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Partially shaded photovoltaic panel

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Abstract. This paper deals with a model of partially shaded photovoltaic module. It is build as an electric circuit consisting of individual solar cells and bypass diodes. The parameters and operating points of individual solar cells change depending on the solar cell temperature and the level of solar irradiance. The output characteristics of the photovoltaic module model are determined numerically by finding solutions for the given electrical circuit, considering solar irradiance on the surface of each individual solar cell. The proposed model can provide realistic behaviour of partially shaded photovoltaic module required in simulation tools used in the development of a micro-inverter. The model was confirmed by measurements performed on the tested photovoltaic module.

Key words

Partially shaded photovoltaic module, solar cell, model, measurements

1. Introduction

Proper models of partially shaded photovoltaic (PV) modules are indispensible for proper evaluation of electricity production in PV systems that are shaded by vegetation or neighbouring objects. They are used as tools in the development and evaluation of maximum power point tracking algorithms and micro-inverters operating connected to partially shaded PV panels. When included in simulation programs, the proposed model of partially shaded PV module can provide realistic behaviour of PV module with micro-inverter, which is substantial at the development stage of a micro-inverter.

There exist many publication that deal with the solar PV cell models and PV module models that can be used in the cases of partial shading. However, those publications, where the calculated and measured characteristics of PV modules are directly compared over a broad range of operation, are extremely rare. The author in [1] proposes an improved PV cell model that should be appropriate for simulation of partially shaded solar PV arrays whilst a proper comparison of calculated and measured PV module characteristics is not given. Similarly, the authors in [2] deal with a solar PV cell model in the program package Matlab/Simulink, whilst an improvement of a PV model is proposed in [3]. The authors in [4] focused on simulation of current-voltage characteristics of PV modules with shaded PV cells.

The goal of this paper is to develop a simple model of a PV module that is able to properly simulate the behaviour of a PV module even in the cases of partial shading, and is suitable to be used as a tool in the development of a micro-inverter. The model is based on the improved single diode model of a solar PV cell [1]. The models of individual solar PV cells and bypass diodes are connected together to form an electric circuit. The obtained circuit model is mathematically described and can be solved using those known methods for solving electric circuits, that enable proper consideration of nonlinear properties and local solar irradiance in each individual solar PV cell in the modelled PV module. Because the proposed PV module model is intended to extend already existing dynamic model of a micro-inverter, prepared in the program package Matlab/Simulink, it is prepared in the same program package.

This paper focuses on the implementation of partially shaded PV module model in the program package Matlab/Simulink and on the evaluation of obtained model over a broad range of operation. The evaluation is based on extensive measurements performed on different PV-modules under controlled conditions of partial shading. The results presented in the paper show a very good agreement between the measured and calculated characteristics current-voltage and power-voltage in different cases of a partially shaded PV module.

2. Model of shaded solar PV cell

The circuit model of a PV module is given by the proper connection of individual models of solar PV cells and bypass diodes. Individual solar PV cells are described by the single diode model, shown in Fig. 1, considering [1] and equations (1) to (3).

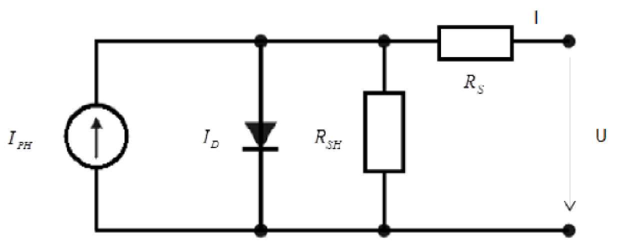

Fig. 1. Single diode solar PV cell model

$$I_{PH} = \left(I_{SC} + \alpha \cdot \left(T_C - T_C^{ref}\right)\right) \cdot G_C \qquad (1)$$

$$I_S = I_{RS} \cdot \left(\frac{T_C}{T_C^{ref}}\right)^3 \cdot e^{\frac{q \cdot E_g \cdot \left(\frac{1}{T_C^{ref}} - \frac{1}{T_C}\right)}{n \cdot k}} \qquad (2)$$

$$I = I_{PH} - I_S \cdot \left(e^{q \cdot \left(\frac{U + I \cdot R_S}{k \cdot T_C \cdot n}\right)} - 1\right) - \left(\frac{U + I \cdot R_S}{R_{SH}}\right) \qquad (3)$$

The photons that hit the solar PV cell cause the photon current I_{PH}. It depends on the cell's short circuit current I_{SC}, the solar irradiance G_C that reaches the solar PV cell, the temperature coefficient α, the cell's operating temperature T_C and the reference temperature T_C^{ref} (normally 25°C). The cell's saturation current is denoted by I_S. The cell's reverse saturation current at the reference temperature T_C^{ref} is denoted by I_{RS}, E_g is the bang-gap energy of the semiconductor, q (1.6 10^{-19} C) is the charge of an electron, k (1.38 10^{-23} J/K) is the Boltzmann constant, whilst n (1.14) is the ideal factor of the diode defined in [4], that depends on applied PV technology. The terminals voltage and currant are marked with U and I, R_S is the series resistance whilst R_{SH} is the shunt resistance.

It must be pointed out that the model must be completed by the equations that establish relations among the actual model parameters and the ones valid under standard test conditions (STC).

The solar irradiance of individual shaded cell G_C (4), required in (1), can be expressed by the cell shading factor S_C, which is 0 for the totally shaded cell and 1 for the cell that is not shaded, and the solar irradiance of not shaded cell G.

$$G_C = S_C G \qquad (4)$$

The shunt resistance R_{SH} of shaded cells is adjusted according to the (5):

$$R_{SH} = R_{SH}^{STC} \frac{1000}{G_C} \qquad (5)$$

where the superscript STC denotes the standard test conditions, while 1000 W/m^2 is the STC solar irradiance. The cell's reverse saturation current I_{RS} is recalculated in (6) using the STC open circuit voltage U_{OC}^{STC}.

$$I_{RS} = \frac{I_{SC} - \frac{U_{OC}^{STC}}{R_{SH}}}{e^{\frac{qU_{OC}^{STC}}{knT_C^{ref}}} - 1} \qquad (6)$$

The current I_{RS} (6) is required to calculate the saturation current of the shaded cell I_S (2). The shaded cell currents I_{PH} (1) and I_S (2) are required to express the relation between the terminals voltage U and current I in the cases of shading (3). Thus, the PV module data, the solar irradiance, the shading factor and the cell and environment temperatures, together with (1) to (6), are sufficient to completely describe a shaded solar PV cell and to build its model.

3. Circuit model of partially shaded PV module

To build a circuit model of partially shaded PV module, which can be used together with models of power electronic equipment, like micro-inverters, the models of individual solar cells and bypass diodes are arranged in such way to form an electric circuit that can be solved using well known methods.

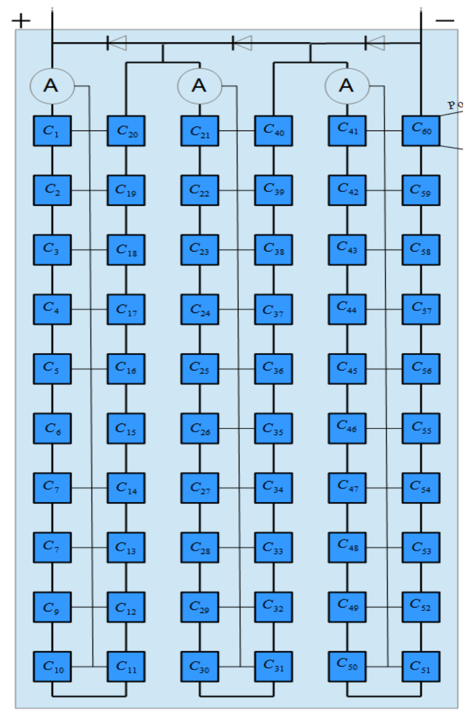

Fig. 2. Circuit model of partially shaded PV module

In the given case, the circuit model of PV module, shown in Fig. 2, was assembled in the program package Matlab/Simulaink using library SymPowerSystems. Models of individual solar PV cells were implemented in the form of controlled voltage sources that were connected in series and in parallel with properly placed bypass diodes, to mimic the tested PV module. During the tests, the load connected to the terminals of the PV module was considered in the form of resistor, the resistance of which was changed in steps. In the future, this passive load will be replaced by a micro-inverter model.

In the PV module model, the models of individual shaded solar PV cells, described by (1) to (6), are represented by controlled voltage sources. These voltage sources, connected together with bypass diodes, build the circuit model of partially shaded PV module, where individual voltage source should be generated according to the solar PV cell model described in the section 2. This means that the equations (1) to (6) should be considered together with the PV module data, data related to the module temperature and the temperature in the environment, and the distribution of solar irradiance on individual solar PV cells. However, there exists a problem that must be solved before the proposed model can be used.

According to (3), the relation between the terminals voltage and current of individual solar PV cell cannot be expressed explicitly. Therefore, these equations, describing individual solar PV cells, have to be solved numerically, as a part of the process in which the equations describing the electrical circuit model of the partially shaded PV module are solved simultaneously.

In order to determine (*I-U*) and (*P-U*) characteristics of a partially shaded PV module by the proposed model, the temperatures and solar irradiance of individual solar cells have to be defined. Then the terminals of the PV module circuit model are connected to the changing resistance. The obtained results are shown in the next section.

4. Results

The tested object was 230 W Polycrystalline PV module containing 60 cells. It is schematically shown in Fig. 2. The measurements were performed under different conditions of partially shaded module using a professional instrument for measurement of PV module characteristics.

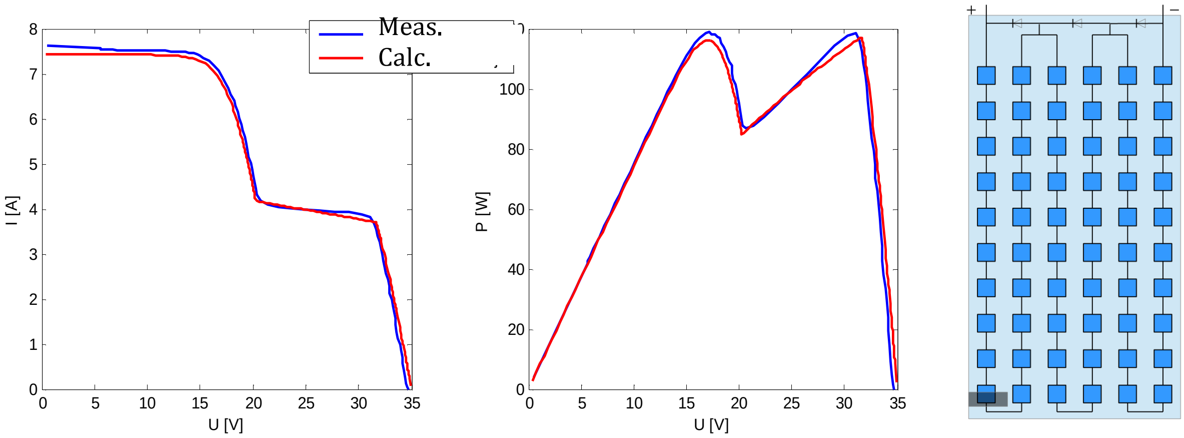

Fig. 3. Measured and calculated current-voltage (I-U) and power-voltage (P-U) characteristics of the tested PV module for solar irradiance *G*=860 W/m^2 and module temperature T=31^{o}C – solar irradiance in the marked solar PV cell is uniformly reduced to 0.35 *G* due to shading.

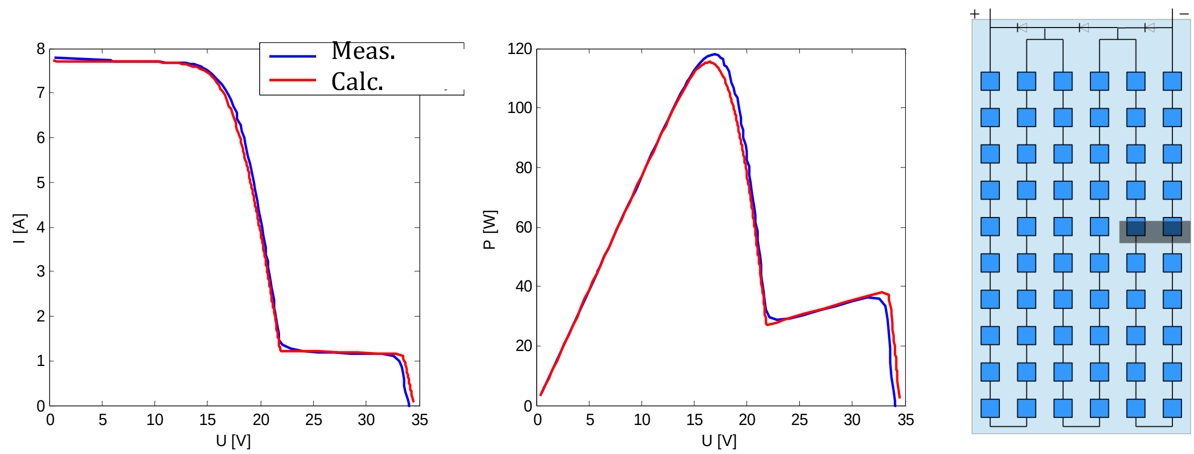

Fig. 4. Measured and calculated current-voltage (I-U) and power-voltage (P-U) characteristics of the tested PV module for solar irradiance *G*=890 W/m^2 and module temperature T=35^{o}C – solar irradiance in the marked solar PV cell is uniformly reduced to 0.15 *G* due to shading.

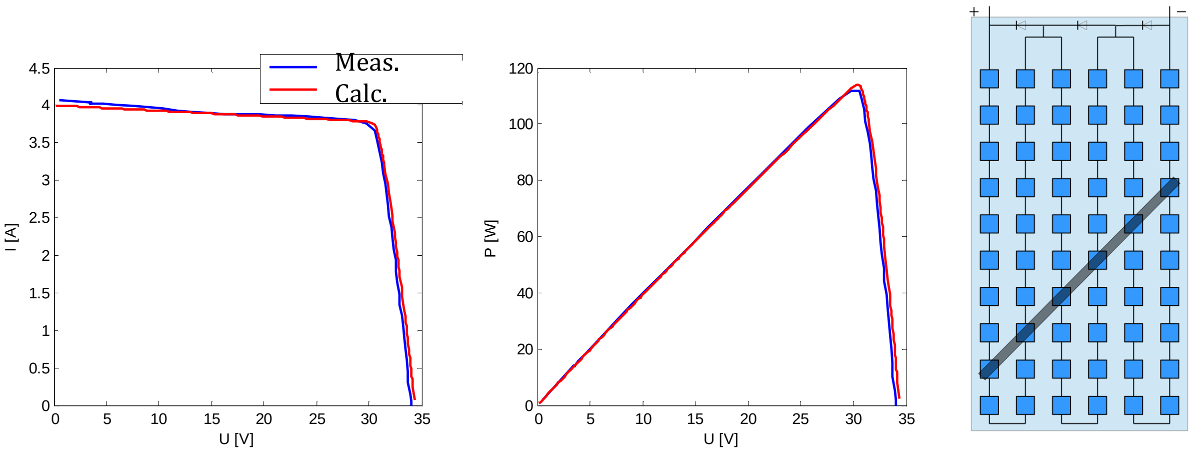

Fig. 5. Measured and calculated current-voltage (I-U) and power-voltage (P-U) characteristics of the tested PV module for solar irradiance G=910 W/m^2 and module temperature T=36^{o}C – solar irradiance in the marked solar PV cells is uniformly reduced to 0.5 G due to shading.

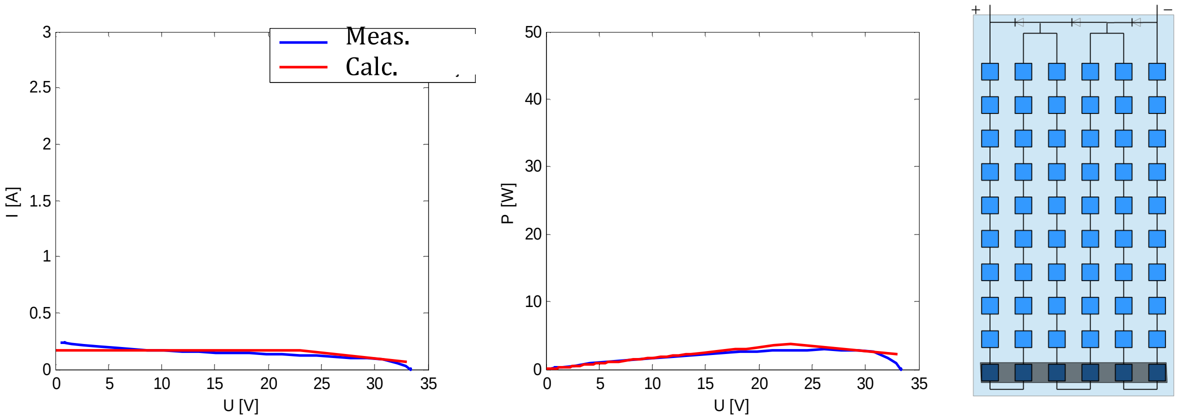

Fig. 6. Measured and calculated current-voltage (I-U) and power-voltage (P-U) characteristics of the tested PV module for solar irradiance G=910 W/m^2 and module temperature T=41^{o}C – solar irradiance in the marked PV cell is uniformly reduced to zero due to shading.

For the tested PV module discussed in this paper, more than 120 different characteristics under different conditions of shading were measured and calculated. However, only some of these characteristics are presented here. The comparison of the measured and by the proposed model calculated characteristics current-voltage (*I-U*) and power-voltage (*P-U*) is shown in Figs. 3 to 6. The results are given for the tested PV module under different conditions of shading. The agreement between the measured and calculated results is good, which indirectly confirms the proposed circuit model of partially shaded PV module.

4. Conclusion

The circuit model of partially shaded PV module, based on the improved solar PV cell model, is proposed in the paper. The developed model is intended to be used as a simulation tool in the development of a micro-inverter. The results presented in the paper show a very good agreement between the measured and calculated characteristics of partially shaded PV module.

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