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Photovoltaic (PV) modules and cells – Measurement of diode ideality factor by quantitative analysis of electroluminescence images

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PHOTOVOLTAIC (PV) MODULES AND CELLS – MEASUREMENT OF DIODE IDEALITY FACTOR BY QUANTITATIVE ANALYSIS OF ELECTROLUMINESCENCE IMAGES

FOREWORD

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

Draft	Report on voting
82/1955/DTS	82/1992/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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- withdrawn,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

INTRODUCTION

EL (Electroluminescence) diagnosis technique has been widely used for the evaluation of photovoltaic cells and modules photographically. EL images can identify various kinds of deficiencies, such as cracks and pin-holes in substrates, breakdown and detachment of electrodes, etc. In addition to these qualitative inspections, the quantitative analysis of EL intensity can reveal the electronic performance of photovoltaic cells [1] to [7][1]. The EL intensity is proportional to the total number of minority carriers in photovoltaic cell bodies. The injection of minority carriers is governed by the I-V characteristics of pn junctions following the diode rectification formula, which yields that the EL intensity dependence upon the injection current will derive the diode ideality factor [8].

The proposed analysis method is not intended to give the criteria for the diagnosis of cells and modules, but the measured values of n are informative for stakeholders to share a common view about degradation phenomena among themselves. This standard measurement technique may be useful for the following stakeholders:

a) Manufacturers – checking validity of samples for both development and quality control (refer to Annex C).
b) Power producers – checking suspicious modules for potential failures (refer to Annex B).
c) Reuse – evaluation of value of second-hand modules (refer to Annex B).

1 Numbers in square brackets refer to the Bibliography.

PHOTOVOLTAIC (PV) MODULES AND CELLS – MEASUREMENT OF DIODE IDEALITY FACTOR BY QUANTITATIVE ANALYSIS OF ELECTROLUMINESCENCE IMAGES

1 Scope

This document specifies a method to measure the diode ideality factor of photovoltaic cells and modules by quantitative analysis of electroluminescence (EL) images.

This document provides a definition of the term diode ideality factor n, as the inverse of increment ratio of natural logarithm of current as a function of applied voltage, which is related to the fill factor FF, and is useful as an effective indicator to represent the output efficiency of photovoltaic cells and modules with the other key parameters open circuit voltage V_{oc} and short circuit current I_{sc}.

This document is only applicable to crystalline silicon photovoltaic cells and modules.

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 60904-13:2018, *Photovoltaic devices – Part 13: Electroluminescence of photovoltaic modules*

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

3 Terms and definitions

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

3.1
electroluminescence
near infra-red light (NIR) and shortwave infra-red (SWIR) light emitted by crystalline silicon photovoltaic cells under current injection in forward bias

Note 1 to entry: The dependence of EL intensity upon injection current is explained in Annex A.

[SOURCE: Reference [6] and IEC TS 60904-13:2018, 3.1]

3.2
dark *I-V*
diagram representing the dependence of the current passing through the diode (i.e. the photovoltaic cell) in the dark versus the applied-voltage

3.3
diode ideality factor
n
inverse of increment ratio of natural logarithm of current as a function of applied voltage; value is normalized by thermal voltage

Note 1 to entry: Thermal voltage: $V_{th} = \frac{kT}{e}$

where

k is the Boltzmann constant;

T is the temperature;

e is the electron charge.

4 Procedures for quantitative analysis of EL intensity

4.1 General

The diode ideality factor n is an important metric to represent the electronic quality of pn junctions based on the material physics. In general, it is defined by the diode current formula (1):

$$I = I_0 \times e^{\left(\frac{V}{n \times \beta}\right)} \quad (1)$$

where

I_0 is the dark saturation current;

β is the thermal voltage.

The value of n reflects the current transport mechanisms through the diodes and is considered to be parametric variable. It should be noted that n has been revealed to be related to the fill factor FF [9] to [11], and will be an effective indicator to represent the output efficiency of photovoltaic cells and modules with other key parameters of the open circuit voltage V_{oc} and the short circuit current I_{sc}.

Usually n is derived from the slope of semi-logarithmic plot of the dark diode current as a function of the applied voltage. Electrical lead wires are needed to measure current voltage (I-V) characteristics, and so the measurement of independent cells composing modules is very difficult.

This newly proposed method utilizing quantitative analysis of EL images has the following novel features:

- Non-contact and remote sensing measurement for both indoor and outdoor applications: It can be used for modules after different accelerated stress tests and/or aged ones installed in the fields.
- Non-destructive method for modules containing multiple cells: Independent measurement of each cell is simultaneously possible by successive EL image capturing at various injection current values.

- The EL intensity dependence on the injection current is analysed to derive n based on a conventional solar cell diode model and dark I-V curve analysis. The use of EL intensity, rather than voltage, simplifies the analysis because the lumped series resistance parameter does not need to be known in order to perform the analysis.

4.2 Samples

Preparation of correlated sample cells and modules is recommended.

4.3 Apparatus

Apparatus of taking EL images shall meet the requirements in IEC TS 60904-13.

4.4 EL image capturing and camera calibration

Taking a sequence of EL images is described in IEC TS 60904-13. EL intensity is measured at various injection current values in the range of 1 % ~ 100 % of I_{sc} (short circuit current). In order to keep the injection current at the designated value during measurements the current shall be set at the appointed value under the constant current (CC) mode control. The fluctuation of sample temperature during measurements yields slight changes in current-voltage characteristics of samples. Cameras with a linear intensity response shall be used. If non-linear, this may be corrected to achieve a linear intensity response function.

4.5 Procedures of analysing data to derive n values (refer to Annex A)

The EL intensity of the test specimens should be taken without changing the capturing conditions, i.e., the configuration of the position of test specimens and the camera and the camera parameter settings (shutter speed, diaphragm, and focal length, brightness and contrast in the software of image capturing).

The EL images should be corrected as described in IEC TS 60904-13. Next, select some cells suitable for the desired analysis from the El images. Then, for those cells, calculate the average intensity of whole cell area including the electrode part, and use it as EL intensity. The EL intensity L is plotted as a function of the injection current I using log-log plot. The diode ideality factor n is obtained from the slope of log-log plot.

$$n = \frac{\Delta \mathrm{Log}\, L}{\Delta \mathrm{Log}\, I} \tag{2}$$

See Figure A.1 for an example.

5 Measurement report

A measurement report with the obtained performance characteristics shall be prepared by the test laboratory or agency. The report shall contain the detail specification of the device under test. The test report shall contain the following information:

a) a title;

b) name and address of the test laboratory and location where the tests were carried out;

c) unique identification of the report and each page;

d) name and address of client, where appropriate;

e) identification, description, characterization, and condition of the device under test;

f) date of receipt of the device under test and date(s) of measurements, where appropriate;

g) identification of measurement equipment used, including camera, detector, and lens and type;

h) information of taking EL images, either by referencing the appropriate clauses of this document and/or referred normative technical specifications, or additional information as needed, describing the applied image corrections, including but not limited to handling of single time events, stuck pixels, and background removal, enhancement with filters or other manipulations of the raw image file.

i) reference to sampling procedure, where relevant;

j) current and voltage applied on the device under test, device temperature, camera settings, working distance, imaging angle (degrees from normal), and nominal ambient light conditions;

k) any deviation from, additions to or exclusions from the test method, and any other information relevant to a specific test such as environmental conditions.

l) photographs obtained during the examinations and derived results supported by tables, graphs, sketches as appropriate showing a scheme for referencing the particular cell (i,j) if the test device is a module, as shown in Figure 1;

1,A	1,B	1,C	1,j
2,A	2,B	2,C	2,j
3,A	3,B	3,C	3,j
4,A	4,B	4,C	4,j
5,A	5,B	5,C	5,j
6,A	6,B	6,C	6,j
7,A	7,B	7,C	7,j
i,A	i,B	i,C	i,j

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Figure 1 – Scheme for labeling position of cells in a module viewed from the light-facing side according to coordinates (i,j)

m) a statement of the estimated uncertainty in the reported value of n;

n) a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of, and the date of the report;

o) a statement to the effect that the results relate only to the devices tested, where relevant;

p) a statement that the report shall not be reproduced except in full, without the written approval of the laboratory;

q) a copy of this report shall be kept by the manufacturer for reference purposes.