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POWER EFFICIENCY MANAGEMENT OF PHOTOVOLTAIC ENERGY SOURCE BASED ON MPPT ALGORITHM

ZARZĄDZANIE SPRAWNOŚCIĄ ENERGETYCZNĄ FOTOWOLTAICZNEGO ŹRÓDŁA ENERGII Z UŻYCIEM ALGORYTMU MPPT

Abstract

In the paper energy supply system based on photovoltaic (PV) arrays was described. Also models of a single PV cell and a voltage boost converter were described. The boost converter was used for holding an appropriate work state of the PV arrays associated with its maximum power point level in various work conditions associated with irradiance level and the arrays temperature. Finally, comparison of two strategies of voltage level control in PV arrays system was put forward. These strategies were used to attain the maximum power point, and to define the work conditions, in which described control algorithms are the most effective.

Keywords: *photo-voltaic arrays*, *Maximum Power Point Tracking (MPPT) algorithm*, *Perturb & Observe (P&O) algorithm*

Streszczenie

W artykule opisano system zasilania z wykorzystaniem baterii ogniw fotowoltaicznych. Przedstawiono model ogniwa fotowoltaicznego oraz przekształtnika podwyższającego napięcie. Przekształtnik ten zastosowano do utrzymywania właściwego stanu pracy związanego z maksymalną mocą osiąganą przez ogniwa w określonych warunkach pracy związanych z nasłonecznieniem i temperaturą ogniw. Przedstawiono porównanie dwu podstawowych strategii sterowania poziomem napięcia w układzie ogniw w celu uzyskania maksymalnego punktu pracy wraz z warunkami, w jakich opisane algorytmy sterowania są najskuteczniejsze.

Słowa kluczowe: *ogniwa fotowoltaiczne*, *algorytm MPPT*, *algorytm P&O*

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1. Introduction

During energetic crisis, people have to search alternative sources of the electrical power. The most popular of all available energy sources, which could be easily transformed to electrical energy, is energy of the Sun. The Sun gives us a huge amount of it, as heat energy and light. Especially the light can be transformed to electrical energy with photovoltaic (PV) cells. These cells nowadays can reach, in the best case, efficiency on the level of 30%, but most of them do not exceed 20%. This barrier is associated with technological limitations, but PV cells as a research object appears to be more complicated than could be seen in superficial observation. It can be noticed on power-voltage and current-voltage characteristics. On the first of them one can observe maximum power point. This point is dependent to electrical current and voltage in the PV circuit system, as also to temperature of the cells. For these reason, the authors have chosen way to efficiency improvement through Maximum Power Point Tracking (MPPT) algorithm.

2. Literature analysis for finding MPPT algorithm solutions

To investigate MPPT algorithm solutions, an appropriate model was needed. This model should be simplified to decrease a simulation time. This simple model is based on equivalent circuit of PV cell and also on equations, which describes PV cell properties [1].

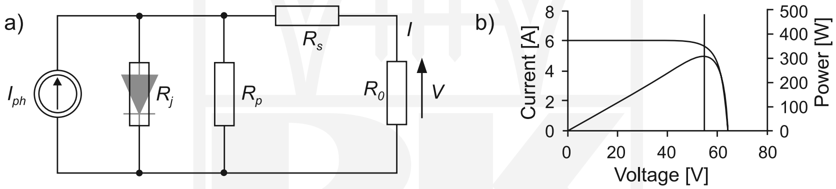

Fig. 1. Equivalent circuit of PV cell (a), PV cell characteristics (b)

Rys. 1. Obwód równoważny dla ogniwa fotowoltaicznego (a), charakterystyki ogniwa (b)

In equivalent circuit (Fig. 1a) I_{ph} represents current directly produced in PV process. R_j is the p-n junction impedance. R_p, R_s and R_0 represent consequently parallel resistance, series resistance and load resistance. Voltage drop on this resistance equals V. The current I in PV cell output is described by equation (1), but its component current I_{ph} is described by equation (2). These equations shows, that produced energy is also temperature-dependent value. These phenomena can be observed also on power-voltage characteristics [2], based on current-voltage dependence of a photodiode [3]. Due to the sign convention of the positive and negative power, its shape is the same as inverted characteristics of photodiode (Fig. 1b).

$$I = I_{ph} - I_{rs} \cdot e^{\left(\frac{q}{kTA}\frac{V}{n_s}\right)} - 1 \tag{1}$$

$$I_{ph} = [I_{scr} + k_i (T - T_T)] \cdot \frac{S}{10} \tag{2}$$

where:

I_{ph} – photocurrent,
I_{rs} – reverse saturation current,
I_{scr} – cell short-circuit current at reference temperature and radiation,
q – charge of an electron,
k – Boltzmann's constant,
k_i – short-circuit current temperature coefficient,
T – cell temperature,
T_r – cell reference temperature,
A – coefficient of cell deviation from ideal p-n junction characteristics,
n_s – number of cells connected in series,
S – irradiance in kW/m^2.

Based on these circuits and equations, a cell array was constructed where the cells are connected in series. Finally these series arrays were connected in parallel in full model named PV array.

3. Structure of the system

The PV array model was used in more complex model with MPPT algorithm control system (Fig. 2). In this system, so called Boost Converter was used. This converter lets control the voltage on the PV array and through this variable it lets hold maximum power point of the system. As a load of the electrical system a simple resistance was used. The below model consist of three main elements. First is above described PV array, second is the boost converter and third is a controller based on MPPT algorithm.

3.1. Boost converter

Because the cell voltage varies with temperature and irradiance, it is necessary to use the boost converter. The purpose of the boost converter is processing voltage from photovoltaic cells array to that adopted for the inverter input voltage level, in accordance with the MPPT algorithm. Boost converter is used in the system for regulation of PV array voltage to hold maximum power point position on power-voltage characteristics through changing irradiance and temperature conditions (Fig. 3). These characteristics are taken for PV cells SunPower SPR-305-WHT connected in configuration: 5 series modules per string and 66 in parallel connection. The boost converter consist of an inductor, which accumulate energy, IGBT transistor, which work as a switch, controlled by Pulse Width Modulation (PWM) element, and diode, which conducts current in one direction, as also capacitor connected in parallel to the load resistance [2] (Fig. 4). In photovoltaic applications boost converter is working typically in continuous coil current flow. Part of the input energy is transferred to the RC circuit via diode during transistor conduction and part of the energy is stored in a coil magnetic field. During open state of the transistor, this stored energy is transferred to the output RC circuit. This action is the basis for increasing the converter output voltage [4].

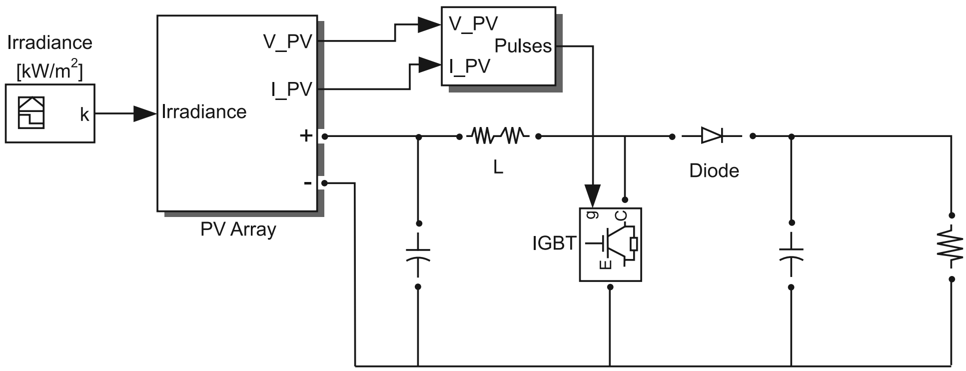

Fig. 2. PV array circuit with MPPT algorithm control in resistance load conditions

Rys. 2. Bateria ogniw PV ze sterowaniem algorytmem MPPT w warunkach obciążenia rezystancją

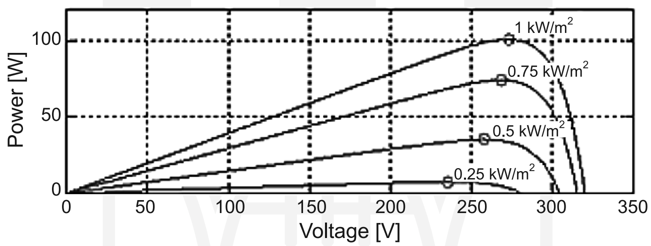

Fig. 3. Set of power-voltage characteristics of PV array for various irradiance conditions

Rys. 3. Bateria ogniw PV ze sterowaniem algorytmem MPPT w warunkach obciążenia rezystancją

During proper work of the boost converter output voltage is greater than input voltage. Relation between these two voltages is expressed in equation (3) [2].

$$V_{out} = \frac{1}{1-D} \cdot V_{in} \tag{3}$$

where:

- D – duty cycle.
- V_{in}, V_{out} – respectively input and output voltage.

After transformation of equation (3), appropriate duty cycle can be calculated according equation (4) to hold correct voltage for control strategy realization. In this equation an assumption that $V_{out} = V_{ref}$ should be taken.

$$D = 1 - \frac{V_{in}}{V_{ref}} \tag{4}$$

If the transistor is in the ON state, the coil current increases, and if the transistor is in the OFF state, the coil current decreases. This causes the output voltage ripple. The ripple should be in the range of up to 2% due to the correct operation of the inverter.

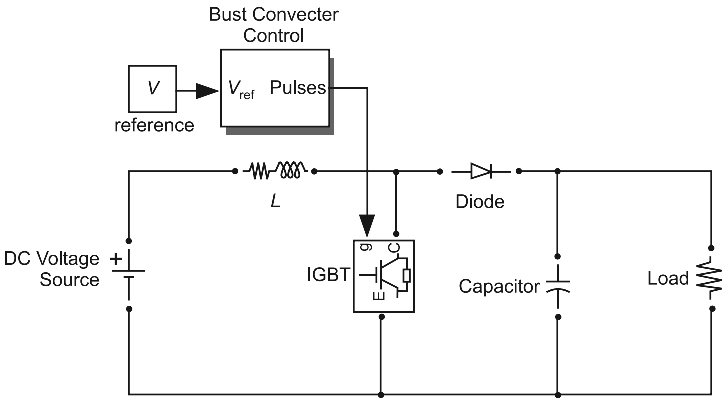

Fig. 4. Boost converter system

Rys. 4. Układ przekształtnika podwyższającego napięcie

Allowable ripple defined as the ratio of output voltage fluctuations and V_{out} are described in the following equation.

$$\frac{\Delta V_{out}}{V_{out}} = \frac{D}{R \cdot f \cdot C} \tag{5}$$

where:

- R – load resistance in Ω,
- C – boost converter capacitance in F,
- f – boost converter frequency in Hz.

For the assumed limit for ripple and frequency, the value of boost converter capacitance C can be determined. Transfer of energy from the lower voltage DC source to a higher voltage DC source by a pulse boost converter is a high conversion efficiency [5] method (typically above 90%). Minimum values for L and C of boost converter depend on the extent of variation Duty Cycle D, load value R and the operating frequency of the system f.

3.2. MPPT Controller

The main aim of MPPT strategy is to hold maximum power point during work of the PV array system. As can be noticed in figure 3 this point depends to irradiance level [6]. It depends also to temperature. The easiest way to find this maximum power point is to observe behavior of the power level. The clue information is if power value decreasing or increasing, during increasing or decreasing voltage value. Based on this information, very simple strategy can be described. Shape of power-voltage characteristics is always similar and can be described with relations enclosed in section 2. Therefore, dependence that when voltage increases and power also increases shows that we are on the left side from maximum power point of voltage-power characteristics (Fig. 3). If voltage decreases but power increases, it is obvious that we are on the right side on the characteristics. Based on this information, the MPPT algorithm was constructed. The algorithm is presented in the Figure 5.

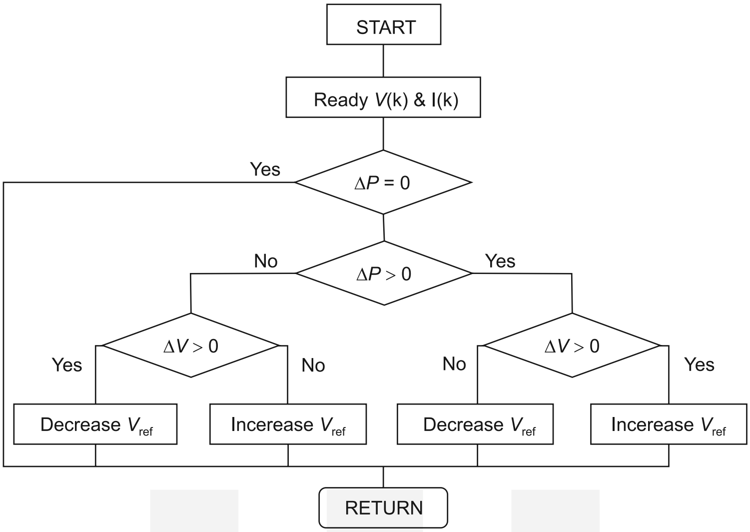

Fig. 5. MPPT algorithm

Rys. 5. Algorytm MPPT

During its work power level and voltage of the PV system oscillates around maximum power point. This main idea of MPPT was developed but only in small range. For example in MPPT algorithm known as Perturb and Observe algorithm, perturbation coefficient is introduced. It decides about step size of the voltage changing during maximum power point searching process.

4. Simulation and results comparison

During simulation process the authors used various irradiance levels to observe full range of power levels. Range of irradiance level enclosed between 0.25 and 1 kW/m^2 (Fig. 6). This changing character simulates character of illumination during normal work of PV arrays when irradiance is changing due to clouds movement. In this simulation two MPPT algorithms were used for power level maximization. Results were introduced in the figure 7, which encloses power level during 3 seconds simulation. This is power produced by PV array system. The first presented algorithm is associated with general MPPT algorithm strategy and its results are represented with blue line. Second algorithm is associated with P&O strategy and its results are represented with green line. Last one, red line represents result for the PV system without control.

During results comparison, the authors calculated coefficients of produced power in comparison to the uncontrolled PV system. This no dimensional coefficient was calculated with equation (6).

$$c_x = \frac{\int P_{\text{controlled}}}{P_{\text{uncontrolled}}} \tag{6}$$

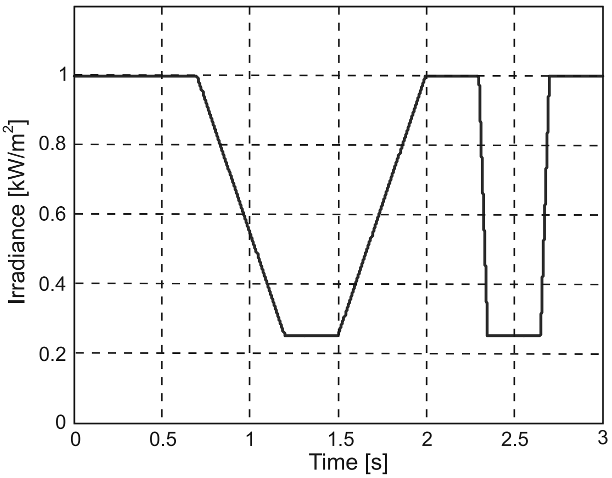

Fig. 6. Various irradiance levels

Rys. 6. Zmienny poziom napromieniowania

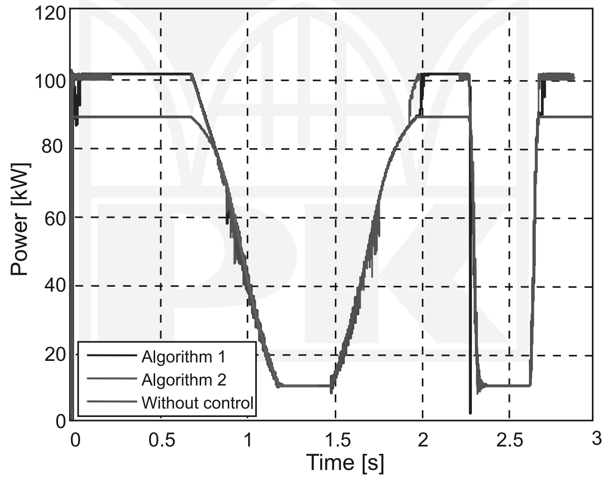

Fig. 7. Level of power produced by PV array

Rys. 7. Poziom mocy produkowanej przez baterię PV

The c_x coefficient for the first algorithm equals 1.0841 and for the second algorithm equals 1.0854. Differences appears to be very small, but range of input radiation is wide, than when we observe time-traces from figure 7, we can notice that differences between these coefficient can be extremely big in range of irradiance between 0.8 and 1 kW/m^2. This means, that these algorithms can be very effective in higher radiation conditions. In above mentioned range also differences between effects of first and second algorithm can be significant. In this comparison P&O algorithm appears to be more effective than traditional MPPT algorithm.

5. Conclusions

As it was said in previous section both presented control algorithms can be very effective in higher radiation conditions, but in lower radiation conditions they could be turned off. It could suggest that these algorithms are not effective or even useless, but it is not true. We have to remember that most of the PV arrays systems works in conditions of higher irradiance and where irradiance is too low the system is turned off. This strategy is especially applied in a solution which cooperates with AC electrical grid, where surplus of produced energy can be send to this grid. In the context of the protection of the Earth from global warming, the use of renewable energy sources is appropriate and cost effective. The use of photovoltaic solar systems leads to improved energy balance in accordance with the requirements of climate. In addition, the pulse energy conversion methods are characterized by high efficiency, aided by the use of algorithms for maximum power point tracking MPPT.

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