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Uncertainty budget assessment of temperature coefficient measurements performed via intra-laboratory comparison between various facilities for PV device calibration

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ABSTRACT

The performance of PV devices at different operating temperatures is important for determining the energy they produce once deployed. Therefore current–voltage characteristics are measured over a range of typical operating temperatures and the temperature coefficients of the main electrical performance parameters are extracted. They are the temperature coefficient α of short-circuit current, β of open-circuit voltage and δ of maximum power. The European Solar Test Installation has recently upgraded its capability to determine these temperature coefficients. The existing two setups were improved to be able to cover extended temperature ranges and two further setups and respective measurement procedures were made operational. For all setups revised uncertainty estimates were calculated. Here the setups and procedures are presented, together with the measurement uncertainty for the three temperature coefficients. Measurements were made on seven PV devices and their consistency compared based on uncertainties. It was found that all setups are fully consistent. The advantages of the different setups are also discussed.

1. Introduction

The variation of the main electrical parameters of a photovoltaic (PV) device due to change in device temperature is usually described by a linear function whose slope is the absolute temperature coefficient (TC) of the considered parameter. The ratio of that slope value to the parameter's value at 25 °C is defined as relative TC and is usually reported on the data sheet of PV modules in units of %/°C or %/K.

TC measurements for PV devices are important for a complete correction of their current-voltage (I-V) characteristics (IEC, 2009a), which is usually measured at some test conditions of irradiance (e.g. 997 W/m^2) and device temperature (e.g. 24.7 °C), to the Standard Test Conditions (STC) of 1000 W/m^2, 25 °C and spectral distribution equal to AM1.5G, tabulated by the standard IEC 60904-3 (IEC, 2016).

Accurate knowledge of the TCs is also indispensable in those cases when the open-circuit voltage of a PV device is used as temperature probe of the device itself, for example in PV fields (Ossenbrink and Münzer, 1992). This is essentially the principle at the base of the V_{OC} method described in (IEC, 2011a) for intrinsic determination of the junction's temperature without the use of external temperature sensors.

Another essential application of TCs is their use for energy rating purposes. The developing standard series IEC 61853 (IEC) deals with the new approach of module performance rating, which goes beyond the traditional one – i.e. module performance at STC. In the energy-rating approach, which includes measurements at STC (IEC, 2011b), the module performance assessment is based on many other aspects related to real conditions met by the PV devices when mounted in the field (Balaska et al., 2017; Campanelli and Osterwald, 2016; Cañete et al., 2014; Dirnberger et al., 2015; Kenny et al., 2013; Schweiger et al., 2017; Viganó et al., 2012), and it may use models based on known characteristics of the module technologies in order to predict the energy that a certain technology or even module can deliver under specified climatic conditions (Balaska et al., 2017; Huld, 2017; Huld et al., 2011; Huld et al., 2010; Huld et al., 2016; Katsumata et al., 2011). The models, though, rely on input data that include measurements of PV module's I-V characteristics under different conditions of temperature and irradiance, which are subject of the standard IEC 61853-1 (IEC, 2011b), and on a linear dependence of the electrical parameters on the temperature, which has to be checked according to IEC 60904-10 (IEC, 2009b) (in order to validate a linear interpolation of the measured data to the necessary conditions of temperature and irradiance).

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Therefore, determination of the TCs for a given PV technology and device with the lowest uncertainty (UC) possible is essential for a full, accurate and reliable advanced characterisation of PV devices.

Some of these aspects were subject of a European project supported by EURAMET that lasted from May 2014 to April 2017, namely the EURAMET EMPR project ENG55 PhotoClass “Towards an energy-based parameter for photovoltaic classification” (PTB, 2014). Within this project, two already-validated facilities for TC measurements of the European Solar Test Installation (ESTI) were upgraded in order to cover broader temperature ranges with improved uncertainty assessment and two new facilities were made operational and validated to increase the availability of resources for PV devices of all sizes, from reference cells up to full-size commercial modules. Therefore, a total of four setups (for both indoors and outdoors measurements) are now available at ESTI.

This paper presents the setups and measurement procedures as well as the results of an extended intra-laboratory measurement campaign, which validated the new facilities within the ESTI Quality System accredited according to the ISO/IEC 17025 (Accredia; ISO, 2005) for PV calibration. The comparison between the measurement results has been carried out by assessment of the E_n numbers (ISO, 2010) associated to them, following the same approach that has been applied also to worldwide inter-laboratory comparison (Salis et al., 2017a). This assessment method, when based on consistent UC calculations and comparable measurements (ISO, 2010), not only is useful in comparing values as results of some measurements, but also does help in evaluating consistency and reliability of the uncertainty that is stated with the measurement result, thus giving indication on whether the UC calculation as well as setups and procedures have to be revised because UC components are over/underestimated or even not entirely considered or not.

2. Methodology for intra-laboratory comparison

2.1. Temperature coefficients (TCs)

TC measurements require the measurement of the relevant electrical parameter over a temperature range of at least 30 °C (IEC, 2009a). Typically, full I-V curves are acquired as the temperature of the device under test (DUT) is varied. For reference cells typically only the short-circuit current I_{SC} is measured. The TCs are then extracted by a least squares linear fit of the electrical parameter versus temperature (IEC, 2009a); the relevant TCs are α (I_{SC}), β (V_{OC}) and δ (P_{MAX}) extracted from the functions I_{SC}(T), V_{OC}(T) and P_{MAX}(T).

The DUT temperature is measured by a Pt100 attached usually on the rear side close to the center of the device. In the case of encapsulated PV reference cells, the internal Pt100 sensor is used instead whenever it is available and this approach possible. It is constantly monitored and acquired for every I-V curve/I_{SC} measurement. Work is on-going to extend the setups to four temperature sensors as required by the relevant IEC standard (IEC, 2009a). At present, the expected temperature non-uniformity of the DUT, which is deemed negligible in the case of cells, is estimated for each measurement facility and considered in the UC calculation for modules (see Section 2.5).

2.2. Comparison general approach

TC measurements were already routinely performed according to the standard IEC 60891 (IEC, 2009a) at some of the ESTI facilities within typical temperature range of [20; 60] °C (Roschier, 2002). As new needs for TC measurements were brought forward by a further development of international standards, such as the energy rating ones (IEC), and by new demands from the PV community itself, ESTI took the decision to improve its existing facilities in order to: (i) widen the temperature range available for the measurements; (ii) extend the number of facilities available for this type of measurement so to offer the best measurement uncertainty according to the PV device type; (iii) support at the highest level possible the continuous development of PV standards also with respect to this specific aspect. As a result, an upgrade of the existing facilities and an extended measurement campaign were carried out in order to validate the resulting setups and procedures. The validation was done for the upgraded or newly developed TC measurement procedures with respect to the already validated ones.

At present, ESTI operates four facilities for TC measurements:

a. An outdoor setup for PV device calibration under natural sunlight (OD);
b. A flash solar simulator (GPS);
c. A large-area continuous solar simulator (Apollo);
d. A steady-state solar simulator for small devices (Wacom).

Among these, the OD and GPS setups were already included in the ESTI Quality System for PV calibration accredited according to ISO/IEC 17025 (ISO, 2005) at the starting time of this comparison. They were upgraded, though, in terms of extension of the achievable temperature range and of temperature control, which translated into a revision of the TC measurement UC. No revalidation of these facilities was deemed necessary as the intervention affected only their corresponding UC calculation.

The other two setups (Apollo and Wacom) were, instead, evaluated from scratch in regard to TC measurements and validated by means of the measurement comparison presented here.

The intra-laboratory comparison was executed according to the standard ISO/IEC 17043 (ISO, 2010). The OD setup was selected as reference for the assessment of the Wacom and the Apollo setups, due to its much better reliability on measurement aspects such as possible spectral effects on I_{SC} and P_{MAX} and spatial non-uniformity issues. Comparison to the GPS was in general also considered, although mainly as consistency check of general agreement with respect to α and δ. A systematic comparison to the GPS in addition to the OD was instead done for β, for which the OD setup has the highest UC whereas the GPS the lowest.

Prior to the comparison of the measurements results from different setups, the UC calculation was completely revised and adapted for all four setups. This involved an improved uncertainty analysis for the two existing setups taking account of their improvement and then a transfer with respective adaptation of the same approach of calculation to the two new setups.

2.3. Comparison samples

Seven PV devices of different size and technology were used to carry out the intra-laboratory comparison that is presented here. One is a reference cell that is ordinarily used as working reference in the calibration measurements at ESTI (PX305C); one is a 20 cm × 20 cm poly c-Si encapsulated cell used for non-uniformity measurements of ESTI's solar simulators (NUF2); two modules of different size in poly c-Si (GC01 and TD81) and two in mono c-Si (ADX00 and ZZ71); one module of about 1.3 m × 1.1 m based on amorphous Si technology (AY81). Table 1 lists all devices with their main characteristics.

2.4. Setups and measurement procedures

The procedures for TC measurements at ESTI have been developed according to the standard IEC 60891 (IEC, 2009a) and are maintained updated to its latest revision. Depending on the device size and/or on the setup involved, different procedures are followed in the present comparison as described hereafter.

2.4.1. Outdoor facility (OD)

ESTI operates a facility for the calibration of PV devices under natural sunlight according to the standards IEC 60904-1 and IEC 60904-1-1 (IEC, 2006, 2017). The main component of the facility