A Proposed Dynamic Model of Photovoltaic-DG Systems

A.E. Hassan M.M. El-Saadawi K.M. Abo-Al-Ez M.S. Kandil

Dept. of Electrical Engineering, Faculty of Engineering, Mansoura University, Egypt

Abstract— Dynamic simulation modeling is so important to predict the energy production of Photovoltaic (PV) systems. It is needed to make informed technical and economical decisions. The simulation models of PV systems in literature are good enough for steady state analysis, but they are not suitable for dynamic analysis of grid operating and control conditions.

This paper proposes a dynamic PV model suitable for Decentralized Generation (DG) applications. The proposed model relates the electrical output of the PV system to various input and environmental parameters. The model is developed in Matlab-Simulink environment, and it is validated comparing the developed PV performance characteristic curves with those of the manufacturer's data sheet and those developed by a commercial software package for a Solarex-MSX 60W PV type.

Index Terms— Photovoltaic (PV) model, Decentralized Generation (DG), Temperature coeffcients.

I. INTRODUCTION

Dynamic modeling and simulation of modern Decentralized Generation (DG) electrical systems is a challenging process because of the several modeling steps presenting the power generation dynamics of the DG systems. The modeling and simulation process could have different complexity levels depending upon the model purpose [1]. Photovoltaic (PV) technology is offering one of the best DG power production options. PV systems are highly reliable. They are suitable for off- grid DG applications requiring less than 10 kW [2], [3]. From a technical point of view, there will be no difficulty in integrating as much PV into low-voltage grids as the peak load of the respective segment [4].

Improving the PV operation and control strategies is not a simple task, and it requires full understanding of system behavior. In order to achieve that, modeling of the PV system is needed for testing different control algorithms and operation senarios before real-time implementation. PV simulation models have been developed for years. Literature review of some of recent work is presented in [5-8]. The research in those literatures used general and simplified mathematical models,The models presented in those literatures are good enough for steady state analysis and they are needed to model the PV system annual performance, but all those models lacked the availability to represent the dynamic analysis with both real grid conditions, and various dynamic control algorithms. Other PV models are available within some commercial softwares as Hybrid2, Somes, Pvsyst, Solar Studio, PV F-chart, PV-design Pro…etc [9]. The software packages are mainly used to determine size, cost and sometimes performance of a propsed PV system. They can perform extensive sensitivity analysis, but they generally do not permit the user to modify the operating algorithms that determine the behavior and interactions on individual system components, which is an essential trail in developing extensive research software. The PV model should be dynamic and flexible enough to easily model the components of the required PV equivalent circuit. The model should predict how PV current and voltage vary with ambient temperature and solar irradiation conditions [10].

At this paper, a PV-DG model is proposed. The proposed model allow the operation of a single solar cell, and hence a panel, to be simulated using available data from manufacturers, and field tests. These data are used to provide values for the model parameters. The model is then tested and verified by comparing the results showing the I-V and P-V charteristcis to the that provided by both the manufacturer for the Solarex MSX60 PV type, and that calculated by a software package (PV-design Pro.). All the proposed modules are built using Matlab-Simulink [11].

II. PV EQUIVALENT ELECTRICAL CIRCUIT

In the crystalline silicon PV module; the complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure.1. For that equivalent circuit; a set of equations have been derived, based on standard theories [12-17]. The that allow the operation of a single solar cell, to be simulated using data from manufacturers or field experiments [16].

The circuit parameters can be represented as follows [13-17]:

- The output-terminal current I is equal to the light-generated current I_L, minus the diode-current I_d and the shunt-leakage current I_{sh}.
- The series resistance R_s represents the internal resistance to the current flow, and depends on the p-n junction depth, the impurities and the contact resistance.
- The shunt resistance R_{sh} is inversely related with leakage current to the ground.

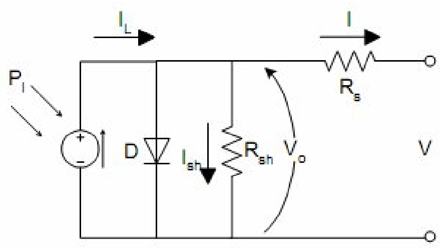


Figure.1 Equivalent electrical circuit of PV module

In an ideal PV cell, Rs = 0 (no series loss), and Rsh = ∞ (no leakage to ground). In a typical high quality one square inch silicon cell, R_s = 0.05 to 0.10 ohm and R_{sh} = 200 to 300 ohms [13]. The PV conversion efficiency is sensitive to small variations in R_s, but is insensitive to variations in R_{sh}. A small increase in R_s can decrease the PV output significantly [13].

III. Mathematical Modeling of the PV System

In the equivalent circuit of Figure 1, the current delivered to the external load can be expressed as:

$$I = I_L - I_d - \frac{V_0}{R_{Sh}} \tag{1}$$

where:

I_L = current generated by the illumination (A),
I_d = diode current (A),
I_{sh} = ground-shunt current (A),
$V_0 = V_{Sh}$ = diode and the shunt resistance voltage (V).

The cell could be represented by a voltage-current equation as:

$$V = V_0 - R_s I \tag{2}$$

where:

V = cell output voltage (V).
I = load (cell) output current (A).
I_L = photo-current (A).
I_0 = reverse diode saturation current (A).

The two most important parameters widely used for describing the cell electrical performance are the open-circuit voltage V_{oc} and the short-circuit current I_{sc}. The short-circuit current is measured by shorting the output terminals, and measuring the terminal current under full illumination. The maximum photo-voltage is produced under the open-circuit voltage. The open circuit voltage V_{oc} of the cell is obtained when the load current is zero, i.e., when I = 0.

IV. Mathematical Modeling of Environmnetal Factors

In this research paper, the accuracy of the proposed PV model is increased by mathematically presenting the temperature dependence of both photocurrent I_L and diode saturation current I_0.

The series resistance R_s is included in the mathematical presentation, but the shunt resistance is ignored. The proposed model uses the simplified single diode equivalent circuit presented in [15].

The general equation describing the (I-V) characteristics of the PV cell is obtained from Equation (1) by ignoring the last term of the shunt resistance and replacing the diode current by the formula used for in [16]:

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_s)}{nKT_r}} - 1\right) \tag{3}$$

where:

q = electron charge = 1.6* 10^{-19} Coulombs.
n = ideality factor.
K = Boltzmann constant = 1.38 * 10^{-23} Joule/^{0}K.
T_r = rated temperature in Kelvin.

Now the non-linear Equation (3) describes the PV cell I-V characteristics, which adopts the equivalent circuit of PV cell presented in Figure 1, include an explicit solar irradiation dependency of the photocurrent (I_L). The diode current (I_d) is modeled as a thermally activated device to account for variations of module performance with temperature. Equation (3) is considered as the benchmark model for a certain level of cell operating temperature (T_r) in (Kelvin), and solar irradiation level (G_r) in (W/m^2). If those two important environmental variables are taken into consideration, the voltage and current output of the PV cell will follow their changes which should be included in the final PV cell model.

When the cell is not exposed to solar radiation, the relationship between the cell's terminal voltage and current is given by the Shockley equation [16]. When the cell is open circuited and illuminated by solar radiation, the photo-current flows entirely in the diode. The (I-V) curve is offset from the origin by the the photo generated current I_L as illustareted in Equation (3).

The value of the saturation current I_0 at different operating temperatures is calulcted as follows [15-17]:

$$I_0 = I_{0(T_r)} * \left(T/T_r\right)^{3/n} * e^{\frac{-qVg}{nK \cdot \left(\frac{1}{T} - \frac{1}{T_r}\right)}} \tag{4}$$

$$I_{0(T_r)} = \frac{I_{SC(Tr)}}{e^{qV_{OC(Tr)}/nKTr}} - 1 \tag{4.a}$$

where:

Vg = The band gap voltage
Voc(Tr) = Open Circuit voltage at rated operating conditions.
$I_{sc}(T_r)$ = Short circuit current at rated operating conditions.

The unknown ideality factor "n" must be estimated. It takes a value from 1 to 2 . A value of 1.3 is suggested as typical in normal operation [8]. The relationship of I_0 in Equation (4) is complex, but fortunately contains no variables that require evaluation [18].

The photo-current I_L(A) is directly proportional to irradiation level G (W/m^2), and can be expressed as [18]:

$$I_L = I_{L(T_r)}\left(1 + \alpha_{Isc}(T - T_r)\right) \tag{5}$$

$$I_{L(T_r)} = G * \frac{I_{SC(Tr,nom)}}{G_r} \tag{5.a}$$

$$\alpha_{Isc} = \frac{dI_{sc}}{dT} \qquad (5.b)$$

where:

α_{Isc} = the short circuit temperature coefficient

As shown by Equation (5); the relationship between the photo-current and temperature is linear. It depends on the change of photo-current with the change of temperature for a constant value (α_{Isc}) specified in equation (5.b).

The open circuit voltage varies with temperature as illustarted in Equation (6):

$$V_{oc(T)} = V_{oc(T_r)}\left(1 - \beta_{Voc}\,(T - T_r)\right) \qquad (6)$$

where:

β_{VOC} = the open circuit temperature coeffcient.

The term "temperature coefficients" has been applied to several different phtovoltaic performance parameters, including voltage, current, and power. Temperature coefficients are used to quantify the relationship between various electrical characteristics of the photovoltaic module and its operating temperature. The manufacturers usually provide data about the temperature coefficients. ASTM standard methods for performance testing of cells and modules adress two temperature coefficents, one for current and one for voltage [19,20]. The open circuit voltage temperature coefficient (β_{VOC}) is usually assumed to be independent of the solar irradiation level. Although this assumption is not strictly correct, it is a reasonable simplification. For a typical flat-plate module with solar irradiation level varying from 100 W/m^2 to 1000 W/m^2 there is typically less than 5% change in the voltage coefficient. On the other hand; the for short circuit temperature coefficient (α_{Isc}) must be scaled by the ratio of actual irradiation level to the level of 1000 W/m^2 used for determining the coefficients [21], as previously illustrated in Equation (5.a). The current coeffcients are automatically scaled for irradiation level independent of the number of modules connected in parallel. The voltage coeffcients are the values expected at ASTM standard conditions.

All the constants in the above equations can be determined by examining the manufacturers ratings of the PV array. These constants are provided for typical rating conditions of 25 ^{0}C cell temperature, a prescribed solar spectrum of 1000 W/m^2 irradiation level, and zero angle of incidence.

The current and power output of photovoltaic modules are approximately proportional to solar irradiation. At a given solar irradiation level, a PV module's output current and operating voltage are determined by the characteristics of the load. The current/voltage (I-V) curve is a representaion of a PV module's possible operating points (voltage/current combinations) at a given cell temperature and solar irradiation level. It should be noted that any increases in cell temperature leads to an increase in current and a decrease in voltage, while this conculsion is opposite for the increase of solar irradiation level [22].

V. Building the PV Simulation Model

Matlab-Simulink environment is used for creating accurate mathematical models of PV system physical behavior [11]. The graphical, block paradigms of the Matlab-Simulink environment are hierarchical and self-documenting. The Simulink block diagram presenting the PV model is the core of the system model. This block contains a group of Simulink sub-blocks connected according to the mathematical equations discussed in section (IV) to build the final proposed model. The model is flexible to presnet any number of PV modules connected in series (to have the desired output voltage), and the the number of parallel branches, according to the power required from the PV system.

A Solarex MSX60 PV type [23] is chosen for PV array modeling. The MSX60 module provides 60 Watts of nominal maximum power, and has 36 series connected polycrystalline silicon cells. The performance of typical MSX60 modules is described by the electrical characteristics parameters shown in Table.1 [22,23].

Table.1 Key specifications of SOLREX MSX60 [22,23]

Description	Value
Typical peak power (Watts)	60
Voltage at peak power (Volts)	17.1
Current at peak power (Amperes)	3.5
Guaranteed minimum peak power (Watts)	58
Short circuit current Isc (Amperes)	3.8
Open circuit voltage Voc (Volts)	21.1
α_{Isc} Temperature coefficient for Isc =	0.00063
β_{Voc} Temperature coefficient for Voc =	0.0042

A Matlab-Simulink model is developed for one cell of the PV module based on the manufacturer data, and the mathematical equations (from eq.3 to eq.6) as shown in Figure 2.

The complete PV cell model for specific type of PV systems is developed by combining three sub-systems as shown in Figure 3:

1. Manufacturer data block: it presents the key specification parameters of the PV module type in Table.1.
2. PV cell model bock: it presents one PV cell model developed in Figure.1.
3. PV voltage block: this block is built to find the value of the PV cell output voltage based on equation (2) to

give the flexibility to use the model as a current or voltage source during computer simulations, and to calculate the cell output power.

As discussed earlier; the input parameters to the proposed model include environmental conditions (ambient temperature and solar irradiation level), number of series connected modules and number of parallel branches. The complete Simulink Solarex MAS60 PV system Figure 4.

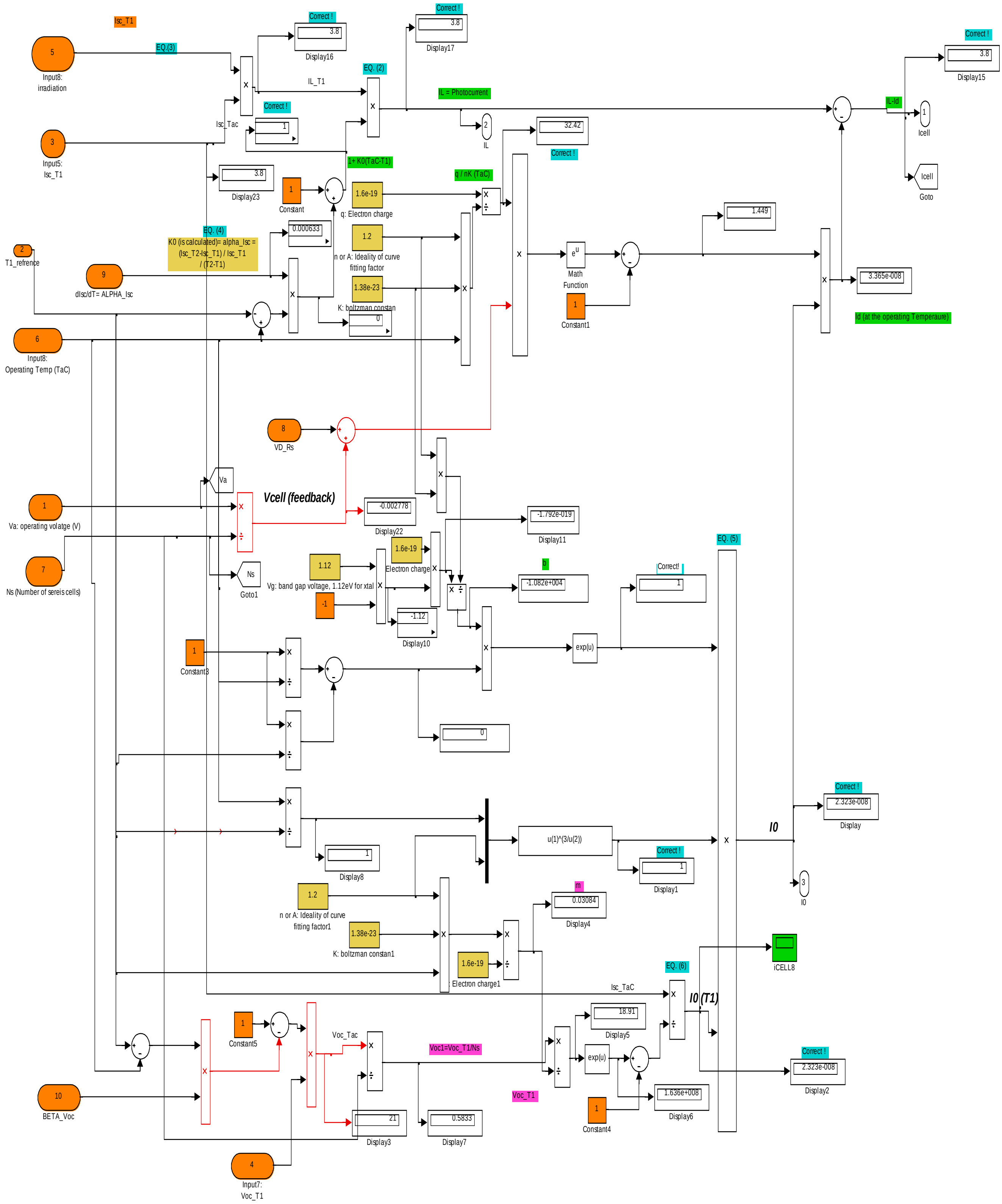


Figure.2 The proposed PV cell Simulink model

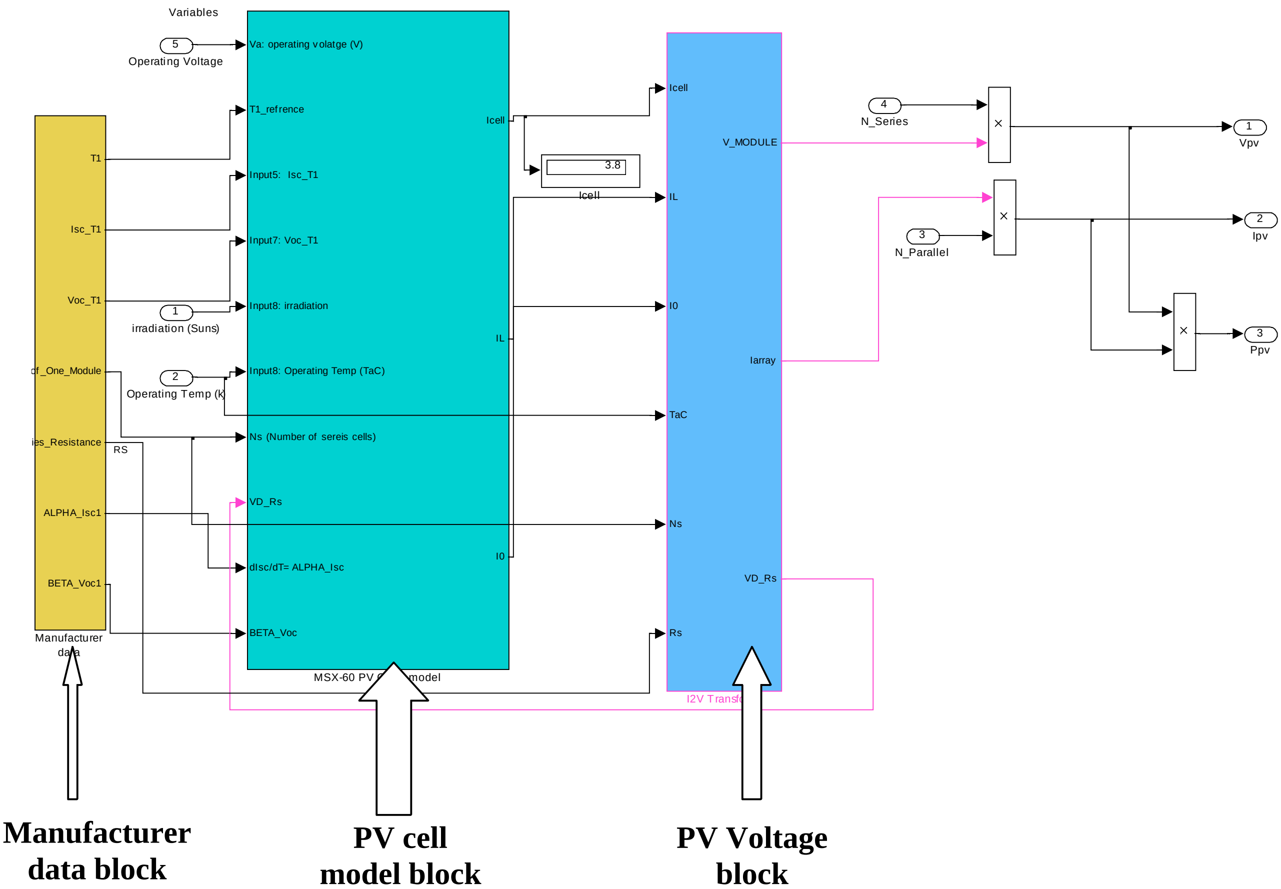


Figure.3 The Complete PV cell SIMULINK block diagram

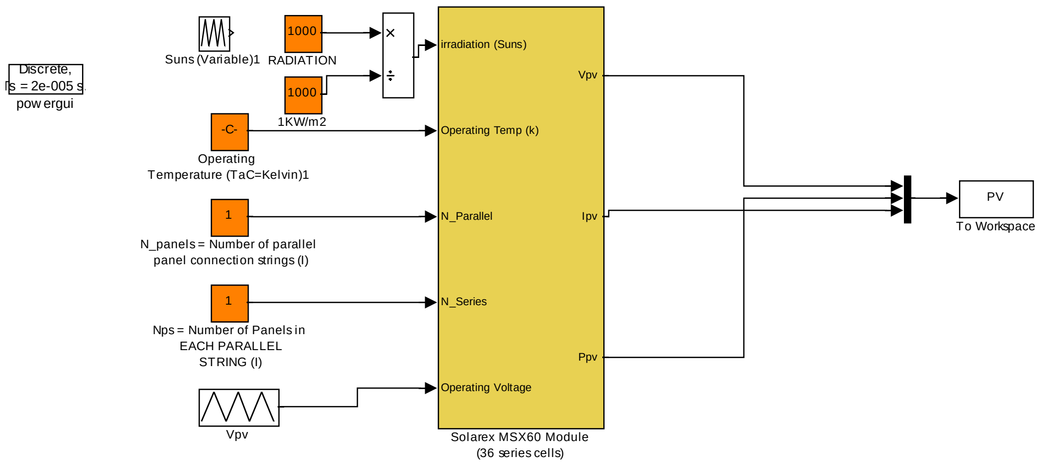


Figure.4 The complete SIMULINK Solarex MAS60 PV system

VI. Testing and Validation of the Proposed Model

The proposed model is able to calculate current, voltage, and power relationships over the entire operating voltage range of the PV array, for different environmental conditions of solar radiations, and ambient temperatures. The I-V and P-V charateriscts are produced by the proposed model for the selected PV array type through Matlab-Simulink environment. The validation of the results are done for the following conditions:

- standard test conditions (full sun radiation; 1000W/m^2 and 25^{0}C temperature).
- different temperature levels.
- different solar radiation levels.

In the following sections; the PV-operating characteristics obtained by the propsed model will be compared to both the results computed by a PV commercial software package, and that given by manufacturer data sheets.

3.1 Model Validation Under Standard Test Conditions

The results are developed for standard test conditions of full sun radiation (1000W/m^2) and 25^{0}C temperature. The I-V and P-V Characteristics of the PV model are presented in Figure.5.

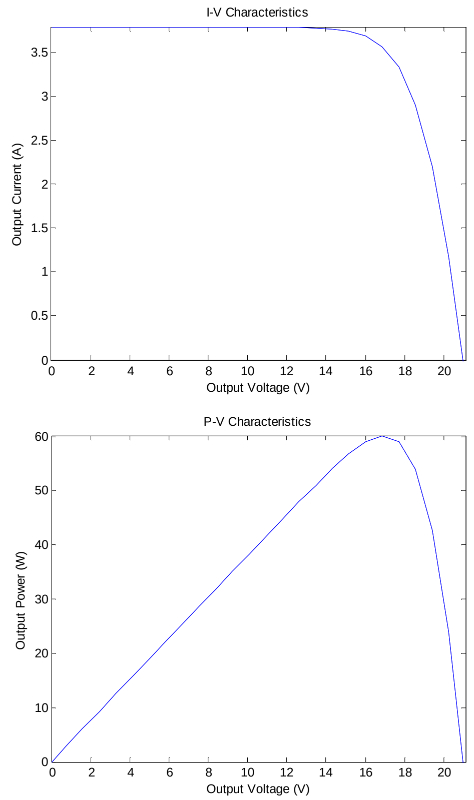


Figure.5 I-V and P-V Characteristics of the PV model

The PV-design Pro software package [24] is used to compute and draw the I-V and P-V characteristics for the same PV type from a large data base built in the software under the same standard test conditions. The PV-design Pro is a detailed simulation program with algorithms developed by King et al. [25]. It is mainly used for the prediction of annual performance of PV systems used in different applications such as PV powered water pumping system. Figure.6 shows the I-V and P-V characteristics for the Solarex MSX 60 as developed by the PV design Pro.

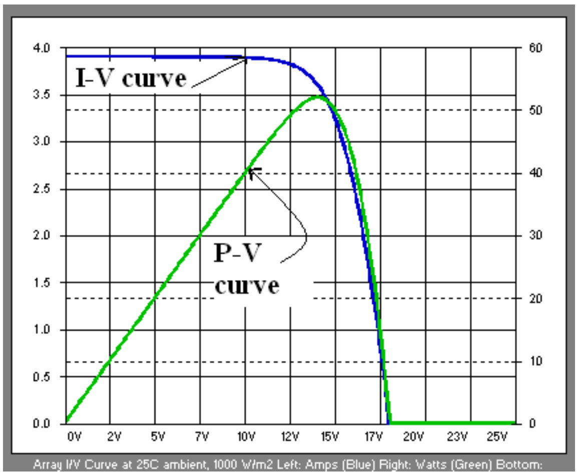


Figure.6 I-V and P-V characteristics of the Solarex MSX 60 by PV design pro. [25]

Table.2 shows the values of maximum power point (MPP) at standard test conditions (1000 W/m^2, 25^{0}C) as obtained from the manufacturer data sheet [23,26], and the PV design Pro. data base, compared with that obtained by developed Simulink model. The I-V charteristcis as obtained from the data sheet for different temperature under full sun of 1000W/m^2 is shown in Figure 7.

Table.2: Maximum power points for different models (25^{0}C and 1000 W/m^2)

Model (at standard test conditions)	Max. Power at MPP (W)	Voltage at MPP (V)	Current at MPP (A)
Manufacturer tests and data sheet	60	17.1	3.5
PV Design Pro. Software	59.85	17.1	3.5
Developed Simulink model	60.1825	16.860	3.569

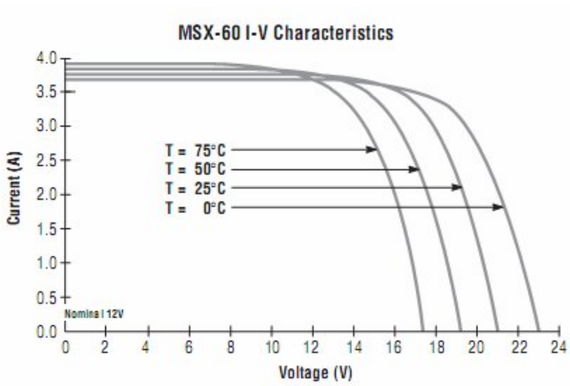


Figure.7 Solarex MSX 60 datasheet I-V characteristics at deffrent temperatures [26]

Comparison of the results in Table.2 shows that it is within acceptable accuracy and that the model is well-designed to simulate the performance characteristics of an the actual PV system .

3.2 Model Validation for Different Temperature Levels and Constant Radiation

To assure the felxibilty and the accuracy of the developed Simulink model, the model is tested under a different temperature level of 50^0C. The the I-V and P-V characteristics for this case study are shown in Figure.8.

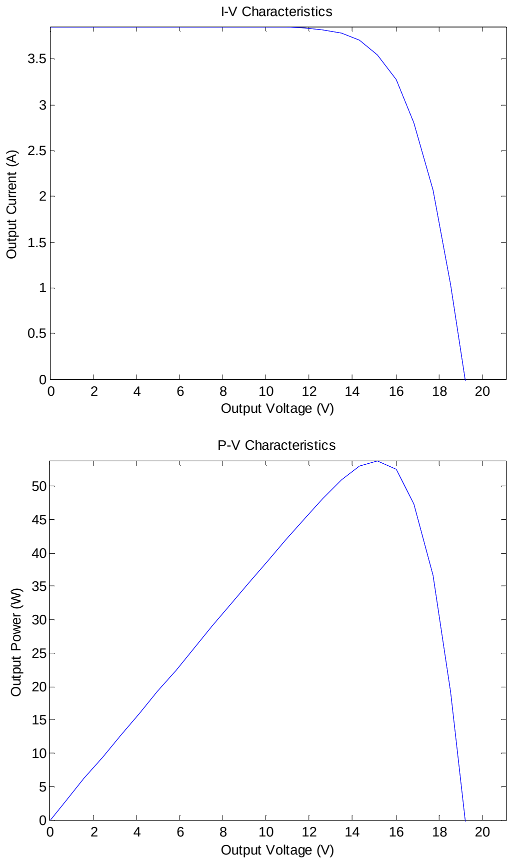


Figure.8 I-V and P-V Characteristics of the PV model at 50C

The PV design Pro. offers a comparison between the I-V characteristics for both 25^0C and 50^0C at a radiation of 1000 W/m^2, from which; it is possible to obtain the values of the the voltage and the current at maximum power points, as presented in Figure.9. The variations of the maximum power values from 25^0C to 50^0C can also obtained by the PV design Pro., from which it is possible to estimate the maximum power as explained by Figure 10. Table 3, shows the values of MPP at this test conditions (1000 W/m^2, 50^0C).

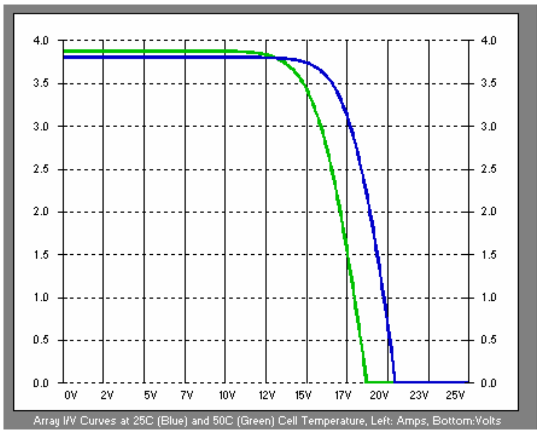


Figure.9 I-V characteristics of the Solarex MSX 60 by PV design pro. At 25^0C and 50^0C with 1000 W/m^2 from the PV design Pro. [24]

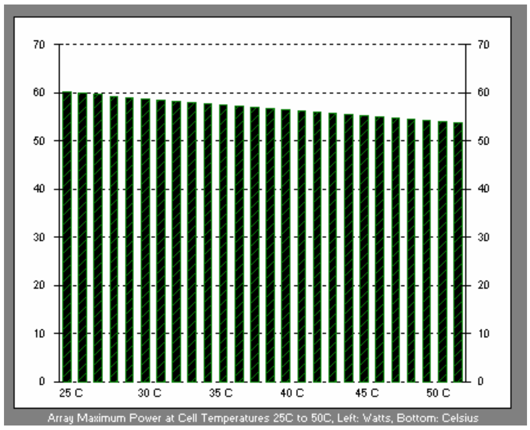


Figure.10 Maximum power variations from 25^0C and 50^0C with 1000 W/m^2 from the PV design Pro. [24]

Table.3: Maximum power points for different models (50^0C and 1000 W/m^2)

Model (at 50^0C and 1000 W/m^2)	**Max. Power at MPP (W)**	**Voltage at MPP (V)**	**Current at MPP (A)**
Manufacturer tests and data sheet	54	15	3.6
PV Design Pro. Software	54.2	14.8	3.648
Developed Simulink model	53.8953	15.1640	3.5542

It is noticed from the results in Table 3 that the developed Simulink model is accurate enough to be used for different operating temperature levels, with constant solar radiation level.

3.3 Model Validation for Different Radiation Levels and Constant Temperature

To show that the proposed model is generic for presenting the PV system, not only at different temperatures, but also for different solar radiation levels, the model is simulated under different radiation levels and the results are compared to assure the accuracy.

The PV-design Pro. offers the I-V characteristics with constant temperature of 25^0C and for different radiation levels from 200 W/m^2 (bottom curve) up to 1000 W/m^2 (upper curve), as shown in Figure.11. The simulations results using the propsed Simulink model developed for both I-V and P-V characteristics are shown in Figures 12 to15.

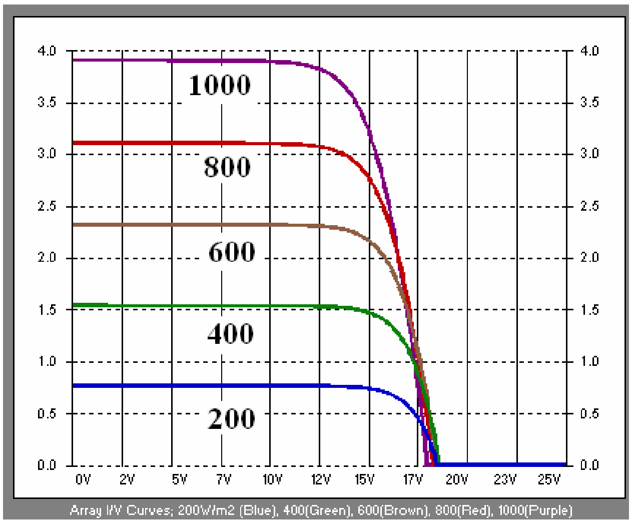


Figure.11 I-V characteristics of the Solarex MSX 60 by PV design pro. At 25°C for radiation levels from 200 W/m^2 to 1000 W/m^2 [25]

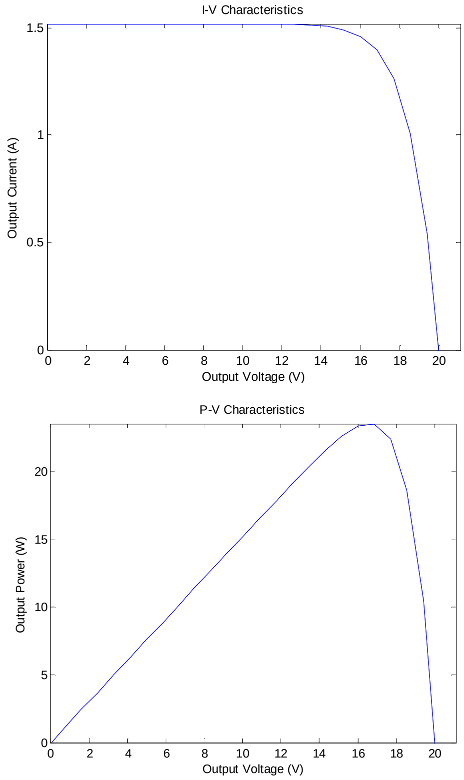


Figure.13 I-V and P-V characteristics at 25^0C and 400 W/m^2

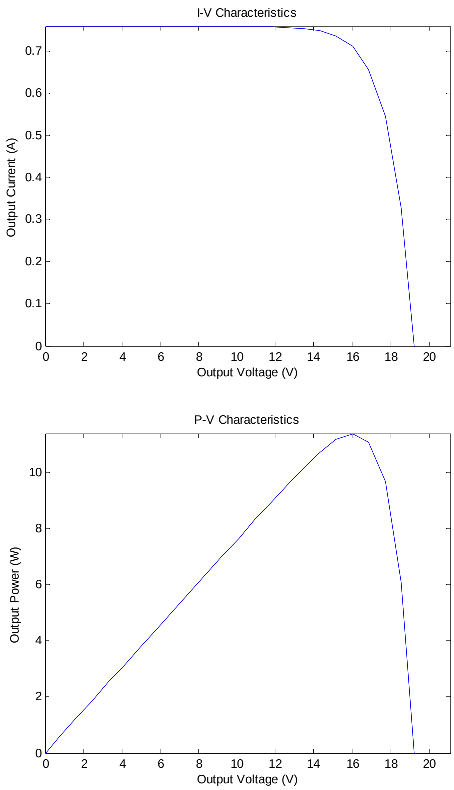


Figure.12 I-V and P-V characteristics at 25^0C and 200 W/m^2

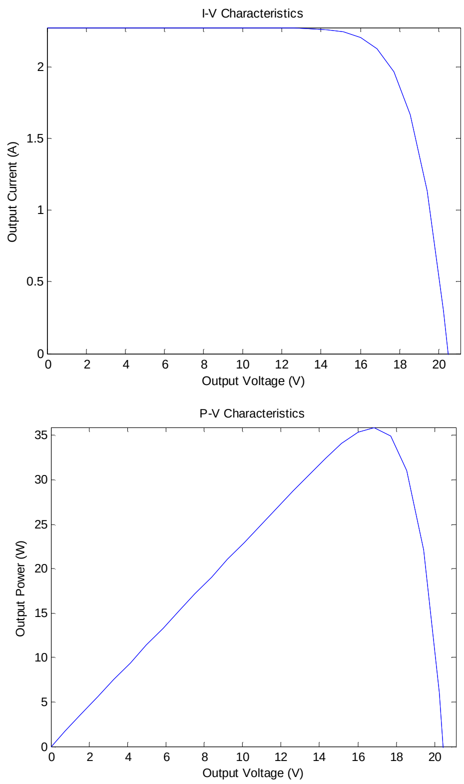
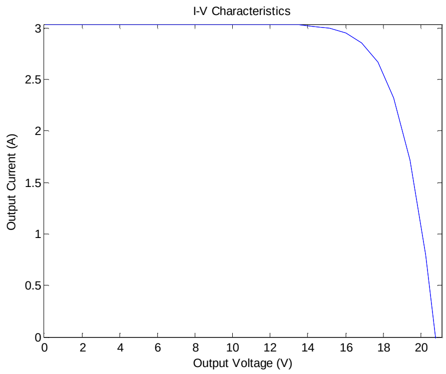


Figure.14 I-V and P-V characteristics at 25^0C and 600 W/m^2



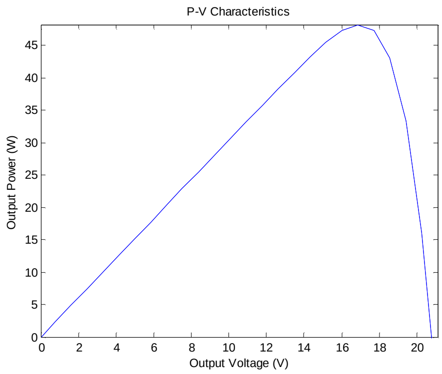


Figure.15 I-V and P-V characteristics at 25^{0}C and 800 W/m^2

The comparison of the I-V characteristics at each radiation level verifies the accuracy of the developed Simulink model. It is clear that the increase of solar radiation levels leads to increases the maximum power developed by the PV system , which is the opposite conclusion concerning the temperature increase. This means that the proposed model behavior is not contradicted with the real behavior of a PV system under different operating conditions.

VII. CONCLUSIONS

This paper introduces a proposed adaptive PV model for. Simulation of the proposed PV model is developed, and demonstrated in Matlab-Simulink environment for a typical 60W solar panel. The proposed model is capable of calculating current, voltage, and power relationships over the entire operating voltage range of the PV array at different levels of environmental conditions, mainly solar radiation levels, and ambient temperatures.

The proposed model has a generic structure so that it can be used for performance testing of different PV commercial types. The proposed model could be used for different Decentralized Generation (DG) applications by establishing propoer interfacing and controllers, which will be investigated in a future work.

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