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RESEARCH ARTICLE OPEN ACCESS

PREVENTIVE DIAGNOSIS OF PHOTOVOLTAIC FACILITIES BASED ON THE INTERPRETATION OF INFRARED IMAGES

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ABSTRACT

Currently, Cuba is struggling to increase the presence of renewable energies in its energy matrix, this in order to reduce dependence on fossil fuels and help curb global climate change. One of the missions of the National Electric Union is to expand the installation of photovoltaic parks throughout the national territory and achieve efficient use of them. The present work aims to present examples of the diagnosis of different types of failures in such facilities, based on the interpretation of infrared images by means of the thermal contrast method It seeks the analysis of non-destructive infrared images of photovoltaic installations, with the goal of detecting failures due to heating of the parts that compose them. The execution of this type of preventive diagnostics, helps to plan maintenance or to carry out immediate repair actions that allow maintaining the efficiency and generation capacity of the photovoltaic parks.

I. INTRODUCTION

Renewable energy sources are part of the solutions for the "sustainable development" that humanity seeks, a development that responds to the needs of today without compromising the ability of future generations to respond to their own [1]. The use of renewable energy also contributes to the global effort to curb climate change, materialized at the political level by the implementation of the Kyoto protocol in 2005 and the signing of the Paris Agreement in 2015 [2]. The Latin American region, despite having a relatively low level of CO2 emissions and a high presence of the use of renewable energy (approximately 28% of the total used), has low diversification of sources, focusing on hydroelectric power [2]. Other unconventional sources such as solar, wind and biomass are little diversified in this geographic region, despite having extensive research on their use in recent years [3].

Cuba, unlike other countries in the region, does not have big rivers that allow boosting the use of hydroelectric energy, for this reason for years the energy matrix relied on thermoelectric plants that use fossil fuels [4]. The 21st century saw an increase in oil prices and with it an increase in the cost of producing electricity. Added to this situation was a greater awareness of the effects of climate change and the fact that improvements in the efficiency of non-conventional renewable energy sources appeared [5]. This environment caused the National Electricity Union (UNE), the entity responsible for operating and managing power generation in the country, began an assessment and gradual introduction of non-conventional energy sources in the energy matrix of the country [4, 6].

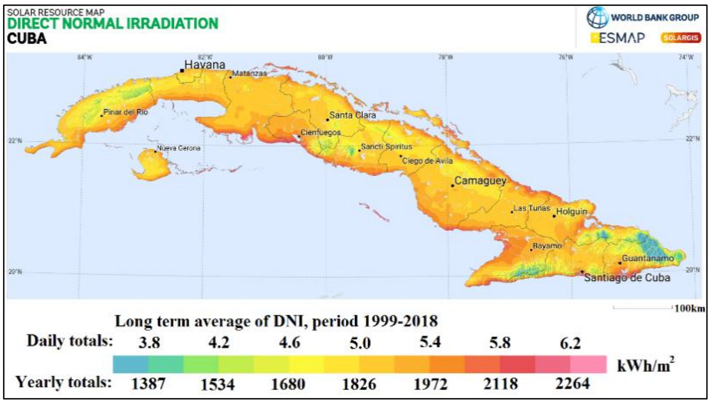

Figure 1: Cuba direct normal irradiation map.
Source: [7].

Within renewable energies, photovoltaics, has had wide national attention in recent years [6, 8-17]. This is due to the ease of its deployment in a tropical country like Cuba, with high levels of solar radiation (Figure 1). Small size photovoltaic systems, interconnected to the grid, have been installed throughout the country [6, 8, 13]. In the same way, isolated micro systems have allowed reaching remote communities that for years were isolated from the national network due to geographic complexities [18], with the consequent improvement in their quality of life. Economic and social objectives have also been enhanced with the installation of these systems to allow them energy autonomy in contingency situations [15].

The deployment of photovoltaic technology has required strategies to be drawn up for its efficient management [12, 17, 19]. Among them, the study of new preventive diagnostic techniques that allow achieving high efficiency rates and a reliable operation. Among the preventive diagnostic techniques, infrared thermography is a very useful tool. It is supported by the images acquired with a thermal camera. In these images, each pixel of the photographed object makes radiometric reference to its temperature. The images, once corrected according to the conditions of the environment (humidity and air temperature, distance to the analyzed object, reflected temperature, incident radiation), allow obtaining a map of the temperature of the object of interest at a distance, accurately and without the need for physical contact with it.

An accurate thermography provides maintenance personnel with the information required to avoid or lessen failures in photovoltaic installations, as a result of the most common faults in their elements. It is noteworthy that thermography, unlike other diagnostic techniques, does not require the stop of the photovoltaic solar park (PVSP) and is carried out with it fully operational. Only simple procedures should be followed that involve the environmental conditions at the time the images are taken and the way the images are acquired.

II. MATERIALS AND METHODS

Photovoltaic systems are made up of photovoltaic panels, electrical elements and electronic devices that make it possible to transform solar radiation into useful electrical energy for consumers. In them, the interconnected photovoltaic panels generate a direct current voltage with which an electronic inverter is supplied that supplies the alternating current normally used in distribution. Photovoltaic systems have a long useful life and are capable (according to their technology) to integrate with different types of architectural structures [20, 21]. In the same way, they are capable of operating with both direct and diffuse solar radiation.

The basis of a photovoltaic system are photovoltaic panels or modules, these contain solar cells (photovoltaic cells) based on semiconductors sensitive to solar radiation, which they transform into electricity. The materials used in the construction of solar cells can vary depending on the application for which they are intended, the most common being silicon, either in a single crystalline, polycrystalline or amorphous structure [20-22]. The solar cells are grouped in series or parallel to achieve the voltage and output power required by the photovoltaic module to which they are integrated.

However, when a cell is damaged or does not generate energy because it does not receive enough solar radiation, it can be polarized in reverse, becoming a charge instead of a generator, which can imply a high dissipation of energy in the form of heat, the so-called “hot spots” [23]. This situation is easily detectable if an infrared thermography is performed, in the same way faulty splices or welds with false contact can be detected [24-26].

In order to achieve quality thermographs, which provide information for decision-making, certain measurement procedures and conditions must be taken into account:

• A thermal imaging camera with the proper accessories and the correct resolution must be used.

• Sufficient solar radiation is required (at least 500 W/m^2, preferably more than 700 W/m^2).

• The viewing angle must be within the safety margins (between 5° and 60°).

• Shading and reflections should be avoided.

The UNE has Testo 875-i infrared cameras for the inspection of the photovoltaic parks currently installed in the country. This camera offers the following features: resolution of 160x120 pixels, a viewing angle of 32x23 degrees, thermal sensitivity of less than 50mK and side-by-side display of the image acquired in the visible and infrared spectrum. The manufacturer has included in its firmware an application for automatic detection of hot and cold spots, along with other adjustment options to speed up the diagnostic process. Likewise, the “Testo IRSoft” software is included for the processing of images acquired on a PC. The software allows to compensate factors such as the ambient temperature, the relative humidity and the distance between the camera and the photographed object.

Starting from the images obtained with the Testo 875-i camera, the operation specialist´s proceed to apply the thermal contrast method to evaluate the detected incidents in it. The thermal contrast method in its simplest mode can be defined as the difference between the temperature in an area under normal conditions (Tsa), and a region with hot spots (Td), as presented in Equation 1. This method, also known as “absolute thermal contrast” and several variants of it, are widely used by professionals in the energy sector and specialists in preventive diagnosis of photovoltaic systems [27-29].

$$\Delta T = Td\ (t) - Tsa(t) \quad (1)$$

This method and its variants suffer from a common lack, that is, the need to find what will be considered the healthy zone of the solar module. In addition, for the correct analysis of the thermal images, the nominal performance of the panel at the time of inspection and the maximum operating temperature must be taken into account. An adequate assessment of all these factors allows the operation specialist´s to conduct an estimated diagnosis of the safety risks related to module’s operating situation. The safety risks, based on the thermal contrast information are divided into several scales:

Td – Tsa ≤ 10ºC → Relevance **Normal**
10ºC < Td – Tsa ≤ 20ºC → Relevance **Low**
20ºC < Td – Tsa ≤ 40ºC → Relevance **Moderate**
40ºC < Td – Tsa ≤ 70ºC → Relevance **Severe**
Td – Tsa > 70ºC → Relevance **Critical** (**Safety hazard**)

Normal: No action is required until the next predictive study.

Low: Monitor to see the evolution of the hot spot using the most appropriate methodology.

Moderate: Act as soon as possible taking into account the dynamics of the power plant and its work shifts, wait for a planned shutdown to correct the problem.

Severe: Urgently study the possibility of stopping the process to correct the problem.

Critical: Stop the process immediately to correct the problem.

In the last two cases, the inspection report will be notified in advance to the power plant administration, in order to fix the problem before it's too late.

In a similar way to the risk analysis, the detection and location of the existing degradations in the solar modules, allows the realization of diagnoses to determine the state of efficiency of the same.

In the next section the inspection of a photovoltaic power plant in operation is carried out by means of the analysis of infrared images.

III. THERMOGRAPHY BASED DIAGNOSTIC EXAMPLES

The “Troncoso 1” PVSP, in the Province of Pinar del Rio, was selected to perform the diagnostic and extract examples of typical faults. This PVSP is based on the DSM-240-C photovoltaic modules of national manufacture [30]. The modules are composed of 60 polycrystalline silicon cells in 156mm X 156mm format, connected in series to provide 29.8V and a current of 8.2A at the maximum power point.

The images were taken manually, with an average solar radiation between 800 W/m^2 and 1000 W/m^2, the software IR Soft V3.3 was used for the analysis of the images. It is valid to emphasize that since each material has a different emissivity, it is necessary to compare temperatures of elements formed by the same material with nominal temperature (denoted as PF1 in the analyzed thermal images).

In Figure 2, on the left side, the captured thermal image is observed (taken from the back of the photovoltaic module), while on the right the same image is shown in the visible spectrum. The IR soft software highlights areas with temperature variations. The thermal inspection carried out shows that there are several cells with evidence of being affected with temperature differences “hot spots” (Table 1).

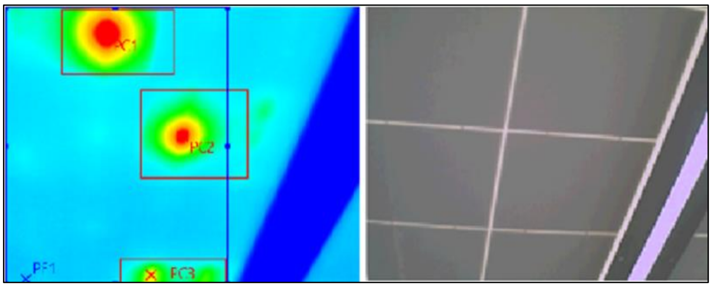

Figure 2: Burns on solar module caused by severe hot spots.
Source: Author, (2020).

Table 1: Markers referring to the analysis of Figure 2.

Name	Temperature	Emissivity	Reflected temperature
PF1	58.9	0.93	20.0
PC1	111.3	0.93	20.0
PC2	95.5	0.93	20.0
PC3	76.3	0.93	20.0

Source: Author, (2020).

The analysis of the thermal image and its visible counterpart shows that the high temperatures detected are associated with two welding tapes on the positive side of the solar cell. It should be noted that the image in the visible spectrum does not show visible damage. The nominal temperature of the module was 58.9 ºC, so the safety risks is considered: “severe”, being necessary to plan corrective actions.

Figure 3 shows a similar case where no visible image damage is observed (right site of image), however, there are hot spots with temperature differences that mark a “severe” safety risk (Table 2). The high temperatures are located in three solder tapes on the positive side of the solar cell.

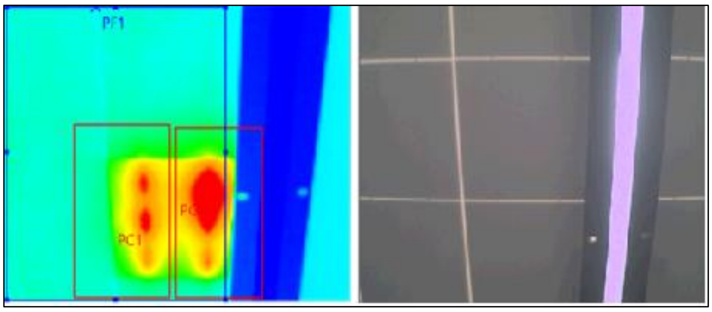

Figure 3: Burns on solar module caused by severe hot spots.
Source: Author, (2020).

Table 2: Markers referring to the analysis of Figure 3.

Name	Temperature	Emissivity	Reflected temperature
PF1	64.6	0.95	20.0
PC1	93.2	0.95	20.0
PC2	123.3	0.95	20.0

Source: Author, (2020).

Figure 4 and 5 shows modules with cells in a state of severe security risk (Tables 3 and 4), the damage can be perceived with the naked eye on the right side of Figure 4 and 5.

Figure 4: Cells with critical damage.
Source: Author, (2020).

Table 3: Markers referring to the analysis of Figure 4.

Name	Temperature	Emissivity	Reflected temperature
PF1	50.4	0.95	20.0
PC1	130.0	0.95	20.0
PC2	82.0	0.95	20.0

Source: Author, (2020).

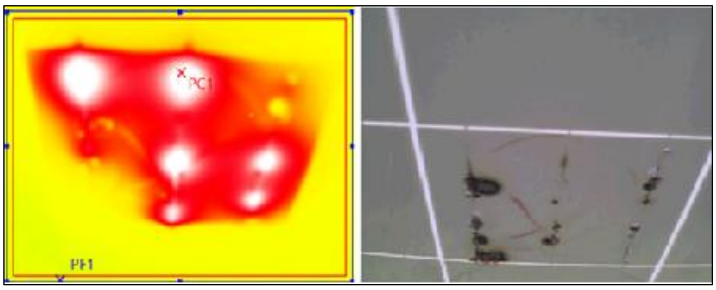

Figure 5: Cells with critical damage.
Source: Author, (2020).

Table 4: Markers referring to the analysis of Figure 5.

Name	Temperature	Emissivity	Reflected temperature
PF1	50.4	0.95	20.0
PC1	130.0	0.95	20.0

Source: Author, (2020).

Figures 6, 7 and 8, unlike the previous ones, were taken from the front of the panel, in them is possible to observe other affectations such as fractures in the glass covert, dirt and oxidation.

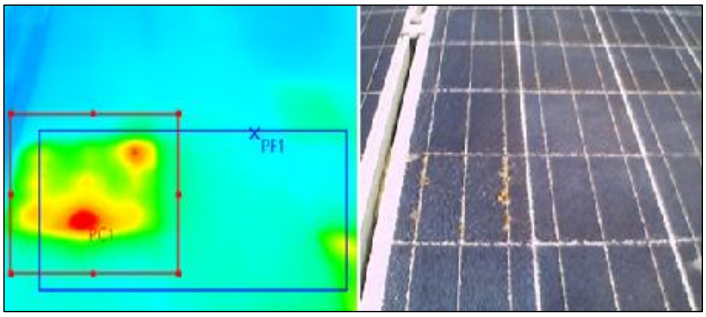

Figure 6: Fractures in the glass covert of the PV module.
Source: Author, (2020).

Table 5: Markers referring to the analysis of Figure 6.

Name	Temperature	Emissivity	Reflected temperature
PF1	52.1	0,93	24.0
PC1	95.4	0,93	24.0

Source: Author, (2020).

The cell damaged by the fractures in the glass covert is clearly identified in the visible spectrum image and its thermal counterpart shows severe damage to it (Table 5).

Figure 7 shows a PV module covered partially by dirt, in it, a loss of efficiency occurs and hot spots appear on its surface, with danger to the integrity of the cells. The impact on the module is considered moderate (Table 6) and a simple cleaning procedure could correct the situation.

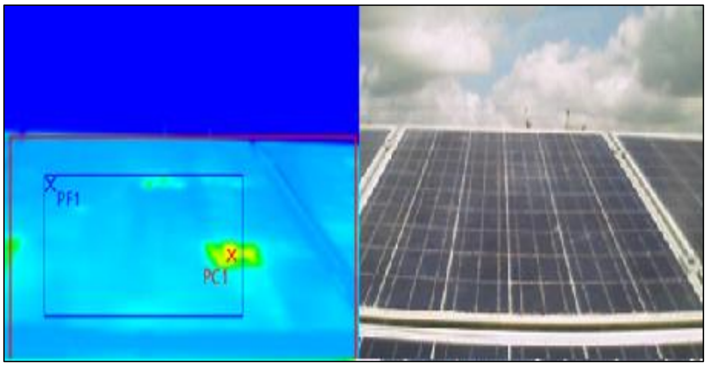

Figure 7: PV module covered partially by dirt.
Source: Author, (2020).

Table 6: Markers referring to the analysis of Figure 7.

Name	Temperature	Emissivity	Reflected temperature
PF1	43.7	0.95	20.0
PC1	69.8	0.95	20.0

Source: Author, (2020).

Figure 8 shows the oxidation of a cell on the edge of a photovoltaic module. The modules are designed to be waterproof, but damage to the sealing system could lead to the entry of rainwater and the consequent damage to the cells.

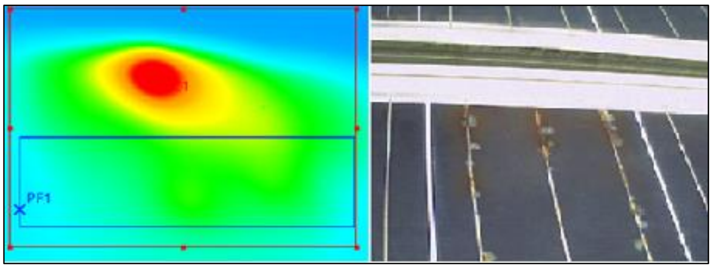

Figure 8: Oxidation of a cell on the edge of a photovoltaic module.
Source: Author, (2020).

Table 7 shows how a hot spot of severe magnitude has emerged in the area in question.

Table 7: Markers referring to the analysis of Figure 8.

Name	Temperature	Emissivity	Reflected temperature
PF1	54.5	0.95	20.0
PC1	100.1	0.95	20.0

Source: Author, (2020).

As can be seen throughout the exposed examples, thermography is a very useful tool when making a preventive diagnosis of photovoltaic installations. At present, its extensive and frequent use is limited by the manual acquisition and processing of the images. A qualified operator normally uses four days for the acquisition of the images associated with a PVSP of 1MW of power, to this must be added the time for image processing that far exceeds the acquisition time. The use of unmanned aerial vehicles (UAV) equipped with thermal imaging cameras and automated image processing software could be a solution to this limitation by reducing the acquisition and processing time [31-34].

IV. CONCLUSIONS

The use of infrared imaging helps to identify damaged areas on photovoltaic modules that are not detectable with the naked eye. With the help of the information obtained from them, the operating personnel can plan actions to avoid serious failures to the facilities.

The thermal contrast method, despite its simplicity, is valid to highlight the defects that may occur in a photovoltaic module, facilitating the diagnostic work. Expanding the use of preventive diagnosis based on thermal images in solar photovoltaic parks installed in our country, can result in better efficiency and use of installed technology.

V. FUTURE WORK

The Automatic Control Department of the Universidad Central "Marta Abreu" de Las Villas features an infrared camera NEC F30, which meets the weight requirements to be integrated into an X8+ UAV also available at the department. Future works will be dedicated to the integration process in order to be able to carry out the inspection of photovoltaic parks using aerial images, reducing exploration times.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Alain Martinez.
Methodology: Alain Martinez.
Investigation: Sandy Morales Galvez.

Discussion of results: Sandy Morales Galvez.
Writing – Original Draft: Sandy Morales Galvez.
Writing – Review and Editing: Alain Martinez.
Resources: Sandy Morales Galvez.
Supervision: Alain Martinez.
Approval of the final text: Alain Martinez.

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