Testing, Analysis and Diagnostics of Chosen Faults of Photovoltaic Systems

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***Abstract*— The paper is focused on the analysis and detection of faults of photovoltaic (PV) elements, especially PV modules, and their impact on the reliable operation of the photovoltaic system. Brief overview of currently used measurement techniques and methods in photovoltaic diagnostics is introduced. The consequences for the safe and reliable supply of electricity from the PV system were demonstrated on silicon photovoltaic modules by modelled faults and evaluate them using selected diagnostic methods. The influence of respective defects and environmental impact was demonstrated using current-voltage (I-V) curves, impedance spectroscopy and thermography. The aim was not to quantify the deterioration of measured samples, but to demonstrate chosen methods and their potential.**

Keywords—photovoltaics, diagnostics, module, measurement, I-V characteristics, impedance spectroscopy, thermography, reliability, safety

I. Introduction

Demand for energy has experienced on a global scale exponential growth in the last thirty years. Electrical energy makes up approximately 10 % of the global energy mix of consumption and further growth is expected. Efforts to find substitutes for conventional energy sources and their wider integration into the conventional energy network are not only the subject of research projects, but currently also a reality in many countries. Renewable resources (RES) have a share of 30 % on a global scale, with the assumption of further growth [1]. This increase is expected not only when we consider the global trend of reducing the carbon footprint, but also by accepting the energy policies - e.g. European Union, or in consideration of the current global situation (e.g. the impact of the military conflict in Ukraine on the prices of energy commodities, inflation, etc.).

The most important steps for the expansion of renewable energy sources are the investigation of the energy potential in individual countries and determination of technical-economic-legislative barriers [2].

The last more than 50 years of intensive research, development and also commercial applications have established photovoltaics as a promising method of electricity production. A great advantage in comparison to other RES and conventional sources is the low cost of operation and maintenance and the ease of installation. The advantages also include the steadily decreasing price of the PV system, thanks to the improvement of production technologies and the increase in the efficiency of PV cells and the modules.

The disadvantage of photovoltaic installations is the occupation of large areas, especially rare agricultural land. The production of electricity only during the day under good sunny conditions and the strong seasonal dependence production also put photovoltaics at a disadvantage compared to conventional sources [3].

Renewable energy sources (RES) represented 22.9 % of total production in Slovakia the year before last, while photovoltaics produced 2.5 % of electricity [4]. The realistic assumption of further expansion of photovoltaic installations is expected not only for current global economic situation, which has resulted in an enormous increase in energy prices, but also for EU's long-term goals in the form of decentralization and decarbonization of the electric power industry. A further increase in the volume of PV installations of small and medium power for public buildings and small and medium-sized enterprises, supported by the "Recovery and Resilience Plan of the Slovak Republic" mechanism, will also contribute to the growing share of PV in the RES mix.

Since the volume of PV installations will increase and their impact on the conventional energy network will no longer be negligible, this phenomenon brings with it new research challenges and goals. In addition to analyzes of the well-known negative effects on the grid [5] (deterioration of the power factor, higher harmonics, overvoltages and other) it is very important to focus on the safe and reliable operation of the PV system as well as the reliability of energy supply from PV source. By the term PV system we understand panels + electronics + accumulators + electrical accessories. The aim of the paper is the identification and classification of faults that occur in PV power plants in real

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operation. Malfunctions of any component of the PV system can seriously affect not only the efficiency of the PV conversion and the related energy production of the source, but also the safety and reliability of the entire PV system. In addition, if some components fail, the situation may lead to fire or injury. If we consider the fact that the source cannot be turned off, the phenomenon of fire brings new risks and problems when extinguishing a burning PV source [6]. Developing methods for detecting and diagnosing faults in PV devices are therefore necessary to increase system reliability and maintain high efficiency and safety of the entire PV system.

II. Photovoltaic Systems and Faults Occurring Most Often in Real Operation

The PV system in general include panels, cabling, overcurrent and overvoltage protection, switches, mechanical assembly components, inverters, accumulators, charge controllers, measurement and regulation elements [7]. Attention will be focused on the most frequently occurring malfunctions and operating conditions of PV panel. The main reason is fact that the PV panel as a source of electrical energy is a key element greatest impact on reducing energy production and possibly endangering safety.

A. Hot Spots

Hot spots (HS) or places of excessive local heating are caused by cell in the PV string (a series of connected PV cells), which has different electrical parameters in the discretion of his I-V characteristic in compare to the electrical properties of the remaining cells, which should be within a certain tolerance the same parameters. This negative phenomenon arises e.g. due to the so-called cold joints, pollution of part of the PV panel, accumulation of dust, cell degradation or e.g. conductive leads on the edges of the cells. The source of partial shading it often is dirt and shadow from a tree/building, cloud or some natural barrier. These shielded cells subsequently consume power from other unshielded cells and could damage the module due to the joule heat. Damaged PV cells (e.g. cracked) are also a frequent cause of HS. One of the techniques for quick detection of HS is infrared measurements, e.g. using a thermographic camera [8]. Hot spots can be eliminated by using bypass diodes, often cleaning of the surface of the modules, using casing materials with good heat dissipation, using the so-called tracking systems, by installing panels at the right angle and eliminating the occurrence of obstacles around the PV system [9].

B. Malfunctions of Bridging and Blocking Diodes

In real PV operation, the effort is to eliminate power losses caused by partial/complete shading of the panel or set of panels (PV field) as well as the creation of the so-called reverse current caused by the flow of energy to the panels in full shading mode (e.g. discharging accumulators through PV arrays at night). Shading even "just" one cell within a PV panel can cause disproportionate power losses approaching 50 %. Simulations showed that the solution to almost completely eliminate the shadowing effect is the anti-parallel connection of a bypass diode to each PV cell within the panel [10]. A diode connected to string of series-connected PV cells is in practice a compromise solution accepting economic and technical optimization.

Blocking diodes are usually connected in series with each series branch (cells, panels, arrays). Blocking diodes, also known as series/isolation diodes, ensure the flow of current in one direction, i.e. out of series array to external load or batteries. The reason is to prevent the current generated by other parallel connected PV panels in the same field from flowing back through the shielded parts of the PV field and to prevent the charged batteries from discharging through this field at night. The type of blocking diode used depends on the power of photovoltaic field and performance parameters. In practice, standard silicon and Schottky diodes are used [11]. A common cause of diode failure is current overload and high voltage in the reverse bias condition [12]. Bypass and blocking diode failures contribute to power loss in many aspects. In addition to power losses (more than 33 % of the output power of the panel), non-eliminated HS due to non-functioning diodes also contribute to the yellowing of casing materials or its cracking and can be the cause of fire. Let us add that bypass or blocking diodes, as it will be shown in the experimental part of this paper, eliminate the shielding effect, but themselves are source of small power loss.

C. Module Failures Associated with External Influences and Causes

The most common failures are color changes of the boxing material, stripping of live parts due to cracks and mechanical damage and delamination. These faults contribute to power losses at a rate of approximately 10 % and can be a source of fire and electric shock risk [12]. The approximate rate of degradation of the rated output of a crystalline silicon PV panel is 0.8 % per year. One of the main reasons for the instability of the performance of PV panels is the production error rate. Another frequent source of performance loss is the so-called light-induced degradation, which is most pronounced in amorphous silicon panels [6]. Amorphous silicon panels lose 10 % to 30 % of output power in the initial stages of operation.

Among the malfunctions due to external influences and causes, we include malfunctions during transportation, clamping, errors in the cable connection, connector malfunctions and the influence of atmospheric electricity. Module cracks caused by shocks and vibrations during transport can be effectively identified using thermography or electroluminescence. Other mechanical damage often occurs when the PV module is incorrectly clamped, which often leads to breaking of the glass of frameless PV modules. The cables and connectors that connect individual modules to each other and to other elements of the PV system have a significant impact on safety and reliability in the production and transmission of electricity. The most frequent malfunctions arise from inappropriate selection of cable, connector and their mutual connection, which often leads to power losses, electric arcs and fires. Lightning strike on the so-called the DC side of system can damage the bridging and blocking diodes or also damage the PV cells that are part of the string within the module [14].

D. Delamination

The PV panel is a multi-layered structure (frame + glass + EVA layer + PV cells + EVA layer + back layer + distribution box), while the PVs are encapsulated, often based on ethylene vinyl acetate (EVA). EVA improves the mechanical properties of the module, protects PV cells from unwanted electrical influences and external environmental factors. The EVA layers are coated whole using a laminator.

Delamination of the EVA layer occurs most often in the corner areas of the PV panel and around the connections. The increased rate of delamination is influenced by the used material and the technological procedure of lamination. Panel delamination can be identified even without complex diagnostic procedures and is manifested by a significant reduction in insulation resistance [15, 16]. According to the standard, the insulation resistance of the PV module should be over 40 MΩ/m^2, which represents an insulation resistance over 24.5 MΩ for a standard panel with 60 cells with a surface area of 1.65 m^2. Damaged modules must be replaced to avoid performance losses and danger. Pulse lock-in thermography is suitable tool to detect delamination. Time-consuming x-ray analysis and an ultrasound scanner are also used to examine less pronounced delaminations [14].

E. Loss of Front/Back Layer Adhesion

The back side of the panel serves to protect the connected PV cells from direct environmental influences and ensure safe operation by protecting against contact with live parts (dangerous DC voltage). The back side of the panel is made of glass or polymer materials.

It is most often made of a highly stable (resistant to UV radiation) polymer, e.g. fluoropolymer. The choice of material affects the price of the panel and the mechanical properties. If the panel is constructed with a front and back glass layer, there are additional mechanical stresses that increase the rate of delamination. Different factors affect the adhesion between the different layers of the panel. In addition to mechanical stress, environmental influences (moisture, temperature changes, UV radiation) also play a significant role, and as a result, this manifests itself in the formation of bubbles on the surface of the panel. The separation of the protective glass, or the so-called delamination of the panel, is basically the separation of the protective glass with EVA-foil from the PV cells. As a result of this separation, bubbles can form between the cells and the protective glass. If moisture and water get into the bubbles, it could have an undesirable effect on the efficiency of the PV conversion due to corrosion processes [17]. Another effect is closely related to delamination and the formation of bubbles, to which, in addition to temperature changes and humidity, the large potential difference between the cells and the frame of the PV panel contributes. Since the panel frame must be grounded for safety reasons, a sharp potential drop causes the migration of particles (ions) from the cells through the insulating layers towards the frame. This phenomenon, which causes a change in the insulation properties and reduces the output power of the panel, is called potential-induced degradation (abbreviation PID) [18].

III. Diagnostic Methods

The methods of detection and diagnosis of faults of PV elements are classified into two main categories:

A. Visual and Thermal Methods

-identification of panel damage, discoloration, browning and surface contamination. Diagnostic methods include infrared and thermal imaging, visual inspection, electroluminescence imaging, lock-in thermography and AI techniques and deep learning methods.

B. Electrical Methods

-measuring of electrical characteristics of PV cells/panels. They make detection of faults on PV elements and provide a comprehensive description of electrical transport processes. Diagnostic methods are based on I-V characteristics analysis, energy loss analysis - sis method, current, voltage, temperature and heat exchange measurement methods, voltage-current spectrum analysis, impedance spectrum analyses, statistical techniques, signal processing techniques and hybrid technologies [19].

A more detailed description of individual techniques go beyond the scope of this publication.

IV. Experimental

The aim of the experimental part was the implementation of model failures most often occurring in real operation. The secondary goal was comparing the influence of the fault on the type of PV cells (panels). Monocrystalline and a polycrystalline panel with a maximum power of 10 W were the object of comparison. We present in this work selected results from a large number of experiments.

A. DC Analysis

Panel shading was chosen as the appropriate model fault for the DC analyses. The following shading variations were chosen: shading 1/3 of the panel, shading of 16 and 32 cells, application of Primalex paint (1/3 panel and the entire surface of the panel), application of soil to the panel and disconnection of the diode in the junction box. The measurement was also carried out in the initial state, i.e. in a condition when impurities or faults on the panels were not presented. An artificial halogen light source, a calibration cell ORIEL-SRC-1000-TC-QZ-N and a tester and analyzer of solar panels – TES PROVA 1010 were used during the measurement. The measurement of I-V characteristics was carried out by a four-quadrant measuring source Keithley 2440 5A.

The measured I-V characteristics at room temperature of single solar cells in the dark are shown in Fig. 1. These measurements are commonly used for basic characterization of the diode behavior and determination of important PV parameters such as series and parallel equivalent resistances.

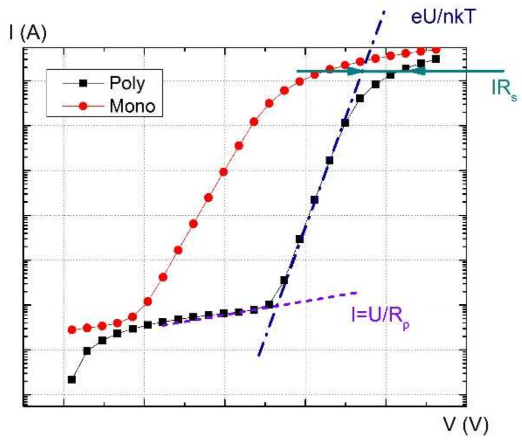

Fig. 1. I-V characteristic of monocrystalline and polycrystalline structure of a PV cell under dc bias.

Fig. 2 shows the I-V characteristics of the monocrystalline panel for different shading variations measured at room temperature. Is possible to observe the change of I-V characteristics regarding shading variations in Fig. 2. A significant short-circuit current change compared to a relatively small open circuit voltage change is obvious. The change in operating parameters is caused by the impact of lower lighting intensity on the panel and the change in the character of the shaded cell - the source becomes a load. When shading a large area of the panel, the shape of the curves takes on a linear character. Elimination of the shading effect would be achievable by adding parallel bypass diodes to the strings of linked cells within the panel. The diodes would prevent HS from forming on the shaded cells and minimize power losses. The investigated panel in this study contained only the so-called reverse diode. In addition to described, we note that disconnecting the blocking diode resulted in an increase in conversion efficiency. Thus, the bridging/blocking diodes also contribute to the power losses.

In addition to the selected presented experimental outputs of the shadowing effect, analysis of the influence of temperature, mechanical damage and water penetration on the I-V curves shape and calculation PV parameters extracted and analyzes the impact on the PV conversion were performed.

B. AC Analyses

Measurements were evaluated using measurements system Solartron and ModulLab MTS software. The PV panels were inserted into the thermochamber SLW 53 Smart for the purposes of realizing measurements of temperature dependences of impedance. The influence of DC bias in the temperature range of 23 °C to 72 °C, mechanical damage and a combination of damage and water action was analyzed. The output of the AC analysis is the impedance spectra and the extracted parameters of the equivalent AC circuit.

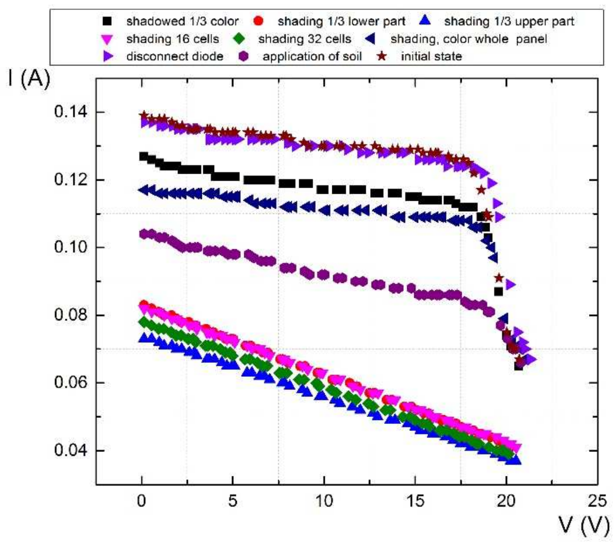

Fig. 2. I-V characteristics of a monocrystalline panel at different shading variations.

A more detailed overview of the effects of shading is illustrated in Tab. 1.

TABLE I. PV PARAMETERS OF MONOCRYSTALLINE PANEL FOR DIFFERENT SHADING VARIATIONS

Type of disorder	U_{0C} [V]	I_{SC} [A]	P_{MAX} [W]	η [%]	FF [%]
Initial state	20.85	0.139	2.26	11.29	0.78
Disconnect diode	21.46	0.138	2.32	11.9	0.78
Shadowed 1/3 color	20.82	0.127	2.06	10.6	0.77
Shading, color whole	21.17	0.117	1.97	10.1	0.79
Soil	20.93	0.105	1.56	8.0	0.71
Shading 16 cells	20.68	0.083	0.85	4.4	0.50
Shading 32 cells	20.26	0.078	0.79	4.0	0.50
Shading 1/3 upper part	20.65	0.074	0.76	3.9	0.50
Shading 1/3	20.37	0.083	0.84	4.3	0.49

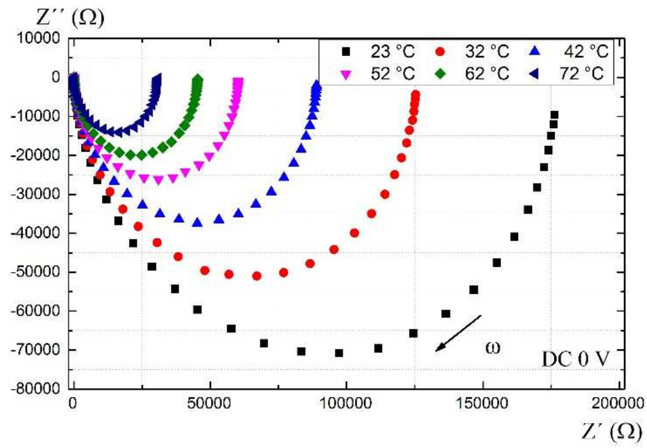

Fig. 3. Temperature dependence of impedance spectra for a monocrystalline panel.

The parameters of the equivalent AC circuit of the panel can be extracted from the obtained impedance data. The displacement of the semicircles from the beginning of the coordinate system represents the series resistance, the diameter of the semicircle represents parallel resistance or shunt and the capacity can be calculated from the maximum of the imaginary component of the impedance [6]. It is clear from Fig. 3, that the change in temperature, which cannot be avoided in real operation, has a significant effect on reducing parallel (shunt or dynamic) resistance of the panel.

The numerically obtained dependence of the parallel resistance for three selected DC bias voltages is shown in Fig. 4. The parallel resistance is strongly dependent on the temperature and, moreover, on the applied DC bias as one can see in Fig. 4.

It was found that, in addition to temperature changes, the shape of the spectra and related changes in electrical transport processes are also affected by mechanical damage and water penetration into the panel structure.

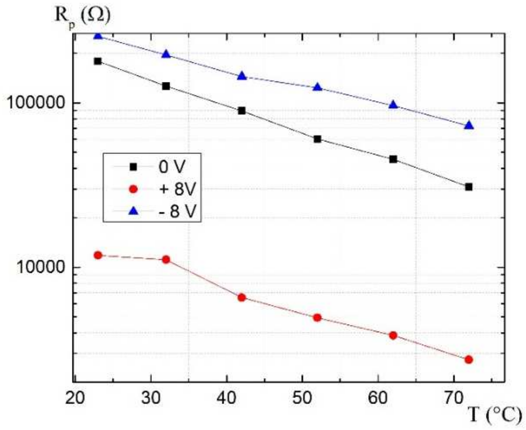

Fig. 4. Temperature dependence of parallel resistance for a monocrystalline panel when the bias is a parameter.

C. Thermography

The measurement were realized in the presence of sunlight, while a TES PROVA 1010 solar analyzer, monocrystalline and polycrystalline panel and Flir i50 thermal imaging.

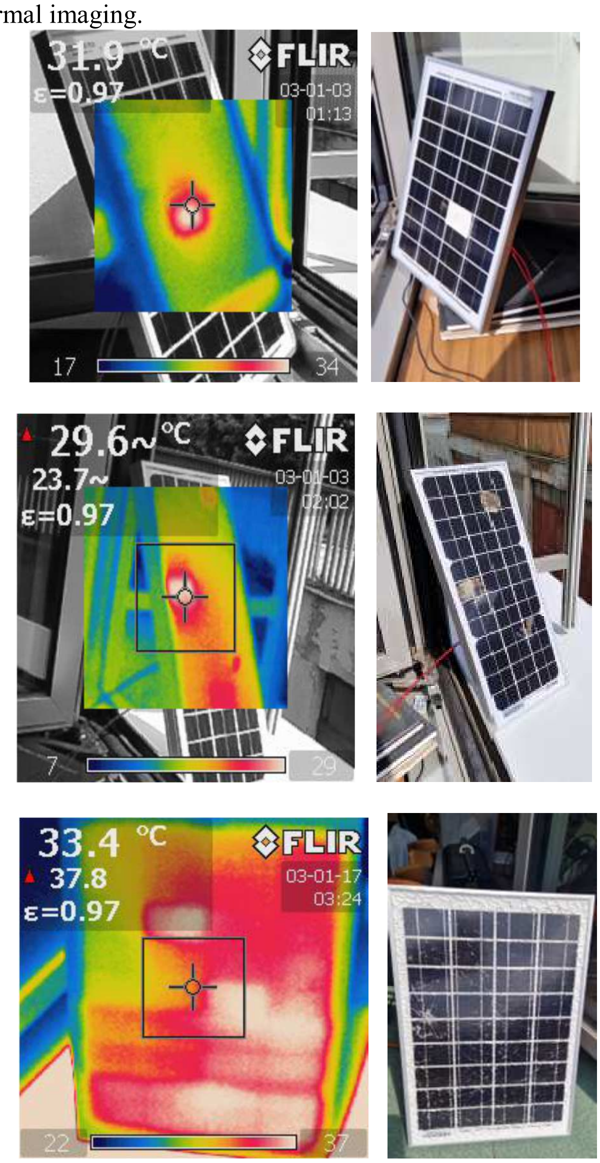

Fig. 5. Mapping of temperature conditions on PV panels using Flir i50 camera and photo (shaded cell - top, panel contaminated with soil – middle, damaged panel - bottom).

Thermographic analyzes (three selected also presented in Fig. 5) confirmed the theoretical assumptions that the simulated hotspot (shaded PV cell) is a place where due to Joule losses local heating occurs. Analogously, cells with different electrical parameters (increased series resistance, shunt, etc.) can also be detected by thermography. It was found that mechanical damage (cracks) and contamination of the panel can be easily detected by the thermographic camera.

V. Conclusions

The paper was focused on the classification of the most frequent faults of PV systems and the analysis of the impact on the safe and reliable operation of such systems. The paper also includes a description of the methods used to diagnostic of PV elements and systems. Selected diagnostic procedures (DC measurements, impedance spectroscopy and thermography) and identification of model faults in operation using these methods are presented in the experimental part.

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