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SADRŽAJ

PREDAVANJA PO POZIVU

AUTORSKI RADOVI

Performance Modelling of PV Arrays Under Specific Working Conditions

Mladen Mitkovski, Vlatko Cingoski and Saso Gelev

***Abstract* — In this paper modeling and simulation of PV arrays under specific working conditions using Matlab/SIMULINK simulation package is presented. A method for simulation of a PV arrays under specific working condition, especially for analyzing the the so-called hot spot heating effect which usually occurs for non-evenly highlighted solar cell is developed and presented. Mitigation of such problems using bypass diodes is also investigated and the inclusion of these diodes is separately investigated for serially and parallely connected set of solar modules. The obtained simulated results are also presented and briefly discussed.**

***Keywords* — PV arrays, mathematical modeling, hot spot effect, bypass diode.**

I. Introduction

The need for electricity every year constantly increases. Although the majority of electricity today is still produced by means of burning of fossil fuels, due to negative effects such as pollutant emissions, the global warming and climate changes, renewable energy sources such as solar energy gradually play a significant role in the electricity generation field.

Advances in photovoltaic (PV) solar energy technology contribute significantly towards tremendous increase of solar cells utilization as electricity generators worldwide. Power production using solar cells, tend to become the most popular and reliable source of energy among renewable energy sources in the near future, mostly because PV systems exhibit significantly low carbon dioxide production proving themselves as one of the most environmentally friendly power generation sources.

The solar cells are essentially semiconductors and their operating principle is based on the photovoltaic effect which occurs when the so-called *p-n* junction, the connection area between one *p*-type and one *n*-type semiconductor are joint together, is exposed to light. The low electric potential produced by a single solar cell that depending on the technology used ranges between 0.5 and 0.8 V, is not sufficient for commercial use. However, by connecting multiple solar cells in series and/or in parallel in PV arrays or so-called photovoltaic modules or panels, one could generate sufficient voltage and currency for practical commercial use.

As the number and size of used modules increases, the possibility that each separate module works under different working conditions during the operation of the whole PV array becomes very common. Cases such as partial shadowing of one or several modules by the surrounding objects, or simply their partial clouding are very common and very unfavorable for the PV generators. PV generators working under these conditions might generate significantly less electricity, their efficiency drops strongly and very often some damages to the structure of the PV array occurred. The main reason is the process called *"hot spot heating."* During this process, the generated power in one solar cell working under normal conditions are partially or even entirely consumed by other, shadowed solar cell, converted into additional heat inside the cell producing local overheating and cell damages [1]. A simple yet efficient method for mitigation of these negative effects can be achieved by adding bridge i.e. bypass diodes in parallel with each solar cell.

In this paper, a new practical approach for performance modeling of solar cell working under specific working conditions with and without bypass diodes is investigated. The model was developed in the Matlab/SIMULINK environment and was successfully tested on several parallel and serial connected solar cells. In the proposed method, each solar cell and its bypass diode were modeled separately, providing opportunity for testing various connecting patterns between modules and investigate the efficiency of the whole PV array. Developed model was tested under various specific working conditions such as parallel or serial shadowing of a group of solar cells, various values for intrinsic impedances of the solar cell, temperature and solar radiation intensity in order to grasp the influence of the shadowing effect on the hot spot heating, efficiency of the PV array and the benefits of the bypass diodes.

II. Model of the Single Solar Cell

The physical properties of a single solar cell were analyzed using an equivalent electric circuit as shown in Fig.1. This electric circuit consists of the current generator I_{pv}, the serial resistance R_s and the parallel resistance R_p, which amounts for several technological parameters of the real solar cells such as contact resistance, impurities or micro defects during the production, and a diode [2.

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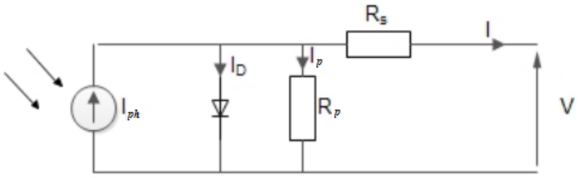


Fig.1. Real solar cell equivalent electric circuit.

The intensity of the generated solar cell current I is given as:

$$I = I_{ph} - I_0\left[e^{\left(\frac{V - I\cdot R_S}{n\cdot V_T}\right)} - 1\right] - \left(\frac{V + I\cdot R_s}{R_p}\right) \qquad (1)$$

where, I_{ph} is the current generated by the current generator, the I_0 is the diode's reverse saturation current, $V_T = kT/q$ is the thermal voltage, q is the electron charge, k is the Boltzmann constant, T is the temperature of the *p-n* junction and n is the diode's ideality factor.

Taking into consideration that a single solar cell voltage at full load ranges between 0.5 to 0.8 VDC and the power generated by a single solar cell is too low, an array of solar cell is usually constructed by interconnecting single solar cells in n_p parallel and/or n_s serial branches. Therefore, the total generated power P by such constructed PV array becomes:

$$V_s = n_s \cdot V_{cell}\ ; \quad I_p = n_p \cdot I_{cell} \qquad (2)$$

$$P = V_s \cdot I_p = n_s \cdot n_p \cdot V \cdot I = n_s \cdot n_p \cdot P_{cell} \qquad (3)$$

where, P_{cell}, V_{cell} and I_{cell} are values of generated power, voltage and current of a single solar cell.

Very often different solar modules which belong to a single PV array or panel have to operate under different working conditions. Cases of partial clouding or shadowing of some models are very common and lead to conditions where different solar cells exhibit abnormal working effects which could affect not only those cells but also other interconnected cells in the whole system. Among these effects the most unwanted is the effect of *"hot spot heating"* effect shown in Fig. 2.

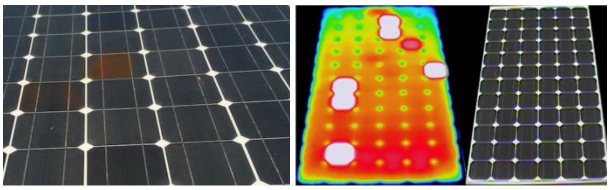


Fig. 2. Hot spot heating of PV panel, a) visual "hot spot" damage, b) infra-red testing of a visibly undamaged panel.

III. Hot Spot Effect

The shading even of just single cell linked in a long PV array made of strings of serially or parallel connected solar cells could halve the power output of the whole array. To closely investigate this effect, we show an example of a solar module with n serially connected cells. One shadowed cell is presented separately with its equivalent scheme as show in Fig. 3. When all other cells are highlighted, the same current I flow through all cells and the voltage at the ends of the whole module is V. In case n^{th} cell is clouded or shadowed, due to the inverse polarization of its diode, the current through the diode should be zero, thus the entire current generated in the remaining *(n-1)* cells of the whole module I, must pass through resistances R_p and R_s of the n^{th} cell, causing voltage drop and reducing the output voltage of the whole module to value V_1. If we assume that $(n\text{-}1)^{th}$ cell module still generate the same amount of current I as in the previous case, then the total voltage V_1 becames:

$$V_1 = V_{(n-1)} - \left(R_s + R_p\right)\cdot I \qquad (4)$$

If we further assume that the voltage inside the module is equally distributed through all cells, then:

$$V_{(n-1)} = \left(\frac{n-1}{n}\right)\cdot V \qquad (5)$$

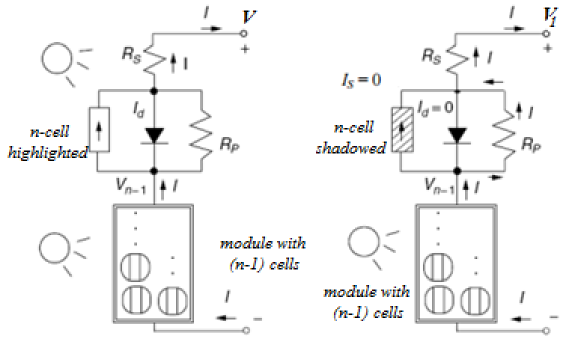


Fig. 3. Comparison between two modules without and with shadowed single PV cell.

By including (5) into (4) and rearranging, one could get the value of the voltage drop at the end of the whole module as a result of shadowing of a single PV cell:

$$\Delta V = V - V_1 = \frac{V}{n} + \mathrm{I}\cdot(\mathrm{R_P} + \mathrm{R_S})$$

$$\cong \frac{V}{n} + \mathrm{I}\cdot\mathrm{R_P} \qquad (\mathrm{R_P} \gg \mathrm{R_S}) \qquad (6)$$

The effect of the single cell shadowing on the *V–I* characteristic of the PV module is presented graphically in Fig. 5. Obviously, the power consumed by shadowed cell is converted into heat, which can cause local overheating and damage of the cell and the whole module.

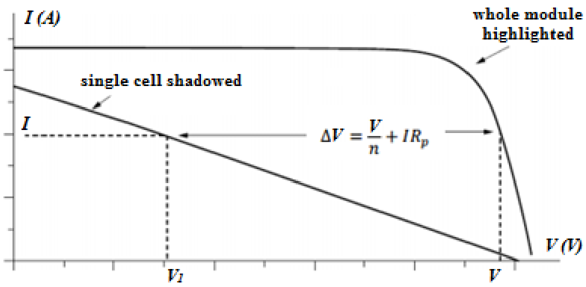


Fig. 4. The influence of the shadowed cell on the *V–I* characteristic of a single PV module.

Mitigation of these negative effects can be achieved by connecting a so-called *bridging* or *bypass diode* in parallel with each cell, as shown in Fig. 5. When the entire module is evenly highlighted, this diode does not conduct electricity, but if the cell is in shadow, the voltage drop of the cell allows current to flow through the diode instead through the resistance. In comparison with evenly highlighted module, in case of a single shadowed PV cell, the voltage drop in the bypass diode is only about 0.6 V which is far less than the voltage drop of overshadowed cell without bypass diode.

In practice, bridging each solar cell with bypass diode is unfeasible. Instead, bridging is usually done for the whole module, or using of a few diodes for bridging a block of cells within a module. Although these diodes do not have a major impact on the effect of shade in a single module, they play an important role when several modules are connected in series.

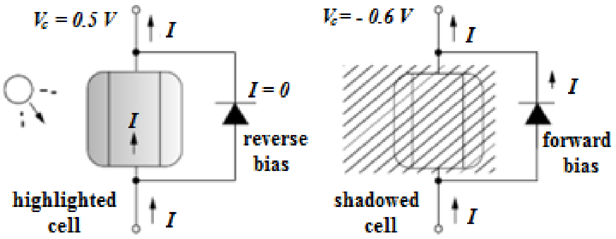


Fig. 5. Mitigation of hot spot effect using bypass diode.

IV. Modeling and Simulation of Solar PV Cells

A. Matlab/SIMULINK modeling of solar PV arrays

Matlab© is a highly-organized programming language for application in engineering and technology. It incorporates computation, visualization and programming within a simple to use environment where problems and solutions are presented in a familiar and user-friendly mathematical notation and collection of procedures called toolbox. One of those frequently used toolboxes is SIMULINK© toolbox, software module for modeling, simulation and analysis of dynamic systems, that supports linear and nonlinear systems, time-continuously and discrete physical models, or any hybrid of these.

There are three options for modeling of solar PV arrays in SIMULINK®. The first option includes modeling tools that can implement any differential or algebraic equations into highly complex mathematical model. The second option is given by Simscape™, which enables direct modeling of the solar cell with the physical components of its equivalent electric circuit (e.g. resistors, diodes) and by implementation of the same mathematical equation. Finally, the third option, comprise modeling of more complex systems using the library called SimElectronics®, which contains a special computation block called *"Solar Cell"*. This block is a source of solar PV power that includes into the model the solar-induced currents and temperature dependences [3].

The *"Solar Cell"* block is formed by a solar cell equivalent electric circuit consisting of resistor R_s connected in series with a parallel combination of current source, two exponential diodes and parallel resistor R_p. Its output current is defined by the following equation:

$$I = I_{ph} - I_{s1} \cdot \left(e^{\frac{V+I\cdot R_S}{n_1 \cdot V_T}} - 1\right) - I_{s2} \cdot \left(e^{\frac{V+I\cdot R_S}{n_2 \cdot V_T}} - 1\right) - \frac{V + I \cdot R_S}{R_P} \quad (7)$$

It is visible that (7) is just a better representation of (1) including two diodes instead of one. Thus, all the parameters in (7) are the same as in (1). The new ones are I_{s1} and I_{s2}, and n_1 and n_2 which represent the inverse saturation currents and the ideality factor for the first and the second diode, respectively.

The model *„Solar Cell“* used for analysis is given in Fig. 6. The *„PV module“* on the left side of Fig. 6, consists of a set of 60 sub-modules named *„1-60“* interconnected each other as show in Fig. 7a. Each *„1-60“*sub-model is separately modeled using one constant value called „PS Constant“ which represents the value of the sunlight intensity for each solar cell seprately. This new approach, enable us to separately define the working conditions for each solar sell in the module and in the whole PV array independently, seting some of them fully highlighted and some of the partially or fully shadowed.

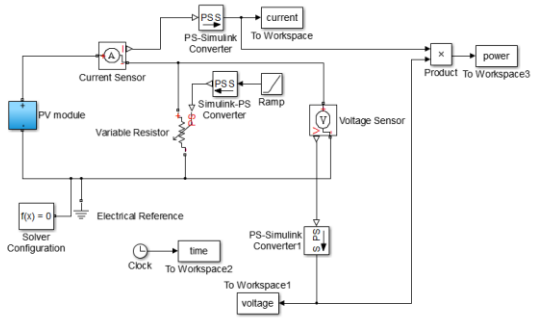


Fig. 6. Matlab/SIMULINK/Simscape analyzed model.

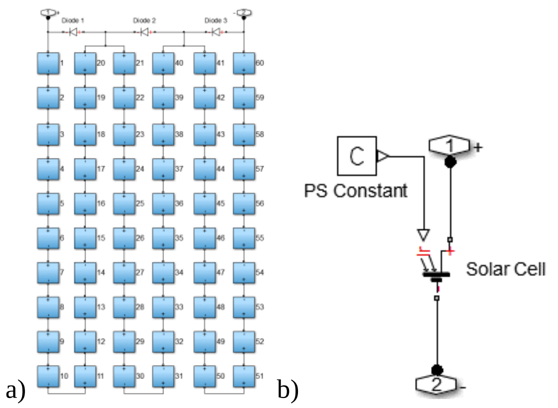


Fig. 7. Solar cell model, a) the whole block, b) single cell.

V. Obrained Results

A. Normal working conditions

For the simulation, we used the data provided from the Canadian Solar polycrystalline PV module CS6P-255P [4]: $I_s=2.7098\cdot e^{-10}$ [A], $I_{ph}=9.0012$ [A], $n=1.0$, $R_s=0.0056$ [Ω], and $R_p=39$ [MΩ]. The *I–V* and *P–V* characteristics obtained in the simulation are given in Fig. 8, and Table I.

Table I. Results Under Normal Working Conditions.

G [W/m^2]	T [°C]	P_m [W]	V_m [V]	I_m [A]
1000	25	255,33	29,98	8,52

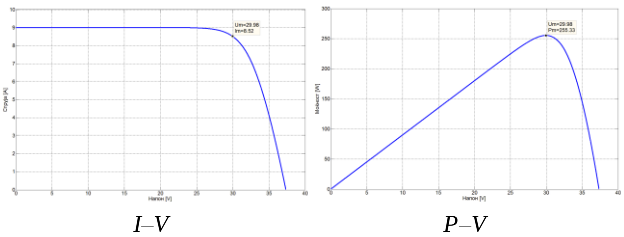


Fig. 8. Characteristic of solar cell under normal conditions.

B. Results obtained under hot spot conditions

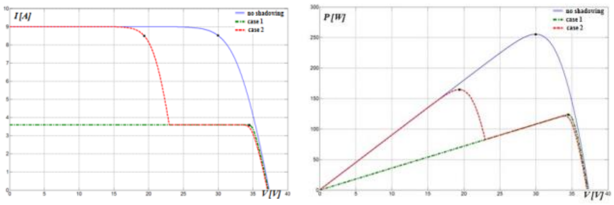
To investigate the effect of the hot spot effect on the output characteristics of the solar PV array, two specific cases showed in Fig. 9 were investigated:

- *Case #1:* horizonal shadowing (cells No. 1, 20, 21, 40, 41 and 60), and
- *Case #2*: vertical shadowing (cells No. 51 – 60).

The obtained results are given in Fig. 10 and Table II.

Horizonal shadowing Vertical shadowing

Fig. 9. Two investigated shadowing models.



I–V *P–V*

Fig. 10. Characteristic of solar cell under hot spot conditions.

TABLE II. RESULTS UNDER HOT SPOT CONDITIONS.

	P_m [W]	V_m [V]	I_m [A]
No shadowing	*255,33*	*29,98*	*8,52*
Case 1	*123,53*	*34,47*	*3,58*
Case 2	*164,70*	*19,38*	*8,50*

C. The influence of the bypass diode

To analyze the influence of the bypass diode on the power output of PV cells, two separate cases were investigated: a serial connection of one highlighted and one shadowed cell (Fig. 11), and a parallel connection of one highlighted and one shadowed cell (Fig. 12).

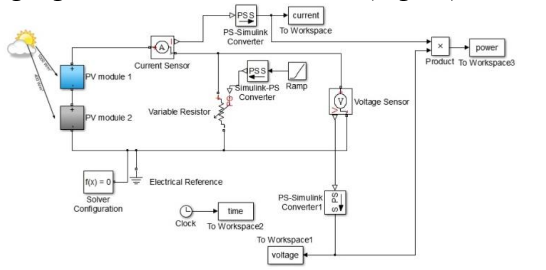


Fig. 11. A model with serially connected solar cells.

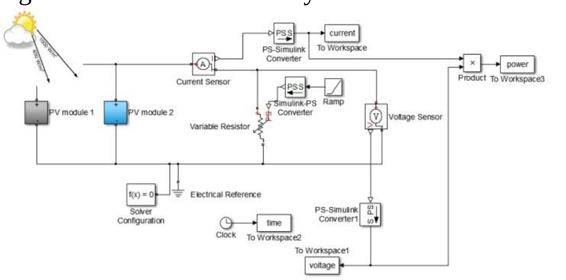


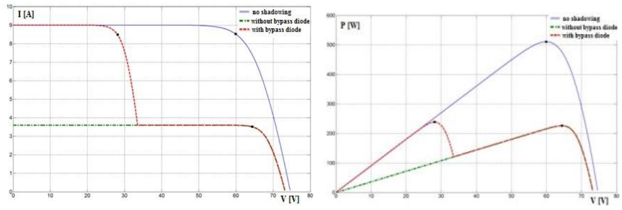
Fig. 12. A model with parallely connected solar cells.

The obtained results for serial connection are given in Table III, and in Fig. 13, while for parallel connection the results are given in Table IV and Fig. 14.

One can easily conclude that the bypass diode has larger influence in cases of serially connected solar cells than in cases of parallel connected. This could be expected since in case of serially connected cells the same current should pass through all cells, while in case of parallel connection, each solar cell contributes separately with its generated current. Additionally, the results show that inclusion of bypass diode for mitigation the problem of hot spot effect is advantageous and should be always considered.

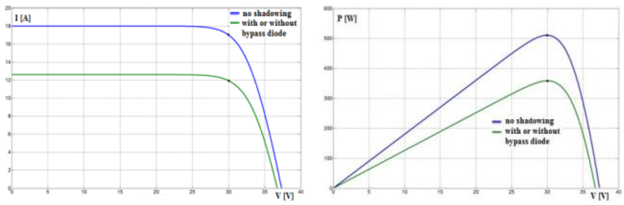
TABLE III. RESULTS FOR SERIAL CONNECTION.

	P_m [W]	V_m [V]	I_m [A]
No shadowing	*510,67*	*59,96*	*8,52*
Without bypass diode	*226,33*	*64,45*	*3,51*
With bypass diode	*238,77*	*28,16*	*8,48*



I–V *P–V*

Fig. 13. Obtained results for serial connection with and without bypass diode.



I–V *P–V*

Fig. 14. Obtained results for parallel connection with and without bypass diode.

Table IV. RESULTS FOR PARALEL CONNECTION.

	P_m [W]	U_m [V]	I_m [A]
No shadowing	*510,67*	*29,98*	*17,03*
With / Without bypass diode	*358,48*	*30,04*	*11,93*

VI. CONCLUSIONS

We presented a method for modeling of solar PV arrays under specific working conditions. The large portion of the research was focus on investigation of the influence that hot spot effect has on the power performance of PV arrays and the potential mitigation methods for solving of such problem. The obtained results show that using adequately selected and positioned bypass diodes might offer cheap and efficient solution.

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