FAULT INSPECTION BY AERIAL INFRARED THERMOGRAPHY IN A PV PLANT AFTER A METEOROLOGICAL TSUNAMI

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4.4 Controle e Monitoramento de Sistemas Fotovoltaicos

Abstract. *Infrared thermography (IRT) has been applied as an effective tool for detecting faults in PV modules. In addition, with the recent development of Unmanned Aerial Vehicles (UAV), they have been used in order to increase the cost effectiveness and employ IRT for large-scale PV plants or roof-mounted PV systems. With the goal of demonstrating the capabilities of the UAV application, especially in aerial thermography analysis, this article presents an experiment applying UAV based IRT, performed for the fault inspection of a PV plant in South Brazil. The local is a 3 MWp PV plant located in the city of Tubarão in the state of Santa Catharina and consists of three 1 MWp-blocks of different PV technologies. On October of 2016, the plant was affected by a meteorological tsunami, causing several damages. The experiment was focused on the detection of the damages on the polycrystalline PV block of the power plant and a DJI Phantom 3 Advanced was equipped with a lightweight infrared camera to perform the aerial IRT. The measurements in the plant were performed in accordance with the international norm IEC TS 62446-3, under stable radiation and weather conditions, exclusively with irradiances above 800 W/m^2 and average wind speeds of 3 m/s. The IRT drone system was essential for identifying damaged and defect portions of the PV power plant fast after the incident. It was possible to detect hot spots, defective bypass-diodes, short- and open-circuited strings. The damages could be noticed even when the UAV flight was at 40 m of altitude. The UAV based IRT assessment helped to identify the defects in a fast manner, without interrupting the power generation. It can be concluded that the technique is very effective, practical and relevant for damage inspection in large PV power plants.*

Keywords: *Unmanned Aerial Vehicle (UAV), Infrared thermography (IRT), Photovoltaics (PV) Plant Monitoring*

1. INTRODUCTION

On a global scale, renewable energies have led to a shift of paradigm in the electricity sector. Mainly the European countries and in recent years China has pushed this development, through their progressive energy policy. Today, photovoltaics (PV) is one of the major protagonists of this development, with an installed capacity of 291 GW in 2016 (IRENA, 2017). Recently, PV has also begun to spread in so called Sunbelt countries like Brazil. A significant growth of at least 3.2 GW is expected until 2024 (ANEEL, 2017).

For the integration of this energy source into the electrical power system and to ensure the reliability of the photovoltaic power generation, operation and maintenance (O&M) of PV power plants is of utmost importance. Therefore, since the early beginning of utility scale photovoltaic power generation, O&M has been adapted as a fundamental method to ensure safety, availability and productivity of the PV plant. During the years various inspection and fault diagnosis methods have been developed. The most common methods are visual inspection, measurement of electrical parameters, electroluminescence and infrared thermography. These methods are combined in the performance assessment, which also analyzes monitoring data to achieve a holistic overview of the state and performance of the power plant.

In order to increase the technological knowledge base of photovoltaics in the Brazilian academy, a research project with the objective to compare and evaluate design and performance assessment methods has been set up. In this context, an experiment with Unmanned Aerial Vehicle (UAV) based Infrared Thermography (IRT) has been performed for the fault inspection of a PV plant in South Brazil that was affected by a meteorological tsunami[1], shown in Fig. 1.

In the following, for a better understanding, a short introduction into aerial infrared thermography for PV applications will be given. Section 2 will treat the experimental setup and the applied methodology will be presented. In section 3 the main results will be presented and discussed. In the final section (4) a conclusion will be drawn.

[1] A meteorological tsunami is a rare meteorological event when meteorological factors causes a giant wave.

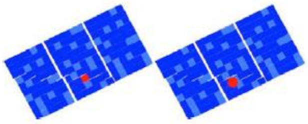
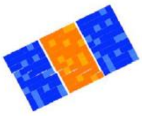
Figure 1 - 3 MWp PV Plant in Tubarão-Santa Catharina, South of Brazil.

1.2 Aerial Infrared Thermography for PV Applications

Infrared thermography (IRT) measures the radiation emitted by the surface of any body in the infrared wavelength spectrum between 1.4 – 15µm. The infrared thermography employed for PV applications usually detects wavelengths in the mid-wavelength range of 7 – 14 µm, which is a trade-off between costs, availability and measuring conditions of IR sensors (Tsanakas et al. 2013).

IRT can be used for the detection of a great number of defects in PV cells, modules and strings, since the majority of the defects have an impact on their thermal behavior. Such thermal patterns have been identified and classified in previous studies (Buerhop et al. 2007, Buerhop et al. 2012, Köntges et al. 2014) and are now standardized in the international norm IEC TS 62446-3 Edition 1.0 2017-06.

Table 1 - Examples of thermal patterns (VATH 2016 adapted).

Fault Type	IR Thermal Pattern
• Short-circuited/ shunted cells • Shadowing	
• Potential induced degradation (PID)	
• Substring open-circuited/ defective bypass diode • Internal short-circuit	
• Open-circuited module • Failed system connection	

IRT is a non-destructive and contactless method that can be performed under steady-state operation conditions. Furthermore, IRT can provide information about the exact physical location of an occurring fault, which allows for posterior electrical diagnosis of the problem. Buerhop et al. (2016) have proven that IRT is a reliable fault diagnosis method, which requires a minimum of instrumentation and can be applied without interrupting the operation of the PV plant.

Traditionally, IRT inspections for PV applications are performed with handheld IR cameras on the ground or on lifting platforms to increase the coverage. This procedure is dependent on human labor and competence and very time-consuming and labor intensive. As a result, the monitoring accuracy is prone to human error and the uncertainty of the method increased.

In order to increase the cost-effectiveness and employ IRT for large-scale PV plants or roof-mounted PV systems with limited access, IRT can be combined with aerial technologies like UAV. The recent developments in the field of UAV made this technology available for civil activities like disaster relief, energy equipment monitoring, environmental control, forest inspection or mine monitoring (Aghaei *et al.*, 2015). Especially in the energy sector UAV are becoming more popular due to their advantage of large area coverage, accurate imagery, high flexibility and reliability (Grimaccia *et al.*, 2014; Tsanakas & Botsaris, 2012).

Currently, PV plant monitoring with UAV, in particular UAV based IRT, is attracting attention. There is still a lot of potential in applying this inspection method for PV plants, which can revolutionize the future PV plant monitoring procedure (Aghaei *et al.*, 2015), especially when combining it with automation technologies, like automated route planning and automatic defect identification.

Aerial IRT is performed by visual and IR sensors that are mounted on the UAV platform. It provides real-time and precise imagery in a time efficient manner. Detectable defects and failures are cracks, corrosion, broken parts, white spots, snail trails, discoloration, dirty points and faults according to the before-mentioned thermal patterns, like hot spots, open-circuited modules or strings and potential induced degradation (Tsanakas & Botsaris, 2012; Bellezza et al., 2014). Depending on the mission and planned direction, UAV can fly at different altitudes to identify specific defects or failures (Leva et al., 2015).

During the flight, various environmental stress factors like weather conditions, air turbulence and sunlight reflection may affect the measurements and consequently the quality of the aerial IR images. In addition, self-shading, high velocity of the UAV, drift and crab during the flight and an oblique orientation angle of the IR sensor should be avoided.

The optimum conditions for aerial IRT monitoring can be summarized as follows (Leva et al., 2015; Aghaei et al., 2016; Aghaei, Leva & Grimaccia, 2016):

1. The angle of the IR sensor mounted on UAV should be oriented as perpendicular toward the PV modules.
2. The minimum flight altitude should be more than five meter in order to avoid any self-shading of the UAV during the inspection.
3. The aerial IRT should be performed on a cloudless, sunny and clear days. In addition, the wind speed should not be exceeded 4 m/s (14.4 km/h, 3Bft); higher wind speeds can cause air turbulences and shake the UAV during the inspection procedure.
4. The best time for aerial thermography by UAV is around noon and before afternoon when the position of the sun is more perpendicular on PV plants. However, the irradiance should be more than 600 W/m² in the plane of PV module. Nevertheless, it depends on the geographical location of PV plant hence it can be performed at various times since the position of the sun differs in the Northern or Southern hemisphere.
5. The direction of the flight should be planned before each inspection mission in order to avoid any drift and crab during the aerial IRT monitoring.

2. EXPERIMENTAL SETUP

The experiment took place at a 3 MWp PV plant located in the city of Tubarão (latitude 28°28’ south, longitude 49°0’ west) in the state of Santa Catharina, in South Brazil. The PV plant, as seen in Fig. 1, consists of three 1 MWpblocks of different PV technologies – namely polycrystalline PV modules at the top of the picture, followed by amorphous silicon modules and CIGS (Cupper Indium Gallium Selenide) modules at the bottom. The experiment was focused on the polycrystalline PV block, which features are presented in Tab. 2. The PV modules are fixed on ground mounted racks that support three rows of twenty portrait-oriented modules with an inclination of 30°, facing north. As the PV plant is part of a R&D project, different inverter topologies have been adopted to test the effect of different inverter concepts and loading on the PV system performance in this climate region.

For the aerial Infrared Thermography, the Unmanned Aerial Vehicle (UAV), DJI Phantom 3 Advanced, was modified and equipped with a lightweight infrared camera (Fig. 3) and a video transmission system, as presented in Fig. 2. The main features of the IRT-measurement system are given in Tab. 3. The thermal images were recorded in greyscale and afterwards selected, cut and colored, for a better visualization of the detected failures. More elaborated image processing techniques were dispensed, since the main objective of this research, was to carry out fault inspections in a cost-effective and fast manner. Other techniques are usually highly time- and resource-consuming, as seen in Tsanakas et al. (2017), and requires collecting radiometric data, which was not possible to obtain with the given equipment. The detected faults were classified according to their thermal pattern.

Table 2 - Main features of the 1 MWp polycrystalline PV power block

Installation year/ Operation period	Module type/ model	Subsystem size (kWp)	Number of Modules	Number of Strings	Inverter size/ model
2014/ 3 years	Polycrystalline/ Yingli Solar YL 245C.29b	216.34	883	56	18 x 10 kW ABB PVI-10.0-TL-OUTD
		111.72	456	24	4 x 27.6 kW ABB TRIO-27.6-TL
		53.90	220	10	55 kW ABB PVI-55
		.161.70	660	30	165 kW ABB PVI-165.0
		485.10	1.980	99	500 kW ABB PVS800-57-0.500kW-A
Total		1,028.76	4.199		

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Figure 2 - Aerial IRT-measurement system

Figure 3 - Lightweight IR camera MicroCAM 2

Table 3 - Features of the IRT system

UAV features		IR camera specifications		Video Transmission System	
Weight	1,280 g	**Sensitivity**	< 60 mK	**Signal**	Analogic video signal
Flight height	6,000 m	**Spectral range**	7 – 17 µm	**Transmitter**	BosCam Transmitter
Flight velocity	max. 16 m/s	**Pixel pitch**	17 µm (640x480)	**Antenna**	Cloverleaf 5.8 GHz
Flight time*	13 min.	**Pixel count/ Frame rate**	307,200/ 30 FPS	**Transmission power**	1W
Flight range	3.5 km	**Weight**	80 g	**Transmission frequency**	5.8 GHz

In addition to the aerial IRT measurements, infrared images of selected specimen with a handheld IR camera, Flir T640, were taken. This was necessary in order to quantify the detected temperature divergences, since the IRT system could not provide radiometric data. The IR camera featured a 640 x 480 uncooled microbolometer with a spectral range of 7.8 – 14 µm.

3. RESULTS

The measurements were divided in two different days. In both, the experiment was set up at 11:00 a.m. under sunny weather conditions, clear sky and irradiances above 800 W/m2, measured in PV array plane. A flight height above 5 m was adopted in order to avoid self-shading and other unintended experimental artefacts. The wind speed was around 3 m/s.

Tab. 4 presents the results obtained with the two days of experiments. It was possible to detect hot spots, actuated bypass-diodes, short- and open-circuited strings. To inspect 1 MW of PV modules, it was necessary about 1 hour. Fig. 4 presents some of the images made with the IRT system.

Table 4 – Results of the experiments

Results of the experiments	
Minimal irradiance	800 W/m2
Average wind speed	3 m/s
Average altitude of flight	5 m
Time of flight for 1 MW inspection	1 hour
Number of open-circuited strings	18 (8.22%)
Number of short-circuited strings	9 (4.11%)
Number of modules with an actuated bypass diode	2 (0.05%)
Number of hot spots	10 (0.24%)

Fig. 4 shows an example of a damaged PV module detected. It also shows some missing modules that were swept away by the wind, hitting and damaging other PV modules. Consequently, the PV module string with missing modules, and the string with the damaged module were both open-circuited. Both strings became uniformly warmer than the others, and were easily and immediately detected using the IRT drone. Other open-circuited strings that have been detected are shown in Fig. 5 and Fig. 6.

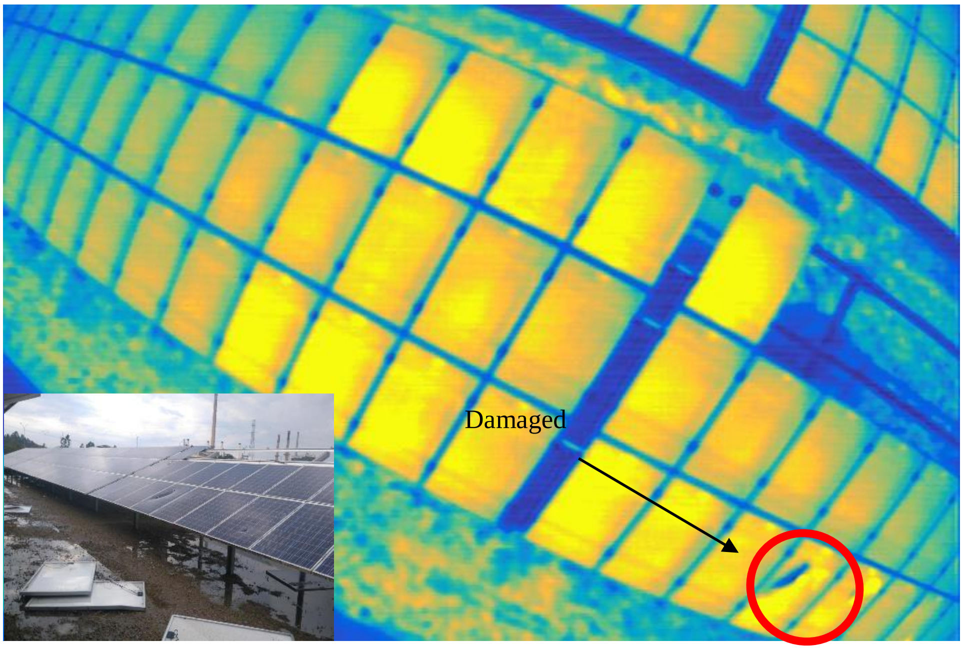

Figure 4 – Damaged PV module pictured by the IRT drone system and by a conventional camera.

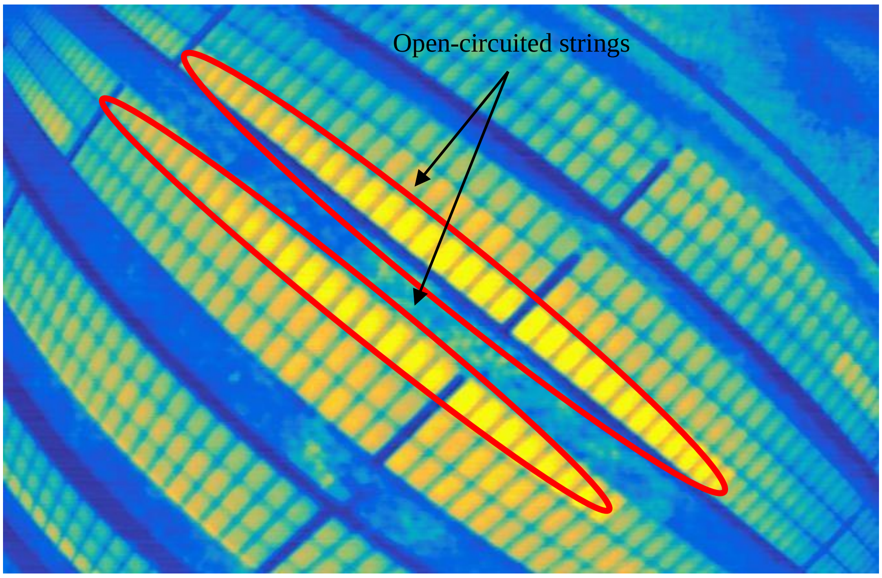

Figure 5 – Open-circuited strings by the IRT drone system.

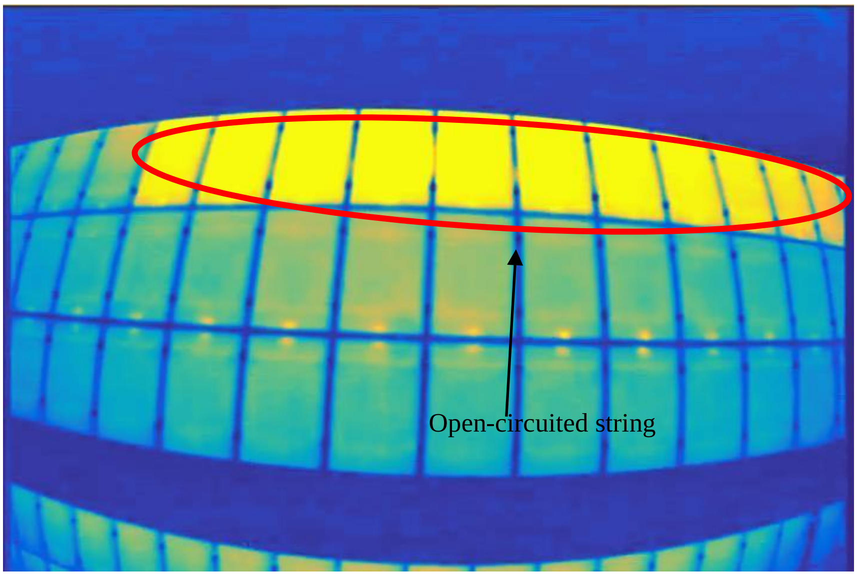

Figure 6 – Open-circuited string image taken with the IRT drone system

Some hot spots could also be detected after the meteorological incident. One of them is seen in Fig. 7, which presents two images taken from different heights. They illustrate how faults can be identified even from high altitudes, allowing the IRT system operator to investigate several modules at the same time. With the experiment, there were hot spots that could be detected even when the UAV was flying at 40 m of altitude. Nevertheless, as previously mentioned, it is important to maintain a certain altitude that will preserve the quality of the image, capturing all the PV cells. In the right picture in Fig.7, another point stands out: the shadow caused by the drone itself. It is important to differentiate such reflections as well as reflections from the sun or other objects from actual potential problems in PV system IR images, otherwise incorrect conclusions can be drawn. The module with the hot spot was individually analyzed and replaced.

Another relevant fault detection issue, made possible using the IRT system, was an actuated bypass diode in one of the three cell strings of an individual PV module, as displayed in Fig. 8. The figure shows that the two middle rows of a PV module are warmer than the other four (PV modules typically have six rows of either 10 or 12 cells each, with each two rows protected by one bypass diode). On the right hand side of this module, another open-circuited string was detected. It is important to notice that the brighter areas on the upper modules of the array are caused by sun reflection, and not by a module fault.

The same modules were also analyzed with the hand-held IR-camera Flir T640, as shown in Fig. 9. The increase in temperature of the module with the actuated bypass diode reaches 2.4 degrees and is slightly higher (0.5 degrees) than the modules of the open-circuited string. That is a certainly low difference of temperature between normal cells and injured ones, and it still could be distinguished.

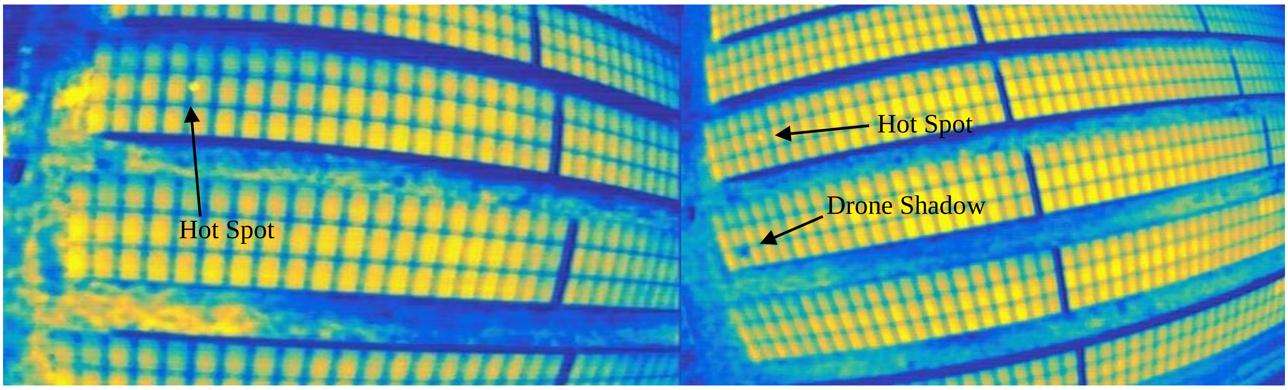

Figure 7 - Hot spot image taken from two different heights with the IRT system.

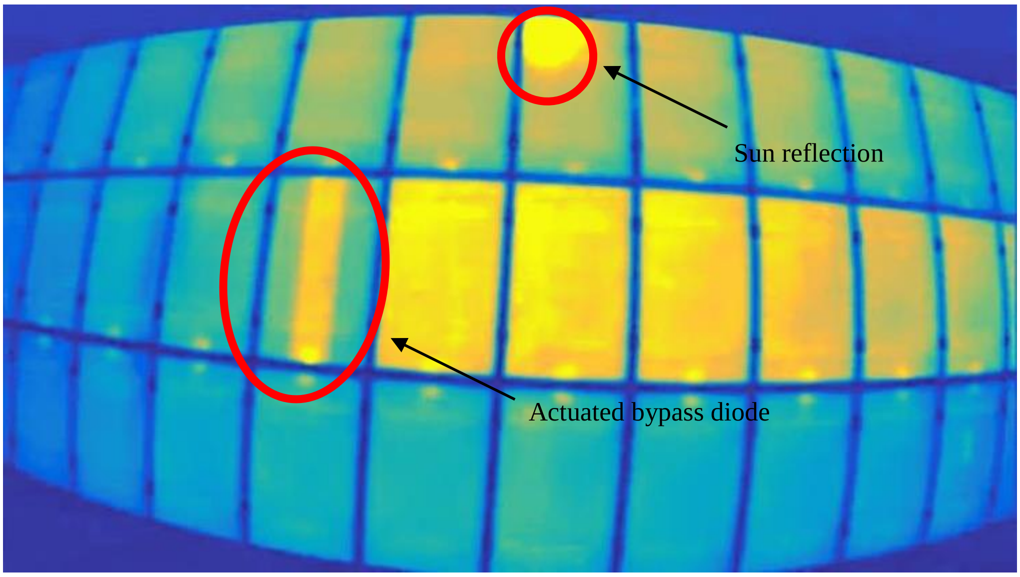

Figure 2 – Actuated bypass diode detected with the IRT system.

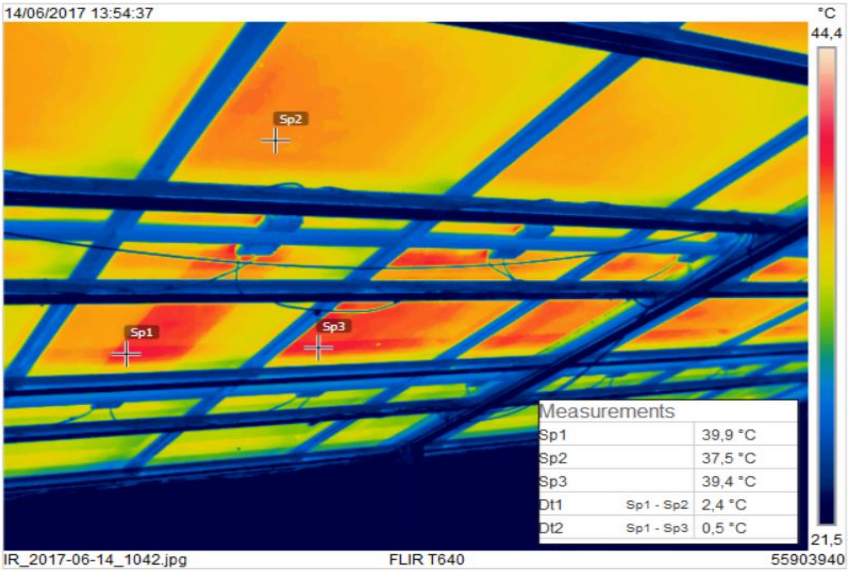

Figure 9 – Actuated bypass diode picture taken with FLIR T640, seen from the back of the module.

Fig. 10 also shows some hot spots detected, accompanied by pictures taken with a conventional camera. Most of the hot spots correspond to broken modules as this case. Even though the cracks are visible with a conventional camera, they are much more prominent in pictures taken with the IRT system and therefore are faster detected. Fig. 11 displays a picture of the same damaged module, but taken with the FLIR T640, presenting the differences of temperatures between cells. In this case, the difference of temperature between the cell and the hot spots is much higher than in Fig. 9, achieving 26.2º. This kind of temperature abnormality is seriously dangerous and should be detected and corrected in order to avoid fires.

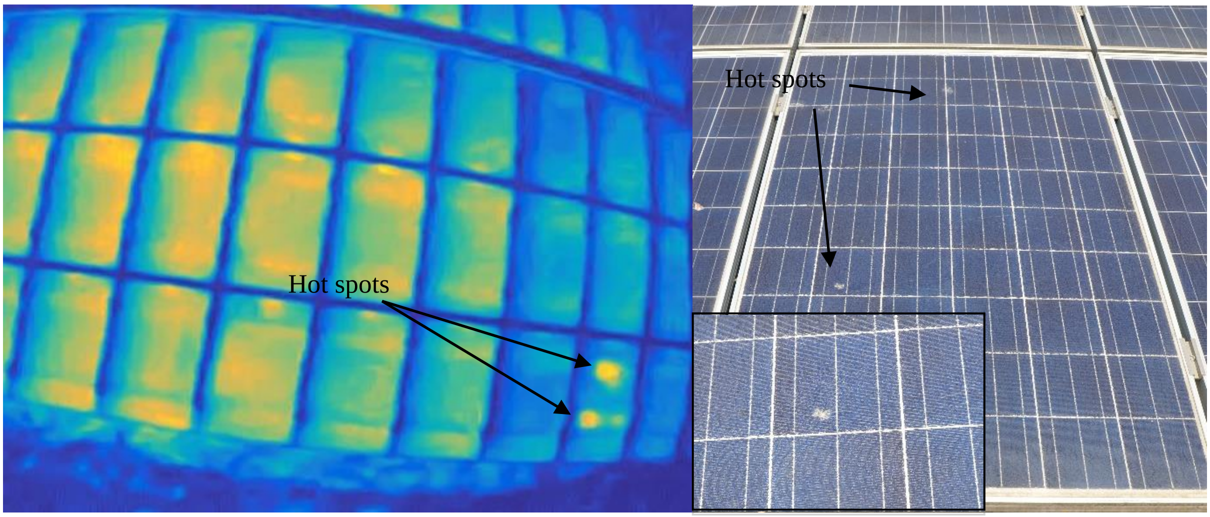

Figure 10 – Hot spots detected with the IRT system.

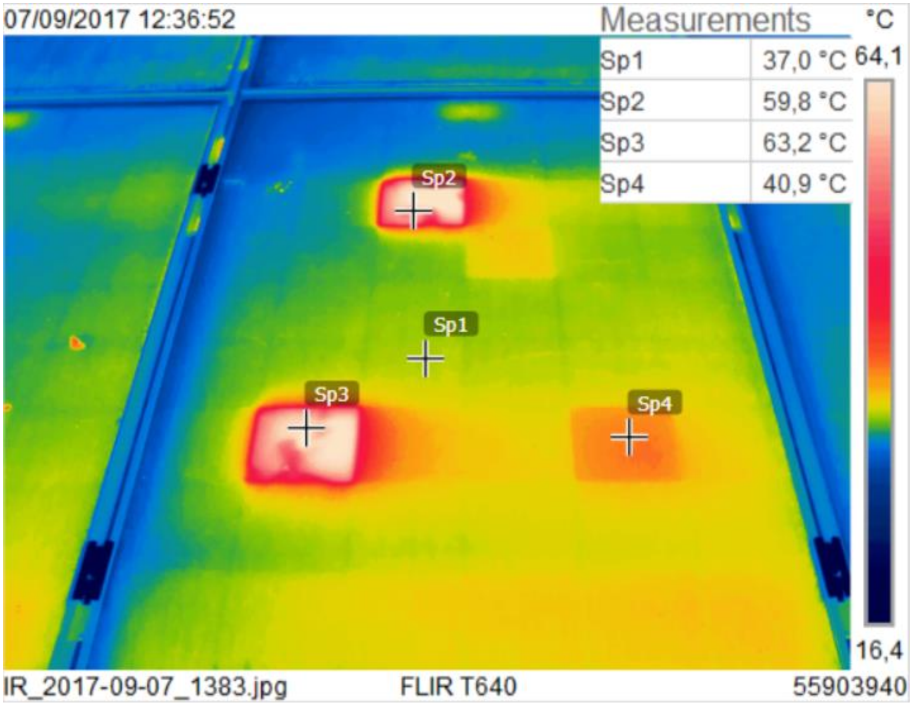

Figure 11 – Hot spots picture taken with FLIR T640.

4. CONCLUSION

The purpose of the current research was to prove that the UAV and IRT sensor onboard is very cost efficient and reliable for a fast inspection of large-scale PV plants. However, some factors must be considered and controlled, in order to obtain adequate and reliable measurement results. Camera tilt angle, minimum irradiance level, height and drone speed, as well as possible reflections of the sun, the drone itself and other objects, must be observed.

The applied IRT system could not do perform radiometric measures, consequently ground thermography was used to complement and detail the information obtained by the aerial IRT system. However, the speed with which preliminary trouble-shooting can be carried out with the drone IRT system is one of its major attributes, and should consolidate the use of this technique in large-scale PV arrays.

The experiment detected short- and open-circuited strings, actuated bypass-diodes and hot spots, even at 40 m of altitude. The assessment helped to identify the defects in a fast manner, without interrupting the power generation. The

IRT UAV system was essential for identifying damaged and defect portions of the PV power plant fast after the incident and it can be concluded that the technique is very effective, practical and relevant for damage inspection in large PV power plants.

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