Trivent Publishing
© The Authors, 2016
Available online at http://trivent-publishing.eu/

Engineering and Industry Series
Volume *Power Systems, Energy Markets and Renewable Energy Sources in South-Eastern Europe*

Electrical Modelling Of a Photovoltaic Module

P. Acharya,[1] M. N. Shaikh ,[2] S. K. Jha,[1] A. P. Papadakis[2]

[1] Department of Electrical and Electronics Engineering, Kathmandu University, Dhulikhel, Nepal, parash.acharya@ku.edu.np, shailendra@ku.edu.np
[2]Department of Electrical Engineering, School of Engineering & Applied Sciences, Frederick University, Cyprus, mnaveed.shaikh1@gmail.com, eng.ap@frederick.ac.cy

Abstract

This paper presents a generalized photovoltaic (PV) model using non-linear equations of current and voltage for the array. The current-voltage (I-V) and power-voltage (P-V) characteristics of the array are determined considering the effect of sunlight irradiance and cell temperature. Within the model, different electrical parameters such as maximum power (Pmp), current at maximum power (Imp), voltage at maximum power (Vmp), open-circuit voltage (Voc) and short-circuit current (Isc) are obtained in terms of solar irradiance and environment temperature changes. These electrical parameters are obtained through an equivalent circuit model which consists of a photocurrent source, a diode, a series resistor and a shunt resistor. The performance of the solar cell is evaluated under the standard test conditions with an average solar spectrum of air mass (AM) coefficient of 1.5, normalized irradiance of 1 kW/m2 and cell temperature of 25oC. A comparative study of the simulation results with the manufacturer's data is performed in order to validate the proposed equivalent electrical model. Furthermore, an experimental test bench is built and the *obtained experimental results are compared with simulation results and are found to be in good agreement.*

Keywords

Maximum power; Photocurrent; Series resistor; Shunt resistor; Standard test conditions

I. Introduction

Renewable energy is regarded as the prominent source to meet future global energy demands due to the declining nature of some other forms of non-renewable conventional sources such as oil, gas, nuclear and coal. Among different renewable energy sources, photovoltaic (PV) is mostly accepted because of its ubiquitous, abundant and sustainable nature. Presently, PV is widely used in electric power applications as it can generate direct current electricity when exposed to the solar radiation without any adverse environmental impacts.

A PV module represents a fundamental power conversion unit of a solar generator system, whose output characteristics depend on the solar insolation and temperature. The PV module has nonlinear electrical characteristics which need to be modelled in order to design and simulate maximum power point tracking (MPPT) controllers. The performance of a solar cell is evaluated under standard test conditions (STC), where an average solar spectrum at air mass (AM) 1.5 is used, the irradiance is normalized at 1 kW/m2 and the cell temperature is defined at 25oC [1].

Please make sure that you use as much as possible normal fonts. Special fonts, such as those used in the Far East (Japanese, Chinese, Korean, etc.) may cause problems during processing. To avoid unnecessary errors you are strongly advised to use the ‘spellchecker’ function of MS Word.

II. Model of a solar cell and PV module

The photovoltaic effect of a semiconductor PN-junction can be used to describe the working principle of a PV array [2]. An equivalent circuit of a PV module can be represented as shown in Fig. 1. In Fig. 1, I_{pc} represents the photocurrent of the PV module under certain solar irradiance and temperature, I_D is the diode current which is given by the classical diode current expression, R_s is the intrinsic resistance (or series resistance) to the current flow and R_{sh} is the parallel (or shunt) resistance. Practically, R_{sh} is very large and hence the current through this resistance can be neglected. The final expression for the load current considering I_{sh} is as shown in equation (1) [2].

$$I = I_{pc} - I_D - I_{sh} = I_{pc} - I_o[\exp(\frac{V+IR_s}{A_{PV} V_T}) - 1] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

In equation (1), I is the output terminal current, Io is the diode saturation current, V is the terminal voltage of the module, APV is the ideality factor which depends on the PV technology, V is the terminal voltage of the module, VT is the thermal voltage of a module whose value is kTc/q, k being the Boltzmann's constant, Tc is the solar cell temperature in Kelvin. Finally, equation (1) can be written as,

$$I = I_{pc} - I_o[\exp(\frac{q(V+IR_s)}{A_{PV} kT_c}) - 1] - \frac{V+IR_s}{R_{sh}} \quad (2)$$

The photocurrent mainly depends upon the solar insolation (or irradiation) which can be expressed as in equation (3) [3].

$$I_{pc} = [I_{sc} + K_i(T_c - T_{ref})] \quad (3)$$

In equation (2), Isc is the short-circuit current at 25oC and 1 kW/m2, Ki is the solar cells short-circuit temperature coefficient, Tref is the cell's temperature and μ is the solar insolation in kW/m2. The diode saturation current varies with the cell temperature as shown in equation (4) below [3].

$$I_o = I_{R_S}(\frac{T_C}{T_{ref}})^3 \exp[\frac{qE_G\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)}{kA_{PV}}] \quad (4)$$

In equation (3), I_{RS} is the cell's reverse saturation current at a reference temperature and a solar radiation and EG is the band-gap energy of the semiconductor used in the cell.

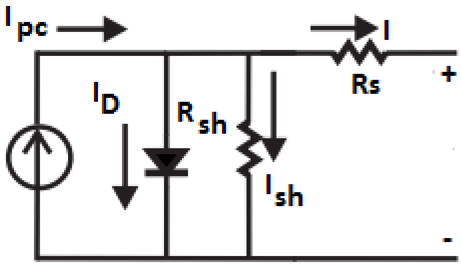


Fig. 1. PV module equivalent circuit

The shunt resistance (Rsh) is inversely proportional with the shunt leakage current to ground. Generally, the PV efficiency is insensitive to the variation in Rsh, hence the shunt-leakage resistance can be assumed to be infinite without any shunt leakage current going to ground. On the other hand, a small variation in Rs will significantly affect the PV output power. Thus, an appropriate simplified model of the solar cell can be developed as shown in Fig. 2. Using an appropriate simplified model of Fig. 2, equation (2) can be written in the form of equation (5) [2].

$$I = I_{pc} - I_o\left[\exp\left(\frac{q(V+IR_s)}{AkT_c}\right) - 1\right] \quad (5)$$

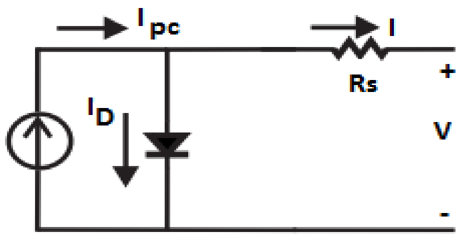


Fig. 2. PV generalized module without shunt resistance

For an ideal PV module, there are no series losses and leakage losses to ground i.e. Rs = 0 and Rsh = ∞. Hence equation (5) can be written as in equation (6) and can be represented as in Fig. 3.

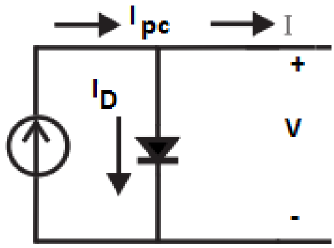


Fig. 3. PV appropriate module without shunt resistance and series resistance

$$I = I_{pc} - I_o\left[\exp\left(\frac{qV}{AkT_c}\right) - 1\right] \quad (6)$$

Individual PV cells are connected in combination of series-parallel configuration in order to produce the required electrical output power. An equivalent electrical circuit for a solar array module arranged in Np parallel and Ns series PV cells is as shown in Fig. 4. The terminal equation in terms of series and parallel arrays is expressed as in equation (7) below.

$$I = N_p I_{pc} - N_p I_o\left[\exp\left(\frac{q\left(\frac{V}{N_s}+\frac{IR_s}{N_p}\right)}{kA_{PV}T_c}\right) - 1\right] - \frac{\frac{N_pV}{N_s}+IR_s}{R_{sh}} \quad (7)$$

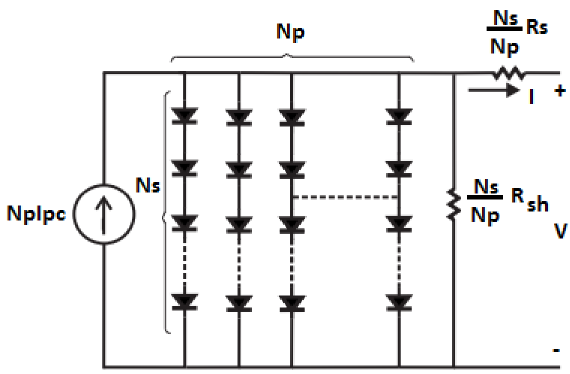


Fig. 4. General equivalent circuit model of PV module

The final equivalent circuit model of the generalized PV module without considering series and shunt resistances is as shown in Fig. 5. Considering Fig. 5, equation (7) is modified and expressed as in equation (8) [3].

$$I = N_p I_{pc} - N_p I_o [\exp(\frac{qV}{N_s k A_{PV} T_c}) - 1] \quad (8)$$

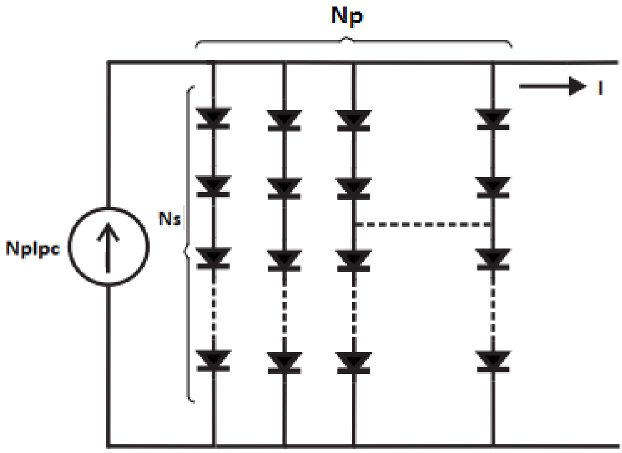


Fig. 5. Appropriate equivalent circuit model of a generalized PV without shunt and series resistances

Generally, the model parameters are determined from the manufacturer's datasheet, two of the most important parameters being the short-circuit current (Isc) and the open-circuit voltage (Voc). Since Ipc >> Io and ignoring the ground and diode leakage currents, Isc is approximately equal to Ipc. Similarly, Voc is obtained assuming the output current equal to zero. Considering Voc at the reference temperature and ignoring shunt-leakage current, reverse saturation current (IRS) at the reference temperature can be approximated as given by equation (9).

$$I_{R_s} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{N_s k A_{pv} T_c}\right) - 1} \quad (9)$$

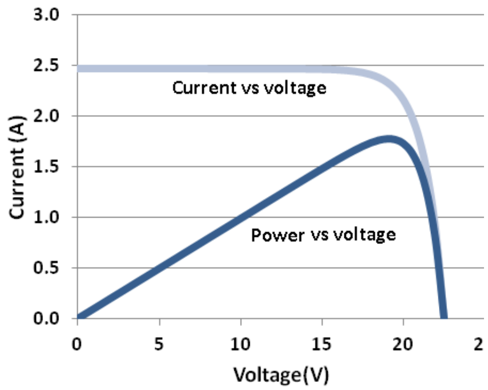
III. Modelling and test results of a PV module

A PV module is developed using equation (1) through to equation (9). The inputs for the model are cell voltages, solar irradiance and cell temperatures. The model could be modified for any number of series and parallel cells, open-circuit voltage and short-circuit current, reference temperature and short-circuit temperature coefficient. Different parameters used for the modelling of the PV arrays are shown in Table 1, which are taken from Dokio solar DSP 40P-10 module datasheet as provided by the manufacturer.

Table 1. Different solar parameters for the model development

Parameters	***Values***
Short-circuit current (I_{sc})	2.47 A
Open-circuit voltage (V_{oc})	22.50 V
Number of parallel cells (N_p)	1
Number of series cells (N_s)	36
Reference temperature (T_{ref})	298 K
Boltzmann's constant (k)	$1.38X10^{-23}m^2\ kg\ s^{-2}K^{-1}$
Ideality factor (A_{pv})	1.3
Electron charge (q)	$1.6X10^{-19}C$
Short-circuit temperature coefficient (K_i)	0.003

The current-voltage (I-V) and power-voltage (P-V) characteristics of the PV array are plotted for a solar irradiance of 1 kW/m2, temperature of 25oC and AM 1.5. The modelling result is compared with the test results of the panel. The test is performed using Quick Sun Solar simulator, version 7.3.14. The modelling and test results are as shown in Fig. 6. Fig. 6 shows the comparison between the modelling and test results of P-V and I-V characteristics of the PV module. The comparison between the modelling, manufacturer and test data are illustrated in Table 2.



(a) (b)

Fig. 6. Comparison of (a) modelling and (b) experimental test results

Table 2. Comparison of three different data at an irradiance of 1 kW/m2 and a temperature of 25 °C

Parameters	**Parameters' values**		
	Manufacturer's data	***Modeling results***	***Experimental results***
Short-circuit current (I_{sc})	2.47 A	2.47 A	2.683 A
Open-circuit voltage (V_{oc})	22.50 V	22.50 V	22.46 V
Maximum power current (I_{mp})	2.22 A	2.38 A	2.502 A
Maximum power Voltage (V_{mp})	18 V	19 V	18.62 V
Maximum power (P_{max})	40 W	41.38 W	39.4 W

IV. Conclusions

A solar PV model has been developed using equivalent electrical circuit of the cell. The modelling results are compared with that of the manufacturer data and practical test results. The comparison between the results shows that the modelling data matches with that of the manufacturer data and test results. The results are obtained at STC conditions. I_{sc} was found in 100% agreement with modelled data while 93% with experimental data. V_{oc} was found in 100% agreement with modelled data and 99% with experimental data. I_{mpp} was found in 93% agreement with modelled data and 88% with experiment data. V_{mpp} was found 94.5% agreement with modelled data and 99% with experimental data. P_{mpp} was found 96.6% agreement with modelled data and 98.5% with experimental data.

References

[1] Chenni, R. Makhlouf, M. Kerbache, T. Bourid, A. “Adetailed modelling method for photovoltaic cells.” *Science Direct Energy* 32 (2007): 1724-1730.

[2] Go, S. I. Ahn, S. Choi, J. Jung, W. Yun-Yun, S. Song, I. K. “Simulation and analysis of existing MPPT control methods in a PV generation system.” *Journal of International Council on Electrical Engineering* 1 (2011): 446-451.

[3] Tsai, H.L. Tu, C.S. Su, Y.J. “Development of generalized photovoltaic model using Matlab/Simulink.” *Proceedings of the World Congress on Engineering and Computer Science, WCECS,* San Francisco, USA, (October 22-24, 2008).