Solar Irradiance Estimation of Photovoltaic Module based on Thevenin Equivalent Circuit Model

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Abstract- This Paper presents an accurate method for estimation of solar irradiance of a PV module. The solar irradiance estimation method is derived using the efficient approximation of a PV model based on Thevenin equivalent circuit. The short linear combination of exponential function is used for constructing a mathematical function that is used to express the Thevenin voltage source of a PV panel. The proposed algorithm for estimation of solar irradiance use Newton Raphson method based on extensively analysis of a photovoltaic mathematical model and it is applied for a wide range of operating point variations. The proposed method has the ability to estimate the parameters, which are required for constructing the mathematical model of a PV in addition to estimate the solar irradiance. The accuracy and effectiveness of the proposed algorithm is demonstrated in MATLAB for a photovoltaic panel by using experimental data, which is obtained from data sheet under different operating conditions.

Keywords—Pyranometer, Solar Irradiance Photovoltaic Model, Thevenin equivalent circuit, Exponential sum models.

1. Introduction

Due to the global concern about climate change and sustainable electrical power supply, renewable energy is increasingly becoming popular all over the world. Among different sources of renewable energy, the photovoltaic (PV) system is a promising energy source and the PV installations are increasing due to their environment-friendly operation [1]. An accurate solar irradiance data at ground level are of particular importance for an efficient estimation of solar energy [2-3]. Direct measurements of solar irradiance at surface can be obtained from pyranometers or reference solar cells [4-5]. Each method has its own merit and limitation. Paper[6,7] focus on utilizing the photovoltaic module itself to measure solar irradiance based on the mathematical photovoltaic model. In paper [6] The correlation between the solar irradiance and the photovoltaic module voltage output is presented. The correlation equation is derives using experimental approach. Paper [7] presents the estimation method of solar irradiance in W/m2 based on the short circuit current output produce by the photovoltaic module.

The solar irradiance estimation method is derived using the efficient approximation of a PV model based on Thevenin equivalent circuit . The most common PV model is the single-diode circuit model, which is a nonlinear model that is fully detailed in works such as [8-9]. Exponential sum models are used frequently in different applications .There are many different ways of estimating parameters in exponential sums and model a fit criterion, which gives a valid result from the fit. [10-12]. So , the construction of a model for a PV panel using Thevenin equivalent circuit based on linearization [16] or exponential sums model [17] is used.

Many investigations were reported above, about solar irradiance estimation but each method has its own limitations that are mentioned as follow. Pyranometer is a common choice as it is widely available off the shelf and measurement setup is relatively simple and straightforward, however it incurs a higher cost. This is because the pyranometer itself is an expensive piece of instrument and it requires additional acquisition hardware to computes and records the measurement. The installation of the pyranometer must be place similar to the photovoltaic module-facing angle in order to provide accurate measurement. Therefore, the additional costs incur for the installation and maintenance of pyranometer is relatively high. On the other hand reference solar cell incurs a lower cost, but with more complicated measurement setup and less accurate. In summary, both approaches still require additional sensing device to achieve solar irradiance measurement. To eliminate the need of additional sensing device, the method presented in paper [5] is based on the correlation between the solar irradiance and the photovoltaic module voltage output. This method does not fit well with the photovoltaic module characteristics, as it is a nonlinear current source. Solar irradiance estimation based on photovoltaic module short circuit current measurement [6] is less accurate (error reach to 15.9%) so it is not suitable for large-scale pv plants. This motivates the author to investigate an accurate method for estimation of solar irradiance of a PV module based on Thevenin Equivalent circuit Model.

In this paper A new advanced method for estimation of surface solar irradiance is investigated to estimate with better accuracy the incident solar radiation at the surface of a PV module. The solar irradiance estimation method is derived using the efficient approximation of a PV model based on Thevenin equivalent circuit. The accuracy and effectiveness of the proposed algorithm is demonstrated in MATLAB for a photovoltaic panel by using experimental data, which is obtained from data sheet under different operating conditions.

2. Equivalent Circuit of the Solar Cell

The single-diode circuit model of a PV cell is shown in figure (1), which is fully detailed in works such as [8-9].

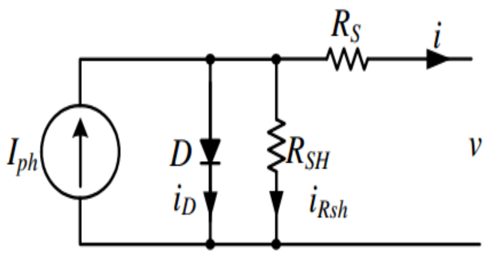

Fig.1: Equivalent circuit of a photovoltaic cell using

From figure (1):

$$I = I_{ph} - I_D - I_{R_{sh}} \tag{1}$$

$$I_D = I_o \left(e^{\frac{V+IR_s}{n_s V_t}} - 1\right) \tag{2}$$

$$V_d = V + IR_s \tag{3}$$

Where

$I_{ph:}$ The photo-generated current

I_o : Dark saturation current,

ns: Number of cells in series,

Rs: Panel series resistance.

Rsh: Panel series resistance.

$$V_t = \frac{AKT}{q} \tag{4}$$

A : Diode quality (ideality) factor

q: Electron charge

T:- Cell Temperature, in Kelvin,

k Boltzmann constant

Corresponding to equations (1-4), the effect of temperature and irradiance variations on V_t and R_s will be eliminated theoretically by transiting this effect into I_o , I_{ph} and R_{sh} values. So, the values of parameters (A,Rs) which are taken as constant values for approximation purpose. And also, it can be calculated by using simplified method [16] at the standard condition (t=25 ,G=1000), as follows:

$$A = \frac{\left(\frac{q}{n_s K T_{stc}}\right)(2V_{mstc} - V_{ocstc})}{\frac{I_{scstc}}{I_{scstc} - I_{mstc}} + \ln\left(1 - \frac{I_{mstc}}{I_{scstc}}\right)} \tag{5}$$

$$R_s = C2 = \frac{n_s V_{tstc} \ln\left(1 - \frac{I_{mstc}}{I_{scstc}}\right) + V_{ocstc} - V_{mstc}}{I_{mstc}} \tag{6}$$

Where

V_m: Voltage at the Maximum Power,

V_{mstc}: Voltage at the Maximum Power (in STC)

I_m: Current at the Maximum Power

V_o: Open circuit Voltage

I_{sc}; short circuit current

STC: - Standard Test Conditions (Gref =1000 W/m²,Tref=25 °C, spectrum AM1.5).

The general current-voltage characteristic of a PV panel based on the single exponential model can be rewritten as follow:

$$I = I_{ph} - I_o \left(e^{\frac{C(V+C_2 I)}{T}} - 1\right) - \frac{V + IC_2}{R_{sh}} \tag{7}$$

Where

$$C = \frac{1}{n_s V_{tstc}} \tag{8}$$

3. Thevenin Equivalent Circuit of a PV Panel based on Exponential Sum Model

Thevenin equivalent circuit of a PV model can be represented in as shown in Figure (2) [16]. The short linear combination of exponential function [10-12] is used for constructing a mathematical function that is used to express the dependent Thevenin voltage (Eq.9). Thevenin equivalent circuit based on short linear combination of exponential function is presented and the effectiveness of this model is demonstrated for different manufacturer panel models under different operating conditions in [17]

$$V_{TH}(V) = X_0 + X_1 e^{\frac{C}{T}(V + \Delta V)} \tag{9}$$

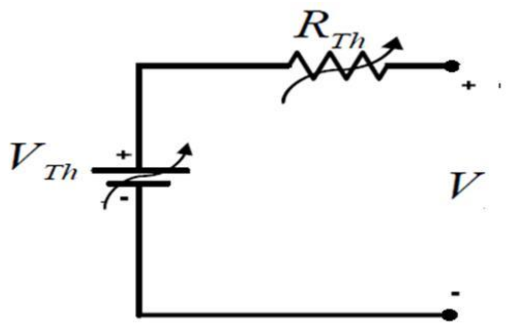

Fig. 2. Thevenin's equivalent circuit of PV.

Equation (10) is used to describe Thevenin's equivalent circuit of a PV module at any operating point*:*

$$X_0+X_1e^{\frac{C(V+IC2)}{T}} - IR_{TH} - V = F1 = 0 \qquad (10)$$

V_{TH} Thevenin Equivalent voltage source of a PV panel.

R_{TH} Thevenin Equivalent resistance of a PV panel.

Equation (12) can be written for the three key-points of the V-I characteristic (the short-circuit point, the maximum power point and the open-circuit point) as follow:

$$X_0+X_1e^{\frac{CC_2I_{sc}}{T}} - I_{sc}R_{TH} = F2 = 0 \qquad (11)$$

$$X_0+X_1e^{\frac{CV_{oc}}{T}} - V_{oc} = F3 = 0 \qquad (12)$$

$$X_0+X_1e^{\frac{C(V_m+C_2I_m)}{T}} - I_mR_{TH} - V_m = F4 = 0 \qquad (13)$$

4. Irradiance Estimation Procedure of a PV Panel

The determination of unknown Irradiances based on thevenin equivalent circuit of PV module at various operating points is described in the following steps:-

<u>Step1:-</u> To apply the proposed method for obtaining irradiances of PV module, the values of (Isc, Voc, Im, and Vm) are obtained from the datasheet of KC200GT solar module [15] at 25 ◦C, AM1.5, and 1000 W/m2 as shown in the table1.

Table 1. the data obtained from the datasheet for KC200GT solar module at 25 ◦C, AM1.5, and 1000 W/m2.

Parameter	KC200GT solar module
Maximum Power (Pmpp)	200 W
Maximum Power Voltage (Vmp)	26.3 V
Maximum Power Current (Imp)	7.61 A
Open Circuit Voltage (Voc)	32.9 V
Short Circuit Current (Isc)	8.21 A
Temperature Coefficient of Voc(Kv)	- 0.123 V/Oc
Temperature Coefficient of Isc (Ki)	+ 3.18 mA/oC
number of cells (ns)	54
C	0.51106
C2	0.19457

<u>Step2:-</u> To apply the proposed method for obtaining Irradiances of PV module, the constant values (C, C2) are calculated based on equations 5-8 and is tabulated in table1.

<u>Step 3:-</u> To include the effects of the environment, e.g. temperature and irradiance on the values of (Isc, Voc, Im, and Vm), The equations necessary to calculate these parameter are described as follow [14]:

$$I_{sc} = I_{sc,ref}\frac{G}{G_{ref}} + K_i(T - T_{ref}) \qquad (14)$$

$$V_{oc} = V_{oc,ref} + V_t \ln\left(\frac{G}{G_{ref}}\right) + K_v(T - T_{ref}) \qquad (15)$$

$$I_m = I_{m,ref}\frac{G}{G_{ref}} + K_i(T - T_{ref}) \qquad (16)$$

$$V_m = V_{m,ref} + V_t \ln\left(\frac{G}{G_{ref}}\right) + K_v(T - T_{ref}) \qquad (17)$$

Where

Ki, Kv Temperature coefficient of the short-circuit current - open-circuit voltage respectively

<u>Step 4:-</u> Eqs. (14) ; (17) can be inserted into Eqs. (10), (11),(12) and (13), It is possible now to determine all the four unknown parameters, the X0, X1, R_{TH} and G. As these equations do not allow separating the unknowns and solving them analytically, they are solved using Newton Raphson iterative method is exploited because it converges remarkably quickly, especially if the iteration begin sufficiently near the desired root. The elements of the resulting Jacobian matrix (J) are obtained by differentiating equations (10), (11),(12) and (13) with respect to the X0, X1, , R_{TH} and G. and are collected into portioned vector matrix forms, as:

$$\begin{bmatrix} \Delta F1 \\ \Delta F2 \\ \Delta F3 \\ \Delta F4 \end{bmatrix} = \begin{bmatrix} \frac{\partial F1}{\partial X_0} & \frac{\partial F1}{\partial X_1} & \frac{\partial F1}{\partial R_{TH}} & \frac{\partial F1}{\partial G} \\ \frac{\partial F2}{\partial X_0} & \frac{\partial F2}{\partial X_1} & \frac{\partial F2}{\partial R_{TH}} & \frac{\partial F2}{\partial G} \\ \frac{\partial F3}{\partial X_0} & \frac{\partial F3}{\partial X_1} & \frac{\partial F3}{\partial R_{TH}} & \frac{\partial F3}{\partial G} \\ \frac{\partial F4}{\partial X_0} & \frac{\partial F4}{\partial X_1} & \frac{\partial F4}{\partial R_{TH}} & \frac{\partial F4}{\partial G} \end{bmatrix} \begin{bmatrix} \Delta X_0 \\ \Delta X_1 \\ \Delta R_{TH} \\ \Delta G \end{bmatrix} \qquad (18)$$

<u>Step 5:-</u> The initial mismatch vector and the inverse of Jacobian matrix are calculated and are used for obtaining initial correction vector as follows:

$$\begin{bmatrix} \Delta X_0 \\ \Delta X_1 \\ \Delta R_{TH} \\ \Delta G \end{bmatrix} = \begin{bmatrix} \frac{\partial F1}{\partial X_0} & \frac{\partial F1}{\partial X_1} & \frac{\partial F1}{\partial R_{TH}} & \frac{\partial F1}{\partial G} \\ \frac{\partial F2}{\partial X_0} & \frac{\partial F2}{\partial X_1} & \frac{\partial F2}{\partial R_{TH}} & \frac{\partial F2}{\partial G} \\ \frac{\partial F3}{\partial X_0} & \frac{\partial F3}{\partial X_1} & \frac{\partial F3}{\partial R_{TH}} & \frac{\partial F3}{\partial G} \\ \frac{\partial F4}{\partial X_0} & \frac{\partial F4}{\partial X_1} & \frac{\partial F4}{\partial R_{TH}} & \frac{\partial F4}{\partial G} \end{bmatrix}^{-1} \begin{bmatrix} \Delta F1 \\ \Delta F2 \\ \Delta F3 \\ \Delta F4 \end{bmatrix} \qquad (19)$$

<u>Step 6:-</u> The initial corrections (Δ X0, Δ X1, , ΔR_{TH} and Δ G) are added to initial estimated values of X0, X1, , R_{TH} and G) to obtain their new values first iteration, the general form can be written as:

$$\begin{bmatrix} X_0 \\ X_1 \\ R_{TH} \\ G \end{bmatrix}^{K+1} = \begin{bmatrix} X_0 \\ X_1 \\ R_{TH} \\ G \end{bmatrix}^{K} + \begin{bmatrix} \Delta X_0 \\ \Delta X_1 \\ \Delta R_{TH} \\ \Delta G \end{bmatrix}^{K} \qquad (20)$$

Step 7:- The process of iteration is repeated until the values of these correction are minimized.

Step 8:- in order to verify the proposed method which is described in pervious steps. It can be tested for different operating points by using the datasheet curves. Whereas, the irradiance estimated values have a standard or true values (can be obtained from datasheet) , so the accuracy of the estimated value is given by a ratio of the error to the true value for any operating point as follow:

$$\text{err\%} = \frac{\text{estimated value} - \text{data sheet value}}{\text{data sheet value}} \times 100 \qquad (21)$$

5. Results and Discussion

In order to verify the proposed method of irradiance estimation, the results obtained from the proposed procedure have been compared with the solar irradiance data acquired from the datasheet of KC200GT solar module [15].

Figure 3 show that, the calculated irradiance based on the proposed method have been compared to the true value (1000 w/m2 at 25 ◦C) at different operating points which are obtained from the product data-sheet at specified true value of irradiance. The accuracy of the estimated value is given by a ratio of the error to the true value based on equation (21) as shown in figure 4. It can be seen from Figs. (3, 4) that, the calculated irradiance based on thevenin PV model are in very good agreement with the true value. From the Fig. (4) show that, The maximum absolute percentage error equal to 0.74%. And the mean absolute percentage error (MAPE) equal to 0.06%

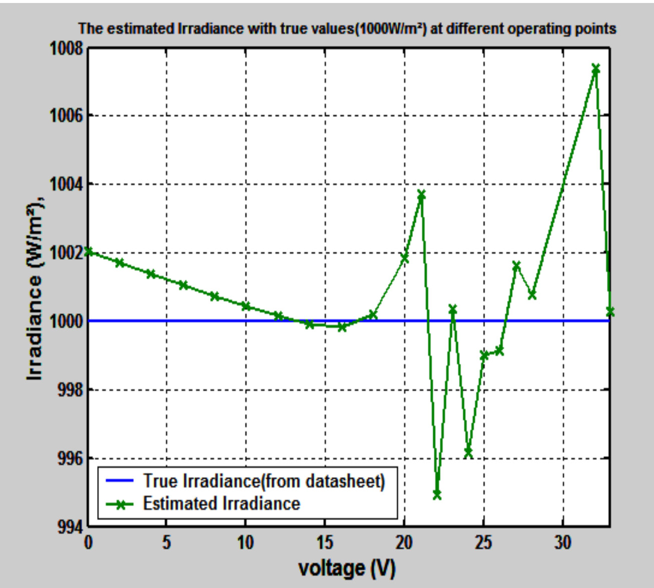

Fig.3. Comparison between the estimated irradiances of the proposed method and the solar irradiance (1000w/m2) using data acquired from the datasheet

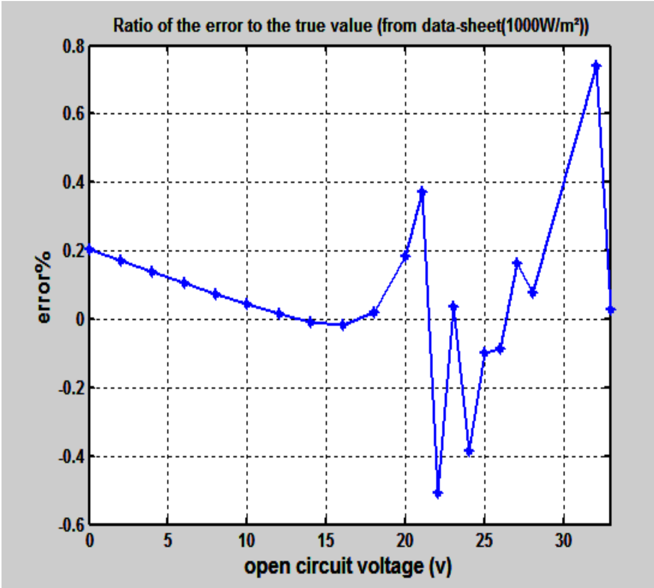

Fig.4. Percentage error of the estimated irradiance to the true value(1000w/m2) using data acquired from the datasheet

Figure 5 show that, The calculated irradiance based on the proposed method at (800 w/m2 at 25 ◦C) The accuracy of the estimated value is given by a ratio of the error to the true value based on equation (21) as shown in figure 6. It can be seen from Figs. (5, 6) that, the calculated irradiance based on thevenin PV model are in very good agreement with the true value. Fig. (6) show that, The maximum absolute percentage error equal to 1.14%. And the mean absolute percentage error (MAPE) equal to 0.61%.

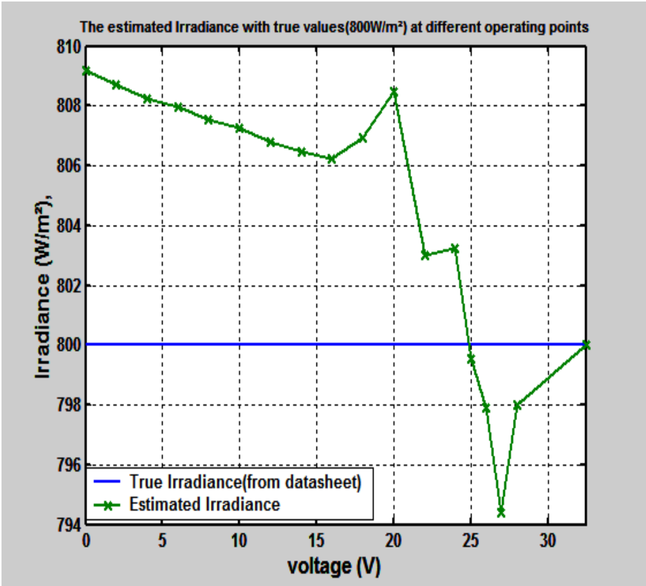

Fig.5. Comparison between the estimated irradiances of the proposed method and the solar irradiance (800w/m2) using data acquired from the datasheet.

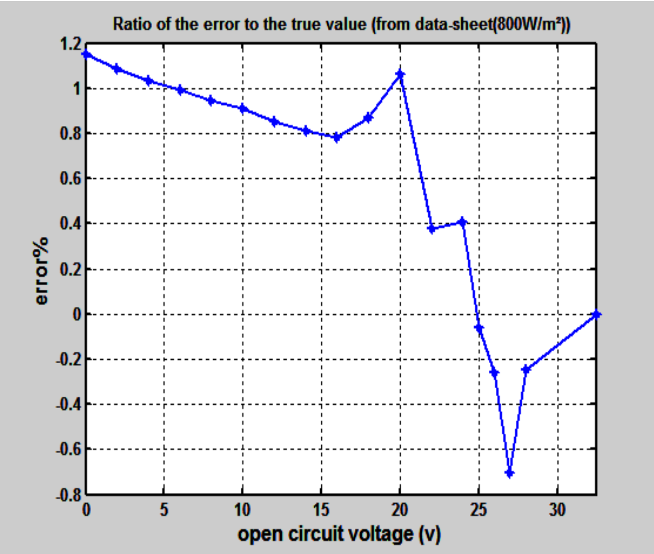

Fig.6. Percentage error of the estimated irradiance to the true value(800w/m2) using data acquired from the datasheet

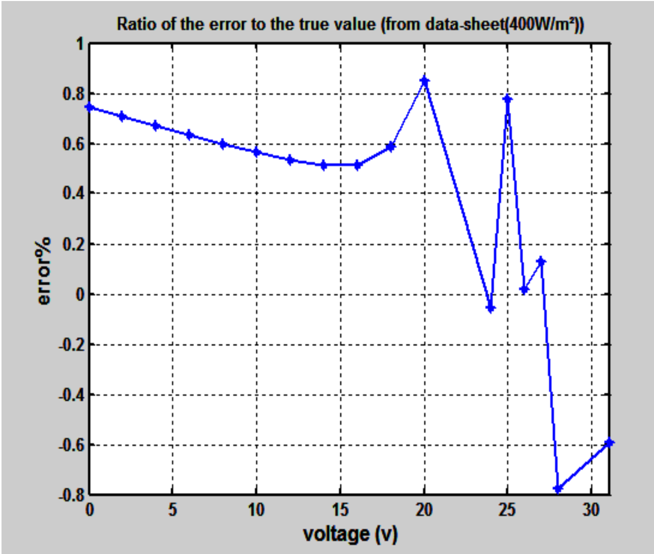

Fig.8. Percentage error of the estimated irradiance to the true value(400w/m2) using data acquired from the datasheet

Also figure 7 and 8 are used for comparison purpose between the estimated irradiance values and true value at (400 w/m2 at 25 ◦C) It can be seen from Figs. (7, 8) that, the calculated irradiance are in very good agreement with the true value. Fig. (8) show that, The maximum absolute percentage error equal to 0.85%. And the mean absolute percentage error (MAPE) equal to 0.37% .

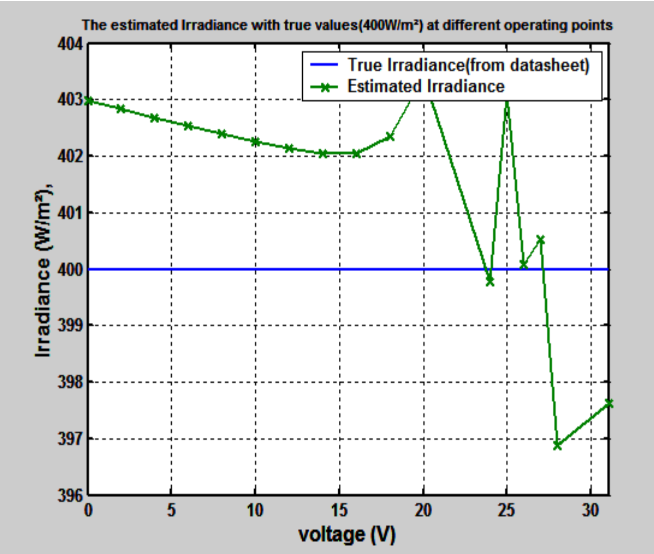

Fig.7. Comparison between the estimated irradiances of the proposed method and the solar irradiance (400w/m2) using data acquired from the datasheet.

It can be seen from Figs. (9, 10,11) that, the calculated V-I curves based on thevenin PV model with estimated irradiances corresponding to figure 3 ,5 and 7 respectively are in very good agreement with the data-sheet values.

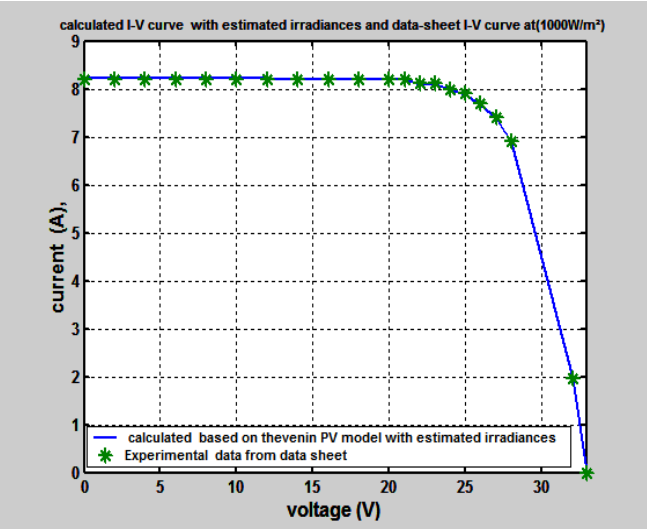

Fig.9. Estimated Voltage-Current characteristics based estimated irradiance (fig.3) and its corresponding characteristic from data sheet at (1000w/m2)

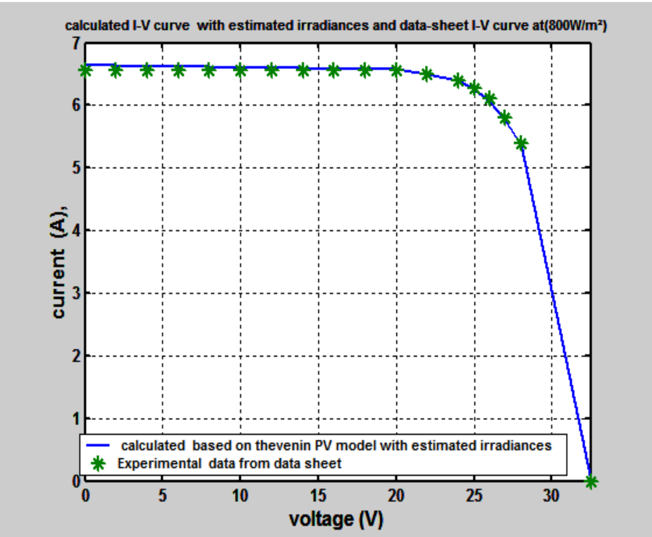

Fig.10. Estimated Voltage-Current characteristics based estimated irradiance (fig.5) and its corresponding characteristic from data sheet at (800w/m2)

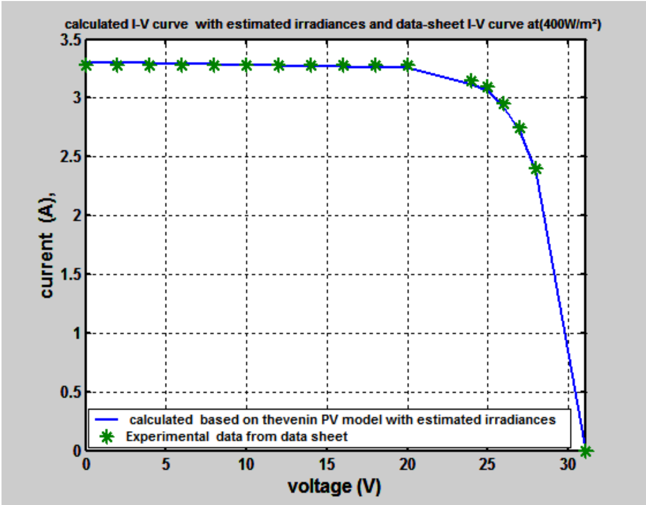

Fig.11. Estimated Voltage-Current characteristics based estimated irradiance (fig.7) and its corresponding characteristic from data sheet at (400w/m2)

6. Conclusions

The proposed solar irradiance estimation method photovoltaic based on thevenin equivalent circuit has been developed and implemented. The short linear combination of exponential function is used for constructing a mathematical function that is used to express the Thevenin equivalent circuit parameters. The proposed algorithm use Newton Raphson method based on extensively analysis of a photovoltaic mathematical model and it can be applied for a wide range of operating point variations. From the present analysis, one can draw the following main conclusions:

1- The proposed solar irradiance estimation method has been successfully derived using photovoltaic mathematical model based on thevenin equivalent circuit.
2- The proposed equations which are expressed in a PV model, allow one to estimate the irradiance of a PV using Newton Raphson method
3- The proposed method has the ability to estimate the parameters, which are required for constructing the mathematical model of a PV in addition to estimate the solar irradiance .
4- The estimation results are evaluated using data acquired from the datasheet of KC200GT solar module and validated using true values of solar irradiance which are obtained from it .
5- The proposed method is suitable for large-scale PV systems because it contributes to the elimination of the installation of expensive pyranometer to monitor solar irradiance for photovoltaic system performance monitoring and efficiency.
6- The results confirm the high quality of the proposed method to estimate the solar irradiance.
7- The calculated (I-V) curves using estimated irradiance based on the proposed method , are in

good agreement with the experimental data at different operating conditions.

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