Electrical Modeling of a Bifacial PV Module Based on a Single Diode Model and Datasheet Values

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Abstract

In this study, a bifacial PV module is modeled based on a single diode model and the electrical data from the manufacturer's datasheet, including key electrical parameters such as the maximum power point, the short circuit current, and the open circuit voltage of the module at nominal condition, as well as temperature coefficients. A well-known electrical modeling algorithm for mono-facial PV module is adopted to model the electrical characteristics of the bifacial PV module. This approach is a fast and simple solution for electrical modeling of the bifacial PV module by utilizing datasheet values as input. The I-V electrical characteristics curve of the modeling result of this study are compared and validated against the I-V curve provided by the manufacturer by computing the relative root mean square error (RRMS) and by considering 107 test points from the manufacturer's datasheet. The computed value for RRMS is around 0.8 %, which shows a close agreement between the modeling result and the manufacturer's test data.

Keywords: Bifacial PV module, single-diode model, modeling, I-V curve.

1. Introduction

In the global energy market, the contribution of solar photovoltaic (PV) generation is vital and ranked third largest among all renewable electric power generation. The evolution of solar PV technology over the years results in new varieties of solar cell designs. Bifacial solar PV technology is the prominent one, which allows the light energy to strike the rear and the front side of the PV, thus producing more output power per square meter area. Because of this feature, its market share is rapidly increasing over conventional monofacial solar PV technology. The performance of a bifacial solar PV system depends on ground reflectivity, otherwise called Albedo, which is one of the critical site characteristics. The high value of albedo results in more rear irradiance and more output power from a bifacial solar PV system. The growing importance of the bifacial PV modules is reflected in projections that it will account for a significant 70% of the market by 2030 [1, 2].

Although bifacial PV technology provides numerous advantages, it also presents challenges in terms of design, installation, and operation that must be overcome to enable broader adoption. A key factor in this process is the development of an accurate electrical equivalent circuit model for bifacial PV modules, which is essential for optimizing performance and determining behavior under varying conditions [3]. Bouchakour et al. [4] utilized an empirical and analytical method, which was used to model a mono-facial PV module based on a single diode model. Sahu et al., 2025 [3] suggested a novel electrical model for electrical characterization of PV module. Becerra et al. [1] compared different electrical models from various researchers including single and double diode models against indoor experimental data with the objective of identifying the most accurate model. A single diode model for bifacial PV model is also presented by other researchers [5]. In this study the electrical characteristics of a bifacial PV module are modelled by adopting a popular single diode electrical model for mono-facial PV module proposed by Villalva et al. [6]. The modeling result of this study is compared against the test data from the manufacturer of the PV module.

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2. Methodology

Table 1 shows technical information from the datasheet of a bifacial PV module manufactured by Longi Solar Technology Co., which is considered in this study. The objective of this study is to analyze the performance of a PV module and to determine how a bifacial PV module performs under different parametric conditions such as cell temperature and irradiation level, by considering the manufacturer's data as input based single diode model.

Tab. 1: Electrical specification of LR6-60BP-310M [7]

Parameter	Values
Maximum Power (P_{max})	310 W
Maximum Power Voltage (V_{mpp})	32.9 V
Maximum Power Current (I_{mpp})	9.44 A
Open Circuit Voltage (V_{oc})	40.2 V
Short Circuit Current (I_{sc})	10.05 A
Temperature Coefficient of V_{oc}	$-0.3\%/o_C$
Temperature Coefficient of I_{sc}	$0.06\%/o_C$
Temperature Coefficient of P_{max}	$-0.3\%/o_C$
Cells	
Number per module	60
Bifaciality	≥ 70 %
Module Characteristics	
Length × Width × Depth	(1664×996×30) mm

NOCT (Nominal Operating Cell Temperature): 45 ± 2 ºC

Bifaciality is the rear and front side ratio of the most descriptive points on I-V curve of the PV module. There are three bifacial coefficients of a bifacial PV module: bifacial coefficient of the short circuit current (φI_{sc}), bifacial coefficient of the open voltage current (φV_{oc}), the bifaciality coefficient of the maximum power (φP_{max}), which are given in eq. (1) [8,9].

$$\varphi I_{sc} = \frac{I_{sc,R}}{I_{sc,F}},$$
$$\varphi V_{oc} = \frac{V_{oc,R}}{V_{oc,F}}, \qquad \text{(eq. 1)}$$
$$\varphi P_{max} = \frac{P_{max,R}}{P_{max,F}},$$

However, manufacturers mostly present the bifaciality coefficient of the maximum power (φP_{max}) as the bifaciality of the PV module [8,9], shown in eq. (2).

$$\varphi = \varphi P_{max} = \frac{P_{max,R}}{P_{max,F}}. \qquad \text{(eq. 2)}$$

The International Electrotechnical Commission (IEC) document: IEC 61724:2021 [8] prescribes representation of the nominal characteristics of the bifacial PV module as the test characteristics of only the front side of the module without including the rear side under standard test condition, which is followed by most of manufacturers [9], as a result it is assumed that the manufacturer's datasheet of Table 1 is a test result of only the front side of the PV module under standard test condition (STC).

Fig. 1 shows an equivalent electrical circuit for the electrical analysis of a bifacial PV module, with two separate circuits for front and rear faces of the PV module. Each face has its respective photocurrent, which are denoted by $I_{PV,F}$ and $I_{PV,R}$, respectively. There is a single diode with a diode current of I_D, and two resistors, parallel and series resistors (i.e., R_P and R_s).

Since the manufacturer presents the test data of the front face of the PV module, modeling of the front is performed as follows.

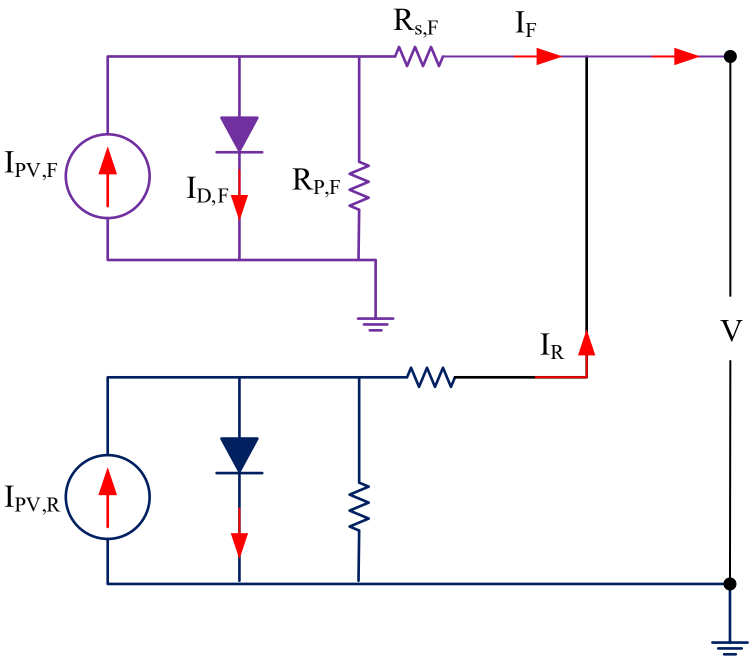

Fig. 1: Equivalent circuit model for a bifacial PV module.

The current output from the front face of the PV module can be determined based on the figure as presented with eq. (3).

$$I_F = I_{PV,F} - I_D - \frac{V+R_{s,F}I_F}{R_{P,F}}. \qquad \text{eq. (3)}$$

The diode current (I_D) in eq. (3) can be given by Eeq. (4).

$$I_D = I_0 \left[exp\left(\frac{V+R_{s,F}I_F}{aN_sV_t}\right) - 1\right] \qquad \text{eq. (4)}$$

where:
a is diode ideality constant.
N_s is number of solar cells in the PV module connected in series.
I_0 is diode saturation current.
The thermal voltage V_t can be expressed in terms of cell temperature (T_c) with eq. (5).

$$V_t = \text{Ҡ}\frac{T_c}{q} \qquad \text{eq. (5)}$$

where, Ҡ is the Boltzmann constant and q is the electron charge.

The diode saturation current (I_0) can be given in terms of its nominal saturation current ($I_{0,n}$) with eq. (6).

$$I_0 = I_{0,n}\left(\frac{T_n}{T_c}\right)^3 exp\left[\frac{qE_g}{a\text{Ҡ}}\left(\frac{1}{T_n} - \frac{1}{T_c}\right)\right] \qquad \text{eq. (6)}$$

where, E_g is the energy band gap and T_n is the nominal cell temperature, which is 25 ºC.

The nominal saturation current of the diode ($I_{0,n}$) can be given with eq. (7).

$$I_{0,n} = \frac{I_{sc,n}}{exp(V_{oc,n}/aV_{t,n})-1} \qquad \text{eq. (7)}$$

where, $I_{sc,n}$ is the short circuit current at nominal condition, which is the nominal 25 ºC cell temperature and the 1000 W.m^{-2} nominal irradiation intensity, $V_{oc,n}$ is the open voltage current at the nominal condition.

The photovoltaic currents of the PV module of the front face ($I_{PV,F}$) can be expressed in terms of the cell temperature (T_c) and irradiation (G) with eq. (8).

$$I_{PV,F}(G_F, T_c) = \left(I_{PV,Fn} + +K_I(T_c - T_n)\right)\frac{G_F}{G_n} \qquad \text{eq. (8)}$$

where,

G_F is the solar radiation on the front face of the PV

T_c is cell temperature

G_n is the nominal solar irradiation which is 1000 W.m^{-2}

T_n is the nominal cell temperature, which is 25 ºC

$I_{PV,Fn}$ is the photovoltaic current from the front face at nominal condition.

K_I is the temperature coefficient for the short circuit current as presented in Table 1

Considering eq. (3), at nominal condition and when the module is in short-circuit, the voltage output from the module (V) is zero, and the current passing through the diode (I_D) is also zero. As a result, the following equation can be obtained:

$$I_{PV,Fn} = I_{sc,n} + I_{R_{p,F},n}. \qquad \text{eq. (9)}$$

$$V_A = I_{sc,n} \times R_{s,F} = I_{R_{p,F},n} \times R_{P,F} \qquad \text{eq. (10)}$$

where, $I_{R_{p,F},n}$ is the current flowing through parallel resistor ($R_{P,F}$).

Combining eq. (9) and eq. (10) results eq. (11).

$$I_{PV,Fn} = I_{sc,n}\frac{R_{P,F}+R_{S,F}}{R_{P,F}}. \qquad \text{eq. (11)}$$

Considering eq. (3) the maximum power current (I_{mpp}) can be expressed in terms of maximum power voltage (V_{mpp}) and parameters at the nominal condition.

$$I_{mpp} = I_{PV,Fn} - \frac{I_{sc,n}}{exp(V_{oc,n}/aV_{t,n})-1}\left[exp\left(\frac{V_{mpp}+R_{S,F}I_{mpp}}{aN_sV_{tn}}\right) - 1\right] - \frac{V_{mpp}+R_{S,F}I_{mpp}}{R_{P,F}}. \qquad \text{eq. (12)}$$

eq. (12) can be rearranged into eq. (13).

$$R_{P,F} = \frac{V_{mpp}+R_{S,F}I_{mpp}}{I_{PV,Fn}-I_{0,n}\left[exp\left(\frac{V_{mpp}+R_{S,F}I_{mpp}}{V_{t,n}a}\right)-1\right]-I_{mpp}}. \quad \text{eq. (13)}$$

Eq. (3) to eq. (13) are used to determine the electrical characteristics of the PV module on the I-V and P-V planes when irradiation is only on the front side of the bifacial PV module, which is the same test condition of the manufacturer. As a result, the equations (i.e., eq. (3) to eq. (13)) can be used to determine the I-V and P-V curves of the PV module when it is illuminated on the front side. Consecutively, the maximum power from the front side can be obtained from the P-V curve for every any solar irradiation and cell temperature value.

$$P_{max,F} = \max\left(Curve_{P-V} = f(T_c, G_F)\right) \quad \text{eq. (14)}$$

where, $[Curve_{P-V} = f(T_c, G_F)]$ is an algorithm developed with equations (i.e., eq. (3) to eq. (13), that takes two changing parameters, which are the PV cell temperature (T_c) and front face solar irradiation to generate a P-V curve. As a result, it is possible to obtain a single P-V curve for front face. The maximum power for the curve can be found from the curve, resulting in the maximum power output when the irradiation is in the front face alone ($P_{max,F}$).

If the irradiation level on the rear face is G_R, the maximum power point from the rear face if it performs with same level of performance of the front can be given as follows.

$$P'_{max,R} = \max\left(Curve_{P-V} = f(T_c, G_R)\right). \quad \text{eq. (15)}$$

However, since the rear face does not perform at the same level as front face, which is expressed as a bifaciality factor, the actual power output from the rear face can be expressed in terms of the bifaciality factor and eq. (16) as follows:

$$P_{max,R} = \varphi P'_{max,R} = \varphi \max\left(Curve_{P-V} = f(T_c, G_R)\right). \quad \text{eq. (16)}$$

3. Result and Discussion

Fig. 2 shows the I-V characteristics curve of the front side of the bifacial PV module at a 1000 W.m^{-2} irradiation level and for different cell temperatures of the bifacial PV module. The figure shows a significant decrease in open circuit voltage (V_{oc}) of the I-V curve with an increase in cell temperature, while there is a very slight rise in short circuit current (I_{sc}). In the figure, I-V curves for the cell temperature of 25 ºC, 45 ºC, and 75 ºC are presented. The figure also shows the comparison of the modeling result in this study with the manufacturer's test data. The manufacturer provided data test for the bifacial PV module on I-V curve. Some points from the test manufacturer's datasheet are extracted using WebPlotDigitizer software and compared against the modeling data as shown in Fig. 2 and Fig. 3 for the purpose of validation.

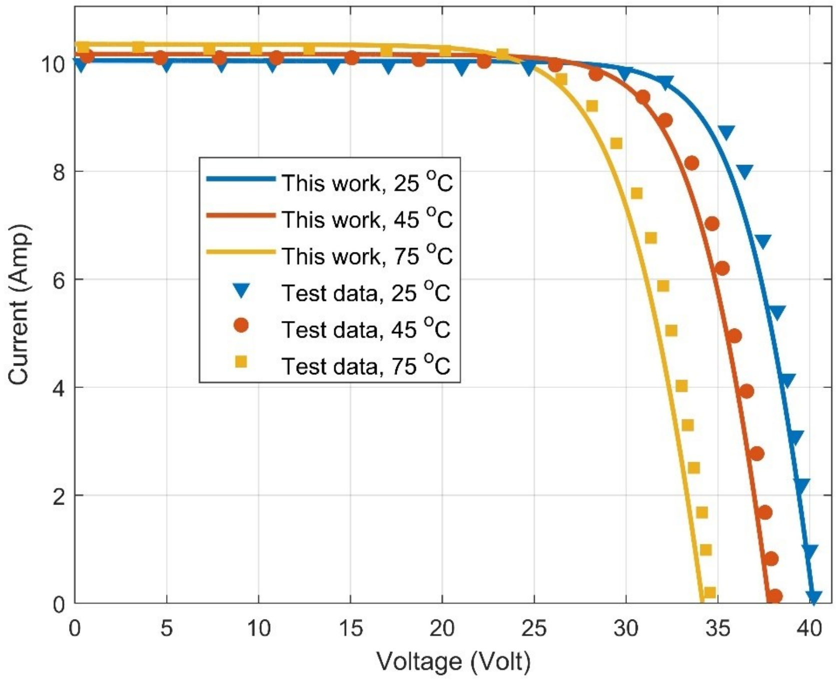

Fig. 2: I-V characteristics at an irradiance of 1000 W.m^{-2} and different cell temperature and comparison with test data.

Fig. 3 shows the I-V curve of the front face of the bifacial PV module at 25 ºC cell temperature and at different insolation of the bifacial PV module. The figure shows a significant increase in short circuit current (I_{sc}) with an increase in irradiance, while the rise in the open circuit voltage (V_{oc}) of the curve with irradiance is small. In the figure, I-V curves for irradiances of 200 W.m^{-2}, 400 W.m^{-2}, 600 W.m^{-2}, 800 W.m^{-2}, and 1000 W.m^{-2} are presented. The figure also shows the comparison of the modeling result in this study with the manufacturer's test data.

Fig. 4 shows the P-V curve of the front face of the PV module at 25 ºC cell temperature and at different insolation of the bifacial PV module. The figure shows a significant increase in maximum power point (mpp) of the P-V curve with an increase in irradiance, while the rise in the open circuit voltage (V_{oc}) of the curve with irradiance is small. In the figure, P-V curves for irradiances of 200 W.m^{-2}, 400 W.m^{-2}, 600 W.m^{-2}, 800 W.m^{-2}, and 1000 W.m^{-2} are presented. The maximum power point for 1000 W.m^{-2} is around 310 W, the maximum power point for 800 W.m^{-2} is around 247 W, the maximum power point for 600 W.m^{-2} is around 184 W, the maximum power point for 400 W.m^{-2} is around 120 W, and the maximum power point for 200 W.m^{-2} is around 57 W.

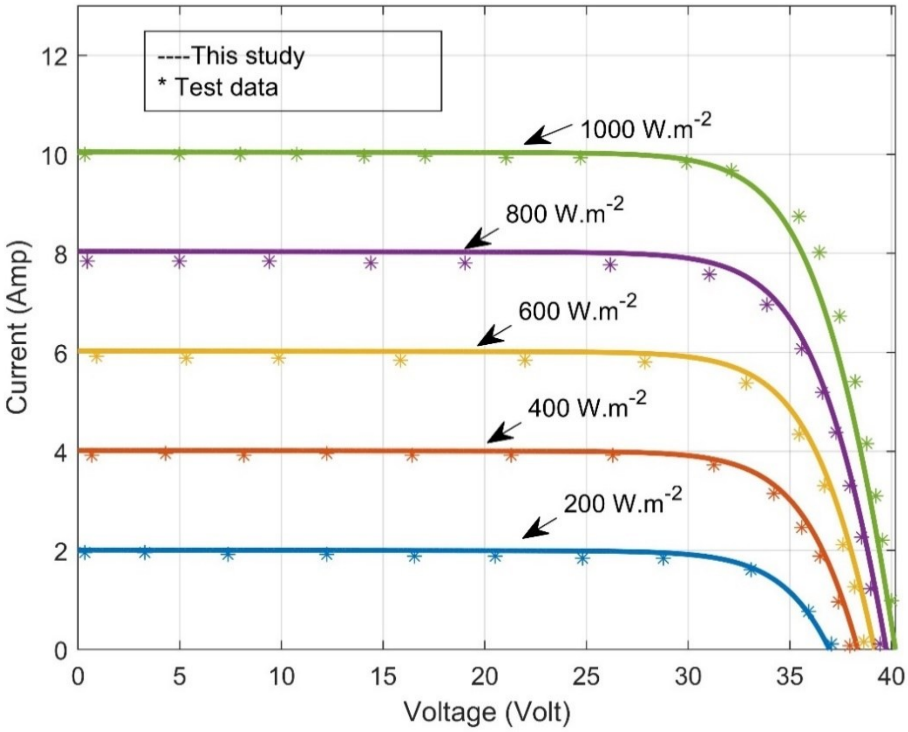

Fig. 3: I-V curves at 25 ºC cell temperature and different irradiances and comparison with test data.

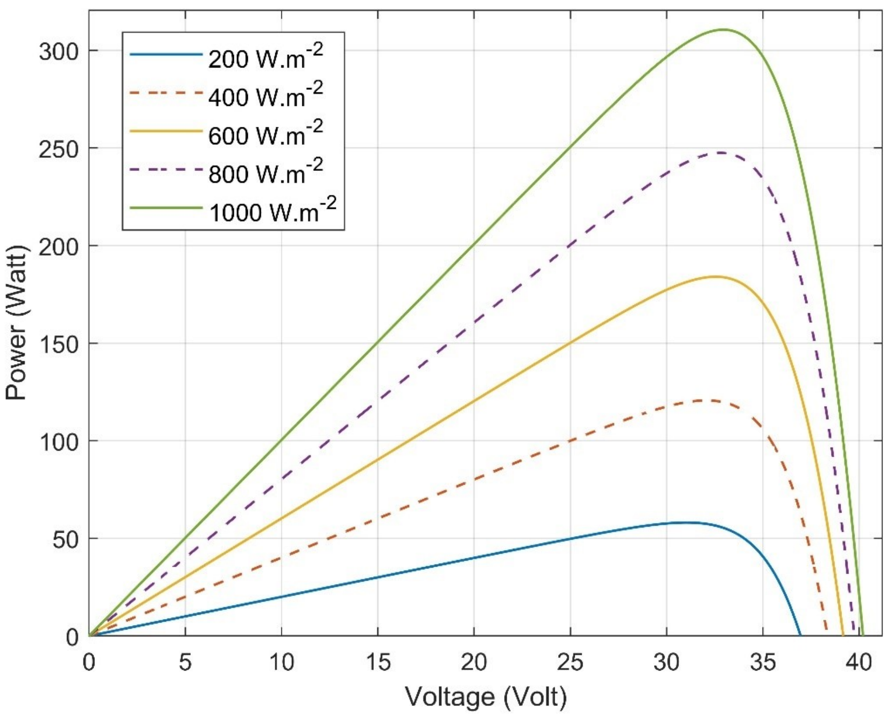

Fig. 4: P-V characteristics at 25 ºC cell temperature and different irradiances.

To assess the effectiveness of the electrical modeling on I-V curve, the curve deviation metric can be computed with the relative root means square error ($RRMS_{I-V}$) as follows:

$$RRMS_{I-V} = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(I_{est}-I_{test})^2}{\sum_{i=1}^{N} I_{test}^2}} \times 100\ \% \qquad \text{eq. (21)}$$

where, N is number of data, I_{est} is the estimated or computed current using the suggested model, I_{test} is the test current from the manufacture's datasheet.

The relative root mean square error (RRMS) between the modeling result of this study against the manufacturer's test data of the I-V curves of Fig. 2 and Fig. 3 is computed by considering 107 points from the two figures. The computed value for RRMS is around 0.8 %, which shows a close agreement between the modeling result and the manufacturer's test data.

4. Conclusion

This study considered the adoption of an algorithm which is typically used to model mono-facial PV modules to model a bifacial PV module using a single-diode model. The algorithm is capable of characterizing the detailed electrical characteristics of a bifacial PV module on the I-V and P-V planes by taking the manufacturer's datasheet as input. Electrical parameters of the PV module including the maximum power point, the short circuit current, and the open circuit voltage of the module at nominal condition, as well as temperature coefficients are taken as inputs to model electrical characteristics of the PV module. The modeling result of this study is compared against the manufacturer's test data, and a relative root mean square error between the modeling result of this study and the manufacturer's test data is computed, which has an approximate value of 0.8 % showing the suggested algorithm is capable of modeling the bifacial PV module accurately.

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