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Efficient Solar Radiation Estimation Method based on a Curve Fitting Approach

Zahra'a Talib Almosawy, Mahmoud Shaker Nasr and Shamam Alwash
Department of Electrical Engineering, College of Engineering,
University of Babylon, Hillah, Iraq

Abstract: This study presents an accurate solar radiation estimation method based on the relationship between the solar radiation and the short circuit current of the PV panel. In order to avoid the interruption of the generated power of the PV panel during the solar estimation period an auxiliary PV panel fixed in the same alignment with other PV panels is used to estimate the solar radiation. The proposed method is implemented and tested using a 3W poly-crystalline PV panel PSP3 and a microcontroller (Arduino Uno). Test results verified the accuracy of the proposed method for several solar radiation cases.

Key words: Curve fitting, photovoltaic modeling, pyranometer, short circuit current, solar radiation, solar radiation estimation

INTRODUCTION

Recently, many countries have used the solar energy in the production of electricity due to the large benefits which can be obtained (Varshney *et al*., 2014). Two important factors that play a key role in determining the efficiency of the solar system are the temperature and the solar radiation. The temperature represents the negative factor which decreases the system efficiency whilst the positive factor is the solar radiation.

The Earth gets solar energy through solar radiation which is the most important element in solar systems. For Photovoltaic (PV) systems, it is very important to measure or estimate the solar radiation used to determine output system performance, efficiency and energy production for the system (Rahman *et al*., 2011). It is therefore, important to develop low-cost instruments that can be used to measure solar radiation in the photovoltaic system accurately.

The Solar Radiation Research Laboratory (SRRL) carried out the first solar radiation measurement in the National Renewable Energy Laboratory (NREL) in 1978 (Tan *et al*., 2013). The most popular device that has been used to measure the solar radiation is the pyrometer device. It is distinguished by its precision and high efficiency for measuring solar radiation. However, this device is very expensive because it needs additional equipment which must be available for measuring and recording the readings of solar radiation. Moreover, the installation and maintenance costs of this device are also very high.

In order to avoid the use of pyranometer, some researches have been developed to estimate the value of solar radiation. Tan *et al*. (2013) presented a solar radiation estimation method which is based on the mathematical model of the PV panel. In this method, the short circuit current and the open circuit voltage measured at the terminal of the PV panel is used to estimate the values of the PV equivalent circuit parameter. The equivalent circuit parameters and the short circuit current measured at the operation time are then used to estimate the solar radiation. However, this method utilizes an approximate mathematical model of PV module which affects the estimation accuracy. In addition, the service power continuity of the load should be interrupted when the solar estimation is required.

Husain *et al*. (2011) utilized the relationship between the measured open circuit voltage of the PV module and the value of solar radiation to develop a mathematical model. The developed model is then used to estimate the solar radiation. However, the open circuit voltage of the PV module is inversely related to the temperature (Loper *et al*., 2012) which is not considered in the developed model. Therefore, this model may not accurate enough to estimate the solar radiation.

Another method is developed to measure the solar radiation using a smartphone sensor. However, this method cannot be used for applications that require good accuracy (Tan *et al*., 2013) as well as the interface with complex hardware devices which is the case of PV system control circuit.

In this study, an accurate solar radiation estimation method based on the relationship between the solar radiation and the short circuit current of the PV panel is presented. In the proposed method, an auxiliary PV panel fixed in the same alignment with other PV panels is used to estimate the solar radiation. Thus, the interruption of the PV generated power during the estimation period is avoided.

Corresponding Author: Zahra'a Talib Almosawy, Department of Electrical Engineering, College of Engineering, University of Babylon, Hillah, Iraq

MATERIALS AND METHODS

Photovoltaic module model: A typical PV cell can be represented by the parallel diode with an ideal DC current source that proportional to the solar radiation of sun (Khabou *et al*., 2018). The equivalent electrical circuit of the PV module is presented in Fig. 1.

In this circuit, R_s is a very small series resistance which represents the contact resistance while R_{sh} is a very large shunt resistance which represents the resistance of the high-conductivity path across the junction of the solar cell (Khabou *et al*., 2018). By neglecting the current in R_{sh}, the expression of the current supplied by the photovoltaic module is Rahman *et al*. (2012):

$$I_{PV} = I_{sc} - I_o e - \frac{V_D^{.n.k.T}}{q} + I_o \quad (1)$$

Where:

- I_{PV} : Photovoltaic module current (A)
- I_{sc} : Short circuit current of PV cell (A)
- I_o : Diode reverse saturation current (A)
- V_D : Voltage through a diode (V)
- q : Electron charge (1.6×10^{-19}C)
- K : Boltzmann constant ($1.381\times10\text{-}23JK^{-1}$))
- T : Junction temperature (K)
- n : Ideality factor of the diode (1<n<2)

In order to illustrate the effect of the temperature and the solar radiation on the open circuit Voltage (V_{oc}) and the short circuit current (I_{sc}) of the PV module, the current-voltage characteristic curves for a PV module at different temperature values and solar radiation are presented in Fig. 2 and 3, respectively. It can be seen from Fig. 2 that the temperature has significant effect on the value of the open circuit voltage (Prakash *et al*., 2014). The open circuit voltage decreases with increasing the temperature. On the other hand, there is no significant change in the short circuit current value when the temperature changes (Prakash *et al*., 2014; Diab *et al*., 2012).

On the contrary, Fig. 3 shows that the change in solar radiation directly affects the short circuit current while there is no significant impact on the open circuit voltage (Bharath *et al*., 2016; Selmi *et al*., 2014). Accordingly, the approximate short circuit current at any solar radiation (G) can be given as Tan *et al*. (2013) and Rahman *et al*. (2012):

$$I_{sc}(G) = I_{sc}(G_r)\frac{G}{G_r} \quad (2)$$

Where:

- $I_{sc}(G_r)$: Short circuit current at the solar radiation (1000 W/m^2)
- G_r : Solar radiation (1000 W/m^2)
- G : Solar radiation (W/m^2)

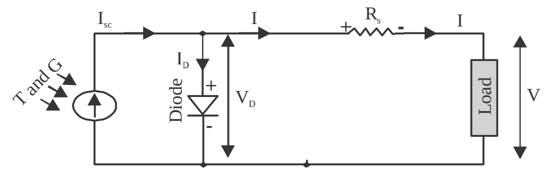

Fig. 1: The solar cell equivalent circuit

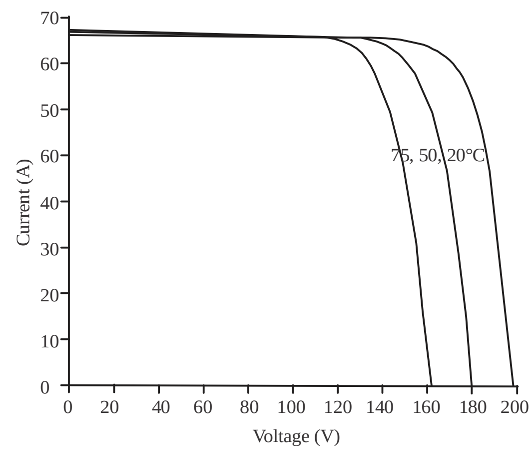

Fig. 2: Current-voltage characteristic curve for a PV module at different temperature values

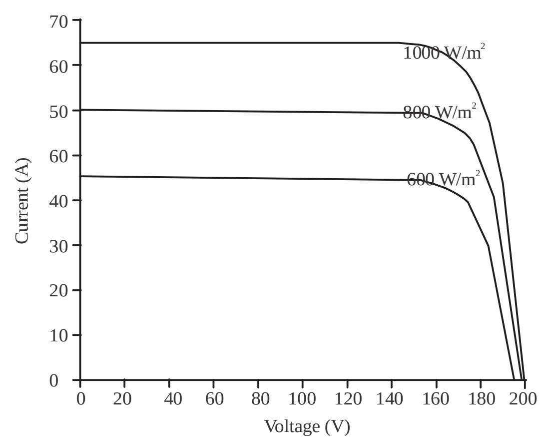

Fig. 3: Current-voltage characteristic curve for a PV module at different solar radiation levels

It is evident from the previous discussions that the short circuit current represents an excellent factor which can be utilized to estimate the solar radiation required for monitoring and controlling of the PV system.

Proposed solar radiation estimation method: The proposed solar radiation estimation method includes formulating a mathematical model based on the relationship between the solar radiation and the short circuit current of the PV panel. In order to obtain the data

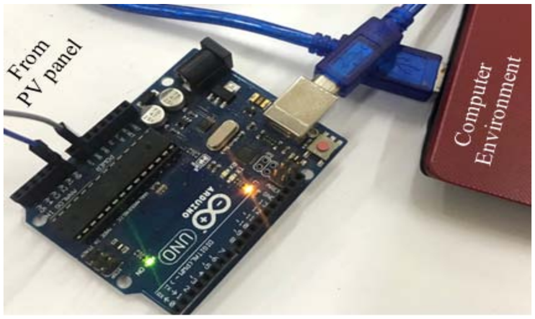

Fig. 4: Practical connection between the Arduino Uno and computer

required to formulate the proposed model, the solar radiation and the short circuit current of the PV panel are measured experimentally at different time periods. The measured data is then sent to MATLAB environment to determine the proposed model using the curve fitting method.

In this research, the relationship between the solar radiation and the short circuit current is formulated as a first-order-polynomial function that is given in Eq. 3:

$$G = a_1 I_{sc} + a_0 \quad (3)$$

Where:

a_0 and a_1 : Polynomial coefficients
I_{sc} : Short circuit current of the PV panel (A)
G : Solar radiation (W/m^2)

After determining the values of the polynomial coefficients a_0 and a_1 using the measured data, Eq. 3 can be used to estimate the solar radiation. Since, the short circuit current which is not affected by the temperature is utilised in the proposed method, it is more accurate than other methods which utilize the open circuit voltage.

In order to avoid the interruption of the service power during the estimation period of the solar radiation, a small size of the PV panel fixed in the same alignment with other panels is used in the proposed method to estimate the solar radiation.

For the practical purposes, Eq. 3 is implemented using a microcontroller (Arduino Uno) to estimate the solar radiation based on the short circuit current measured at the terminal of the PV panel. The estimated value can be sent to the control circuit of the PV system or to the computer for monitoring and recording purposes. Figure 4 shows the practical connection between the solar panel and the computer.

Due to the prices of the Arduino Uno and the utilized PV panel for estimating the solar radiation, the proposed method is considered cheaper than other methods. In addition, the proposed solar radiation estimator can be used in the algorithm of MPPT controller. Figure 5 shows the block diagram for the control panel of the solar system. Figure 6 shows the recorded solar radiation that has been measured by a pyranometer device in. The solar radiation and the short circuit current of the auxiliary PV panel are presented in Fig. 7.

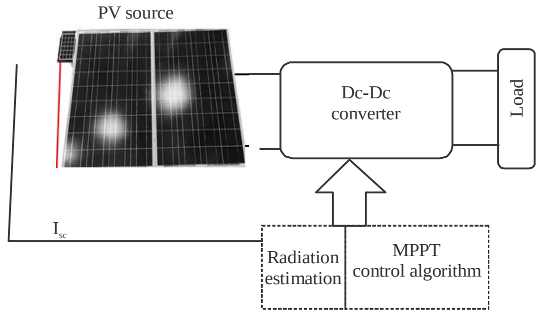

Fig. 5: Block diagram for solar panel control

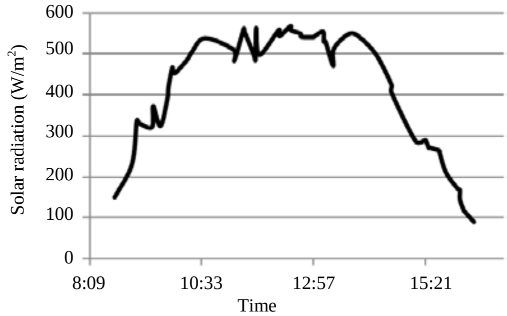

Fig. 6: Measured solar radiation

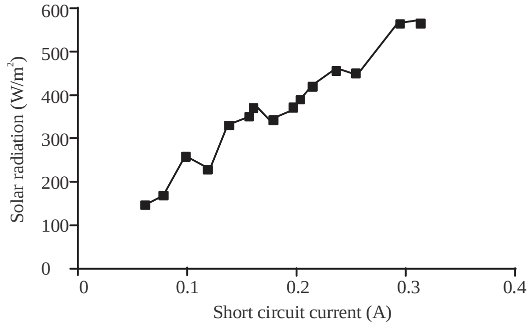

Fig. 7: Solar radiation and the short circuit current of the auxiliary PV panel

RESULTS AND DISCUSSION

The proposed method is tested and evaluated using a 3W poly-crystalline PV panel PSP3. This panel is fixed in the same alignment with other panels that are used to generate the electrical power as shown in Fig. 8. For several solar radiation cases, the short circuit current is measured at the terminal of the 3W PV panel. The solar

Table 1: Short circuit current of PV panel at different solar radiation levels (100-1000 W/m^2)

Solar radiation (W/m^2)	Short circuit current (A)
1000	0.56.0
900	0.5029
800	0.4471
700	0.3913
600	0.3355
500	0.2796
400	0.2238
300	0.1679
200	0.1119
100	0.05599

Table 2: Polynomial equation constants

Polynomial equation constant	Values
α^0	-4×10^{-12}
α_1	1788.9

Fig. 8: 3W Poly-crystalline PV panel

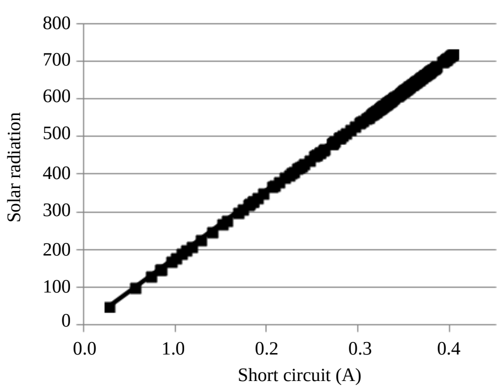

Fig. 9: Estimated solar radiation with respect to measure short circuit current of PV panel

radiation is also measured using pyranometer. Some of these data are illustrated in Table 1. Using MATLAB curve fitting tool box, the first order polynomial equation that represents the relationship between the solar radiation and the short circuit current of the PV panel is determined (Fig. 9). The constants of the polynomial equation obtained from the curve fitting are presented in Table 2. In order to demonstrate the accuracy of the proposed method to estimate the solar radiation, a comparison between the measured and the estimated values of the solar radiation are presented in Table 3. It can be seen from these results that the error between the measured and estimated values of the solar radiation is very small. These results verify the accuracy of the proposed method.

Table 3: Comparison between the measured and estimated solar radiation

Measured solar radiation (W/m^2)	Short circuit current (A)	Estimation solar radiation (W/m^2)	Error (W/m^2)
130	0.0727	129.9994	0.0006
149.31	0.0835	149.3093	0.0007
392.63	0.2195	392.6281	0.0019
400	0.2236	399.9980	0.0020
430	0.2404	429.9979	0.0021
440	0.2460	439.9978	0.0022
569	0.3181	568.9972	0.0028
599	0.3348	598.9971	0.0029
620	0.3466	619.9970	0.0030
721	0.4030	720.9965	0.0035
733	0.4098	732.9964	0.0036
761	0.4254	760.9963	0.0037
830	0.4640	829.9959	0.0041
884	0.4942	883.9957	0.0043
897	0.5014	896.9956	0.00439
898	0.5020	897.9956	0.00440
900	0.5031	899.9956	0.00441

CONCLUSION

Many scientific applications require knowledge of solar radiation value. One of these application is the photovoltaic power systems. Therefore, it is very important to provide a device for estimating the solar radiation with high accuracy and low cost. This study presented an accurate solar radiation estimation method based on the relationship between the solar radiation and the short circuit current of the PV panel using curve fitting approach. It is very cheap as compared with other methods. The proposed method was implemented and tested using an auxiliary PV panel (3W poly-crystalline PV panel PSP3 type). The results demonstrated the accuracy and the ability of the proposed method to estimate the solar radiation with high accuracy and low cost.

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