Qualification of Photovoltaic (PV) Power Plants using Mobile Test Equipment

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Executive Summary

The energy production of a PV power plant plays a significant role in the market evaluation of a project, as it is a key input into the financial models of the profitability of a solar project [1]. In this regard, the technical conditions of the PV array and of the PV modules have a great impact on the systems performance and the value of assets (assets' performance).

To give plant operators or asset managers confidence that PV power plants perform at current standards and provide the promised yield, on-site inspection methods with portable test equipment (mobile PV test centres) are commonly used. There are various fields of application for mobile PV test centres at different project phases:

a) Acceptance testing before commissioning;
b) Fault detection and identification of defective or degraded PV modules in operating PV arrays;
c) Inspection of PV power plants prior to change of ownership;
d) Periodical inspections to document the technical conditions of PV arrays regarding long-term reliability and durability of components.

It is worth mentioning that it is advisable to analyze historic performance data (if available or accessible) prior to on-site inspection. For example, the daytime dependent or seasonal variation of DC and AC performance ratios (PR) can already provide indications of potential problems and identify parts of the PV array for follow-up inspection.

On-site inspection of a PV array shall start with a visual inspection of the cabling and the PV modules. This initial diagnosis can already give indications whether PV modules are the origin of power loss or whether site-specific factors such as soiling or shading are relevant. Observed visual defects of PV modules such as glass breakage, burn marks, delamination, browning or damaged backsheets can already explain the power loss of a given PV system and facilitate the decision on the best choice of characterization methods to give the requested answers.

In practice, a 100% technical inspection of a multi-megawatt PV power plant will not be feasible. But rapid advances in infrared (IR) inspection with drones make it possible to obtain an overall picture of the status of an operational PV array. Such information can be also used to identify candidate PV strings or PV modules for further detailed analysis using mobile PV test centres.

In this report, various on-site inspection techniques using portable test equipment are presented. These are ranging from PV output power characterization, to imaging techniques and spectroscopic methods for materials analysis. Besides technical information and existing field experience, also good practice recommendations for field use and uncertainties compared to laboratory inspection methods are covered. A brief summary of ten inspection methods covered in this report is given below. From here the reader can jump directly into the relevant chapter of this report, where detailed information on the inspection method is given.

The presented on-site inspection methods are helpful tools to identify drivers for underperforming PV power plants. Their particular strength lies in the fact that the tests are carried without dismantling and shipping the PV modules to a laboratory, which often means long transport routes, transport risks and a long down time of the PV strings. Furthermore, on-site inspection methods allow a more targeted failure analysis, as PV modules are not blindly selected. The quality and significance of the inspection results are comparable to that of laboratory tests.

On the other hand, on-site inspections are dependent on the weather conditions, which is a disadvantage compared to work under controlled conditions in a laboratory. Thus, on-site inspections require a higher organizational effort and a careful planning.

A single inspection method mainly deals with a specific type of PV module defect and cannot deliver a comprehensive failure analysis. For example, electroluminescence (EL) or photoluminescence (PL) imaging can reveal cell cracks in a PV module or can give an indication for PID. But no conclusions can be made concerning the output power of the PV module. Accordingly, it makes sense to combine imaging inspection techniques with output power measurements. In this sense, the objectives of on-site inspection must be specified in advance. If applicable, the most appropriate combination of inspection methods must be considered in order to obtain meaningful results.

Electrical inspection on PV string level provides indications of defective or degraded PV modules and only conclusions for the average PV module performance can be made. This may not be sufficient for warranty claims, which usually require an individual proof that the PV module performance is outside the manufacturers' specification. To overcome this, additional inspection of PV modules with a mobile PV test centre may become necessary.

Except the application of drone flying and of a mobile PV test centre, the presented on-site inspection methods are applied to installed PV modules or PV strings. In these cases, the test equipment must be moved in the field and operation will require a power supply. This may lead to restrictions in work, as the necessary infrastructure such as paved paths may not be available. Furthermore, you have to consider that PV modules installed in upper rows of the mounting structure may not be accessible.

In the case that the inspection method requires a disconnection of PV modules or PV strings, it is essential to observe that the maximum system voltage of PV strings can reach up to 1500 V. Working under high electrical voltage requires that the safety regulations of the country are respected and that work is only be performed by a qualified electrician with appropriate training. Furthermore, personal protective equipment is required and qualified tools must be used.

Because a 100% inspection of PV modules is not feasible, specific sampling methodologies and statistical evaluation methods need to be considered, which shall assure that a representative amount of PV modules will be inspected. However, such statistical methods are not internationally harmonized and are often decided on a case-by-case basis.

Drone-mounted electroluminescence & thermal infrared inspection of PV arrays

Optical methods of fault detection in PV power plants have been commonly used in the PV industry for many years. These methods are usually conducted manually and are time consuming, limiting their uptake. With the advent of light weight non-contact imaging techniques, Remotely Piloted Aircraft Systems (RPAS) are becoming increasingly popular in commercial and research applications. These systems can have significant time and cost savings compared to traditional manual measurements. Chapter 2 outlines the current standards and opportunities for using drones for field measurements of

PV systems. We discuss the types of defects identifiable from drone based measurements and identify key uncertainties or challenges with the measurements. This section provides a recommendation on best practice for drone based measurements of PV systems.

Daylight I-V measurement of PV strings and PV modules

The electrical performance of a PV array results from its current-voltage characteristic (I-V curve). The shape of the I-V curve determines the position of the maximum power point (MPP), which corresponds to the working point of the inverter. I-V curve measurement is performed with an I-V curve analyzer, which is connected to the PV string terminals inside the field combiner boxes or at the DC cables entering the inverter. I-V inspection is performed in conjunction with solar irradiance and module temperature measurements. Once measurement is completed, the PV string I-V curve is translated to standard test conditions (STC), which then allows an assessment of the average PV module output power. In Chapter 3, a failure catalogue is presented for deviations between the STC translated measured I-V curve and the calculated nominal I-V curve of the PV string.

PV module characterization with mobile PV test centre

Mobile PV test centres with integrated solar simulators allow testing of a large number of PV modules in the field. The test is highly reproducible as being almost independent of the weather conditions. A test sequence of a PV module can combine electrical output power measurements with electroluminescence imaging and safety relevant tests like bypass diode functionality and insulation resistance. Sequential testing with a high level of automation permits to obtain a complete quality picture of a statistical relevant number of PV modules. The solar simulator makes the equipment very expensive and large compared to the other field inspection methods described in this report. The complexity of the equipment requires well trained personnel and adequate quality assurance measures to guarantee a low measurement uncertainty, which is the base for warranty claims.

Dark I-V measurement of PV strings and PV modules

Dark current-voltage (I-V) characteristics measurement means I-V measurement of PV strings at night time. The relationship and differences between dark I-V and daylight I-V measurements are explained, and the measurement accuracy requirements are discussed. A short comparison of available measuring systems is given. Additionally, it is explained how damaged or degraded PV modules influence the shape of dark I-V curves. Multiple effects and defects are discussed, such as series or parallel resistance issues, cell cracks, and PID. Finally, best practice of performing on-site dark I-V measurements is discussed.

PV plant testing vehicle for PV strings

PV power plants can be classified into grid-connected and stand-alone systems. No matter how the design and type of the PV power plant is, the performance parameters basically include the current-voltage characteristics of PV arrays and efficiencies of inverters. The performance of a PV power plant can be measured by PV testing vehicle reconstructed from a delivery van or box truck. The testing vehicle consists of meteorological monitoring system, DC and AC combiner box testing devices, PV string and centralized inverter testing facilities. Instead of portable test instruments, the PV plant testing vehicle has a multi-functional design and can perform testing, analyzing performance parameters of all kinds of PV power plants.

Electrical impedance spectroscopy of PV strings

Electrical impedance spectroscopy represents a methodology to collect information on the characteristics and performance of PV modules within a PV string by analyzing the systems linear voltage response to an input sinusoidal oscillating (harmonic) current perturbation over a range of frequencies. This measurement provides a frequency-dependent impedance consisting of a real and an imaginary part, which can be further analyzed to extract information on specific features within the PV string such as non-operative PV modules, by-pass diode failures, performance loss due to PID or ground faults.

Daylight electroluminescence (EL) imaging

EL is the emission of optical radiation resulting from the application of electrical energy to the solar cells. A defect or inefficient area in the cell generating less irradiation will be darker in the EL image. Therefore, we can detect defects of the cells such as busbar corrosion, cracks and other defects in PV modules and extrapolate the quality of a PV Power Plant. The major challenge for outdoor EL inspection in the daytime is the near infrared (NIR) emission from the sunlight, which is higher than the emission from the solar cell. Thus, performing outdoor EL inspection requires a special setup to filter the signal irradiated from the cells. Different technologies and inspection methods are discussed in Chapter 8 with regard to their impact to the quality of the result, as well as feasibility to perform the measurements in the field.

UV fluorescence imaging

The UV fluorescence method measures the UV fluorescence of the polymer in the PV module to draw indirect conclusion on the PV module' health state or on the bill of materials used in the module. The method allows to detect cell cracks and temperature related defects, like hot spots, cell interconnect ribbon breakage and detection of hot cells with inactive cell parts. Furthermore, the method reveals if more than one type of encapsulation or backsheet material is used in PV modules. Especially for cell cracks, it is the only method to identify the timely order of cell crack occurrence. For example, this is useful to distinguish between cell cracks caused during installation or by a hail storm. For field application an UV source and a photo camera are needed. No disconnection of PV modules in the PV system is required. The method is very fast when searching for cell cracks or heat related defects in PV modules.

Advanced outdoor photoluminescence imaging

Outdoor photoluminescence imaging is a new approach for finding electronically active faults and degradation effects in solar PV modules deployed in the field. This approach has the advantages that it can both provide more detail than thermal infrared imaging and has the potential to be significantly faster than the routinely used electroluminescence imaging. The core concept behind this technique is to use the sun as an illumination source, and via altering of the operating point of the modules being imagined to allow extraction of the weak luminescence signal. The use of adequate optical filtering is mandatory. The output data of this technique is almost identical to that of electroluminescence imaging but it can be performed without electrical changes to the PV system. Chapter 10 covers the current approaches being used as well as their respective advantages and disadvantages.

Spectroscopic methods for polymeric materials

The application of spectroscopic characterization techniques allows for direct material analysis in the field without dismantling PV modules, transporting them to the laboratory, cutting them in smaller pieces and analyzing them with conventional spectrometers. Spectroscopic methods can be used to identify the polymeric compounds of PV modules (encapsulants, backsheets), which is important when degradation and/or failures occur. NIR and Raman spectroscopy are suitable to identify the encapsulant within the PV module. With FTIR-spectroscopy the outer layer of the polymeric backsheet can easily be identified and surface degradation effects (e.g. oxidation, hydrolysis) can be detected. NIR spectroscopy allows for the non-destructive determination of the entire composition of the multilayer backsheet composite.