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Procedia Technology 17 (2014) 295 – 302

Procedia Technology

Conference on Electronics, Telecommunications and Computers – CETC 2013

Effect of Shading on Series Solar Modules: Simulation and Experimental Results

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Abstract

This paper is on the five-parameter modeling for photovoltaic systems. Normally, the technical information for photovoltaic panels is too restricted to identify the five parameters. So, an undemanding heuristic method is adopted in this paper, requiring only information on open circuit, maximum power point and short circuit conditions. The I-V and the P-V curves for a series connected monocrystalline photovoltaic system is obtained from the parameters identification using the heuristic method and validated by comparison with experimental curves. Also, a simulation for partial shading on the photovoltaic system is presented to illustrate a feasible assessment during the design of a PV system for loss of energy conversion due to shading.

Peer-review under responsibility of ISEL – Instituto Superior de Engenharia de Lisboa, Lisbon, PORTUGAL.

Keywords: PV system; effect of shading; algorithm for parameter estimation; simulation; experimental results

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1. Introduction

The demand for energy, the shortage of fossil fuels and the need for carbon footprint reduction have resulted in a global awareness of the importance of energy savings and energy efficiency [1] and programs on the Demand-side Management have been developed in order to assist consumers on energy usage. Also, renewable energy sources coming from wind and solar energy sources are attractive to go into exploitation, considering not only large scale systems, but also micro and mini scale conversion systems, i.e., Disperse Generation (DG) owned by consumer.

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Peer-review under responsibility of ISEL – Instituto Superior de Engenharia de Lisboa, Lisbon, PORTUGAL.
doi:10.1016/j.protcy.2014.10.240

Among the DG the solar generator usually known by the name of photovoltaic (PV) system is in nowadays in a number of power systems and envisaged as a financially viable promising industrial energy conversion. A PV system directly converts solar energy into electric energy. The main device for the energy conversion of a PV system is a solar cell. Cells are grouped to form modules, modules to form panels and panels to form arrays. A PV system may be either an array with one panel or a set of panels connected in series or parallel to form large a PV system without or with a tracking sun system. Although costly, the tracking system allows a more propitious instantaneous orientation for the panels in order to achieve higher values of energy capturing during sunny days due to the diverse perpendicular positions to collect the sun´s irradiation.

The performance of the PV system depends on the operating conditions especially on solar irradiation, temperature, configuration and shading. The shading on PV panel, for instances, due to a passing cloud or neighboring buildings causes not only energy loss in the conversion, but also further non-linearity on the I-V characteristics [2]. A shaded panel of a non-uniform illuminated PV system can be submitted to a negative voltage. If there is no protection, cell breakdowns can happen during non-uniform illumination. Hence, normally in order to protect the cells an extra pn-junction is implemented as a bypass diode. For instance, one bypass diode connected in parallel with each set of 18 cells [3] or with a panel is common practice as a compromise between protection and increase on the cost due to the extra pn-junction.

Also shading pattern with hasty change is not easy for the tracking of the maximum power point (MPP), because with non-uniform illumination usually there will be multiple local MPPs and they will change as fast as does the illumination. Under shadowing conditions a PV array layout can have large energy losses and even small shadows can noticeably affect the energy yield [4]. In order to better understand these issues, for example from partial shading, and improve MPP tracking, models that resolve this problem at the level of individual cells are required.

Nomenclature

D_2	bypass diode
G	solar irradiance
I_0	diode reverse bias saturation current
I_D	current at diode D_1
I_{MP}	maximum power point current
I_p	leakage current
I_s	photo generated electric current
I_{sc}	short-circuit current
k	Boltzman constant
m	ideality factor
q	electron charge
R_p	equivalent shunt resistance
R_s	equivalent series resistance
T	cell p-n junction temperature in [K]
V_{MP}	maximum power point voltage
V_{oc}	open-circuit voltage
V_T	thermal voltage of the solar cell
α_{sc}	current temperature coefficient
β_{oc}	voltage temperature coefficient

2. Modelling

There are very elaborate models done for a solar cell [5], but in this paper in order to study the effect of shading on PV systems, the equivalent circuit with five parameters was the followed option. This equivalent circuit consists on a current controlled generator, a single-diode, a shunt and series resistances. This option is chosen not only because of the simplicity of the modeling, but also in consideration to the state of the art on the formalist used for the identification of the parameters. The five parameters equivalent circuit and the bypass diode protection are shown in Fig. 1.

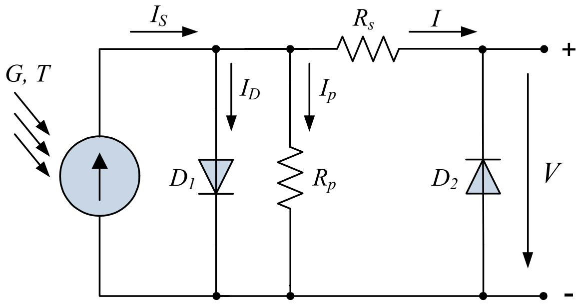

Fig. 1. Equivalent circuit.

The I-V characteristic associated with the equivalent circuit five parameters modelling shown in Fig. 1 is an implicit function given by:

$$I = I_s - I_0(e^{\frac{V+IR_s}{mV_T}} - 1) - \frac{V + IR_s}{R_p} \tag{1}$$

where V_T is the pn-junction thermal voltage given by:

$$V_T = \frac{kT}{q} \tag{2}$$

Equation (1) has to be solved using a numeric iterative method, for instance the Newton-Raphson method. From (1), considering short-circuit conditions, I_s is given by:

$$I_s = \frac{I_{sc}\left(R_s + R_p\right)}{R_p} + I_0(e^{\frac{I_{sc}R_s}{mV_T}} - 1) \tag{3}$$

The second term of (3) is usually small in comparison with the first term [6,7], because the diode reverse bias saturation current, I_0, is a value in the range of a few micro Ampere and the series resistance, R_s, is a small value. So, the usually approximation by defect considered for I_s is given by:

$$I_s \approx \frac{I_{sc}\left(R_s + R_p\right)}{R_p} \tag{4}$$

The diode reverse bias saturation current, I_0, considering open circuit conditions in (1) is given by:

$$I_0 = \frac{I_s - \frac{V_{oc}}{R_p}}{e^{\frac{V_{oc}}{mV_T}} - 1} \tag{5}$$

Substituting (4) into (5) and considering that the exponential term is significantly greater than one unit, I_0 is approximated given by:

$$I_0 = \frac{I_{sc}(R_s + R_p) - V_{oc}}{R_p} e^{-\frac{V_{oc}}{mV_T}} \tag{6}$$

The derivative of the current in (1) in order to the output voltage at MPP is given by:

$$\left(\frac{\partial I}{\partial V}\right)_{MP} = -\frac{V_{MP} - I_{MP}R_s}{V_{MP}} \left(\frac{I_0 e^{\frac{V_{MP} + I_{MP} R_s}{mV_T}}}{mV_T} - \frac{1}{R_p} \right) \tag{7}$$

Attending that at MPP the derivative of the electric power in order to the voltage has a null value, the derivative in (7) is also equal to the symmetric of the quotient between the maximum power point current, I_{MP} , and the maximum power point voltage, V_{MP} . So, by equating the two derivatives, the I_{MP} is computed by the implicit expression given by:

$$I_{MP} = (V_{MP} - I_{MP}R_s)\left(\frac{I_0 e^{\frac{V_{MP} + I_{MP} R_s}{mV_T}}}{mV_T} - \frac{1}{R_p} \right) \tag{8}$$

Assuming (8) [7], the equivalent shunt resistance R_p is approximated by a function of the ideality factor m and of equivalent series resistance R_s, given by:

$$R_p \approx \frac{(V_{MP} - I_{MP}R_s)V_{MP} - mV_T V_{MP}}{(V_{MP} - I_{MP}R_s)(I_{sc} - I_{MP}) - mV_T I_{MP}} - R_s \tag{9}$$

and R_s from (6) of [7] is approximated by a function of m and of R_p , given by:

$$R_s = \frac{1}{I_{MP}} \{ V_{oc} - V_{MP} - mV_T \ln [\frac{V_{MP} + mV_T - I_{MP}R_s}{mV_T} \frac{I_{sc}(R_s + R_p) - V_{oc}}{I_{sc}(R_s + R_p) - 2V_{MP}}] \} \tag{10}$$

The ideality factor can be evaluated using (1) at MPP, replacing I_S given by (4), I_0 given by (6) and taking logarithms [7]. Hence m is approximated by a function of R_s and of R_p, given by:

$$m \approx \frac{V_{oc} - V_{MP} - I_{MP}R_s}{V_T \ln [\frac{I_{sc}(R_s + R_p) - V_{oc}}{(I_{sc} - I_{MP})(R_s + R_p) - V_{MP}}]} \tag{11}$$

The system with the implicit expressions (9), (10) and (11) allows to compute the unknowns m, R_s and R_p.
Because $R_s > 0$, (10) imposes the following implicit relation given by:

$$m < \frac{V_{oc} - V_{MP}}{V_T \ln \frac{V_{MP} + mV_T - I_{MP}R_s}{mV_T} \frac{I_{sc}(R_s + R_p) - V_{oc}}{I_{sc}(R_s + R_p) - 2V_{MP}}} \tag{12}$$

and to assure that $R_p < \infty$, then the denominator in (9) must be greater than zero [7]:

$$m < \frac{(V_{MP} - I_{MP}R_s)(I_{sc} - I_{MP})}{I_{MP}V_T} \tag{13}$$

A weighting factor less than one should be considered in the right side of (13) to set up an equality in order to find an approximation for m . So, a plausible assumption to set up the equality in order to compute m [7] is given by:

$$I_{MP} / I_{sc} \tag{14}$$

The above set of expressions (4), (6), (9), (10) and (11) are used to determine as a heuristic method to find an approximation for the values of the five parameters of the equivalent circuit, using only data from open circuit, maximum power point and short circuit conditions. With these five parameters, equation (1) is solved using Newton-Raphson method in order to obtain the I-V values. This heuristic method was successfully subjected to experimental and simulation tests.

3. Case Study

The heuristic method modelling for the solar cell equivalent circuit with single-diode, shunt and series resistances was implemented in Matlab/Simulink. The simulation results reported are carried out for a monocrystalline PV module technology with two modules connected in series. The experimental data measured are provided in [8], obtained in a photovoltaic facility located at 38°46’18.50’’N, 9°10’38.50’’W, at Laboratório Nacional de Energia e Geologia (LNEG) in Lisbon, Portugal. The I-V curves were extrapolated to STC, according with the usual method [9,10]. The tracer used showing the I-V curve is shown in Fig. 2.

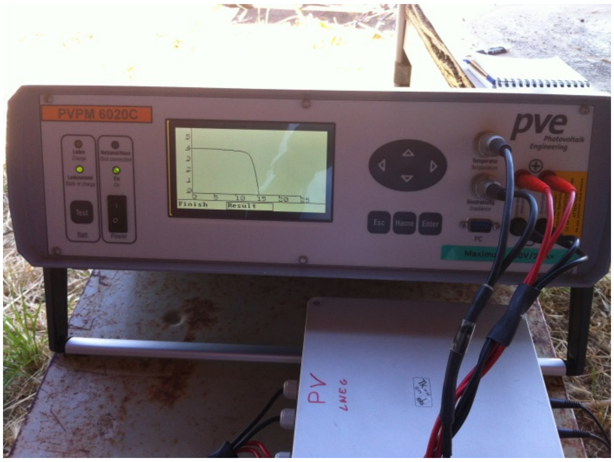

Fig. 2. The I-V curve tracer.

Table 1 summarizes the data for the silicon monocrystalline solar module Siemens SP75 at STC [11].

Table 1. Data for the Siemens SP75 solar module at STC

Technology	V_m^*	I_m^*	V_{oc}^*	I_{sc}^*	*Cells*	α_{sc}	β_{oc}
Monocrystalline	17 V	4.4 A	21.7 V	4.8 A	72	2.6 mA/ºC	-77 mV/ºC

The PV system tested formed by two monocrystalline solar modules connected in series [8] without tracking of the sun are implemented as shown in Fig. 3.

Fig. 3. PV system formed by two monocrystalline solar modules connected in series [8].

The partial shading simulation was carried with the two PV modules associated in series having the protection diodes as shown in Fig. 4.

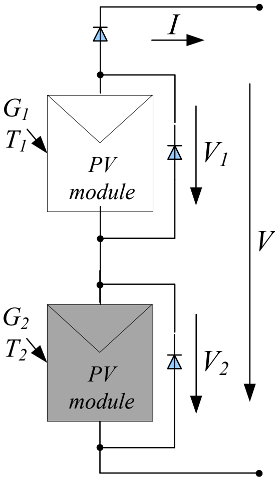

Fig. 4. Partial shading configuration.

The partial shading is given by the following settings: $G_1 = 1000\ W/m^2$ and $G_2 = 700\ W/m^2$. The circuit equivalent of both modules is as shown in Fig. 1, because every cell of a module is assumed to be subjected to the same solar irradiance, i.e., uniform illumination is assumed over each module, but with different values. The I-V curves simulated and experimental without shading and simulated with shading are respectively shown in Fig. 5.

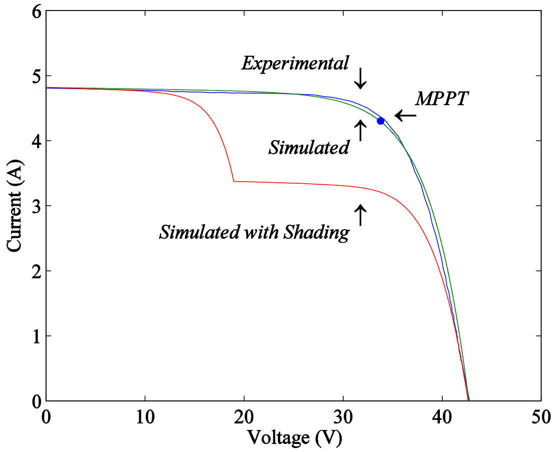

Fig. 5. Simulated and the experimental I-V curves without shading and simulated with shading.

The P-V curves simulated and experimental without shading and simulated with shading are respectively shown in Fig. 6.

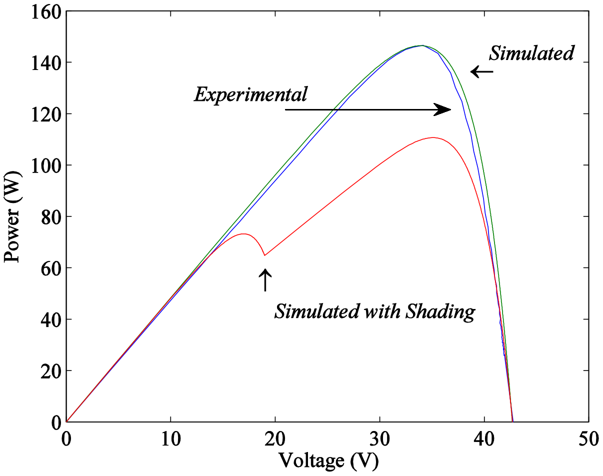

Fig. 6. Simulated and the experimental P-V curves without shading and simulated with shading.

Fig. 5 and Fig. 6 reveal the implication in the I-V and P-V curves due to the shading, i.e., due to the non-uniform illumination on the two series modules there are two local MPPs, which can pose a difficulty to the MPP tracking system and there is loss on the expected energy conversion.

4. Conclusions

The five-parameter solar cell equivalent circuit is applied in order to acquire I-V and P-V curves. The five parameters are estimated by a heuristic method using a set of expressions requiring only the normal given information by the producers of PV modules about open circuit, maximum power and short circuit data.

Once the identification of parameters is done, a simulation of the shading effects is possible. The simulation can show the effect of partial shading in reducing the energy obtained by a solar PV system, which should be taken in consideration during the economic evolution in the design phase.

Comparison between simulated and the experimental results shows that the heuristic method is a satisfactory one. A case study with a shading effect simulation is presented to show the consequence in what concerns capturing of maximum energy, i.e., MPP tracking.

Acknowledgements

This work was partially supported by Fundação Ciência e Tecnologia, through IDMEC under LAETA and by Universidade de Évora, Cátedra BES–Energias Renováveis. The authors gratefully acknowledge to Ms. L. Giacobbe for providing the measured data of amorphous PV modules at LNEG.

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