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New seven parameters model for amorphous silicon and thin film PV modules based on solar irradiance

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ABSTRACT

Variation of solar irradiances on the value of seven parameters of two-diode model plays an important role in a photovoltaic (PV) modules performance to develop design and fabrication of PV modules. This paper proposes a novel modeling approach for amorphous silicon thin film PV module to determine the effect of solar irradiance change on seven parameters of two-diode model and to describe the I-V characteristic curves for each generic condition of operative solar irradiance. The proposed model is based on the rate change of seven parameters with respect to irradiance change. The rate change of seven parameters is derived from current equation of two-diode model at maximum power point (MPP) of different solar irradiance levels. The values of the parameters of the two-diode model are extracted with respect to different solar irradiance levels using precise Runge-Kutta-Merson iterative method. To validate the capability of the new proposed method, the new proposed method is verified on three different amorphous silicon and thin film PV modules, U-EA110, MPV95-S, and MST-43LV, for various I-V and P-V manufacturer curves. Results are compared with the data issued by different manufacturers. The I-V and P-V curves of manufacturing three different amorphous and thin film PV modules have a good agreement as compared with computed results of proposed model.

1. Introduction

Photovoltaic (PV) systems are friendly for environment to meet growth in the electricity demand. For the solar production industry, global annual installation of PV modules is projected to rise from 22.9 GWp in 2009 to more than 179 GWp in 2030 (Eke and Oktik, 2012). The rapid growth of PV system utilizations is due to its availability everywhere which avoids transmission costs and losses, free, and without pollution. Silicon is the basic material required for the production of solar cells based crystalline or thin film technology (A. Elbaset et al., 2014). Most of the world market is based on crystalline silicon and the sharing of thin film technology. It is expected to gain a much larger share of the PV market in the future due to lower production costs as comparing to the more material-intensive crystalline technology. The available three different types of PV modules in the market are Crystalline Silicon, Amorphous Silicon and other Thin Film technology. Crystalline Silicon modules are the oldest, most reliable and highly efficient PV modules in the market today (Eke and Oktik, 2012; A. Elbaset et al., 2014; Lo Brano et al., 2010; Agroui et al., 2011; Mermoud and Lejeune, 2010; Ghoneim et al., 2011).

Thin film PV modules are constructed by depositing extremely thin layers of photo-sensitive materials onto a low-cost backing such as glass, stainless steel or plastic. Thin film PV modules based on amorphous silicon (a-Si), cadmium telluride (CdTe), Copper Indium diselenide (CIS) and Gallium Arsenide (GaAs) technologies have gained a strong foothold in the world PV market. Amorphous silicon and thin film PV modules represent a specific type of PV units, differing from the mono-crystalline and polycrystalline silicon modules in both manufacturing technology and nature of physical processes taking place in converting solar energy to electricity (Eke and Oktik, 2012). These modules become one of the most promising attractive techniques to decrease the prices of PV module due to limited quantity of pure materials, their simplicity for manufacturing processes, their ease of installation and flexibility, and finally increasing of PV system performance (Eke and Oktik, 2012; Agroui et al., 2011; Mermoud and Lejeune, 2010; Ghoneim et al., 2011).

Normally, the PV solar modules require concrete mathematical model to predict the performance of PV system at various weather conditions which are different from those characterized by the

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manufacturer's datasheet. Mathematical model of PV solar modules are consisting of a photo-current source, one or more resistors, and semiconductor diodes to trade-off between accuracy and simplicity (Lineykin et al., 2014). There are different kinds of mathematical models presented in various literatures (Lineykin et al., 2014; Bonkoungou et al., 2013; Surya Kumari and Sai Babu, 2012; Sheik, 2011; Ishaque et al., 2011a,b,c, 2010; Maherchandani et al., 2012; Tsai et al., 2008; Ramabadran and Salai, 2009) in the past few decades, like single diode model (Lineykin et al., 2014; Bonkoungou et al., 2013; Surya Kumari and Sai Babu, 2012; Sheik, 2011), two-diode model (Ishaque et al., 2011a,b,c, 2010), and model with partial shading considerations and much more (Ramabadran and Salai, 2009). The single diode model can be completely characterized by five parameters, namely, shunt and series resistances, diode ideality factor, photo-current, and diode saturation current. While two-diode model is characterized by seven parameters which are photo-current, two saturation diode currents, series and shunt resistances, and two ideality diode factors respectively.

Eke and Oktik (2012), Mermoud and Lejeune (2010) and Ghoneim et al. (2011) proposed single diode model of amorphous and thin film modules. The experimental modules parameters have significantly different response with respect to the changes in solar irradiance with time seasonal variations during experimental periods. Correlations between internal parameters, namely series resistance (R_S), shunt resistance (R_{Sh}), photo-current (I_{Ph}), diode saturation current (I_S) and ideality factor (a) of module with solar irradiation and atmospheric data were done and investigated. These proposals represent the experimental versions for specific solar PV modules. A. Elbaset et al. (2014) used two-diode models based on Newton-Raphson method for describing PV system performance, but such proposal has constant parameters with all irradiation levels except photo-current. This proposal was not suitable for amorphous modules at different irradiance levels except standard test conditions. Lo Brano et al. (2010) presented a new five-parameter for single diode model that is capable of analytically describing the I-V characteristic of a PV module for each generic condition of operative temperature and solar irradiance. The parameters of the equivalent electrical circuit are extracted by solving a system of equations based on data commonly issued by manufacturers in standard test conditions with a trial and error process. The proposal had been random relations between irradiance and model parameters. Agroui et al. (2011) summarized the electrical and thermal characterizations of thin film PV modules based on amorphous triple junctions and Copper Indium Selenide (CIS) thin film solar cells. The measured values of modules were referred to standard test conditions (STCs) by three conversion methods suggested by A. A.J. Anderson and G. Blaesser as well as the equations already standardized as IEC 60891, but these methods were not suitable for system performance at different weather conditions and system simulations. In Lineykin et al. (2014) an approach of single diode extracting seven-parameter by adding two parameters for different irradiance levels was proposed for amorphous silicon module, but this proposal used complex technique to extract single diode module parameters with respect to different irradiance levels. Maherchandani et al. (2012) presented an efficient and accurate single diode model for the estimation of the solar cell parameters using the hybrid genetic algorithm and Nelder-Mead simplex search method from the given voltage-current data. Tsai et al. (2008) presented implementation of a generalized PV model based on single diode model using Matlab/Simulink software package, which can be representative of PV cell, module, and array for easy use on simulation platform. In Ramabadran and Salai (2009), a Matlab-based modeling and simulation scheme suitable for studying the I-V and P-V characteristics of a PV array under a non-uniform insolation due to partial shading has been studied. Saravanan and Panneerselvam (2013) proposed an improved model approach to single diode PV model by hybrid genetic algorithm particle swarm optimization (GA-PSO) technique. In Ghani et al. (2016), a new method was presented to determine four of the five parameter values using the data typically provided by the manufacturer. This method was based on calculating the values for the series and shunt resistances and the photo-generated and reverse saturation currents by solving the underlying non-linear equations at short circuit, maximum-power-point, and open-circuit conditions numerically. The proposed algorithm was experimentally validated against a crystalline silicone type solar cell. In Chan and Phang (1987), Analytical solutions for the rapid extraction of single-and double-diode model parameters from experimental data have been described. Wolf and Rauschenbach (1963) represented the PV cell with an equivalent electric circuit that composed of different lumped components, each one made up of a current generator, a diode and a series resistance. New features of the p-n junction characteristic were discussed. Bühler and Krenzinger (2013) presented a method for PV parameter extraction according to a modified double-diode model was proposed. In this model, the ideality diode factor related to the recombination of the charge carriers in the space-charge region was assumed as a variable with value equal or larger than 2.

AlHajri et al. (2012) presented an application of pattern search optimization technique for extracting the parameters of different solar cell models. These models were single diode, double diode, and PV module. In Sandrolini et al. (2010), a numerical procedure for the extraction of the double-diode model parameters of PV modules was described. A particle swarm optimization (PSO) algorithm was used to fit the calculated current–voltage characteristic of a PV module to the experimental one. The literature review shows that, most of models were not suitable for amorphous modules due to change of values of module parameters model with irradiance change.

In this paper, a new version of two-diode model is used to model amorphous and thin film PV modules at different irradiance levels. The seven parameters of two-diode model are formulated in partial derivative with respect to irradiance level to estimate their accurate values. These parameters are derived at different irradiance levels using Runge-Kutta-Merson iterative method.

2. Methodology

2.1. A new seven parameters model based on solar irradiance change

In order to determine the effect of solar irradiance change on seven parameters of two-diode model, the procedure for obtaining a set of seven parameters must be repeated for all of the "known" I-V curves corresponding to different levels of irradiation, each time extracting a set of seven-parameter. The seven parameters of PV module are known as, photo-current I_{ph}; saturation currents of two diodes I_{s1}, I_{s2}; series and shunt resistances R_s and R_{sh}; and ideality factors of two diodes a_1 and a_2. The two-diode equivalent circuits based model for a-Si thin film PV module is shown in Figs. 1 and 2 for cells and modules (A. Elbaset

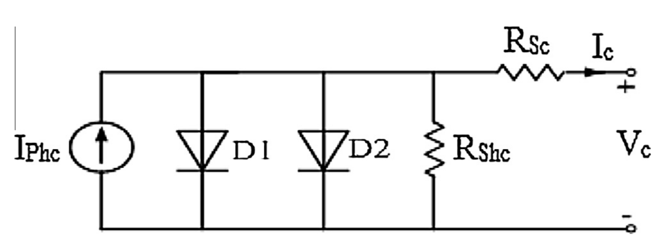


Fig. 1. Two-diode circuit model of PV cell model.

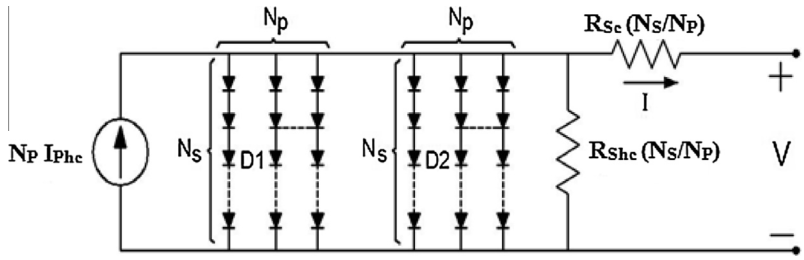


Fig. 2. Equivalent circuit model of generalized PV.

et al., 2014). The equivalent circuit of the PV module is arranged in series and parallel cells with number of series cells, N_S and number of parallel cells, Np.

The equations of current and its derivative with respect to voltage of the PV module are written as follows (A. Elbaset et al., 2014):

$$I = I_{Ph} - I_{S1}\left\{e^{\left(\frac{V+I\cdot R_S}{a_1 V_T}\right)} - 1\right\} - I_{S2}\left\{e^{\left(\frac{V+I\cdot R_S}{a_2 V_T}\right)} - 1\right\} - \left\{\frac{V + I\cdot R_S}{R_{Sh}}\right\} \quad (1)$$

$$\frac{dI}{dv} = -\frac{I_{S1}}{a_1 V_T}\left(1 + R_S\frac{dI}{dV}\right)\left\{e^{\left(\frac{V+I\cdot R_S}{a_1 V_T}\right)}\right\} - \frac{I_{S2}}{a_2 V_T}\left(1 + R_S\frac{dI}{dV}\right)\left\{e^{\left(\frac{V+I\cdot R_S}{a_2 V_T}\right)}\right\} - \left\{\frac{1}{R_{Sh}}\right\}\left(1 + R_S\frac{dI}{dV}\right) \quad (2)$$

where

I and V are output current and voltage of PV module respectively.
I_{Ph} is the photo-current of PV module = $N_P * I_{Phc}$
I_{S1} is diffusion saturated current of module for diodes, D1, $I_{S1} = N_P * I_{S1c}$, I_{S1c} is the cell diffusion saturated current of D1 (A),
I_{S2} is recombination saturated current of module for diodes, D2, $I_{S2} = N_P * I_{S2c}$, I_{S2c} is the cell recombination saturated current of D2 (A),
V_T is the thermal voltage of series diodes, ($V_T = N_S \cdot kT/q$),
k is Boltzmann constant ($1.38 * 10^{-23}$ J/Kelvin),
q is electron charge ($1.6 * 10^{-19}$ C),
T is the cell working temperature (Kelvin),
a_1 and a_2 are ideality factors of D_1 and D_2 respectively,
R_S is the module series resistance (Ω), $R_S = R_{Sc}(N_S/N_P)$, R_{Sc} is the cell series resistance (Ω), and
R_{Sh} is the module shunt resistance (Ω), $R_{Sh} = R_{Shc}(N_S/N_P)$, R_{Shc} is the cell shunt resistance (Ω).

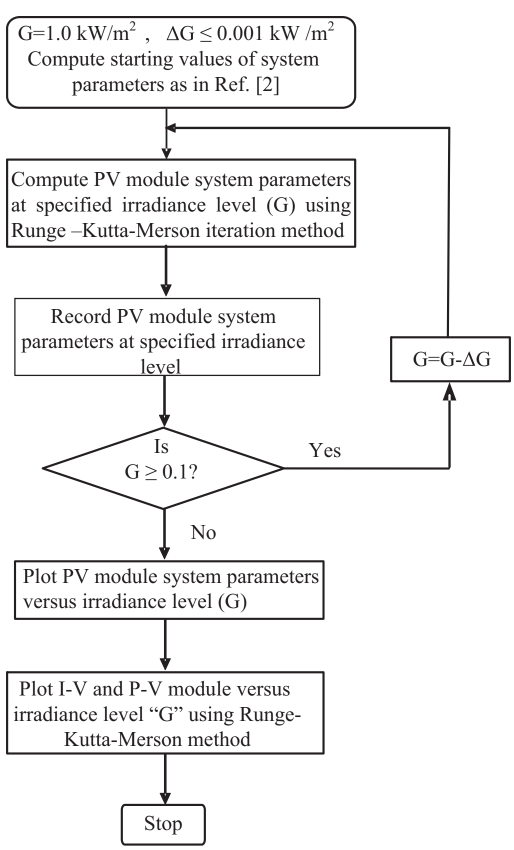


Fig. 3. Computer algorithm of the proposed two-diode module model.

The photo-current of PV module with respect to irradiance levels can be written as follows (Ishaque et al., 2011a; Tsai et al., 2008):

$$I_{Ph} = (G/G_{STC}) \cdot I_{Ph\ at\ STC} = G \cdot I_{Ph0} \quad (3)$$

where

I_{Ph0} is photo-current of PV module at standard test conditions (STC),
G is the solar irradiance level at any weather conditions in kW/m^2
G_{STC} is solar irradiance level at STC [G_{STC} = 1 kW/m^2].

The fact that the "basic" maximum power current–voltage pair belongs to the I-V curve leads the following maximum power condition relation (A. Elbaset et al., 2014):

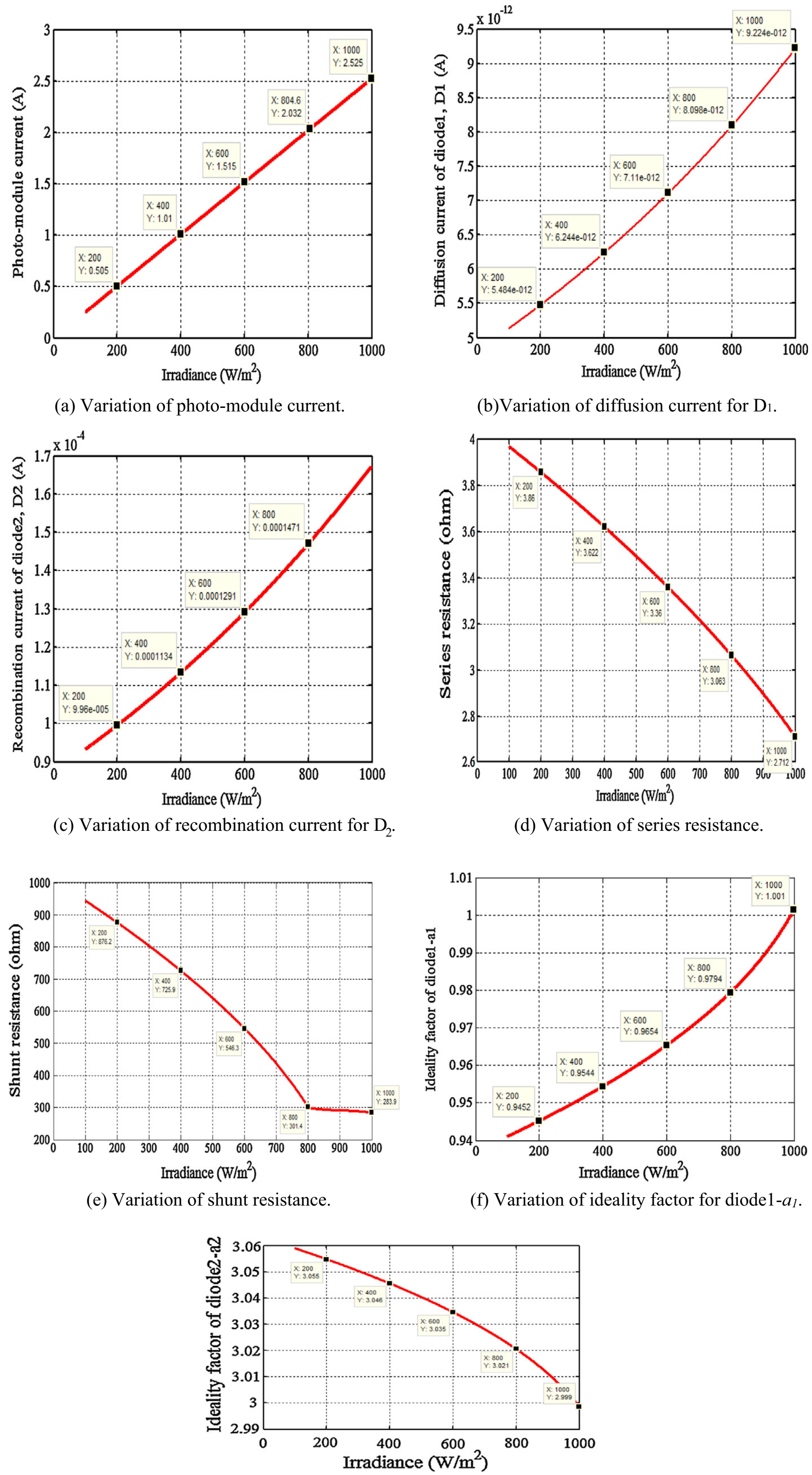
$$I_{mp} = I_{Ph} - I_{S1}\left\{e^{\left(\frac{V_{mp}+I_{mp}\cdot R_S}{a_1 V_T}\right)} - 1\right\} - I_{S2}\left\{e^{\left(\frac{V_{mp}+I_{mp}\cdot R_S}{a_2 V_T}\right)} - 1\right\} - \left\{\frac{V_{mp} + I_{mp}\cdot R_S}{R_{Sh}}\right\} \quad (4)$$

From P-V curves, it can be seen that, at the maximum power point (MPP), the power derivative is zero, i.e.,

$$\left.\frac{dP}{dV}\right|_{V=V_{mp},P=P_m} = \left.\frac{dIV}{dV}\right|_{V=V_{mp},I=I_{mp}} = 0 \quad (5)$$

Table 1
Datasheet parameters of UEA-110, MPV95-S, and MST-43LV modules.

Datasheet parameter	U-EA110	MPV95-S	MST-43LV
P_{mp} (W)	110 (−5%/+10%)	95 ± 5%	43 ± 10%
V_{oc} (V)	71	98	22.70
I_{sc} (A)	2.50	1.56	3.30
V_{mp} (V)	54	74	16.5
I_{mp} (A)	2.04	1.30	2.60
N_S	106	156	64
N_P	1	1	1
Manufacture	Japan – U.S.A – Germany	Germany	U.S.A



(a) Variation of photo-module current.

(b) Variation of diffusion current for D1.

(c) Variation of recombination current for D_2.

(d) Variation of series resistance.

(e) Variation of shunt resistance.

(f) Variation of ideality factor for diode1-a_1.

(g) Variation of ideality factor for diode2-a_2.

Fig. 4. Effect of solar irradiance change on the value of seven parameters.

Rearranging (5) as follows:

$$\left.\frac{d(IV)}{dV}\right|_{V=V_{mp},I=I_{mp}} = \left(I + V\cdot\frac{dI}{dV}\right)\Big|_{V=V_{mp},I=I_{mp}} \quad (6)$$

On the other side, the current derivative $\left(\frac{dI}{dV}\right)$ at maximum power point (MPP) is written as follows (A. Elbaset et al., 2014):

$$\left.\frac{dI}{dV}\right|_{V=V_{mp},I=I_{mp}} = -\frac{I_{mp}}{V_{mp}} \quad (7)$$

From Eqs. (2) & (7) it can be concluded that, the reciprocal R_{Sh} can be obtained as follows:

$$\frac{1.0}{R_{Sh}} = \frac{I_{mp}}{V_{mp} - I_{mp}R_S} - \frac{I_{S1}}{a_1V_T}\left\{e^{\left(\frac{V_{mp}+I_{mp}\cdot R_S}{a_1V_T}\right)}\right\} - \frac{I_{S2}}{a_2V_T}\left\{e^{\left(\frac{V_{mp}+I_{mp}\cdot R_S}{a_2V_T}\right)}\right\} \quad (8)$$

In this paper, relation between diffusion and recombination saturated currents of diode, I_{S1} and I_{S2}, can be assumed as follows:

$$I_{S2} = K_S I_{S1} \quad (9)$$

where Ks: constant.

Eq. (1) can be rewritten at "MPP" with the aid of Eqs. (3), (8–9) as follows:

$$2V_{mp}I_{mp} = GV_2I_{Ph0} - V_2I_{D1} + V_3E_{D1} - V_2I_{D2} + V_3E_{D2} \quad (10)$$

where

$$V_1 = V_{mp} + I_{mp}R_S \quad (11)$$

$$V_2 = V_{mp} - I_{mp}R_S \quad (12)$$

$$V_3 = V_1V_2 = (V_{mp})^2 - (I_{mp}R_S)^2 \quad (13)$$

$$I_{D1} = I_{S1}\left(e^{\frac{V_1}{a_1V_T}} - 1\right) \quad (14)$$

$$\frac{\partial V_{mp}}{\partial G} = \frac{I_{Ph0}V_2}{I_{mp} - GI_{Ph0} + I_{D1} + I_{D2} + V_1(E_{D1}+E_{D2}) - 2V_{mp}(E_{D1}+E_{D2}) - \frac{V_3}{V_T}\left(\frac{E_{D1}}{a_1} + \frac{E_{D2}}{a_2}\right)} \quad (28)$$

$$\frac{\partial I_{mp}}{\partial G} = \frac{I_{Ph0}V_2}{2V_{mp} + R_S[GI_{Ph0} - I_{D1} - I_{D2} + V_1(E_{D1}+E_{D2}) + 2I_{mp}R_S(E_{D1}+E_{D2}) - \frac{V_3}{V_T}\left(\frac{E_{D1}}{a_1} + \frac{E_{D2}}{a_2}\right)} \quad (29)$$

$$I_{D2} = K_SI_{S1}\left(e^{\frac{V_1}{a_2V_T}} - 1\right) \quad (15)$$

$$E_{D1} = I_{S1}\left(\frac{e^{\frac{V_1}{a_1V_T}}}{a_1V_T}\right) \quad (16)$$

$$E_{D2} = K_SI_{S1}\left(\frac{e^{\frac{V_1}{a_2V_T}}}{a_2V_T}\right) \quad (17)$$

The first and the second equations of the parameters I_{S1}, and R_S with respect to solar irradiance level "G" are obtained from partial derivative of Eq. (10) as follows:

$$\frac{\partial I_{S1}}{\partial G} = \frac{I_{Ph0}V_2}{V_2\left(e^{\frac{V_1}{a_1V_T}} - 1\right) - V_3\left(\frac{e^{\frac{V_1}{a_1V_T}}}{a_1V_T}\right) + K_SV_2\left(e^{\frac{V_1}{a_2V_T}} - 1\right) - K_SV_3\left(\frac{e^{\frac{V_1}{a_2V_T}}}{a_2V_T}\right)} \quad (18)$$

$$\frac{\partial R_S}{\partial G} = \frac{I_{Ph0}V_2}{I_{mp}[GI_{Ph0} - I_{D1} - I_{D2} + E_{D3}]} \quad (19)$$

where

$$E_{D3} = E_{D1}\left(V_2 + 2I_{mp}R_S - \frac{V_3}{a_1V_T}\right) + E_{D2}\left(V_2 + 2I_{mp}R_S - \frac{V_3}{a_2V_T}\right) \quad (20)$$

The third equation is for R_{Sh} that can be obtained by multiplying Eq. (1) by R_{Sh} and taking partial derivative with respect to irradiance "G" as follows:

$$\frac{\partial R_{Sh}}{\partial G} = -\frac{I_{Ph0}R_{Sh}}{GI_{Ph0} - I_{mp} - I_{D1} - I_{D2}} \quad (21)$$

The ideality factors a_1 and a_2 for two-diode D_1 and D_2 of amorphous and thin film diode module model are given as follows (Sheik, 2011):

$$a_1 + a_2 = 3 \quad \text{for thin film modules.} \quad (22)$$

$$a_1 + a_2 = 4 \quad \text{for amorphous modules.} \quad (23)$$

From Eqs. (22) and (23), the following equations are obtained as follows:

$$a_2 = 3 - a_1 \quad (24)$$

$$a_2 = 4 - a_1 \quad (25)$$

$$\frac{\partial a_2}{\partial G} = -\frac{\partial a_1}{\partial G} \quad (26)$$

The fourth equation is for ideality factor, a_1 for diode D_1 which can be obtained from partial derivative of Eq. (10) with the aid of Eq. (24) or (25) as follows:-

$$\frac{\partial a_1}{\partial G} = \frac{I_{Ph0}V_2}{V_3\left\{\frac{V_1E_{D1}}{(a_1)^2V_T} - \frac{V_1E_{D2}}{(a_2)^2V_T}\right\}} \quad (27)$$

The fifth and sixth equations are for V_{mp} and I_{mp} with respect to irradiance level "G" which can be expressed from partial derivative of Eq. (10) as follows:

2.2. Runge-Kutta-Merson method for seven parameters at different irradiance levels

The Runge-Kutta Merson iterative procedure is preferred to other iterative methods such as Newton-Raphson in Cohen (1973) and Dorn and Mecracken (1972) due to the following:

(1) It is adaptive adjustable step size iterative method.
(2) It is self-starting within the limited range " (i.e., unlike multi-step methods, we do not have to treat the first few steps taken by a single-step integration method as special cases).
(3) It is more accurate because it has five iterations for each step size within limited truncation error.
(4) It is very stable, robustness, and used by Matlab Simulink.
(5) It is easy to implement.

Table 2
Parameters of module U-EA110 at different irradiance levels.

Module parameters	Irradiance levels in W/m^2				
	1000	800	600	400	200
I_{Ph} (A)	2.525	2.020	1.515	1.010	0.505
I_{S1} (A)	$9.224 * 10^{-12}$	$8.097 * 10^{-12}$	$7.110 * 10^{-12}$	$6.244 * 10^{-12}$	$5.484 * 10^{-12}$
I_{S2} (A)	$1.675 * 10^{-04}$	$1.471 * 10^{-04}$	$1.291 * 10^{-04}$	$1.134 * 10^{-04}$	$9.966 * 10^{-05}$
R_S (Ω)	2.712	3.064	3.360	3.622	3.860
R_{Sh} (Ω)	283.906	301.300	546.300	725.900	876.200
a_1	1.001	0.979	0.965	0.944	0.945
a_2	2.999	3.021	3.035	3.046	3.055

Solving six-partial derivative equation using Runge-Kutta-Merson iterative method in the following form Cohen (1973) and Dorn and Mecracken (1972):

$$X_{i(n+1)} = X_{in} + \frac{[k_{i1} + 4k_{i3} + k_{i5}]}{2} \tag{30}$$

where
i is the order of equation.
n is the order of iteration.

$$k_{i1} = \frac{\Delta G_n}{3}\frac{\partial}{\partial G_n}(X_{in}, G_n) \tag{31}$$

$$k_{i2} = \frac{\Delta G_n}{3}\frac{\partial}{\partial G_n}\left(X_{in} + k_{i1}, G_n + \frac{\Delta G_n}{3}\right) \tag{32}$$

$$k_{i3} = \frac{\Delta G_n}{3}\frac{\partial}{\partial G_n}\left(X_{in} + 0.5(k_{i1} + k_{i2}), G_n + \frac{\Delta G_n}{3}\right) \tag{33}$$

$$k_{i4} = \frac{\Delta G_n}{3}\frac{\partial}{\partial G_n}\left(X_{in} + \frac{3k_{i1} + 9k_{i2}}{8}, G_n + \frac{\Delta G_n}{2}\right) \tag{34}$$

$$k_{i5} = \frac{\Delta G_n}{3}\frac{\partial}{\partial G_n}\left(X_{in} + \frac{3k_{i1} - 9k_{i3}}{2} + 6k_{i4}, G_n + \Delta G_n\right) \tag{35}$$

$$\text{Truncation error} = \max \cdot (k_{i1} - (9k_{i3}/2) + 4k_{i4} - 0.5k_{i5}) \tag{36}$$

X_{in} is the Runge-Kutta-Merson matrix in the following form:

$$\begin{bmatrix} X_{1(n+1)} \\ X_{2(n+1)} \\ X_{3(n+1)} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ X_{6(n+1)} \end{bmatrix} = \begin{bmatrix} X_{1(n)} + [k_{11} + k_{14} + k_{15}]/2 \\ X_{2(n)} + [k_{21} + k_{24} + k_{25}]/2 \\ X_{3(n)} + [k_{31} + k_{34} + k_{35}]/2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ X_{6(n)} + [k_{61} + k_{64} + k_{65}]/2 \end{bmatrix} \tag{37}$$

where
$X_1 = I_{S1}$, $X_2 = R_S$, $X_3 = R_{Sh}$, $X_4 = a_1$, $X_5 = V_{mp}$, and $X_6 = I_{mp}$
G_n is the irradiance level at step n, ΔG_n is the irradiance step change size.

3. Computer algorithm

Computer algorithm shown in Fig. 3 is established to solve six-partial derivative equation using Runge-Kutta-Merson method (Cohen, 1973; Dorn and Mecracken, 1972). The main steps of computer algorithm are summarized as follows:

(1) Computing the initial values of PV module parameters at STC as in A. Elbaset et al. (2014).
(2) Formation partial derivative of (I_{S1}, R_S, R_{Sh}, a_1, V_{mp}, I_{mp}) with respect to solar irradiance as in six previous Eqs. (11)–(13), (19)–(21).
(3) Computing the seven parameters of a-Si thin film PV module parameters using Runge-Kutta-Merson iteration method.

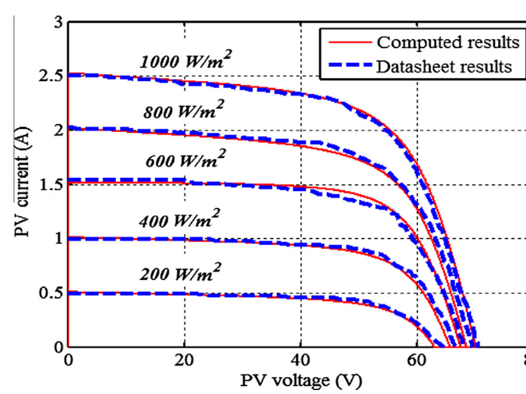


Fig. 5. I-V curves of computed and manufacturing results for U-EA110 module.

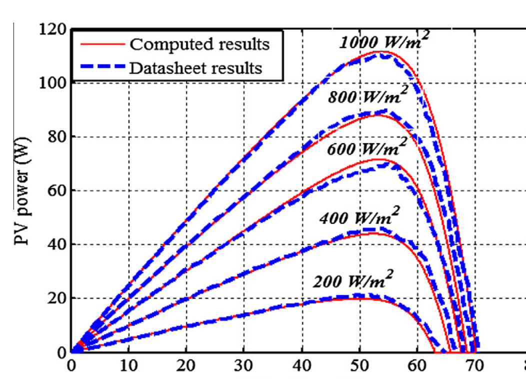
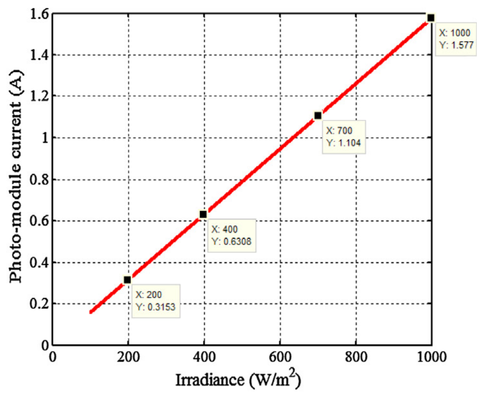
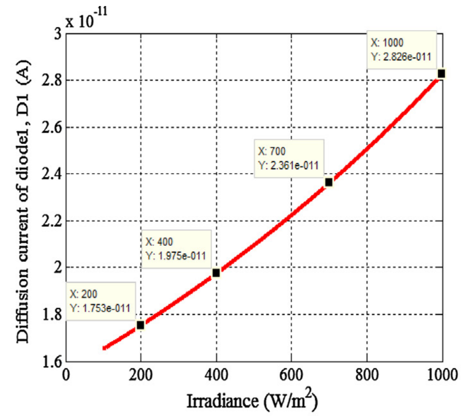


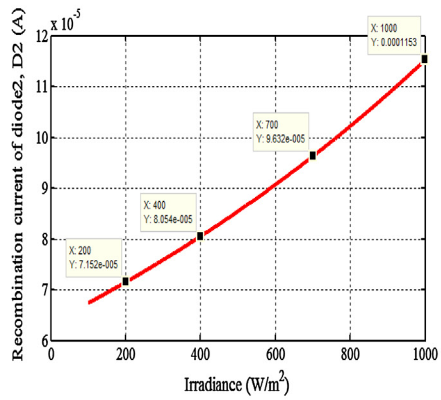
Fig. 6. P-V curves of computed and manufacturing results for U-EA110 module.



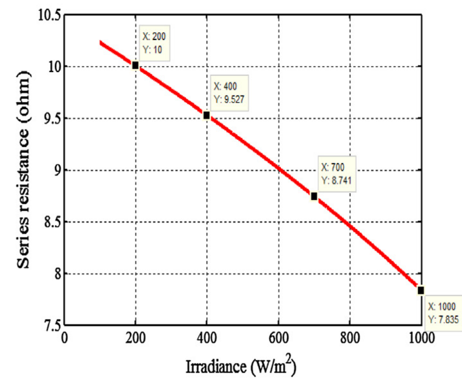
(a) Variation of photo-module current.



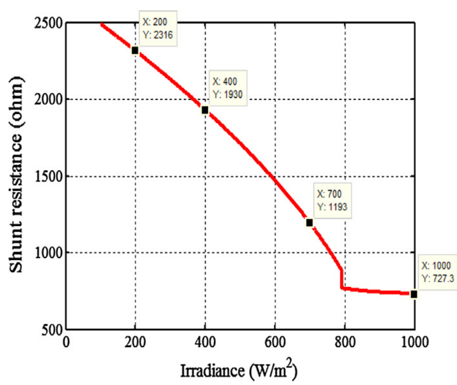
(b) Variation of diffusion current for D_1.



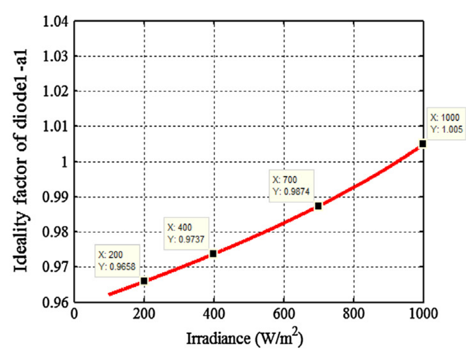
(c) Variation of recombination current for D_2.



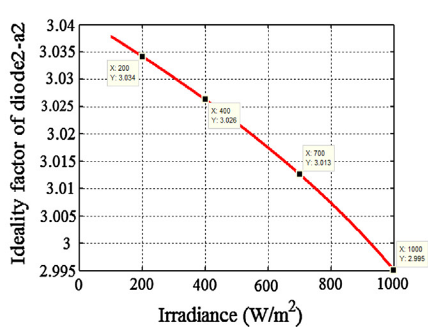
(d) Variation of series resistance.



(e) Variation of shunt resistance.



(f) Variation of ideality factor for diode1-a_1.



(g) Variation of ideality factor for diode2-a_2.

Fig. 7. Variation of the value of seven parameters with irradiance change for MPV95-S module.

Table 3
Parameters of module MPV95-S at different solar irradiance levels.

Module parameters	Irradiance levels in W/m^2			
	1000	700	400	200
I_{Ph} (A)	1.5570	1.104	0.6308	0.3154
I_{S1} (A)	$2.8256 * 10^{-11}$	$2.361 * 10^{-11}$	$1.975 * 10^{-11}$	$1.753 * 10^{-11}$
I_{S2} (A)	$1.1526 * 10^{-04}$	$9.632 * 10^{-05}$	$8.054 * 10^{-05}$	$7.152 * 10^{-05}$
R_S (Ω)	7.835	8.741	9.527	10.000
R_{Sh} (Ω)	727.4420	1193	1930	2316
a_1	1.0049	0.987	0.974	0.966
a_2	2.9951	3.013	3.026	3.034

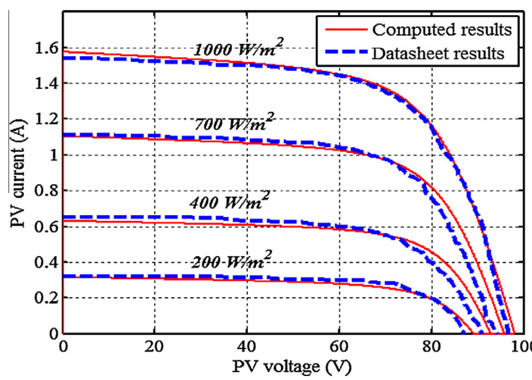


Fig. 8. I-V curves of computed and manufacturing results for MSV-95.

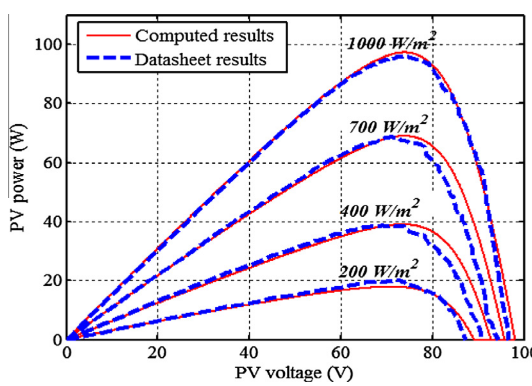


Fig. 9. P-V curves of computed and manufacturing results for MSV-95.

(4) Establishing I-V and P-V characteristic curves of PV module parameters versus different irradiance levels using Runge-Kutta-Merson method.

4. Validation of the proposed method

The new proposed model has been validated according to solar irradiance change and by the available data of selected amorphous silicon and thin film PV modules, U-EA110, MPV95-S, and MST-43LV. The manufacturer's electrical values for the three different amorphous silicon and thin film PV modules under STC are given in Table 1 (Kaneka; MPV-S-Our; Solarex's, 1999). The effect of solar irradiances on the values of seven parameters of the selected amorphous silicon and thin film PV modules is given as follows:

4.1. U-EA110 (a-Si) PV module

In order to reveal the values of seven parameters of U-EA110 (a-Si) which are depended on solar irradiance, the proposed methodology of seven parameters must be applied for all "known" I-V curves at different levels of solar irradiance. The seven parameters as related to irradiance levels "G" are shown in Fig. 4. Fig. 4 shows that, the photo-module current I_{Ph}, the diffusion (I_{S1}), the recombination currents (I_{S2}) of diodes (D_1&D_2), and the diode ideality factor, a_1 are reduced their values with reducing irradiance levels. Also, the series module resistance, R_S, the shunt module resistance, R_{Sh} and ideality diode factor, a_2 are increased their values with reducing irradiance levels as shown in Fig. 4. Table 2 summarizes seven parameters values as related to different irradiance levels to obtain I-V and P-V curves of U-EA110.

Effects of the variation of solar irradiance on the I-V and P-V characteristics curves are shown in Figs. 5 and 6 for U-EA110 module at different solar irradiance levels at 25 °C. These curves are recoded with the aid of Table 2 and using Runge-Kutta-numerical iteration method. The I-V and P-V computed curves are compared with manufacturer curves of Kaneka. These figures show a good agreement and matching between manufacturer curves and computed results of the proposed model at different solar irradiance levels.

4.2. MPV95-S (a-Si) PV module

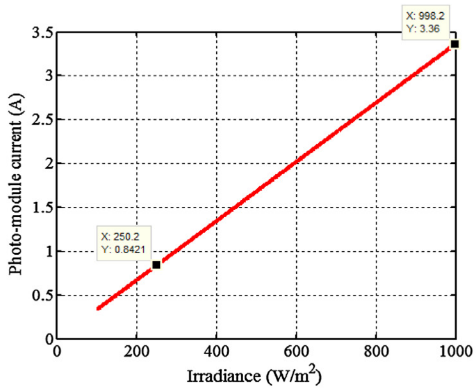
Fig. 7 shows seven parameters values as related to different irradiance levels. The parameter curves have the same relations as previously discussed for module U-EA110.

Seven parameters values of MPV95-S as related to different irradiance levels are recorded in Table 3 from seven parameters irradiance curves of Fig. 7. I-V and P-V curves of MPV95-S are shown in Figs. 8 and 9. The results show high agreement between manufacturer curves of MPV-S-Our and computed results of the proposed model at different irradiances. Normally, the difference in results is due to the measurements accuracy.

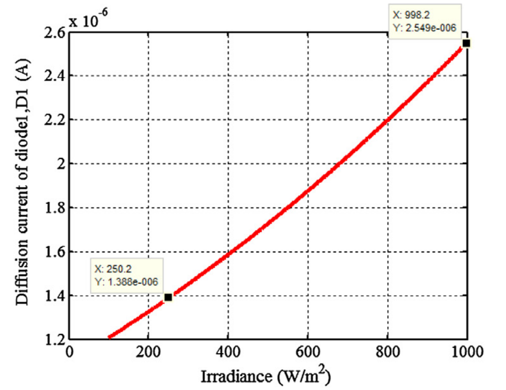
4.3. MST-43LV thin film PV module

The seven parameters values as related to different irradiance levels are shown in Fig. 10. The parameter values have the same relations as previously discussed for module U-EA110.

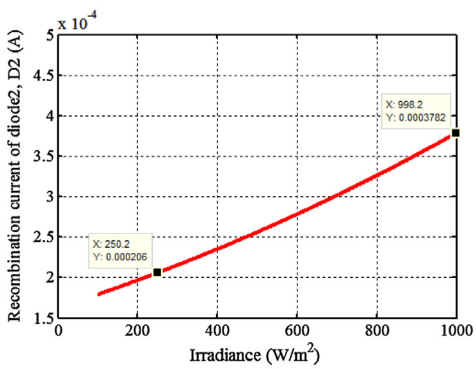
The relations between seven parameters of MST-43LV and different irradiance levels are recorded in Table 4 using the proposed method. I-V and P-V curves of MST-43LV are shown in Figs. 11 and 12. The I-V and P-V computed curves show a good agreement with corresponding manufacturer curves of Solarex's (1999) at different irradiance levels.



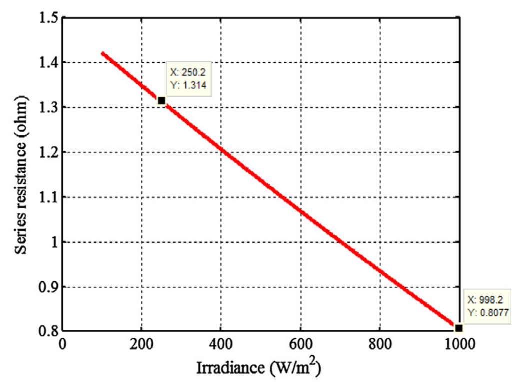
(a) Variation of photo- module current.



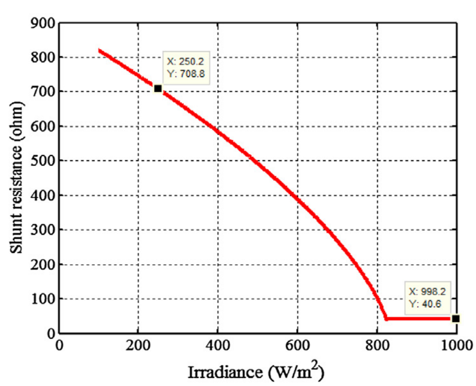
(b) Variation of diffusion current for D_1.



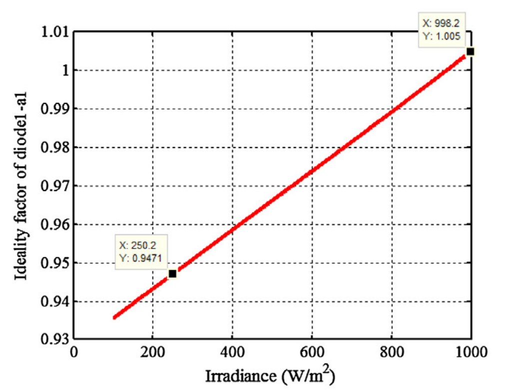
(c) Variation of recombination current for D_2.



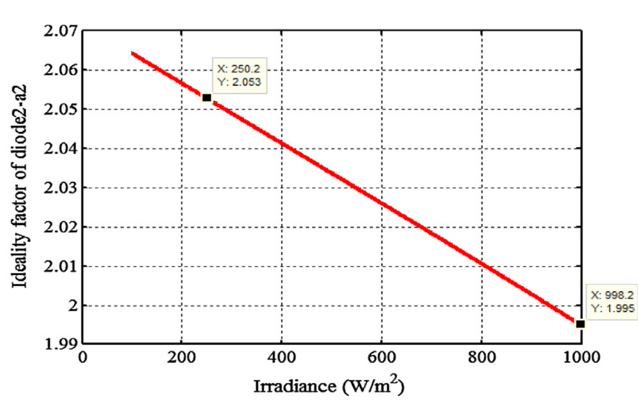
(d) Variation of series resistance.



(e) Variation of shunt resistance.



(f) Variation of ideality factor for diode1-a_1.



(g) Variation of ideality factor for diode2-a_2.

Fig. 10. Variation of seven-parameter with solar irradiance change for MST-43LV module.

Table 4
Parameters of MST-43LV module at different irradiance levels.

Module parameters	Irradiance levels in W/m^2	
	1000	250
I_{Ph} (A)	3.366	0.8415
I_{S1} (A)	$2.539 * 10^{-06}$	$1.391 * 10^{-06}$
I_{S2} (A)	$3.7869 * 10^{-04}$	$2.063 * 10^{-04}$
R_S (Ω)	0.8065	1.313
R_{Sh} (Ω)	40.895	707.4
a_1	1.005	0.947
a_2	1.995	2.053

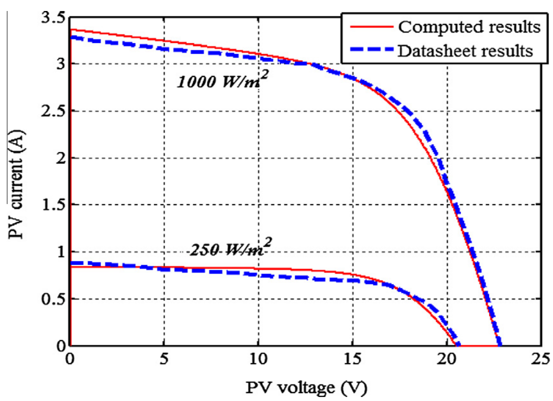


Fig. 11. I-V curves of computed and manufacturing results for MST-43LV.

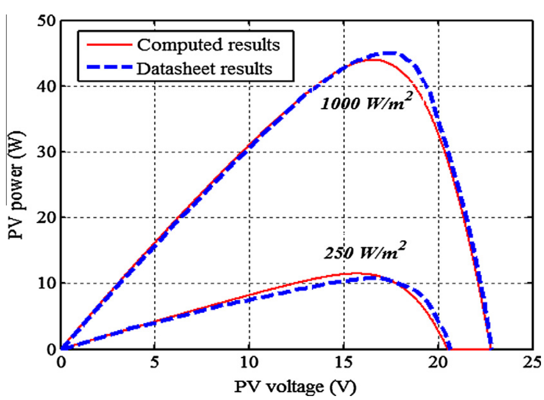


Fig. 12. P-V curves of computed and manufacturing results for MST- 43LV.

5. Conclusion

The effects of irradiance change on the values of seven parameters of two-diode module model are derived with respect to solar irradiance levels at standard test conditions of maximum power point (MPP). The seven parameters values at different irradiance levels are computed with the aid of Runge-Kutta-Merson numerical iterative method. The I-V and P-V curves of three different solar amorphous and thin film modules (U-EA110, MSPV95-S, and MST-43LV) are compared with respect to manufacturing curves. The computed results of the proposed model are satisfied good agreement with corresponding manufacturing results. The proposed model is enhancement the design and operation of solar amorphous and thin film modules at different irradiance levels.

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