Faults in photovoltaic modules and possibilities for their detection by thermographic studies

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***Abstract* — This paper presents a review of the studies of photovoltaic modules through passive thermography. The different types of faults in photovoltaic panels and their representation in the thermographic images are considered. The factors that influence the study and the ways to avoid them are described.**

Keywords— diagnostics, maintenance, photovoltaic modules, thermographic study

I. INTRODUCTION

Conventional fossil fuels, such as oil, natural gas, and coal, are gradually running towards exhaustion. On the other hand, more and more attention is paid to the issue of protecting the environment from technological pollution from the use of traditional forms of energy production. As a result of the technological developments, in recent years, renewable energy sources are being implemented at a record rate. This applies especially for photovoltaic systems.

Predicting the reliability of photovoltaic (PV) modules requires in-depth knowledge and full understanding of the design of the system, the operating environment, and the mechanisms that lead to a system failure.

Photovoltaic power plants are built outdoors and are exposed to severe environmental conditions much more than other electrical equipment. Therefore, there is always a possibility of a fault occurring in some of the system components. This is why it is necessary to undertake periodic preventive maintenance and, if necessary, repair of defective elements to ensure the efficient operation of the plant.

With the incrementing use of photovoltaic systems in both the commercial and the private sector, there is a rising need to find a suitable inspection method for these systems. This method must guarantee the safe and cost-effective operation of photovoltaic systems, enabling the monitoring of the technical condition and the timely diagnosis of the individual elements of the system [1].

II. THE PHOTOVOLTAIC MODULE

All types of photovoltaic modules have similar construction. The typical structure of a photovoltaic module is shown in Fig. 1. It is built from a number of photovoltaic cells that are connected in series and/or parallel to obtain the appropriate output voltage and power. The protection of photovoltaic cells from the environmental influences and mechanical stresses is achieved by encapsulation. The encapsulation is usually made of ethylene vinyl acetate (EVA) or other material with high transmissivity. The front surface of the panel is covered with protective tempered glass. This whole structure is housed in a frame made from anodized aluminum that provides mechanical strength and installation convenience. At the rear of the module is a junction box, providing an electrical connection [4].

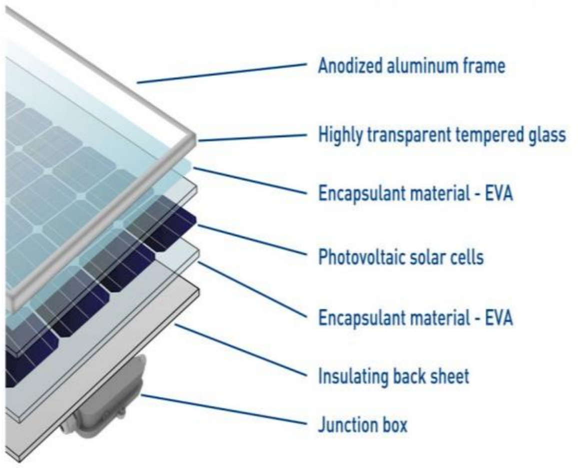

Fig. 1. Structure of the PV module

The principle of operation of the photovoltaic module, in normal operating mode, is illustrated by Fig. 2. The PV modules used for large power production include between 36 and 72 individual solar cells. Almost all photovoltaic modules include integrated bypass diodes as shown in Fig. 2. Polycrystalline photovoltaic modules usually have three of them, which are located in the junction box and each can bypass one-third of the panel when needed.

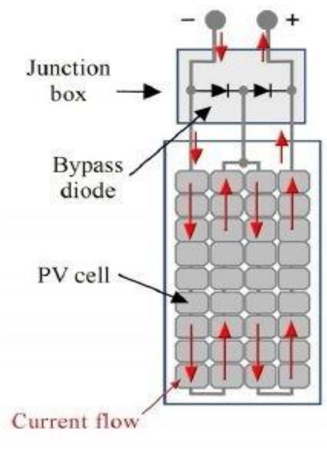

Fig. 2. PV module in normal operating mode

Fig.3 shows the two-diode equivalent circuit of a photovoltaic module. Under normal operating conditions, the performance of the photovoltaic cells decreases due to the power dissipated in its internal resistance. The internal

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resistance is modeled as a parallel-connected shunt resistance (R_{sh}), taking into account the presence of a leakage current between the individual cells, and series-connected series resistance (R_s) taking into account the voltage drop in the cells, in the solder joints, and in the cable connectors [2,3].

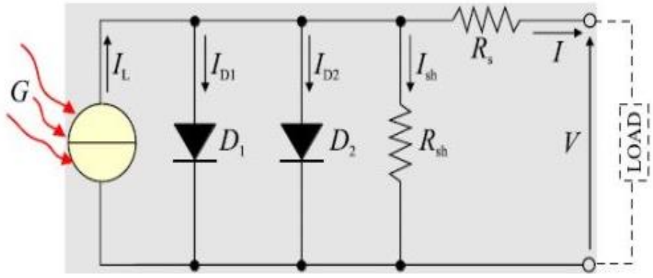

Fig. 3. PV module – two-diode equivalent circuit model

The current through the load, when using a mathematical model with a two-diode equivalent circuit, can be determined by the following equation:

$$I = I_L - I_{D1} - I_{D2} - I_{sh} =$$
$$I_L - I_{01}\left[\exp\frac{q(V+IR_S)}{n_1 k_B T} - 1\right] - I_{02}\left[\exp\frac{q(V+IR_S)}{n_2 k_B T} - 1\right] - \frac{V+IR_S}{R_{sh}} \quad (1)$$

where: I_{01} and I_{02} are the saturation currents of D_1 and D_2;

n_1, n_2 – coefficients taking into account the diffusion and recombination of current-carriers at temperature T;

V is the load voltage;

q – elementary charge;

k_B – Boltzmann's constant.

III. Typical Faults in Photovoltaic Modules and Their Detection by Using Thermography

The performance of photovoltaic modules may deteriorate for a variety of reasons. Experience from the exploitation of photovoltaic systems shows that the main reasons for the loss of performance of photovoltaic panels are:

- degradation (aging) of optical materials;
- degradation (aging) of semiconductor devices;
- loss of the encapsulation hermeticity;
- disruption of the connection between individual cells and sub-modules;
- short circuits between individual cells and sub-modules.

Three levels of faults can be distinguished in photovoltaic systems: cell level, module level, and array level. Cell-level faults include cracks, corrosion from water penetration, and degradation of the material due to the influence of ultraviolet radiation or temperature. Module-level faults are associated with open circuit modes or short circuits as a result of damage to cells, coatings or sealing materials, as well as partial shading of the photovoltaic module. String level failures consist of open circuits or short circuits, polarity mismatches of individual modules, sub-modules, or cells in the string, and partial or full shading of modules. All types of defects, on all fault levels, are associated with local or zonal temperature rises (hot spots or areas). Thus the task of detecting the fault in the PV modules becomes a task of detecting the temperature differences.

Thermography is an important diagnostic tool as it shows the change in temperature distribution, as is the case with the faults of the photovoltaic modules. The temporary rise in temperature in a solar cell or cells is allowed to be in the limits of 30 °C.

Thermography can also be successfully used in combination with other diagnostic methods such as fault detection based on the output characteristics.

A. Degradation of optical materials

The state of optical and encapsulating materials is crucial for the long-term functionality and efficiency of cells in photovoltaic modules. The degradation of these materials is caused by both external factors - dynamic temperature changes, mechanical stresses and shocks, moisture, UV radiation, etc., and internal factors - low quality material (impurity) or production process. To reduce the share of these faults, trends in the development of photovoltaic module production technologies are aimed at using new promising materials with improved characteristics: dielectric strength, water vapor transmission rate (WVTR), thermal conductivity, etc.

The faults related to the degradation of the optical and encapsulating materials are: disturbance of the adhesiveness between the safety glass and lamination or between the different layers of lamination, change of the color of the lamination, appearance of air inclusions under the lamination and contamination (soiling) or cracking of the safety glass.

The thermographic image of a photovoltaic module with air inclusions below the lamination is shown in Fig. 3.

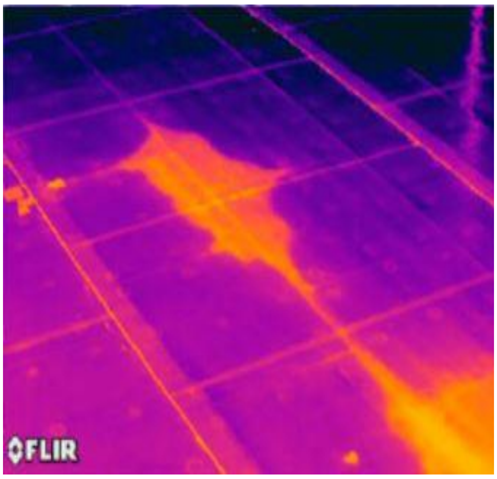

Fig. 4. Thermographic image of photovoltaic panel with air inclusions under lamination

The representation of these faults in thermographic images is expressed in the appearance of areas with a higher temperature. These areas do not follow the boundaries of the structural elements of the module. The increase in temperature occurs due to a decrease in thermal conductivity in the damaged areas. Typical values of temperature rise for these faults are in the range 1-5 K.

B. Polarity mismatches

In order to reduce the current density, high-power photovoltaic systems are designed for high voltages, therefore large numbers of cells are connected in series.

Therefore the same current flows through all of the series-connected cells. When the string includes a cell with lower output power, the current in the string is determined by the current of the faulty cell. This results in a change in the overall current-voltage characteristic. The voltage drop on the faulty cell changes its sign and the cell begins to act as a consumer of electrical power.

There are many reasons for reducing the power (current) generated by individual cells: shading individual cells, changing the characteristics of cells as they age, and in rare cases production defects. The most common cause for polarity mismatch is partial shading [4,8]. Fig. 5 shows a thermographic image of photovoltaic panels with partial shading caused by a lightning rod. The temperature differences that occur when the polarity of individual cells do not match are in the range of 15 to 45 K depending on the nature and degree of the fault, and the realized maximum temperatures can exceed 90°C.

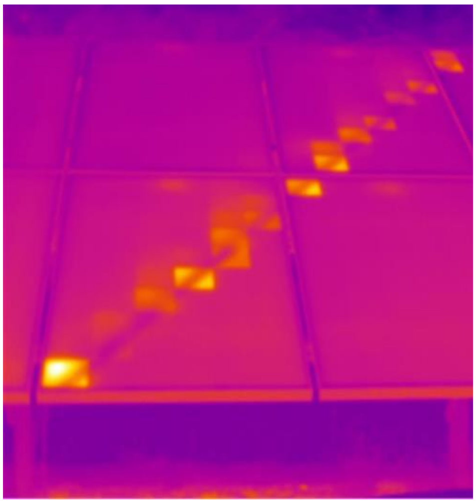

Fig. 5. Thermographic image of photovoltaic panels with shaded cells

In continuous operation, the temperature of the reverse-biased cell may exceed the critical value of ~ 150°C, which can lead to a disturbance of the tightness of the lamination and propagation of the fault. If the reverse voltage exceeds the cell breakdown voltage, it can irreversibly damage the cell by a thermal breakdown. Because of that, a shunt diode is connected to the string, to reduce the energy dissipated in the faulty cells.

C. Faults in the connections between the individual cells

The typical faults in the intercellular connections include: interruptions or short circuits in the interconnection ribbons of the individual cells and missing or resistive solder joints between the ribbons and contacts of the cells. These faults are caused by mechanical stresses, sudden temperature changes, manufacturing process errors.

In normal operating mode, the proper functioning photovoltaic cells have an almost uniform current density. In this case, energy losses, in the form of heat dissipated in the cell, are also distributed over the entire surface of the cell and cause very little increase in its temperature. Damage to the connections between individual cells results in uneven current density. In this case, energy losses are concentrated in places with the highest current density. This causes local overheating, which can cause damage to adjacent cells if the temperature is high enough.

The thermographic image of a photovoltaic cell, in which problems with intercellular connections are observed, is shown in Fig. 6.

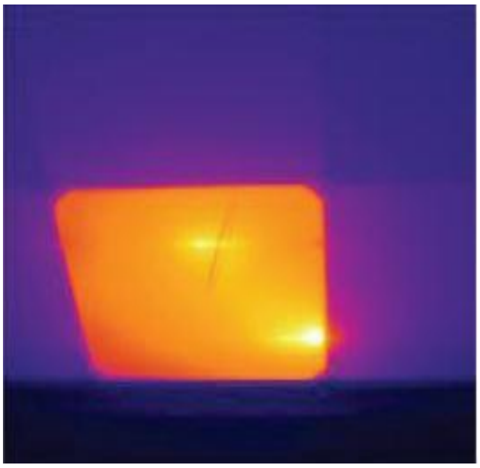

Fig. 6. Thermographic image of a photovoltaic cell with damaged intercellular connections

These failures are classified into three groups, depending on the performance reduction and the safety risks at work:

- Group I

Interruption of one of the interconnection ribbons at given side of the cell. Thermographic images show an increase in temperature covering some parts of faulty cells. For faults in this group, the reduction in performance shall be limited to $\Delta P<35\%$ and the maximum temperature shall be below 100°C.

- Group II

Disruption of both interconnection ribbons at given side of the cell. The circuit is interrupted and the cells in the corresponding string begin to work in idling mode. Productivity loss is limited up to $\Delta P<50\%$. The thermographic images show a uniform increase in the temperature of the sub-module. The typical value of the temperature rise is in the range of 3-5 K. In this case, the safety risks at continuous operation depend only on the reliable functioning of the bypass diodes.

- Group III

Interruption of both interconnection ribbons at given side of the cell, and fault occurring in the bypass diode. Local overheating occurs at the point of interruption, in which the temperature could rise above 500°C.

D. Cracks in the cells

Cracks of photovoltaic cells can occur at both the stage of their production and installation, as well as in the stage of normal operation. The main causes of photovoltaic cells rupture during operation are the dynamic thermal loads and hail damages.

In some cases, cracks lead to the separation of part of the cell from the interconnection ribbons providing the electrical connection of the cell. This leads to a decrease in the power (current) produced by this cell. Individual cracks can affect the power generated differently depending on their size, position, and orientation. Based on how much the power output is reduced, cell cracks can be classified into the three categories shown in Table 1.

TABLE I. CATEGORIES OF CRACKS IN PHOTOVOLTAIC CELLS

Type of the crack	Category
Dendritic	III
Cross line	II
In several directions	III
Parallel to the interconnection buses	III
Perpendicular to the interconnection buses	I
Diagonal (± 45 °) of the electrical interconnection buses	II

The thermographic image of a PV module with cracked cells is shown in Fig. 7. Depending on the category in which the cell cracks fall to, they appear in the thermographic image as uneven heating due to increased cell resistance at the site of the crack, or significant overheating of a part of the cell. The difference in temperature of the faulty and normal functioning cells from the photovoltaic module reaches from 35 to 55 K.

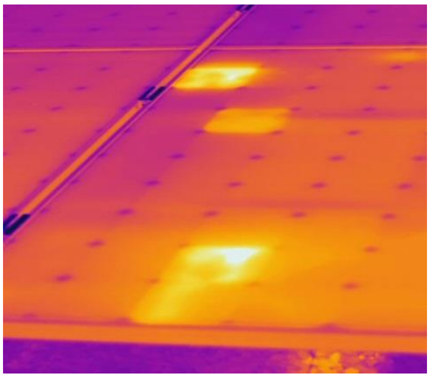

Fig. 7. Thermographic image of a photovoltaic panel with cracked cells

E. Faults in the bypass diodes

The bypass diode is intended to protect a section of the panel that produces less current, i.e. there are cells with reduced performance. Therefore, proper use of bypass diodes can prevent damage due to inadmissible temperature rise [6].

Faults of the bypass diodes include: electrical breakdown of the elements (short circuit) or rupture of the elements. The main causes of these faults are the thermal impacts at continuous operation.

The thermographic image, of a PV module with defective (short-circuited) bypass diode, is shown in Fig. 8.

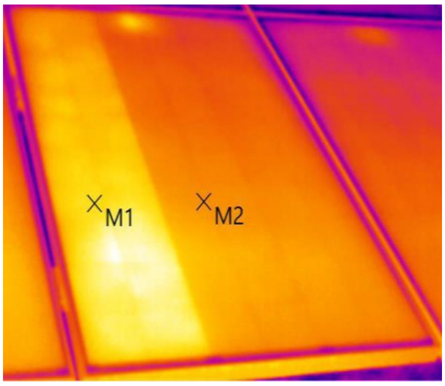

Fig. 8. Thermographic image of a photovoltaic module with short circuited bypass diode

In the thermographic images, this type of faults is represented in two characteristic patterns:

- Local temperature rise at the bottom of the module. This kind of representation is typical for the modules that include cells with similar characteristics.
- Rise in the temperature of individual cells. The distribution of the overheated cell is random in the so-called patchwork pattern. This kind of representation is typical for the modules that include cells with significant differences in their characteristics.

The typical values of the temperature rise of the module in both cases range from 3-10 K.

F. Faults in the junction box

This class of faults includes short circuits and interruptions in the connection wires and failures in the protection and switchgear devices. As a result of these faults, the individual modules could operate in idle mode (Fig.9.) or in short circuit mode. Some of these faults occur during the stage of normal exploitation and are related to damages caused by environmental conditions, mechanical stresses, overloads, etc. The rest arise from the improper installation or repair of the photovoltaic system.

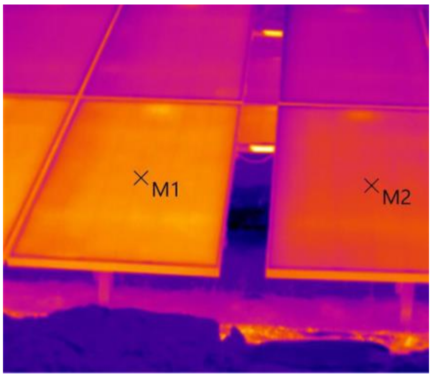

Fig. 9. Thermographic image of a photovoltaic modules working in idle mode

The typical temperature rises of the modules are 2-7 K for the modules operating in idle mode, and 3-13 K for the modules operating short-circuit mode.

IV. FACTORS INFLUENCING THERMOGRAPHIC STUDIES OF PHOTOVOLTAIC MODULES

As already mentioned, the PV power plants are built outdoors, which means that there are many factors that can affect the thermographic measurement of the temperature.

One of the main problems to be considered when performing thermal imaging testing of photovoltaic modules is the problem of the reflected temperature. Obtaining accurate temperature measurements from glass surfaces is not a simple task since these surfaces have extremely high reflectivity and behave differently for different wavelengths. If not taken into account, the reflected temperature of the protective glass may result in a temperature reading error that may reach up to 25°C.

Given the aforesaid, it is recommended that the angle of view of the photovoltaic module should be 5-60° when conducting the thermographic study [5].

The second factor that significantly affects the measurements is the value of emissivity. Due to the presence of the protective glass, the emissivity varies significantly with the viewing angle. It is recommended that emissivity should be measured several times before starting the thermographic study.

The measurement can also be affected by a group of factors related to operating conditions and environmental conditions. To minimize the influence of these factors, it is advisable to carry out the study under the so-called standard test conditions in order to achieve the most accurate results. The standard test conditions give the admissible values for solar radiation, ambient temperature, wind speed, and minimum load, under which the test can be conducted [7].

Among the other factors, the accuracy of the results obtained also depends on the characteristics of the used thermal imaging camera. In order to obtain reliable results, it is recommended that the instantaneous field of view (IFOV) of the camera has to be such that each photovoltaic cell covers at least 5x5 pixels from the camera's infrared detector. The thermal resolution of the camera has to be <100mK.

V. CONCLUSION

Thermography is an important tool for assessing the technical status and performance of photovoltaic modules that meet current requirements.

Thermal imaging technology enables the detection and classification of a wide range of faults in photovoltaic modules.

The use of this technique facilitates periodic inspections, ensuring timely diagnosis of faults and maintaining the efficient operation of photovoltaic power plants.

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