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Analysis of a Piecewise Linear Model for Rapid Simulation of PV Modules

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Abstract – The simulation and measurement of various photovoltaic (PV) cell models are described in this paper. Models of four-diode, rectangular, and nonlinear PV cells are presented. In addition, normalizations have been added to improve calculations and simulations. Experimental measurements are used to assess the validity of the nonlinear model. The dark I-V PV array test configuration accurately demonstrates the PV array's properties. The proposed model is the piecewise linear (PWL) "4-diode" model, which allows rapid simulation. This is an appropriate solution in terms of the model's diode count. When more diodes are employed, the I-V curve is smoother. In this case, however, both the simulation time and model complexity increase significantly.

Keywords – Dark I-V, Inverter, Modeling, Photovoltaics, Simulation, Solar Cell

I. Introduction

A photovoltaic (or solar) cell is an electrically optimized diode that can convert solar photons into electricity. The amount of usable solar power, expressed in watts per square meter, is known as irradiance. The efficiency of a photovoltaic cell is measured by how quickly it can transform sunlight into electricity. Depending on factors like the quality of the semiconductor material used, the amount of irradiance, and the temperature. The efficiency of practical photovoltaic (PV) cells can vary anywhere from 5% to 20%.

A PV module is comprised of a collection of PV cells that are interconnected in a series configuration, thereby increasing their output voltage and power. PV modules are connected in either series or parallel configurations to achieve the desired power output, resulting in the formation of a PV array. Current versus voltage (I-V) curves, such as shown in Fig. 1, are commonly used to depict the electrical behavior of PV modules. V_{OC}, the open-circuit voltage, I_{SC}, the short-circuit current, and P_0, the maximum power point where the product of V and I is at a maximum are the three essential quantities defined by this curve. This is the optimum functioning point of the solar cell. At point P_0, the voltage and current are V_0 and I_0.

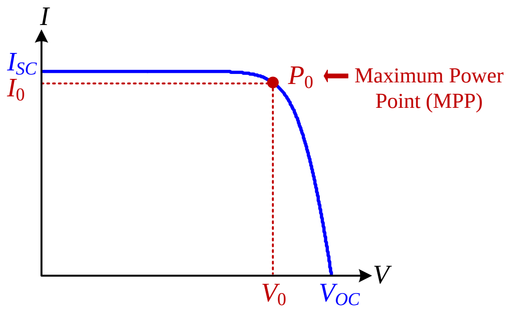


Fig. 1: Typical PV module I-V curve displaying the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), maximum power point (P_0), voltage at MPP (V_0) and current at MPP (I_0).

II. PV Modules

The PV array is made up of two 80 W PV modules (BP380U) that are connected in series and produce an output of about 160 W [1]. The manufacturer's specifications for the BP380U PV module are shown in Table 1 for nominal or standard test conditions (STC). The specified parameters comprise a solar irradiance of 1000 W/m^2, a temperature of 25 degrees Celsius (equivalent to 298 Kelvin) for the cell or module, and a solar spectral irradiance distribution characterized by a standard air mass of 1.5. This section outlines three models of photovoltaic cells which can be utilized in simulations of grid-connected inverters. All of the models are based on the BP380U photovoltaic module and show variations in complexity.

Table 1. 80 W BP Solar BP380U module nominal specifications.

Parameter	Value
Rated Maximum Power (P_0)	80 W
Voltage at P_0 (V_0)	17.6 V
Current at P_0 (I_0)	4.55 A
Short Circuit Current (I_{SC})	4.8 A
Open Circuit Voltage (V_{OC})	22.1 V
Temperature Coefficient of I_{SC} (α)	(0.065 ± 0.015)%/°C
Temperature Coefficient of V_{OC} (β)	-(80 ± 10)mV/ °C

A. *Non-Linear Model*

The theoretical framework presented in Table 2 is based on a nonlinear model that assumes the existence of a diode featuring a parallel light-induced current that is assumed to be equivalent to I_{SC}. Incorporating parallel, also known as shunt, and series, denoted as R_S, resistances into the model enhances its precision. Nevertheless, the impact of R_P is deemed insignificant in comparison to R_S, and as such, it has been excluded from this simplified model. A similar two diode model version of this nonlinear model was also introduced in [2].

The nonlinear model is based on the ideal diode equation, which establishes a correlation between the voltage and current of the diode. The determination of the relationship between the output current (I) and output voltage (V) of a photovoltaic cell involves consideration of the parallel connection of the diode to the current source induced by light.

$$I = I_{SC} - I_S(e^{\frac{q(V+IR_S)}{nkT}} - 1) \quad (1)$$

where q represents the electron charge, n is the ideality factor of the diode, k is the Boltzmann constant, and T the temperature of the PV cell. (1) applies to a single cell and can be scaled proportionally for modules. R_S must be multiplied by the number of module series resistances, N_S, for module calculations. Consequently, the voltage and current values in (1) represent the module.

The parameters in (1) can be determined using the following three equations: In the first column of Table 3, the parameters show the nominal nonlinear model specifications.

$$I_{SC(T,G)} = I_{SC(nom)} \frac{G}{G_{nom}} (1 + \alpha (T - T_{nom})) \quad (2)$$

According to the graphs in Table 2, the short circuit current (and consequently the power) is directly proportional to the G irradiation. The temperature range for the BP380U module I_{SC} is 25 to 75°C, as shown in Table 4.

$$I_{S(T,G)} = \frac{I_{SC(T,G)}}{e^{\frac{q V_{OC(T_{nom})}}{n k T(T_{nom})}} - 1} \left(\frac{T}{T_{nom}}\right)^{\frac{3}{n}} e^{\frac{q V_g}{n k}\left(\frac{1}{T_{nom}} - \frac{1}{T}\right)} \quad (3)$$

The method presented in equation (3) demonstrates the computation of the saturation current, denoted as I_S, through the utilization of equation (2) and the nominal open-circuit voltage.

$$R_S = -\left.\frac{dV}{dI}\right|_{V_{OC}} - \frac{1}{X_V} \quad \text{where,} \quad X_V = \frac{q I_{S(T_{nom})}}{n k T} e^{\frac{q V_{OC(T_{nom})}}{n k T_{nom}}} \quad (4)$$

Table 2. Simulation models for the BP380U PV module, as well as current and power-voltage characteristics for different irradiance values. The dots in the graphs represent the MPP (P_0)

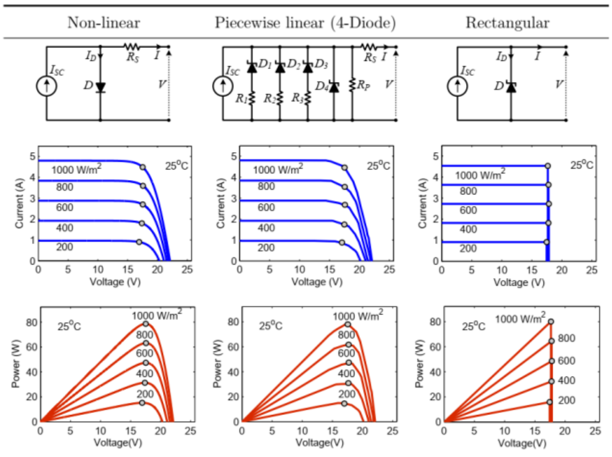


Table 3. Model parameters for PV modules at nominal operating conditions

Non-linear	Piecewise linear	Rectangular
$n = 1.02$	$I_{SC} = 4.8$ A	$I_{SC} = 4.533$ A
V_g (band gap V.) = 1.21 V	$D_1 = 18.5$ V	$D = 17.66$ V
N_S (module cell number) = 36	$D_2 = 21.5$ V	
k (Boltzman constant) = 1.38×10^{-23} J/K	$D_3 = 22.75$ V	
q (charge on an electron) = 1.60×10^{-19} C	$D_4 = 23.5$ V	
$R_S = 10.5$ mΩ	$R_1 = 8$ Ω	
	$R_2 = 2$ Ω	
	$R_3 = 0.5$ Ω	
	$R_P = 100$k Ω	
	$R_S = 0.5$ Ω	

The I-V curve evaluated at the voltage point of maximum power V_{OC} has the potential to substantially alter the MPP. To derive the value of R_S, equation (1) is differentiated and assessed at the point where $(dV{=}dI)|_{VOC}$; $I = 0$. The resulting expression is then rearranged in a manner that is expressed in terms of R_S (4) [3], [4]. From the datasheet provided by the manufacturer of the photovoltaic module, the slope of the voltage-current curve can be calculated. The latter part of this equation is equivalent to the slope of the natural curve described by the ideal diode equation (4). Therefore, the module resistance R_S is calculated as the difference between the slope found in the ideal diode equation and the slope found in the module datasheet.

Additionally, the slope of the I-V curve close to the maximum power point is influenced by the diode ideality factor *n*. In this study, *n* was used at a value of 1.02, which was found by matching the manufacturer's I-V curves to typical values between 1 and 2.

B. *Piecewise Linear Model*

The piecewise linear (PWL) "4-diode" model is the second model, which allows for rapid simulation. This is a reasonable compromise in terms of the model's diode count. When more diodes are utilized, the I-V curve becomes smoother. However, the complexity and simulation time of the model are significantly increased.

Table 2 second column shows the equivalent circuit diagram of the model which is powered by a source of constant current equal to I_{SC} and is based on ideal zener diodes with fixed voltage drops. The voltage drop across the single diode D_4 is V_{OC}. This model has both R_S and R_P. By changing the voltage drops and resistances (the series resistances of the diodes), the vertex points of the I-V curve are recalculated to match the experimental results of a specific PV module. Table 3 shows the parameters of the 4-diode circuit based on the PV module BP380U under nominal conditions. The impact of irradiance is demonstrated through the utilization of I-V and P-V curves, which have been generated using the PWL model, as depicted in Table 2.

C. *Rectangular Model*

The I-V curve of an ideal solar cell closely resembles a rectangular shape, as shown by the data presented in Table 2. The model employs a single zener diode and a constant-current source. The rectangular model is utilized to determine the zener diode voltage drop and short-circuit current based on the figures obtained at the MPP. The rectangular model based on BP380U is shown in Table 3 under nominal conditions. This approach also enables rapid simulation.

D. *Normalized Irradiance and Temperature Curves*

The non-linear model predictions for the I-V and P-V curves of the BP380U, corresponding to different irradiance and temperature values, are presented in Table 4. The first section of the table presents actual information, where the maximum power point (MPP) is indicated by circular markers. The normalized values of the first-row reference to the maximum power point under nominal conditions (1000 W/m^2 and 25°C) are presented in the second row. Subsequently, the normalized plots at the maximum power points are presented.

Table 4. The effect of various normalizations on the BP380U module's I-V and P-V curves as temperature and irradiance change. The first row contains actual curves. Second row: all curves have been normalized to the MPP under nominal conditions. Each curve is normalized to its respective MPP in the third row. The MPP is shown as circles

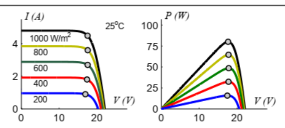
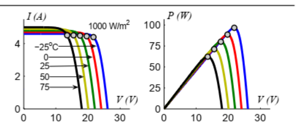
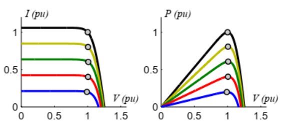
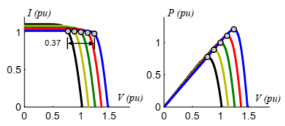
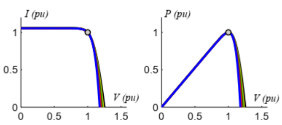
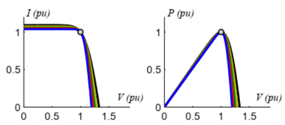
Model	Irradiance Changes	Temperature Changes
Actual		
Norm. at MPP under nom.		
Norm. all at MPPs		

Fig. 2 illustrates the impact of different levels of irradiance and temperature on the maximum power point voltage V_0 of a photovoltaic (PV) module. Fig. 2(a) depicts the irradiance effect. The voltage V_0 experiences a significant decrease with an increase in temperature, as illustrated in Fig. 2(b). This is attributed to the fact that the voltage remains mostly constant, except for low levels of irradiance.

According to the normalized I-V curve presented in Table 4, there is a voltage difference of 0.37 per unit between temperatures of -25°C and 75°C. It has a substantial impact on the resultant power output, estimated to be around 35%. The utilization of these normalised values enables the identification of the most suitable input voltage range for maximum power point tracking in power converter design [5].

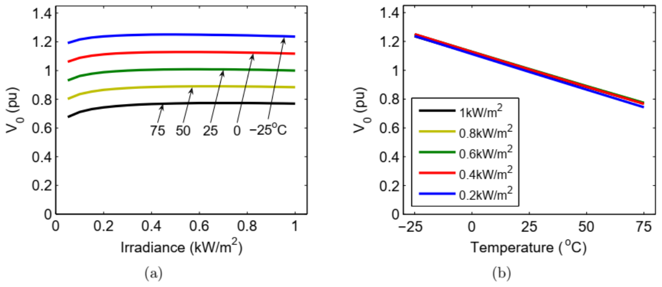


Fig. 2 Variations in voltage with respect to (a) irradiance and (b) temperature at MPP

As demonstrated in the third row of Table 4, the curves have been normalized according to their respective MPP values. The analysis indicates that the normalized configurations of the current-voltage and power-voltage plots remain substantially unaltered by fluctuations in temperature and irradiation. The average single-phase output power reduction of photovoltaic arrays can be calculated using the normalized I-V and P-V curves [6].

III. Experimental Results

The BP380U photovoltaic module performed outdoor testing under direct sunlight. The irradiation and temperature levels were not determined during the testing process. The study involves a comparison between the measured results and non-linear model calculations for various irradiance levels, utilizing the specifications of the BP380U photovoltaic module. The findings are illustrated in Fig. 3(a). The results of the experiment were found to be in good agreement with 850 W/m^2 of irradiance and a cell temperature of 50°C.

The nonlinear model calculations for different temperatures are illustrated in Fig. 3(b). They demonstrate excellent correspondence with the manufacturer's data when compared.

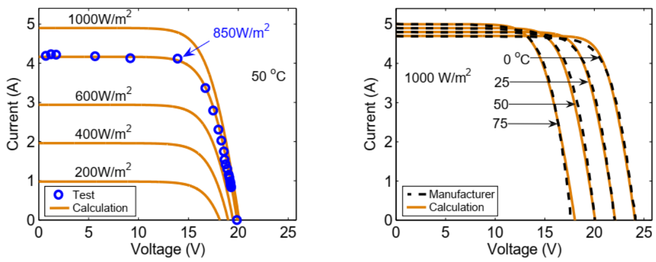


Fig. 3 Non-linear I-V curves for different irradiance and temperature values, for both (a) outdoor tests and (b) values given in the manufacturer's datasheet

A. Dark I-V Method

Additionally, the dark current-voltage (dark I-V) measurement technique is frequently used to examine the performance characteristics of solar cells [7]. This test circuit is depicted in Fig. 4(a), while the grid-connected current-source inverter (GC-CSI) block diagram is shown in Fig. 4(b). The constant-current source (CCS) for the dark I-V configuration is set to an I_{SC} to produce 1000 W/m^2 of irradiance. Covering the PV module to reduce light-induced current and simulating light-induced current with an external CCS are the steps. This enables tests to be conducted indoors, and the irradiance level can be adjusted and maintained throughout. This temperature may not be realistic for PV modules as they generally operate above 25°C except in cold weather.

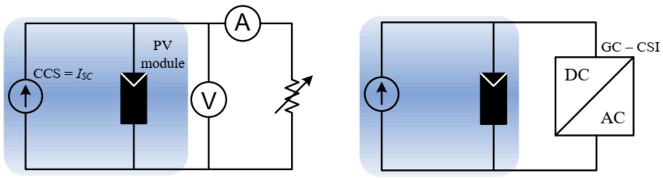


Fig. 4 (a) Test setup for dark I-V,

(b) Block diagram for GC-CSI using dark I-V

Fig. 5 presents a comparative analysis between the measurements obtained through the dark I-V method and the calculations derived from the non-linear model. A PV array is obtained for the current source inverter application by connecting two PV modules in series. Since the PV module temperature was not measured, the non-linear model was used to simulate two different temperatures (15°C and 25°C). Whilst neither curve is an exact match to the dark I-V test results, it can be observed that the curve at 25°C exhibits a closer correlation near the maximum power point.

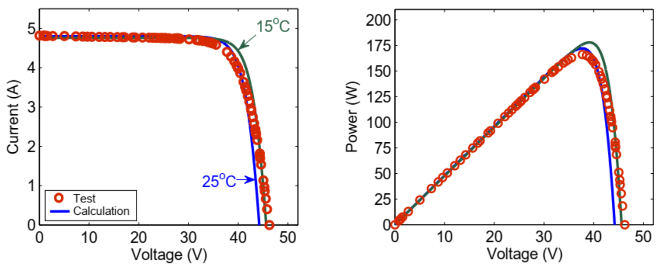


Fig. 5 The nonlinear model shows (a) I-V and (b) P-V curves for temperatures of 15°C and 25°C, as well as dark I-V results at an irradiance of 1000 W/m^2

IV. CONCLUSIONS

This paper described three different PV cell models that can be used to investigate grid-connected inverter simulations in future research. Models of nonlinear, 4-diode, and rectangular PV cells were described.

A four-diode model has been shown to provide a highly accurate model while allowing for rapid calculations in computer simulations. In addition, normalizations were introduced for these models. The input voltage of a PV inverter can be calculated using normalisations based on nominal conditions. Individually normalized nonlinear model normalisations will be applicable for the power loss analysis of PV modules.

Outdoor measurements and manufacturer data were used to validate the nonlinear model provided in this study. The nonlinear model was also used to explain and confirm the dark I-V test configuration. For testing grid-connected inverter prototypes, the dark I-V method can be used to provide simple access and a flexible test arrangement.

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