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PHOTOVOLTAIC POWER PLANT INSPECTION AND DIAGNOSTIC

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Abstract. *This paper presents methods of photovoltaic panel inspection in the field. The aim is to verify value of on-site tests. The basic parameters for comparing the quality of photovoltaic panels are indicated by the manufacturer's datasheet. Diagnostic in the field commonly uses a combination of different analyzers and infrared cameras. The paper compares the evaluation of the parameters at different climatic conditions by special photovoltaic analyzer, conventional analyzer with recalculation according the IEC standards and flash tester. The comparison of different methods and analyzers has been performed with the practical experience from the measurements. Further, the standards for the inspection of photovoltaic panels and best practices for their implementation are described.*

Keywords: photovoltaic, inspection, diagnostic, performance test, flash test

KONTROLA I DIAGNOSTYKA ELEKTROWNI FOTOWOLTAICZNEJ

Streszczenie. W artykule przedstawiono metody kontroli panelu fotowoltaicznego w miejscu montażu. Celem jest sprawdzenie wartości testów na on-site. Podstawowe parametry służące do porównywania jakości paneli słonecznych są wskazywane przez producenta w arkuszu produktu. Do diagnostyki na miejscu powszechnie używa się kombinacji różnych analizatorów oraz kamer termowizyjnych. W artykule dokonano porównania oceny parametrów w różnych warunkach klimatycznych przez specjalny analizator fotowoltaiczny, zwykły analizator z przeliczaniem zgodnie z normami IEC i flash-tester. Porównanie różnych metod i analizatorów została wykonana na podstawie praktycznych doświadczeń z pomiarów. Ponadto, opisane są standardy kontroli paneli fotowoltaicznych, a także najlepsze praktyki w ich realizacji.

Słowa kluczowe: fotowoltaika, kontrola, diagnostyka, test wydajności, flash test

Introduction

Periodic inspections of photovoltaic power plants are necessary for safe operation and to ensure the investments returns. However, the massive development of the photovoltaic (PV) installations in the Czech Republic within the years 2009–2012 resulted to the decrease of the installation quality. A lot of systems were not sufficiently designed or the low quality components have been used. Improper initial testing and poorly scheduled maintenance led to decrease of the power, revenues of the power plants and to unsafe and underperforming systems with reduced value to their owners.

The minimum requirements for the system documentation, initial tests, and inspection criteria for grid-connected PV systems are described in the standard EN 62446 [12].

The standard EN 61557 describes the safety requirements in low voltage distribution systems up to 1 000 V AC and 1 500 VDC The inspection should be performed in the way that prevents the total power outage, if possible. Tests of the PV modules during inspections are carried out without removal and avoid further transport costs and additional laboratory testing. The aim of the inspection is primarily to avoid any problems and financial losses [11].

1. Minimal inspection according to the standard EN 62446

It sets minimum requirements and a description of the documentation. There is described a procedure for inspection of the DC wiring, surge protectors, AC system, recommendation regarding the setting and wiring of the inverter (must correspond with the local requirements to the grid). Furthermore, there are requirements for safety, informative and other signs and labels.

During the initial inspection, in case of loss of documentation or periodic inspection, the check of the string wiring and proper polarity, measuring of the voltage at open circuit and short circuit current should be performed. Correct settings of the protections should be verified.

Operational measurements to check of the maximum power point tracker (MPPT) function, measuring the parameters in maximum power point, to compare string power with another or with expected values can be used to analyze the real state of the power plant. The measurements must be performed with the stable ambient conditions during the measurements. The standard IEC 61215 considers the condition stable, when there is change of the irradiation lower than 5% during the measurement.

Next step is the functional test and inspection of the inverter, AC disconnect switch, verification of the insulation resistances of each string.

The output of the initial or periodic inspection is the protocol, with the measured values and completed checklist. The model protocol and checklist are the appendices of the EN 62446 standard.

As an additional method is recommended the infrared (IR) camera testing, it is used to detect anomalies and potential defects [1].

2. Detection of common PV panels defects

The initial way of PV panels defect detection is optical inspection of the five „major visual defect“ defined in the IEC 61215 [10] an discussed in [1, 2]:

- Broken, cracked or torn of any part of the PV panel.
- Bent or misaligned of any part of the PV panel.
- Crack in a cell of the PV panel.
- Bubbles or delamination occurred in the layers of the PV panel.
- Loss of mechanical integrity of the PV panel or its frame.

Next possibility is comparing with the maximum power point P_{mpp}. It is common parameter that indicates the performance of the PV panel. It can be measured with a sun simulator in a laboratory or outdoor without the PV panel removal. The inspected PV panel or string must be disconnected of the power plant for the moment of testing. The IEC standard 61646 gives possibility to perform test in range of cell temperature 25 – 50°C and irradiation 700 – 1100 W/m^2. Laboratories can perform the test at Standard Test Conditions (STC). Conditions according to standard IEC 61215 are defined by IEC 60904-3, irradiance level equal to 1000W/m^2, spectrum of radiaton similar is to radiation of the sun incident on the earth in latitude 35°N in summer (air mass equal to 1.5) and temperature of the panel equal to 25°C.

3. Procedure of periodical inspection according to IEC standard

3.1. Documentation

Inspection starts with check of the available documentation provided by the customer. Documentation should include:

- Plan of review and permitting process with local building officials.

- Interconnection approval from the local utility.
- Installation and maintenance contractors.
- Owners and caretakers.
- Information about emergency services.
- DC and AC power ratings.
- Contacts of owner/designer and other responsible person.
- Single line diagram of system that includes information about size and rating of all components.
- Data sheets and specification for all major components.
- Operation and maintenance information including procedures for verifying proper system operation and performance, and how to determine if there is a problem.
- Copies of all inspection and verification data.

Documentation is compared with the current state of installation. If the documents are different, the differences are described in the protocol.

3.2. Inspection of PV system

Visual inspection should be performed after the document inspection. It focuses on the details that:

- All components shall be properly listed.
- Quality of installation of mechanical and electronically parts.
- Check ventilation to avoid overheat.
- Calculation of circuit voltages and currents.
- Determining conductor and over current device sizes and ratings.
- Locating disconnecting means.
- Wiring methods and connectors.
- Equipment and system grounding.
- Markings and labels.
- Connecting to other sources.
- Installing batteries and charge controllers.

3.3. Testing and measurement

Measuring of parameters that are needed for performance evaluation should be performed with the devices that meet the required accuracies according to the used standards. During the measurements should be checked the following:

- Continuity and resistance testing.
- Polarity testing to verify correct polarity for DC circuits.
- Voltage and current testing.
- Insulation resistance testing.
- Performance testing.

4. Comparing P_{mpp} at standard test conditions

There are multiple ways to measuring the P_{mpp} of the PV panels. For proper evaluation and the possibility of comparison, the P_{mpp} must be measured directly at STC. If it is not possible, the measured P_{mpp} can be recalculated to the STC values.

For the comparison of P_{mpp} values at STC, the following devices have been used and obtained results have been compared.

4.1. Flash tester Pasan SunSim 3C

Flash tester simulates the ideal laboratory conditions of radiation and temperature. The tester compares the measured parameters to the parameters given by a manufacturer. The panels are tested for STC values. The measuring device Pasan SunSim 3C, with the accuracy class A+/A+/A+ according to IEC 60904-9 has been used for the experiment. Uncertainty of the device is shown in Table 1.

Table 1. Uncertainty of the PV panel parameters measured by the Pasan SunSim 3C

Parameter	Uncertainty
I_{SC}	2.9%
U_{OC}	1.7%
FF	4.2%
P_{mpp}	3.2%
U_{mpp}	2.0%
I_{mpp}	3.1%

4.2. METREL MI 3108 Eurotest PV

Metrel MI3108 Eurotest PV (shown in Fig. 1) is the measuring device for complete testing of PV power plants according to EN 61557, and other requirements for testing single-phase installations.

For the PV installation is important, that the testing procedure implements the standard EN 62446, including measurement IV characteristics and parameters at STC. The MI3108 is also capable to measure the entire string up to 1000 V with 15 A current limit.

Fig. 1. Metrel MI3108 Eurotest PV

The analyzer MI3108 is designed for the outdoor inspection and allows the additional measuring of solar irradiation and PV panel temperature with calibrated sensors. These values are used to recalculation of the measured parameters to the STC values.

Measured data are stored in the internal memory and are organized in the selected structure for proper identification of the tested object.

The error of the measuring of MI3108 is shown in Tab. 2.

Table 2. Measurements error of the MI3108

Name	Range	Resolution	Error
DC Voltage	15.1–199.9 V	0.1 V	±(2% rdg. + 2 digits)
DC Current	0–9.99 A	0.01 A	±(2% rdg. + 3 digits)
DC Power	0–1999 W	1 W	±(3% rdg. + 5 digits)

4.3. Prova 210A and conversion of parameters to STC

Prova 210A is a simple IV characteristics analyzer. According to its input ranges (shown in Table 3) is suitable for single PV panel testing.

In the first step, it is necessary to measure the basic parameters of the PV panel during the given climatic conditions. These parameters are in the next step recalculated using equations into STC values.

Fig. 2. Prova 210A

Measurement with this analyzer can be set as automated. It can measure multiple IV curves in requested period, but it need additional datalogger with sensors for measuring the solar irradiation and temperature of the PV panel. Disadvantage of this analyzer is the fact, that the recalculation of the measured values to the STC isn't performed automatically during the inspection.

The manufacturer has declared measurements error demonstrated in Table 3.

Table 3. Measurements ranges and error of the Prova 210

Name	Range	Resolution	Error
Voltage	0-10 V	0.001 V	± 1% ± (1% V_{OC} ± 0.1V)
Voltage	10-60 V	0.01 V	± 1% ± (1% V_{OC} ± 0.1V)
I_{SC}	0.01-10 A	1 mA	± 1% ± (1% I_{SC} ± 9 mA)
I_{SC}	10-12 A	10 mA	± 1% ± (1% I_{SC} ± 0.09 A)
Current	0.01-10 A	1 mA	± 1% ± 9 mA
Current	6-10 A	10 mA	± 1% ± 0.09 A

4.4. Hioki power analyzer 3390

Hioki power analyzers are the top quality power measuring instruments for measuring single and three-phase lines with a high degree of precision and accuracy. The 3390 is a high-precision, four channel, broad-range power analyzer for measuring electrical power from DC to inverter.

The disadvantage of the analyzer is that it is designed for the laboratory use and isn't suitable for infield inspection because of the energy supply demands and weight.

Measurements error is given by the manufacturer for analog DC input ±0.1% rdg. ±0.1% f.s. and it complies with the standard IEC 60904 which defines the error of the analyzer used for performing the IV curve measurements to be lower than 0.2%.

4.5. Description of procedures for temperature and irradiance corrections according to IEC 60891

The preliminary requirements for conversion the measured data to STC values are the following:

1) The irradiation sensor is placed with a maximal difference of 2° compared to the measured panel.
2) The level of irradiation during the measurement cannot change by more than 2%.
3) The intensity of irradiation should be higher than 800 W/m^2 according to the IEC 60904.
4) The temperature sensor with the error max. ±1% should be used (IEC 60904).

In the next step, the measured data can be recalculated to current at STC (I_2) and voltage at STC (V_2) using the following equations:

$$I_2 = I_1 + I_{SC} \cdot \left(\frac{G_2}{G_1} - 1\right) + N \cdot \alpha \cdot (T_2 - T_1)\ [\text{A}] \qquad (1)$$

where: I_1 – current measured directly at the panel [A], I_{sc} – short-circuit current [A], G_2 – irradiation at the STC [W/m^2], G_1 – irradiation during the measurements [W/m^2], N – number of panels connected in parallel, α – current coefficient for temperature correction [A/°C], T_2 – temperature at STC [°C], T_1 –temperature during the measurement [°C].

$$V_2 = V_1 - \frac{M}{N} \cdot R_S \cdot (I_2 - I_1) + M \cdot \beta \cdot (T_2 - T_1) + -M \cdot \gamma \cdot I_2 \cdot (T_2 - T_1) \qquad (2)$$

where: V_1 – voltage measured directly at the panel [V], M – number of panels connected in serial, R_s – internal series resistance [Ω], β – voltage coefficient for temperature correction [V/°C], γ – curve correction factor [Ω/°C].

The thermal correction coefficients are determined by the manufacturer and can be found in datasheet of the examined PV panel. They express the temperature dependency of the voltage and current at constant irradiation.

In case of lack of the values or datasheet, these parameters can be examined with the use of laboratory methods. Using linear regression can be obtained results regarding relative temperature coefficient.

The precise value of the correction factor γ is not usually written in the datasheet. It is necessary to determine the value by experiment. Procedure is described in the IEC 60891 standard.

4.6. Comparison of results

Experimental validation of described methods and analyzers has been performed. The aim is to determine the value of P_{mpp} of the selected panel. As the reference PV panel has been chosen SolarWatt BLUE 60P, s.n.: 1F50135085 manufactured by CONERGIA. All measurements except of the flash test have been performed under real conditions. The tested panel has been situated on the roof of the Department of Electrical Power Engineer, Brno University of Technology. Therefore, it's been possible to use also the Hioki analyzer, which isn't primarily designed for in field tests.

First measurement has been performed with the use of PV analyzer Metrel, which shows the STC values of the measured panel directly on the display. The calculation of the STC values is performed according to the IEC 60891.

Second analyzer Prova 210 does not recalculate the measured values to STC values. It also needs to measure the irradiation and temperature of the panel with external sensors. For the experiment the Kipp&Zonen CMP21 precise pyranometer and PT-100 temperature sensor have been used. LogBox SD has been used as the datalogger. These sensors meet the standards requirements. Based on timestamps, all measured data were processed on the PC and used the equations (1) and (2) mentioned above.

As the third method, the flash tester has been used to determine the STC value of P_{mpp}. Measurement has taken place in the specialized laboratory under stable conditions. The results from the measurements contain the error caused by the artificial light source. The device meets the requirements for the error of measuring the P_{mpp}, which has to be lower than 1% for repeated measurements.

The last method is taken as the reference for comparison. It uses the precise power analyzer Hioki 3390. The analyzer meets the requirements of the IEC 60904, which demands the maximum error of measured voltage and current equal to ±0.2%. Recalculated STC results are according to the IEC 60891.

The results of individual methods are presented in Table 4.

The measurements performed with the Hioki are considered as the reference, because its accuracy and no artificial light source minimize the potential error during the measurements. The difference of other methods has been calculated as the results are in Table 5.

For the evaluation of P_{mpp} is important precise value of the I_{mpp} and V_{mpp}. Metrel MI3108 indicated minimal difference of the measured values compared to Hioki 3390. Based on the differences can be stated, that the specialized analyzers provide the adequate method for PV panel on-site inspection and testing according to the IEC 61215.

Table 4. Measurements results of PV panel SolarWatt 240Wp

	Nominal	Metrel	Prova	Pasant	Hioki
I_{mpp}[A]	8.03	7.93	7.95	7.98	7.79
V_{mpp} [V]	29.9	29.10	29.01	28.99	29.2
I_{SC} [A]	8.50	8.46	8.52	8.56	8.61
V_{OC} [V]	37.2	36.74	36.57	37.21	36.75
P_{mpp} [Wp]	240	230.9	230.7	231.47	227.924

Table 5. Difference of measurements results compared to Hioki 3390

Difference compared to the Hioki [%]				
	Nominal	Metrel	Prova	Pasant
I_{mpp} [A]	3.08	1.08	2.05	2.44
V_{mpp} [V]	2.40	-0.34	-0.65	-0.72
I_{SC} [A]	-1.28	-1.74	-1.05	-0.58
V_{OC} [V]	1.22	-0.03	-0.49	1.25
P_{mpp} [Wp]	5.30	1.31	1.22	1.56

This standard defines, that the P_{mpp} must be within the range of ±5% compared to the expected nominal parameter.

The manufacturer defines the maximal decrease of the power as -0.345% per year from 2 to 29 year of age. The guarantee also defines that the PV panel has higher power than 97% of nominal value in the time of manufacturing. But in this case has to be applied the standard IEC 61215. That means that if the measured power will be higher than 92% of nominal value in the time of manufacturing, the PV panel meets its parameters.

The expected value of nominal power after three years of operation is calculated as following:

$$P_{exp,nom} = P_{nom} \cdot (1-p) \cdot (1+q)^{n-1} = \\ = 240 \cdot (1-0.03) \cdot (1-0.00345)^{3-1} = 231.196\ \text{Wp} \quad (3)$$

where: P_{nom} – nominal power of the PV panel at the time of manufacturing [Wp], p – is the nominal power tolerance at the time of manufacturing [%], q – power decrease coefficient [%/yr.], n – number of years of operation.

Based on the results of the reference measurement performed by Hioki, the power decrease for the selected PV panel is equal to -1.415% compared to the expected nominal value after three year of operation. This value is within the range of ±5% and the panel meets the P_{mpp} according to the IEC 61215 standard [10].

The presented methods are sufficiently precise and meets the requirements of IEC 62446 standard. The IEC 60904 for on-site evaluation is very strict and less suitable because it demands the high value of solar irradiation. This shortens the time window for appropriate measurements during day.

5. Conclusions

The paper presents the requirements on the PV power plants inspection according to the IEC standards to ensure the adequate profit. Properly performed diagnostic of PV panels is based on the use of specialized PV analyzers and can be used to minimize the power losses and energy outcomes.

Next part of the paper deals with the comparison of methods for determining the STC parameters of the panels during on-site measurement. The benefit of the Metrel MI3108 is the evaluation of the results directly in the device and its power input range up to 15 kWp allows measuring of entire strings. This speeds up the inspection. Results from Prova 210 need additional processing with the use of PC. Its voltage input limit restricts the usage only for individual PV panel tests. Other methods are suitable for laboratory uses. The flash tester provides stable and repeatable conditions which can be used during entire year. Its disadvantage is the inaccuracy of the results caused by the artificial radiation source. As the reference measurement has been considered the result from power analyzer Hioki which provides accurate results. The parameters have been recalculated to STC conditions using the IEC standards and the precise values of solar irradiation and temperature measured by additional sensors.

The measurement results of the tested PV panel indicate minimal degradation and meet the power values declared by the manufacturer.

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References

[1] Bastidas-Rodriguez J.D., Petrone G., Ramos-Paja C.A., Spagnuolo G.: Photovoltaic modules diagnostic: An overview. IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society. 2013, 96–101 [DOI: 10.1109/IECON.2013.6699117].

[2] Hu Y., Gao B., Song X., Tian G., Li K., He X.: Photovoltaic fault detection using a parameter based model. In Solar Energy. 96, 2013, 96–102 [DOI: 10.1016/j.solener.2013.07.004].

[3] Mastny P.: The Specifics of the Operation of Photovoltaic Systems in the Czech Republic. In Recent Advances in Energy, Environment and Economic Development. Mathematics and Computers in Science and Engineering Series. Paris, France: WSEAS Press, 2012.

[4] Mastny P., Drapela J., Bernath F., Mastna Z.: Renewable Energy Sources - Hybrid Systems. In Receant Researches in Electric Power and Energy Systems. Electrical engineering Series. Chania, Crete Island, Greece: WSEAS Press, 2013.

[5] Mastny P., Drapela J., Slezingr J., Moravek J.: Operational Characteristics of Photovoltaic Systems - Virtual Laboratory. In Proceedings of the 15th International Scientific Conference on Electric Power Engineering (EPE). Brno University of Technology, 2014, 357–361.

[6] Spagnolo G.S., Del Vecchio P., Makary G., Papalillo D., Martocchia A.: A review of IR thermography applied to PV systems. 11th International Conference on Environment and Electrical Engineering. 2012, 879–884 [DOI: 10.1109/EEEIC.2012.6221500].

[7] Takashima T., Yamaguchi J., Otani K., Oozeki T., Kato K., Ishida M.: Experimental studies of fault location in PV module strings. In Solar Energy Materials and Solar Cells. 93 (6–7), 2009, 1079–1082 [DOI: 10.1016/j.solmat.2008.11.060].

[8] ČSN EN 60891. Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics. Geneva: IEC, 2009.

[9] ČSN EN 60904. Measurement of photovoltaic current-voltage characteristics. Geneva: IEC, 2006.

[10] ČSN EN 61215. Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval. Geneva: IEC, 2006.

[11] ČSN EN 61557. Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures. Geneva: IEC, 2009.

[12] ČSN EN 62446. Grid connected photovoltaic systems – Minimum requirements for system documentation, commissioning tests and inspection. Geneva: IEC, 2010.

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