

Validation of Advanced PV Performance Model for Silfab Solar Panels

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October 2021

Abstract

This report presents a practical photovoltaic (PV) model that can be used to characterize the performance of real solar panels operating under different operating conditions with good accuracy. The model is an adaptation of the five-parameter model proposed by the National Renewable Energy Laboratories (NREL). We use the developed model to characterize actual Silfab solar panels operating under different conditions.

We present the five-parameter NREL performance model and solve for the unknown model variables using MATLAB. The PV panel specific model parameters are obtained either experimentally or from the data sheets. Once the model is developed, we use MATLAB to simulate PV systems under a variety of operating conditions.

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1 Introduction

1.1 Purpose

Photovoltaic panels have been increasing in popularity and application in recent years. In the United States alone, solar power grew from 0.34 GW in 2008 to 97.2 GW in 2020 [1]. The need for discrete power supplies and a shift towards renewable energy growth has fueled this expansion. The wide-ranging application of PV systems means that not all systems always operate under ideal conditions. Variations in sunlight, temperature, soiling, and shading can significantly impact the performance of these systems.

1.2 Problem Statement

Photovoltaic panels (PV) are often operated under nonideal conditions. Natural weather fluctuations and vegetation growth can impede PV panel energy generation. Often, after prolonged exposure to the environment, PV panels become soiled or degraded. Soiling can be due to dust, dirt, and other organic materials. In addition, the panels can be shaded by surrounding infrastructure or the environment. Both soiling and shading of PV panels result in the reduced effectiveness of the PV system. This report discusses the effects of shading and soiling on photovoltaic panels solar power generation. Photovoltaic systems operate optimally within a specific range of conditions. Deviations from these conditions can significantly impact the performance of these PV systems.

1.3 Proposed Solution

We explore the effects of shading and soiling of PV panels and investigate how these varying conditions affect the operating conditions of the system. This process includes developing a practical model for a real PV system. The goal of this research is to develop a more in-depth

understanding of the effects of the shading and soiling on PV systems interfaced with a variety of inverter technologies.

Solar panel modeling is the process of developing a model that can simulate physical PV panel operation with mathematical equations. The user can manipulate different parameters in the model to simulate a variety of real-world conditions. Modeling allows the user to bypass the complexity of the real system to more effectively understand different factors that can change the behavior of the system in a short amount of time. An effective model is easy to simulate and provides accurate prediction of a real PV system operating under different conditions. These studies using models allow engineers to better understand how to design, install, and implement real solar PV systems.

2 PV Model

2.1 Model of Solar Cell

The solar cell can be modeled as a simple equivalent circuit with a diode that is connected in parallel to an ideal current source [2]. The amount of current generated by the source is proportional to the amount of solar radiation impinging on the cell. The equivalent circuit for the PV cell has two important parameters. The first parameter is the short circuit current (I_{sc}), which is the current that flows across the terminals when they are shorted. The second parameter is the open circuit voltage (V_{oc}), which is the voltage across the terminals when the circuit is open [3].

Figure 1 shows the basic lossless model of a PV cell.

The equivalent lossless circuit for the PV cell shown in Fig. 1 can be described by the current equation where I is the current, I_{sc} is the short circuit current, and I_d is the diode current [3].

$$I = I_{sc} - I_d \quad (1)$$

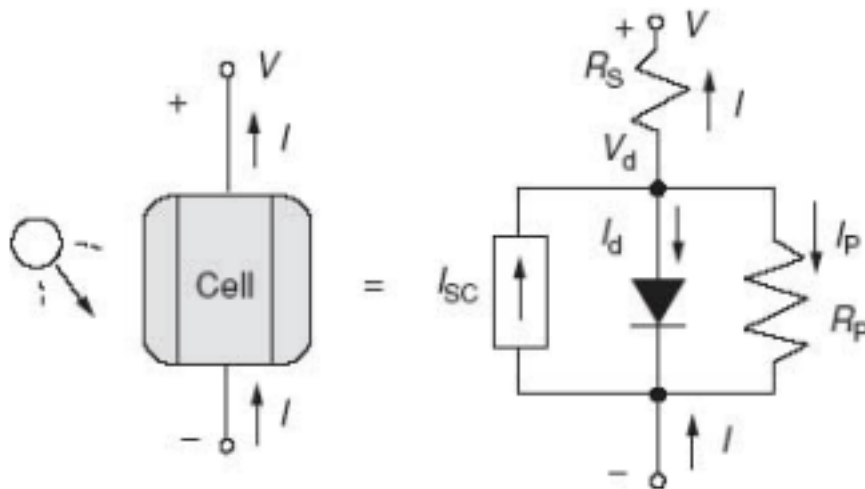


Figure 1: Lossy equivalent circuit for a PV Cell [3]

The equivalent circuit for a PV cell can be expanded to include parallel and series resistance.

These resistances account for parallel and for series losses that can result from resistances in the semiconductor. The model of a lossy equivalent circuit is shown in Fig. 2.

Mathematically, it can be shown that the terminal current of this circuit model can be described by

$$I = I_{sc} - I_0 \left(\exp\left(\frac{q}{kT}(V + IR_s) - 1\right) - \frac{V + IR_s}{R_p} \right) \quad (2)$$

where I_0 is the dark saturation current, q is the electronic charge, V is the voltage, k is the Boltzmann's constant, T is the cell temperature, R_s is the series resistance and R_p is the parallel resistance.

The IV curve plotted from Equation (2) shows a decrease in voltage as the current increases due to the series and parallel resistances. Figure 3 shows the IV curve plotted from Equation (2) with $R_p = 1\Omega$ and $R_s = 0.05\Omega$. For comparison, the IV curve for $R_p = \infty$ and $R_s = 0$ is also shown in the same figure.

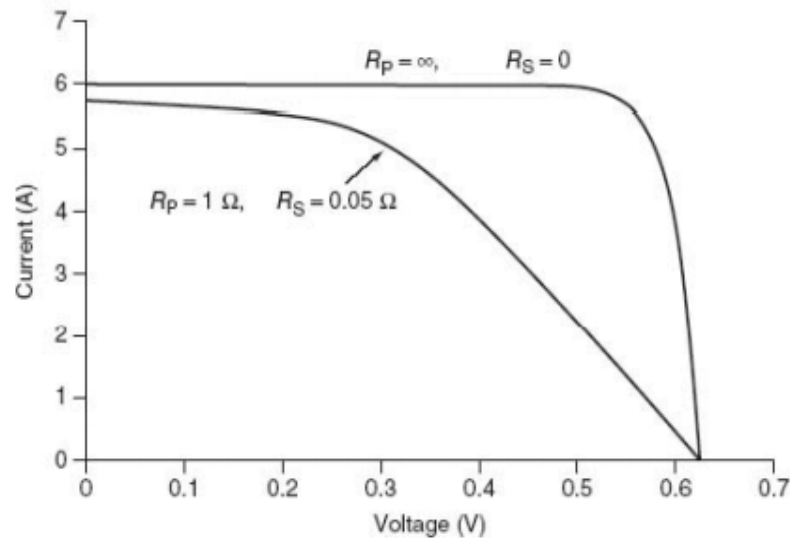


Figure 2: The IV curve of PV cell [3].

2.2 Model of Solar Panel

A solar module consists of many solar cells connected in series to increase the output voltage.

Typically, modules have either 36, 72, 96, or 128 cells connected in series.

The modules are then connected into an array in both parallel and series arrangements.

Connecting the modules in parallel increases the current capacity while connecting the modules

in series increases the voltage. Figure 4 shows the IV curve for a typical PV array. The location (V_{MP}, I_{MP}) on the IV curve is the point of maximum power output.

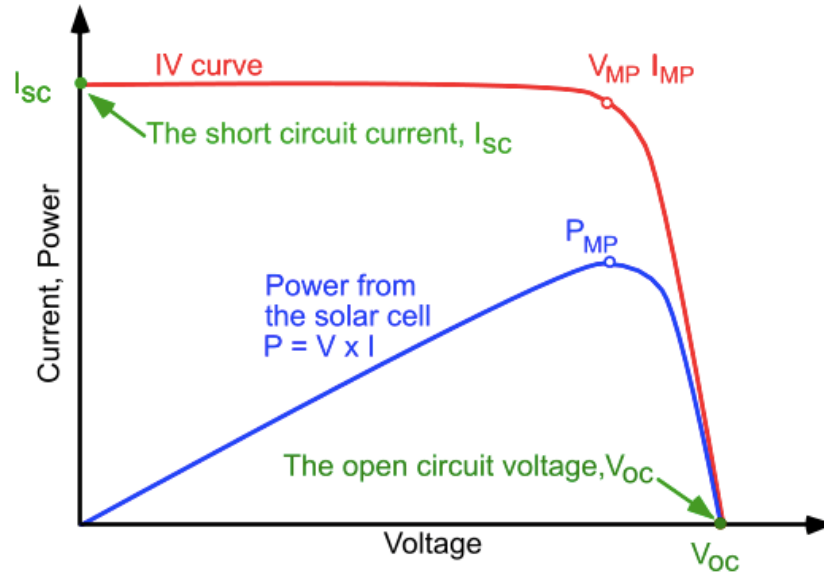


Figure 3: IV Curve for PV Array [4].

2.3 Advanced Five-Parameter Model of Solar Panel

The five-parameter model for solar panels was developed by National Renewable Energy Laboratory (NREL). This model includes additional parameters to characterize the IV curve of cells, modules, and arrays more accurately. It also includes many other improvements to the basic model of a PV panel. These modifications were built upon a previous model developed by Desoto et al [6].

Solving for the variables used in the five-parameter model requires manufacturer provided data for the open-circuit voltage (V_{OC}), the short-circuit current (I_{SC}), maximum power point current (I_{MP}), voltage (V_{MP}), the temperature coefficients of open-circuit voltage (β_T), and short-circuit

current (α_T) [5]. The five unknown parameters used in this model are listed in Table 1 and is solved using MATLAB.

Table 1: Unknown Parameters in the Five-Parameter Model

Photocurrent	$I_{irr,ref}$	Current that flows through the panel at Standard Reference Conditions
Diode Saturation Current	$I_{0,ref}$	Diode saturation current that flows in the opposite direction for cell temperature at Standard Reference Condition
Ideality Factor	N_{ref}	Measure of accuracy in matching ideal diode equation
Shunt Resistance	$R_{p,ref}$	Shunt resistance modelling losses
Series Resistance	$R_{s,ref}$	Series resistance modelling losses

The unknown parameters of this model can be solved through a system of nonlinear equations. The five equations contain the unknown variables. The operational data of a PV system is used to solve for the five unknown parameters in the model. The physical constants and the operation parameters are listed in Table 2.

Table 2: Constants in the Five-Parameter Model

Electronic charge	q	1.6×10^{-19}	Value of electronic charge
Boltzmann's constant	k	1.38×10^{-23}	Value of Boltzmann's constant
Short-circuit current	$I_{SC,ref}$	8.10	Current when output is a short
Open-circuit voltage	$V_{OC,ref}$	36.5	Voltage when output is open
Cell Temperature (degrees Celsius)	T_{ref}	25	Cell temperature
Cells in series	N_s	36	Number of cells in a series
Strings in parallel	N_p	6	Number of strings in parallel
Maximum power point voltage	$V_{MP,ref}$	29.1	Voltage at the maximum power
Maximum power point current	$I_{MP,ref}$	7.4	Current at the maximum power

2.4 Five-Parameter Equations

The first equation is a derived from the open-circuit equation at the Standard Reference Condition (SRC). The values of the constituent variables in Equation (2) are $I_A = 0$ and V_A is set equal to the open circuit voltage ($V_{OC,ref}$).

The second equation is derived from the short-circuit equation at the SRC. The values of the constituent variables in Equation (2) are $V_A = 0$ and $I_A = I_{SC,ref}$.

The third equation is derived from the current and voltage at the maximum power point at SRC.

The values $V_A = V_{MP,ref}$ and $I_A = I_{MP,ref}$ are substituted into Equation (2).

The fourth equation is an adaptation of Equation (2) where at the maximum point, the derivative of power is equal to zero. In order to solve it, we use the fact power $P = V_A I_A$ in the equation.

The fifth equation is also derived from the Equation (2) and includes the correction for the temperature of the open-circuit voltage (β_T). The following equations are the result of applying these procedures.

Equation (3) describes the open-circuit conditions at SRC where V_A is equal to the open circuit voltage ($V_{OC,ref}$) and $I_A = 0$. It is derived from the relationship between current and voltage in a PV array with the cells in series (N_S) and the strings in parallel (N_P).

$$0 = N_p I_{irr,ref} - N_p I_{0,ref} \left[\exp\left(\frac{q V_{OC,ref}}{N_S n_{ref} k T_{ref}}\right) - 1 \right] - \frac{V_{OC,ref}}{\frac{N_S}{N_P} R_{P,ref}} \quad (3)$$

Equation (4) describes the short-circuit conditions at SRC where $V_A = 0$ and $I_A = I_{SC,ref}$.

$$I_{SC,ref} = N_p I_{irr,ref} - N_p I_{0,ref} \left[\exp\left(\frac{q I_{SC,ref} R_{S,ref}}{N_P n_{ref} k T_{ref}}\right) - 1 \right] - \frac{I_{SC,ref} \frac{N_S}{N_P} R_{S,ref}}{\frac{N_S}{N_P} R_{P,ref}} \quad (4)$$

Equation (5) describes the IV relationship at the maximum power point at SRC, where V_A is equal to the maximum power point voltage ($V_{MP,ref}$) and I_A is equal to the maximum power point current ($I_{MP,ref}$).

$$I_{mp,ref} = N_p I_{irr,ref} - N_p I_{0,ref} \left[\exp\left(\frac{q(V_{mp,ref} + I_{mp,ref} \frac{N_s}{N_p} R_{s,ref})}{N_s n_{ref} k T_{ref}}\right) - 1 \right] - \frac{V_{mp,ref} + I_{mp,ref} \frac{N_s}{N_p} R_{s,ref}}{\frac{N_s}{N_p} R_{p,ref}} \quad (5)$$

Equation (6) is derived from where the derivative of the max power point (M_{pp}) is equal to zero.

The derivative of the max power point is zero because the max power point is a constant value.

$$\frac{I_{mp,ref}}{V_{mp,ref}} = \frac{\frac{q N_p I_{0,ref}}{N_s n_{ref} k T_{ref}} \left[\exp\left(\frac{q(V_{mp,ref} + I_{mp,ref} \frac{N_s}{N_p} R_{s,ref})}{N_s n_{ref} k T_{ref}}\right) + \frac{1}{\frac{N_s}{N_p} R_{p,ref}} \right]}{1 + \frac{q I_{0,ref} R_{s,ref}}{n_{ref} k T_{ref}} \exp\left(\frac{q(V_{mp,ref} + I_{mp,ref} \frac{N_s}{N_p} R_{s,ref})}{N_s n_{ref} k T_{ref}}\right) + \frac{R_{s,ref}}{R_{p,ref}}}$$

Equation (7) describes the temperature coefficient of the open-circuit voltage. The parameter V_{OC} is the open circuit at the cell temperature (T).

$$0 = N_p I_{irr} - N_p I_0 \left[\exp\left(\frac{q V_{OC}(T)}{N_s n k T}\right) - 1 \right] - \frac{V_{OC}(T)}{\frac{N_s}{N_p} R_p} = V_{OC,ref} + \beta_T (T - T_{ref}) \quad (7)$$

We used MATLAB as to develop the five-parameter model for Silfab solar panels. We entered the five equations listed above into a MATLAB and then used it to solve for the five unknown parameters. We also used the software to plot the resulting IV curve.

The equations for the five-parameter model allows user to input operational data provided by photovoltaic manufacturers and use those specifications to develop a working model to test a variety of shading and soiling conditions. Modeling in this process allows the user to test a variety of operational data in a controlled and efficient setting without the need for direct access to the photovoltaic panels and inverter technologies.

3 Simulation Results and Testing

3.1 Mathematical Solution

The five unknown values were solved using MATLAB software. The five equations (3) – (7) were entered into MATLAB as a system of equations and solved using *fsolve*. Manufacturer data from Table 2 was used for all other values in the equations. The software solved the system of equations and the solution is presented in Table 3.

Table 3: Output Values in the Five-Parameter Model

Ideality Factor	n_{ref}	0.56	Measure of accuracy in matching ideal diode equation
Photocurrent	$I_{irr,ref}$	4.88	Current that flows through the panel at Standard reference conditions
Diode Saturation Current	$I_{0,ref}$	0.00	Diode saturation current that flows in the opposite direction for cell temperature at Standard Reference Condition
Shunt Resistance	$R_{p,ref}$	51.50	Measure of accuracy in matching ideal diode equation
Series Resistance	$R_{s,ref}$	0.50	Resistance of low resistance resistors in parallel; also known as parallel leakage resistance

3.2 MATLAB Simulation

The model of the PV system took approximately three months to develop and refine before it produced accurate data outputs for the system of equations. Each successive iteration of the MATLAB program was tested for accuracy and then additional modifications were made to improve the function of the program. We used version MATLAB 2020 and it was run on a 2017 MacBook Air using a 1.8 GHz Dual-Core Intel Core i5 processor. The computation times for solving the unknown parameters took on average 5 seconds.

4 Conclusion

4.1 Summary

Solar power has a massive potential for growth as costs decrease and through diversity of application. Photovoltaic systems have the potential to shape the way our energy systems evolve and technology progresses. Understanding the impacts of environmental conditions on PV panels will help overcome many of the traditional issues faced by the implementation of systems.

Accurate modeling of PV panels has allowed for understanding many PV design issues without actually building the PV panel. Effective modeling can streamline the engineering development process and allow for greater advancements in understanding.

Through this project, we have worked towards developing a functional five-parameter model based on the work from NREL. These equations were integrated into a model to solve for five unknown parameters.

4.2 Future Work

Moving forward with this project, we plan to test the model against the actual performance of Silfab PV panels. This will be done once the school opens again without COVID restrictions. We will use SILFAB 245 HE photovoltaic panels provided by Silfab Solar [7] to model shading and soiling conditions. Data gathered from this process will be used to plot the IV curve of photovoltaic panels and expand the understanding of varying conditions on the design of photovoltaic panels and inverter technologies.

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