IEC TS 62804-2

Edition 1.0 2022-03

TECHNICAL SPECIFICATION

colour inside

Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation –
Part 2: Thin-film

IEC TS 62804-2:2022-03(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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PHOTOVOLTAIC (PV) MODULES – TEST METHODS FOR THE DETECTION OF POTENTIAL-INDUCED DEGRADATION –

Part 2: Thin-film

FOREWORD

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IEC TS 62804-2 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems. It is a Technical Specification.

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

Draft	Report on voting
82/1958/DTS	82/2001A/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.

A list of all parts in the IEC 62804 series, published under the general title *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation*, can be found on the IEC website.

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/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- withdrawn,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.

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INTRODUCTION

Potential-induced degradation (PID) refers to any PV module degradation that is caused by the stress of an electric potential between the active cell circuit and the external surfaces or parts of the PV module.

The applied stresses, with system voltage being the principal factor in IEC 62804 series documents, manifest themselves in different degradation modes that depend in part on the module technology. Therefore, a series of technical specifications is being developed to define PID tests for different PV module technologies and differing PID modes.

IEC TS 62804-1:2015, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon* defines test methods for evaluating power loss by PID in crystalline silicon PV modules.

IEC TS 62804-1-1:2020, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1-1: Crystalline silicon – Delamination* defines a test method for evaluating delamination by PID associated with electrochemical processes in crystalline silicon PV modules.

This part of IEC 62804 defines test methods for evaluating power loss by PID in thin-film PV modules with moisture sensitive components and those which use moisture barrier encapsulation because of such sensitivity.

A future document will be required for evaluating corrosion and delamination associated with electrochemical processes in thin-film PV modules and modules with moisture sensitive components with moisture barrier packaging. Further documents in the series may be introduced in the future for emerging module technologies, mechanisms, or evaluation methods.

In addition to the IEC 62804 series, IEC 61215-2:2021 contains a PID test (MQT 21) with methods and severities from IEC TS 62804-1:2015 method (a) with modifications to avoid some recognized test-specific degradation and polarization for application to various flat plate module types. The PID test method in IEC 61215-2:2021 is shorter and simpler than those given in this document.

Voltage potential that exists between the active circuit and the module surfaces directly or indirectly connected to earth can lead to module degradation by multiple mechanisms including ionic transport in the encapsulant, superstrate or substrate; hot carriers in the cell, redistribution of charges that degrade the active layer of the cell or its surfaces, failure of adhesion at interfaces, and corrosion of module components. Along with the factor of system voltage, these processes are most active in wet or damp environments, and in environments prone to soiling of modules with conductive, acidic, caustic, or ionic species that lead to increased conduction on the module surfaces. Certain failure mechanisms may only be active with the module electrically biased in one polarity depending on the cell construction, module materials, and design. The testing in this document therefore specifies the evaluation of the effects of voltage stress in both polarities for modules that may be operated in either polarity, or when applicable, uniquely in the polarity defined by the manufacturer's documented specifications and installation instructions.

Considering this document is applicable to modules with a functional moisture barrier packaging, a procedure is provided in Annex A to evaluate the functionality of the moisture barrier for the purposes of PID evaluation. If the moisture barrier is not sufficiently functional, the moisture ingress is likely to affect (usually increase) PID rate during accelerated testing in the environmental chamber and largely invalidate projections that this document provides about PID rate in the field.

There are many module designs, which span crystalline silicon, compound semiconductor, thin-film and tandem technologies. These can exhibit differing sensitivities of the absorber layer, differing laminate constructions and interfaces, and different mounting types with differing ability to resist charge transfer between the laminate and ground. Based on the great variability in acceleration factor between use condition and test, which has been measured in one instance involving a thin-film module technology to vary between one and two orders of magnitude with the singular change of the edge clip material holding the module [1][1], a unique stress level for accelerated testing of all module types covered by this document is not given at this time. Instead, a protocol for evaluating the acceleration factor for PID degradation of thin film modules with respect to climate zones is provided. Use of the acceleration factor method is therefore motivated because considerable variability in acceleration factor has been found depending on the thin film product and mounting [1]. Whether the phenomenon is specific to thin film products has not been clarified.

To overcome the significant variability, this document offers procedures for evaluating the relative rate (or acceleration) of current transfer and degradation in the chamber versus the field, which has been found useful for evaluating thin-film technologies in the absence of the variable of moisture ingress into the module [2-6]. The user may therefore calculate the relative PID resistance in the chamber condition versus the field condition which to better forecast the power degradation rate by PID in the use. Using of rate of coulomb transfer in the field and chamber as a basis provides a platform for comparison of test results. With the understanding of how many coulombs are transferred in the use environment per year, one can project power loss by PID for the desired number of years in the use environment based on the measured coulombs transferred and any observed power loss by PID in the environmental chamber, in the absence of moisture ingress and significant power recovery if the factor of system voltage bias is removed.

Differing module constructions transfer PID-inducing current between the cells and ground differently as a function of extent of moisture on the surfaces and temperature. The charge density profile of transferred coulombs across the module will vary as a function of temperature and humidity on the module surfaces as well. To maintain representative temperatures and humilities for the PID testing, an option to accelerate the PID testing with the factor of elevated system voltage in the field is additionally offered in this document.

Thin-film modules may exhibit metastability and other effects, whereby the history of exposure to factors including light and heat may influence power performance either reversibly or irreversibly. Without attention to this, such effects can hinder the quantification of the PID incurred in the PID stress test. To normalize for such extraneous power changes exhibited by modules in this PID test, the power performance after a PID chamber stress test is examined relative to any change in power of in-chamber control modules undergoing the same stress regime excluding the factor of system voltage stress.

This document also includes options to mitigate power changes due other test-specific effects resulting from the unrepresentative conditions of heat and darkness that IEC 61215-2 MQT 19, Stabilization, alone will not correct. These options include application of light or forward bias voltage before and during the PID stress test. This document additionally contains a light and heat exposure sequence that may be optionally applied to the modules after the PID stress test to obtain the power performance of the module after such recovery procedure. During IEC 61215-2 MQT 19, Stabilization, the factor of system voltage is not applied, a condition that does not normally occur in the field.

The voltage levels applied in testing are the modules' nameplate-rated system voltage. This results in a voltage level that is typically above that experienced in the field because:

a) voltage levels are reduced due to their elevated operating temperature under sunlight,
b) they are operated at maximum power and therefore a lower maximum power voltage than system voltage that is associated with the open-circuit voltage of the modules,
c) most of the modules are not at the extremes of the series string, and
d) due to safety factors or other design criteria, modules may be in strings below the module rated system voltage.

[1] Numbers in square brackets refer to the Bibliography.

However, modules connected in series strings that are in open circuit and uncontrolled by a maximum power tracker, for reasons including being disconnected from their load, may experience uncontrolled and significantly higher voltages than experienced by the modules maintained at the maximum power point even though system installation standards require voltage levels to be below system voltage. The voltage levels applied in testing is thus the modules' nameplate-rated system voltage. This provides a small element of acceleration over typical use conditions, while maintaining a system voltage level that modules may actually experience in the field.

It is known that variability in manufacturing processes can affect the susceptibility of modules to system voltage stress. Periodic retesting of modules by the test protocols contained herein with internal quality assurance programs such as given in IEC 62941, and with external audits, will aid in verifying not only the durability of the design of the module to system voltage stress, but also the effects of any variability of the materials and manufacturing processes. Due to the extended length of time required to perform the tests contained herein, it is anticipated that module manufacturers themselves will apply them.

PHOTOVOLTAIC (PV) MODULES – TEST METHODS FOR THE DETECTION OF POTENTIAL-INDUCED DEGRADATION –

Part 2: Thin-film

1 Scope

This part of IEC 62804 defines apparatus and procedures to test and evaluate the durability of photovoltaic (PV) modules to power loss by the effects of high voltage stress in a damp heat environment, referred to as potential-induced degradation (PID). This document defines a test method that compares the coulomb transfer between the active cell circuit and ground through the module packaging under voltage stress during accelerated stress testing with the coulomb transfer during outdoor testing to determine an acceleration factor for the PID. It is designed for thin-film PV modules and modules containing moisture sensitive films protected by vapour barrier packaging, principally with one or two glass surfaces. This document tests for the degradation mechanisms involving mobile ions influencing the electric field over the semiconductor absorber layer or electronically interacting with the films such that module power is affected. This document does not specifically test for electrochemical corrosion or delamination associated with application of system voltage. This document does not contain pass or fail criteria and it is not intended for design qualification.

The procedures contained herein, with testing in chamber in combination with in the field or testing in the field alone are intended for use when it is desired to quantify the acceleration provided by the applied stress levels over regular use conditions in the natural environment using coulombs transferred between the module and ground as the index for damage incurred by PID. The procedures for quantifying the acceleration are not recommended when coulombs transferred are not an indicator of damage by PID to the module. The procedures are not directly applicable when moisture ingress into the module laminate occurs affecting PID rate, and to the extent that there is power recovery when the factor of system voltage bias is removed after correctly applying the procedures herein, within the period of testing.

The protocols given herein give results according to the chamber stress levels applied and the module grounding configuration used in the test. Because the stress method of testing in an environmental chamber employs a non-condensing humidity level to serve as a conductive pathway to electrical ground, it frequently applies relatively less stress toward the centre of the module face. Also, the method can evaluate the effectiveness of some construction methods to mitigate PID; for example, the use of rear rail mounts, edge clips, and insulating frames. The test, however, does not include all the factors existing in the natural environment that can affect the PID rate. The actual durability of modules to system voltage stress depends on the actual environmental conditions under which they are operated.

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 60068-2-78:2012, *Environmental testing – Part 2-78: Tests – Test Cab: Damp heat, steady state*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 60721-2-1:2013, *Classification of environmental conditions – Part 2-1: Environmental conditions appearing in nature – Temperature and humidity*

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

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

IEC 61215-1, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements*

IEC 61215-2:2021, *Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test* procedures

IEC 61724-1, *Photovoltaic system performance – Part 1: Monitoring*

IEC 61730-1, *Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction*

IEC 61730-2, *Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing*

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

IEC 61853-1:2011, *Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating*

IEC TS 62804-1:2015, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon*

IEC TS 62804-1-1:2020, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1-1: Crystalline silicon – Delamination*

IEC 62941, *Terrestrial photovoltaic (PV) modules – Quality system for PV module manufacturing*

3 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

4 Samples

All samples for test shall be of representative and identical materials, construction process, and characteristics. For application of the tests in either 5.2 or 5.3, procure two samples for each polarity of the system voltage that is specified or allowed in the module documentation, along with two samples to be used as control modules. If the polarity of the modules connected into module strings is not specified, two replicas for each polarity are required. If the module documentation and the nameplate specify usage of the module in strings of only one voltage polarity with respect to ground (one terminal of the module string tied to ground), then the modules selected for testing under system voltage bias shall be stressed only in that specified polarity. Procure double the number of representative and identical samples for performing the tests in both 5.2 and 5.3 or testing according to 5.2.6. If additional certainty is sought, for example, if there are concerns of partial shading of modules leading to localized damage of the absorber layer, the number of modules for test and for use as controls may be increased.

Sample types chosen for application of this document shall be protected by functioning vapour barrier of the module encapsulation. Annex A is given for the evaluation of effective moisture barrier of the module type for the purposes of PID evaluation.

The PV module samples shall have been manufactured from specified materials and components in accordance with the relevant drawings and process sheets and have been subjected to the manufacturer's normal inspection, quality control and production acceptance procedures. The PV modules shall be complete in every detail and shall be accompanied by the manufacturer's handling, mounting, and connection instructions. When the PV modules to be tested are prototypes of a new design and not from production, this fact shall be noted in the test report (see Clause 6).

When submitted to another party for testing, the submitted modules shall be complete and accompanied by the manufacturer's handling, mounting and connection instructions, including the maximum permissible system voltage. Markings on the module shall conform to the requirements of IEC 61215-1 and IEC 61730-1.

The test results apply only to the module construction tested. To evaluate modules using more than one component source, module design, cell design, process design, or differing process set points and tolerances, then a set of modules for each permutation shall be procured for testing. Changes of the junction box, cables, and connectors do not indicate retest unless modifications to the module laminate for any electrical penetration of conductors through it are made. In cases where the cell, module, or materials process variability or tolerances are large, testing of more than two samples per polarity will be useful for improving the confidence in the results.

If the PV module is provided with and is specified for use with a specific means for grounding, then the grounding means shall be included and considered a part of the test sample. If the PV module is provided with and is specified for use with means for mounting that could additionally influence the module grounding, then the means for mounting shall be included and considered a part of the test sample.

5 Tests

5.1 General

Measurement of current transfer between the cell circuits of modules and ground in the natural environment is employed for evaluating the resistance of the particular design to system voltage stress in the given environment. Tests are grouped into methods that either:

a) evaluate the relative rate (or acceleration) of current transfer and degradation in the chamber versus the field, or

b) use of modules in the field with increased system voltage applied as an accelerant.

The schema of test procedures is shown in Table 1. In view of the potential for metastabilities and test-specific artifacts that may vary among module types, in conjunction with Table 1, consult with the manufacturer for information, guidance, and recommendations for selecting appropriate test procedures.

Table 1 – General schema of test procedures

<table>
<tr>
<td>Environmental chamber testing procedure – chamber tests for leakage current determination and degradation extent, for use in combination with the outdoor testing procedure below. Select from:

5.3.2: Test of modules in the dark and unpowered state, for use when extent of PID is independent of illumination or photocurrent.

-or-

5.3.3: Testing in chamber with current or light bias for use when, respectively, forward bias current can sufficiently simulate the effects of illumination, or illumination itself is required because of PID-sensitivity to these factors.</td>
<td rowspan="2">Outdoor testing (only) procedure using elevated system voltage bias

For use to achieve testing with representative field conditions of temperature and moisture, which affects the electric field over the module surface, and the illumination. See:

5.2.6 Acceleration by elevated system voltage testing outdoor. This includes methods for evaluation of linearity of leakage current, a requirement for implementation of this method

(references 5.2.2 through 5.2.5 procedures and measurement methods)</td>
</tr>
<tr>
<td>Outdoor testing procedure – outdoor tests for leakage current determination: 5.2.2 through 5.2.5.

For use in combination with an environmental chamber testing procedure above.</td>
</tr>
<tr>
<td colspan="2">On the left are the environmental chamber test procedures for use in combination with the outdoor testing procedure for leakage current determination in the field. On the right is the alternative outdoor testing (only) procedure that uses elevated system voltage bias to achieve acceleration.</td>
</tr>
</table>

5.2 Test procedures – Outdoor measurements

5.2.1 General

The test procedures described in 5.2.2 to 5.2.5 are for outdoor measurements done in conjunction with chamber testing for determination of acceleration in chamber over the outdoor environment. Comparison of the current leaking between the active cell circuit and ground in the field to that in accelerated testing in chamber as obtained using the test procedures given in 5.3 is used to quantify the acceleration provided by the accelerated stress testing over that of the natural environment.

A method using uniquely outdoor measurements with increased system voltage to provide acceleration is also given; for this, see 5.2.6.

NOTE Magnitude of leakage current itself is not a universal indicator of susceptibility or damage to the module. It is however useful as relative indicator of rate of some PID mechanisms when comparing the PID stress on a given design over various environments.

This subclause gives apparatus including two basic configurations for applying system voltage bias, requirements for monitoring current transfer, and methods for mounting modules. Such outdoor tests entail apparatus not within usual norms and constraints for PV systems, and as a result, handling and access shall be limited to trained electrical workers.

Module characterization includes module diagnostics (electroluminescence, maximum power determination at low light) as optional procedures which will aid in identifying the nature of any power loss of the modules incurred over the duration of the testing.

5.2.2 Apparatus

5.2.2.1 Mounting

Two mounting angles are defined as follows. The configuration or configurations used in this test may be chosen in view of the following considerations.

a) Horizontal: for modules that may be mounted horizontally in the field. This configuration is generally considered most stressful because water may accumulate on the superstrate.

b) Latitude tilt: for modules whereby mounting them horizontally voids manufacturer warranty.

Module mounting shall be ground mount using an open rack (with free air flow around the modules) and on ground (e.g., soil, sand, dirt) that is level (not concrete or asphalt) with an elevation of 0,75 m to 1,00 m from ground to lowest point of the module to achieve representative transpiration of humidity from the ground.

5.2.2.2 Electrical connections

Insulated wire rated for the intended test voltage; module manufacturer-specified or stainless-steel hardware for electrical connection to the modules.

5.2.2.3 Method for measuring irradiance

A method for measuring global horizontal irradiance is required. Implement and mount a Class B or Class A irradiance sensor for measuring global horizontal irradiance according to IEC 61724-1 placed within 25,0 m of the PV modules be analysed.

5.2.2.4 Voltage bias

A method for applying module nameplate rated system voltage with tolerance of 5 % to the cell circuit of the module when global horizontal irradiance is greater than 10 W/m². In conjunction with the requirements for number of samples indicated in Clause 4, the apparatus for controlling voltage bias to modules shall include connections:

a) at nameplate rated system voltage for two modules for each polarity to be measured biased;
b) with one of the polarities connected to ground, a configuration where all modules to be tested outdoors are unbiased and have one polarity connected to ground
   - for two outdoor control modules
   - for all the modules undergoing the outdoor preconditioning step (5.2.5.3).

An array of PV modules may be used for as a source for application of voltage bias if they are measured to apply voltage bias to modules under test in a manner that meets the above requirements of this subclause.

5.2.2.5 Method for maintaining modules mounted outdoors at maximum power

This may include load resistors, electronic maximum power trackers, or electronic loads, such that the module power is maintained within at P_{max} optimized in the range of 200 W/m² to 800 W/m² irradiance on the plane of the module. If performing the test at low light per 5.2.6.3.2.3, then select the load to maintain within 25 % of P_{max} for the selected irradiance level.

5.2.2.6 Method for current-voltage measurements

Method for measuring current-voltage measurements of the modules under test as described in IEC 60904-1.

5.2.2.7 Measuring voltage bias and current transfer to ground

5.2.2.7.1 General

Requirements for measuring applied voltage and current transfer to ground are described. The voltage measurement shall be capable of resolving the voltage bias on the module or modules within 2,5 V. The current measurement shall be capable of resolving current from the modules under test with resolution of 1 x 10^{-8} A. The voltage bias and current measurement interval associated with each module shall be 1 min or less. Measurement of current to ground on unbiased modules is optional. The upper range of current measurement will be larger as system voltages and module size increases.

NOTE 1 x 10^{-4} A upper limit for current measurement between module and ground is found sufficient for presently shipping commercial modules in most environments.

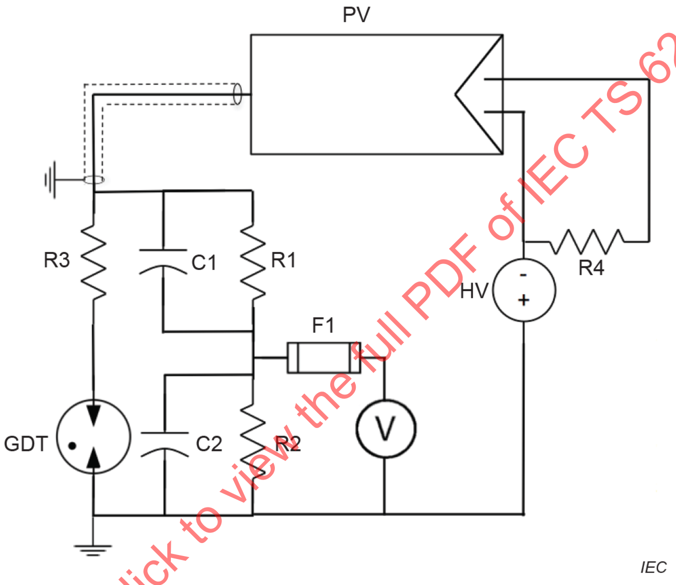
Example circuits for electrical loading, application of system voltage bias, and evaluation of the current transfer between module and ground is shown in Figure 1 and Figure 3. The example circuits may require modification to achieve the requirements of this document, depending on the module type.

Optionally, sensors and data logger for recording the environmental conditions (air temperature, relative humidity), module temperatures to an accuracy of ± 1,0 °C, of modules in 1 min or lesser intervals may be employed. Temperature sensors and their wires mounted to the module shall be electrically insulating at all applied temperatures and humidity levels so that they do not impact the voltage bias and leakage current that is measured from the module.

5.2.2.7.2 Monitoring the ground return current

Figure 1 shows a circuit for monitoring current transfer, where current is measured on the ground return.

In this configuration, isolated mounting as shown in Figure 1 is required. Here, the resistor R4 shall be optimized to achieve P_{mpp} under solar irradiance of between 200 W/m² and 800 W/m². Alternatively, a power optimizer to maintain P_{mpp} under an arbitrary solar irradiance level may be implemented. High resistor values resulting from this range are sometimes selected to reduce effects of shading damage. To make the test as representative as possible, choose resistor values that lead to temperatures, leakage current, and times of wetness that mimic the module under test in an array connected to a power optimizers (maximum power point trackers) of a PV inverter.



Key

PV Photovoltaic module with grounding points or grounded mounting points connected to coaxial wire

C1, C2 Ceramic capacitor

R1 Metal film resistor

R2 Metal film resistor

R3 Metal film resistor

R4 Load for maintaining module within maximum power specified by this document

GDT Gaz discharge tube (Neon Lamp), overvoltage protection

F1 Fuse

HV System voltage bias supply

Equipment shall be selected for anticipated power applied.

Figure 1 – Circuit suitable for electrical loading, application of system voltage bias and evaluation of leakage current from the module on the ground return-side

Methods for test that require apparatus for mounting modules isolated from ground shall use electrically insulating standoff mounts rated for voltage potential of a factor of three greater than the voltage to be applied in the system. The insulator mounts shall be installed completely under the module, greater than 20 cm from the module edge to the exterior mount edge (measuring in the horizontal vector) as to minimize these isolating mounts' exposure to rain. Reference the illustration in Figure 2. The insulator mounts shall be specified for outdoor use and constructed of materials resistant to humidity absorption and weathering, for example, glazed ceramic or porcelain. Fiberglass-resin mounts are not considered suitable

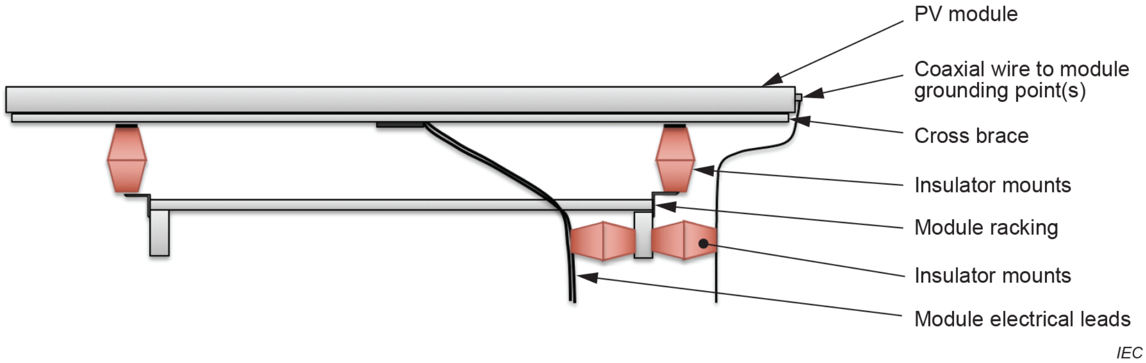
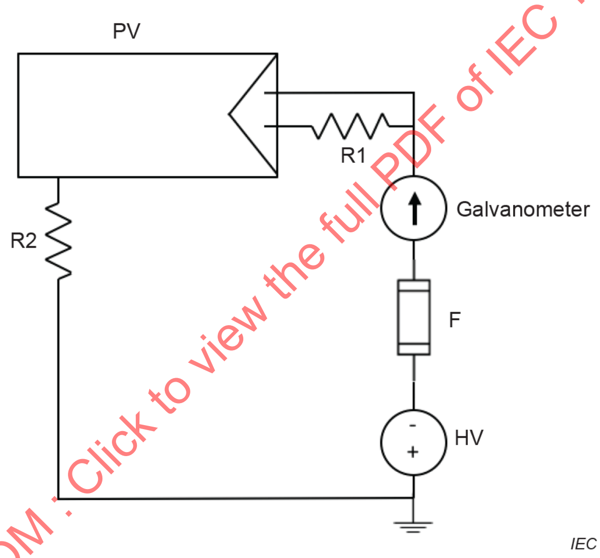


Figure 2 – Module mounting configuration for isolation and measurement of current transfer to ground

5.2.2.7.3 Voltage supply-side current monitoring

Figure 3 shows a configuration for measurement of leakage current using instrumentation on the voltage supply side. An insulation resistance testing apparatus may be used to supply system voltage bias and for measurement of current transfer when also meeting the other requirements of this document. Choice of load (R1) is in accordance with that for R4 in 5.2.2.7.2.



Key

PV Photovoltaic module with manufacturer-specified mounting and grounding
R1 Load for maintaining module within maximum power specified by this document
R2 Resistance of installation mounting
F Fuse
HV System voltage bias supply
Equipment shall be selected for anticipated power applied.

Figure 3 – Circuit suitable for electrical loading, application of system voltage bias and evaluation of leakage current from the module

5.2.3 Optional monitoring

Optional monitoring that may be useful for characterizing the modules subjected to field exposure include:

Module temperature: Temperature sensors and their wires mounted to the module shall be electrically insulating at all temperatures and humidity levels so that they do not impact the voltage bias and leakage current between the module and the intended grounding points.

Ambient temperature, relative humidity and rain. Reference IEC 61724-1.

Record such optional monitoring in the same interval as that of leakage current specified in 5.2.2.7.

5.2.4 Test conditions

Modules shall be fielded in the environment of the intended use condition, within the classifications of open-air climates in geographical areas of the world given in IEC 60721-2-1, e.g., tropical, arid, temperate, and cold, or in the specific PV field location of interest. Of these, tropical climates have the most elevated levels of temperature and humidity, which are also major stress factors for PID.

Duration of application of system voltage according to 5.2.2.4 shall be 6 months minimum, including entire periods of maximum seasonal rain and heat; and preferably one year. For at least 95 % of the selected duration of testing period, modules shall be mounted and functionally biased at the module nameplate rated system voltage in the appropriate polarity when global horizontal irradiance is greater than 10 W/m^2 only.

Considering that test conditions change with installation location and weather, the measurements obtained pertain to the particular location and the weather during the test. Uncertainty in statistical distributions will be reduced if measurements are performed longer and in various locations corresponding to the climate zone of interest.

For evaluation of suitability of the module design for any temperate climate except ocean environments or for over water applications, perform the outdoor test in the least stressful tropical climate, e.g., in a tropical climate zone bordering a temperate climate zone. Evaluate modules for ocean or for over water applications in those respective environments.

5.2.5 Procedure

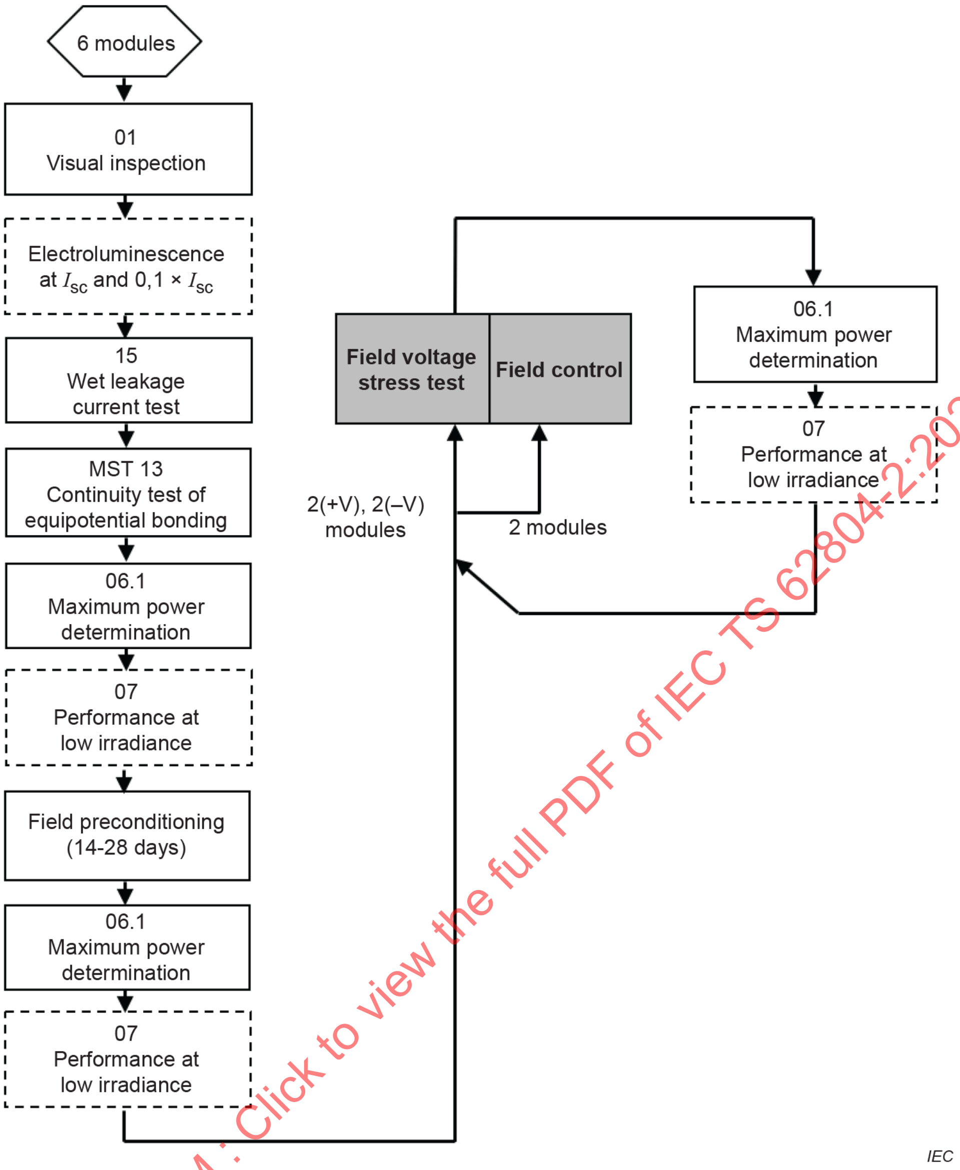
5.2.5.1 General

The testing procedure for the outdoor measurements is illustrated in Figure 4 and described below.

5.2.5.2 Pre-stress characterization

a) Perform IEC 61215-2 MQT 01 visual inspection on samples that were collected in the manner and in the quantities described in Clause 4. If there is evidence of major visual defects as defined in IEC 61215-1, then this test procedure shall be terminated or restarted at Clause 4 with different samples in a manner consistent with the requirement that modules of identical materials, construction process, and characteristics be selected for all testing of the module type.

b) Optional: Perform electroluminescence imaging according to IEC TS 60904-13 at short circuit current, I_{sc}, and at 0,1 x I_{sc}. Because I_{sc} applied for long times can affect P_{max} of some technologies (such as thin film), duration of I_{sc} application should be minimized and for not more than 120 s when imaging module technologies with such sensitivities.



Numbers refer to module quality tests (MQT) in IEC 61215-2, excepting a module safety test (MST, as indicated) which references IEC 61730-2.

Dashed line boxes indicate the step is optional.

Figure 4 – Test flow for performing PID tests in the field associated with procedures described in 5.2.2 to 5.2.5 for evaluation of coulombic transfer from the cell circuit of the module to earth

c) Perform IEC 61215-2 MQT 15 Wet leakage current test. If a wetting agent is used in the wet leakage current test, all surfaces of the modules shall be immediately and thoroughly rinsed following the wet leakage current test with water of resistivity not less than 0,05 MΩ cm that is used to generate humidity for the testing described in 5.3.2.3.2 and according to IEC 60068-2-78:2012, 4.1. In all cases, all surfaces of the module should be wiped dry with clean cotton or paper towels and not evaporatively air-dried as the final step for the goal of avoiding sediments on the module face. This test procedure shall be terminated at this point if the module does not meet the requirements of the IEC 61215-2 MQT 15 wet leakage current test.

d) Perform IEC 61730-2 MST 13 continuity test of equipotential bonding if the module has exposed conductive parts. The current for determining the resistance between conductive parts is however not specified; any current or voltage such that resistance can be evaluated may be applied.

e) Perform IEC 61215-2 MQT 06.1 maximum power determination at STC.

f) Optional: Perform IEC 61215-2 MQT 07 performance at low irradiance, including on the in-chamber control modules.

NOTE Loss of module power due to PID when associated with junction shunting of the cells is much more apparent at low irradiance. Actual worst-case irradiance conditions may be found by testing at various irradiance levels.

5.2.5.3 Field preconditioning of modules

Mount all modules outdoors, including load, with apparatus described in 5.2.2.1 and 5.2.2.4 b), maintaining all modules without external bias applied, disconnected from other modules, and according to 5.2.2.5, maintaining modules at maximum power for a minimum of 21 days. Follow manufacturer's instructions concerning module grounding.

5.2.5.4 Pre-stress characterization

Perform IEC 61215-2 MQT 06.1 maximum power determination as in 5.2.5.2e) and optionally 5.2.5.2f). If modules are dismounted for performing the maximum power determination, perform maximum power determination within 12 h of dismounting.

5.2.5.5 Application of system voltage bias

Remount modules for application of system voltage bias on one terminal of designated modules (two per polarity) and two modules with one terminal connected to ground according to 5.2.2.4b).

a) The method of the connection at the grounding point shall be based on the installation manual. For continuous metallic frames encasing the perimeter of the module that have grounding points or that have points for mounting the module that are not specified to be used on insulating mounting structures, the ground terminal of the voltage power supply shall be connected to a grounding point of the module with the manufacturer-specified grounding hardware, or if not specified, an insulated wire terminated with a crimped-on ring terminal attached with a stainless steel nut, bolt, and star washer. Thin layer coatings on the metallic frame shall be removed by abrasion to achieve metal-to-metal contact between the connector and the module frame.

b) In the case of modules with frames that are not continuous or compliant with IEC 61730-2 MST 13, non-metallic frames, and metallic frames with insulating surfaces that cannot be reasonably penetrated anywhere by abrasion, all module mounting points and grounding points available on the module shall be connected at those points of attachment to one another and to the ground terminal of the DC voltage supply with insulated wire terminated with a crimped-on screw connector and stainless steel annulus washers in contact with the module.

c) Modules without frames (frameless modules) should be tested with the supplied mounting brackets, connecting parts and materials that are consistent in every way with that specified in the module installation manual. If none are specified in the installation manual or if the specifications do not indicate a specific bracket model or materials and dimensions of mounting brackets, then the stress test shall include a conductively adhered conductive foil on the perimeter of the module that spans from the module edges to the active cell circuit. Electrical connection to the foil, which simulates a grounded module frame, is used for grounding purposes.

d) The testing shall reasonably accommodate requests by the module manufacturer to reproduce manufacturer-specified mounting configurations that could influence the electrical resistance between the module surfaces and ground; specifically, if

   1) the PV module is provided or is specified for use with an insulating structure for mounting, and

   2) the module (external body) is designed and specified not to be connected to ground, then such method of mounting the module shall be implemented to the extent possible. Further, in these cases, voltage supply-side current monitoring as described in 5.2.2.7.3 shall be implemented. The base of that structure or portion designed to be mounted to a building structure or on the ground shall be thoroughly grounded and connected to the ground terminal of the DC voltage power supply during the course of the test.

e) After mounting according to 5.2.2.1 and above-described connections of the module to load, circuit to ground, and the voltage supply circuit for application of system voltage bias, apply system voltage bias.

5.2.5.6 Calculation of coulomb transfer

Coulomb transfer in the field for each module is calculated as $(Q/t)_{field}$. Where Q is A·s measured cumulatively over the duration of the field test, and t is the number of full days (24 h periods) that the system was biased according to the test conditions in 5.2.4.

5.2.5.7 Interim and post stress characterization

At the end of the PID field test, or optionally during the course of outdoor measurements, dismount modules and perform maximum power determination in 5.2.5.2 e) and optionally 5.2.5.2 f) within 4 h of dismounting. If optional interim maximum power data points are collected during the course of the outdoor measurements and modules are to be remounted, modules do not necessarily require same day remounting but shall continue to meet the requirements of 5.2.4 and 5.2.5.5.

5.2.6 Acceleration by elevated system voltage testing outdoors

5.2.6.1 General

This method uses uniquely outdoor measurements. The PV modules under test are mounted in the intended use climate with application of voltage stress at a level beyond the nameplate system voltage rating to provide acceleration. The encapsulation of the module type is first examined for constant resistance over the system voltage range to be accelerated by means of Ohm's law. If resistance of the module package is constant within the tolerance specified in 5.2.6.3.3, the procedure given in 5.2.6.3.4 to accelerate PID by applying elevated system voltage on the modules in the use environment is permitted to be applied.

5.2.6.2 Apparatus

a) Implement either 1) or 2) from the following to evaluate linearity of leakage current through the module packaging as function of applied system voltage to the module's cell circuit:

   1) a wet leakage current test apparatus according to IEC 61215-2 MQT 15 (water resistivity control and surfactant omitted) and DC voltage source capable of applying voltage continuously in the range of 0 times to 5 times the module's IEC nameplate-rated system voltage and allowed polarities; or

   2) an outdoor apparatus as given in 5.2.2 and 5.2.3 (5.2.3 is not optional when implementing this method), with the additional requirements of a 45° ± 10° module tilt from horizontal and sufficient clearance for the water spray specified below, a DC voltage source capable of applying voltage continuously in the range of 0 times to 5 times the module's IEC nameplate-rated system voltage and allowed polarities, and the additional capability of applying spray to simulate rain or condensation with flow rate of 0,25 l/min to 0,65 l/m per square metre of module surface uniformly on each face of the module. An example spray head is Spray Systems Co. standard nozzle type 1/8 GG-1 with a spray angle of about 55°. When using 250 kPa water pressure, it covers a circle of more than 1,4 m diameter at a working distance of 1,33 m, so two nozzles would be sufficient of a module of 1 m x 2 m dimension[2]. Alternatively, a spray nozzle of the type that is used to verify protection against spraying and splashing water in IEC 60529, with second characteristic numerals 3 and 4 operated at 100 kPa water pressure may be used with similar working distance and area. Water may be controlled to spray intermittently using a solenoid with a period of 30 s or less if desired to achieve the above specified flow rate with the chosen nozzle type.

   For both these methods, equipment to measure leakage current through the module packaging associated with application of the applied voltage, such as given in Figure 1, Figure 2 and Figure 3, and temperature of the modules in an electrically isolated manner, such as with an insulating polymer-coated thermocouple, is required.

b) An apparatus and setup described 5.2.2, 5.2.3 (not optional when implementing this procedure) and 5.2.4, which gives the requirements for mounting the module in the

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[2] Spray Systems Co. standard nozzle type 1/8 GG-1 is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

environment of the intended use condition, with the additional requirement of the DC voltage source capable of applying 5 times the module's IEC rated nameplate system voltage and allowed polarities for testing over the course of 1 year duration.

5.2.6.3 Procedure

5.2.6.3.1 General

Procedures are given to evaluate linearity of leakage current through the module encapsulation as function of applied system voltage. Such linearity as determined by the procedures described in 5.2.6.3.2 is a requirement for evaluation in 5.2.6.3.3. These are followed by a procedure to evaluate leakage current under elevated system voltage bias over the long term in the use environment in 5.2.6.3.4.

5.2.6.3.2 Measurement of leakage current

5.2.6.3.2.1 General

For each polarity to be tested, select two representative modules at random from those selected in Clause 4. Perform either the method in 5.2.6.3.2.2 or the method in 5.2.6.3.2.3. Samples implemented for this procedure are permitted to be reuses in other tests given in this document.

5.2.6.3.2.2 Method using IEC 61215 MQT 15 wet leakage current test apparatus

Using the apparatus described in 5.2.6.2 a 1) apply the procedure in IEC 61215 MQT 15 with the selected module(s) with the following modifications. After applying the voltage with the test equipment to maximum nameplate-rated system voltage of the module, maintain the voltage at this level for 2 min to 10 min and then determine the current or electrical resistance between the active cell circuit and ground; then increase the voltage level and maintain the voltage for same (fixed) duration used the first time. Proceed to repeat the measurements at two, three, four and five times the rated maximum system voltage of the module. If in-rush during application of voltage causes excessive current draw or power supply circuit breaker activation, ramp rates to the system voltage level increments shall be reduced.

5.2.6.3.2.3 Method using outdoor apparatus

Using two modules and the apparatus and method specified in 5.2.6.2 a 2), select a single module temperature and single measured irradiance incident on the module and maintain that temperature within ± 4 °C and irradiance incident on the module within ± 100 W/m^2 for the collection of valid data for this test. The test may be repeated on the same set of modules as necessary and data selected out of a larger data set to obtain data conforming to the required tolerance.

NOTE Maintaining tighter tolerance for temperature and irradiance facilitates meeting the resistance linearity requirements.

Proceed with applying voltage to the cell circuit of the module with levels and duration described in 5.2.6.3.2.2.

5.2.6.3.3 Evaluation of linearity of leakage current

Plot measured current level transferred as a function of the five applied voltage levels and apply a fitting line by minimization of the least squares to the first three low voltage points, also coercing the line through the origin. If the differences of the currents measured in the fourth and the fifth points differ from that predicted by the line by more than 50 %, then the module type is not permitted to be tested outdoor under elevated system voltage bias in that polarity according to 5.2.6.3.4.

5.2.6.3.4 Accelerated testing outdoors under elevated system voltage bias

a) Mount module in the climate to be analysed according to 5.2.4, implementing the apparatus requirements introduced in 5.2.6.2 b), including outdoor controls discussed in 5.2.2.4 to measure the extent of power change that the modules may incur for reasons other than PID. Perform 5.2.5, the procedure for outdoor measurement for a duration of 1 calendar year, applying five times the system voltage specified therein. The calculation in 5.2.5.6 need not be performed, but leakage current shall be monitored as an indicator for continuity of application of system voltage stress.

b) After the final measurements, using fractional averages calculate the net fractional power change, which is the difference between the final power relative to that of the initial (determined after field preconditioning) of the unbiased (U) control modules, $(P_i - P_f)_U / P_{i\,U}$ and the fractional average of the final power relative to that of the initial $(P_i - P_f)_{VB} / P_{i\,VB}$ for the voltage biased (VB) modules:

$$D = (P_i - P_f)_U / P_{i\,U} - (P_i - P_f)_{VB} / P_{i\,VB} \quad (1)$$

c) Calculate the projected time t_F for the equivalent coulomb transfer in the field based on the acceleration by system voltage, for the selected failure criterion, given here for the example of failure criterion of a net fractional power change of -0,05; Y is the equivalent years tested in the field considering acceleration linearly by elevated by system voltage, for example, with 1 year of field testing at 5 times system voltage, the equivalent years is $Y = 1 \times 5 = 5$, and D, the net fractional degradation calculated in b) above.

$$t_F = -0{,}05\left(\frac{Y}{D}\right) \quad (2)$$

5.3 Test procedures – Accelerated testing in environmental chamber

5.3.1 General

This subclause describes methods for accelerated testing for the evaluation of PID, including the evaluation of change in module power due to PID and the measurement of leakage current in an environmental chamber.

In-chamber control modules that do not have voltage stress applied are tested alongside the modules to which system voltage stress is applied. Changes in power of the voltage-stressed modules are examined relative to the power changes of the in-chamber control modules to isolate the component of any loss in power associated with the voltage stress.

There are three procedures given for PID testing with system voltage applied to the module cell circuit in an environmental chamber. These are:

a) with the modules dark and unpowered as described in 5.3.2.2 and 5.3.2.3; and stress testing with current flow through the cell circuit covered in 5.3.3 and 5.3.3.3, either

b) with voltage applied across the module leads as described in 5.3.3.3.5.1 ,or

c) with low light as described in 5.3.3.3.5.2.

The different procedures for accelerated testing in an environmental chamber are described for performing PID stress tests with modules dark and unpowered in Figure 5, and for PID stress tests with current flow, either performed concurrently with the application of light bias or forward bias voltage in Figure 11.

Testing for degradation under system voltage stress in the dark may lead to greater degradation in solar modules than would occur in the field in some module types. Clarification of actual PID in such modules tested in the dark without current flow through the cell circuit may not be achieved with use of in-chamber control modules and post-stress test stabilization procedures alone. Therefore, the additional options are given for testing in a manner that better replicate the electronic state of PV modules in the natural environment, e.g., with the cell junctions biased approximately as they are under illumination. Preliminary testing to understand the behaviour of the module type under the test conditions laid out in 5.3.2.2 and 5.3.2.3 (dark and unpowered) and 5.3.3 and 5.3.3.3 (with light bias or with forward bias voltage) is recommended. Performing tests under light bias may be selected because it most closely represents the natural environment; however, performing one of the alternative and simpler tests that do not require constant illumination may be used if the modules do not show substantially poorer PID performance through that testing compared to testing under illumination. While the in-chamber control modules aid in normalizing for effects seen due to chamber accelerated test conditions, substantially different module power performance results using the dark, unpowered tests or with current flow by electrical bias applied compared with testing under illumination may yield unrepresentative PID behaviour that will confound the results and indicate incorrect application of this document.

In all test methods, the modules are placed in the environmental chamber at the eventual stress temperature, and depending on the test type, the factors of darkness, forward bias voltage, or light is applied before application of the factor of system voltage bias. This is to actuate any processes these environments might precipitate first, before the PID test, to avoid convolution with the measurement of PID if they were allowed to occur simultaneously.

An optional stabilization procedure after stress testing is given with which recovery of:

d) power associated with termination of the application of PID-inducing system voltage stress, and

e) metastability

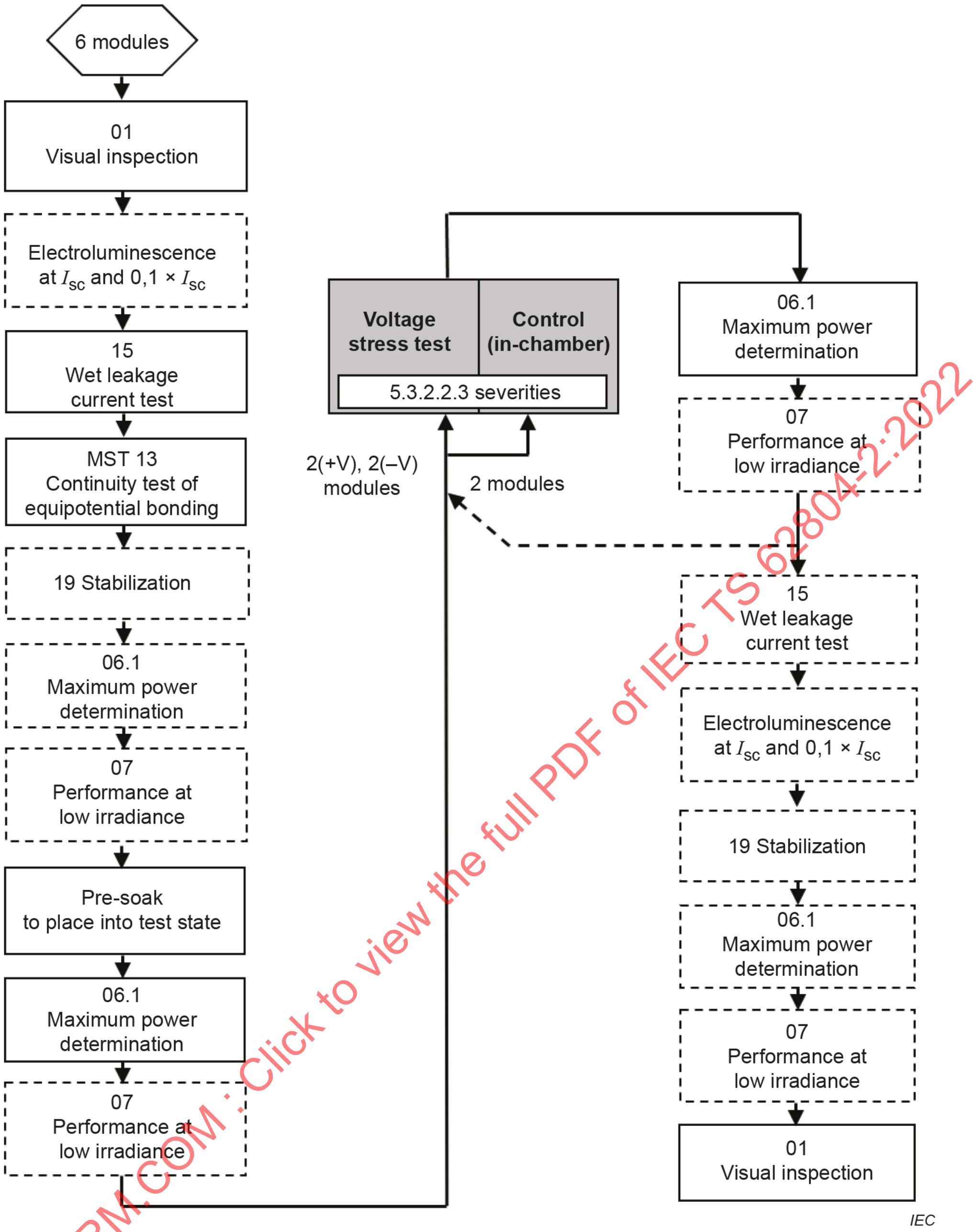
can both be independently evaluated.

The procedures given in the following clauses shall be performed in the order given. Any intended or unintended changes and deviations shall be recorded and reported in detail, as indicated in Clause 6n).

5.3.2 Test of modules in the dark and unpowered state

5.3.2.1 General

The testing procedure for modules undergoing accelerated testing in the dark and unpowered state is illustrated in Figure 5 and described below.



Numbers refer to module quality tests (MQT) in IEC 61215-2, excepting a module safety test (MST) which references IEC 61730-2.

Dashed line boxes indicate the step is optional.

Figure 5 – PID test flow for performing voltage stress test with module dark and unpowered

5.3.2.2 Initial characterization of modules and pre-stress tests for test of modules dark and unpowered

a) Perform IEC 61215-2 MQT 01 visual inspection on samples that were collected in the manner and in the quantities described in Clause 4. If there is evidence of major visual defects as defined in IEC 61215-1, then this test procedure shall be terminated or restarted at Clause 4 with different samples in a manner consistent with the requirement that modules of identical materials, construction process, and characteristics be selected for all testing of the module type.

b) Optional: Perform electroluminescence imaging according to IEC TS 60904-13 at short circuit current, I_{sc}, and at 0,1 x I_{sc}. Because I_{sc} applied for long times can affect P_{max} of some technologies (such as thin film), duration of I_{sc} application should be minimized and for not more than 120 s when imaging module technologies with such sensitivities.

NOTE 1 Electroluminescence images are useful to identify degraded cells, which appear darker than the others.

c) Perform IEC 61215-2 MQT 15 Wet leakage current test. If a wetting agent is used in the wet leakage current test, all surfaces of the modules shall be immediately and thoroughly rinsed following the wet leakage current test with water of resistivity not less than 0,05 MΩ cm that is used to generate humidity for the testing described in 5.3.2.3 (below) and according to IEC 60068-2-78:2012, 4.1. In all cases, all surfaces of the module should be wiped dry with clean cotton or paper towels and not evaporatively air-dried as the final step for the goal of avoiding sediments on the module face. This test procedure shall be terminated at this point if the module does not meet the requirements of IEC 61215-2 MQT 15 wet leakage current test.

d) Perform IEC 61730-2 MST 13 continuity test of equipotential bonding if the module has exposed conductive parts. The current for determining the resistance between conductive parts is however not specified; any current or voltage such that resistance can be evaluated may be applied.

e) Optional stabilization shall be according to IEC 61215-2 MQT 19 followed by IEC 61215-2 MQT 06.1, Maximum power determination, and also optionally by IEC 61215-2 MQT 07, Performance at low irradiance, including the in-chamber control modules.

NOTE 2 In addition to any optionally applied IEC 61215-2 MQT 19 Stabilization performed, a pre-soak is performed to activate any temperature dependent changes that may occur in the module during the PID tests, before performing the PID stress test.

f) Perform pre-soak to place modules into a dark state. The conditions for the pre-soak are 85 °C ± 2 °C and less than 5 % relative humidity. 96 h is the nominal duration to actuate any rapidly occurring thermally-activated transients in power before the module is placed in the dark for the eventual PID stress test. It is not necessary to eliminate module power transients completely during this process. This pre-soak step may be omitted if it can be shown that the in-chamber control modules in the subsequent application of the PID stress test each exhibit less than 3,0 % relative change in power.

If the severity temperature chosen for PID stress testing in 5.3.2.3.3 is 85 °C, the pre-soak period may be reduced in length below 96 h if the initial transients are substantially eliminated sooner. The following formula shall be taken as the criterion to assess whether each module has reached its stabilized electrical power output.

$$(P_{\text{max}}-P_{\text{min}}) \;/\; P_{\text{average}} < 0{,}02 \qquad (3)$$

Here, P_{max}, P_{min} and P_{average} are defined as extreme values of three consecutive output power measurements P1, P2 and P3 by measuring I-V curves, either with IEC 61215-2 MQT 06.1 at STC, or forward bias I_d V curves in the dark at the 85 °C ± 2 °C temperature.

If performing forward bias I_d V curves in the dark, measure to the magnitude of I_{sc} for each module in 24 h intervals during pre-soaking at the pre-soak temperature and translation of the obtained current values, I_d to the first quadrant by $I = -I_d + I_{sc}$ (I_d is the current through the module when in forward bias in the dark and I_{sc} is taken from the module nameplate). Maximum power P is taken from the $|I \times V|$ product where it is a maximum.

If removing modules from pre-soak for measurement by IEC 61215-2 MQT 06.1 at STC, modules shall be kept in the dark with a blanket or cover and tested according to IEC 61215-2 MQT 06.1 within 4 h from reduction from pre-soak temperature and returned to pre-soak temperature within 18 h of reduction of the pre-soak temperature.

If the severity temperature chosen for PID stress testing in 5.3.2.3.3.4 is less than 85 °C, do not apply Formula (3) for the evaluation of shortening the pre-soak time; Instead apply the eventual chosen PID stress temperature severity for the last 36 h to 48 h of the 96 h pre-soak step.

g) Perform IEC 61215-2 MQT 06.1 maximum power determination at STC, including on the in-chamber control modules; however, if this procedure (at STC) was performed as the last stage of item f) above, the value obtained from that test may instead be used for the purpose of not repeating maximum power determination at STC .

h) Optional: Perform IEC 61215-2 MQT 07 performance at low irradiance, including on the in-chamber control modules.

NOTE 3 Loss of module power due to PID when associated with junction shunting of the cells is more apparent at low irradiance. Actual worst-case irradiance conditions may be found by testing at various irradiance levels.

5.3.2.3 Voltage stress tests

5.3.2.3.1 General

5.3.2.3 describes a method whereby the modules are placed at stress temperature in darkness, unpowered, with added humidity, and system voltage bias applied as illustrated in Figure 6. 5.3.3 describes alternative methods where light bias or forward bias voltage is additionally applied to the modules during the course of voltage stress testing. Modules shall undergo procedures described in either 5.3.2.3 or one of the procedures in 5.3.3.

5.3.2.3.2 Apparatus

a) DC voltage power source capable of applying the maximum system voltage in the designated polarity of the modules under test with sufficient current to maintain the set-point voltage with tolerance of 1,0 % and an appropriate device for resolving and monitoring the leakage current through the module encapsulation to 10 nA within 5 % accuracy.

b) Insulated wire rated for the intended test voltage, temperature, and humidity; module manufacturer-specified or stainless steel hardware for electrical connection to the modules.

c) Sensors and data logger for recording the environmental conditions (chamber air temperature, relative humidity), module temperatures to an accuracy of ± 1,0 °C in a manner that demonstrates uniformity over the modules in the testing space, and leakage currents (optional: applied bias voltage) of each module in 1 min or lesser intervals. Temperature sensors and their wires mounted to the module shall be electrically insulating at all applied temperatures and humidity levels so that they do not impact the voltage bias and leakage current from the module.

NOTE 1 Current and voltage measurement and their recording are intended as indicators of stability, uniformity, and continuity of the stress test conditions and not intended as performance criteria for the module under test.

d) An environmental chamber capable of controlling temperature and humidity independently to achieve the stress levels for the test, with requirements for the test chamber and its usage given in IEC 60068-2-78:2012, 4.1 and 4.4, respectively; however, this document shall supersede where conditions and specifications differ. Module supports that are non-porous (less than 0,02 % weight gain over the course of the stress test) in the test environment and that are electrically insulating at the test conditions (electrical resistivity greater than 1 x 10^{17} Ω -cm). Module support parts shaped to minimize contact area and thus current transfer with the module are to be used.

NOTE 2 Glazed porcelain and polytetrafluoroethylene with minimized module contact area are examples of suitable electrical insulators.

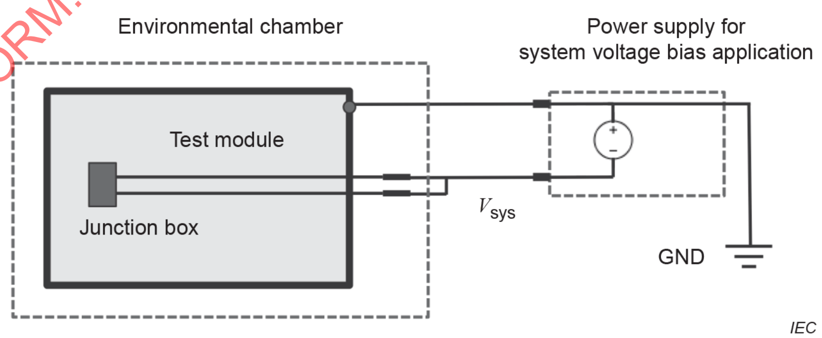


Figure 6 – Apparatus for applying system voltage bias (V_{sys}) to a PV module in an environmental chamber

5.3.2.3.3 Severities

5.3.2.3.3.1 General

Current transfer through the module packaging is a dominant factor leading to PID. It increases as a function of surface conductivity on the module surface from moisture and is found to increase with temperature in an Arrhenius manner. Several options are given for configuration of the acceleration and achieving field representation. Trade-offs are discussed in the following subclauses.

5.3.2.3.3.2 Damp heat

Damp heat testing without modification of the module, as described in the following clause, is possible if there is no or little insulation between the grounding points, frame and module glass. In this configuration, the conduction path for the accelerated testing of PID may be enabled by adsorbed humidity on the insulation or, in some cases, the higher ionic conductivity at the elevated test temperature of the insulation between the grounded frame or grounded mounting points and the glass.

5.3.2.3.3.3 Damp heat with edge insulation defeated

A damp heat test with edge insulation defeated is advised for achieving higher acceleration in the chamber when there is insulation between the grounded parts and module superstrate or substrate, that in the presence of condensed moisture and soiling as occurs in the natural environment, would have its surface insulation resistance reduced. This method of applying voltage stress may also be used if it is desired to increase the current transfer between the active cell circuit and ground. This method is offered as an option for higher acceleration in the chamber test; it is not required.

Place conductive tape with electrically conductive adhesive of 5 mm ± 2 mm width on the glass module superstrate and substrate nearest to where grounded metallization exists that may become electrically connected to the superstrate or substrate when there is condensed moisture. For a fully framed module, this may be on the entire perimeter of the module face. For a module specified for use with edge clips or clamps, this would correspond to the length of the metal portion of the edge clamps. It may also include parts of the module where water might sit for extended periods of time or surfaces where soil accumulates. Make the tape narrower (e.g, 3 mm), as necessary, to avoid placing this tape on glass over the active cell area. Perform the procedure maintaining dimensions and offsets within 1 mm tolerance to achieve repeatability. Changes to such dimensions represents a change in the severities, and a different test condition as a result. The conductive tape is not placed on non-glass superstrates or substrates but is placed on both sides of modules having both glass superstrates and substrates. The conducting tape segments are electrically connected together and grounded.

NOTE This procedure is for acceleration of coulomb transfer of in-chamber modules to compensate the lack of condensed humidity and soiling that occurs in the natural environment. Examples where this procedure might be chosen are given in the academic literature [1], *i.e.,* for high resistance EPDM (ethylene propylene diene monomer) rubber used between the glass-faced module laminate and metallic mounting clips that are grounded. Because the natural environment does have condensed humidity and soiling, preparing modules with conductive tape with electrically conductive adhesive for outdoor testing is not required. The placement of conductive tape on the module glass for chamber tests provides an acceleration over what one would get with the highly insulating mounts. This acceleration is measured and accounted for by examination of the relative magnitude of coulomb transfer between module and ground in the chamber testing and in the field testing.

5.3.2.3.3.4 Chamber test conditions

The prescribed severities for test are:

- Module temperature: 45 °C ± 2 °C, 60 °C ± 2 °C or 85 °C ± 2 °C.
- Module surface relative humidity: 85 % ± 3 % or 95 % ± 3 % relative humidity.
- Voltage: module rated system voltage and polarities.

95 % relative humidity setpoint may be selected to achieve higher surface conductivity to produce current transfer approaching a wet module in the field and when the environmental chamber is capable of maintaining the level to the specified tolerance, without leading to condensation on the module. Lower temperature may be chosen to increase the ratio of conduction of glass face to that of glass bulk, and to approach and therefore better represent the module operating in the natural environment, however, a longer time will be required to achieve similar coulomb transfer.

See Annex B, Table B.1 for limitations with respect to conditions that may require high chamber ambient relative humidity conditions that are difficult for climatic chambers to achieve or that are likely to precipitate unwanted condensation when attempting to achieve certain module surface relative humidity levels.

If the procedure for grounding the modulein 5.3.2.3.3.3 is implemented, use the module temperature severity of 45 °C to prevent excessive through-glass conduction.

5.3.2.3.3.5 Durations

Referencing Figure 7, there are two parameters of duration specified.

– X: the duration between the time both the module temperature and the module surface relative humidity have reached the specified severity and the application of the module rated system voltage is applied. This shall be a minimum of 12 h and a maximum of 24 h to allow the chamber and modules to come to equilibrium.

  NOTE The time period X serves as a stabilization time to achieve temperature equilibrium in the chamber and its contents before humidity is introduced, to minimize condensation.

– Y: the duration of application of module rated system voltage, specified temperature, and module surface relative humidity severities.

  The module rated system voltage shall be additionally applied during ramp down of temperature to ambient conditions and not considered in the duration parameter Y.

– Based on the coulomb transfer per day exhibited in the field expressed by $(Q/t)_{field}$, and the coulomb transfer per day in the chamber expressed by $(Q/t)_{chamber}$, the duration in days, Y, in the chamber is estimated using Formula (4):

$$Y = n_{field} \times \frac{(Q/t)_{field}}{(Q/t)_{chamber}} \qquad (4)$$

  where n_{field} represents the number of days in the field to be forecast in an accelerated manner. Actual duration of testing is however based on the failure criterion selected in 5.3.2.3.3.7 k), *e.g.*, 0,05, 0,10, 0,20 fractional power loss by PID, if such degradation in the chamber is measured. If $(Q/t)_{field}$ from 5.3.4.2 has been determined, Y may alternatively be calculated choosing n_{field} of 1 825 d representing 5 y in the field and using $(Q/t)_{chamber}$ collected in this subclause if power degradation of modules with system voltage applied does not exceed those of the in-chamber controls undergoing this subclause within this period.

  Current transfer between the active cell circuit and ground is highly dependent on the module type, and $(Q/t)_{field}$ may vary between module types by several orders of magnitude. Therefore, determination of the value $(Q/t)_{field}$ using the procedure in 5.2.5 is necessary.

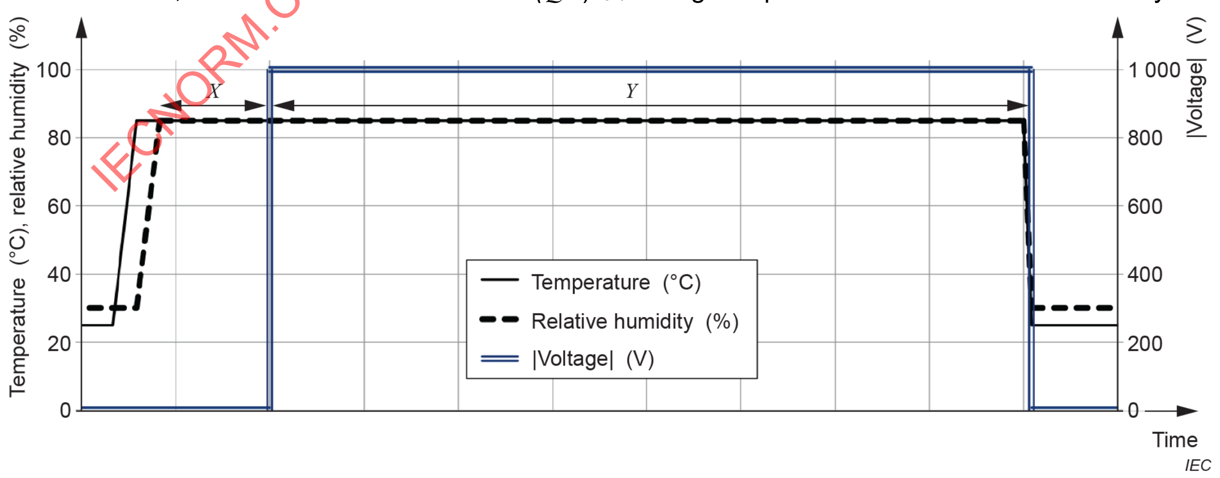


Figure 7 – Example test time-temperature-humidity-voltage profile for application of stress in an environmental chamber

5.3.2.3.3.6 Environmental chamber control and tolerances

The ramps to and from the stress conditions and the stress test itself shall be performed in a continuous and uninterrupted manner excepting for handling of interim measurements, with timelines and temperatures indicated in 5.3.2.3.3.7k).

The total temperature tolerance of ± 2 °C is intended to take account of absolute errors in the measurement, slow changes of temperature, and temperature variations of the working space. However, to maintain the relative humidity within the required tolerances, it is necessary to keep the temperature difference between any two points in the working space at any moment within narrower limits. The required humidity conditions will not be achieved if such temperature differences exceed 1 °C. It may also be necessary to keep short-term fluctuations within ± 0,5 °C to maintain the required humidity. The chamber and module loading configurations within the chamber shall be characterized for achieving the required severities and tolerances at the various positions within the test space.

5.3.2.3.3.7 Procedure

a) The modules shall be placed into an environmental chamber supported by the non-porous electrically insulating mounting material. Modules shall be placed by default in any upright position; however, this placement may be changed if it is helpful to better achieve the intended goals of this test method, including improved air circulation, temperature and relative humidity uniformity, tolerances, and set points, or implementation of the module's specifically documented mounting or grounding instructions.

b) The insulator mounts shall be used to prevent alternative paths for leakage current between the biased active cell circuit and the intended ground points where current detection circuitry may be connected, and for the safety of personnel and equipment. The insulation of the individual modules from each other is also required to control the path to ground and to insure correct voltage potential on the modules.

c) The method of the connection at the grounding point shall be based on the installation manual. For continuous metallic frames encasing the perimeter of the module that have grounding points or that have points for mounting the module that are not specified to be used on insulating mounting structures, the ground terminal of the voltage power supply shall be connected to a grounding point of the module with the manufacturer-specified grounding hardware, or if not specified, an insulated wire terminated with a crimped-on ring terminal attached with a stainless steel nut, bolt, and star washer. Thin layer coatings on the metallic frame shall be removed by abrasion to achieve metal-to-metal contact between the connector and the module frame.

d) In the case of modules with frames that are not continuous or compliant with IEC 61730-2 MST 13, non-metallic frames, and metallic frames with insulating surfaces that cannot be reasonably penetrated anywhere by abrasion, all module mounting points and grounding points available on the module shall be connected at those points of attachment to one another and to the ground terminal of the DC voltage supply with insulated wire terminated with a crimped-on screw connector and stainless steel annulus washers in contact with the module.

e) Modules without frames (frameless modules) should be tested with the supplied mounting brackets, connecting parts and materials that are consistent in every way with that specified in the module installation manual. If none are specified in the installation manual or if the specifications do not indicate a specific bracket model or materials and dimensions of mounting brackets, then the stress test shall include a conductively adhered conductive foil on the perimeter of the module that spans from the module edges to the active cell circuit. The foil, which simulates a grounded module frame, is connected to the ground terminal of the DC voltage supply.

f) The testing shall reasonably accommodate requests by the module manufacturer to reproduce manufacturer-specified mounting configurations that could influence the electrical resistance between the module surfaces and ground. Specifically, if

   1) the PV module is provided or is specified for use with an insulating structure for mounting, and

   2) the module is designed and specified not to be connected to ground.

g) Then such method of mounting the module shall be implemented to the extent possible. The base of that structure or portion designed to be mounted to a building structure or on the ground shall be thoroughly grounded and connected to the ground terminal of the DC voltage power supply during the course of the test.

h) Positive and negative electrical terminal wires (leads, tags, studs, screws, connectors) of the module shall be connected to one another and to the appropriate energized DC voltage terminal of the power supply with insulated wire rated for the intended test voltage. The control modules placed in the environmental chamber shall not have these electrical connections.

i) Stresses are applied to the module in chamber according to the severities listed in 5.3.2.3.3 referencing the example profile in Figure 7. Recording of sensor data shall be commenced. The chamber temperature shall be ramped from ambient to the specified stress temperature. When the chamber air temperature and the module temperature reach the set point within tolerance, increase the relative humidity to arrive at the prescribed severity. The start of the time duration X is when the temperature and relative humidity set points are reached within the prescribed tolerances. At the end of this period, switch on the voltage to the prescribed stress level (rated maximum system voltage and polarity) to start the duration Y. The prescribed dwell period begins when the voltage has arrived at the prescribed severity. See item f) for the case of interruptions for removal of the module for interim maximum power measurements or other reasons.

j) For the cooling phase to ambient temperature (25 °C or less) at the end of the damp heat dwell, turn off the humidity generation and simultaneously begin to cool the chamber so that the modules reach the ambient temperature in a maximum of 1 h. The specified applied voltage shall be switched off when the module temperature reaches 25 °C ± 5 °C.

k) For removal to obtain interim measurements of module maximum power during the course of accelerated testing to characterize the degradation as a function of stress time. The chamber is cooled according to item e), above, after which modules (in-chamber controls and those under voltage bias stress) are removed for IEC 61215-2 MQT 06.1 maximum power determination between 2 h and 6 h after removal. If the modules are to be returned to chamber, they shall be returned for application of the stress within 10 h after the completion of item e).

l) Degradation of each module associated with the application of the system voltage stress is evaluated with respect to the average of the unbiased controls to isolate the degradation due to the applied system voltage. The fraction power loss P_{r_i} at test interval i attributed to PID is calculated as the fraction change in power for a module under system voltage bias relative to the unbiased controls with formula (5),

$$P_{r_i} = \frac{1+\frac{P_{\max \mathrm{VB}_i} - P_{\max \mathrm{VB}_0}}{P_{\max \mathrm{VB}_0}}}{1+\frac{\bar{P}_{\max \mathrm{c}_i} - \bar{P}_{\max \mathrm{c}_0}}{\bar{P}_{\max \mathrm{c}_0}}} - 1 \qquad (5)$$

where

$P_{\max \mathrm{VB}_i}$ is the power of the module under system voltage bias.

The power of each corresponding module right before the start of application of system voltage stress is $P_{\max \mathrm{VB}_0}$. The average power of the unbiased in-chamber control modules is $\bar{P}_{\max \mathrm{c}_i}$ which is normalized to that determined directly preceding the application of system voltage stress, $\bar{P}_{\max \mathrm{c}_0}$.

m) While interim measurements of module maximum power are not specifically required, it will be highly beneficial to obtain them so that the transferred charge corresponding to the chosen threshold degradation levels (e.g., 0,05, 0,10, or 0,20) can be more clearly observed and reported.

5.3.3 Testing in chamber with light bias or current

5.3.3.1 General

Subclause 5.3.3, with references to commonalities in previous clauses, describes tests where either light bias or forward bias voltage is applied to cells in the modules during the course of voltage stress testing. Levels of voltage or irradiance are maintained less than or equal *to* V_{Pmax}

or 200 W/m², respectively, but will likely need to be set lower to achieve the specified severities of module surface relative humidity that shall be maintained (See Annex B). A pre-soak procedure is additionally applied to put the cells in the module in a similar light bias or forward bias state, and to minimize changes associated with metastability that the modules may display during the course of the testing. Despite these procedures, there can still be changes in module performance not associated with PID. Therefore, modules under voltage stress are compared with in-chamber control modules which are similarly biased with light or forward voltage, but without the nameplate-rated system voltage bias, to evaluate the power performance changes associated with PID. An optional stabilization procedure before and after stress testing is given with which recovery of power associated with termination of the application of PID-inducing system voltage stress and metastability can be both independently evaluated.

Optimization of settings of temperature and relative humidity will be required with application of light or current to maintain the module at the specified temperature and relative humidity. The procedures for achieving specified conditions shall be performed within the first 12 h of the X duration period defined in 5.3.2.3.3.

5.3.3.2.2 describes the apparatus for implementing forward bias voltage. 5.3.3.2.3 describes the apparatus for implementing light bias. Considering that power is being applied to the module by light or current, the method to compensate chamber temperature and relative humidity to maintain the module surface according to the specified severities is given in 5.3.3.2.4. The apparatus and procedures for testing in chamber with light bias or forward bias voltage follow.

5.3.3.2 Apparatus

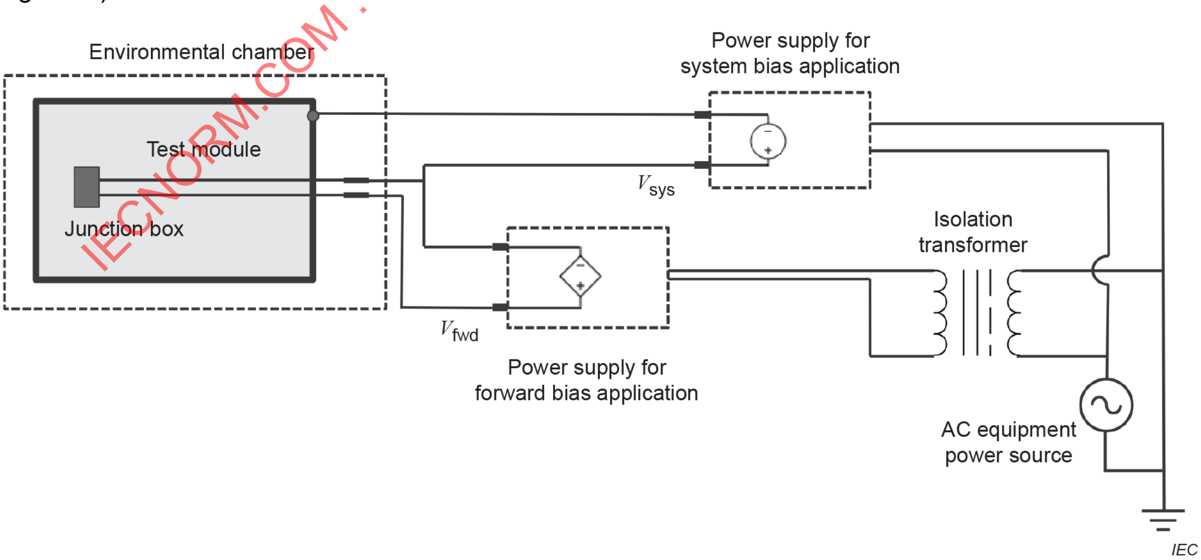
5.3.3.2.1 General

In addition to the apparatus described in 5.3.2.3.2, apparatus described here is required for applying the stress test with forward bias voltage or light bias.

5.3.3.2.2 Apparatus for application of forward bias voltage

Power supplies for application of forward bias voltage in the cell circuit of each of the modules undergoing voltage stress testing in the damp heat environmental chamber are required if it is desired to apply forward bias voltage during the testing for PID.

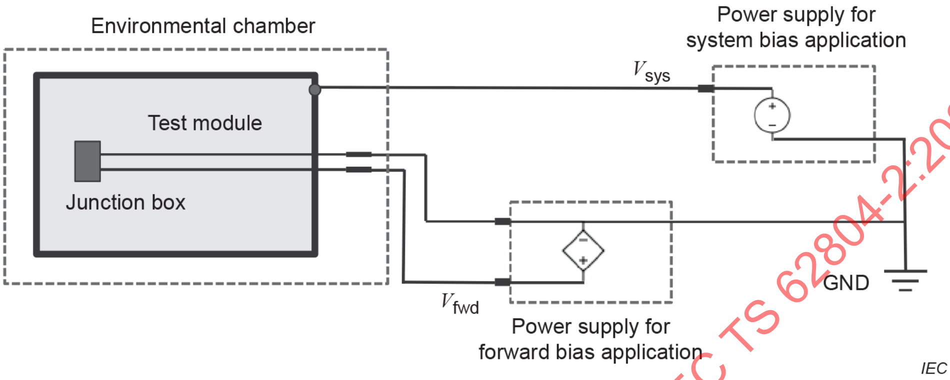
In one configuration, the power supply for application of forward bias voltage is isolated by an isolation transformer and one DC terminal of the forward biasing power supply is connected to the system voltage terminal of the power supply for application of the system voltage bias (see Figure 8).



The system voltage (V_{sys}) applied to the active cell circuit as shown is positive.

Figure 8 – Schematic for isolated power supply for application of forward bias voltage (V_{fwd})

In an alternative configuration, system voltage is applied to the normally grounded module frame, grounding, or mounting points and the power source for forward bias voltage application has one DC terminal tied to ground (see Figure 9). The system voltage bias applied to the module grounding points is applied in the polarity to achieve the same electric field direction as would occur in fielded PV system. These grounding points for the module shall be electrically isolated from the environmental chamber to accurately monitor leakage current through the module laminate and to prevent overloading of the power supply applying system voltage. A safety interlock that turns off the power supplies for the application of system voltage bias to the module frames is a requirement for safety for this configuration.



The system voltage applied to the active cell circuit is negative and forward bias voltage is applied through the cell circuit.

Figure 9 – Schematic for application of system voltage (V_{sys}) bias on test module on normally grounded parts

5.3.3.2.3 Apparatus for application of irradiance

In addition to the apparatus described in 5.3.2.3.2, light sources for application of irradiance on each glass surface of the module undergoing voltage stress testing in the damp heat environmental chamber are required if it is desired to apply irradiance during the testing for PID. The apparatus shall be capable of applying the irradiance level selected for application on the module, which may be in the range of 5 W/m² to 200 W/m² with deviation over the face not exceeding plus or minus 20 % the nominal applied irradiance on each glass surface of the module. Any wavelength of the solar spectrum may be applied, but it may not exceed 20 % of the global spectral irradiance according to IEC 60904-3 at any wavelength.

The primary purpose of application of light during the PID test is to place the cells under an electric field as they normally are in the use condition. However, for some PID mechanisms, it may be desirable to ensure that the UV component of the IEC 60904-3 spectrum is contained for better representation of the solar spectrum and its effect, especially in PV modules that contain photoconductive layers above the electrically active absorber layer which may slow the rate of PID.

The modules under light bias are connected to the electrical circuit as shown in Figure 10. Resistor R_B of 5 000 Ω ± 1 000 Ω is placed in the circuit as shown to approach V_{oc} condition under low light while maintaining similar severities (system voltage level stress) over both electrical terminals of the module, to approximate to the junction potential of V_{Pmax} under higher illumination levels.

NOTE The above-specified value of R_B is suited for most technologies available on the market to approach V_{oc} condition under low light.

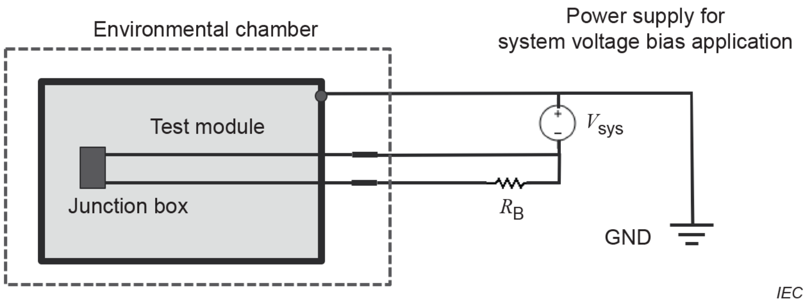


Figure 10 – Apparatus for applying system voltage bias (V_{sys}) to a PV module in an environmental chamber under light bias

Place sensors that are electrically isolating at the chamber stress test conditions for monitoring temperature at three points on each module according to locations given in IEC 61853-1:2011, Figure 1; however, place the temperature measurement sensors covered by aluminium tape, each no larger than 1 cm x 1 cm on the module glass on the side facing light bias.

5.3.3.2.4 Setting temperature and relative humidity

When applying current or light on the module, it will be necessary to adjust chamber temperature so that the module temperature at all measurement points is maintained at the selected stress test conditions specified in 5.3.2.3.3.

Adjust relative humidity of the chamber so that the module surface relative humidity is maintained at the specified severities given in 5.3.2.3.3. To achieve this, calculate the required dew point (T_d) for the modules under irradiance and temperature specified in 5.3.2.2.3 by formula (6),

$$T_d = \frac{243{,}04 \times \left(\ln\left(\frac{RH}{100}\right) + \left(\frac{17{,}625 \times T}{243{,}04 + T}\right)\right)}{17{,}625 - \ln\left(\frac{RH}{100}\right) - \left(\frac{17{,}625 \times T}{243{,}04 + T}\right)} \quad (6)$$

where

T is the module temperature (°C), and

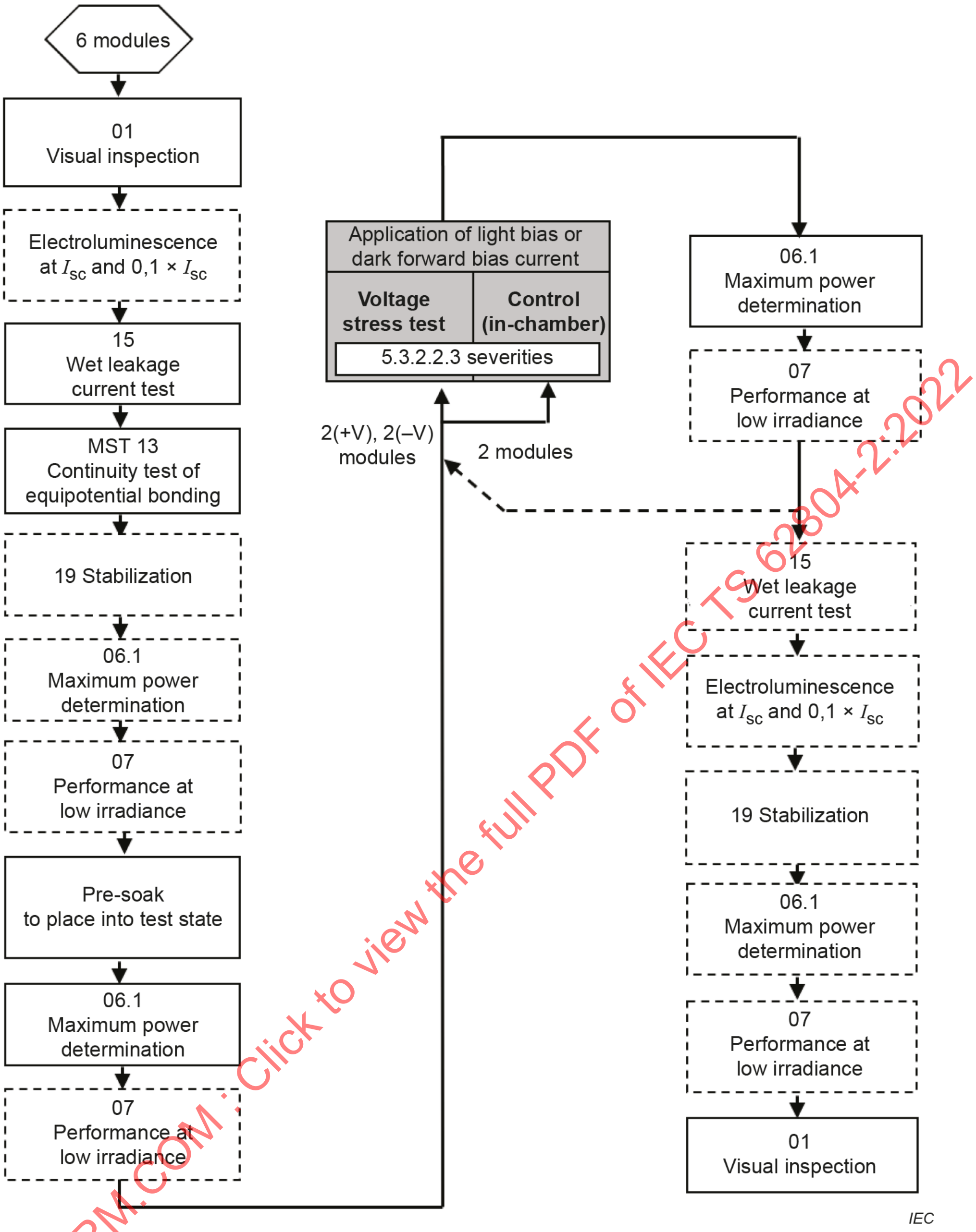
RH (%) is the module surface relative humidity to be achieved according the severities specified in 5.3.2.3.3.

NOTE For the severities of 85 °C and 85 % relative humidity, T_d = 81,0 °C.

Following, determine the chamber relative humidity required to maintain the dew point T_d. Calculate and make adjustments to achieve the required chamber relative humidity according to the determined T_d and the chamber temperature (T_c) at which the modules are maintained at the temperature specified in 5.3.2.2.3 by formula (7),

$$RH[\%] = \frac{100 \times e^{\left(\frac{17{,}625 \times T_d}{243{,}04 + T_d}\right)}}{e^{\left(\frac{17{,}625 \times Tc}{243{,}04 + Tc}\right)}} \quad (7)$$

Because of heating of the module associated with applying voltage on the module leads or light on the module, it will be necessary to limit the chosen applied levels (forward bias voltage V_{fwd} , irradiance, module relative humidity) and maintain air circulation sufficiently elevated, or else it will not be possible to raise the humidity level in the chamber sufficiently high to maintain the required surface relative humidity.



Numbers refer to module quality tests (MQT) in IEC 61215-2, excepting a module safety test (MST) that references IEC 61730-2.

Dashed line boxes indicate the step is optional.

Figure 11 – PID test flow for modules placed under voltage stress and with light bias or dark forward bias voltage

5.3.3.3 Procedure for stress testing with application of light bias or dark forward bias voltage

5.3.3.3.1 General

The testing procedure for modules placed under voltage stress with application of light bias or dark forward bias voltage is illustrated in Figure 11 and described below.

5.3.3.3.2 Pre-stress tests

Perform procedures in 5.3.2.2, procedures a), b), c), d), and e). Tests indicated as optional remain optional.

Pre-soak to place the module into the dark state (85 °C, and less than 5 % relative humidity) is omitted.

5.3.3.3.3 Pre-soak with application of light bias or forward bias voltage

5.3.3.3.3.1 General

Perform pre-soak to place modules into the state for test. Details concerning duration and levels are given in this subclause below.

5.3.3.3.3.2 Pre-soak duration

The conditions for the pre-soak are 85 °C ± 2 °C and less than 5 % relative humidity. Optionally, 5.3.3.3.3.3-described pre-soak bias where either forward bias voltage or light bias may be applied. 96 h is the nominal duration to actuate any relatively rapidly occurring initial transients in power that may occur at the eventual PID stress condition. It is not necessary to eliminate module power transients completely during this process. This pre-soak step may be omitted if it can be shown that the in-chamber control modules during the subsequent application of the 5.3.3.3.5 stress test that the module type exhibits less than 3,0 % relative change in power.

The pre-soak period may be reduced in length below 96 h if the initial transients are substantially eliminated sooner. Formula (3) and description for its use in 5.3.2.2f) shall be taken as the criterion to assess whether each module has reached its stabilized electrical power output. For this assessment, remove the module from pre-soak conditions and apply the method of IEC 61215-2 MQT 19, whereby output power is determined in minimum intervals of at least 20 h at the pre-soak temperature or at STC. When removing modules from pre-soak for measurement by IEC 61215-2 MQT 06.1 at STC, modules shall be kept in the dark with a blanket or cover and tested according to IEC 61215-2 MQT 06.1 within 4 h from reduction from pre-soak temperature and returned to pre-soak temperature within 18 h of from reduction of the pre-soak temperature.

Apply the eventual chosen PID stress temperature severity, forward bias level, or irradiance, according to 5.3.3.3.3.3, for the last 36 h to 48 h of the 96 h pre-soak step. This final stage may be extended if further stability is desired or required; Formula (3) and the description for its use in 5.3.2.2 f) may be used to evaluate such stability.

5.3.3.3.3.3 Pre-soak levels

a) Forward bias voltage

   For the purposes of performing pre-soak in the case of application of forward bias voltage to the module, apply forward bias voltage to the modules under test (including in-chamber controls) with application of voltage V_{fwd} up to V_{Pmax} as indicated by the module nameplate (STC) in a configuration given in 5.3.3.2.2. It is required to use the same voltage V_{fwd} during the pre-soak as will be applied in the stress test. Monitor each module temperature to maintain the temperature requirements of 5.3.2.3.3 primarily by adjusting the chamber temperature.

b) Light bias

   In the case of the PID test with application of light bias to the module, perform pre-soak either according to 5.3.3.2.3 a) or apply light to the modules under test (including in-chamber controls) in the range of 5 W/m^2 up to 200 W/m^2 and with modules in the configuration given in 5.3.3.2.3. It is required to use the same irradiance during the pre-soak as will be applied in the subsequently performed stress test under voltage bias. Monitor each module temperature to maintain the temperature requirements of 5.3.2.3.3 primarily by adjusting the chamber temperature.

5.3.3.3.4 Pre-stress test maximum power determination

a) Perform IEC 61215-2 MQT 06.1 maximum power determination at STC, including on the in-chamber control modules; however, if this procedure was performed as the last stage of 5.3.3.3.3, the value obtained from that test may instead be used such that it is not repeated.

b) Optionally perform IEC 61215-2 MQT 07, Performance at low irradiance, including the in-chamber control modules.

c) Maintain modules in the dark while modules wait for voltage stress tests. Note time interval requirements listed in the following clauses for the commencement of the voltage stress testing.

5.3.3.3.5 Voltage stress tests – with forward bias voltage or light bias

5.3.3.3.5.1 Voltage stress with modules under forward bias voltage

If it is chosen to perform voltage stress tests with forward bias voltage, within 12 h of performing 5.3.3.3.4, perform the procedure in 5.3.2 on modules to be tested and the in-chamber control modules, implementing 5.3.3.2.2 and 5.3.3.2.4 modifications for chamber relative humidity and the testing under forward bias current. Apply the forward bias voltage V_{fwd} used in 5.3.3.3.3.3 a) to all modules including the in-chamber control modules subjected to chosen 5.3.2.3.3 Severities during the course of the chamber test. Perform interim and final measurements of module power according to 5.3.2.3.3.7k).

5.3.3.3.5.2 Voltage stress with modules under light

If it chosen to perform voltage stress tests under illumination, within 12 h of performing 5.3.3.3.4, perform 5.3.2 on modules to be tested and the in-chamber control modules, implementing 5.3.3.2.3 and 5.3.3.2.4 modifications for applying light, loading modules and maintaining chamber relative humidity. Apply the light bias to all modules at the same level used in 5.3.3.3.3.3 b), including those subjected to module rated system voltage and the in-chamber control modules.

Monitor each module temperature to maintain the temperature requirements of 5.3.2.3.3 applying the procedure in 5.3.3.2.4 to maintain the module temperature and relative humidity. Interim and final measurements of module power change are performed according to 5.3.2.3.3.7 k).

5.3.3.4 Post-stress tests

a) The post-stress test procedure given hare are applicable after any of the above described PID accelerated stress test procedures in an environmental chamber.

b) Perform IEC 61215-2 MQT 06.1 maximum power determination between 2 h and 6 h after completion of 5.3.2.3, including the control module. Maintain the modules indoors at 25 °C or below and under a light-blocking blanket (< 0,1 % ambient light transmission) until ready for the maximum power determination.

c) Optional: Perform IEC 61215-2 MQT 07 performance at low irradiance, including on the control module.

d) Optional: Perform IEC 61215-2 MQT 15 wet leakage current test within 8 h after completion of 5.3.2.2.

NOTE The decision to perform IEC 61215-2 MQT 15 wet leakage current test after stress testing may be based on observations of, for example, large increases in leakage current from the module during stress testing.

e) Optional: Perform electroluminescence imaging at I_{sc} and 0,1 x I_{sc} within two days of completion of 5.3.2. Because I_{sc} applied for long times can affect P_{max} of some technologies (such as thin film), duration of I_{sc} application should be minimized and for not more than 120 s when imaging module technologies with such sensitivities. IEC TS 60904-13 may be referenced to perform the electroluminescence imaging.

f) For comparison purposes if optional 5.3.2.2e) was performed or if is desired to evaluate recovery of PID and metastability, optionally perform the procedure in 5.3.2.2e) to obtain the power performance of the modules after stabilization and any PID recovery when the PID stress factor of system voltage is turned off. Include the control modules when evaluating the power performance by the method of IEC 61215-2 MQT 06.1 and 07.

g) Any PID recovery, in fractional form, during this process is calculated for each module under voltage stress be formula (8)

$$P_r = \frac{1+\frac{P_{\max SR} - P_{\max VB}}{P_{\max VB}}}{1+\frac{\bar{P}_{\max CR} - \bar{P}_{\max CF}}{\bar{P}_{\max CF}}} - 1 \qquad (8)$$

where $P_{\max\mathrm{VB}}$ is the power of that module after application of the system voltage stress and before the stabilization and PID recovery procedure. $P_{\max\mathrm{SR}}$ is the power of that module that had been biased with system voltage stress after this stabilization and PID recovery procedure. The corresponding average power of the two control modules at these stages before and after the post stress test stabilization and PID recovery procedure are respectively $\bar{P}_{\max\mathrm{CF}}$ and $\bar{P}_{\max\mathrm{CR}}$ of which the difference between these represents the extent of change in power due to non-PID effects after the PID stress testing including changes in the metastability state associated with the stabilization procedure.

h) Perform IEC 61215-2 MQT 01 visual inspection.

5.3.4 Acceleration factor determination—coulomb basis

5.3.4.1 Determination of coulombs transferred at relative power loss levels

Evaluate the coulombs transferred to ground from each module biased with system voltage stress in chamber, $Q_{\mathrm{F}_{\mathrm{chamber}}}$, corresponding to the chosen failure criterion from the fraction power loss attributed to PID as a function of stress time determined in 5.3.2.3.3.7. To apply this subclause, sufficient stress levels or duration to show power degradation in the stress tests performed according to 5.3, is required. Example fraction power losses include 0,05, 0,10, and 0,20, as determined by formula (3), where power loss of the modules under stress is relative to the in-chamber controls. If module power was not measured at one of these thresholds within 5 % relative, fitting curves between at least two adjacent points within 50 % less than and within 50 % greater than threshold power loss may be interpolated. For example, if seeking the coulomb transfer $Q_{\mathrm{F}_{\mathrm{chamber}}}$ for a threshold power loss fraction of 0,05, degradation and coulomb transfer may be linearly interpolated if at least one power measurement each was obtained between 0,025 and 0,05 and between 0,05 and 0,075. Interpolation is performed with formula (9) and referencing the example in Table 2, for interpolating between subsequent measurements of coulombs Q_i and Q_{i+1} and corresponding fraction power loss relative to the controls P_{R_i} and $P_{\mathrm{R}_{i+1}}$, given here for the example of power change fraction of -0,05 (power loss),

$$Q_{-0,05} = Q_i + (-0,05 - P_{\mathrm{R}_i}) \frac{Q_{i+1} - Q_i}{P_{\mathrm{R}_{i+1}} - P_{\mathrm{R}_i}} \quad (9)$$

5.3.4.2 Projected time for the equivalent coulomb transfer in the field

Evaluate the coulombs per unit time the module-type transfers current to ground under bias in the outdoor environment, $(Q/t)_{field}$. The projected time for the equivalent coulomb transfer in the field corresponding to the failure level in the chamber is calculated with formula (10),

$$t_{\mathrm{F}} = Q_{\mathrm{F}_{\mathrm{chamber}}} / (Q/t)_{field} \quad (10)$$

In the case that a coulomb transferred does an equivalent amount of damage in the field or in the chamber, Formula (10) may be used to estimate rate of power loss due to PID in the field.

Formula (10) will not be valid if there is moisture ingress into the module because this can change the sensitivity of the module to system voltage and affect the rate of PID-related power loss. See Annex A for a procedure to evaluate if there is moisture ingress that will affect PID rate. Moisture ingress may not be visibly observable. Additionally, any effect of light on PID rate as discussed in 5.3.2.3.1 shall be properly accounted for, which may require testing under light or forward bias voltage if stress testing in the dark does not produce representative PID rates. Formula (9) will not be valid if there are significant module PID power recovery processes occurring in the field.

5.3.4.3 Case where no module degradation by PID in the chamber is observed

This subclause applies when degradation by PID (relative to the in-chamber controls) is not seen in the chamber and when to the extent of coulomb transfer for the modules in chamber is equal to or greater than 5 years in the field, as determined with the value $(Q/t)_{field}$ using the procedure in 5.3.4, linearly extrapolated. The time linearly extrapolated to with $(Q/t)_{field}$ is N. Formula (8) is modified with the value $Q_{\mathrm{T\_chamber}}$, which is the total coulombs transferred under bias in chamber of a module under stress when the degradation relative to the in-chamber control is zero, within measurement error of the module tester.

$$t_{\mathrm{F\_lower\ limit}\ (N)} = Q_{\mathrm{T\_chamber}} / (Q/t)_{field} \quad (11)$$