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TECHNICAL REPORT

Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials

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CONTENTS

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FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 63228, which is a Technical Report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
82/1502/DTR	82/1555A/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

For years, considerable research effort worldwide has been invested in the development of new thin-film photovoltaic (PV) technologies that may offer lower cost production, new applications or both. In particular, organic photovoltaics (OPV), dye-sensitised solar cells (DSC) and perovskite solar cells (PSC) have generated great interest and the market potential of these products is being explored.

To date, the performance of all new PV technologies has typically been determined using the test methods described in the IEC 60904 series and IEC 60891. However, these three technologies in particular present some additional measurement challenges that are at present not dealt with in these documents.

This document provides an overview of current best practices for measuring the performance of PV devices subject to these challenges. It seeks to highlight where the existing standards fail to accommodate the requirements of these technologies, to identify what additional measures may be needed for accurate determination of the device efficiency, and how these measures might be standardised in the future.

It is recognised that this is a rapidly developing field and many items presented are subject to ongoing active research. Therefore, currently no concrete suggestions can be made to amend existing IEC standards with respect to these technologies. However, as the field matures, it is expected that procedures evolve and lead to agreement between experts, so that they can be introduced into international standards. Whether this will consist of amending existing standards or in the issue of a separate standard collecting all procedures relevant to these technologies will be decided in the future.

MEASUREMENT PROTOCOLS FOR PHOTOVOLTAIC DEVICES BASED ON ORGANIC, DYE-SENSITIZED OR PEROVSKITE MATERIALS

1 Scope

This Technical Report summarises present perspectives on the performance evaluation of emerging PV technologies, specifically OPV, DSC and PSC devices. These devices present some challenges for accurate measurement under the existing IEC 60904 series of standards, which were developed in the context of silicon wafer solar cells. These challenges can be different for different devices, but in general they arise due to one or more of the following: instability in performance over time; unusual spectral responsivity; small device size; difficulty in measuring temperature; a transient response to external stimulus; optical interference effects; and a non-linear current response to irradiance. These challenges can lead to the cell output in laboratory testing being significantly different to the output that would be observed in a real application.

The primary focus of the report is measurement of the current-voltage (I-V) relationship under illumination for the purpose of determining the device output power, or power conversion efficiency. Where appropriate, the report makes reference to the IEC 60904 series which describes the standard approach to measuring the performance of all PV devices. The report also references existing published standards that seek to accommodate OPV, DSC or PSC devices.

The report does not seek to find consensus on measurement protocols at this stage. A lot of work has been done by the community toward that aim, but more work is needed. The report therefore seeks to document current knowledge and practices, hence serving as a reference and a tool for conducting further discussion. It is hoped that by identifying the issues that remain unresolved, the report will focus efforts toward resolving those issues, such that a guiding Technical Specification can be prepared in the near future. A robust Technical Specification will bring clarity and confidence to the markets for these PV products as they develop.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

3 Terms, definitions and conventions

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.2 Conventions

Clauses 5 to 12 of this report each deal with a separate issue relating to the measurement of solar cell performance. Each of those sections is structured as follows:

- General
- Review of currently available standards
- Examples of how the issue is currently handled by researchers around the world
- Summary and possible next steps

At times throughout the report, it is instructive to indicate that a particular issue may be specific to only one or two of the PV technologies being discussed. To assist with this, a key has been included at the end of some paragraphs. The key indicates applicability to a particular technology with a filled square, and uses an open square for the technology to which the issue does not apply. For example, (■OPV ■DSC □PSC) indicates that the above issue applies to OPV and DSC technologies, but not to PSC technologies.

4 Draft terminology for discussion

4.1 General

Any study of the various standards for PV measurement, or the scientific literature on the topic, will show that while some terms are well-defined and applied with consistency, others are not. In particular, certain terms relating to the stability of PV devices and their measurements, have not to date been considered important enough to standardize.

For emerging PV devices however, the topic of stabilization is of profound importance, particularly where accurate and representative measurements are desired. For this reason, an attempt is made here to identify the most commonly used definitions for three key terms. It is hoped that by providing draft definitions for these terms here, the industrial and research communities may arrive at a common language to describe these concepts.

4.2 Draft terms

4.2.1 Steady-state

The term steady-state is used in this document to describe the response of a PV device where that response has achieved a defined level of short-term stability under the prevailing conditions of irradiance, temperature and voltage bias. The term may be applied to any point on an appropriately measured I-V curve, and by extension, to any parameter extracted from such a curve. A steady-state *I-V* curve is one in which the voltage sweep rate is slow enough to allow each current measurement to stabilize to within a defined stability criterion. The efficiency of a solar cell determined from such a measurement is independent of the I-V sweep parameters (to within the margin of the stability criterion) and, ideally, represents the efficiency the cell would exhibit under a maximum power point tracker at the time of the measurement. Note there is no requirement for the cell performance to be stable in the long term.

4.2.2 Pre-conditioning

The term pre-conditioning is used to refer to the practice of holding a photovoltaic device under a certain set of conditions, again irradiance, temperature and voltage bias, for some period immediately prior to making a current-voltage (I-V) measurement. The practice of pre-conditioning has historically been applied as an attempt to create short-term stability in the device, so that a subsequent I-V measurement reflects or approximates the steady-state device performance in a relatively rapid sweep, so limiting device degradation during the measurement. In some cases pre-conditioning may also be used to artificially inflate the measured device efficiency, although this latter practice is discouraged.

4.2.3 Stabilization

In IEC TS 61836, conditioning refers to a process for stabilizing a device prior to an environmental test. It is always performed prior to that test; however, it is unclear whether it shall be performed immediately before the test (as per pre-conditioning above), or whether instead it is designed to stabilize the device in the long term.

To make the above distinction clear, in this document the term stabilize is used to describe treatments that result in the performance of a PV device being stable over much longer time periods. A measurement of the device performance parameters may or may not be independent of the I-V sweep parameters, however steady-state measurements on a stabilized device produce the same result regardless of any reasonable device exposure and/or time between measurements. This definition is consistent with the historical use of this term in the published PV efficiency tables.

5 Pre-conditioning

5.1 General

The practice of pre-conditioning an unstable PV device prior to *I-V* measurement is contentious, owing to its ability to influence the measurement, sometimes producing a result that would not represent the device's performance in a real-world environment. Nevertheless, many endorse its use as a way of achieving reproducible results. Certainly, pre-exposure of a solar device with light seems reasonable, given the environment it will ultimately be used in. This clause seeks to briefly summarize the practices that invoke pre-conditioning and the standards that refer to it. At present, there is no single pre-conditioning procedure recognized as effective for all devices, even within a given technology type.

5.2 Review of currently available standards

5.2.1 IEC 60904-1

IEC 60904-1 (*Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*) [1] provides no guidance for devices that are unstable on the timescale of the *I-V* curve measurement. The only reference to device instability in that document is as follows: "In measuring PV devices which are non-stable, care shall be taken in selecting a representative spectral responsivity".

At the time of preparing this report, a new edition of IEC 60904-1 is in draft. The draft currently includes text that extends the above statement to include reference to "pre-conditioning"; however, the use of that term is more akin to what we have defined above as *stabilization*. This is understandable for OPV and DSC devices, where long term stabilization can usually be achieved with pre-treatment. However, to accommodate PSC devices, it may be of value to distinguish between pre-conditioning and stabilization using the definitions above.

The draft of IEC 60904-1 suggests that guidance on pre-conditioning can be taken from the Clause on Stabilization (Test MQT 19) in the current IEC 61215 series (described specifically in IEC 61215-2:2016 [2]). The MQT 19 method contains good detail, particularly in regard to stabilization by light soaking. Regarding other types of stabilization, the document permits any method provided the method is validated, and a validation procedure is described in the document.

In summary, the MQT 19 procedure states that all PV modules should be electrically stabilized prior to measurement. It defines electrical stabilization as a stabilization of the observed output power value (P) according to

$$(P_{\mathrm{max}} - P_{\mathrm{min}}) / P_{\mathrm{average}} < x \qquad (1)$$

where P_{max}, P_{min} and $P_{average}$ are the extreme values of P taken from a sequence of three measurements interleaved with periods of irradiation to a defined minimum dose. The values of both x and the minimum dose are defined in the technology specific sub-parts of IEC 61215-1 [3] (IEC 61215-1-1 for crystalline silicon, IEC 61215-1-2 for cadmium telluride, IEC 61215-1-3 for amorphous silicon and IEC 61215-1-4 for copper indium gallium (di)selenide). Presently, there is no current plan to include sub-parts for OPV, DSC or PSC into the IEC 61215 series, although this is likely at some point in the future if these technologies reach market maturity.

5.2.2 SEMI-PV57

The SEMI-PV57 [4] is a standard from Semiconductor Equipment and Materials International (SEMI) about test method for current-voltage performance measurement of organic photovoltaic and dye-sensitized solar cell. In SEMI-PV57 is stated that in order to anneal and stabilize the electrical characteristics of a device under test using simulated solar irradiation for 10 minutes to 30 minutes, some requirements are recommended as follows (SEMI-PV57, 9.6.1):

– use a reference device to adjust the irradiance in the range 600 W/m^2 to 1 000 W/m^2, then record the irradiance (SEMI-PV57, 9.6.2);
– mount the device within the light field and monitor its maximum power using a source-measure unit (SMU) or variable resistive load;
– stabilization is achieved when the check criteria defined in Formula (2), based on measurements from two consecutive periods of at least 43 kWh/m^2, each integrated over periods when the temperature is in the range 40 °C to 60 °C, are in agreement to better than 2 %.

$$\text{check criteria} \equiv (P_{max} - P_{min}) / P_{average} \times 100\ \% \qquad (2)$$

This method is very similar to the MQT 19 method described in IEC 61215-2 and summarised in 5.2.1 above and uses the dose of 43 kWh/m^2 used for the thin-film a-Si devices as in IEC 61215-1-3.

This standard is similar to IEC 60904-1 but does not address preconditioning or stabilization criteria.

(■ OPV ■ DSC □ PSC)

5.3 Some examples of pre-conditioning procedures applied to OPV/DSC/PSC

5.3.1 General

A number of different approaches to device pre-conditioning are described in the literature. Different groups appear to be using procedures suited to their own particular material system. The situation is further complicated by degradation effects, which impact different devices in different ways. The most common approaches are described briefly in 5.3.2 to 5.3.4, and the issue also comes into the subsequent clause on I-V measurement.

5.3.2 Avoidance of light soaking

Some groups do not recommend pre-conditioning with light, based on the fact that light can cause degradation, or in some cases even artificial enhancement in the device. The latter may occur if the device incorporates doped oxides as barrier layers, as many oxides are photoactive under the UV component of the light source. Ultraviolet (UV) is often not present in a real application, owing to absorption by encapsulating layers in the final commercial product.

Even in the absence of UV effects or light-induced degradation, PSC devices are well-known to be sensitive to the exposure history, with effects that vary with the voltage bias during any recent light exposure. A recent report based on a multi-lab intercomparison experiment [5], identified a persistent relationship between the measured cell efficiency and the type of light soak performed. Light soaking at the short-circuit condition was observed to produce low hysteresis, but also the lowest efficiency result. Avoidance of light soaking produced a similar result. Light soaking at V_{mp} produced a higher efficiency with some hysteresis. Light soaking at the open circuit condition produced the largest hysteresis and hence no efficiency could reliably be extracted.

The argument to avoid light soaking in PSC devices is understandable, given the complexities of the device response described above.

(□ OPV □ DSC ■ PSC)

5.3.3 Pre-conditioning by light soaking

The impact of light soaking is not restricted to PSC devices. In addition to irreversible degradation, effects on OPV and DSC devices can include short-term variations owing to reversible degradation and/or annealing, as well as recovery from dark ageing. For these reasons, light soaking is a common form of pre-conditioning treatment for these devices.

A light soaking pre-treatment has been shown to have a stabilizing effect on the performance of OPV and DSC devices, especially for devices that were kept in the dark beforehand ([6] and [7]). For devices stored in the dark for long periods, a suitable treatment is to hold the device for around 40 minutes at open circuit under broadband illumination, with irradiance around 1 000 W/m^2 and temperature held around 25 °C. This pre-conditioning treatment primarily stabilises the fill-factor of the resulting I-V curve. After this treatment, shorter light soaking treatments of around 10 minutes are usually sufficient to bring the device back to its light-stable performance, provided only a few days have passed since the last full light soak.

In accelerated ageing studies of OPV mini-modules, the need for longer light-soaking treatments (up to about 1 h) with increased ageing was noticed, particularly for devices kept under humidity stress [7].

The enormous range of device behaviours at the R&D stage means that standardising a light soaking procedure for pre-conditioning will not be an easy task. This may be made simpler once device technologies mature to a stage at which they can be stabilized using a procedure such as MQT 19 in IEC 61215-1. Stabilization will not necessarily remove the need for special steps to achieve a steady-state measurement, such as pre-conditioning, or one of the other techniques discussed in Clause 6.

(■ OPV ■ DSC □ PSC)

5.3.4 Recognition of a diurnal instability

Some groups have identified the fact that some devices, particularly PSC, can exhibit a reversible instability over the 24 hour day-night cycle [8], [9] and [10]. They contend that this means it is not appropriate to seek a single stabilized device performance, but instead a fair assessment should consider that the real application also includes nighttime. How this should be measured in the laboratory remains an issue for discussion; however, it may mean that pre-conditioning before I-V measurement is not useful, or perhaps should be performed in two parts, one for the morning performance and the other for the afternoon performance.

(□ OPV □ DSC ■ PSC)