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FAULT DIAGNOSIS OF PHOTOVOLTAIC MODULES BY MONITORING THE I-V CHARACTERISTICS AND PROCESSING THERMAL IMAGES

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Abstract: This paper diagnoses faults on photovoltaic (PV) modules before and after the commissioning of the "Zvizdan" photovoltaic power plant, aiming to ensure reliable and safe operation of the plant and reduce technical losses to optimize the production of PV modules. All PV modules are inspected with thermal camera, with a focus on safety and reliability before commissioning, and on minimizing production losses after commissioning. Then, the I V curve parameters of modules showing faults in thermal images are measured and compared with manufacturer's data. Results of this research provide deeper insights into the efficiency reduction of PV modules caused by various faults and they question a need for module replacement due to economic losses and protection of the system from extreme events such as fires.

Keywords: photovoltaic modules, thermal images, I V curve, efficiency, faults

INTRODUCTION

In recent years, there has been an exponential growth in photovoltaic power stations across the world. This brings many problems associated with reliability of photovoltaic (hereafter referred to as PV) modules and the optimization of electrical energy production from them. Generally, major faults develop from several smaller issues, indicating that the regular application of methodologies for fault detection and identification could prevent large scale failures [1].

In this paper, a practical example of the "Zvizdan" PV power plant is used to diagnose and analyze early faults and errors in bifacial PV modules, both before and after the plant's commissioning. Faults detected in the early stages typically occur in less than 1% of the total number of modules. Infrared thermography (IRT) method allows a quick and non invasive assessment of the technical condition of the PV modules without interrupting the power supply. Regular monitoring of the modules with an infrared camera enables the inspection of a large number of modules in a relatively short time and facilitates rapid intervention on targeted problematic modules. This approach reduces maintenance costs by more accurately locating faults and helps protect the system from extreme events, such as fires. Measuring the current voltage (I V) characteristic and its main parameters allows a more precise evaluation of the PV modules' efficiency. Regular monitoring also helps identify changes in the characteristics of the PV modules due to aging, damage or other factors. This provides a deeper insight into the efficiency reduction of PV modules and it questions a need for module replacement due to economic losses.

1. MEASUREMENT DATA ANALYSIS

For the purpose of this research, the DJI Mavic 3T drone with a thermal camera was used to analyze the temperature of the modules, and the Metrel MI 3115 PV Analyser was used to measure the I V curve and its main parameters. Measurements should be conducted in calm weather conditions, with good irradiance (min. 600 W/m^2) and clear skies to avoid cloud shading during recording. IRT is not performed directly, perpendicular to the module, but at an angle between 5° and 60° [2]. IRT provides a temperature display of the imaged surface, and areas with higher surface temperatures (hot spots) are characterized as potential fault locations. Once modules with hot spot areas are identified, the I V curve is measured. This requires stopping the operation of the PV power plant, physically disconnecting the identified module, and using insulation equipment.

1.1. Functional PV module

Figure 1.a shows a thermal image of functional PV modules, without any hot-spot areas. On all modules, including the ones shown, two horizontal parallel lines can be observed. Analysis of thermal images revealed a temperature rise of 2°C to 3°C compared to the rest

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of the module, which does not qualify as hot spot areas. The cause of this temperature rise is slight shading from the underside of the module, which occurs due to the proximity of the substructure on which the bifacial PV modules are placed, initially designed for monofacial modules. Two modules were selected as reference modules for measuring the I V characteristic and its main parameters, one from the upper string and one from the lower string. Figure 1.b shows the I V characteristic of the PV module from the lower string.

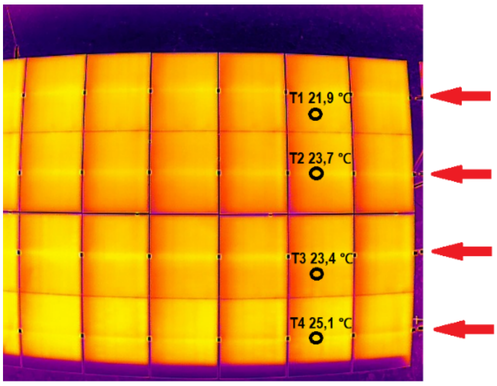

Figure 1.a: Thermal image of functional PV modules

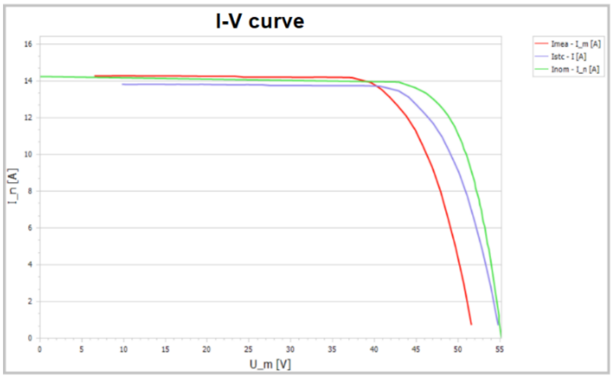

Figure 1.b: I-V curve of functional PV modules

In the I V characteristic, three graphs are visible (Figure 1.b). The red graph represents the actual measured I V characteristic. It directly depends on the current measurement conditions (cell temperature, irradiance, etc.). In order to compare the characteristics of different modules, it is necessary to standardize them to the same measurement conditions. Since this is not possible, the measured characteristic of all modules is recalculated to STC conditions for each measurement, enabling a comparative analysis of the modules (blue graph). The STC measurement conditions are an irradiance of 1000 W/m² and a cell temperature of 25 °C. The green graph represents the nominal characteristic, with its main parameters taken from the manufacturer's datasheet, a summary of which is provided in Table I.

Table I. Electrical parameters of PV module JA Solar - JAM78D40-615/MB

Parameters	Symbol	Value
Open-circuit voltage	V_{oc}	55,2 [V]
Short-circuit current	I_{sc}	14,23 [A]
Maximum power point voltage	V_{mp}	46,07 [V]
Maximum power point current	I_{mp}	13,35 [A]
Maximum power	P_{max}	615 [W]
Relative change of Pmax	ΔP_{mpp}	-
Irradiation	I_{rr}	1000 [W/m²]
Cell temperature	T_{cell}	25 °C

The measurement results of electrical parameters for two selected PV modules are shown in the Table II.

Table II. Measurement results of the electrical parameters of the functional PV modules (blue graph)

PV module	Manufacturer's data	Upper string PV module	Lower string PV module
V_{oc}	55,2 [V]	54,4 [V]	54,4 [V]
I_{sc}	14,23 [A]	14,06 [A]	13,81 [A]
V_{mp}	46,07 [V]	43,5 [V]	44,1 [V]
I_{mp}	13,35 [A]	13,88 [A]	13,11 [A]
P_{max}	615 [W]	604 [W]	578 [W]
ΔP_{mpp}	-	-1,75 %	-6,09 %
I_{rr}	1000 [W/m²]	1032 [W/m²]	1022 [W/m²]
T_{cell}	25 °C	44,5 °C	47,1 °C

The measurement results show a power loss increase of 2% to 5% for the lower row of PV modules (Table II). The reason for this could be lower irradiance on the underside of the modules, greater susceptibility to contamination, reduced cooling, and shading from the adjacent row of PV modules. Therefore, a combiner box containing all functional modules was selected, and the results of the power loss are shown in Table III. The same table also shows the varying power loss across all modules.

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Table III. Measurement results of the power loss for all strings in a single combiner box.

Upper string	Relative power change of upper string	Lower string	Relative power change of lower string
S01.	-1,11 %	S02.	-4,18 %
S03.	-1,67 %	S04.	-4,83 %
S05.	-0,96 %	S06.	-5,79 %
S07.	-2,42 %	S08.	-4,85 %
S09.	-1,99 %	S10.	-5,93 %
S11.	-1,65 %	S12.	-4,47 %
S13.	-1,33 %	S14.	-4,48 %
S15.	-1,66 %	S16.	-7,08 %
S17.	-1,86 %	S18.	-4,23 %

1.2. Junction box fault

The tested PV modules contain three bypass diodes, all located in a single junction box. Overheating of the junction box is most commonly caused by inadequate design, manufacturing defects, wiring issues, such as poor connections, or mechanical stress during transport. Inadequate design or improper sealing of the junction box allows moisture ingress, which causes corrosion of the internal connections (Figure 2). This results in wiring failure, leading to internal arcing.

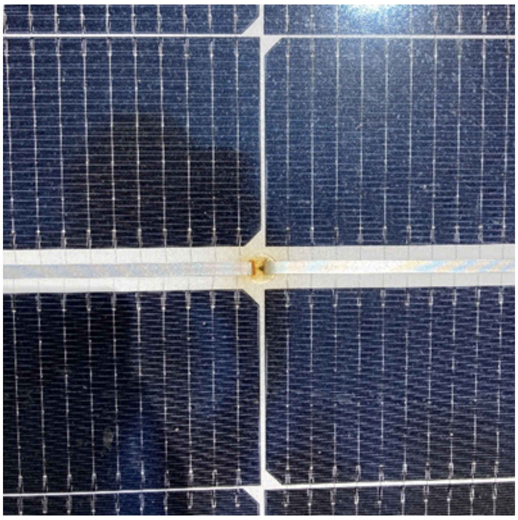

Figure 2: Corrosion at the installation site of the junction box

Internal arcing can occur due to the formation of a crack either at the interface between the solder joint and the silver (Ag) electrode (Ag leaching) or within the solder joint itself due to thermal stress, which reduces the joint's strength (solder joint degradation). In the case of Ag leaching, when the solder joints come into contact with the Ag electrodes of the solar cell, they get dissolved with the solder electrodes (Tin Lead (Pb Sn)), forming an Ag3Sn compound. This Ag leaching effect causes a crack in the soldered interface due to thermal expansion, which, in extreme cases, leads to a connection breakdown. [3]

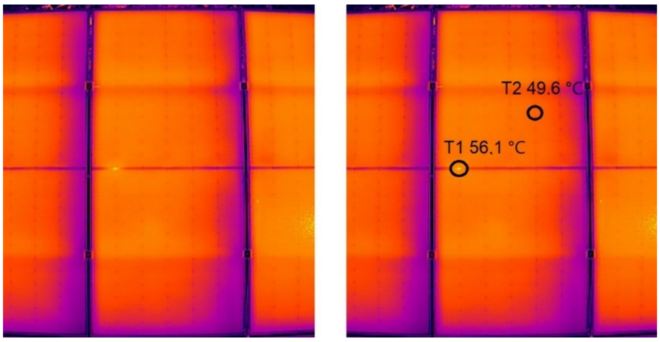

Figure 3: Thermal image of junction box fault

Excessive heating of the junction box leads to energy loss due to resistance within the bypass diode (conversion to thermal energy), which can reduce the module's efficiency or even cause failure. Therefore, this type of issue requires regular monitoring. Figure 3 shows one of the observed cases, where, despite temperature variations, there is no impact on the rest of the module or production efficiency, making this example not concerning at this stage. The cold periodic (purple) areas are caused by shading and the drone's angle.

1.3. Cell string and junction box failures

In addition to the junction box fault described in Chapter 1.2, this type of issue also involves faults in the interconnection of PV cells. Interconnection failure can be caused by cell cracking during the manufacturing process, particularly during the stringing process, electrochemical corrosion, a defect in a single cell causing the series string to be interrupted, or a short circuit in the cell string caused by a failure in the junction box. Any fault in the PV cells or contact lines results in thermal expansion and contraction, as well as mechanical stress, leading to a loss in output power. The power loss increases linearly over time. In addition to the decrease in efficiency, this type of

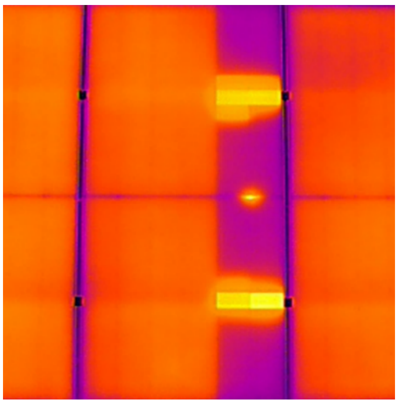

Figure 4.a: Thermal image of cell string and junction box failures

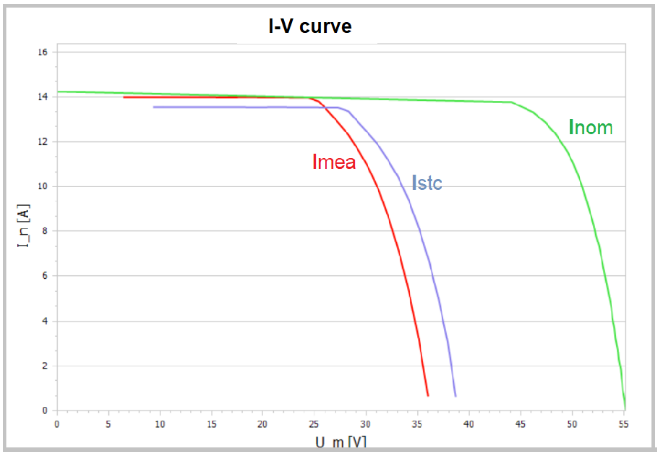

Figure 4.b: I V characteristic for cell string and junction box failures

issue is also hazardous for safety reasons. Extreme conditions may lead to fire or, in the case of broken contact lines, electric shock. [1]

Table IV. Measurement results of the electrical parameters of the PV module with cell string and junction box failures

PV module	Reference	Tested
V_{oc}	54,4 [V]	37,7 [V]
I_{sc}	13,81 [A]	13,54 [A]
V_{mp}	44,1 [V]	28,3 [V]
I_{mp}	13,11 [A]	13,35 [A]
P_{max}	578 [W]	377 [W]
ΔP_{mpp}	-6,09 %	-38,67 %
I_{rr}	1022 [W/m²]	1019 [W/m²]
T_{cell}	47,1 °C	53,6 °C

1.4. Combined external and internal failures

In addition to cell string and junction box failures, cracking of the glass on the PV module has also been found in this type of issue. It is clear that the cracking of the PV module is not a manufacturing defect and is one of the main external causes of module failure. The effects of glass breakage result in module overheating, electrical safety issues, and performance degradation during long-term operation, as moisture can enter through the cracks, leading to corrosion (delamination - see Chapter 1.6). The mismatch in cell currents causes visible distortion in the I V characteristic (Figure 5.b).

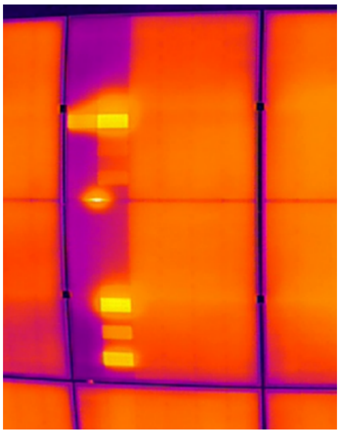

Figure 5.a: Thermal image of combined external and internal failures

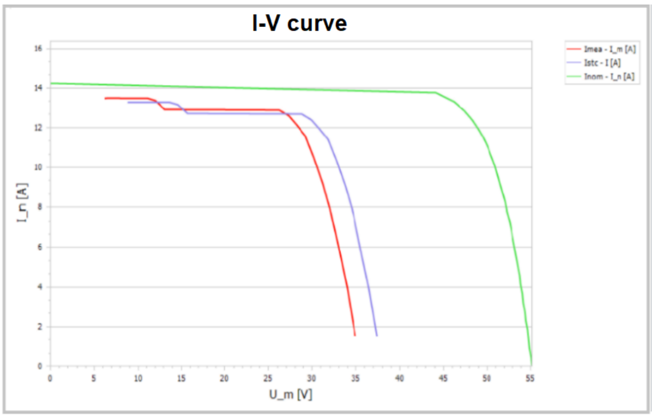

Figure 5.b: I V characteristic for combined external and internal failures

Table V. Measurement results of the electrical parameters of the PV modul with combined external and internal failures

PV module	Reference	Tested
V_{oc}	54,4 [V]	37,3 [V]
I_{sc}	13,81 [A]	13,3 [A]
V_{mp}	44,1 [V]	29,9 [V]
I_{mp}	13,11 [A]	12,4 [A]
P_{max}	578 [W]	370 [W]
ΔP_{mpp}	-6,09 %	-39,77 %
I_{rr}	1022 [W/m²]	1003 [W/m²]
T_{cell}	47,1 °C	51 °C

1.5. Hot spot caused by excessive tightening torque on the clamp bolt

Among the installation issues related to modules, the most common fault is caused by the clamps. It has been shown that clamp designs with sharp edges, narrow clamps, improper positioning, and excessive tightening of the bolts on the module clamps cause excessive pressure on the PV modules, leading to glass cracking, especially in frameless PV modules [1]. Although the PV modules installed at the "Zvizdan"

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PVPP are framed and no visible glass cracking was observed, thermal images revealed hot spots near the clamps on some modules (Figures 6.a and 7.a). As a result, a torque tightening check was performed on the identified modules using a torque wrench. The specified torque for tightening the clamp bolts on the PV module frame during installation is 8 Nm. When the required torque is reached with the torque wrench, the operator hears a “click”. If a click is heard during the first tightening without the bolt moving, it indicates that the application is already too tight. The testing was carried out on a sample from a single string, resulting in a torque range of 13 Nm to 20 Nm, which concludes that the tightening torque was increased across the entire plant, and in some modules to the extent that it could cause hot spots. Two examples are attached below, the first from the upper string, the second from the lower string.

Example 1:

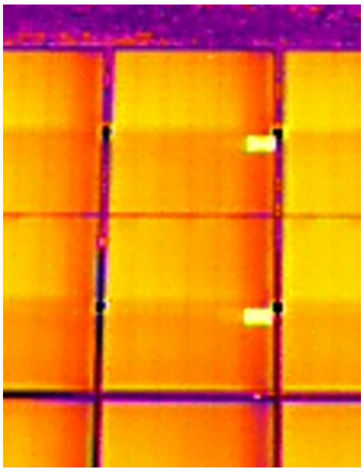

Figure 6.a: Hot spots caused by clamps on the upper PV module

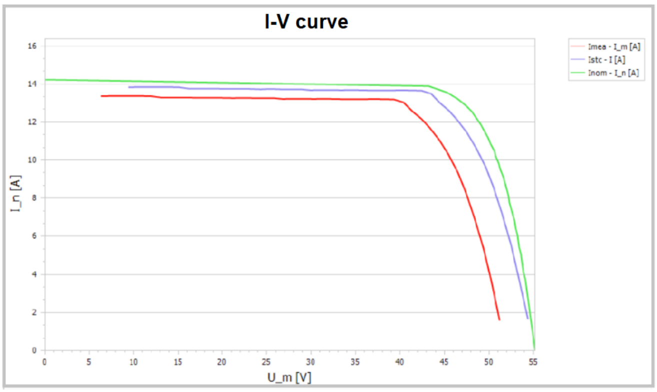

Figure 6.b: I V characteristics of the upper PV module with clamp induced hot spots

Table VI. Measurement results of the electrical parameters of the upper PV module with clamp induced hot spots

PV module	Reference module in the upper string	Tested module in the upper string
V_{oc}	54,4 [V]	54,4 [V]
I_{sc}	14,06 [A]	13,86 [A]
V_{mp}	43,5 [V]	43,5 [V]
I_{mp}	13,88 [A]	13,49 [A]
P_{max}	604 [W]	585 [W]
ΔP_{mpp}	-1,75 %	-4,69 %
I_{rr}	1032 [W/m2]	956 [W/m2]
T_{cell}	44,5 °C	45,8 °C

Example 2:

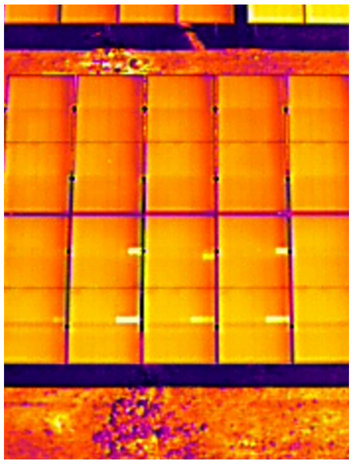

Figure 7.a: Hot spots caused by clamps on lower PV modules

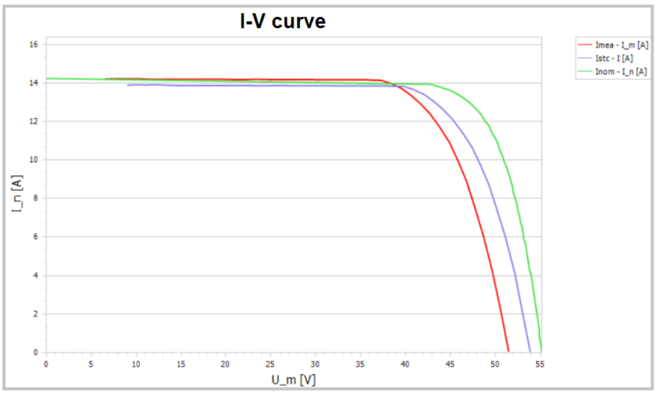

Figure 7.b: I V characteristics of the lower PV module with clamp induced hot spots

Table VII. Measurement results of the electrical parameters of the lower PV module with clamp induced hot spots

PV module	Reference module in the upper string	Tested module in the upper string
V_{oc}	54,4 [V]	53,3 [V]
I_{sc}	13,81 [A]	13,93 [A]
V_{mp}	44,1 [V]	42,1 [V]
I_{mp}	13,11 [A]	13,39 [A]
P_{max}	578 [W]	564 [W]
ΔP_{mpp}	-6,09 %	-8,30 %
I_{rr}	1022 [W/m2]	1071 [W/m2]
T_{cell}	47,1 °C	47,0 °C

1.6. Delamination

Delamination of PV modules is a phenomenon in which the layers of the module, i.e., the glass, silicon cells and encapsulant, separate from one another. The effect of delamination occurs due to environmental factors, primarily humidity, moisture and temperature variations. Theoretically, 90% of modules are prone to delamination. Delamination does not lead to module failure but results in optical reflection, which causes subsequent power loss, while also posing a safety concern. The efficiency of PV modules degrades at a very slow rate, approximately 0.5% per year. This suggests that such issues are more common after a longer period of time [1]. The observed example of delamination at the "Zvizdan" PVPP (Figure 8) cannot yet be detected with a thermal camera at this stage and has no impact on the module's performance.

Figure 8: Example of delamination in the PVPP "Zvizdan"

2. OVERVIEW OF REGISTERED FAULTS

Table VIII shows all registered faults at the PVPP "Zvizdan" categorized by fault type. For each fault type, the average power loss based on the tested sample is also presented. At the current stage, the number of recorded faults (54) relative to the total number of PV modules (48,144) implies a negligible annual production loss.

Table VIII. Analysis of registered faults

Fault type	Quantity	Safety issue	Average power loss
Junction box fault	3	Extreme conditions may lead to fire.	No effect on power loss.
Cell string and junction box failures	26	Failure may cause fire, electric shock, and physical danger.	-37,97 %
Combined external and internal failures	2	Failure may cause fire, electric shock, and physical danger.	-39,77 %
Hot spot caused by excessive tightening torque on the clamp screw	22	No effect on safety until the module eventually cracks. At that point, the fault may cause a physical danger.	Lower string modules: -7,74 % Upper string modules: -3,93 %
Delamination	1	Failure may cause fire, electric shock, and physical danger.	No effect on power loss at this stage.

3. CONCLUSION

The application of the fault diagnostic methodology should improve the system's efficiency, reliability, safety, and fault tolerance. The reliability of the tests presented, particularly the infrared thermography tests, is influenced by various dynamic testing conditions, such as irradiation, reflection, ambient temperature, and the temperature of the PV cell. These factors can affect the accuracy of measurements and cause slight deviations in the results. One of the key conclusions of this paper is the significant decrease in efficiency in the lower row of functioning PV modules compared to the upper row. These measurement results should be taken into account when designing and planning future PV power plants, especially those with bifacial modules. In cases of "cell string and junction box failures" and "combined external and internal failures", the average power loss is so significant that, for both safety and economic reasons, the affected modules should be replaced with new ones, while modules from other categories require regular monitoring. This paper presents research conducted during the early

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stages of a PV power plant's operation. A further direction for future research is the application of the fault diagnostic methodology during the later stages of PV power plant operation. This would enable the analysis of faults caused by system degradation and, in particular, the monitoring of the development of hot spot areas caused by excessive tightening torque on the clamp bolts.

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BIOGRAPHY

Antonio Vico is electrical engineer with a focus on renewable energy. He earned his Master's degree from the University of Mostar in 2021. Currently, Antonio works at FEAL Group, where he plays a crucial role in the development of new renewable energy projects and the maintenance of existing ones. His work includes overseeing operations at a wind farm and multiple solar plants. Additionally, Antonio has gained valuable experience as an electrical testing engineer, specializing in power systems. He is also actively involved in power spot markets, such as CROPEX, where he applies his expertise in energy trading and market dynamics.

Iva Bračić has recently graduated with a Master's degree in Electrical Engineering, specializing in Power Engineering, from the Faculty of Mechanical Engineering, Computing, and Electrical Engineering, University of Mostar. She was a teaching assistant for the practical lectures of the Digital Electronics course.

Anela Pralas graduated from the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split. She worked in real sector as elecrical engineer for eight years in field of development, construction and control on different projects such as electrical design projects, distribution network and photovoltaic power plants projects. Since 2019 she has been employed at JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar in the Development Division as an expert for renawable energy sources. Currently, she is a project manager on large wind power plant project. Also, she works as assistant at the Faculty of Mechanical Engineering, Computing and Electrical Engineering, University of Mostar.