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TECHNICAL SPECIFICATION

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

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

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

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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.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under 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- withdrawn,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.

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.

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

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

IEC

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.

Annex A
(normative)

EL intensity dependence on the injection current

A.1 General

Injection current into a module correlates with the EL intensity produced by that module. In this annex, the relation between injection current and EL intensity is indicated using current formula of pn junction diode.

A.2 Derivation of diode ideality factor

The electroluminescence (EL) from Si photovoltaic cells is caused by the radiative recombination of minority carriers, and the EL intensity is proportional to the total number of the minority carriers mainly in the base layers of photovoltaic cells [8]. The EL intensity can be related to n using formulas (A.1) and (A.2).

$$L = \mathrm{A}e^{\left(\frac{\mathrm{e}V}{\mathrm{k}T}\right)} \quad \rightarrow \quad \ln L = \ln A + \frac{\mathrm{e}}{\mathrm{k}T} \times V \qquad \text{(A.1)}$$

where

L is the EL intensity;

V is the forward voltage;

A is a constant.

$$I = I_0 \times e^{\left(\frac{\mathrm{e}V}{n \times \mathrm{k}T}\right)} \quad \rightarrow \quad \ln I = \ln I_0 + \frac{\mathrm{e}}{n \times \mathrm{k}T} \times V \qquad \text{(A.2)}$$

where

I is the injection current;

I_0 is the dark saturation current.

Then $\ln L = \mathrm{C} + n \times \ln I$

where

C is a constant.

When the average EL intensity L as a function of the injection current I using log-log plot is plotted, the differential of the curve is n. When the value of n varies as a function of I (i.e., V), n is called as local diode ideality factor.

$$n = \frac{\Delta \ln L}{\Delta \ln I} = \frac{\Delta \mathrm{Log}\, L}{\Delta \mathrm{Log}\, I} \qquad \text{(A.3)}$$

The EL intensity dependence on the injection current is analysed to derive n, and so the series resistance effect is removed. See Figure A.1.

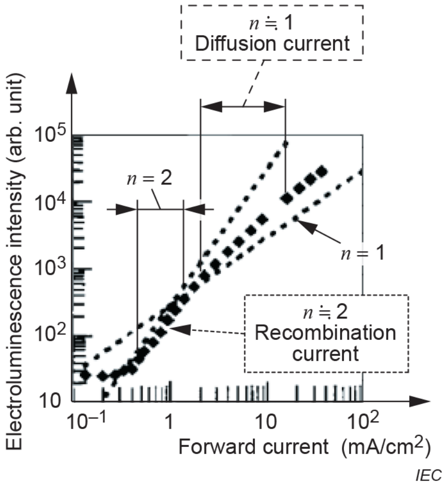

Figure A.1 – Electroluminescence intensity dependence on injection current

Annex B
(informative)

Examples of measurements of diode ideality factor *n*

B.1 General

Some samples of *n* value measurements by this standard method are shown in this annex.

B.2 Examples of *n* value of cells

B.2.1 Example 1 – Module without defect

B.2.1.1 EL image and EL intensity

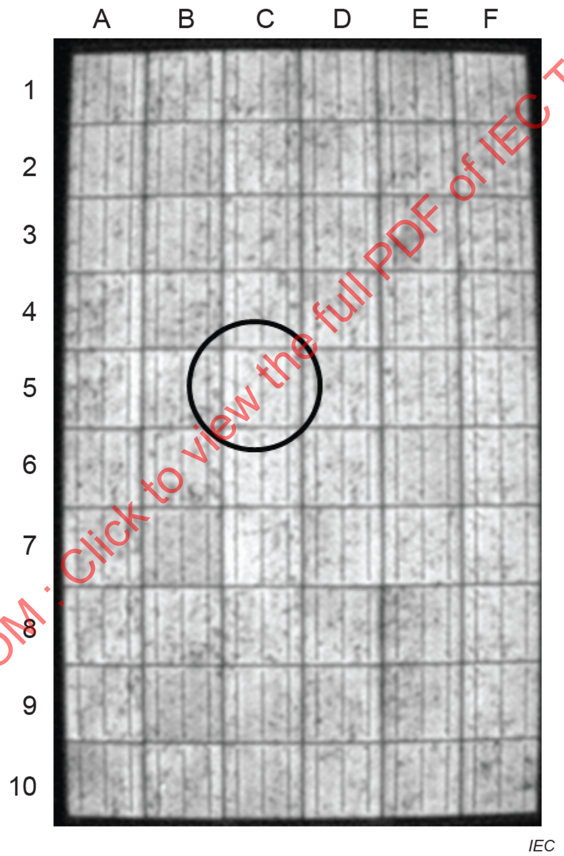

Figure B.1 – EL image (module without defect)

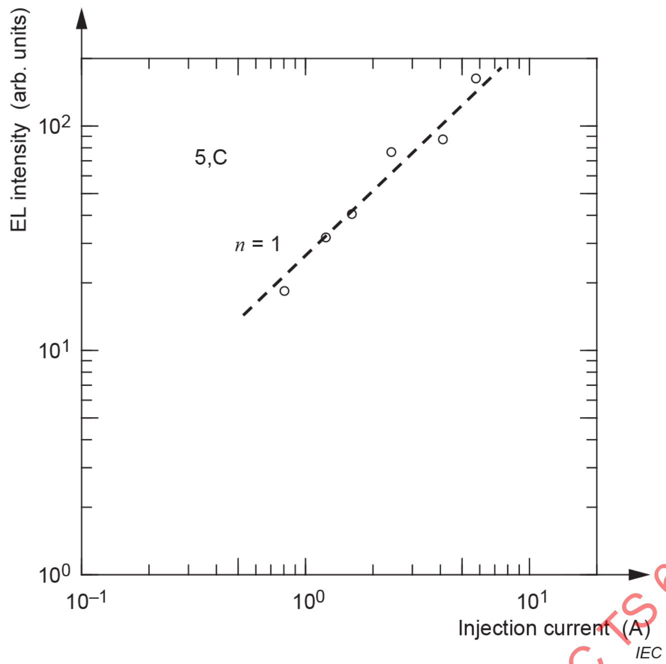

Figure B.2 – EL intensity dependence on injection current (module without defect)

Table B.1 – Performance of module without defect (module A) (at STC)

	I_{sc}	$V_{oc\ cell}$	FF	P_{max}	I_{mp}	I_{sc}-I_{mp}	$V_{mp\ cell}$	η
	A	V		W	A	A	V	%
Module A	8,38	0,613	0,748	231,0	7,87	0,51	0,489	14,1

P_{max}: maximum output power.

I_{mp}: current at maximum output power.

V_{mp}: voltage at maximum output power.

η: 100 × P_{max}(kW)/S, S: module area (m^2).

B.2.1.2 Measurement report

The EL image of Figure B.1 cell 5,C shows uniform emission. The intensity dependence upon the injection current of Figure B.1 cell 5,C provided n = 1 in all the range of injection current. Other cells of Figure B.1 give the same results. Figure B.2 shows the EL intensity as a function of injection current. Table B.1 lists the electrical parameters of the module used in this example.

B.2.2 Module with defect

B.2.2.1 Example 2 – Aged module at outdoor field for 5 years

B.2.2.1.1 EL image and EL intensity

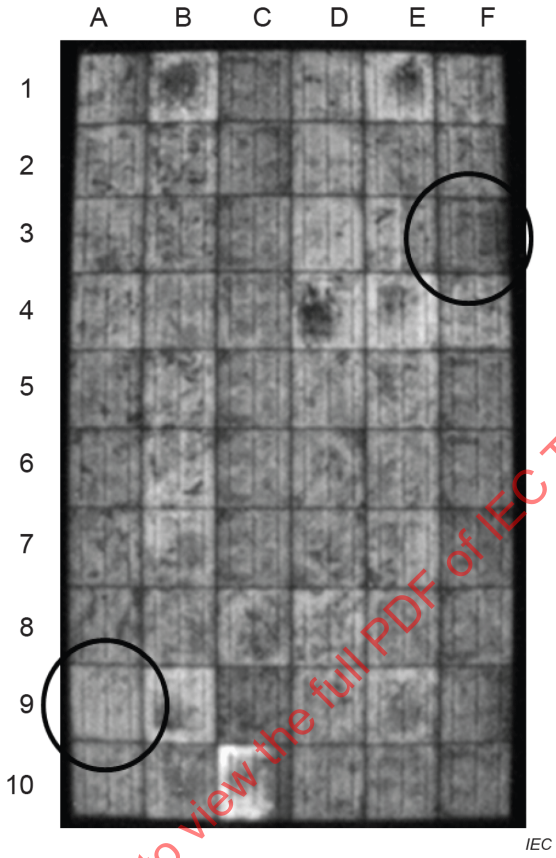

Figure B.3 – EL image (aged module)

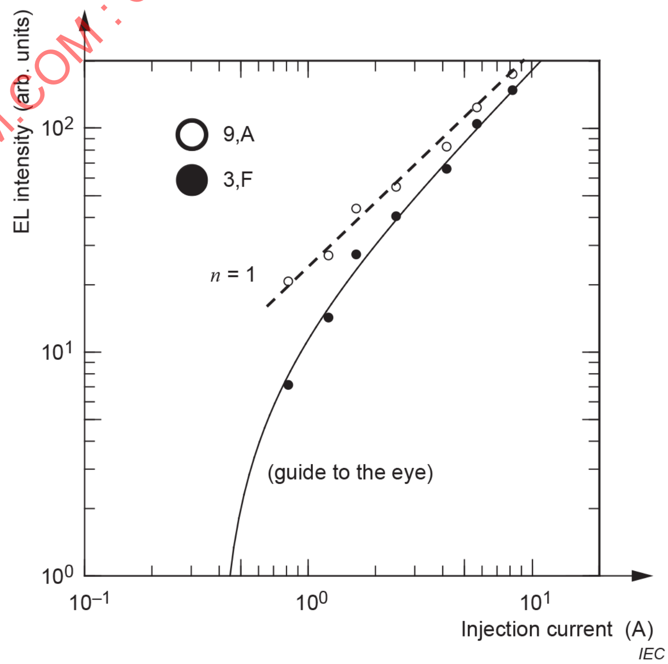

Figure B.4 – EL intensity dependence on injection current (aged module)

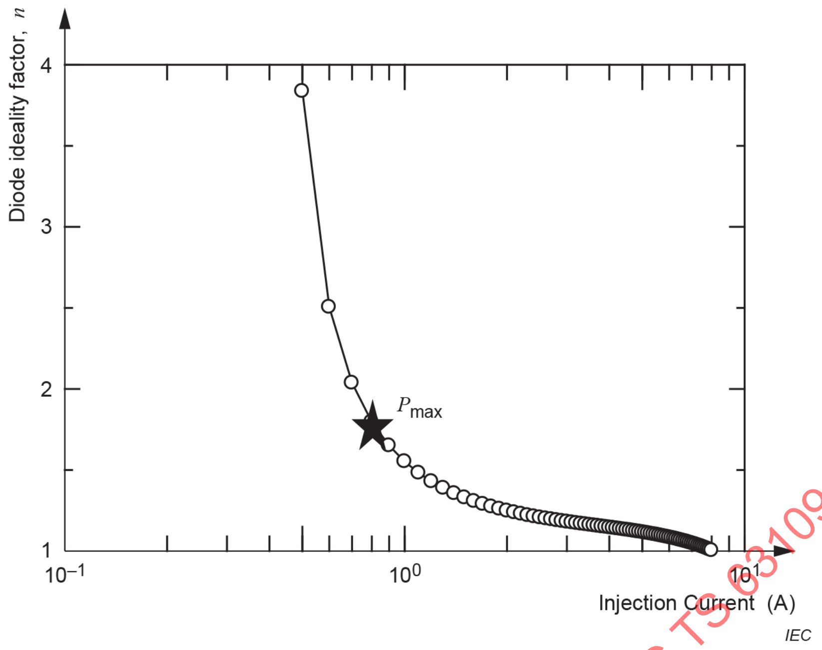

Figure B.5 – Diode ideality factor n of 3,F

Table B.2 – Performance of aged module (module B) (at STC)

	I_{sc}	$V_{oc\ cell}$	FF	P_{max}	I_{mp}	I_{sc}-I_{mp}	$V_{mp\ cell}$	η
	A	V		W	A	A	V	%
Module B	8,33	0,61	0,702	214,2	7,47	0,86	0,478	13,1

B.2.2.1.2 Measurement report

Some cells (Figure B.3, 1,B, 1,E etc.) show degradation of electrode damages inspected by EL images (dark parts), see also Figure B.4 and Table B.2. The cell of Figure B.3, 9,A shows normal behaviour and n = 1. The cell of Figure B.3, 3,F shows uniform EL emission, but EL intensity decreases super-linearly with decreasing the injection current. The n increases with decreasing the injection current as shown in Figure B.5, and nearly 2 at the V_{mp} point (corresponding to the injection current of I_{sc} – I_{mp} = 0,86 A. See Annex C for the discussions). PID is thought to occur in the cell of Figure B.3 position 3,F (for details of PID refer to IEC TS 62804-1[13]).

B.2.2.2 Example 3 – Defective module due to PID

B.2.2.2.1 EL image and EL intensity

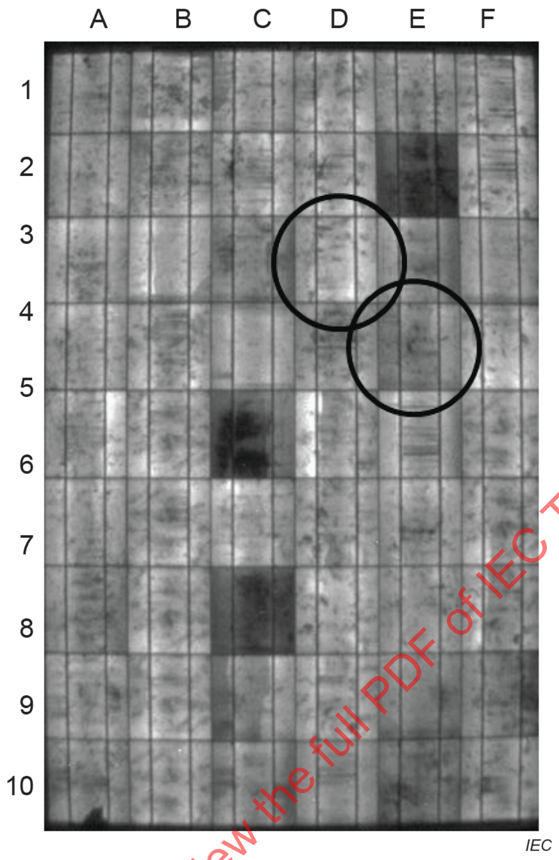

Figure B.6 – EL image (defective module)

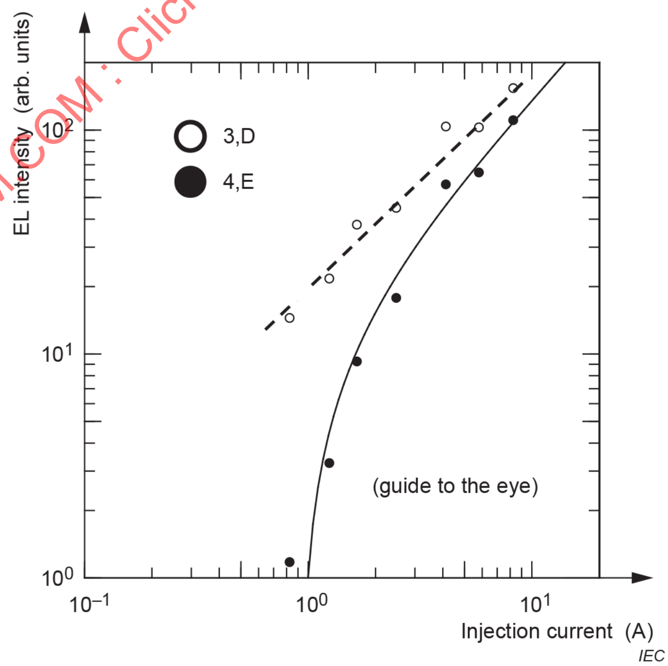

Figure B.7 – EL intensity dependence on injection current (defective module)

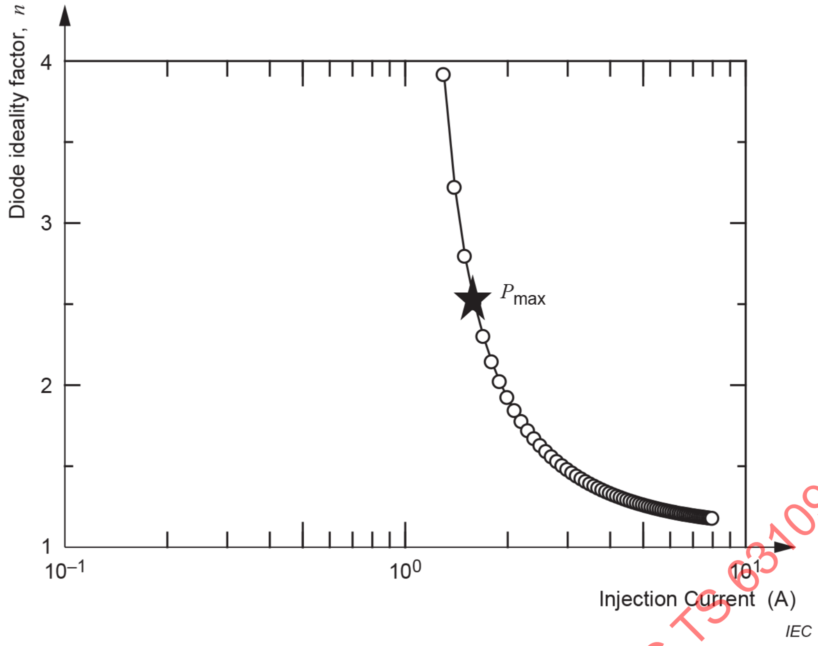

Figure B.8 – Diode ideality factor n of 4,E

Table B.3 – Performance of PID module (at STC)

	I_{sc}	$V_{oc\ cell}$	FF	P_{max}	I_{mp}	I_{sc}-I_{mp}	$V_{mp\ cell}$	η
	A	V		W	A	A	V	%
Module C	8,33	0,600	0,62	167,2	6,86	1,47	0,451	11,5

B.2.2.2.2 Measurement report

The cell of Figure B.6, 3,D shows normal behaviour and n = 1.The cell of Figure B.6 ,4,E shows uniform EL emission, but EL intensity decreases super-linearly with decreasing the injection current, see also Figure B.7 and Table B.3. The n increases with decreasing the injection current as shown in Figure B.8, and is about 2,5 at the V_{mp} point (corresponding to the injection current of I_{sc} – I_{mp} = 1,47 A. See Annex C for the discussions). PID is thought to occur in the cell of Figure B.6, position 4,E.

Annex C
(informative)

Diode ideality factor *n* as an indicator of the output performance of PV modules – Measurement using proposed single diode model

C.1 General

This Annex C shows that the diode ideality factor n is an effective indicator to represent the output performance of PV modules and cells based on the proposed practical single diode model. PV modules are physically pn junctions, and current voltage (I-V) characteristics in dark (without illumination) are presented as formulas (C.1) and (C.2).

$$I_{\mathrm{d}} = I_{\mathrm{o}} \times \left(\mathrm{e}^{\left(\frac{V_{\mathrm{dk}} - I_{\mathrm{dk}} \times R_{\mathrm{s}}}{n \times V_{\mathrm{th}}}\right)} - 1 \right) \tag{C.1}$$

$$I_{\mathrm{dk}} = I_{\mathrm{d}} + \frac{V_{\mathrm{d}}}{R_{\mathrm{sh}}} \tag{C.2}$$

where

I_{o} is the dark saturation current;

$V_{\mathrm{th}}(=\frac{\mathrm{k}T}{\mathrm{e}})$ is the thermal voltage;

R_{s} is the lumped series resistance;

R_{sh} is the shunt resistance.

The metric quantities are I_{d}: current passing through the pn diode, V_{dk}: applied DC voltage by power supply, and I_{dk}: injection current by the power supply, as shown in the equivalent circuit of Figure C.1. The notation n is called "diode ideality factor" and is governed by physical mechanisms of current types flowing through pn junctions; n = 1: diffusion current, n = 2: generation and recombination current, n > 2: small shunt resistance, large series resistance, and/or other mechanisms. The equivalent circuit model of Figure C.1 including the physical quantities of R_{s} and R_{sh} has been usually used to explain the measured I-V characteristics considering that the values of n and I_{o} are constant. But it is difficult to reveal I-V behaviour in the whole measured I (or V) range. Some research has also presented the two-diode model taking into account n = 1 and n = 2 with respective dark saturation currents of I_{o1} and I_{o2}.

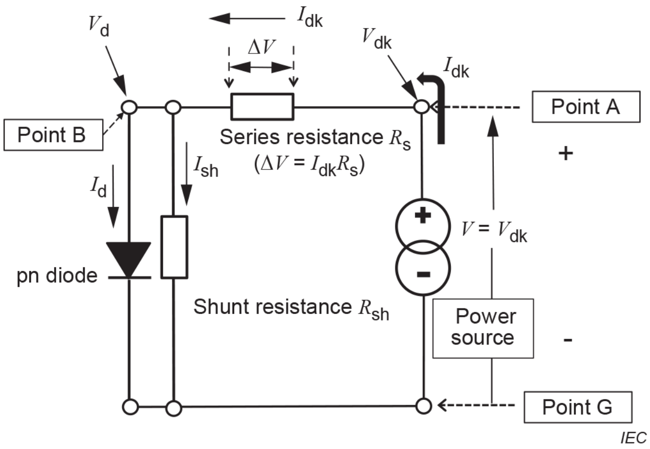

Figure C.1 – Equivalent circuit model in dark considering series resistance R_s and shunt resistance R_{sh}

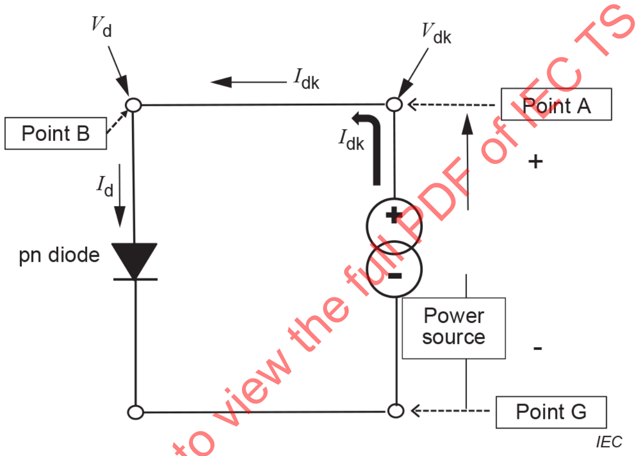

Figure C.2 – Equivalent circuit model in dark for the practical single diode model

C.2 Practical single diode model

In order to indicate the performance of PV modules the practical pn diode model is proposed to analyse the I-V characteristics in the specific narrow range. As shown in the equivalent circuit of practical single diode model of Figure C.2, there are no R_s and/or R_{sh} quantities, and then, the I-V characteristic is shown by formula (C.3).

$$I_{dk} = I_0 \times e^{\left(\frac{V_{dk}}{n \times V_{th}}\right)} \quad \text{(C.3)}$$

The ideality factor n is considered to be parametric variable with the variable value of I_o, too. Formula (C.3) is valid in a specific narrow range by varying the parametric values of n and I_o. The dark I-V characteristic is schematically shown in Figure C.3 and Figure C.4 using linear and semi-logarithmic coordinates, respectively. The specific narrow range should be set around P_m* which is an equivalent point as the maximum power point, P_m, in the case of photo-response.

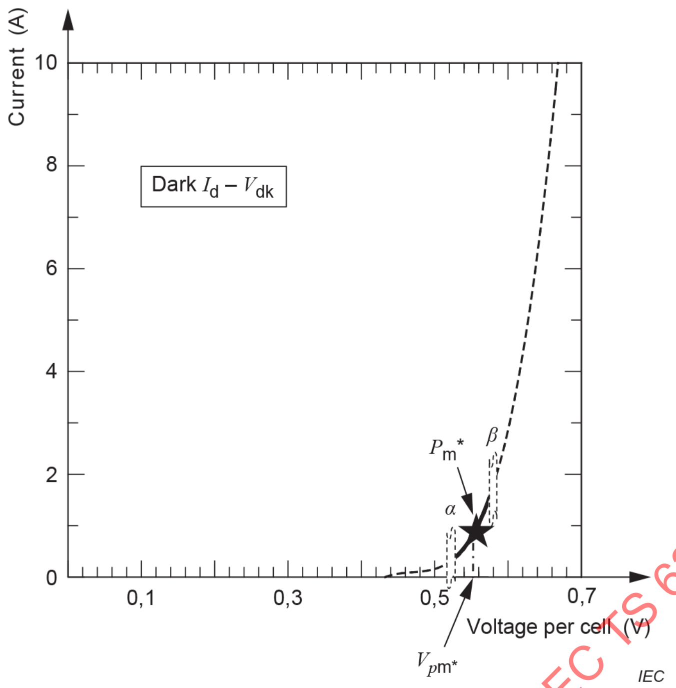

Figure C.3 – Schematic *I-V* characteristic in dark using linear coordinates

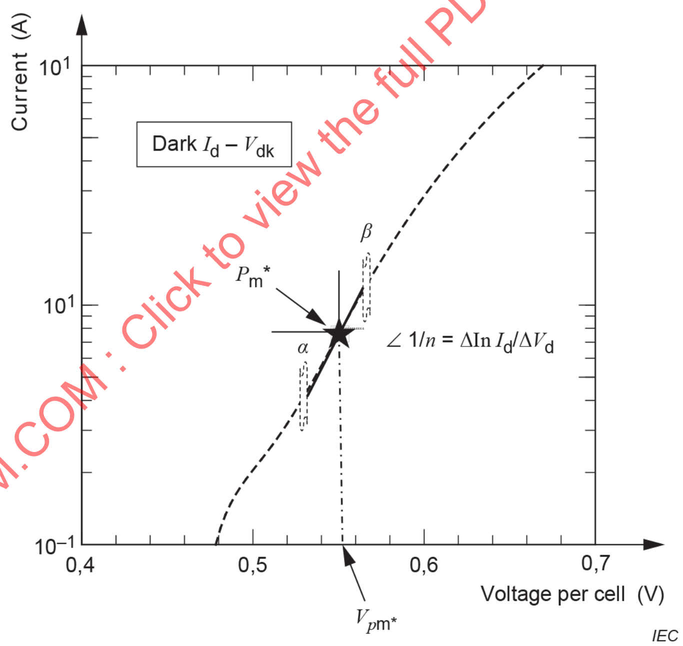

Figure C.4 – Schematic *I-V* characteristic in dark using semi-logarithmic scales

The concerned setting range is represented by the section $\alpha - \beta$, since the conversion efficiency of PV modules and cells is determined by the values of V_{mp} and I_{mp} at P_m. The differential of formula (C.3) gives formula (C.4),

$$n \times V_{th} = \frac{\Delta V_{dk}}{\Delta \ln I_{dk}} \qquad \text{(C.4)}$$

where

$I_{dk} = I_d$,

$V_d = V_{dk}$, and

n is derived (see Figure C.4).

The n value reflects the effects of R_s and R_{sh} in addition to the current transport mechanisms through the diodes, and the value of n represents behaviour of I-V characteristic as explained below. The defined n is also specified as local diode ideality factor [12] when it is expressed as a function of V (or I). Formula (C.3) is valid in a narrow range. If the successive series of setting narrow ranges are considered, n is obtained as a function of V. The value of n is also derived by the EL intensity dependence upon the injection current (see Annex A) based on the proposed practical single diode model. The indicator n is related to the curvature of I-V characteristic in the linear plot shown in Figure C.3. A small n represents steep increase of the current in so-called threshold voltage region (typically 0,5 V to 0,6 V) of pn diode behaviour, and a large one represents gradual increase in the same region. The I-V characteristic in a high voltage region (> 0,65 V to 0,7 V) is affected by the lumped series resistance R_s causing voltage drop.

Under photo-irradiation, the equivalent circuit shown in Figure C.5 is usually considered to explain the photo response of PV modules and cells using formulas (C.5) and (C.6).

$$I_{ph} = I_L - I_o \times \left(e^{\left(\frac{V_{ph} + I_{ph} \times R_s}{n \times V_{th}} \right)} - 1 \right) - I_{sh} \quad \text{(C.5)}$$

$$I_{sh} = \frac{V_{ph} + I_{ph} \times R_s}{R_{sh}} \quad \text{(C.6)}$$

where

I_L is the current source generated by photons,

I_{ph} is the current passing through the load,

V_{ph} is the photo-induced voltage at the load,

I_{sh} is the current passing through the shunt resistance,

other notations are the same as in formula (C.1).

The current passing through the pn diode, I_d, is expressed as the second term in the right-hand side of formula (C.5).

When the practical single diode model following the same consideration as in the dark I-V characteristics is applied, the equivalent circuit shown in Figure C.6 is adopted. Then, formulas (C.7) and (C.8) lead to formula (C.9) which is the same as formula (C.4).

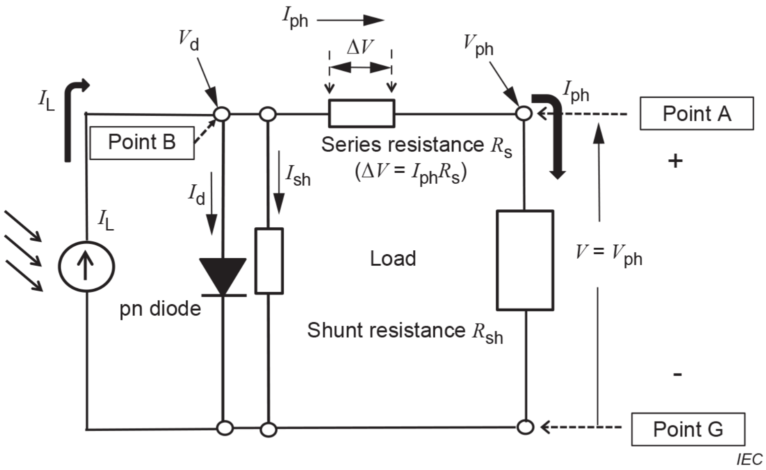

Figure C.5 – Equivalent circuit model under photo irradiation considering series resistance R_s

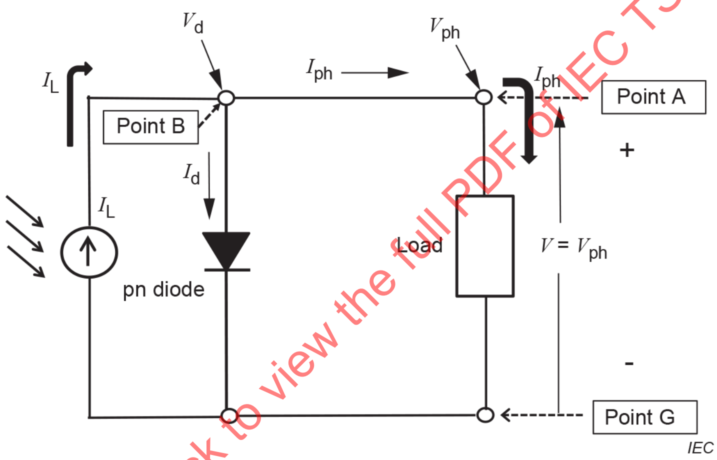

Figure C.6 – Equivalent circuit model under photo irradiation for practical single diode model

$$I_{ph} = I_L - I_0 \times e^{\left(\frac{V_{ph}}{n \times V_{th}}\right)} \tag{C.7}$$

$$I_d = I_0 \times e^{\left(\frac{V_d}{n \times V_{th}}\right)} \tag{C.8}$$

$$n \times V_{th} = \frac{\Delta V_{ph}}{\Delta \ln I_d} \tag{C.9}$$

where

$I_d = I_L - I_{ph}$,

$V_{ph} = V_d$.