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Modeling and Simulation issues on PhotoVoltaic systems, for Mechatronics design of solar electric applications.

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ABSTRACT

This paper, based on desired representation accuracy and specific application, proposes different and new generalized mathematical and Simulink models of Photovoltaic (PV) system. Proposed models are developed and tested to allow designer to have maximum numerical visual and graphical data to select, design and analyze a given PV system for desired output performance and characteristics, under given input operating conditions, to meet desired outputs for specific application requirements. This paper also proposes MATLAB scripts for calculating and plotting the I-V and P-V characteristics of a given PV system. Testing results show the simplicity, accuracy and applicability of the presented models in Mechatronics design of solar electric applications. The proposed mathematical, Simulink and scripts Models are intended for research and education purposes.

Keywords: Mechatronics, Photovoltaic (PV) system, Modeling, simulation

1. INTRODUCTION

The key to success in Mechatronics design is a *balance between* two sets of skills modeling/analysis skills and experimentation/hardware implementation skills. Modeling, simulation, analysis and evaluation processes in Mechatronics design consists of two levels, sub-systems models and whole system model with various sub-system models interacting similar to real situation, the subsystems models and the whole system model, are to be tested and analyzed for desired system requirements and performance (Farhan A. Salem,et all, 2013). For Mechatronics design of solar electric applications, and to help in facing the two top challenges in Mechatronics design of solar electric applications; early identifying system level problems and ensuring that all design requirements are met, this paper proposes mathematical and Simulink models of Photovoltaic module subsystem. Based on desired representation accuracy and specific application, different mathematical and Simulink models are to be developed and tested, these models allow designer to have the maximum output data to select, tested, analyze and evaluate the PV system for desired outputs under given working conditions, to meet specific application requirements. With the growing requirements to improve fuel consumption economy and reduce related emissions, solar energy became the world's major renewable energy source. PhotoVoltaic (PV) generator system converts sunlight (Solar energy) into electricity. It is a clean, available everywhere in different quantities and renewable, energy with a long service life, high reliability, little operation and maintenance costs. PV system is a whole assembly of solar cells, connections, protective parts, supports etc. The basic device of a PV system is the single PV cell. Fragile cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be warranted for up to 25 years. Each individual cell is a functioning power generating device, the power produced by a single PV cell is not enough for general use, where, each solar cell generates approximately 1.75 watts (0.5V DC and 3.5 amps) and converts only 12 to 20 % of the sun's light into electricity, Therefore, in most commercial PV products, PV cells are generally connected in series configuration to form a PV module (the fundamental building block of PV systems, see Figure 1) in order to obtain adequate working voltage, generally of 36-cells to charge a 12V battery and similarly a 72-cell module is appropriate for a 24V battery. PV modules are then arranged in series-parallel structure (series connections for high voltage requirement and in parallel connections for high current requirement) to form PV panels (consisting of one or more PV modules) to produce enough high power to achieve desired power output (Huan-Liang Tsai, ET ALL,2008). Panels can be grouped to form large photovoltaic arrays. The term array is usually employed to describe a complete power-generating unit, consisting of any number of PV modules and panels. The performance (output characteristics) of a PV array system depends on the operating conditions, as well as, the solar cell and array design quality, where the output voltage, current and power of PV array system vary as functions of solar irradiation level β, temperature T , voltage V, and load current I. Therefore the effects of these three quantities must be considered in the design of PV array systems, so that any change in temperature and solar irradiation levels should not adversely affect the PV array output to the load/utility, which is either a power company utility grid or any stand alone electrical type load(J. Surya Kumari, et all, 2012). A PV cell is basically a semiconductor diode whose *p*–*n* junction is exposed to light (Sergio Daher, et all, 2008). The mono-crystalline and multi-crystalline silicon cells shown in Figure 2 are the only found at commercial scale at the present time. The PV phenomenon may be described as the absorption of solar radiation, the generation and transport of free carriers at the *p–n* junction, and the collection of these electric charges at the terminals of the PV device (Soeren Baekhoeg Kjaer, et all,2005)(J.M.A. Myrzik, et all,2003). The rate of generation of electric carriers depends on the flux of incident light and the capacity of absorption of the semiconductor. The capacity of absorption depends mainly on the semiconductor bandgap, on the reflectance of the cell surface (that depends on the shape and treatment of the surface), on the intrinsic concentration of carriers of the semiconductor, on the electronic mobility, on the recombination rate, on the temperature, and on several other factors (J. Surya Kumari, et all, 2003).

2. MODELING AND SIMULATION OF THE PV SYSTEM

Solar (photovoltaic) cells consist of a p-n junction fabricated in a thin wafer or layer of Mono-crystalline or multi-crystalline silicon semiconductor, as shown in Figure 2. PV system naturally exhibits a nonlinear I-V and P-V output characteristics which vary with irradiation level β, cell temperature T , voltage V, and load current I. In the dark, the I-V output characteristic of a solar cell has an exponential characteristic similar to that of a diode (G. Walker, 2001). When solar energy (photons) hits the solar cell, with energy greater than bandgap energy of the semiconductor, electrons are knocked loose from the atoms in the material, creating electron-hole pairs (Lorenzo, E., 1994). These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation. When the cell is short circuited (zero load resistance), this current flows in the external circuit; when open circuited, this current is shunted internally by the intrinsic p-n junction diode. The characteristics of this diode therefore set the open circuit voltage characteristics of the PV solar cell (G. Walker,2001), based on this the simplest equivalent circuit of a PV solar cell consists of a diode, a photo current, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, all as shown in Figure 3(a), this equivalent circuit is called a single diode model. The diode determines the I-V characteristics of the cell (Francisco M. González-Longatt, 2005). An even more exact mathematical description of a PV cell, which is called the double (exponential) diode model as shown in Figure 3(b) (J. A. Gow, et all,1999), is derived from the physical behavior of PV solar cell constructed from polycrystalline silicon. This model is composed of a light-generated current source, two diodes, a series resistance and a parallel resistance. However, there are some limitations to develop expressions for the V-I curve parameters subject to the implicit and nonlinear nature of the model, therefore, this model is rarely used in the subsequent literature and is not taken into consideration for the generalized PV model. A model of PV solar cell with suitable complexity is shown in Figure 3(c), since a small variation in series resistance R_S will significantly affect the PV output power, and the PV efficiency is insensitive to variation in shunt resistance R_{SH} ,therefore the effect of R_{SH} can be neglected, and correspondingly, a simplified model is shown in Figure 3(d) (I. H. Altas, et all, 2007) where R_S effect becomes very conspicuous in a PV module that consists of many series-connected cells, and the value of resistance is multiplied by the number of cells, meanwhile R_{SH} will only become noticeable when a number of PV modules are connected in parallel for a larger system A general mathematical description of I-V output characteristics for a PV cell has been studied for over the pass four decades and can be found in different resources including (Huan-Liang Tsai, ET ALL,2008), (J. Surya Kumari, et all, 2012),(Farhan A. Salem,et all, 2013*),(*Soeren Baekhoeg Kjaer, et all,2005)(J.M.A. Myrzik, et all,2003),(Lorenzo, E., 1994),(G. Walker, 2001),[2-30]. The output net current of PV cell I, and the V-I characteristic equation of a PV cell, is found by applying the Kirchoff's current law (KCL) on the equivalent simplified single diode circuit shown in Figure 3(d). The net output current is the difference of two currents; the light-generated photocurrent I_{ph} and diode current I_d(Francisco M. González-Longatt,2005),(Akihiro Oi.,2005),(Kinal Kachhiya, et all, 2005),(Tarak Salmi, et all, 2005)and
is given by Eq.(1)

$$I = I_{ph} - I_d \qquad (1)$$

The light-generated photocurrent I_{ph}
is generated by the incident light and directly proportional to the sun irradiation β and operating temperature, I_{ph} isgiven by Eq.(2).

$$I_{ph} = \left(I_{sc} + K_i\,(T - T_{ref}\,)\right)\frac{\beta}{1000} \qquad (2)$$

The cell's short-circuit current I_{SC},
is the current through the solar cell when the voltage across the solar cell is zero (see figure 3(e)(f)), I_{SC} is calculated when the voltage equals to zero *I (at V=0) = Isc*, at *T= 25°C* and the solar insolation $\beta=1kW/m^2$, given in datasheet specifications of PV panel.

The diode current I_d
is given by Eq.(3).

$$\mathrm{I}_d = \mathrm{I}_s \left(e^{\frac{q(V+IR_S)}{NKT}} - 1 \right) \quad (3)$$

Based on this, the basic equation for output net current of PV cell I, of the PV cell represented as single diode with *series* resistance R_S and *without* shunt resistance R_{SH}, shown in Figure 3(c), is obtained by substituting Eqs.(2) and Eq.(3) in Eq.(1) , this gives Eq.(4):

$$\mathrm{I} = \mathrm{I}_{ph} - \mathrm{I}_s \left(e^{\frac{q(V+IR_S)}{NKT}} - 1 \right) \quad (4)$$

Referring to Eq.(4), since, the short-circuit current I_{sc}, is calculated when the voltage equals to zero ($V=0$), I_{sc} can be given by Eq.(5):

$$I_{sc} = I \ (at \ V = 0)$$

$$I_{sc} = \mathrm{I}_{ph} - \mathrm{I}_s \left(e^{\frac{q(IR_S)}{NKT}} - 1 \right) \quad (5)$$

Normally the series resistance *Rs*, is small *(0.05 to 0.10)* and can be neglected in Eq.(5). Hence, as a good approximation the following equation can be used:

$$I_{sc} = I = I_s \ , \quad at \ V = 0$$

The basic given by Eq. (4) does not represent the actual I-V characteristics of practical and real operation of PV cell, because in the real operation of the solar cell some losses exist, to get a more real behavior and to pick up these losses in real PV cell, a third current based *on* R_s and R_{sh}, called shunt current I_{Rsh} and given by Eq.(6), is added, with these additions the corresponding equivalent circuit diagram is as shown in Figure 3(a)(Ramos Hernanz, et all, 2010), and the net current of the cell will be given by Eq.(7), this equation shows that the output current generated depends on the PV cell voltage *V*, solar irradiance β on PV cell, and ambient temperature *T*. Eq.(7) describes the single-diode model presented in Figure 3(e), this model offers a good compromise between simplicity and accuracy and for simplicity is studied in this paper. Characteristic I-V curve of a practical photovoltaic device and the three
remarkable points,
is shown in Figure 3(e).

$$I_{RSH} = \frac{V + R_S I}{R_{sh}} \quad (6)$$

$$I = I_{ph} - I_d - \mathrm{I}_{RSH}$$

$$\mathrm{I} = \mathrm{I}_{ph} - \mathrm{I}_s \left(e^{\frac{q(V+IR_S)}{NKT}} - 1 \right) - \frac{V + R_S I}{R_{sh}} \quad (7)$$

$$\mathrm{I} = \left(I_{sc} + K_i \left(T - T_{ref} \right) \right) \frac{\beta}{1000} - \mathrm{I}_s \left(e^{\frac{q(V+IR_S)}{NKT}} - 1 \right) - \frac{V + R_S I}{R_{sh}}$$

Since the value of series resistor R_s is very small (0.05 to 0.10) and the value of shunt resistor R_{sh} resistors is very large (200 to 1000), to simplify the analysis and based on applied modeling application, R_s and R_{SH} may be neglected, hence, in an ideal PV cell, (shown in Figure 3(d)) there is no series loss and no leakage to ground, (R_s =0, $R_{sh}=\infty$) , that is a relatively common assumption (F. González-Longatt,2006), substituting R_s =0, $R_{sh}=\infty$ in Eq.(7), we have the equation for net current I, and I-V characteristics of the PV simplified and Ideal single diode model of PV Cell , shown in Figure 3(d), and given by Eq.(8)

$$\mathrm{I} = \mathrm{I}_{ph} - \mathrm{I}_s \left(e^{\frac{qV}{NKT}} - 1 \right) \quad (8)$$

The I-V characteristics of the solar cell with single-diode and only series resistance R_s shown in Figure 3(c) is given by Eq.(9):

$$\mathrm{I} = \mathrm{I}_{ph} - \mathrm{I}_s \left(e^{\frac{q(V + IR_S)}{NKT}} - 1 \right) \tag{9}$$

The diode reverse saturation current I_S

is constant under the constant temperature *T*, and found by setting the open-circuit condition, using Eq. (8), let $I = 0$ (no output current) and solve for I_S, gives Eq.(10), the corresponding Simulink model is shown in Figure 4. The diode reverse saturation current I_s, varies as a function of the temperature *T*, as given by Eq.(11), based on this equation, the reverse saturation current subsystem Simulink model shown in Figure 5 is developed.

$$I_S = \frac{I_{Sc}}{\left(e^{\frac{qV}{NKT}} - 1 \right)} \Rightarrow I_s \Big|_{module} = \frac{I_{sc}}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT} \right]} - 1 \right)} \tag{10}$$

$$I_S(T) = I_S \left[\frac{T}{T_{ref}} \right]^3 e^{\left[\left(\frac{T}{T_{ref}} - 1 \right) \frac{qE_g}{NKT} \right]}$$

$$I_S(T) = I_S \left[\frac{T}{T_{ref}} \right]^3 e^{\left[\left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \frac{qE_g}{NKT} \right]} \tag{11}$$

Substituting all derived equations of corresponding currents in Eq.(7), the net current of PV cell is given by:

$$\mathrm{I} = \left(I_{sc} + K_i \left(T - T_{ref} \right) \right) \frac{\beta}{1000} - \frac{I_{sc}}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT} \right]} - 1 \right)} \left(e^{\frac{q(V + IR_S)}{NKT}} - 1 \right) - \frac{V + R_S I}{R_{sh}}$$

$$\mathrm{I} = \left[\left(I_{sc} + K_i \left(T - T_{ref} \right) \right) \frac{\beta}{1000} \right] - \left(\frac{\frac{N_P V}{N_S} + R_S I_{filter}}{R_{sh}} \right) - \left(\frac{I_{sc} \left(\frac{\mathrm{T}_1}{\mathrm{T}_{ref}} \right)^3}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT_1} \right]} - 1 \right)} \right) \left(e^{\left[\frac{qV_{OC} \left(\frac{1}{T_{ref}} - \frac{1}{T_1} \right)}{NK} \right]} \right) \left(e^{\frac{q\left(\frac{V}{N_S} + \frac{I_{filter} R_S}{N_P} \right)}{NKT_1}} - 1 \right)$$

PV module mathematical model

The current output of given PV module, considering the number of parallel and series connections of cells N_P , N_S, is given by Eq.(12), including for a PV cell $N_S = N_P = 1$, and for three PV cell model representations shown in Figure 3.

$$\mathrm{I} = N_P \mathrm{I}_{ph} - N_P \mathrm{I}_s \left(e^{\frac{q\left(\frac{V}{N_S} + \frac{IR_S}{N_P} \right)}{NKT}} - 1 \right) - \frac{\frac{N_P V}{N_S} + R_S I}{R_{sh}}$$

$$\mathrm{I} = N_P \mathrm{I}_{ph} - N_P \mathrm{I}_s \left(e^{\frac{q(V + IR_S)}{N_s NKT}} - 1 \right) \tag{12}$$

$$\mathrm{I} = N_P \mathrm{I}_{ph} - N_P \mathrm{I}_s \left(e^{\frac{qV}{N_s NKT}} - 1 \right)$$

The maximum PV voltage

Since the PV cell efficiency is insensitive to variation in shunt resistance R_{SH} , the effect of parallel resistance R_{SH} can be neglected (Figure 3(c) in Eq. (7), *the maximum PV voltage* can be represented by Eq. (13), and corresponding Simulink model shown in Figure 6 is implemented.

$$V = \frac{NKT}{q}\ln\left(\frac{I_{ph}+I_s+I}{I_s}\right) - IR_s \qquad (13)$$

***Open circuit voltage Vo*;** Corresponds to the voltage drop across the diode (*p-n junction*), when it is traversed by the photocurrent I_{ph} when the generator current is $I = 0$. It reflects the voltage of the cell in the night**,** and given by Eq. (14):

$$V_o = \frac{NKT}{q}\ln\left(\frac{I_{ph}}{I_s}\right) \quad for \quad I = 0 \qquad (14)$$

The double (exponential) diode model

shown in Figure 3(b), considering the effects of series *Rs* and R_{SH} resistances and recombination, that can be represented by the second diode (D_2) in the equivalent circuit as shown in Figure 3(b), the I-V relationship of PV cell is can be described by Eq.(15). In this equation notice that, combining the two diodes, Eq.(15) will have the form given in Eq.(7), a detailed derivation of mathematical model and corresponding currents can be found in (Basim Alsayid,2012).A more sophisticated models that present better accuracy and serve for different purposes have been proposed in different resources including (www.solardirect.com)(J. A. Gow, et all, 1999)(J. A. Gow, et all, 1996)(N. Pongratananukul, et all, 2004)(S. Chowdhury, et all, 2004)(J. Hyvarinen, et all, 2003). (Kensuke Nishioka, et all,2007)proposed a three-diode model to include the influence of effects which are not considered by the previous models .

$$I = I_{ph} - I_{s1}\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) - I_{s2}\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) - \frac{V+R_S I}{R_{sh}} \qquad (15)$$

The power delivered by a PV

system of one or more photovoltaic cells is dependent on the irradiance, temperature, and the current drawn from the cells. The power output of a PV system is given by Eq.(16):

$$P = V * I \qquad (16)$$

Maximum Power Point, MPP,

is the operating point at which the power is maximum across the load and given by Eq.(17):

$$P_{max} = V_{max} * I_{max} \qquad (17)$$

Efficiency (**Maximum**)

of solar cell is the ratio between the maximum power P_{max} and the incident light power, and given by Eq.(18), where P_{in} is taken as the product of the solar irradiation of the incident light *(G=β/1000),* measured in W/m^2, with the surface area (*A*) of the solar cell in m^2 (S.Sheik Mohammed, 2011), and given by Eq.(19):

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{max}}{P_{in}} \qquad (18)$$

$$P_{in} = \frac{A*\beta}{1000} \qquad (19)$$

Fill factor (FF)

The departure of the I-*V* characteristic of a real cell from that of a perfect cell is measured by the *fill factor* (FF) of the cell, it is a measure of quality of the solar cell, It is calculated by Eq.(20),by comparing the maximum power (P_{max}) to the theoretical power (P_{th}) that would be output at both the open circuit voltage and short circuit current together(S.Sheik Mohammed, 2011).

$$FF = \frac{P_{max}}{P_{th}} = \frac{P_{max}}{I_{sc} * V_o} \qquad (20)$$

2.1 Simulation of the PV system

Beside proposed Simulink subsystems models shown in Figure 4, Figure 5 and Figure 6, and based on desired representation accuracy and specific application, other Simulink models can be developed, to allow designer to have the maximum output data to select, tested, analyze and evaluate the PV system for desired output performance under given working conditions, to meet specific application requirements. Based on Eq.(7), PV cell Simulink model shown in Figure 7 is developed. The variable operating ambient temperature *T*, and solar irradiation level *β*, affects the cell output voltage *V*, and cell photocurrent *I*. Considering these effects, the proposed Simulink model, contains two subsystems; subsystem shown in Figure8 for PV cell photocurrent given by Eq.(2) . Also, based on all presented equations, another general PV Simulink model with corresponding subsystem and mask, shown in Figure 9, is be proposed. Based on PV cell representation shown in Figure 3(a), and considering Eq.(7), two Simulink models shown in Figure 9(a)(b)(c), are developed, where model shown in Figure 9(c) is a refined and generalized model with most required output data for PV cell performance analysis, including cell-panel currents, volts, power and efficiency. Combining proposed sub-models shown in Figure 4, Figure 6(a)(b), and Figure 8 another PV system model is developed and given in Figure 10.

3. THE DEPENDENCE, EFFECTING FACTORS AND PERFORMANCE (OUTPUT CHARACTERISTICS) OF A PV SYSTEM

The developed Simulink sub-models of each component I_{ph} ,I_d, I_S and I_{Rsh} of E.(7) and given in Figure 8, Figure 4, Figure 5 Figure 6, Figure 11 and generalized model shown in Figure 9(c) can be used to test, analyze and study the effects of each of operating conditions and cell parameters on the performance and output characteristics of a PV array system.

3.1 The PV system performance dependence on variable operating T, and irradiation β.

The performance (output characteristics) of a PV array system depends on the operating conditions, as well as, the solar cell and array design quality, the operating conditions include ; the variable operating ambient temperature T, and solar irradiation level β, both affects the cell output voltage V, and cell output photocurrent I, where when the ambient temperature and irradiation levels change, the cell operating temperature also changes, resulting in a new output voltage and a new photocurrent value. Running model given in Figure 9, for parameters defined in Table 1, at standard operating conditions; irradiation B=1000, and T=25 and will result in P-V and I-V characteristics shown in Figure 13(a,b) these curves show, this is 3.926 Watt PV cell, I_{SC} = 8.13 A , Vo= 0.6120V , I_{max} =7.852 A , V_{max} =0.5 V, (MPP = I_{max} * V_{max} =7.852 *0.5=3.926). Running this model for defined parameters defined in Table 1, under the following operating conditions; B=200, and T=50 will result P-V and I-V characteristics shown in Figure 13(c,d) these resulting curves show, with increase in temperature at constant irradiation, the power output reduces, also, by increasing operating temperature, the current output increases and the voltage output reduces. The effects temperature T, and solar irradiation level β are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photocurrent, respectively, as given by Eq.(21) (J. Surya Kumari,et all, 2012)). The change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants C_{SV} and C_{SI} , as given by Eq.(22). The ambient temperature change, ΔTC, occurs due to the change in the solar irradiation level and is obtained using Eq.(23), to obtain the array voltage V, the output voltage Vc of the cell is multiplied by the number of the cells in series , based on these equations, Simulink model shown in Figure 11 is developed. The dependence of PV array system performance (output characteristics) on the operating conditions, T, β, can be seen in Figure 12(a) and Figure 14(b)

$$C_{TV}=1+\beta_T\left(T_a-T_x\right) \qquad C_{TI}=1+\frac{\lambda_T}{S_C}\left(T_x-T_a\right) \tag{21}$$

$$C_{SV}=1+\beta_T\alpha_s\left(S_x-S_C\right) \qquad C_{SI}=1+\frac{1}{S_C}\left(S_x-S_C\right) \tag{22}$$

$$\Delta TC=1+\alpha_s\left(S_X-S_C\right) \tag{23}$$

Where

S_c : the reference solar irradiation level during the cell testing to obtain the modified cell model.
S_x : the new level of the solar irradiation.
T_a : The variable ambient temperature.
T_x : New level of operating temperature.
β_T : 0.004 ,
λ_T = 0.06 at 20-250C.
α_s: represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level (0.2)

3.2 Effect of varying the shunt resistance R_{SH}

Running model given in Figure 9 for parameters defined in Table 1, at *standard* operating conditions*;* irradiation B=1000, and T=25 and variable shunt resistance R_{SH}, shows that for higher output power and higher fill factor of any PV cell, the shunt resistance R_{SH}, should be large enough

3.3 Effect of varying the diode reverse saturation current I_S.

The diode reverse saturation current varies as a cubic function of the temperature, an increase in I_S decreases the open-circuit voltage *Vo*, and decreases the power output.

4. Modeling and simulation of PV system ; module, panel and array

The power produced by a single PV cell is not enough for general use, where, each solar cell generates less than 2W at approximately, 0.5V, therefore the PV cells are connected in series-parallel configuration on modules, where series connections for high voltage requirement and in parallel connections (see Figure 1), or PV panels consisting of one or more PV modules, to produce and achieve desired power output. Panels can be grouped to form large photovoltaic arrays. The term *array* is usually employed to describe a complete power-generating unit, consisting of any number of PV modules and panels. In PV Simulink model shown in Figure 9 (a), by defining number of series and parallel PV cells (N_S,N_P,), the corresponding PV module can be evaluated. Also by defining number of series and parallel PV cell to be one ($N_S=N_P=1$), a PV, will result in sub block shown in Figure 15(a), this model can be used to develop required PV module, panel or array, as an example a PV module constructed of *four series* PV cell is developed and shown in Figure 15(a), running this model for defined parameters listed in table-1 and at *standard* operating conditions*;* will result in P-V and I-V characteristics shown in Figure 15(b). Comparing these characteristics with single PV cell P-V and I-V characteristics shown in Figure 13(a,b)**,** show that the current is kept constant at 8.13 A, but the output voltage is the sum of four PV cells voltages

5. Model programming in MATLAB

A MATLAB scripts including built-in function and m.file can be designed to return the I-V and P-V characteristics. Based on previous studies (G. Walker,2001)(F. González-Longatt, 2006)(Akihiro Oi.,2005)(Ramos Hernanz,et all, 2010)single diode (exponential) model of the PV model shown in Figure 3(a) provides fairly accurate results, since this model does not include the effect of parallel resistance, the I-V characteristics of the solar cell with single-diode and series resistance are given by Eq.(24):

$$\mathrm{I} = \mathrm{I}_{ph} - \mathrm{I}_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) \quad (24)$$

To calculate the net current, three variables to be defined; Va = Module operating voltage , β= Irradiance, Suns = 1000 W/m2. The equations used in calculations are as follows:
The current is given by Eq.(25):

$$I = I(\mathrm{T}_1) + \mathrm{K}_i(\mathrm{T} - \mathrm{T}_1) \quad (25)$$

Where:

$$I(\mathrm{T}_1) = \beta\frac{I_{sc}}{\beta_o} = \beta\frac{I_{sc}(\mathrm{T}_{1,\mathrm{ref}})}{\beta_o}$$

$$\mathrm{K}_i = \frac{I_{sc}(\mathrm{T}_2) - I_{sc}(\mathrm{T}_1)}{(\mathrm{T}_2 - \mathrm{T}_1)}$$

The inverse saturation current of the diode can be defined, as shown next by Eq.(26):

$$I_S(T) = I_S(\mathrm{T}_1)\left[\frac{T}{T_{ref}}\right]^3 e^{\left[\left(\frac{1}{T_{ref}} - \frac{1}{T_1}\right)\frac{qE_g}{NKT_1}\right]} \quad (26)$$

$$I_s(\mathrm{T}_1) = \frac{I_{sc}(\mathrm{T}_1)}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT}\right]} - 1\right)}$$

The Open circuit voltage V_O, depending on PV cell, e.g. $V_O = 21.08$, at temperature 25°C. The V_O per cell at temperature T_1, is given by:

$$\mathrm{Vo}(T_1) = V_{O\_}T / Ns;$$

I_{SC} is delivered under rated irradiation (1000 Wm^2) and temperature $T=25^\circ C$, in our case I_{SC} =8.13 A(also *2.55A*), and correspondingly, $I(T_1)$ is obtained by Eq.(27):

$$I(\mathrm{T}_1) = \frac{I_{sc}(\mathrm{T}_{1,\mathrm{ref}})}{\beta_o} \quad (27)$$

When $V = 0$, light generated photocurrent I_{ph_T1} = array short circuit current, the light-generated photocurrent I_{ph} ,at the nominal condition ($25^{\circ}C$ and 1000 W/m^2),

$$I_{ph\_T1} = \beta \frac{I_{sc}}{\beta_o}$$

$$I_{ph} = I_{ph\_T1} * \left(1 + a\left(T - T_1\right)\right);$$

The temperature coefficient of I_{SC}, (K_i, a) are calculated by:

$$K_i = \frac{I_{sc}(T_2) - I_{sc}(T_1)}{(T_2 - T_1)}$$

$$A = \frac{I_{sc2} - I_{sc1}}{I_{sc}\left(\frac{1}{T_2 - T_1}\right)}$$

The actual working temperature T(in K), is given by:

$$T = T_{ref} + T_{aC} = 237 + T_{aC}$$

The reference temperature is given by $T_{ref} = 273 + 25;$ The thermo voltage of cell V_t , is given by:

$$V_t = KT / q \text{ , and for array } (V_t = N_s KT / q)$$

The diode reverse saturation current I_s, varies as a function of the temperature and given by :

$$I_S(T) = I_S(T_1)\left[\frac{T}{T_{ref}}\right]^3 e^{\left[\left(\frac{1}{T_{ref}} - \frac{1}{T_1}\right)\frac{qE_g}{NKT_1}\right]}$$

$$I_s(T_1) = \frac{I_{sc}(T_1)}{\left(e^{\left[\frac{qV_{OC}}{N_S KAT_1}\right]} - 1\right)}$$

The series resistance Rs of the PV module has a large impact on the slope of the *I-V* curve near the open-circuit voltage (*Voc*), where a small variation in R_S will significantly affect the PV output power, series resistance R_S , per cell is determined by differentiating the Eq. (24)

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) \Rightarrow dI = 0 - I_S q\left(\frac{dV + R_S dI}{NKT}\right) e^{\left(\frac{qV+IR_S}{NKT}\right)} R_s = -\frac{dI}{dV} - \frac{\frac{NKT}{q}}{I_S e^{\left(\frac{qV+IR_S}{NKT}\right)}}$$

By evaluating the equation at the open circuit voltage that is *V=Vo and* letting I=0 .

$$R_s = -dVdI_{Vo} - \frac{1}{Xv}$$

$$dVdI_{Vo} = -1.15/Ns/2$$

$$Xv = Ir_{T1}/\left(\frac{NKT_1}{q}\right) * e^{\left(\frac{Vo_{T_1}}{NKT_1}\right)}$$

The thermo voltage of cell

$$Vt_T = \frac{NKT}{q}$$

For rapid convergence of the answer, the Newton's method described by Eq.(27):can be applied:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \qquad (27)$$

where: $f'(x)$ is the derivative of the function, $f(x) = 0$, n x is a present value, and n+1 x is a next value. Rewriting Eq. (24) gives Eq.(28), then substituting in Eq.(27) gives Eq.(29): (Akihiro Oi,2005)

$$f(I) = I_{ph} - I - I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right) = 0 \qquad (28)$$

$$I_{n+1} = \frac{I_{ph} - I_n - I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right)}{-1 - I_S \frac{qR_S}{NKT} e^{\frac{q(V+I_nR_S)}{NKT}}} \tag{29}$$

5.1 Proposed MATLAB script file for calculating PV system I-V and P-V characteristics

Using MATLAB, for given PV module with particular characteristics, two versions can be proposed of an m.file and built in function with corresponding name pviv, in both scripts user needs to define PV module datasheet parameters. The codes are listed below in section Xxx Based on proposed MATLAB function pviv with defined parameters, and using Simulink block named Embedded MATLAB Function, Simulink model shown in Figure 16 is proposed. Running proposed scripts for constant irradiation β and variable temperature T and for defined parameters including (Ns = 36; $I_{sc}(T_1)$ = 3.80; I_{sc} (T_2)= 3.92; Vo1=21.07; Vo2=17.07;), will return in V-I and P-V characteristic curves shown in

Figure(14).

Running proposed scripts for constant temperature T and variable irradiation β, for previously defined parameters will return the V-I and P-V characteristic curves shown in Figure 12. These curves show, the variable operating ambient temperature and solar irradiation level, affects the cell output voltage V, and cell photocurrent I. where with increase in temperature at constant irradiation, the power output reduces, also, by increasing operating temperature, the current output increases and the voltage output reduces

5.2 MATLAB M.file for calculating PV module current

```
clc, clear all
disp( '  ')
disp( '=========================== ')
disp( '     Program for calculating PV module current under ')
disp( '       given Voltage, Irradiance and Temperature ')
disp( '============================= ')
% Defining input variables
Va = input(' Enter Module operating voltage (V):');
B = input(' Enter Irradiance : ');
Tw=input( ' Enter Module temperature in deg C : ' );% Tac
Ns = input(' Enter number of series connected cells :');
Np=input(' Enter number of parallel connected cells :');1;
Vo1=input( ' Enter the Open circuit voltage, Voc,  at reference temp
(T1=25):');
Vo2=input( ' Enter the Open circuit voltage, Voc,  At temp T2 : ');
Isc_T1=input('Enter the short circuit Current per cell at reference temp T1:');
Isc_T2 = input(' Enter the short circuit Current per cell at temp T2 : ');
t2 = input(' Enter the given temp t2 : ');
% Calculating cell voltage
Vc = Va/Ns;
K = 1.38e-23; % Boltzmann's constant
q = 1.60e-19; % Electron charge
N = 1.2; % "diode quality" factor
```

```
Vg = 1.12;
Eg=1.12; % the band gap energy of the semiconductor
% Calculating open circuit voltage per cell at temperatures T1 and T2
Vo_T1 = Vo1 /Ns;
Vo_T2 = Vo2 /Ns;
T1 = 273 + 25;
T2 = 273 + t2;Tref=T1;
Tac = 273 + Tw; % array working temp.
% Calculating photon generated current @ given irradiance
Iph_T1 = Isc_T1 * B;
% Calculate short-circuit current for Tac
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);
Iph = Iph_T1 * (1 + a*(Tac - T1));
% Calculating the thermo voltage of cell at reference temp
Vt_T1 = K * T1 / q; % = A * kT/q
% Calculating reverse saturation current for given temperature
Ir_T1 = Isc_T1 / (exp(Vo_T1/(N*Vt_T1))-1);
Ir_T2 = Isc_T2 / (exp(Vo_T2/(N*Vt_T1))-1);
b = Eg * q/(N*K);
Ir = Ir_T1 * (Tac/T1).^(3/N) .* exp(-b.*(1./Tac - 1/T1));
% Calculating series resistance per cell
X2v = Ir_T1/(N*Vt_T1) * exp(Vo_T1/(N*Vt_T1));
dVdI_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell, from manufacturers graph
Rs = - dVdI_Voc - 1/X2v; % series resistance per cell
Vt_Ta = N*K*Tac / q; % = A * kT/q
Ia = zeros(size(Vc));
disp( '============================== ')
for j=1:6;
Ia = Ia - (Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))./ (-1 - (Ir.*(
exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);end
```

5.3 MATLAB function named pviv, for calculating PV module current

The proposed m.file can be modified and rewritten in built-in function file, the script is given below:

```
function  Ia  = pviv( Va,B,Tw )
% pviv
% Built-in function for calculating PV module current under ')
% given Voltage Va, Irradiance B, and Temperature Tw
% pviv function requires defining cell or module electric
% characteristics
clc,
```

```
disp( '  ')
disp( '============================ ')
disp( '  Built-in function for calculating PV module current under ')
disp( '       given Voltage, Irradiance and Temperature ')
disp( '============================= ')
% Defining input variables
Ns = input(' Enter number of series connected cells :');
Np=input(' Enter number of parallel connected cells :');1;
Vo1=input('Enter the Open circuit voltage, Voc, at reference temp (T1=25) :');
Vo2=input( ' Enter the Open circuit voltage, Voc,  At temp T2 : ');
Isc_T1 = input(' Enter the short circuit Current per cell at reference temp T1
: ');
Isc_T2 = input(' Enter the short circuit Current per cell at temp T2 : ');
t2 = input(' Enter the given temp t2 : ');
% Calculating cell voltage
Vc = Va/Ns;
K = 1.38e-23; % Boltzman's constant
q = 1.60e-19; % Electron charge
N = 1.2; % "diode quality" factor
Vg = 1.12;
Eg=1.12; % the band gap energy of the semiconductor
% Calculating open circuit voltage per cell at temperatures T1 and T2
Vo_T1 = Vo1 /Ns;
Vo_T2 = Vo2 /Ns;
T1 = 273 + 25;
T2 = 273 + t2;Tref=T1;
Tac = 273 + Tw; % array working temp.
% Calculating photon generated current @ given irradiance
Iph_T1 = Isc_T1 * B;
% Calculate short-circuit current for TaK
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);
Iph = Iph_T1 * (1 + a*(Tac - T1));
% Calculating the thermo voltage of cell at reference temp
Vt_T1 = K * T1 / q; % = A * kT/q
% Calculating reverse saturation current for given temperature
Ir_T1 = Isc_T1 / (exp(Vo_T1/(N*Vt_T1))-1);
Ir_T2 = Isc_T2 / (exp(Vo_T2/(N*Vt_T1))-1);
b = Eg * q/(N*K);
Ir = Ir_T1 * (Tac/T1).^(3/N) .* exp(-b.*(1./Tac - 1/T1));
% Calculating series resistance per cell
X2v = Ir_T1/(N*Vt_T1) * exp(Vo_T1/(N*Vt_T1));
dVdI_Voc = - 1.15/Ns / 2; % dV/dI at Voc per cell, from manufacturers graph
Rs = - dVdI_Voc - 1/X2v; % series resistance per cell
Vt_Ta = N*K*Tac / q; % = A * kT/q
Ia = zeros(size(Vc));
disp( '=========================== ')
for j=1:6;
Ia = Ia - (Iph - Ia - Ir.*( exp((Vc+Ia.*Rs)./Vt_Ta) -1))./ (-1 - (Ir.*(
exp((Vc+Ia.*Rs)./Vt_Ta) -1)).*Rs./Vt_Ta);
end
end
```

5.4 Script for plotting I-V and P-V curves of PV module

To plot the I-V and P-V curves for temperature values of [0:20:80], the following code can be used , the values of Voltage V_a, Irradiance B, and Temperature T_w can be set to desired values, to study their effect, notice that, this code will recall the built-in function pviv during calculations

```
clear;B = 1;
figure, hold on
```

```
for TaC=0:20:80
Va = linspace (0, 48-TaC/8, 200);
Ia = msx60i(Va, B, TaC);
plot(Va, Ia)
end
title(' Photovoltaic Module I-V Curve')
xlabel('Module Voltage (V)')
ylabel('Module Current (A)')
axis([0 50 0 5])
gtext('0C')
gtext('20C')
gtext('40C')
gtext('60C')
gtext('80C')

figure, hold on
for TaC=0:20:80
Va = linspace (0, 48-TaC/8, 200);
Ia = msx60i(Va, B, TaC);
Pa= Va.*Ia;
plot(Va, Pa)
end
title(' Photovoltaic Module P-V Curve'), xlabel('Module Voltage
(V)'),ylabel('Module Current (A)'),axis([0 25 0 80]), gtext('0C'),
gtext('20C'), gtext('40C'), gtext('60C'), gtext('80C')
```

6. MAXIMUM POWER POINT AND MPP TRACKING

The power delivered by a PV system of one or more photovoltaic cells is dependent on the irradiance, temperature, and the current drawn from the cells. The power output of a PV system is given by:

$$P = V * I$$

With incremental change in current ΔI ,and voltage ΔV, the modified power is given by Eq.(30), by solving and then ignoring small terms, Eq.(30) simplifies to Eq.(31), since no changes power at peak point, that is ΔP=0,by manipulating and in the limits , will result in Eq.(32)

$$(P + \Delta P) = (V + \Delta V) * (I + \Delta I) \tag{30}$$

$$\Delta P = \Delta V * V + \Delta I * I \tag{31}$$

$$\frac{\Delta V}{\Delta I} = \frac{dV}{dI} = -\frac{V}{I} \tag{32}$$

Maximum Power Point,
MPP, is the operating point at which the power is maximum across the load and given by:

$$P_{max} = V_{max} * I_{max}$$

6.1 Maximum power point tracking (MPPT)
The power delivered by a PV system is dependent on the irradiance, temperature, and the current drawn from the cells. To maximize a PV system's output power, it is necessary continuously tracking the maximum power point (MPP) of the system. Maximum Power Point Tracking (MPPT) it is a technique used to get the maximum possible power from PV system. There are many different approaches to maximizing the power from a PV system, to make best and maximum use of solar PV system, two main ways; *the first* is mechanically tracking the sun and always orienting the panel in such a direction as to receive maximum solar radiation under changing positions of the sun. The second is *electrically* tracking the operating point by manipulating the load to maximize the power output under changing conditions of insolation and temperature (Abu Tariq, et all, 2011) (H. D. Maheshappa, et all,1998)(Altas. I, et all, 2007)(Khan, B.H,2006). A maximum power point tracker is a high efficiency DC/ DC converter which functions as an optimal electrical load for a PV cell, most commonly for a solar panel or array, and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive(Abu Tariq,2011). Referring to Figure 3(f) and Figure 14, the property that is utilized to track the MPP, is based on that, from the shown shape of P-V characteristic, at MPP, the slope, *dP/dV* is zero. The equations cab be derived as follows:

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$$slope\Big|_{MPP} = \frac{dP}{dV} = 0$$

$$\frac{dP}{dV} > 0 \ \ ,at\ the\ left\ of\ \ MMP$$

$$\frac{dP}{dV} < 0 \ \ ,at\ the\ \text{right}\ of\ \ MMP$$

Practically, Voltage is adjusted and power output is sensed; Voltage is increased as long as dP/dV is *positive*. If *dP/dV* is sensed *negative*, the operating voltage is decreased, if *dP/dV* is near zero, the voltage is held adjusted. The proposed controller circuit that forces the system to operate at its optimal operating point under variable temperature and irradiation conditions is shown in Figure 17(Manish Jain, et all,)

7. CONCLUSIONS AND FUTURE WORKS

For Mechatronics design of solar electric applications, different and a generalized mathematical and Simulink models of PV system are developed and tested in MATLAB/Simulink, based on desired representation accuracy and specific application, proposed models allow designer to tested and analyze the PV panel for most desired output numerical visual and graphical data, for given input operating conditions, to meet specific application requirements. Also, MATLAB scripts for calculating and plotting the I-V and P-V characteristics of PV module are proposed. The main characteristics and parameters that have to be considered in modeling and simulation a photovoltaic module are introduced. The proposed mathematical, Simulink and scripts Models are intended for research and education purposes. As future work, the proposed models and scripts are to be used in author's future works in modeling, simulation and testing of particular solar electric applications including Photovoltaic-Converter system control issues**,** Mechatronics design of solar electric vehicle and standalone sun tracker systems.

Table 1 Nomenclature and electric characteristic

I A	The net cell current (*the module current*),
Isc=8.13 A,2.55A ,	The short-circuit current, at reference temp
I_{SC} A	The cell's short-circuit current, given in datasheet specifications of PV panel.
I_{ph} A	The light-generated *photocurrent* at the nominal condition (25°C and 1000 W/m²), it is directly proportional to the Sun irradiation
E_g =1.1	The band gap energy of the semiconductor
$V_t = KT/q$ V	The thermo voltage of cell. For array :($V_t = N_s KT/q$)
I_s A	The reverse saturation (or leakage) current of the diode
R_{sh} Ohm	The shunt resistors of the cell, usually the value of R_{sh} is very large (*1000* Ohm)
R_S Ohm	The series resistors of the PV cell, (0.001 to 0.10 Ohm),it may be neglected to simplify the analysis.
V	The voltage across the diode
q=1.6e-19 C	The electron charge
B_o=*1000*	The Sun irradiation, W/m^2
β W/m²	The irradiation on the device surface , (considered : 200 , 500)
Ki=0.0017 A/◦C	The cell's short circuit current temperature coefficient
Vo= 30.6/50	Open circuit voltage, V
Ns= 48 , 36	Series connections of cells in the given photovoltaic module
Np=1 , 30	Parallel connections of cells in the given photovoltaic module
K=1.38e-23	The Boltzmann's constant, J/oK;
N=1.2	diode ideality factor, takes the value between 1 and 2
T= 50,75	Working temperature of the *p-n* junction , Kelvin
T_{ref}=273	The nominal reference temperature, Kelvin
A = 0.0025	Cell surface area, m²

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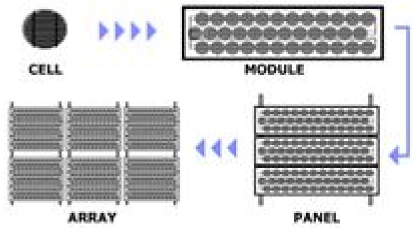

Figure 1, from solar cell to solar array [7]

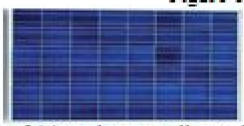

Figure 2(a) multi-crystalline silicon

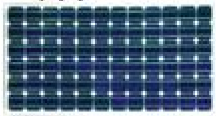

Figure 2(b) Mono-crystalline silicon

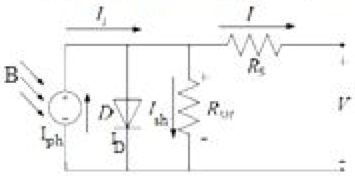

Figure 3 (a) Single diode (exponential) model of the PV model

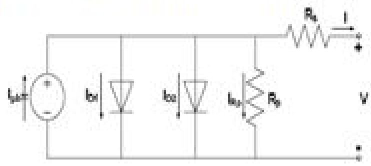

Figure 3 (b) PV Double diode (exponential) model

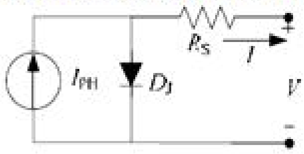

Figure 3 (c) Single diode (Appropriate,) model of PV Cell

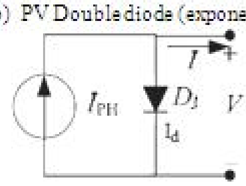

Figure 3 (d) PV *Simplified Ideal* single diode model

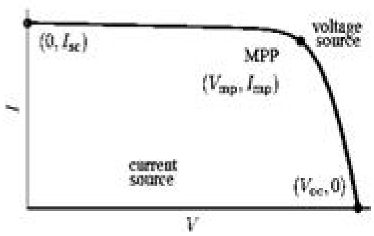

Figure 3(e) Characteristic I-V curve of a practical photovoltaic device and the three remarkable points: short circuit (0, I_{sc}), maximum power point (V_{mp}, I_{mp}) and open-circuit(V_o, 0)[13]

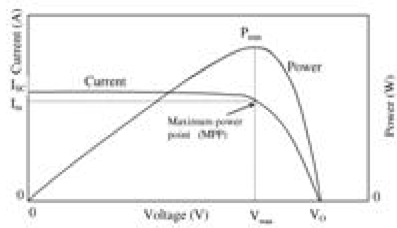

Figure 3(f) Typical characteristic I-V and P-V curve of a practical photovoltaic device and the three remarkable points [14]

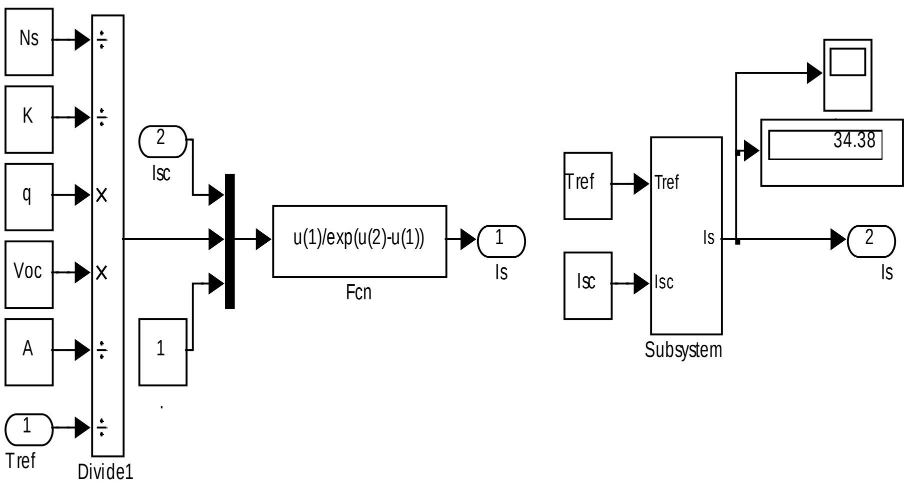

Figure 4 Simulink model of the module reverse saturation current subsystem

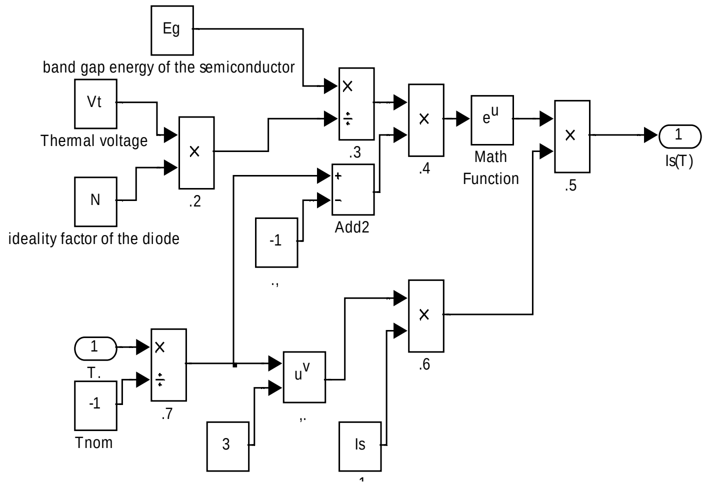

Figure 4 Simulink model of the module reverse saturation current subsystem

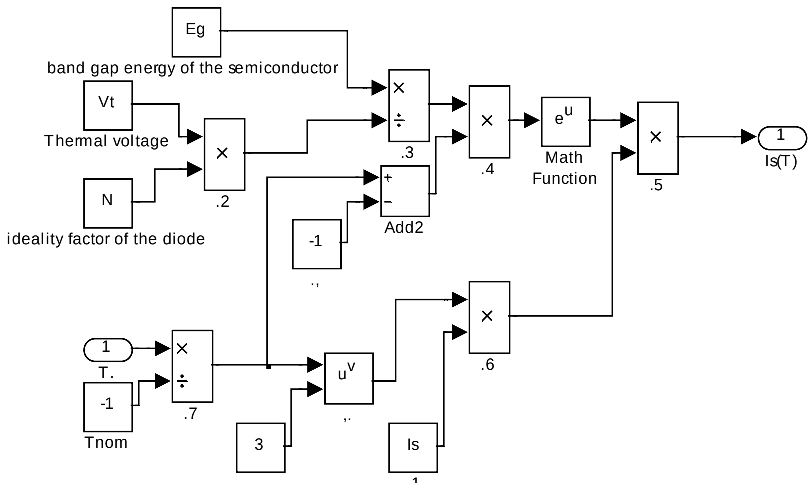

Figure 5(a) The diode reverse saturation current I_s subsystem model

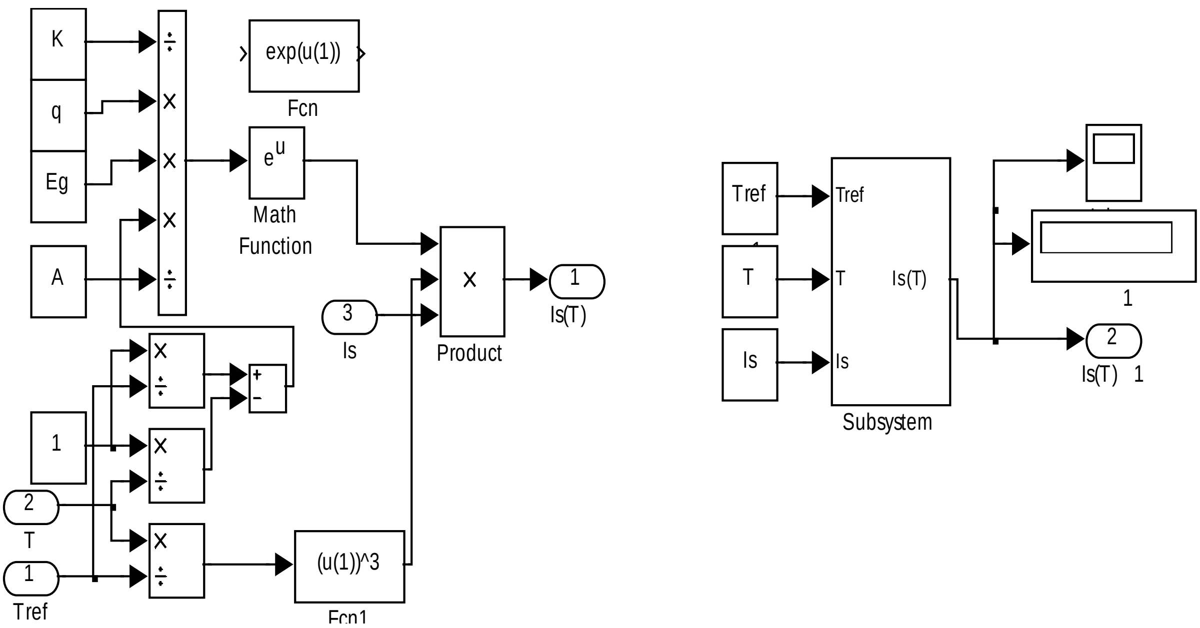

Figure 5(b)

Figure 5(a)(b) Simulink temperature effect subsystems on module reverse saturation cu

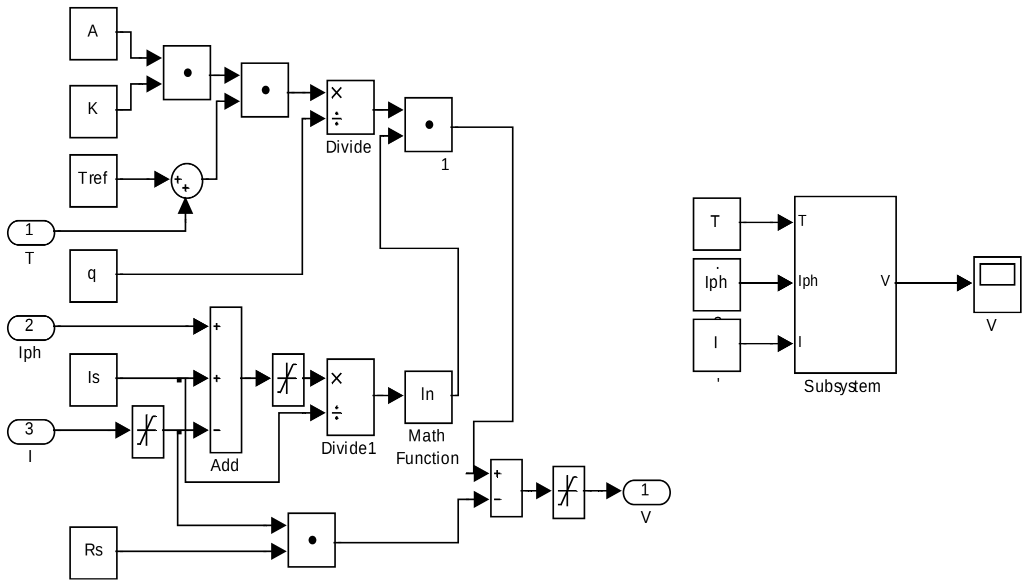

Figure 6 The maximum PV voltage represented by Eq. (13),

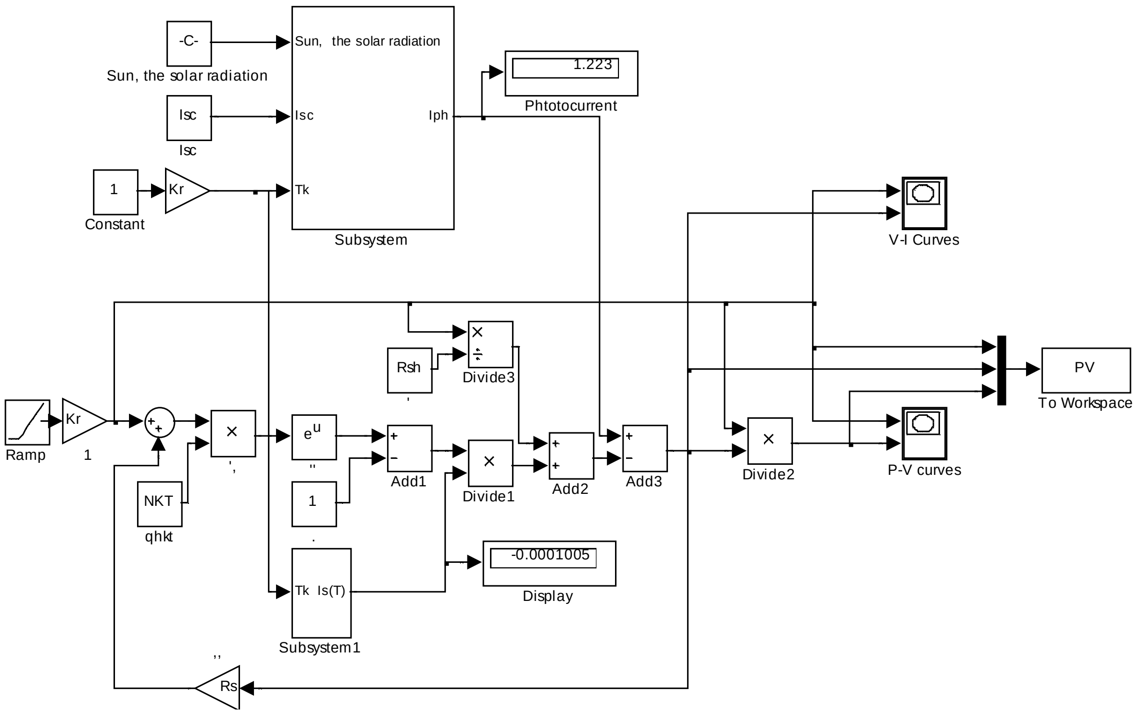

Figure 7 PV cell model Based on Eq.(7)

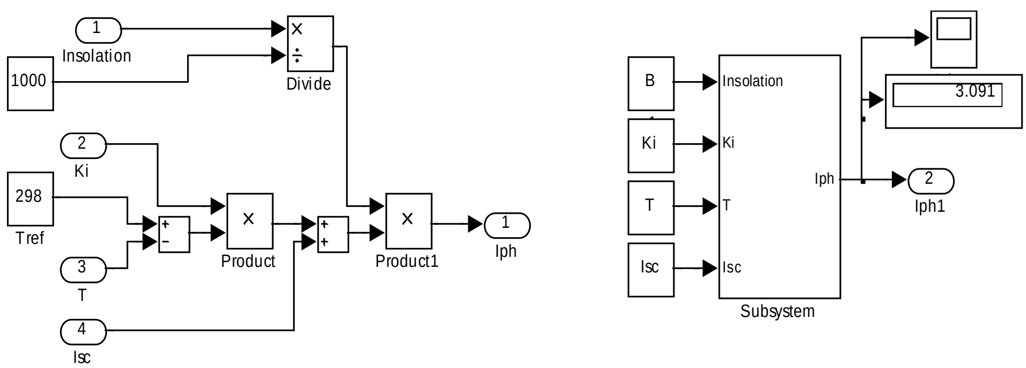

Figure 8 PV cell photocurrent I_{ph} subsystem Simulink model

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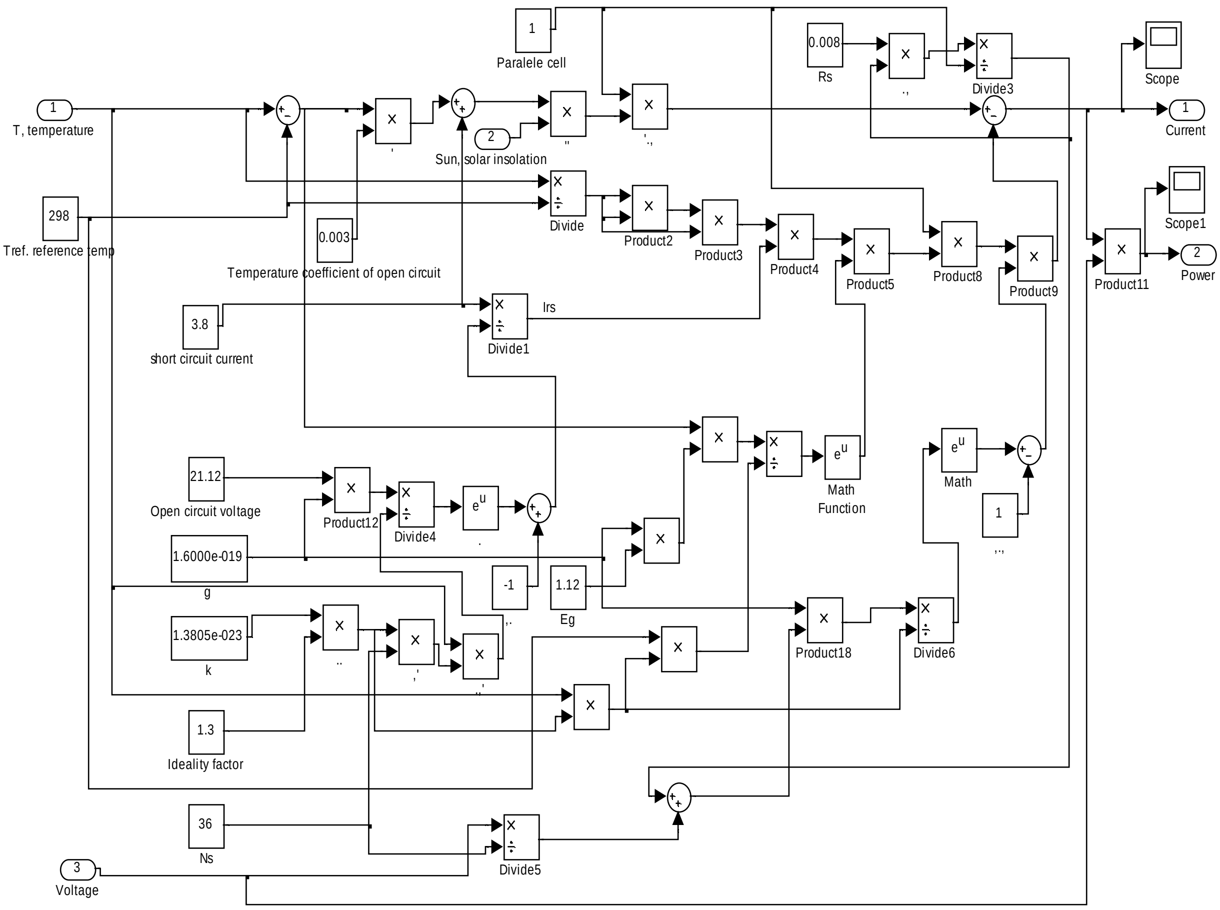

Figure 9(a) PV cell-system subsystem model

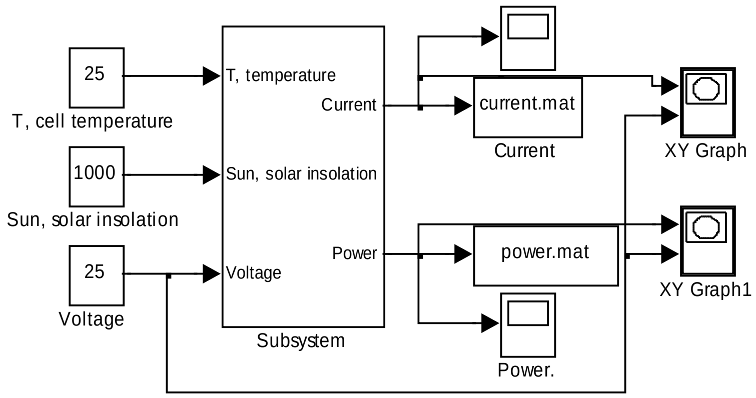

Figure 9(b) PV cell-system subsystem mask

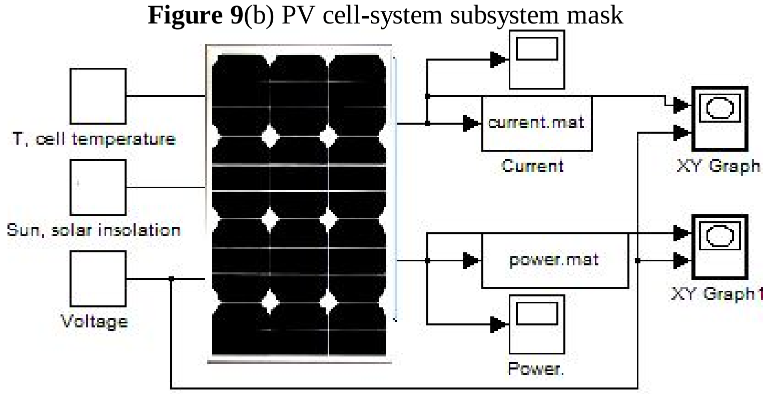

Figure 9(c) PV cell-system subsystem mask

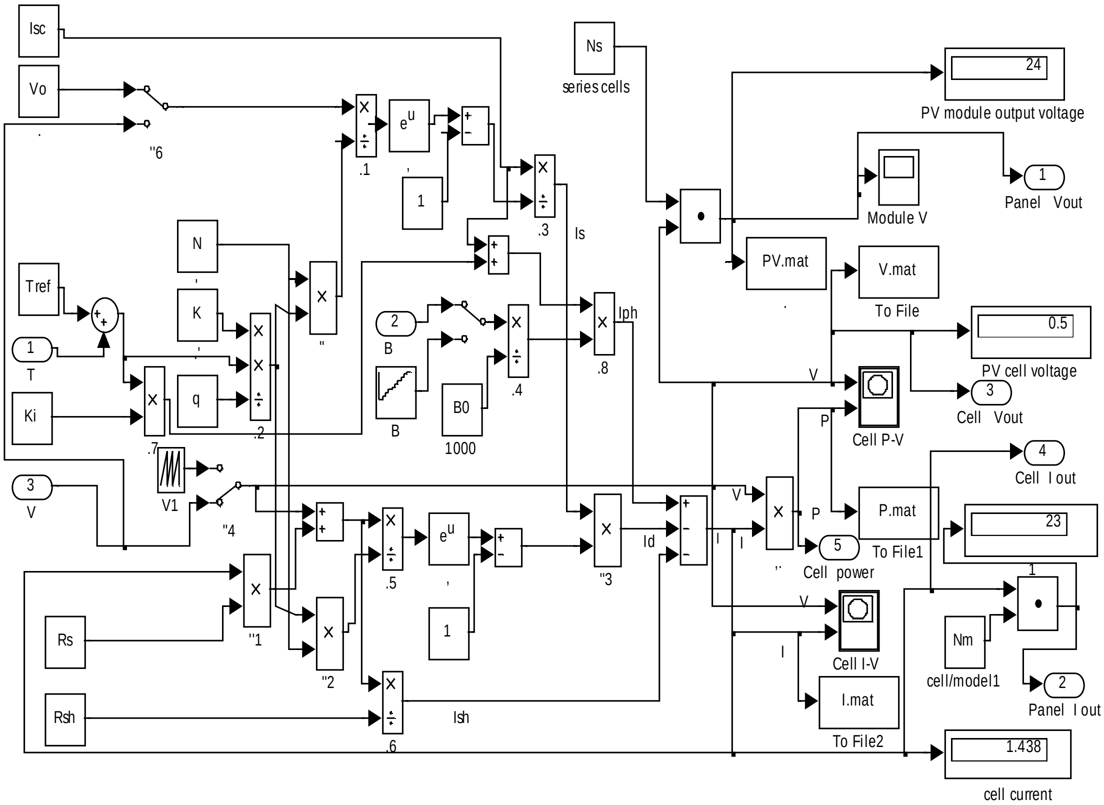

Figure 9 (a) PV Panel Simulink model

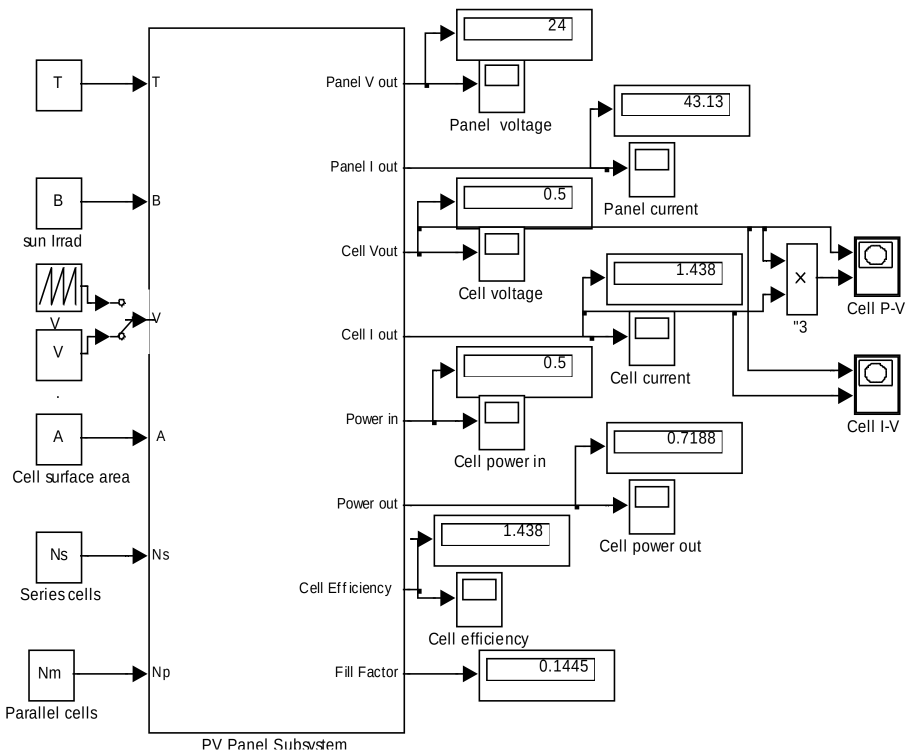

Figure 9(c) Generalized PV Cell-Panel model

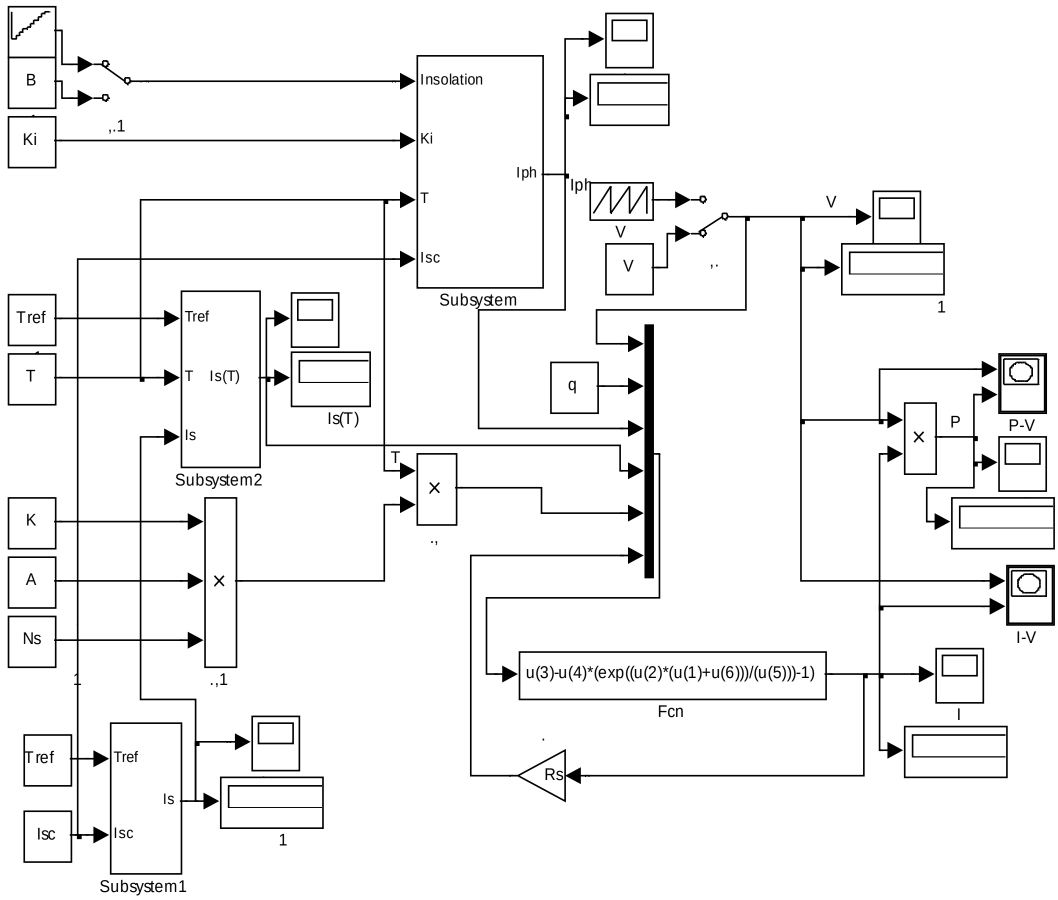

Figure 10 PV system model implemented by combining proposed sub-models shown in Figure 4, Figure 6(a)(b) and Figure 8

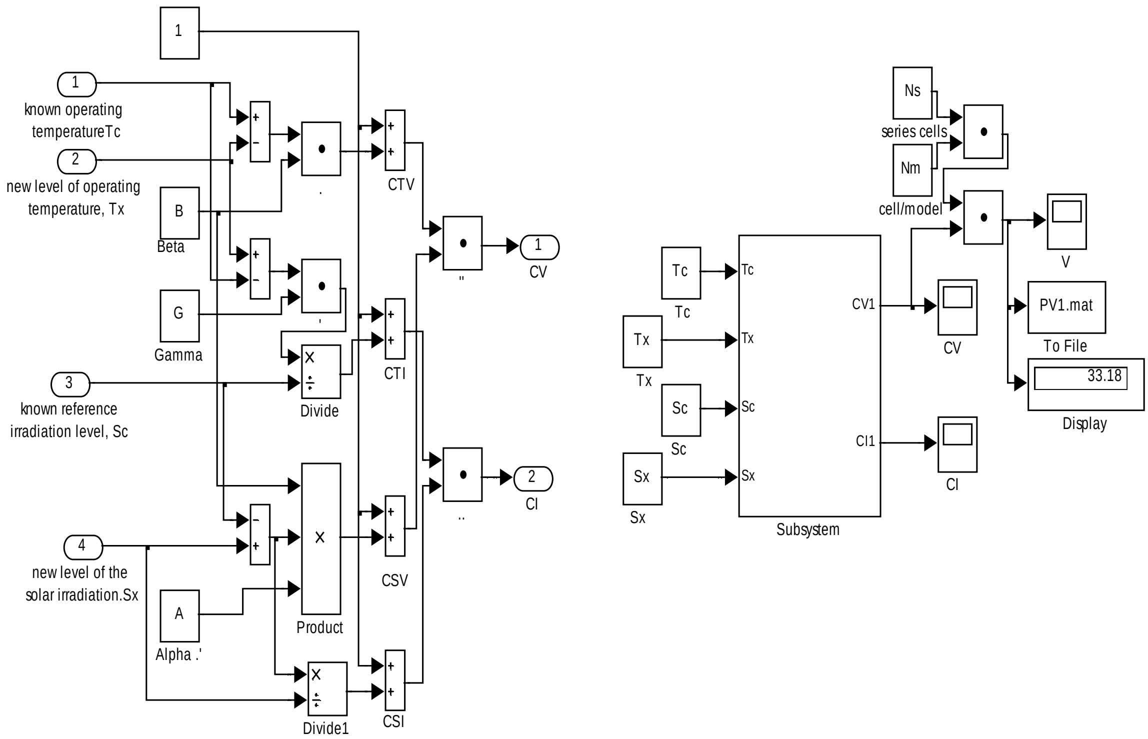

Figure 11 (14) Effects of variable operating ambient temperature *T*, and solar irradiation level *β*, to obtain the array voltage *V*, the output voltage *Vc* of the cell is multiplied by the number of the cells in series.

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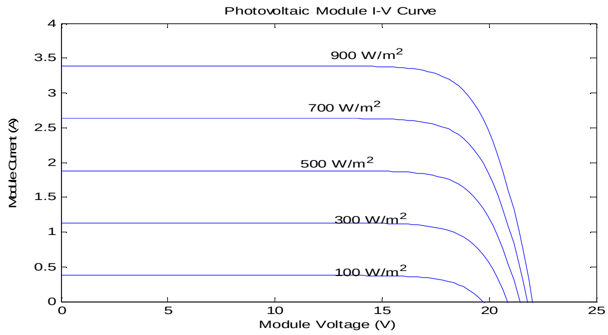

Figure 12(a) V-I Characteristics for variable irradiation β=0.1:.2:1 and const. temperature =1000

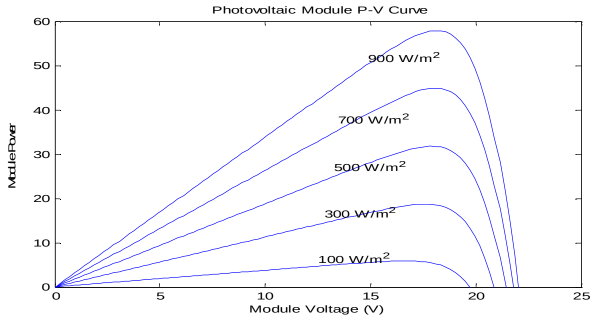

Figure 12(b) P-V Characteristics for variable irradiation β=0.1:.2:1 and const. temperature =1000

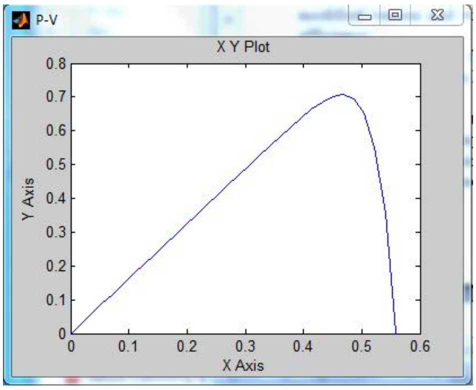

Figure 13(b) P-V Characteristics for β=200, and T=50

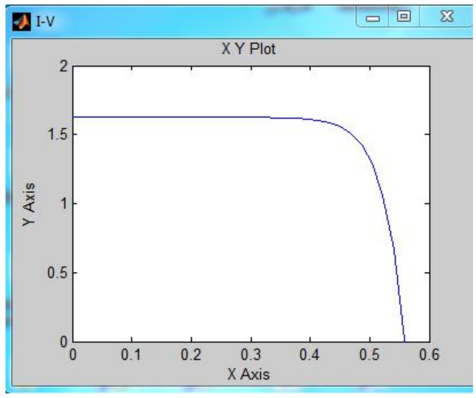

Figure 13(a) V-I Characteristics for β=200, and T=50

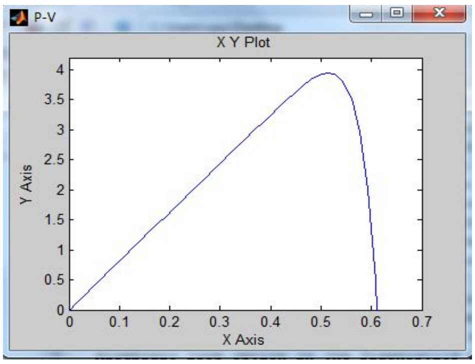

Figure 13(b) P-V Characteristics for β=1000, and T=25

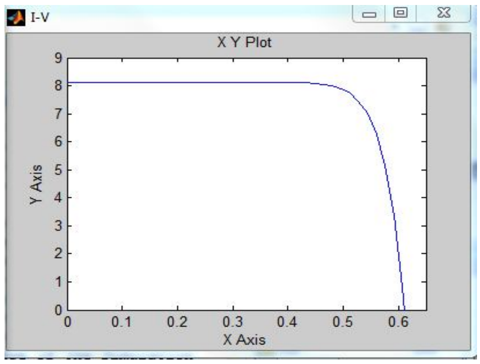

Figure 13(a) V-I Characteristics for β=1000, and T=25

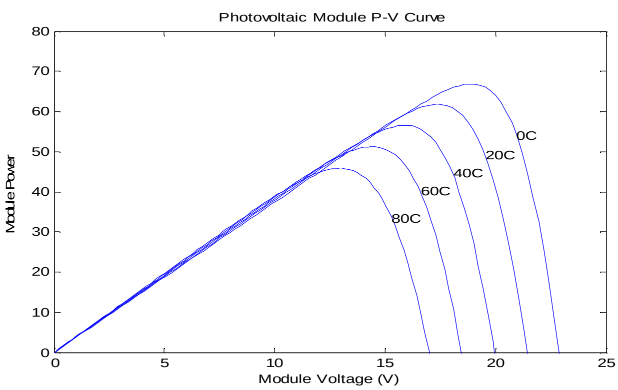

Figure 14(b) P-V Characteristics for variable temperature T=0:20:80 and const. irradiation β=1000, where increase in temperature at constant irradiation**,** the power output reduces,

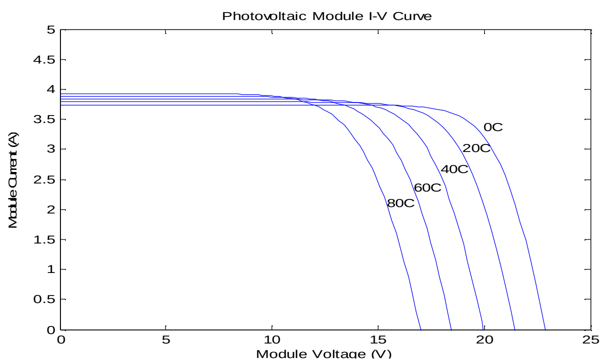

Figure 14(a) I-V Characteristics for T=0:20:80 and const. irradiation, where increasing operating temperature, the current output increases and the voltage output reduces

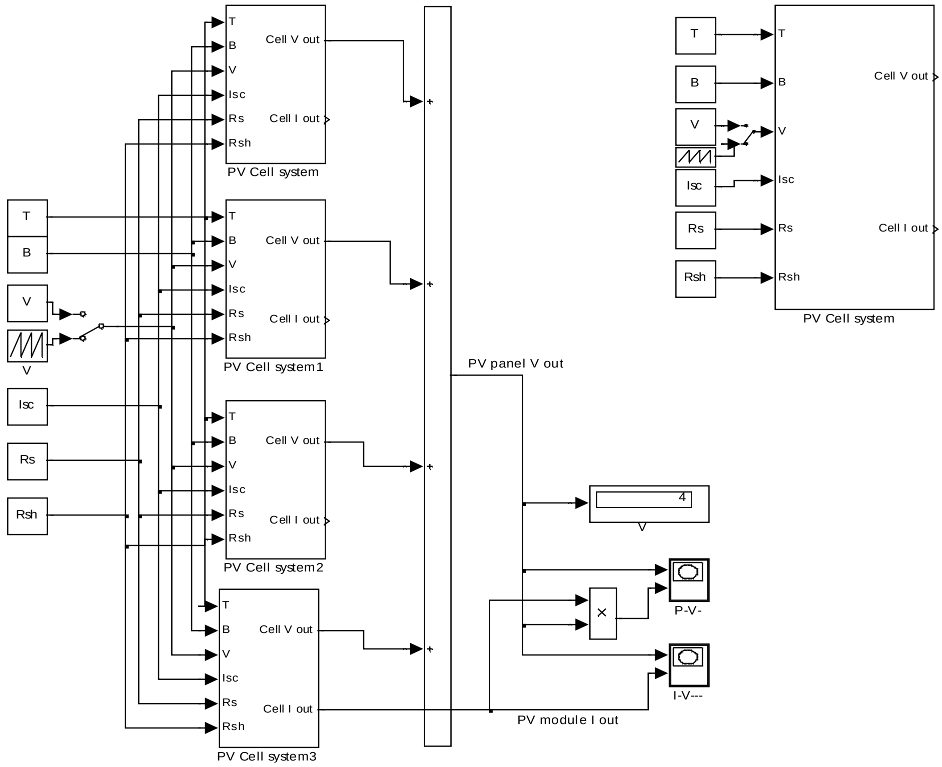

Figure 15(a) PV cell sub block for developing PV modules, panels and arrays (right side) PV module model (left side) of four series cells

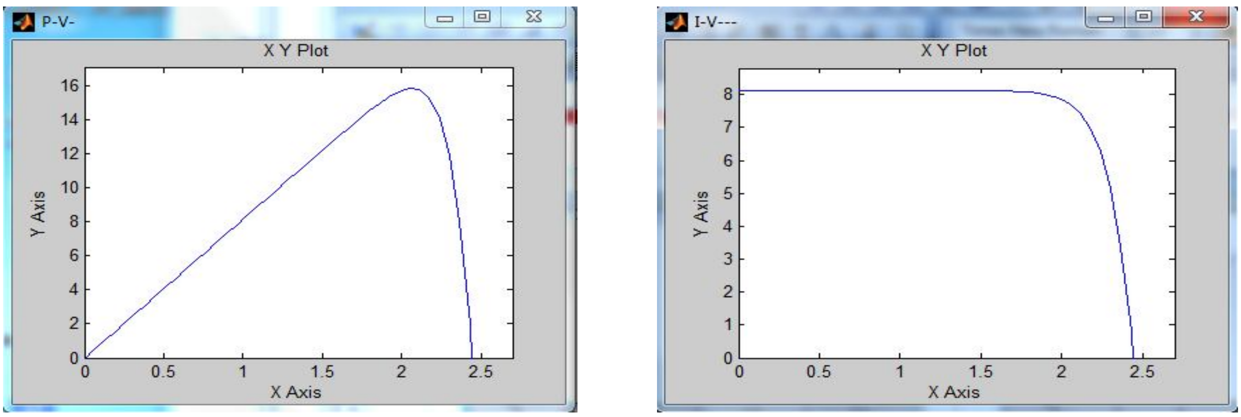

Figure 15(b) P-V and I-V characteristics of PV module consisting of four series PV cells

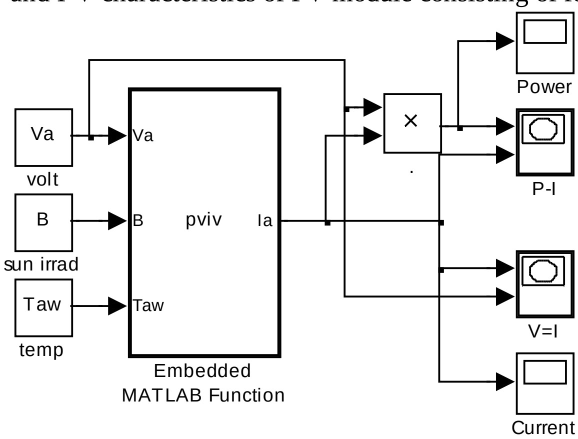

Figure 16 Simulink model using Embedded MATLAB Function

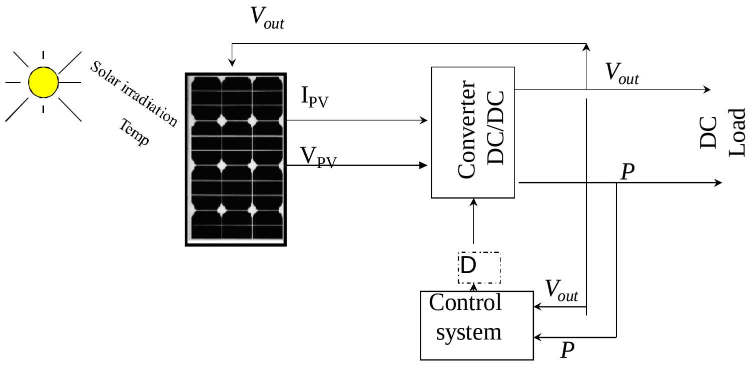

Figure 17(a)

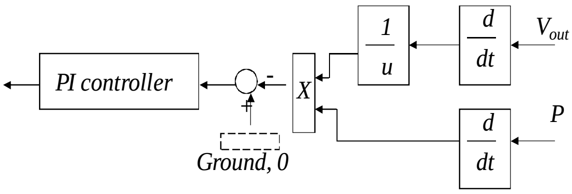

Figure 17(b)

Figure 17(a)(b) MPPT block diagram representation