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Damage Detection and Performance Evaluation of Photovoltaic Panels Used in Rural Area through Thermography Analysis

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ABSTRACT

In recent years, due to environmental issues, the installation of distributed production sources such as solar sources in electrical energy production systems has been expanding. It is very important to know the state of health of installed photovoltaic panels and their depreciation rate to maximize the amount of output energy of these panels. In this research, some common types of panel defects were investigated experimentally by thermal imager. The parameters affecting the thermal images were investigated by taking images of two similar panels, one a sound panel and a damaged panel and the performance parameters of the panels were measured by a solar analyzer. Based on the results obtained by using thermal images and image processing in MATLAB software, it was identified the defect location of the panel in a short time. According to the investigations, the histogram diagram of the healthy panel corresponds to the normal distribution, while the histogram diagram of the defective panel does not correspond to the normal distribution diagram and has an elongation to the left. Checking the voltage and power parameters of the panels shows that in the defective panels, the voltage has dropped by 1.2 V and the power has dropped by 26.8 W.

INTRODUCTION

In recent year photovoltaic panels have been used to provide electricity in many rural and agricultural sectors. Iran is located in a geological region with suitable solar radiation having an average higher than the world average and more than 280 sunny days. Electricity production in Iran from solar power plants is about 49% of renewable energy, which is more than other renewable power plants. Solar sources in electrical energy production systems have expanded day by day. The use of solar technology on a large scale and because of the construction of large solar power plants has been a growing trend in recent years and is expanding rapidly. On the other hand, this equipment needs periodic and preventive visits in order to identify them and repair or replace them before the occurrence of breakdowns and defects in the used equipment (Aghaei, 2020). Therefore, we need a suitable diagnostic method that has the ability to provide accurate and unambiguous information in this field. Various techniques are used to detect and analyze defects in photovoltaic modules. There are several different panel analysis techniques, each analyzing different power loss modes and characteristics. One of the non-destructive methods of fluorescence imaging is that the photovoltaic modules must be in the open for at least a year and a half for this method to be effective (Khatri *et al.*, 2011). In another study, two methods of electroluminescence and thermography have been combined (Botsaris and Tsanakas, 2010). The comparison between luminescence imaging and thermography proves that there is no superiority between these two methods in detecting the defects of solar cells, but in any case, thermography has advantages over other methods. For example, thermal cameras are portable and mounted (Berardone *et al.*, 2018). In another research, thermographic imaging of two power plants was done by drone. Infrared imaging by unmanned aerial vehicles shows individual hot solar panels and cells as quickly as possible (Acciani *et al.*, 2010). The efficiency of solar panels strongly depends on the temperature of photovoltaic modules, and overheating reduces the energy produced (Pilla *et al.*, 2002). Thermography has been used to detect cracks in solar cells (Kauppinen *et al.*, 2015).

In this research, some important types of panel defects were investigated experimentally by thermal imager and compare the results with the image processing results. The parameters affecting the thermal imaging of the panel were studied, and then two similar panel, a sound panel and an artificially damaged panel were tested with the same weather and position conditions. To check the panels, the voltage, current and power of the panels were measured by a solar analyzer. The thermal images taken by the thermography camera were processed by MATLAB software and the histogram of the images was checked.

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MATERIALS AND METHODS

Inspection of panel defects

In general, any impact on the module or photovoltaic device that reduces the performance of the plant or even affects the characteristics of the module is considered a failure. Failures are unexpected or unusual occurrences that have not been observed before in a photovoltaic plant. However, failures are often not the cause of power loss in photovoltaic plants. These defects affect the appearance of photovoltaic modules (Dolara *et al.*, 2014). Some examples of defects are given in Table 1.

Table 1. Summary of defects of solar panels (Bhoopathy *et al.*, 2018)

Study defects in PV module	
Manufacturing defects in module construction	• Presence of gas bubbles in EVA • Presence of defective cells • Presence of internal particles
Errors in module shipping	• Broken module glass
Damage during operation	• Temporary shading of leaves and bird droppings • Lightning strike, hail • Module with defective and partially defective diodes • Insufficient electrical contact • Corrosion, delamination, moisture • Damage to the insulating layer • Failure of connection box and cables • Hot spots • Broken glass • Leaving the cell • Snail track

Infrared analysis and thermal camera specifications

A thermographic camera is a non-contact thermometer and is also known by different names such as infrared thermal camera, thermovision and thermal imager. An infrared image is created by recording the effect of infrared waves emitted by the object, which is transmitted through the field of view of the camera and its special lens on the infrared sensor or film. The total radiation that passes through the lens of the infrared camera consists of the radiation emitted by the body itself and the radiation reflected from the surrounding environment. For this reason, we need the correct radiation coefficient and apparent reflected temperature. Thermographic cameras cannot measure the temperature of objects directly, but only measure the thermal energy radiated from the surface of the object and calculate the temperature of the object with the help of that. The portable thermal imaging camera used in this research, TESTO 2-881 model, has a spectral range of 8-14 micrometers and temperature measurement from -20 to 350 °C with the ability to upgrade to 550 °C. The technical specifications of the thermal imager are shown in Table 2.

Table 2. Technical specifications of the thermal imager used in this research

Thermal imaging camera	TESTO 2-881
Thermal imaging resolution	320 pixels and ability to upgrade to 640 pixels
Temperature sensitivity	less than 80 mK
Lens specifications	wide field of view and detect the coldest and hottest points
Temperature measurement range	from -20 °C to 350 °C with the ability to upgrade to 550 °C
Spectral range	8-14 µm

Investigating the parameters affecting the thermographic imaging of the panel

During the thermographic photography of the panels, there are several parameters that lead to the incorrect temperature of the thermal images and create obvious error effects. These parameters are distance, angle and oscillating radiation. Observing the distance between the thermal camera and the solar panel was one of the essential things that must be observed when taking pictures. When the distance between the camera and the panel was one meter or less, the image of the camera and the person behind the camera created a thermal reflection on the panel, and the thermal image gave incorrect information about the panel. Also, if the distance between the camera and the panel was large, the thermal image still gave false information about the panel. To check the panel, a distance of 2 to 3 meters between the thermography camera and the panel was considered. The right angle was required for taking pictures. If the angle of the camera and the panel was not right, the image will give false information about the panel. According to the researches, the best angle of the camera and the solar panel is between 60 and 90 degrees (Kauppinen et al., 2015). If during the recording of thermographic images, the radiation was changed by a cloud moving in front of the sun, the thermographic images were unusable.

Processing and analysis of thermal images

Image processing refers to a set of techniques that are designed to convert an image into a digital format and perform computational operations on it. The purpose of performing computational operations related to image processing in MATLAB was to produce an improved version of digital images or to extract meaningful and useful information from them. To analyze and process an image and identify it for MATLAB software, the image must be understood by the system. The only understandable language of a computer system is numbers. For this reason, the images were converted into a matrix of numbers that the software was only related to these numbers. Thermographic images of the panels were processed in MATLAB software and TESTO thermal camera software was used for validation. In MATLAB software, the RGB color space and the separation of each of its channels R, G, B and the HSV color space and the separation of its H, S, V and GRAY channels and the histogram diagram of thermal images were used.

RESULTS AND DISCUSSION

Characteristics of the studied solar system

The Lorentz LA80-12S model panel whose technical specifications are shown in Table 3 was used. The images were recorded using a portable thermal imaging camera model 881 TESTO. The radiation coefficient of the camera is considered to be 0.85 (Dolara et al., 2014). The relationship between the voltage, current, and power of the panel was measured and checked using the PROVA model 1011 solar analyzer whose technical specifications are shown in Table 4.

Experiments were conducted on dry, cloudless days with intense sunlight and ideally at outdoor temperatures (Fig. 1). Recording of thermographic images and measurement of voltage, current, and power parameters is possible only with radiation intensity of 700 to 1000 W/m² at the module level. Otherwise, on the one hand, the accuracy of electrical measurement is very low and on the other hand, the contrast of thermographic images is very low.

Table 3. Technical specifications of the solar panel

Technical specifications of PV-module LA80-12S	
Max power (+15% / -5%)	80 W
Current max power (I_{mp})	4.8 A
Voltage max power (V_{mp})	16.8 V
Short circuit Current (I_{sc})	5.3 A
Open circuit Voltage (V_{oc})	20.2 V
Max system voltage	600 V
Cell technology	Monocrystalline

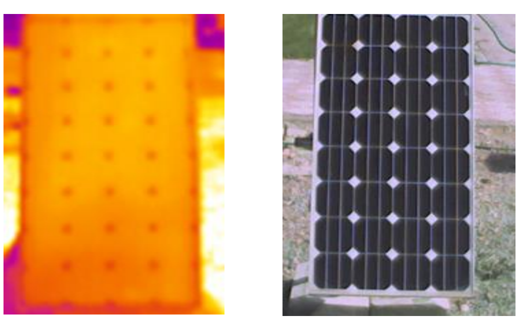
Table 4. Technical specifications of the solar panel analyzer

Photovoltaic tester model	PROVA1011, made by PROVA Taiwan company
Current-Voltage (I-V) Test Chart	1000V 12A Solar Systems
Measuring solar power	maximum voltage and current at maximum power, Searching for the maximum solar power automatically (P max)
measuring voltage in open circuit mode	from 1-1000V
measurement current in short circuit mode	from 0.1-12A
Solar panel temperature measurement	from -20 to 150 °C,
sunlight radiation measurement	2 to 2000 W per square meter

Fig 1. The details of taking a thermal image of the panel

In this section, we will examine thermal images of two similar panels, one is a healthy panel and the other is an artificially defective panel. Thermal images are processed by MATLAB software and camera software, and finally, the voltage, current, and power diagram of the panel are checked, which helps to better understand the status of the module and interpret the thermographic images.

Fig. 2 shows the thermal and digital images of the healthy panel.



a b

Fig 2. Part of the digital image and Part b of the thermal image

In Fig. 3, thermal images are processed by MATLAB software.

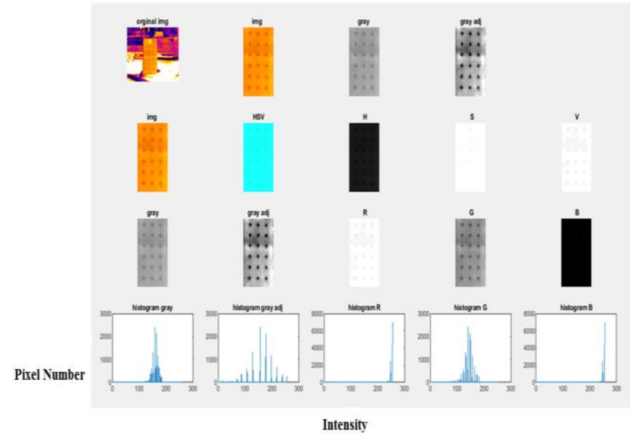


Fig 3. Thermal image processing

According to the investigations, the HSV color space and the G channel show the panel defects better, and the histogram of the G channel and the GRAY image correspond to the normal distribution diagram (Fig. 4).

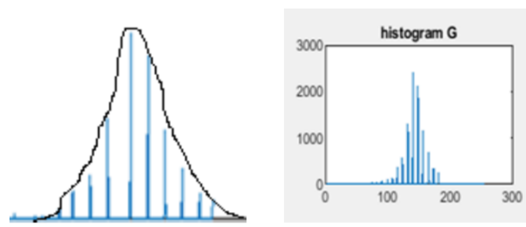


Fig 4. Thermal image histogram

In the histogram of the thermal image obtained by the camera software according to the temperature of the panel points, the horizontal axis of the temperature graph and the vertical axis show the percentage of the number of points that have a certain temperature (Fig. 5). According to the graph, the lowest temperature is 32 °C, the highest temperature is 38.6 °C and the average temperature in most places is 35.7 °C. The histogram of Fig. 5 and the histogram of Fig. 4 both correspond to the normal distribution diagram.

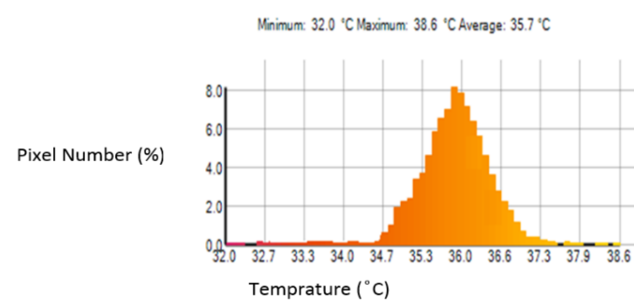


Fig 5. Histogram related to the camera software

The current and voltage curve (white color) and power and voltage curve (red color) are shown (Fig. 6) and the reading are given in Table 5 blow it. Solar cells are like light diodes and will have different outputs with the amount of radiation that reaches them. The voltage produced in them is reduced by the series resistance of raw materials and metal connections. The production current will also change with the parallel resistance (shunt).

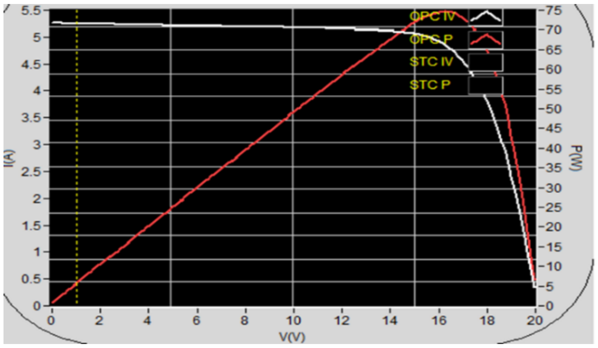


Fig 6. Voltage, current, and power diagram of a healthy panel

Table5. Voltage, current, and power of a healthy panel

	OPC		STC	
P_{MAX} [w]	75		80	
Isc [A]	5.3		5.3	
Voc [V]	20		20.2	
STC	$T_C = 25°C$	I_{RR} =1000 W/m^2	$I_{mp} = 4.8$	$V_{mp} = 16.8$
OPC	$T_C = 38°C$	I_{RR} = 900 W/m^2	$I_{mp} = 4.8$	$V_{mp} = 16$

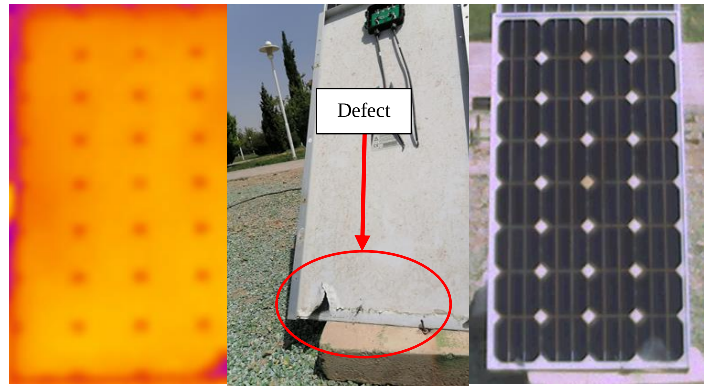
When the current is zero, it means we have an open circuit state. The open circuit voltage will be the maximum possible value. When the voltage is zero, a short circuit has occurred and we will have the highest current (Short Circuit Current). According to the curve in Fig. 6, almost close to the open circuit voltage, a jump can be seen in the curve, that point is called the maximum power point of the cell. The current and voltage at that point are I_{mp} (Current Max Power) and V_{mp} (Voltage max Power) and the multiplication of two parameters is called the rated power of the cell.

All these parameters are measured in STC (Standard T_{test} Condition) (conditions: radiation intensity 1000 W/m^2 and cell temperature 25°C) and are placed on the back of the panel in the form of a plaque. Reducing the intensity of radiation and increasing the temperature of the cell causes a decrease in the power of the panel. In Fig. 6, the FF (Fill Factor) (specifies the maximum power that can be extracted from the cell) is equal to 0.7 STC. Other parameters in OPC (Operating Condition) include a short circuit current of 3.5A, open circuit voltage of 20 V, Imp equals 4.8A and V_{mp} equals 16.8V, which is equal to standard conditions.

In general, in Fig. 6, the voltage and power of the panel do not show a significant drop.

Panel defects

Fig. 7 shows the thermal and digital image of a healthy panel that is artificially damaged. Fig. 8 shows the image processing of the defective panel. The HSV color space and the H channel of the defective cell are shown in white and the rest of the channels are shown in a darker color. Fig. 9 shows the faulty cell in the camera software as the coldest point.



a) Digital image b) The defective part from the back of the panel c) Timage of the panel

Fig 7. Thermal and digital image of the defective panel

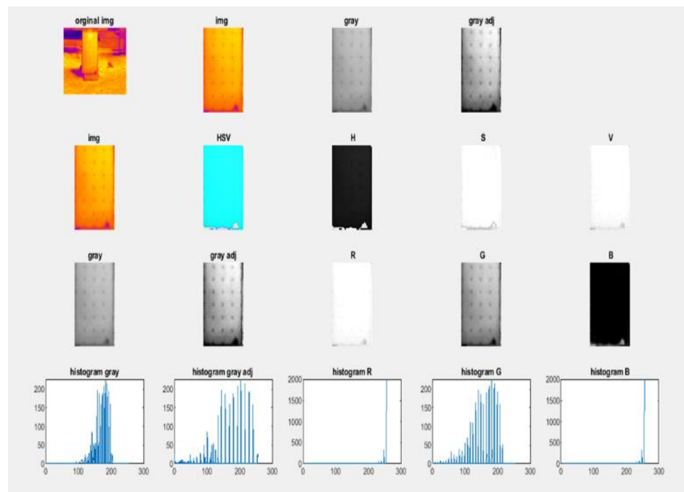
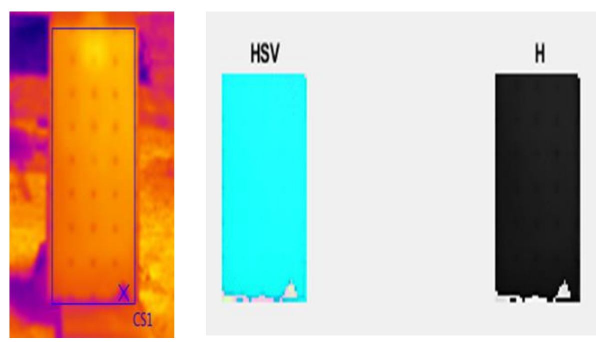


Fig 8. Defective thermal image processing



a b

Fig 9. a) The coldest point (cs) Camera software and b) Image processing in MATLAB

Fig. 10 shows the histogram of the thermal image obtained by the camera software according to the temperature of the panel points. The horizontal axis shows the temperature and the vertical axis shows the percentage of points that have a certain temperature. According to the graph, the lowest temperature is 32.6 °C, the highest temperature is 48.2 °C, and the average temperature in most places is 39 °C. In the histogram of Fig. 8 and Fig. 10, both graphs stretch to the left, which does not correspond to the normal distribution graph.

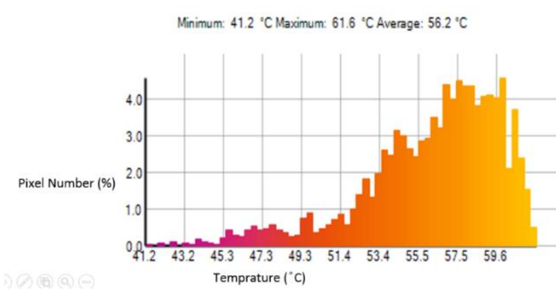


Fig 10. Camera software histogram

Fig. 11 shows the current and voltage curve (white color) and the power and voltage curve (red color). The reading from this figure are shown in Table 6. The FF has decreased significantly from 0.7 to 0.5, and other parameters, including the short circuit current, have increased slightly from 5.3 to 5.4A. The open circuit voltage has decreased from 20.2V to 19.04V and the panel power has decreased significantly. As it is clear from Fig. 11, when the panel is healthy, it can produce nearly 80 W of power, and when the panel is defective, the power is reduced to 53.3 W. In general, Fig. 11 shows a significant drop in panel power.

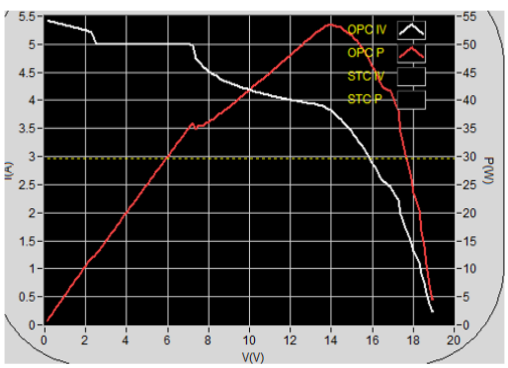


Fig 11. Voltage, current, and power diagram of a defective panel

Table 6. Voltage, current, and power of a defective panel

	OPC	STC
P_{MAX} [W]	53.3	80
I_{SC} [A]	5.4	5.3
V_{OC} [V]	19.04	20.2
OPC	TC = 46°C, I_{RR} = 900 W/m^2, I_{mp} = 3.9A, V_{mp} = 14V, F=0.5	
STC	TC = 25°C, I_{RR}=1000 W/m^2, I_{mp} = 4.8A V_{mp} =16.8V, FF=0.7	

CONCLUSIONS

During their operational life, photovoltaic modules may have various defects during manufacturing or during transportation, and installation, or during their lifetime. Thermography imaging techniques can detect and investigate defects in the shortest possible time. The failure of solar modules can be divided into three categories: failure at the beginning, in the middle of life, and wear failure at the end of life. Initial failures occur shortly after the modules are installed in the power plant. Defective modules fail quickly and have a significant impact on costs for manufacturers and installers. Intermediate failures occur when photovoltaic modules remain in the operational field for years and are subject to severe thermo mechanical stresses. Failure of the junction box and cables, hot spots and signs of wear on cells and back plates of photovoltaic modules, broken glass, electrical disconnection of parts of cells due to cell breakage, and damage to connection strips lead to intermediate failure. Deterioration defects not only reduce the performance of photovoltaic modules but can also cause safety hazards and the working life stops when the power generation falls below a certain limit. In this research, two-panel samples were examined.

In solar power plants, checking each panel manually by measuring voltage, power, and current is very time-consuming and tiring, and the exact defect of the panel cannot be identified. Using a thermographic camera and a drone, the images taken from the panels can be checked by high-speed image processing and the exact location of the panel defect can be identified. Even before installing the panels, you can use this method to ensure the health of the panels, and that the panel is not damaged before installation.

According to the presented results, thermal image processing by MATLAB software determines the hot spot and the cold spot of the desired panel as quickly as possible. The hot spots and cold spots obtained by the TESTO camera software correspond to the points specified in the image processing in MATLAB. Image processing fully identifies the defective part of the panel. The histogram chart obtained in terms of temperature by TESTO camera software matches the histogram chart obtained in terms of color intensity from image processing in MATLAB. According to the investigations, the histogram chart of the healthy panel corresponds to the normal distribution, while the histogram chart of the defective panel does not match the normal distribution chart and has an elongation to the left. Checking the voltage and power parameters of the panels shows that in the defective panels, the voltage has dropped by 1.2 V and the power has dropped by 26.8 W.

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