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Analysis of Hot Spots on Photovoltaic Panels

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Abstract: The increase in photovoltaic systems necessitates addressing hot spot issues. Analysis reveals that shading, dust, and manufacturing defects can lead to hot spot formation. A proposed voltage measurement method, based on the Hot Spot Index (HSI), enables hot spot identification and localization. Experiments confirm its effectiveness in detection. Additionally, nearby surrounding areas are also affected, indicating their potential thermal impact. This proactive approach allows minimizing the adverse effects of hot spots on the performance and lifespan of PV systems.

Keywords: Photovoltaic panels, hot spots, comparative voltage measurement, Hot Spot Index, PV system performance.

1. Introduction

The necessity to reduce greenhouse gas emissions and the increasing demand for electrical energy has led to a higher proportion of electricity production from renewable sources. In Slovakia, besides hydroelectric power plants, conditions also favor the direct conversion of solar energy into electrical energy. The increase in installed photovoltaic power plants has been significant in recent years, influenced by several factors. Firstly, state support provides subsidies for the establishment of photovoltaic sources, and secondly, there are concerns among households and industries regarding the rising prices of electricity recorded in the recent period [1], [2].

The increased number of photovoltaic sources brings with it an increased risk to their stable operation for distribution companies as well as for the operator of the photovoltaic source. During the operation of the photovoltaic source, numerous problems arise, which will be discussed in this paper. These problems result in a reduction in the amount of electricity generated, thereby prolonging the return on investment [1], [3].

Photovoltaic energy sources are unidirectional sources, hence the need for transformation of DC energy to AC energy. Losses occur during this transformation, depending on various factors. The operation of the photovoltaic source itself is accompanied by many changing conditions - varying temperature conditions and changing solar radiation. These significant changes influence the generated output from the photovoltaic source (PVS). Many parameters, such as the temperature of the photovoltaic panel, its degradation, defects, and others, cause significant differences in the amount of electricity generated. On the other hand, photovoltaic power plants pose significant challenges during their operation [4], [5].

2. Hot spots

Hot spots are a common occurrence and are difficult to predict. Temperatures in these areas can reach up to 150°C, leading to permanent and irreversible damage to the photovoltaic panel, such as glass breakage due to high temperature, degradation of cells, and therefore, of the panel, etc. When PV cells are connected in series and one of the cells is shaded, the overall current in the series connection of these cells decreases, causing the good cells to produce higher voltage, which often can adversely affect the bad cell [1], [6].

The operating current of this entire series section approaches the short-circuit current of the shaded cell. The energy generated in the good cells will concentrate in the shaded PV cell, increasing the overall temperature of the faulty PV cell because a large amount of energy is concentrated on a small area. This energy is "consumed" in this faulty PV cell and converted into heat, which can reach up to the aforementioned 150°C. The huge consumption of energy in a small area leads to local overheating in the PV panel. This causes a reduction in the efficiency of the PV panel and a decrease in the amount of electrical energy produced in this panel as well as in the entire photovoltaic system. In severe cases, hot spots can cause permanent damage to the PV panel, reduce its lifespan, and thereby increase the payback period of the photovoltaic power plant [1], [5], [7].

The main cause of hot spots on PV panels is shading. When a part of a PV panel is shaded, the PV cells connected in series generate a large reverse voltage on the shaded PV cell. This causes heat to accumulate in the shaded area, leading to an increase in temperature in the affected area and the formation of hot spots. Additionally, shading can reduce the overall efficiency of the PV panel because the PV cells in the shaded area are not able to produce electricity at the same rate as the rest of the PV panel. Another factor contributing to the formation of hot spots is the accumulation of dust and dirt on the PV panel. Dirt and dust on the surface of the PV panel can reduce the amount of sunlight reaching the PV cells, decreasing their efficiency. This leads to reduced performance and increased temperature of the photovoltaic panel. Moreover, impurities can affect the airflow over and around the panel, which is crucial for heat dissipation and maintaining a consistent temperature of the PV panel. As has been mentioned multiple times, temperature significantly affects the operation of the photovoltaic panel, resulting in reduced power generation from this photovoltaic panel as well as the entire system. The design and construction of the PV panel can also play a role in the occurrence of hot spots. Insufficient insulation or inadequate ventilation can lead to overheating and the formation of hot spots, as heat cannot be efficiently dispersed. In some cases, the cells themselves may be poorly designed or manufactured, leading to reduced performance and an increase in the amount of generated heat [8], [9].

To prevent the formation of hot spots, it's necessary to consider the causes of their formation. Regular cleaning of PV panels is essential to prevent hot spots, although it can be inefficient during normal operation. Occasional rain can help in cleaning PV panels. Proper insulation and cooling of PV panels can also help in dispersing heat and preventing overheating, though this affects the cost of the PV system design. In case of shading, the use of bypass diodes is also a possibility. Bypass diodes have become a common component of PV panels, so in such cases, the performance of the PV system is less affected by shading or the failure of a single PV panel. Currently, most panels use three diodes for 60 or 72 PV cells, or one diode for every 20 or 24 PV cells. Bypass diodes are typically calculated for a specific current and voltage. Therefore, they are selected based on the specifications of the specific PV panel in which they are used. They are usually placed on the back of the panel and are designed to be as compact as possible [1], [7].

Hot spots arise due to the heterogeneity of PV modules due to uneven illumination. These undesirable locations can occur due to shadows, dirt, and damage to PV modules, or manufacturing defects. Consequently, temperature increases, leading to decreased efficiency and panel lifespan. Hot spot detection is critical because traditional methods such as thermography are time-consuming and require direct sunlight to create significant temperature differences for accurate detection. Temperature also affects the shape of the V-A characteristics, causing the voltage of the PV module to decrease with increasing temperature. Therefore, if a hot spot occurs during PV system operation, it will primarily manifest as a voltage drop, as shown in *Fig. 1*, where the shaded cell generates lower current, causing a bypass diode to activate and leading to a reduction in the overall output voltage of the string.

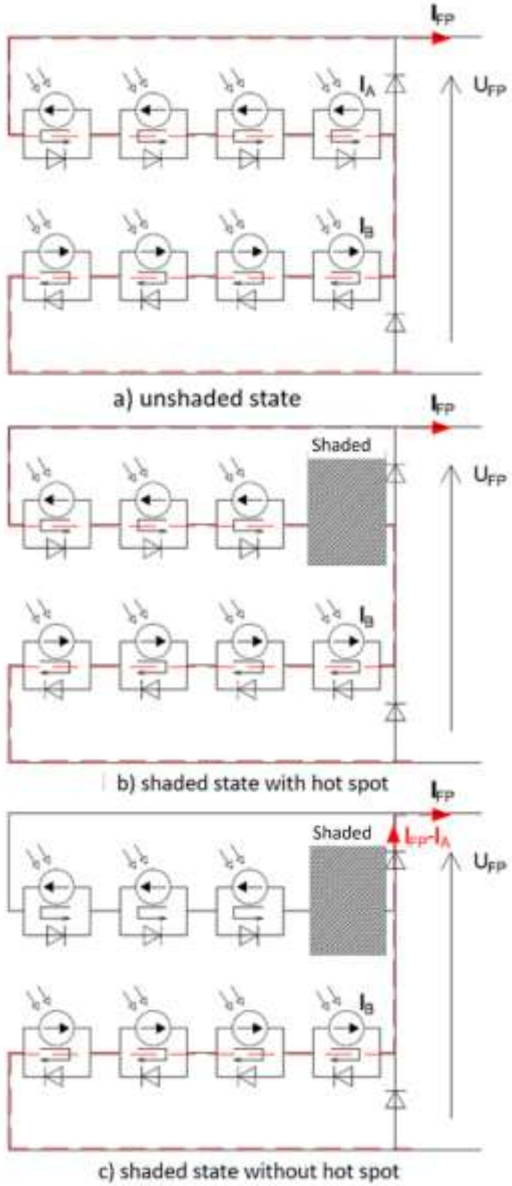

Figure 1: Three scenarios for explaining the hot spots creating

Fig. 1 illustrates and compares three scenarios:
a) Unshaded state;
b) Shaded state (one module shaded) with a hot spot;
c) Shaded state (one module shaded) without a hot spot.

In the unshaded state (a), the PV module operates smoothly, and currents I_A and I_B are equal, both equal to I_{FP}. However, in scenario b), where one module on the PV array is shaded and afflicted with a hot spot, the situation differs. Comparing scenarios b) and c), there is a discrepancy in the value of the generated current I_{FP}. In scenario c), if the PV array did not contain a hot spot, the bypass diode would be activated, allowing current I_B to flow only in the lower part of the circuit. However, in the region affected by the hot spot, the value of the parallel resistor decreases, diverting current to the upper part of the PV array without activating the bypass diode. On the other hand, if one section of the PV array is completely shaded (with a high value of the parallel resistor), the bypass diode reacts, preventing current flow through the upper part. Additionally, if the PV array did not include bypass diodes, the generated current in the entire series section (upper + lower part) would be zero.

3. Evaluation of hot spots areas

Fig. 2 depicts a simulation model consisting of three PV cells connected in series. The second PV cell is shaded (voltage on the voltage-controlled current source is set to 0), and a hot spot is created on this PV cell - the value of the second parallel resistor RP2 is set to 0.01 Ω. As mentioned earlier, the hot spot causes a decrease in the value of the parallel resistance in the branch where the hot spot is located.

The resulting V-A characteristic of the PV array with and without a hot spot is depicted in *Fig. 3*, where the following observations can be made:

a) The hot spot caused a change in the shape of the V-A characteristic, as evident in *Fig. 3*. This change in shape also manifested in an alteration of the knee shape of the V-A characteristic.

b) The short-circuit current (I_{SC}) was not reduced by the presence of the hot spot; it remained the same at 10A, similar to the shaded PV array. It means that the short-circuit current remains approximately the same, but the shape of the knee changes, which also causes a shift in the MPP point.

c) The open-circuit voltage (U_{OC}) decreased from 68.5 V to 67 V, representing a decrease of 2.2% due to the hot spot. In contrast, for the shaded PV array, the U_{OC} decreased from 68.5 V to 45.3 V, a decrease of 34%. These results indicate that in the case of a shaded PV array without a hot spot, the U_{OC} decreases substantially more than in the case of a shaded PV array with a hot spot. If the part where the hot spot appeared were not 100 percent shaded, it is assumed that the open-circuit voltage would decrease less. However, the statement in the first sentence would still hold true.

d) A load line, depicted in black, intersects the V-A characteristics in all three cases in *Fig. 3*. A voltage drop from 65.4 V (blue curve - normal) to 43.6 V (green curve - shaded) or to 63 V (red curve - hot spot) can be observed.

e) In the absence of bypass diodes, the current value would be 0A for the shaded PV array (green curve).

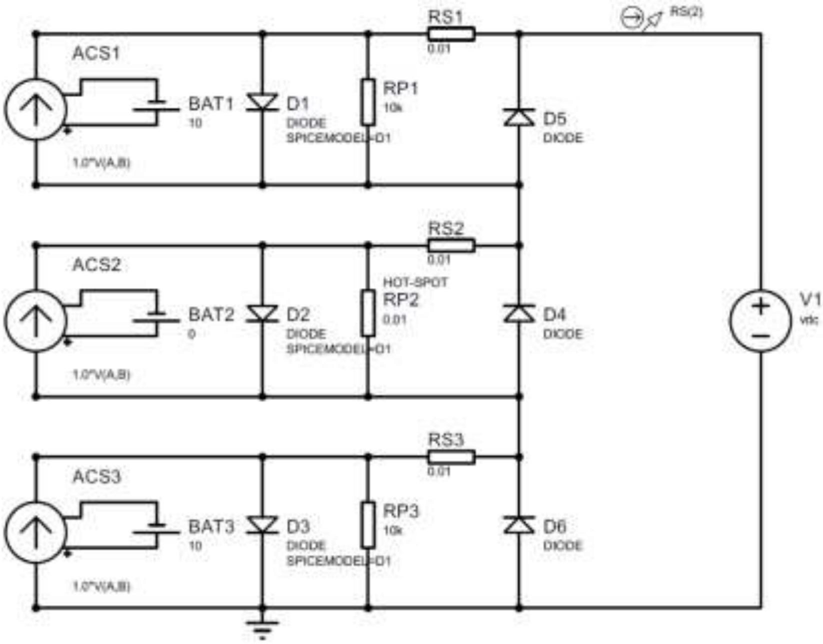

Figure 2: Simulation model for understanding hot spots

From the results shown in *Fig. 3*, it is observable that there is a greater voltage drop in the shaded PV array compared to the case with a hot spot. Therefore, if a hot spot occurs during the operation of the PV system, it will result in a less significant voltage drop than when that part is shaded. In the case of shading, the shaded part acts as an open circuit, leading to a voltage drop, and the current bypasses this part through the bypass diode.

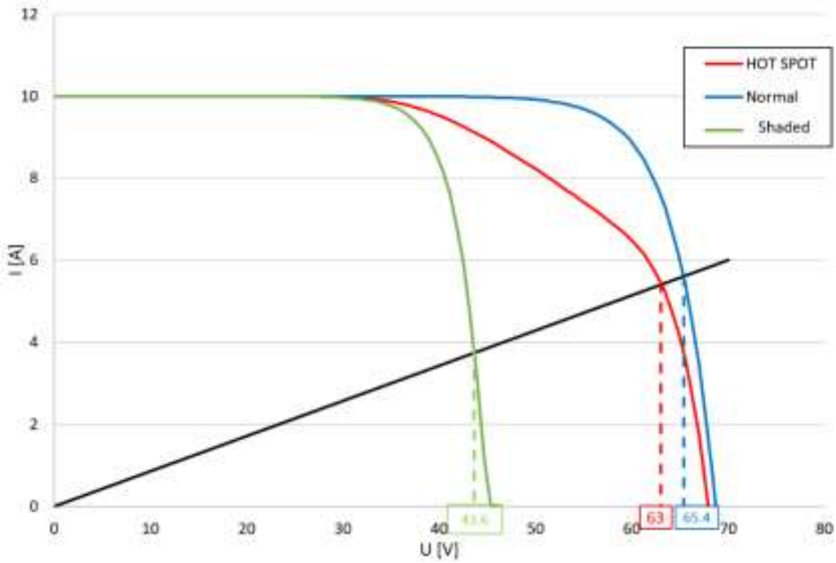

Figure 3: Comparison of V-A characteristics of PV panels – HOT SPOT (red), Normal (blue), and Shaded (green)

Based on the aforementioned, it is possible to measure the voltage on the PV array while gradually shading a certain portion of it. By comparing the voltages, the Hot Spot Index (*HSI*) can be calculated using the formula:

$$HSI = \frac{U_0 - U_1}{U_0} . 100\% , \tag{1}$$

where *HSI* is the hot spot index, U_0 is the voltage of the PV array without hot spots or other defects, and U_1 is the voltage of the PV array during subsequent measurements. If this procedure is repeated for each part of the PV array, it is possible to identify whether a hot spot has formed on the PV array and also where exactly this hot spot is located on the PV array. In the first step, the first part of the PV array was shaded, which was then connected to the load, and subsequently, the voltage U_1 was measured. Each part of the PV array was gradually shaded, and the voltage U_1 was again measured on the next part of the PV array. The reference value U_0 was the voltage value under the same load, but for the PV array without defects. In this way, measurements were taken for 2 photovoltaic panels, assuming the existence of a hot spot. The photovoltaic panel was divided into 60 parts, each gradually shaded, and the *HSI* index was calculated step by step.

During this measurement, the intensity of sunlight impacting the PV array during the measurement is not crucial since this measurement falls into the category of comparative measurements. However, it is important for this value to change as little as possible. To ensure the highest precision of the measurement, the measurements were conducted during the night in a laboratory setting. The photovoltaic panels were illuminated by a projector, which provided a constant illumination value. Additionally, the projector allowed for setting boundaries for the illumination incident on the PV array. After illuminating the photovoltaic panel with the projector, a portion of the PV array was shaded for 10 seconds. After this period, measurements were taken 5 times, and subsequently, the average voltage value U_1 and then the *HSI* index value were calculated.

In *Fig. 4* and *Fig. 5*, the values of the *HSI* index for each shaded part of the PV array and for both photovoltaic panels are displayed. In the graphs, red columns are marked where the existence of a hot spot is presumed. These red columns exhibited significantly lower values compared to the remaining columns.

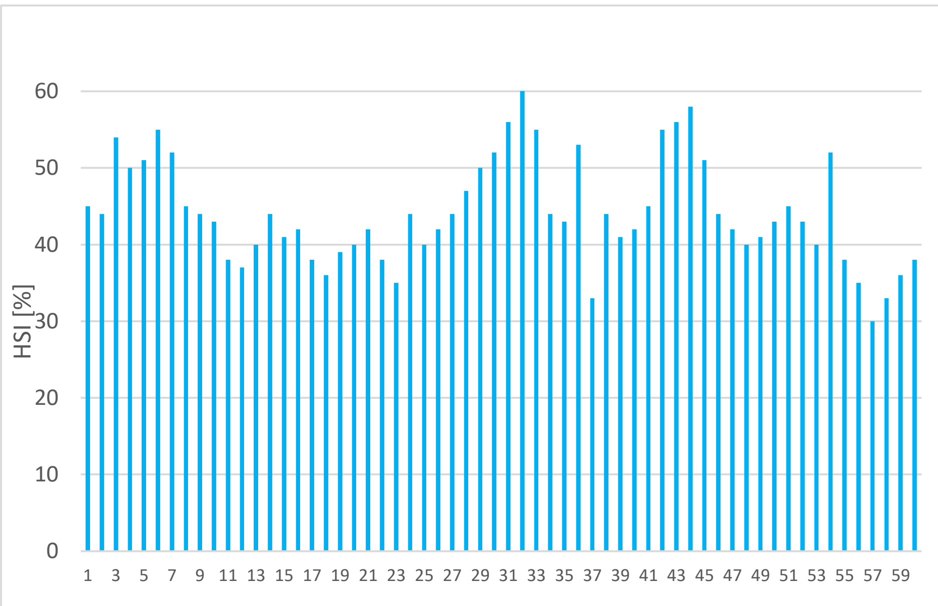

Figure 4: Photovoltaic panel without hot spot

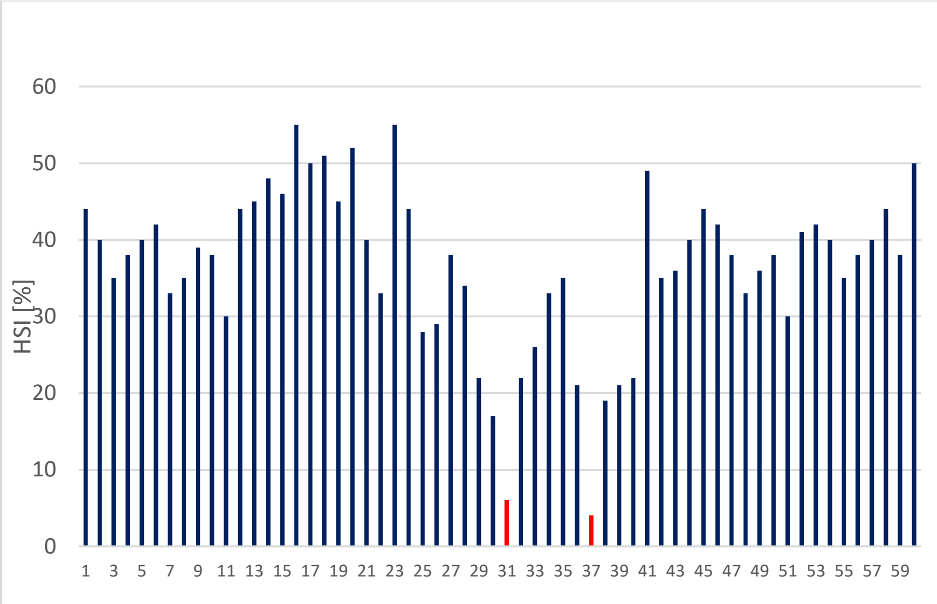

Figure 5: Photovoltaic panel with two hot spot area

In *Fig. 4*, the *HSI* index for the 1st PV panel is depicted, where it can be observed that none of the shaded areas reached markedly lower values than the remaining shaded areas. Therefore, it can be assumed that no hot spot is present on this PV panel. Furthermore, in the case shown in *Fig. 5*, it can be observed that the parts of the PV panel surrounding the area with the hot spot achieve low *HSI* index values. It can be assumed that these surrounding parts are also affected. Therefore, it can be inferred that the occurrence of one "faulty" spot with a hot spot may influence nearby areas with its elevated temperature.

4. Conclusion and discussion

The study examines issues associated with the formation of hot spots on photovoltaic panels. It identifies shading, dust, and manufacturing defects as causes of hot spot formation. A proposed voltage measurement method based on the Hot Spot Index (*HSI*) enables hot spot identification and localization. Experiments confirm its effectiveness in detection. Additionally, it is revealed that nearby areas are also affected, indicating their potential thermal impact. This proactive approach allows minimizing the adverse effects of hot spots on the performance and lifespan of PV systems. This manuscript emphasizes the importance of identifying and monitoring hot spots on photovoltaic panels. The proposed *HSI* measurement method has proven to be an effective tool for detecting and locating these issues. The insights gained enable a better understanding of the mechanisms behind hot spot formation and support the implementation of preventive measures to minimize their negative impacts. This analysis contributes to optimizing the performance and longevity of photovoltaic systems.

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