Solar Cell Simulation Model for Photovoltaic Power Generation System

Jialin Liu*‡, Raymond Hou*

*Department of Electrical and Computer Engineering, Faculty of Applied Science, University of British Columbia

(jialin.liu@alumni.ubc.ca)

‡ Corresponding Author; Jialin Liu, 2332 Main Mall, University of British Columbia, Vancouver, BC, Canada, «corrtel», jialin.liu@alumni.ubc.ca

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Abstract- The development of the solar cell simulation model is very popular today due to the extensive research in the solar panel maximum power point tracking (MPPT) which requires a robust model that could be integrated with converters and inverters and could work under various load conditions. For that purpose, the accuracy and compatibility of the model with other power electronics are major concerns for the development. In this paper, a comprehensive but straightforward solar cell model is introduced. This model minimizes mathematical approximation during the output current and voltage derivation process and is specially designed for integrating with converters and inverters. Simulation results are given for validating the proposed model.

Keywords- Solar cell model, photovoltaic, simulation, software.

1. Introduction

Nowadays there is a growing concern regarding the effects of fossil fuels in the environment, solar cell panels have become more and more popular since solar energy is renewable and widely available. As a result, solar cell energy generation has great potential in the renewable energy area. Various experiments are carried out to study the effects of changing operating parameters in terms of the solar cell performance. Therefore, a solid solar cell model needs to be developed to facilitate such experiments. A Matlab Simulink solar cell model that behaves accurately under a variety of situations is developed and discussed in this paper.

By careful evaluation of previous models [2]-[8] in the area, a number of fundamental problems were identified.

The model has no feedback current or voltage. It is well known [1] that the output voltage and current are interdependent. However many existing models use independent current or voltage as the solar cell's input to produce the other parameter[2][5][7][8]. That does not guarantee that the model could work well if other things are connected at the output since feedback has to be used in that case.

The model outputs a current instead of a voltage [2]-[8]. It is known [1] that for converters and inverters a controlled voltage source is normally used. Therefore, the model does not well fit the converters and inverters connected to it.

The model uses constant values for some parameters such as the reverse saturation voltage (Vrs) and the thermal voltage (Vth) to approximate the results [2]-[8]. In addition, some parameters are eliminated for easy calculation. Such approximations reduce the accuracy of the model.

This paper presents a model that does not use any approximations except for user defined parameters such as the ideality factor. The model has excellent performance in terms of accuracy. Accuracy is very important nowadays in this area since current MPPT algorithms are trying to make improvements in power extraction by a few percentages which places high demand on the accuracy of the solar cell model. In addition, the model uses the output current as a feedback input instead of an independent input to generate an output voltage. In this way, it is shown that the model could work with inverters or converters connected to its output since independent current input might cause conflicts with the output which should be the same as the input. Moreover, the generation of an output voltage makes it suitable to be used with converters connected to it. Besides, this model could be built with any general purpose simulation software.

The solar cell equivalent circuit and relevant equations are discussed in section 2. In section 3, the solar cell model implemented in Matlab Simulink is described. In section 4 the simulation results are presented, a reference solar cell model and its PV and IV curves are shown first, then the effects of changing solar cell operating parameters including changing the temperature, irradiance, series and parallel resistance and series and parallel cell connections are presented in figures comparing to the reference. Section 5 finally presents the conclusion.

2. Solar Cell Model Equivalent Circuit

The equivalent circuit of the solar cell is shown below in Fig.1.

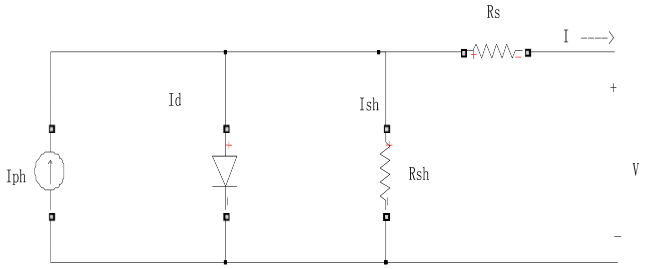

Fig. 1. Solar cell model equivalent circuit.

In this equivalent circuit, a current source (Iph), a diode, a series resistor (Rs) and a parallel resistor (Rsh) are included. The relevant equations are given below.

*Ish=(V+I*Rs)/Rsh* (1)

Iph=[Isc+KI(T-Tref)]*Ir/Irref* (2)

*Irs=Isc/(exp(q*Voc/(A*k*Tref))-1)* (3)

Is=Irs(T/Tref)^3*exp((q*Eg/A*k)*(1/Tref-1/T))* (4)

Id=Is(exp((V+I*Rs)/(A*Vt*Ns))-1)* (5)

*I=Iph*Np-Id*Np-Ish*Np* (6)

*V=A*Vt*Ns*ln[(Iph*Np-I-Ish*Np)/Is*Np+1]-I*Rs* (7)

Where:
Ish is the shunt current.
Iph is the photocurrent.
Irs is the reverse saturation current at the Tref
Is is the reverse saturation current.
Id is the diode current.
I is the load current.
V is the load voltage.
Tref is the reference temperature.
q is one electron charge.
Irref is reference irradiance.
KI is the short circuit current temperature coefficient.
Eg is the bandgap energy.
Isc is the short circuit current.
Voc is the open circuit voltage.
Ir is the actual irradiance.
A is the ideality factor.
Np is the number of cells connected in parallel.
Ns is the number of cells connected in series.
T is the actual temperature.

3. Solar Cell Model Implementation

Based on the circuit and equations above, a solar cell model is built in Matlab Simulink. The top level Simulink model is shown in Fig.2 below.

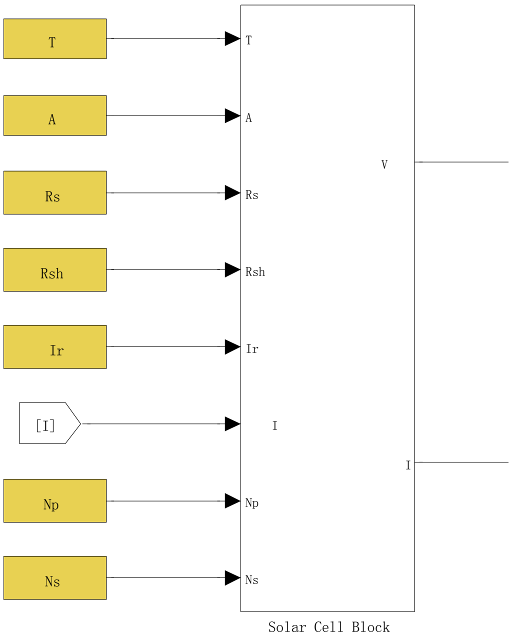

Fig. 2. Solar cell Matlab model top level.

As can be seen from this figure, T, A, Rs, Rsh, Ir, Np and Ns need to be defined as inputs for the model. In addition, output current is swept and fed back to the model which in turn outputs a voltage. The V-I graph and P-I graph could be generated during the simulation.

The details inside the solar cell block are given in the Appendix.

In this solar cell block, the needed constants are defined. Moreover, the relevant equations are separately expressed with Simulink math operation blocks with the equations written on the top of each one.

The values of the constants used in the simulation are listed in Table 1 below.

Table 1. Constant values used in the simulation

Constant Name	Constant Value
Tref	298.15 K
q	1.6e-19 C
k	1.38e-23 J/K
Irref	1 W/m^2 per unit
KI	0.0017 A/K
Eg	1.115 eV
Isc	3.8 A
Voc	0.6 V
A	1.5

4. Simulation Results

In reality, many factors could affect the performance of solar cells. Those parameters are not constant but changing all the time. Solar cells are usually studied under changing conditions including changing temperatures, series and parallel resistances and irradiances. In this section, a reference PV curve and a reference IV curve are presented. Then scenarios of different changing parameters are analyzed. Finally, the effects of connecting solar cells in series and parallel are also presented.

4.1. Reference PV and IV Curves

For all the simulations presented in this paper, a set of reference input parameters are used to generate a reference PV curve and a reference IV curve. The reference PV curve and IV curve are used to be compared with cases in which one of the parameters is different. The reference input parameters are listed in Table 2 below.

Table 2. Reference parameter values.

Reference Input Parameters	Values
T	25 C
Ir	1 W/m^2 per unit
Rs	0.001 Ω
Rsh	10000 Ω
Ns	1
Np	1

The corresponding reference IV and PV curves are presented below in Fig.5. The reference IV and PV curves are always represented in red in all the figures below.

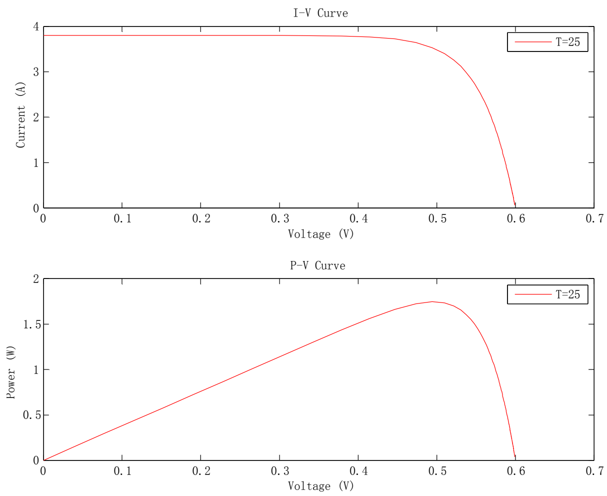

Fig. 3. Reference PV and IV curves.

4.2. Effects of Changing Temperature

In the following IV and PV curves in Fig.6, the reference PV and IV curves are compared with the PV and IV curves with a temperature of 75 °C.

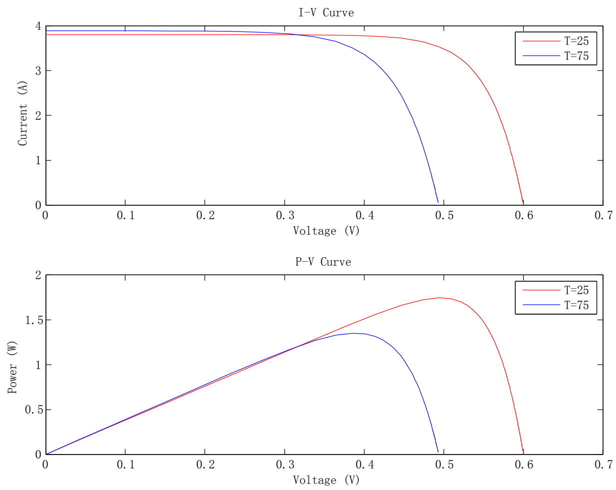

Fig. 4. Effects of changing the temperature.

From the comparison, it is seen that an increase in temperature leads to an increase in the open circuit voltage and a slight decrease in the short circuit current. Such changes could also be validated mathematically from equation (6) and (7) after substituting equation (2) and (4) in them.

4.3. Effects of Temperature Change

In the following IV and PV curves in Fig.7, the reference PV and IV curves are compared with the PV and IV curves with an irradiance of 1.5 W/m^2 per unit.

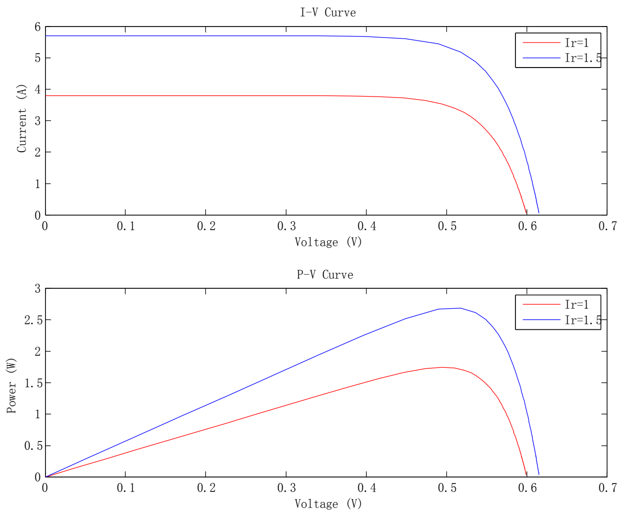

Fig. 5. Effects of changing the irradiance.

From the comparison, it is seen that an increase in the irradiance leads to a small increase in the open circuit voltage and a large increase in the short circuit current. Such changes could also be validated mathematically from equation (2) and (7).

4.4. Effects of Series Resistance Change

In the following IV and PV curves in Fig.8, the reference PV and IV curves are compared with the PV and IV curves with a series resistance of 0.01Ω.

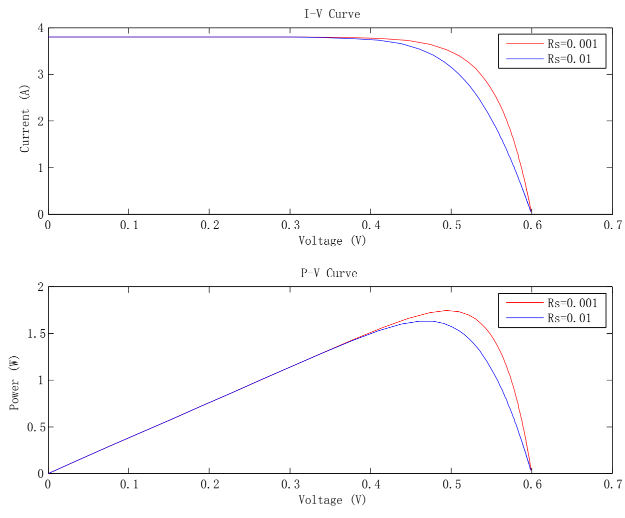

Fig. 6. Effects of changing the series resistance.

From the comparison, it is seen that an increase in the series resistance causes an inward bending at the corners of both the IV and PV curves with no change in Isc or Voc. Such changes could also be validated mathematically from equation (6) and (7).

4.5. Effects of Changing the Parallel Resistance

In the following IV and PV curves in Fig.9, the reference PV and IV curves are compared with the PV and IV curves with a parallel resistance of 1 Ω.

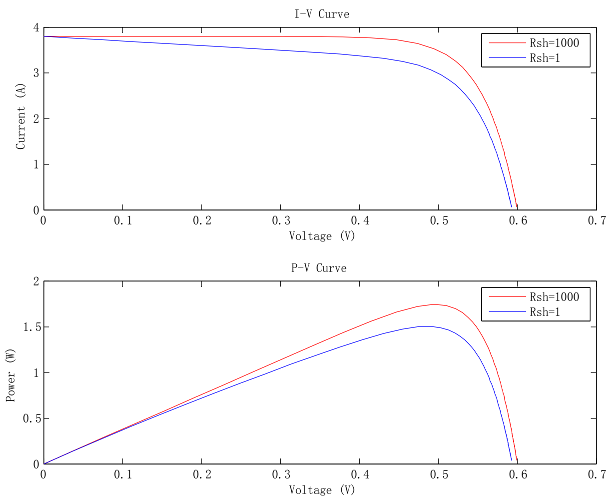

Fig. 9. Effects of changing the parallel resistance.

From the comparison, it is seen that a decrease in the parallel resistance causes an inward bending throughout both the IV and PV curves with no change in Isc and a small decrease in Voc. Such changes could also be validated mathematically from equation (6) and (7).

4.6. Effects of Adding Cells in Series

In the following IV and PV curves in Fig.10, the reference PV and IV curves are compared with the PV and IV curves of two identical reference solar cells connected in series.

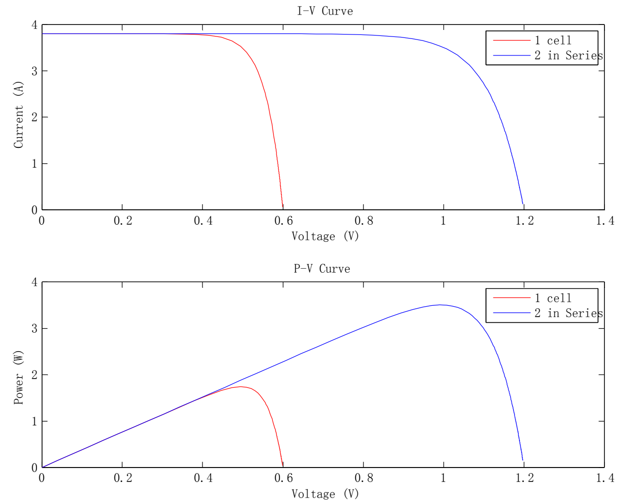

Fig. 7. Effects of having two cells in series.

From the comparison, it is seen that a when two cells are connected in series, Voc doubles which obeys the voltage addition rule of series connections. Such changes could also be validated mathematically from equation (7).

Effects of Adding Cells in Parallel

In the following IV and PV curves in Fig.11, the reference PV and IV curves are compared with the PV and IV curves of two identical reference solar cells connected in parallel.

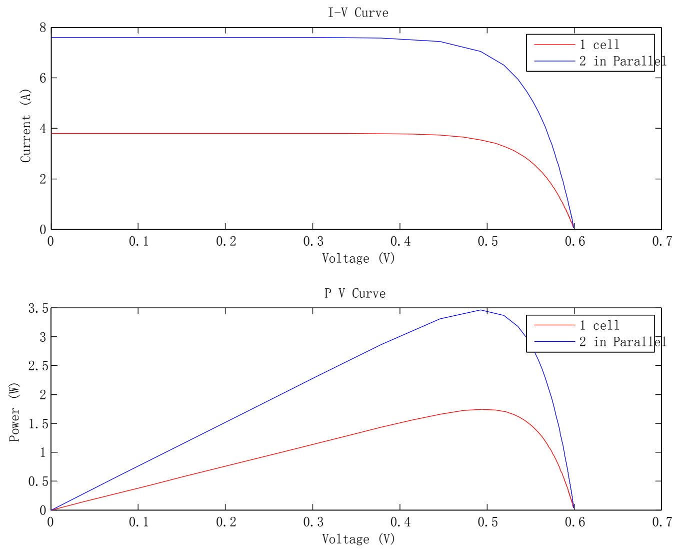

Fig. 8. Effects of having two cells in parallel.

From the comparison, it is seen that a when two cells are connected in parallel, Isc doubles which obeys the current addition rule of parallel connection. Such changes could also be validated mathematically from equations (7).

5. Conclusion

This paper presents a new solar cell model using Matlab Simulink mathematical operation blocks. This model shows the effects of changing different solar cell parameters in terms of the IV and PV curve of a solar cell. The model has excellent accuracy in generating the IV and PV curves. In addition, its voltage output and current feedback feature makes it very suitable for integrating with inverters and converters. Moreover this model could be built with any general purpose simulation software. The model could be used for hardware-in-the-loop simulation.

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