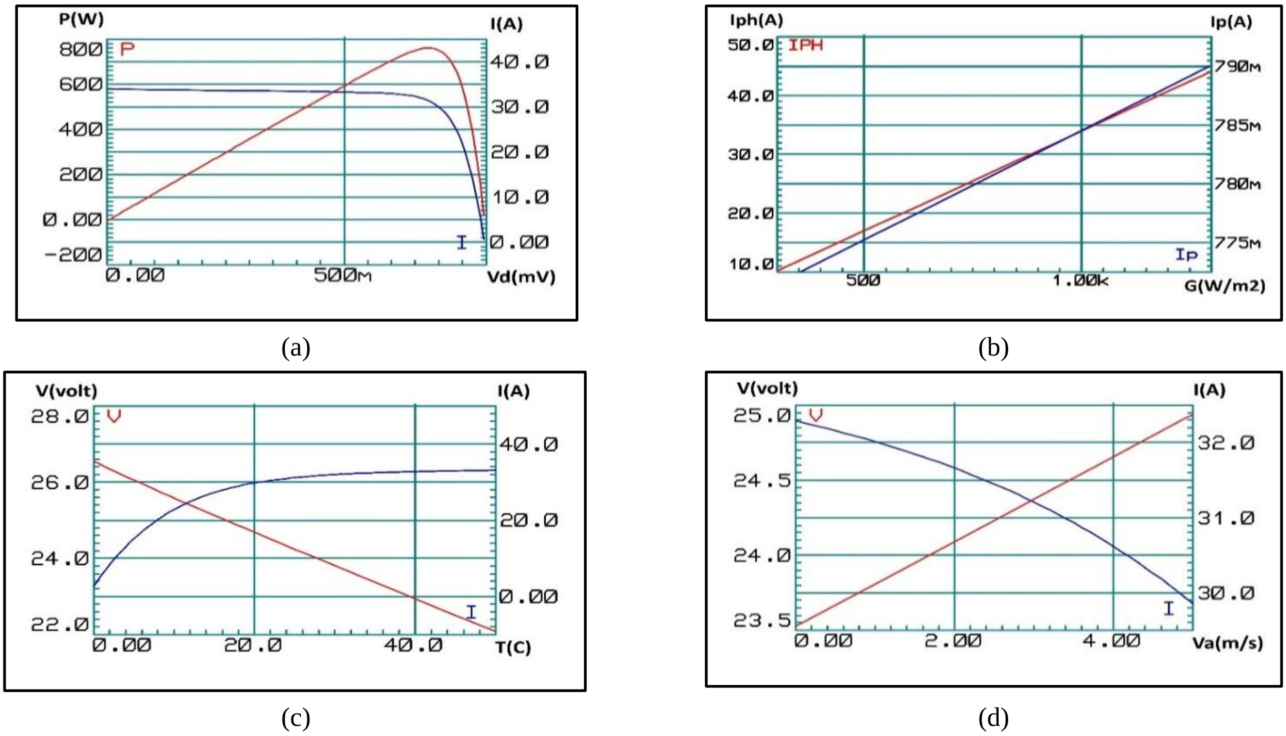


Figure 12. PV Module Output Characteristics, (a) Module, Power and Current versus diode voltage, (b) Module Voltage and Current versus Solar Irradiance, (c)Module Voltage and Current versus Ambient Temperature, and (d) PV Module Voltage and Current versus Wind Speed.

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