FAULT INSPECTION OF CIGS PV PLANT USING AERIAL INFRARED THERMOGRAPHY

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ABSTRACT: Aerial infrared thermography (aIRT) has become an important method for the fault inspection of large, utility-scale photovoltaic (PV) plants. The method uses an infrared (IR) camera mounted on a drone to detect the faults, which produce changes in the thermal behaviour of PV modules, in an efficient manner. There is plenty of research in the field for crystalline silicon modules, but not for thin-film PV technologies. In this work, a CIGS thin-film PV plant is inspected by aIRT in order to investigate this process and to find which faults can be detected by aIRT. The inspection at 20 m altitude of the 1 MW_p plant of 1.4 hectares took about 12 minutes, and the analysis of the video data about 30 minutes. Such an inspection allows the detection of the following faults: disconnected strings, short-circuits, bypassed modules, most of the cell breaks, hot junction boxes and bad soldering problems. Other faults could not be detected by this method, namely glass breaks and certain cell breaks.
Keywords: CIGS, Thin Film, Defects, Aerial Infrared Thermography (aIRT), Fault Inspection

1 INTRODUCTION

In recent years, the photovoltaic (PV) market has grown exponentially. The cumulative installed PV capacity surpassed worldwide 500 GW in 2019, which provides some 2% of the world's total electricity [1]. At the same time, the reliability of PV plants is becoming more important for the stability of the grid. That requires the implementation of a well-functioning operation & maintenance procedure. Furthermore, operators of PV plants are interested in high-quality O&M services, as they reduce the potential risks and improve the levelised cost of electricity and the return on investment [2].

The performance of a PV power plant is usually monitored by a supervisory control and data acquisition (SCADA) or monitoring system. It provides information about the power output of the inverter, combiner box or string level, each offering more detailed information than the previous. Power losses detected by the monitoring system can indicate faults and failures such as soiling, disconnected strings or defected modules, which require maintenance [3]. Depending on the level on which the system takes the information, not all faults can be detected or they cannot be localised exactly. A powerful tool to detect and localise faults is the aerial infrared thermography (aIRT), where an infrared (IR) camera is mounted on an unmanned aerial vehicle (UAV), also known as a drone, to inspect a PV power plant. In the IR images, faults can be recognised by means of a raised temperature, because most of the faults in a PV module produce heat. Compared to conventional methods of fault inspection, aIRT offers many advantages. The inspection is contactless and can be performed without interrupting the operation of the plant. It is fast, flexible, provides immediate results and is cost-effective. Besides that, it allows the inspection of very large areas and provides access to installations with limited accessibility such as roof mounted PV [4-6].

There is a lot of research done in the field of aIRT [4-10]. Most of the literature investigate PV systems with crystalline silicon (c-Si) cells, as this is the most common PV technology. There are very few publications [8-10] about aIRT measurements on thin-film PV modules since this technology is still not widespread. The share of thin-film technologies was about 5% of the total annual PV production in 2017 [1]. Due to the low material demand and simpler manufacturing process of this technology, it has the potential for low-cost production and may play an important role in the future PV market next to the more traditional c-Si [3].

This paper examines the aIRT of CIGS thin-film PV systems, as there is very little research in this field so far. It investigates how practical aIRT is for the fault inspection of CIGS PV systems and which faults it can detect. Furthermore, it shows how to optimise the inspection process by choosing the right altitude and routes for the UAV flight.

2 METHODS

For this experiment, aIRT flights were carried out on a 3 MW_p utility-scale PV R&D power plant. After analysing the recorded video footage, faults were investigated in a visual inspection from the ground on a one-to-one basis.

2.1 Experimental site

The experimental site is called "Usina Solar Cidade Azul". It is an R&D PV power plant located in Tubarão, in the state of Santa Catarina (SC), in the South of Brazil (28° South, 49° West). The plant has a nominal power output of 3 MW_p and is divided into three 1 MW_p subsystems, employing three different PV technologies; multi-crystalline silicon (mc-SI), copper indium gallium diselenide (CIGS) and tandem amorphous-microcrystalline silicon (a-Si/µc-Si). Figure 1 shows the PV plant. The modules are fixed on ground-mounted racks and tilted at 30° facing true North. This work focuses on the CIGS portion of the plant. This block takes up 1.4 hectares and consists of 7480 CIGS PowerMax STRONG modules produced by Avancis with a nominal power of 120 or 130 W_p each.

In 2016, a meteorological tsunami hit the coast of the region where the plant is located, and wind gusts up to 210 km/h caused havoc in the region. Twenty of the 20'000 modules (0.1%) were separated from their racks and several array wires and modules were compromised, which made this plant a good experimental site for an aIRT fault inspection .

Additional experiments were carried out at the Fotovoltaica-UFSC laboratory, in order to test a fault

type that was not found on the power plant. The laboratory is shown in Figure 2 and is located in the North of the island of Florianopolis in SC (27° South, 48° West), some 160 km North of the R&D PV power plant. The examined PV system is a carport with the same CIGS modules used at the power plant.



Figure 1: Experimental site: the 3 MW_p R&D power plant "Cidade Azul" with three different PV technologies



Figure 2: Aerial image of the Fotovoltaica-UFSC laboratory (www.fotovoltaica.ufsc.br). The carport used for the experiment is indicated.

2.2 Measurement systems

The experimental setup for the aIRT measurements includes a DJI Phantom 3 Professional UAV, which has been modified and equipped with a lightweight (80g) IR camera. It has first been presented in [11] and is shown in Figure 3. The high-resolving (307 200 pixels) IR camera is a Thermoteknix MicroCAM 2. It is based on an amorphous silicon IR detector, which functions in the longwave IR spectrum between 7 and 17 µm. The sensitivity, which is described by the noise equivalent temperature difference (NETD), is below 60 mK. The camera provides grey scale images, in which dark shades indicate cold temperatures and bright shades represent hot temperatures. The images are sent in real time to a computer and are there recorded to a video. For this purpose, the original telemetry system of the drone was replaced by a BosCam first-person view (FPV) transmitter and a Cloverleaf antenna.

Other measuring devices were used to gain a deeper understanding of the faults found by aIRT. A FLIR handheld IR camera and a digital camera were used to take close up images of the faults. The electrical condition of PV modules was investigated with a current measuring device and I-V curve tracer.

The minimum requirements for outdoor infrared thermography of PV systems are defined by IEC 62446-3:2017 [12], and were met in this work.



Figure 3: UAV used for the aerial inspection, equipped with an IR camera and a transmission system

3 RESULTS AND DISCUSSION

3.1 Experimental artefacts

Experimental artefacts that may lead to misinterpretation of the IR images occurred during the aIRT measurements. The most important of them are reflections. Objects like clouds, the Sun, the drone or the neighbouring module tables are reflected on the observed module and may show a wrong temperature in the IR image. Two examples are given in Figure 4. These reflections can be misinterpreted for a fault or can cover a fault, thus making it not visible. Another artefact is caused by the angle of view of the camera to the surface of the modules. Modules observed under a greater angle appear warmer than the ones observed under a flat angle. This is caused by the IR reflectivity of the module's front glass, which is changing with the angle of view [13]. Therefore, it is suggested to have an angle close to 90°. However, this is not always possible, thus the influence of the angle of view has to be considered carefully.

Another effect that can lead to misinterpretation is the change of temperature of the module in certain areas. The metal structure on which the PV modules are mounted as well as the frame of the module have an effect on the temperature of the module above. They act like a cooling fin and transport the heat from the module, resulting in a local cooling which can be seen on the IR image. Examples of the visible mounting structure are presented in Figure 5.

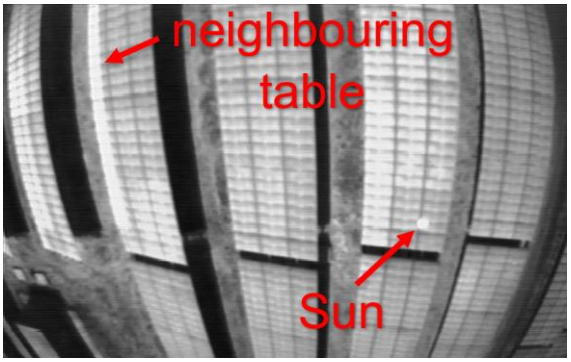


Figure 4: Examples of reflections

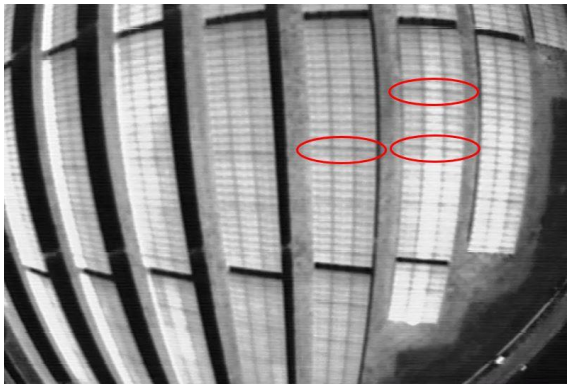


Figure 5: Cooling effect of the mounting structure

3.2 Route and height

Flights with different routes and heights were carried out in order to evaluate the best way to do an aerial inspection of a PV plant. Furthermore, the drone was controlled manually and automatically by means of an application for flight route planning. The different flights and their durations are presented in Table I. In an altitude of 20 meters, two different routes were tested, one parallel to the module rows and one orthogonal to them. The two routes showed small differences in the behaviour of the reflections, but none of them could be determined as superior to the other and they both take about the same time. Therefore, it is sufficient to do only one of the routes. The comparison of the manual and the automatic flights showed that the automatic flight is faster and has a more stable image especially in windy conditions. Flights at higher altitudes are significantly faster, but many faults cannot be detected.

Table I: Duration of flights with different methods over 1.4 ha plant

		Automatic flight		**Manual flight**	
Altitude	*Route*	*Speed*	*Duration*	*Speed*	*Duration*
20 m	parallel	2 m/s	12 min	0 – 6 m/s	15 min
20 m	orthog.	2 m/s	11 min	-	-
30 m	parallel	3 m/s	5.5 min	0 – 6 m/s	10 min
50 m	parallel	3 m/s	3.5 min	-	-

3.3 Faults

The most common fault was the disconnection of strings, mostly caused by burned connections in string boxes. When a string is disconnected and does not produce electricity, the irradiated energy from the sun is not converted into a current but into heat caused by carrier recombination, thus the string gets warmer than a connected one. Therefore, these open-circuited strings could be detected by aIRT by means of a uniform raised temperature, detectable from 20, 30 and 50 m. However, it was not always easy to determine whether a substring is really open or not, as shown in Figure 6. In these cases, the string currents can be measured to control the state of the string. If the monitoring system of the plant is detailed enough, it can also help to identify the open strings. Bypassed modules showed the same thermal behaviour as disconnected strings, as they also do not generate electricity. They could be detected from all the three altitudes, too. If another fault is in a bypassed module or in an open string, it won't be detected, since there is no current to heat the fault and make it visible to the aIRT. Thus, plants with a lot of open strings might hide some other faults in them.

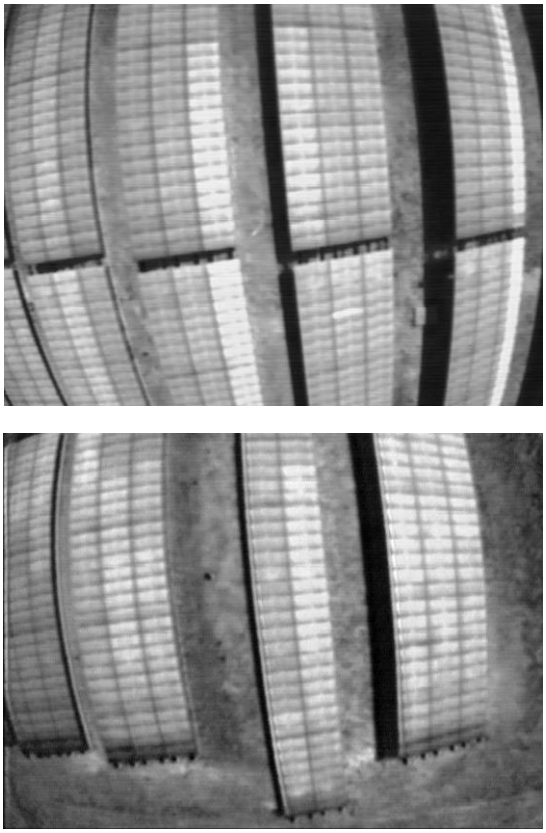


Figure 6: Comparison between open strings that are easy to detect (top image) and strings in which it is hard to determine whether they are open or not (bottom image).

Another frequent fault was the breakage of the front glass. However, none of them was visible on the aIRT images. Instead, they were detected during the visual inspection of other faults. The CIGS modules on the plant were manufactured in the substrate configuration, which means that the active thin-film layers are deposited on the backside glass [14]. If the frontside glass breaks, these layers remain intact, the module can function normally, and no heat is produced that could be detected by aIRT. The I-V curve measurement confirmed that this fault does not lead to an immediate power loss. However, moisture ingress through the glass break may lead to other defects and power losses after some time.

Due to the configuration of the modules, the cell layers break when the backside glass breaks. This was the case for several modules on the power plant. Most of them could be detected by aIRT because the defect led to the heating of some cells as depicted in the example of Figure 7. On the digital image is visible that the crack is in the lower right corner isolating this area. The cells in these modules reach from top to bottom of the module and are connected in series from left to right. It is expected that the cells on the left, largely unaffected by the crack, are functioning normally. The current produced in these cells has to go through the smaller, defected cells on the right, therefore the current density increases and leads to the hot spot heating. The temperature difference between the hot spot and the unaffected cells was about 9°C in this module. It showed a power loss of 22% and was detected from 20, 30 and 50 m. One module with broken backside glass and cell layers, presented in Figure 8, did not lead to a hot spot warm enough to be detected by aIRT. It was only found during the visual inspection of other faults. Because the

crack in this module is perpendicular to the cells and parallel to the direction of the current flow, it is expected that there is no change in the current density, which could lead to a heating effect. However, this module had a significant power loss of 16%.

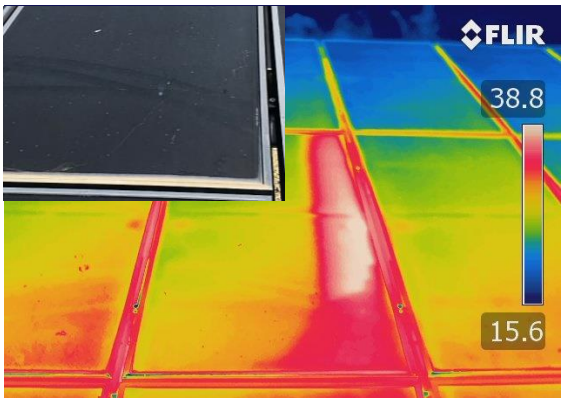


Figure 7: Cracked backside glass and cell layers causing a hot spot visible in the handheld FLIR IR image.

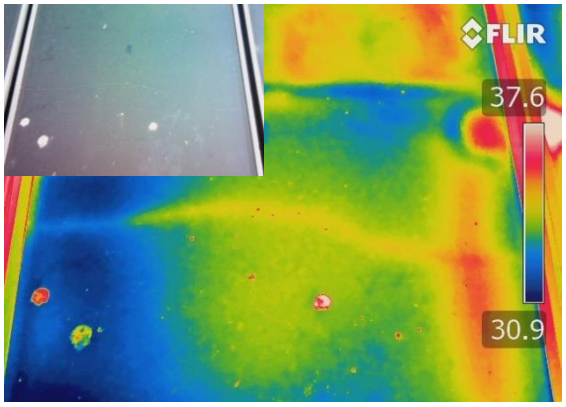


Figure 8: Visual image of a broken module and its IR image taken with a handheld camera. The breakage of the backside glass and the cell layers in this module do not lead to a hot spot heating because the crack is parallel to the current flow.

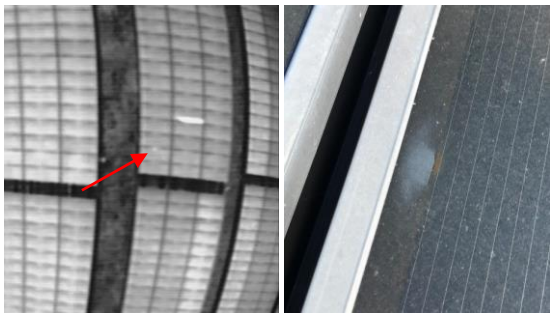


Figure 9: Hot junction box in combination with corrosion on the cell layer and whitening of the encapsulating band.

Many modules on the plant featured junction boxes with an abnormal temperature rise. They were all detected by aIRT due to a small hot spot on the side of the module where the junction box is located, as presented in Figure 9. Some of them occurred in combination with corrosion on the cell layer, like the example in Figure 9, and most of them with a whitening of the encapsulating band between frame and cells. It is assumed that these two effects are result of the heat caused by a problem inside the junction box. Measurements showed that the defected junction box in Figure 9 caused a power loss of 23%. It could only be detected from a height of 20 m. Therefore, altitudes higher than 20 m are not suitable for the detection of this kind of fault. One module showed a fault that looked like a hot junction box on the aIRT image, but it turned out to be a bad soldering problem at the connection between cells and junction box. This fault was detected only from 20 m and caused a power loss of 14%.

Several modules were found with small holes in the scribing lines between the cells around a junction box, visible from the backside of the module as in Figure 10. They are expected to be type A shunts that originated from an imperfect laser scribing process [15]. However, these modules all showed different heat patterns, thus no correlation could be made between the shunts and the heat patterns.

Some other faults were found and investigated. Many of them showed strange behaviours and need further investigations to understand them better and to make proper statements about their detectability by aIRT.



Figure 10: Holes in the scribing lines are expected to be type A shunts.

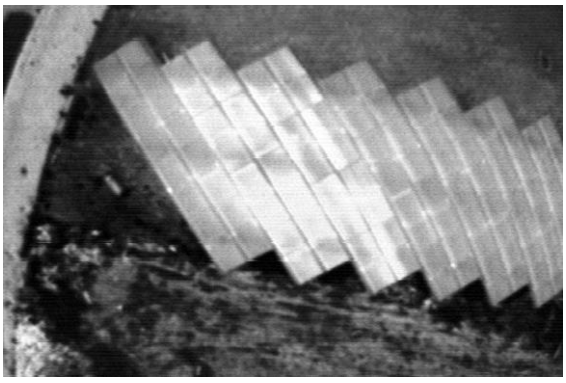


Figure 11: Short circuited substring (red arrow) next to an open string (left) and a normally functioning one (right).

An additional experiment was carried out on the carport outside of the laboratory to test the behaviour of CIGS modules under short-circuit conditions. Short-circuited modules show a specific heat pattern shown in Figure 11. Some cells randomly turn warmer than others, leading to these longish bright shapes on the aIRT image. This fault could be easily detected from 10 m. From 20 m it was harder to recognise but still detectable.

4 CONCLUSIONS

This work showed that aIRT is a fast and practical inspection method to find faults in CIGS thin-film PV plants. The following faults are detectable by aIRT from 20 m altitude:

- Open strings
- Short circuits
- Bypassed modules
- Cell breaks (if the breakage leads to hot spot)
- Hot junction boxes
- Bad soldering problems

Other faults are not detectable by aIRT, namely:

- Glass breaks (if in substrate configuration)
- Cell breaks (if the breakage does not lead to a change in the temperature of the module)

There are other faults possible in thin-film PV plants such as shunts, delamination, discolouration, PID and TOC-corrosion. These faults could not be found on the plant or examined enough in this work to make a statement about their detectability. Only PID is known from the literature to be detectable by aIRT [10].

The inspection of a 1 MWp power plant of 1.4 hectares takes 12 minutes and the analysis of the recorded videos around 30 minutes. If the flights are performed in higher altitudes, the inspection time reduces significantly (3.5 min at 50 m high) but some faults become undetectable. The choice of the right altitude is key for an effective aerial inspection. For large-scale PV plants, it is suggested to only do flights at 50 m to reduce costs. This inspection will only reveal the open strings, the bypassed modules and some cell breaks. However, disconnected strings are the most important faults, as they have by far the biggest impact on the power losses of a PV plant.

A next step in the development of aerial inspections to speed up the process and lower the costs is the usage of artificial intelligence for the analysis of the IR images, the detection of the faults and the categorisation of them. This would be a huge contribution to the effectivity and cost reduction of aerial inspections [16].

5 ACKNOWLEDGEMENTS

The authors acknowledge with thanks the Alexander von Humboldt Foundation for the Research Linkage Group grant, which funded the IR camera used in this work. ENGIE Brasil Energia is gratefully acknowledged for access to the 3 MWp R&D PV power plant described in this work. The Brazilian Research Council CNPq is also acknowledged for financial support.

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