

A HYBRID MAXIMUM POWER POINT SEARCH METHOD USING TEMPERATURE MEASUREMENTS IN PARTIAL SHADING CONDITIONS

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Abstract

Photovoltaic panels have a non-linear current-voltage characteristics to produce the maximum power at only one point called the maximum power point. In the case of the uniform illumination a single solar panel shows only one maximum power, which is also the global maximum power point. In the case an irregularly illuminated photovoltaic panel many local maxima on the power-voltage curve can be observed and only one of them is the global maximum. The proposed algorithm detects whether a solar panel is in the uniform insolation conditions. Then an appropriate strategy of tracking the maximum power point is taken using a decision algorithm. The proposed method is simulated in the environment created by the authors, which allows to stimulate photovoltaic panels in real conditions of lighting, temperature and shading.

Keywords: maximum power point, partial shading, perturb and observe, temperature measurement.

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1. Introduction

The output power of a photovoltaic panel is dependent on the temperature and sunlight. There are many algorithms for tracking the maximum power point; they differ in complexity and a number of parameters derived from a photovoltaic system. These methods can be divided into active and passive methods. The passive methods use a model of the solar cell or photovoltaic panel properties. The active methods use instantaneous parameters of a photovoltaic system [20]. The first group includes look-up table methods, regression methods, open circuit voltage and short circuit current methods [2]. The second group of methods includes the majority of maximum power point tracking methods, i.e. the perturb and observe (P&O), the ripple correlation control (RRC), the incremental conductance (IC), modulation methods, methods based on fuzzy logic regulators, the artificial intelligence [19] and others [2]. In recent years, calculation methods (soft computing) started to gain in importance. They can include evolutionary algorithms, swarm optimization algorithms and others [14]. There are also algorithms that use a combination of active and passive methods in order to improve the properties of maximum power point search algorithms [21].

An occurrence of shading on the panel surfaces is a negative phenomenon, which makes the task of obtaining the maximum available power difficult. Therefore, the authors of [8] suggested a different classification of the maximum power point search algorithms: algorithms working under the uniform insolation and algorithms for partial shading conditions. The first group includes the traditional algorithms qualified for online and offline methods. The second one includes modified or hybrid algorithms to track the maximum power point under a partial shading. They include the power curve searching algorithms [7,13], the DIRECT search algorithm [16] and a method using a division of the open circuit voltage [11].

One of the most frequently used passive methods is the short circuit current method [2,4,6,8,14,20]. It uses the relationship between the short-circuit current - I_{SC} and the current in the MPP (Maximum Power Point) - I_{MPP} , Eq. (1),

$$I_{MPP} \approx kI_{SC}, \tag{1}$$

where k is a proportionality factor and it has a value between 0.8 and 0.9. Its value depends on solar cells that are used and it is empirically determined on the basis of measuring the short-circuit current and the current at the MPP. It is a very fast method. However, it has several drawbacks, which is the reason of its rare usage. The main disadvantage is a need to disconnect the load during the measurement of the short-circuit current. In addition, for large photovoltaic panels the short-circuit current measurement in a wide range of changes requires using complex circuit solutions. Moreover, the properties of photovoltaic cells change in time. Another - similar, but less accurate - is the open circuit method [2,4,6,8,14,20]. It uses the relationship between the open circuit voltage - V_{OC} and the voltage at the MPP - V_{MPP} , Eq. (2),

$$V_{MPP} \approx kV_{OC}, \tag{2}$$

where k is a proportionality factor and it has a value between 0.7 and 0.8. Similarly to the previous method, its value depends on used photovoltaic cells and is empirically determined by measuring the open circuit voltage and the voltage at the MPP in various atmospheric conditions. The drawbacks of this method are similar to the short-circuit current method. The difference lies in much less complex solutions needed to measure the open circuit voltage.

One of the simplest methods of an active search of the MPP is the perturb and observe / hill climbing method [2,4,6,8,14,19,20]. Let X be the instantaneous current or voltage value. The first step of the algorithm is to determine the reference power. Then X is changed by a value of C , called a step disturbance, and the power is re-measured. If - as a result of an operating point perturbation - the power increased, it is assumed that the perturbation has a good direction and in the next step it will be preserved with the same direction. However, if the value of the power is diminished, the direction of the perturbation has to be changed. In this algorithm, the most important thing is to determine the correct value of a perturbation step. The smaller steps, the lower the power losses, but the algorithm needs more time to converge to the MPP. Therefore, in many publications a variable perturbation step is used in order to maintain a balance between the speed of convergence and power losses. In the literature two basic types of the perturb and observe search algorithms can be found: the fixed and adaptive step ones. In [1] the authors determine the starting point of the P & O algorithm at $0.7V_{OC}$ and the step is set at $10\%V_{OC}$. Then in each subsequent cycle the step is divided by two until it reaches $0.5\%V_{OC}$. In [15] Moradi et al. use the slope of the power curve to determine the value of the disorder C , Eq. (3),

$$C(k+1) = C(k) + M \frac{\Delta P}{P}, \tag{3}$$

where M is the correction factor. Both modifications are, however, prone to search errors, if they follow rapid changes in the light intensity. In other publications [1], authors use an additional step to increase the resistance of the algorithm in fast changing of the illumination, or use a hybrid MPP tracking (MPPT) method which involves offline methods [3,15,18,24]: fuzzy tracking techniques, such as fuzzy logic regulators, and artificial neural networks.

The curve searching algorithm [18] rests upon a steady search of the entire voltage range from 0 to the open circuit voltage at a certain voltage. Subsequently, the point with the highest power is selected and in relation to this point the P & O search algorithm is running. This is a very simple and at the same time effective method of tracking the MPP. A disadvantage of this method is the necessity of searching the entire voltage-power curve, which is associated with a low ability of tracking changes in insolation. The DIRECT search algorithm [16] is the same as the previous one, but with the exception that the step of the algorithm is variable. Initially, it is equal to half of the open circuit voltage, then the step is divided by two. Each

time an interval with the highest power is chosen. Then the P & O algorithm is run. The method using the open circuit voltage to determinate the MPP [11] is a different one. The authors have proven that each local maximum is related to the no-load voltage according to Eq. (2). By measuring the open circuit voltage the authors define the first point, which becomes the open circuit voltage for the calculation of the next point. Then the point with the highest available power is selected with respect to which the P & O algorithm is run. The above-mentioned algorithms, in the conditions of a partial shading, search the entire current-voltage curve what makes their tracking performance small.

Fuzzy controllers do not require a mathematical model of the system, what in itself is a significant advantage because uncertainties - such as a non-modelling physical size, a non-linearity and unpredictable changes in the operating point - can be perfectly levelled [12,23]. However, this requires from the designer the prior knowledge of how the output reacts to the relative quality of inputs. The ability of artificial neural networks to identify and estimate the unknown parameters inspires to use it for tracking the MPP [22]. Input variables for artificial neural networks can be: the PV panel parameters, such as V_{OC} and I_{SC} , the insolation and the temperature in any combination. The output is normally a reference signal which can be either a voltage, current or fill rate. In order to accurately determine the MPP, weights of related neurons must be carefully calculated in the framework as a part of a comprehensive training process. Once trained, the artificial neural network can be used as an estimator of the MPP, which gives the reference value (V_{MPP} or I_{MPP}) for the MPPT controller. Other fuzzy calculation methods, that are gaining attention, are the evolutionary algorithms (EA). They are stochastic methods which seem to be very effective for optimization of the real non-linear and multi-modal objective function[7,8,10]. The effectiveness results from basing the technique on a search optimization, which in fact should be able to locate the MPP regardless of environmental changes. In the literature, various methods for the EA are presented. The most popular include the Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Differential Evolution (DE).

Due to the computational complexity of genetic algorithms and artificial intelligence methods it is necessary to use devices with a high computational power what significantly increases the cost of the entire PV system. In addition, their use does not significantly increase the efficiency of the MPP tracking.

The MPP searching algorithm at a partial shading should be characterized by a high speed and an accuracy of determining the global maximum, because of the possibility of rapid changes of illumination.

2. The proposed method

The proposed method is an attempt to combine two methods: the open circuit voltage method and the P & O method with a variable step. It uses them to determine the MPP in uneven lighting conditions. When compared to [18], the open circuit voltage is determined on the base of the parameters of the PV module, Eq. (4),

$$V_{OC} = V_{OC,STC} + K_V \Delta T, \quad (4)$$

where $V_{OC,STC}$ is the open circuit voltage at reference conditions, K_V is the temperature coefficient given by the producer, ΔT is the difference between the panel temperature and the temperature in standard conditions. Substituting the above equation to Eq. (2), the voltage in the MPP of a single module is:

$$V_{MPP} = k(V_{OC,STC} + K_V \Delta T). \quad (5)$$

The voltage of each of the local maxima may be determined using the equation:

$$V_{LMPP,n} = \sum_1^m V_{MPP,m}, \quad (6)$$

where $V_{LMPP,n}$ is the voltage of the n-th local maximum and $V_{MPP,m}$ - the voltage of the maximum power of the m-th module.

To speed up the detection of the MPP the authors of [15] introduce a condition that if the quotient of a current change (resulting from an abnormal operation) point to the current point of $0.8 V_{oc}$ is not lower than the same quotient in terms of the standard test condition then the condition is that of the uniform insolation. This simplification can be described by the following equation [15]:

$$\frac{\Delta I_c}{I_c} < \frac{\Delta I_{c, stc}}{I_{c, stc}}, \tag{7}$$

where I_c is the actual current, ΔI_c is the increase in the current, and $I_{c, stc}$ is the current in standard test conditions.

It is not necessary to check the above relationship each time the temperature of each module is measured, because the surfaces of shaded solar modules have different temperatures. In the above method, this relationship is checked only in the case where all modules have the same temperature.

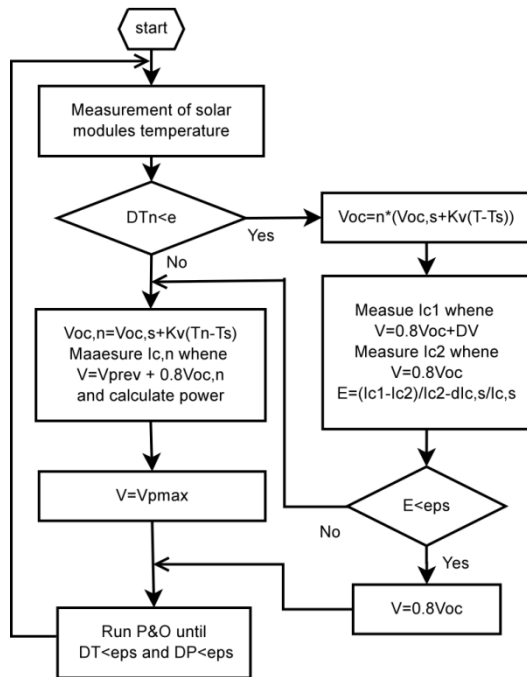


Fig. 1. A block diagram of the proposed algorithm.

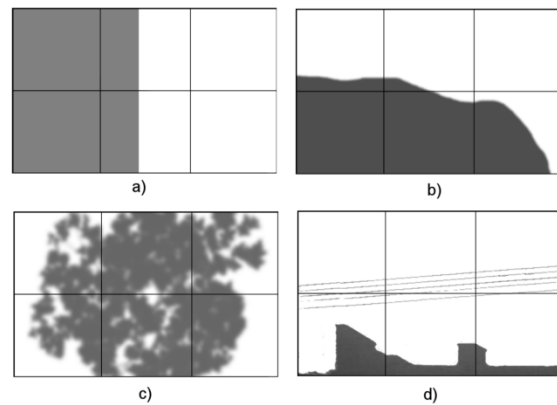


Fig. 2. Shading patterns used in the simulations: a) gradual and equal shading of the whole solar panel, b) shading caused by a cloud, c) shading caused by a tree, d) shading caused by a building.

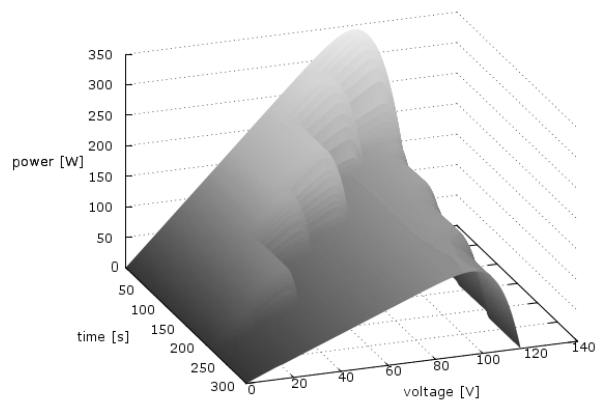


Fig. 3. An example of the power-voltage curve caused by shading in Fig. 2b.

Taking measurements of temperature the MPPT system can estimate the occurrence of local maxima points in time dependent only on the number of photovoltaic modules in series.

Additionally, thanks to the use of temperature sensors, the system can analyze damages of photovoltaic panels and detect hot spots.

Another important advantage of the proposed algorithm is that there is no need to separate the circuit. The open circuit voltage measurement should be performed in a steady state and because of that there must be some delay, during which the load is not supplied with energy. In the developed algorithm, the open circuit voltage is estimated on the basis of the measured temperature, which significantly reduces the time necessary to determine the global maximum.

A block diagram of the proposed algorithm is shown in Fig. 1. At the beginning the temperature is measured. If the temperature difference of the individual modules is not greater than ϵ the algorithm verifies the condition of Eq. (7). If the condition is fulfilled the P & O algorithm is used with the starting point equal to $0.8(V_{OC, stc} + K_V(T_{mean} - T_{stc}))$. If the condition is not met, or if the temperature difference of the individual modules is greater than ϵ , the algorithm would measure the power at the points calculated with Eq. (6). Regarding the MPP the P & O algorithm is running until there is no change in the temperature or the power greater than ϵ .

3. Simulation results

The simulations were carried out in the designed by the authors software which allows verifying the MPP searching algorithms under real shading conditions. The photovoltaic panel model consists of six serially connected modules MSX-60PV with the parameters shown in Tab. 1 with the bypass diodes neutralising negative current cases by a partial shading condition.

Tab. 1. The parameters of the PV module.

| Parameter | Variable | Value |
|-------------------------------------|-----------|-------------------------|
| Maximum power | P_{MPP} | 60W |
| Voltage at MPP | V_{MPP} | 17.1V |
| Current at MPP | I_{MPP} | 3.5A |
| Open circuit voltage | V_{OC} | 21.1V |
| Short circuit current | I_{SC} | 3.8A |
| Temperature coefficient of V_{OC} | K_V | $-80 \pm 10\text{mV/K}$ |

The software used to verify the algorithm uses a model of the photovoltaic module which is described in the MatlabTM / Octave environment. The software simulates the photovoltaic panel using Octave Api. The model of a single photovoltaic module has been developed on the basis of the articles [5,9].

3.1 Verification of the algorithm in various lighting conditions

The simulations of the algorithm were performed for the shading as in Fig. 2. An example of the power-voltage caused by the shadow of Fig. 2b is shown in Fig. 3. A number of local maxima are changing their positions and are changing in time. Additionally, it can be seen characteristic changing due to the temperature changes.

As a result of the run of the maximum power tracker with the presented algorithm, the following characteristics of the power-time are shown in Figs. 4,5,6,7. One can observe the action of the main loop using the P & O algorithm, as well as the action of the

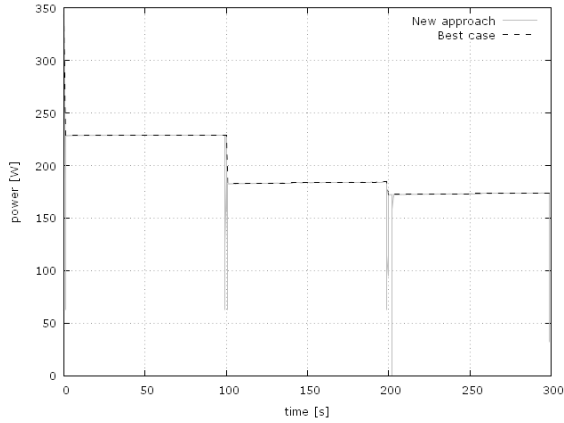


Fig. 4. Tracker power curve compared to the maximum available power for shading in Figure 2a.

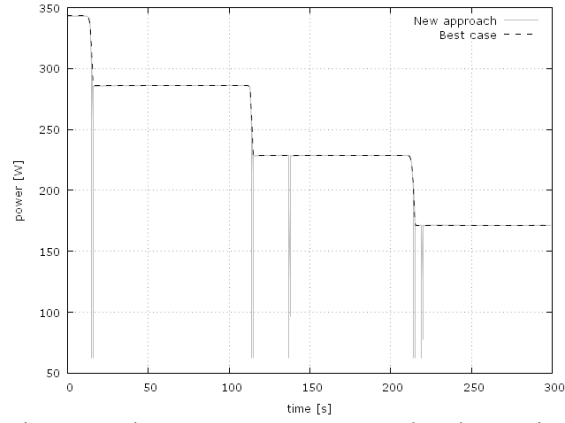


Fig. 6. Tracker power curve compared to the maximum available power for shading in Figure 2b.

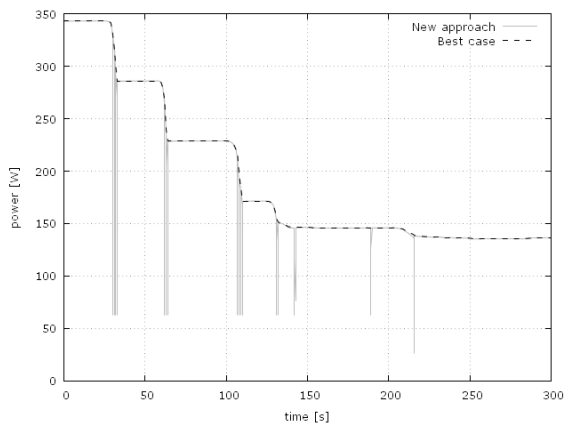


Fig. 5. Tracker power curve compared to the maximum available power for shading in Figure 2c.

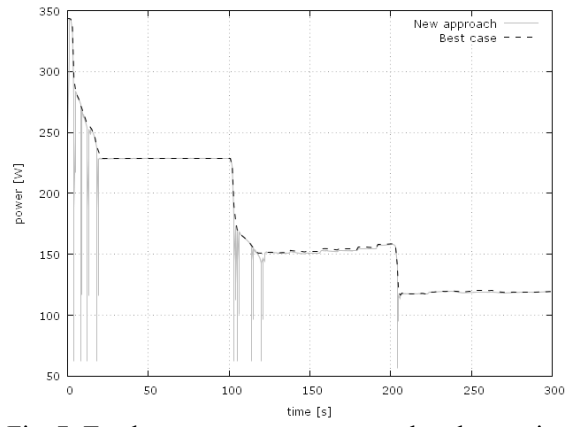


Fig. 7. Tracker power curve compared to the maximum available power for shading in Figure 2d.

coarse loop of the MPP searching. The algorithm quickly finds the MPP, and its convergence is directly proportional to the amount of PV modules in series. The coarse searching loop was launched in two cases: if the change of the power was greater than 2W, and if the temperature change of a single module was greater than 2°C. In each of the examined cases the algorithm showed the tendency to erroneous determination of the global maximum, so the main loop searching for the MPP was working correctly.

The derived results confirm the correctness of the algorithm as well as the speed of its operation, even in very fast changing illumination conditions.

3.2 Examination of the influence of the parameters specified by the manufacturer on the operation of the algorithm

The analysis was performed for the shading including one of the modules. As a result the local maximum appeared on the power-voltage characteristics. The main parameters examining the proposed algorithm are: the open circuit voltage and the coefficient of the temperature. The sunlight was set to 1000W/m². The ambient temperature was varied from 10 to 40°C. The temperature of the panel did not exceed 70°C. The sampling frequency was set to 100Hz. The initial step of the P & O algorithm was set to 0.2V.

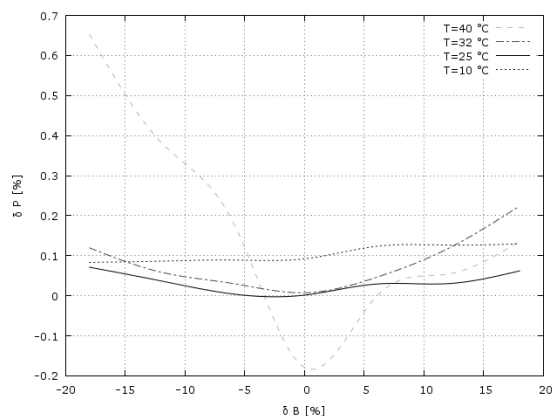


Fig. 8. Dependency lookup failure of the global maximum, depending on the value of the coefficient of the temperature and the ambient temperature.

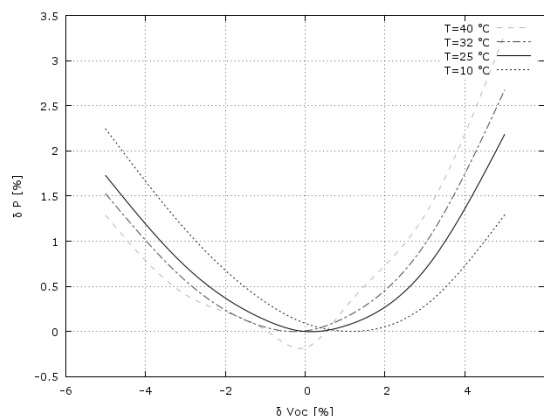


Fig. 9. Dependency lookup failure of the global maximum, depending on the value of the open circuit voltage and the ambient temperature.

The change of the coefficient of the temperature B in the range of $\pm 20\%$ does not affect the convergence time of the P & O algorithm at the MPP. The searching time varies from 140 to 150 samples in the case of the maximum deflection. It results directly from a small, less than 1%, power change during the coarse searching algorithm, Fig. 8. The higher the ambient temperature, the stronger the influence of the coefficient on the accuracy of the coarse searching loop and on the ability to track the global maximum. However, even in the worst case an error does not exceed 1%.

Fig. 9 shows how the open circuit voltage and temperature influence the power. The open circuit voltage value has a greater impact on the problem of determining the global maximum point for higher ambient temperatures. An error can reach a value of 3.5% for the ambient temperature above 40°C and the five-percent deviation. By applying the P & O algorithm with a variable step the time of searching the global maximum point reaches 180 samples.

4. Conclusions

The presented method is highly effective in fast changing and fixed light conditions. It has got all the advantages of the P & O method with a variable step. The analysis of various shadings, various values of the open circuit voltage and the coefficient of the temperature given by the manufacturer confirms the correctness of the proposed algorithm.

The advantage of the proposed method is that there is no need to separate the circuit in order to measure the open circuit voltage. The measured temperature greatly accelerates the searching speed of the MPP. Additionally, we are able to track the hot spots and appropriately quickly respond to overheating.

By applying the curve searching algorithm the proposed method is characterized by a fast convergence to the global MPP as well as by a fast response to changes in the insolation.

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