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Maximum power point tracking efficiency of grid connected photovoltaic inverters

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MAXIMUM POWER POINT TRACKING EFFICIENCY OF GRID CONNECTED PHOTOVOLTAIC INVERTERS

FOREWORD

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International Standard IEC 62891 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this standard is based on the following documents:

FDIS	Report on voting
82/1723/FDIS	82/1736/RVD

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

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

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

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MAXIMUM POWER POINT TRACKING EFFICIENCY OF GRID CONNECTED PHOTOVOLTAIC INVERTERS

1 Scope

This document provides a procedure for the measurement of the efficiency of the maximum power point tracking (MPPT) of inverters used in grid-connected photovoltaic (PV) systems. Both the static and dynamic MPPT efficiency are considered. Based on the static MPPT efficiency calculated in this document and steady state conversion efficiency determined in IEC 61683 the overall efficiency can be calculated.

The dynamic MPPT efficiency is indicated separately.

NOTE This document addresses PV inverters connected to an AC grid. However, this procedure may also be used for other power conversion devices with MPPT functionality used in PV systems, such as charge controllers or optimizers.

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 61683, *Photovoltaic systems – Power conditioners – Procedure for measuring efficiency*

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

EN 50160, *Voltage characteristics of electricity supplied by public distribution networks*

3 Terms and definitions

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

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

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

3.1 Inverter input (PV generator)

3.1.1
maximum input voltage
V_{DCmax}
allowed maximum voltage at the inverter input

Note 1 to entry: Exceeding of V_{DCmax} may destroy the equipment under test.

3.1.2
minimum input voltage
V_{DCmin}
minimum input voltage for the inverter to energize the utility grid, independent of mode of operation

3.1.3
rated input voltage
$V_{\mathrm{DC,r}}$
input voltage specified by the manufacturer, to which other data sheet information refers

3.1.4
maximum MPP voltage
V_{MPPmax}
maximum voltage at which the inverter can convert its rated power under MPPT conditions

3.1.5
minimum MPP voltage
V_{MPPmin}
minimum voltage at which the inverter can convert its rated power under MPPT conditions

Note 1 to entry: The actual minimum MPP voltage may depend on the grid voltage level.

3.1.6
rated input power
$P_{\mathrm{DC,r}}$
rated input power of the inverter, which can be converted under continuous operating conditions

3.1.7
maximum input current
$I_{\mathrm{DC,max}}$
maximum input current of the inverter under continuous operating conditions

Note 1 to entry: At inverters with several independent inputs, this value may depend on the chosen input configuration.

3.2 Inverter output (grid)

3.2.1
rated grid voltage
$V_{\mathrm{AC,r}}$
utility grid voltage to which other data sheet information refers

3.2.2
rated power
$P_{\mathrm{AC,r}}$
active power the inverter can deliver in continuous operation

3.3 Measured quantities

3.3.1
PV simulator MPP-Power
$P_{\mathrm{MPP,\,PVS}}$
MPP power provided by the PV simulator

3.3.2
input power
P_{DC}
measured input power of the device under test

3.3.3
PV simulator MPP voltage
$V_{\mathbf{MPP,\ PVS}}$
MPP voltage provided by the PV simulator

3.3.4
input voltage
$V_{\mathbf{DC}}$
measured input voltage of the device under test

3.3.5
PV simulator MPP current
$I_{\mathbf{MPP,\ PVS}}$
MPP current provided by the PV simulator

3.3.6
input current
$I_{\mathbf{DC}}$
measured input current of the device under test

3.3.7
output power
$P_{\mathbf{AC}}$
measured AC output power of the device under test

3.3.8
output voltage
$V_{\mathbf{AC}}$
measured AC voltage

3.3.9
output current
$I_{\mathbf{AC}}$
measured AC output current of the device under test

3.4 Calculated quantities

3.4.1
MPPT efficiency, energetic
$\eta_{\mathbf{MPPT}}$
ratio of the energy drawn by the device under test within a defined measuring period T_M to the energy provided theoretically by the PV simulator at the maximum power point (MPP):

$$\eta_{\mathrm{MPPT}} = \frac{\int_0^{T_\mathrm{M}} p_{\mathrm{DC}}(t) \cdot dt}{\int_0^{T_\mathrm{M}} p_{\mathrm{MPP}}(t) \cdot dt} \tag{1}$$

where

$P_{\mathrm{DC}}(t)$ is the instantaneous value of the power drawn by the device under test;

$P_{\mathrm{MPP}}(t)$ is the instantaneous value of the MPP power provided theoretically by the PV simulator.

3.4.2
conversion efficiency, energetic
η_{conv}
.ratio of the energy delivered by the device under test at the AC terminal within a defined measuring period T_M to the energy accepted by the device under test at the DC terminal:

$$\eta_{\text{conv}} = \frac{\int_0^{T_M} p_{\text{AC}}(t) \cdot dt}{\int_0^{T_M} p_{\text{DC}}(t) \cdot dt} \tag{2}$$

where

$P_{AC}(t)$ is the instantaneous value of the delivered power at the AC terminal of the device under test;

$P_{DC}(t)$ is the instantaneous value of the accepted power at the DC terminal of the device under test.

3.4.3
overall efficiency, energetic
η_t
ratio of the energy delivered by the device under test at the AC terminals within a defined measuring period T_M to the energy provided theoretically by the PV simulator:

$$\eta_t = \frac{\int_0^{T_M} p_{\text{AC}}(t) \cdot \text{dt}}{\int_0^{T_M} p_{\text{MPP}}(t) \cdot \text{dt}} \text{ respectively } \eta_t = \eta_{\text{conv}} \cdot \eta_{\text{MPPT}} \tag{3}$$

3.5
photovoltaic array simulator
current source emulating the static and dynamic behaviour of a PV array, in particular the current-voltage characteristic (see IEC TS 61836).

Note 1 to entry: The requirements are outlined in Clause A.1.

4 MPPT efficiencies

4.1 General description

The MPPT efficiency describes the accuracy of an inverter to set its operating conditions to match the maximum power point on the characteristic curve of a PV generator. The overall MPPT efficiency is divided into static and dynamic efficiency components.

Because inverters with poor MPPT performance operate at a DC input voltage that is different from MPP voltage, and static power conversion efficiency depends on DC input voltage, the measurements of static MPPT efficiency and static power conversion efficiency according to 4.3 shall be performed simultaneously.

a) Static MPPT efficiency

The static MPPT efficiency is determined by means of measurement as follows:

$$\eta_{\mathrm{MPPTstat}} = \frac{1}{P_{\mathrm{MPP,PVS}} \cdot T_{\mathrm{M}}} \sum_i V_{\mathrm{DC},i} \cdot I_{\mathrm{DC},i} \cdot \Delta T \tag{4}$$

where

$V_{\mathrm{DC},i}$ is the sampled value of the inverter's input voltage;

$I_{\mathrm{DC},i}$ is the sampled value of the inverter's input current;

T_{M} is the overall measuring period;

$\Delta\mathrm{T}$ is the period between two subsequent sample values.

The static MPPT efficiency describes the accuracy of an inverter to regulate on the maximum power point on a given static characteristic curve of a PV generator.

$V_{\mathrm{DC},i}$ and $I_{\mathrm{DC},i}$ shall be sampled at the same time.

b) Dynamic MPPT efficiency

Variations of the irradiation intensity and the resulting transition of the inverter to the new operation point are not considered with the static MPPT efficiency. For the evaluation of this transient characteristic the dynamic MPPT efficiency is specified. The dynamic MPPT efficiency is defined as:

$$\eta_{\mathrm{MPPTdyn}} = \frac{1}{\sum_j P_{\mathrm{MPP,PVS},j} \cdot \Delta T_j} \sum_i V_{\mathrm{DC},i} \cdot I_{\mathrm{DC},i} \cdot \Delta T_i \tag{5}$$

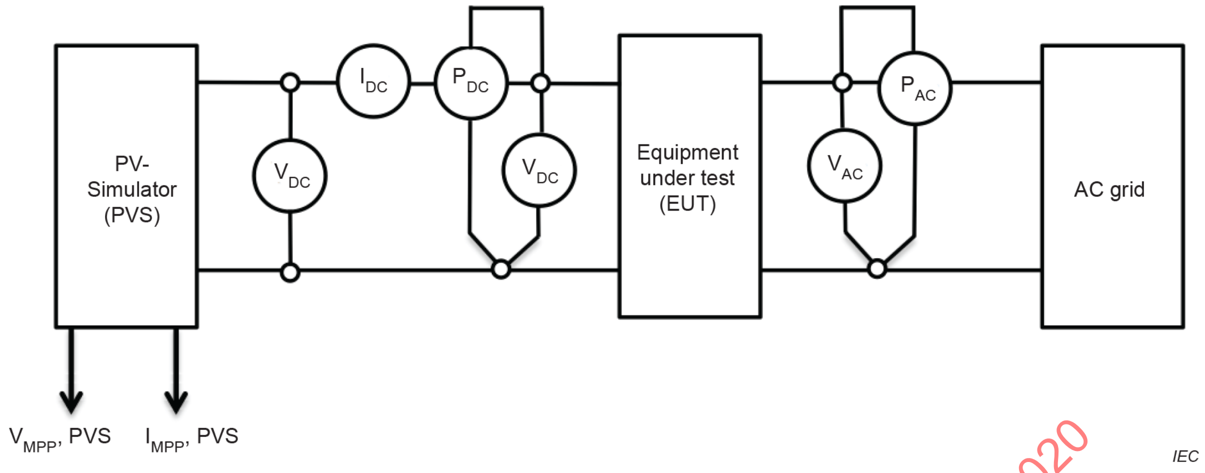
where

ΔT_j is the period in which the power $P_{\mathrm{MPP,PVS},j}$ is provided;

ΔT_i is the period in which the power $V_{\mathrm{DC},i}$ and $I_{\mathrm{DC},i}$ are sampled.

4.2 Test set-up

The generic test set-up for single phase grid connected inverters is depicted in Figure 1. The diagram can also be considered as a single-phase representation of a test-circuit for multi phase inverters.



Key

EUT Equipment under test (inverter);

I_{DC} DC current meter;

V_{DC} DC voltage meter;

P_{DC} DC power meter;

V_{AC} AC voltage meter;

P_{AC} AC power meter.

Figure 1 – Example test set-up for MPPT efficiency measurements

The DC source connected to the PV input of the inverter shall be a PV simulator in accordance to the specifications in Clause A.1.

The AC supply of the inverter shall be in accordance to the specifications in Clause A.2.

For the conversion efficiency, the DC and AC voltages shall be measured as close as possible to the inverter terminals. For MPPT efficiency, the DC voltage shall be measured as close as possible to the PV simulator. For combined conversion and MPPT efficiency measurements, two voltage measurements will be required at the output of the PVS and the DC input of the EUT, in order to avoid measurement errors resulting from the voltage drop between the PVS and the EUT.

4.3 Static MPPT efficiency

4.3.1 Test conditions

The measurement of the conversion and static MPPT efficiency shall be performed simultaneously with test specifications as defined in Table 1.

For test devices with several independent MPPT input terminals, the measurements shall be performed for all input configurations as intended by the manufacturer. Unless otherwise provided by the manufacturer, the total power shall be split equally on the individual input terminals.

Table 1 – Test specifications for static MPPT efficiency

MPP voltage of the simulated I/V characteristic of the PV generator	Simulated I/V characteristic (see Annex C)	MPP power of the simulated I/V characteristic normalised to rated DC power [d], $P_{MPP,PVS}/P_{DC,r}$ [f]							
		0,05	0,10	0,20	0,25	0,30	0,50	0,75	1,00
V_{MPPmax} or ($0,8 \cdot V_{DCmax}$ [a,c])	c-Si								
$V_{DC,r}$ [e]	c-Si								
V_{MPPmin}	c-Si								
V_{MPPmax} or ($0,7 \cdot V_{DCmax}$ [a,c])	TF [b]								
$V_{DC,r}$	TF [b]								
V_{MPPmin}	TF [b]								

The MPP voltages at the different test conditions (V_{MPPmax}, $V_{DC,r}$, V_{MPPmin}) shall be kept constant during the test for each power level.

[a] The lower of the two values shall be used. The specified MPP voltages ensure that the correct MPPT operation is not affected by reaching voltage limits.

[b] For devices under test that are not intended for the operation with thin-film technologies, these measuring points can be omitted.

[c] For other cell technologies the value $V_{MPPmax} = n \cdot V_{DCmax}$ shall be set accordingly.

[d] In order to specify the static MPPT efficiency in terms of normalised rated AC power, the procedure in Annex E shall be used.

[e] If this value is not specified by the manufacturer, $V_{DC,r} = (V_{MPPmax} + V_{MPPmin})/2$ shall be used.

[f] If this value is not specified by the manufacturer, it can be defined as $P_{DC,r} = P_{AC,r} / \eta_{conv,r}$, in which $\eta_{conv,r}$ is the conversion efficiency at rated DC voltage. If the rated conversion efficiency is not specified, it shall be measured.

The measurement shall be performed at nominal grid voltage $V_{AC,r}$ in order to avoid any impact of the grid voltage level on the measurement results. Deviations shall be documented in the measurement report.

The measurement should be performed at an ambient temperature of 25 °C ± 5 °C. Other ambient temperatures can be mutually agreed. The actual ambient temperature shall be specified in the test report.

4.3.2 Measurement procedure

For each of the above specified test conditions a corresponding I/V characteristic has to be defined which shall be emulated by means of the PV simulator.

NOTE The requirements on the accuracy of the defined characteristic are outlined in Annex C.

After commissioning the device under test the stabilization of the MPP tracking shall be awaited firstly.

Given the multitude of various MPPT methods and their parameters, a specific waiting period is not defined in this standard. The stabilization time depends on the characteristics of the device under test and shall be set accordingly in each case. The stabilization time shall be documented in the test report. If a stabilisation of the MPPT can’t be observed due to the behaviour of the device under test, a latency of at least 5 min is defined.

The measuring time for each test condition as specified in Table 1 amounts to 10 min. For the first power level of each MPP voltage setting, the stabilisation of the MPPT-tracker has to be awaited. If a stabilisation cannot be observed a stabilisation time of at least 5 min is defined.

After a change of the power level a general stabilisation period of 2 min should be used. Data recorded during the stabilisation periods are not to be considered for the calculation of the static MPPT and conversion efficiency.

After the stabilisation of the MPP tracking the following parameters shall be logged:

– $P_{\text{MPP,PVS}}$; MPP power provided by the PV simulator;
– P_{DC}; measured input power of the device under test;
– $V_{\text{MPP,PVS}}$; MPP voltage provided by the PV simulator;
– $I_{\text{MPP,PVS}}$; MPP current provided by the PV simulator;
– I_{DC}; measured input current of the device under test.
– P_{AC}; measured AC output power of the device under test

Both the sampling and recording rate are not specified. However, they shall be sufficiently high in order to map the specific MPP tracking behaviour of the device under test correctly. This covers in particular the fluctuation of the input voltage appearing at PV inverters with a multiple of the grid frequency.

V_{DC} may be calculated from P_{DC} and I_{DC}.

4.3.3 Evaluation – Calculation of static MPPT efficiency

For each measured power level specified in Table 1, static MPPT efficiency η_{MPPT} shall be calculated as energetic averages according to the definitions 3.4.2 and 3.4.1. The results shall be documented in the measurement report for each test condition according to Table 1.

Furthermore, modifications of the internal setting of the device under test, conspicuous behaviour during the measurement, as well as variations from the defined procedure, shall be documented.

4.4 Test conditions for dynamic MPPT efficiency

4.4.1 Dynamic MPPT efficiency

The measurement of the dynamic MPPT efficiency shall be performed according to the test conditions as outlined in the tables in Annex B.

The dynamics of the test sequences are generated by changes in solar irradiance. Measurements shall be performed with a c-Si PV model as a basis and can additionally be made with a TF model (see Table C.1). The chosen model (PV technology) shall be documented in the report.

NOTE Alternative test procedures are in discussion for a future edition.

Dynamic MPPT efficiency test shall be performed at rated DC voltage. For test devices with several independent MPPT input terminals, the measurements shall be performed for all input configurations as intended by the manufacturer. Unless otherwise provided by the manufacturer, the total power shall be split equally on the individual input terminals.

The measurement should be performed at an ambient temperature of 25 °C ± 5 °C. Other ambient temperatures can be mutually agreed upon. The actual ambient temperature shall be specified in the test report.

4.4.2 Measurement procedure

For each of the test conditions specified in Annex B, a corresponding I/V characteristic shall be defined and shall be emulated by means of the PV simulator. A radiation intensity of 1 000 W/m^2 is related to the rated DC power $P_{\mathrm{DC,\,r}}$ of the device under test. Prior to each test sequence a waiting period (initial set-up time) shall be implemented to allow the stabilization of the device under test. Values measured during this initial set-up time are not considered for calculation of the dynamic MPPT efficiency according to 4.4.3.

NOTE The requirements on the accuracy of the defined characteristic are outlined in Annex C.

Given the multitude of various MPPT methods and their parameters, a specific waiting period is not defined in this standard. The stabilization time depends on the characteristics of the device under test and shall be set accordingly in each case. The stabilization time shall be documented in the test report. If a stabilisation of the MPPT cannot be observed due to the behaviour of the device under test, a latency of at least 5 min is defined.

For the evaluation and the determination of the dynamic MPPT efficiency the following parameters are to be recorded during the measurement:

- P_{MPPPVS}; MPP power provided by the PV simulator;
- P_{DC}; measured input power of the device under test;
- $V_{\mathrm{MPP,PVS}}$; MPP voltage provided by the PV simulator;
- V_{DC}; measured input voltage of the device under test;
- $I_{\mathrm{MPP,PVS}}$; MPP current provided by the PV simulator;
- I_{DC}; measured input current of the device under test.

Both the sampling and recording rate are not specified. However, they shall be sufficiently high in order to map the specific MPP tracking behaviour of the device under test correctly. This covers in particular the fluctuation of the input voltage appearing at PV inverters with a multiple of the grid frequency. V_{DC} and I_{DC} shall be sampled at exactly the same time.

P_{DC} may be calculated from V_{DC} and I_{DC}.

4.4.3 Evaluation – Calculation of the dynamic MPPT efficiency

The overall dynamic MPPT efficiency is the mean value of the single dynamic MPPT efficiencies of the test sequences according to Table B.1 and Table B.2. It is calculated by:

$$\eta_{\mathrm{MPPTdyn},t} = \frac{1}{N}\sum_{i=1}^{N} a_i \cdot \eta_{\mathrm{MPPTdyn},i} \tag{6}$$

where

$\eta_{\mathrm{MPPTdyn},t}$ is the averaged dynamic MPPT efficiency;

$\eta_{\mathrm{MPPTdyn},i}$ is the dynamic MPPT efficiency for each test sequence;

N is the number of test sequences;

a_i is the weighting factor.

Unless other values are defined and reported, the weighting factor is assumed to be a_i = 1, i = 1..N.

For each test sequence specified in Annex B the dynamic MPPT efficiency $\eta_{\mathrm{MPPT,dyn}}$ is to be calculated based on the recorded data according the definition. The results are to be documented in the measuring report.

For each test sequence the calculated MPPT efficiency is to be documented with a table in the measuring report.

Furthermore, modifications of the internal setting of the device under test, conspicuous behaviour during the measurement, as well as variations from the defined procedure, shall be documented.

5 Calculation of the overall efficiency

The DC power is converted to the AC power P_{AC} by means of the conversion efficiency η_{conv}. The actual DC power P_{DC} of the device under test is the product of the static MPPT efficiency $\eta_{MPPTstat}$ and the MPP power provided by the PV simulator $P_{MPP,\ PVS}$:

$$P_{AC} = \eta_{conv} \cdot P_{DC} = \eta_{conv} \cdot \eta_{MPPTstat} \cdot P_{MPP,PVS} = \eta_t \cdot P_{MPP,\ PVS} \tag{7}$$

The overall efficiency η_t can also be considered as:

$$\eta_t = \eta_{conv} \cdot \eta_{MPPTstat} = \frac{P_{AC}}{P_{MPP,PVS}} \tag{8}$$

Formula (8) is to be applied for each power and voltage level of Table 1. By the application of EUR and CEC weighting factors according to Clause D.1 and Clause D.2, the efficiencies can summarised for each voltage level (V_{MPPmax}, $V_{DC,r}$, V_{MPPmin}). As a result, the weighted overall efficiencies $\eta_{t,EUR}$ and $\eta_{t,CEC}$ are obtained.

Annex A
(normative)

Requirements on the measuring apparatus

A.1 PV generator simulator

A.1.1 General

In order to determine the MPPT efficiency according to Clause 4 correctly, the PV simulator used for the measurements shall be appropriate to emulate the stationary and the dynamic characteristic of a PV generator exactly.

In the following the minimal requirements are defined, which shall be met by the used PV simulator.

Generally the requirements in Table A.1 regarding the dependency of the MPP voltage on the irradiation, the relation of MPP voltage to open circuit voltage and the relation of MPP current to short circuit current shall be met. Further requirements for the static and dynamic case are outlined the following subclauses.

Table A.1 – General requirements on the simulated I/V characteristic of the PV generator

	cSi- technology	Thin film technology	Tolerance %
$\dfrac{V_{\text{MPP, G = 200 W/m}^2}}{V_{\text{MPP, G = 1 000 W/m}^2}}$	0,95	0,98	± 1
$\dfrac{V_{\text{MPP; STC}}}{V_{\text{OC, STC}}}$	0,8	0,72	< 1
$\dfrac{I_{\text{MPP;STC}}}{I_{\text{SC,STC}}}$	0,9	0,8	< 1

A.1.2 Requirements on the static characteristic

Related to the output of the PV simulator the current/voltage characteristic shall comply with the specified models of the PV generator as defined in Annex C. In this the parameters to be set for the respective partial tests (V_{OC}, V_{MPP}, P_{MPP}, FF_{V}, FF_{I}) are decisive. The actual current/voltage characteristic of the PV simulator shall not deviate more the 1 % in the power within the voltage range of 0,9 × $V_{\text{MPP, PVS}}$ to 1,1 × $V_{\text{MPP, PVS}}$ related to the predetermined characteristic at rated conditions.

The PV simulator shall be able to emulate the current/voltage characteristic of the PV generator model according to Annex C even for transient changing values of V_{OC}, V_{MPP}, P_{MPP}, etc. Any occurring steps of these parameters (e.g. at specified ramps) should be as low as possible, but at least smaller than 1 % of the related output value.

If the device under test operates at voltages below 0,9 × $V_{\text{MPP, PVS}}$ the PV simulator shall be able to emulate the PV characteristic according to the model in Annex C even in this voltage range.

A.1.3 Requirement on the transient stability

During the measurement time the MPP power shall not change by more than 0,1 % relative to the specified I/V characteristic at rated conditions.

A.1.4 Requirements on the dynamic characteristic

The PV simulator shall be suited to allow for a proper operation of the device under test with respect to the MPP tracking. This requires a sufficient dynamic response of the PV simulator in order to follow the dynamic voltage changes that occur in the measurement (e.g. the typical ripple of single-phase inverters with twice the grid frequency).

The actual requirements for the dynamic response characteristics of the PV simulator may vary strongly due to properties of the device under test. Thus the possibility exists that test devices may demand greater dynamic requirements. An insufficient dynamic response may affect the MPPT behaviour of the device under test. This applies in particular to MPPT methods, which are based on a correlation between the input current and the input voltage. Prior to the MPPT test a comparative measurement (e.g. at a real PV generator) may be required in order to assure that the MPP tracking is not affected unduly by the PV simulator.

A.1.5 Requirements on electrical characteristic

For devices under test without galvanic isolation between DC side and AC side, the output of the PV simulator shall be non grounded and suited for voltages which occur between the DC input of the device under test and PE. The capacitance between the output of the PV simulator and ground should be as low as possible in order to avoid any negative impact on the EMC characteristic or the residual current detector of the device under test.

A.1.6 Calibration – Uncertainty

Differences between the emulated current/voltage characteristic of the PV simulator and the default setting may affect the measurement results strongly. Thus, before the measurement it shall be assured by an appropriate calibration, that on the one hand the PV simulator works as intended with the device under test and on the other hand the actual parameters generated by the PV simulator (V_{OC}, V_{MPP}, P_{MPP}, etc.) are sufficiently known.

A.2 AC power supply

As AC source for the measurements a grid simulator should be used preferably, which provides a stable and interference-free AC voltage according to EN 50160.

If a grid simulator is not used it shall be assured that the behaviour of the device under test is not unallowably affected by means of the grid (e.g. voltage level and voltage distortions).

Generally all measurements shall be performed at the rated grid voltage $V_{\mathrm{AC,r}}$ (−3 % to +3 %) and rated grid frequency $f_{\mathrm{AC,r}}$ ± 0,1 Hz as specified by the manufacturer of the device under test.

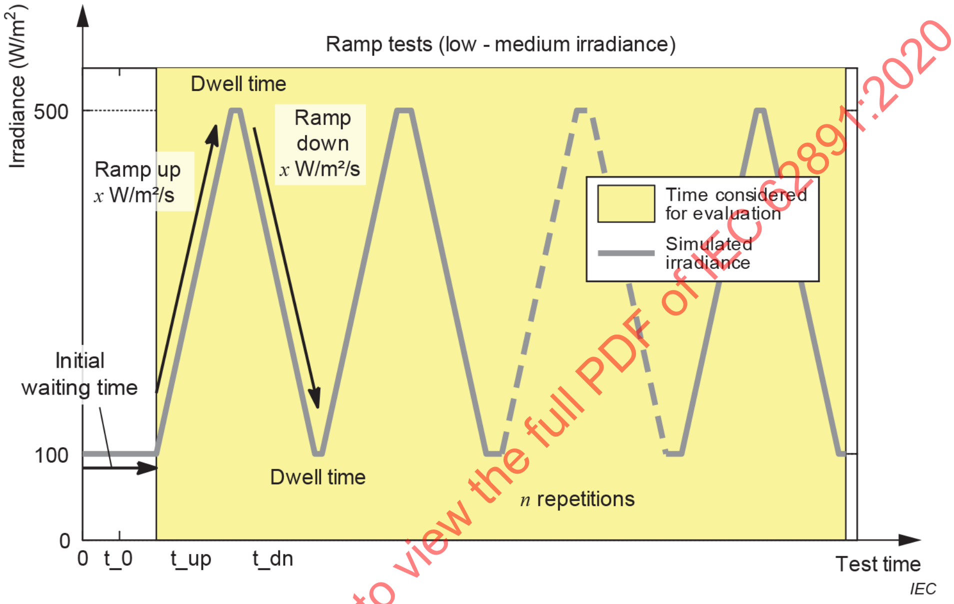
NOTE Compliance with these limits assures that abnormal effects on the behaviour of the device under test due to the grid voltage are avoided.

Annex B
(normative)

Test conditions for dynamic MPPT efficiency

B.1 Test profiles

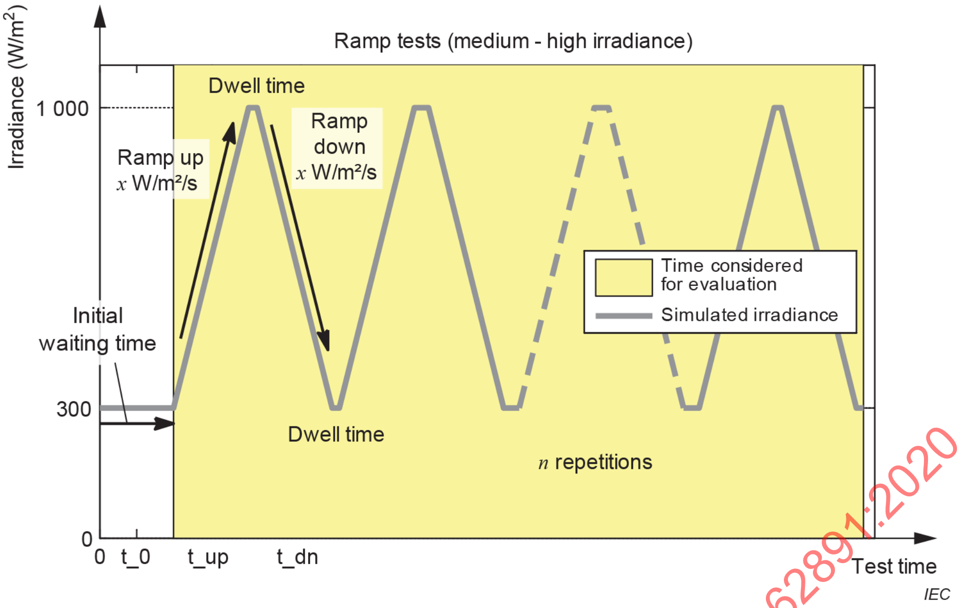
Test for the dynamic MPPT efficiency are to be performed with the following sequences. The percentage specification of the radiation intensity is related to standard test conditions (STC). 100 % corresponds to 1 000 W/m^2 at 25 °C. See Figure B.1 and Figure B.2.



Key

n	repetitions
t_1	brackets the rise time
t_2	dwell time on high level (value +H)
t_3	fall time
(value + L)	dwell time on low level.

Figure B.1 – Test sequence for fluctuations between small and medium irradiation intensities



Key

n	repetitions
t_1	brackets the rise time
t_2	dwell time on high level (value +H)
t_3	fall time
(value + L)	dwell time on low level.

Figure B.2 – Test sequence for fluctuations between medium and high irradiation intensities

B.2 Test sequence with ramps 10 % – 50 % G_{STC} (See Table B.1)

Table B.1 – Dynamic MPPT-Test 10 % → 50 % G_{STC} (valid for the evaluation of $\eta_{MPPTdyn}$)

From-to	Delta		Dwell time setting			Waiting time setting
W/m²	W/m²		s			s
100-500	400					300
#	**Slope**	**Ramp UP**	**Dwell time**	**Ramp DN**	**Dwell time**	**Duration**
Number	W/m²/s	s	s	s	s	s
2	0,5	800	10	800	10	3 540
2	1	400	10	400	10	1 940
3	2	200	10	200	10	1 560
4	3	133	10	133	10	1 444
6	5	80	10	80	10	1 380
8	7	57	10	57	10	1 372
10	10	40	10	40	10	1 300
10	14	29	10	29	10	1 080
10	20	20	10	20	10	900
10	30	13	10	13	10	760
10	50	8	10	8	10	660
					Total	15 936
						04:25:36

NOTE Ramp and dwell times are given as rounded values.

B.3 Test sequence with ramps 30 % – 100 % G_{STC} (See Table B.2)

Table B.2 – Dynamic MPPT-Test 30 % → 100 % G_{STC} (valid for the evaluation of $\eta_{MPPTdyn}$)

From-to	Delta		Dwell time setting			Waiting time setting
W/m²	W/m²		s			s
300-1 000	700					300
#	Slope	Ramp UP	Dwell time	Ramp DN	Dwell time	Duration
Number	W/m²/s	s	s	s	S	s
10	10	70	10	70	10	1 900
10	14	50	10	50	10	1 500
10	20	35	10	35	10	1 200
10	30	23	10	23	10	960
10	50	14	10	14	10	780
10	100	7	10	7	10	640
					Total	6 980
						01:56:20
NOTE Ramp and dwell times are given as rounded values.						

B.4 Start-up and shut-down test with slow ramps (See Table B.3 and Figure B.3)

Table B.3 – Dynamic MPPT- Slow Ramp 1 % → 10 % G_{STC} (valid for the evaluation of $\eta_{MPPTdyn}$)

From-to W/m²	Delta W/m²		Dwell time setting s			Waiting time setting s	
10-100	90		30			300	
# Number	Slope W/m²/s	Ramp UP s	Dwell time s	Ramp DN s	Dwell time s	Duration s	
1	0,1	980	30	980	30	2 320	
					Total	2 320	s
						00:38:40	h

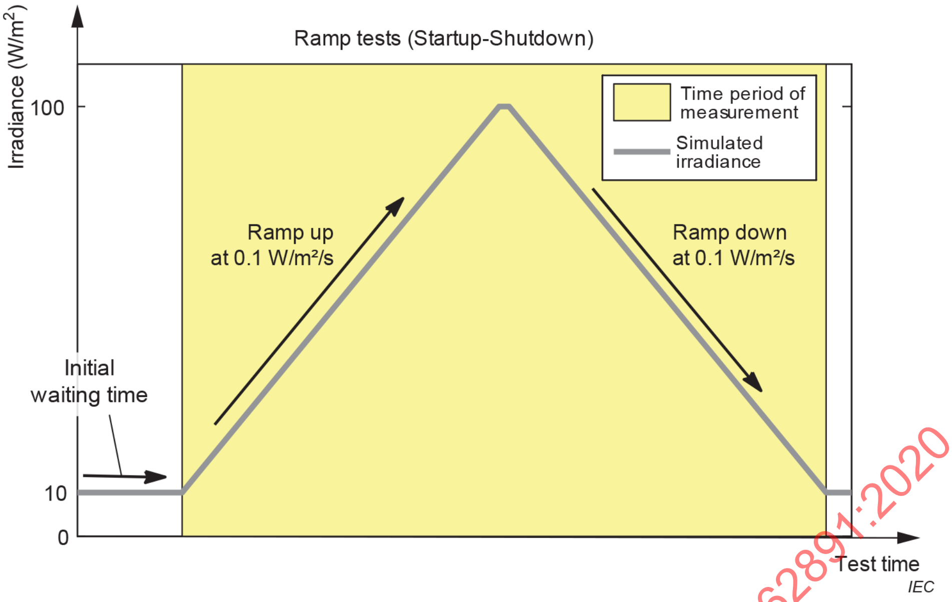


Figure B.3 – Test sequence for the start-up and shut-down test of grid connected inverters

B.5 Total test duration

The total test duration is the sum of the test sequences according to Clauses B.2, B.3 and B.4.

Annex C
(normative)

Models of current/voltage characteristic of PV generator

C.1 PV generator model for MPPT performance tests

This annex defines a PV generator model for MPPT performance tests. Refer to Table A.1 for technology-dependent parameters.

For the measurements of the static and dynamic MPPT efficiency, changes of module temperature shall be neglected and shall be considered constant at T_{PV} = 25 °C.

MPP to open circuit voltage ratio:

$$FF_{\mathrm{V}} = \frac{V_{\mathrm{MPP;\,STC}}}{V_{\mathrm{OC,\ STC}}} \tag{C.1}$$

MPP to short circuit current ratio:

$$FF_{\mathrm{I}} = \frac{I_{\mathrm{MPP;STC}}}{I_{\mathrm{SC,STC}}} \tag{C.2}$$

Formula for the PV current as a function of PV voltage:

$$I_{\mathrm{PV}} = I_{\mathrm{SC}} - I_0 \left(e^{\frac{V_{\mathrm{PV}}}{V_{\mathrm{OC}} C_{\mathrm{AQ}}}} - 1 \right) \tag{C.3}$$

Irradiance G and temperature T dependent short circuit current in Formula (C.3):

$$I_{\mathrm{SC}} = I_{\mathrm{SC,STC}} \frac{G}{G_{\mathrm{STC}}} \cdot \left(1 + \alpha \cdot \left(T_{\mathrm{PV}} - T_{\mathrm{STC}}\right)\right) \tag{C.4}$$

Irradiance and temperature dependent open circuit voltage in Formula (C.3):

$$V_{\mathrm{OC}} = V_{\mathrm{OC,STC}} \left(1 + \beta \left(T_{\mathrm{PV}} - T_{\mathrm{STC}}\right)\right) \left(\ln\left(\frac{G}{C_{\mathrm{G}}} + 1\right) C_{\mathrm{V}} - C_{\mathrm{R}} G \right) \tag{C.5}$$

$$I_0 = I_{\mathrm{SC,STC}} \left(1 - FF_{\mathrm{I}}\right)^{\left(1/\left(1 - FF_{\mathrm{V}}\right)\right)} \frac{G}{G_{\mathrm{STC}}} \tag{C.6}$$

Constant C_{AQ} in Formula (C.3):

$$C_{\mathrm{AQ}} = \frac{FF_{\mathrm{V}} - 1}{\ln\left(1 - FF_{\mathrm{I}}\right)} \tag{C.7}$$

Voltage ratio from V_{MPP} at an irradiance of 200 W/m^2 to V_{MPP} at an irradiance of 1 000 W/m^2:

$$V_{L2H} = \frac{V_{MPP_{G\,=\,200\,W/m^2}}}{V_{MPP_{G\,=\,1\,000\,W/m^2}}} \tag{C.8}$$

In order to fulfil the requirements of Table 1 (constant V_{MPP} at each power step), for V_{oc} in Formula (C.3) $V_{oc,STC}$ should be used rather than the value from (C.5).

The parameter of the PV generator model shall be set as follows (see Table C.1):

Table C.1 – Technology-dependent parameters

		cSi- technology	Thin film technology	Tolerance %
FF_V	[ ]	0,8	0,72	< 1
FF_I	[ ]	0,9	0,8	< 1
C_G	[W/m^2]	2,514 E−03	1,252 E−03	-
C_V	[ ]	8,593 E−02	8,419 E−02	-
C_R	[m^2/W]	1,088 E−04	1,476 E−04	-
v_{L2H}	[ ]	0,95	0,98	± 1
α	[%/°C]	0,04	0,02	
β	[%/°C]	−0,4	−0,2	

Example 1: cSi-PV generator (see Table C.2 and Figure C.1)

Objective: $P_{MPP,STC}$ = 1 000 W, $V_{MPP,STC}$ = 100 V, cSi –Technology, T_{PV} = 25 °C

$$V_{OC,STC} = \frac{V_{MPP,STC}}{FF_V} = \frac{100\ \text{V}}{0{,}8} = 125\ \text{V} \tag{C.9}$$

$$I_{MPP;STC} = \frac{P_{MPP,STC}}{V_{SC,STC}} = \frac{1\ 000\ \text{W}}{100\ \text{V}} = 10\ \text{A} \tag{C.10}$$

$$I_{SC;STC} = \frac{I_{MPP;STC}}{FF_I} = \frac{10\ \text{A}}{0{,}905} = 11\ \text{A} \tag{C.11}$$

Table C.2 – MPP-values obtained with the cSi PV model

G W/m^2	V_{MPP} V	P_{MPP} W
50	84,6	42,3
100	90,0	89,9
200	94,9	189,6
300	97,3	291,6
500	99,5	497,0
750	100,3	751,3
1 000	100	999,3

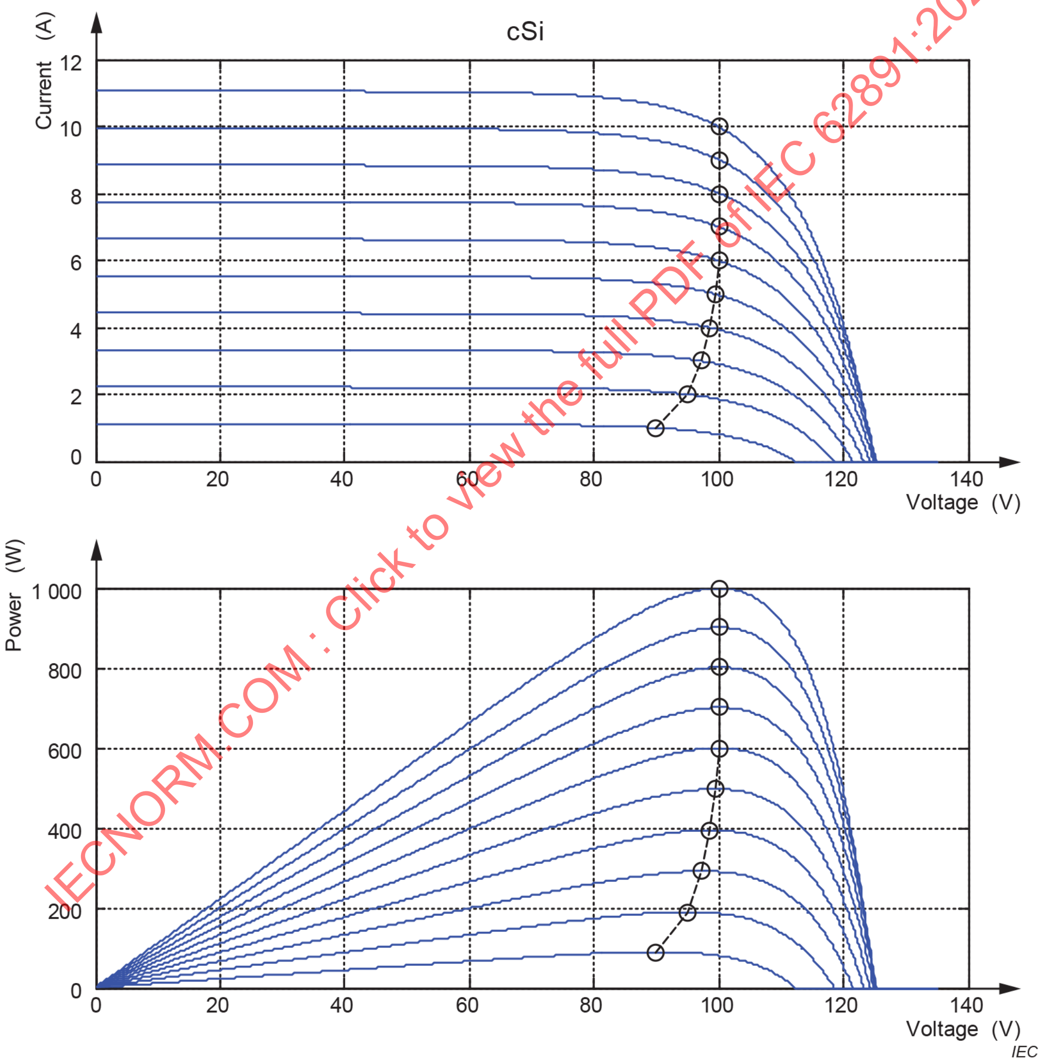


Figure C.1 – Irradiation-dependent V-I- and V-P characteristic of a c-Si PV generator

Example 2: TF-PV generator (see Figure C.2 and Table C.3)

Objective: $P_{\mathrm{MPP,STC}}$ = 1 000 W, $V_{\mathrm{MPP,STC}}$ = 100 V, TF–Technology, T_{PV} = 25 °C

$$V_{\mathrm{OC,STC}} = \frac{V_{\mathrm{MPP,STC}}}{FF_{\mathrm{V}}} = \frac{100\ \mathrm{V}}{0{,}715} = 140\ \mathrm{V} \tag{C.12}$$

$$I_{\mathrm{MPP;STC}} = \frac{P_{\mathrm{MPP,STC}}}{V_{\mathrm{SC,STC}}} = \frac{1\ 000\ \mathrm{W}}{100\ \mathrm{V}} = 10\ \mathrm{A} \tag{C.13}$$

$$I_{\mathrm{SC;STC}} = \frac{I_{\mathrm{MPP;STC}}}{FF_{\mathrm{I}}} = \frac{10\ \mathrm{A}}{0{,}808} = 12{,}4\ \mathrm{A} \tag{C.14}$$

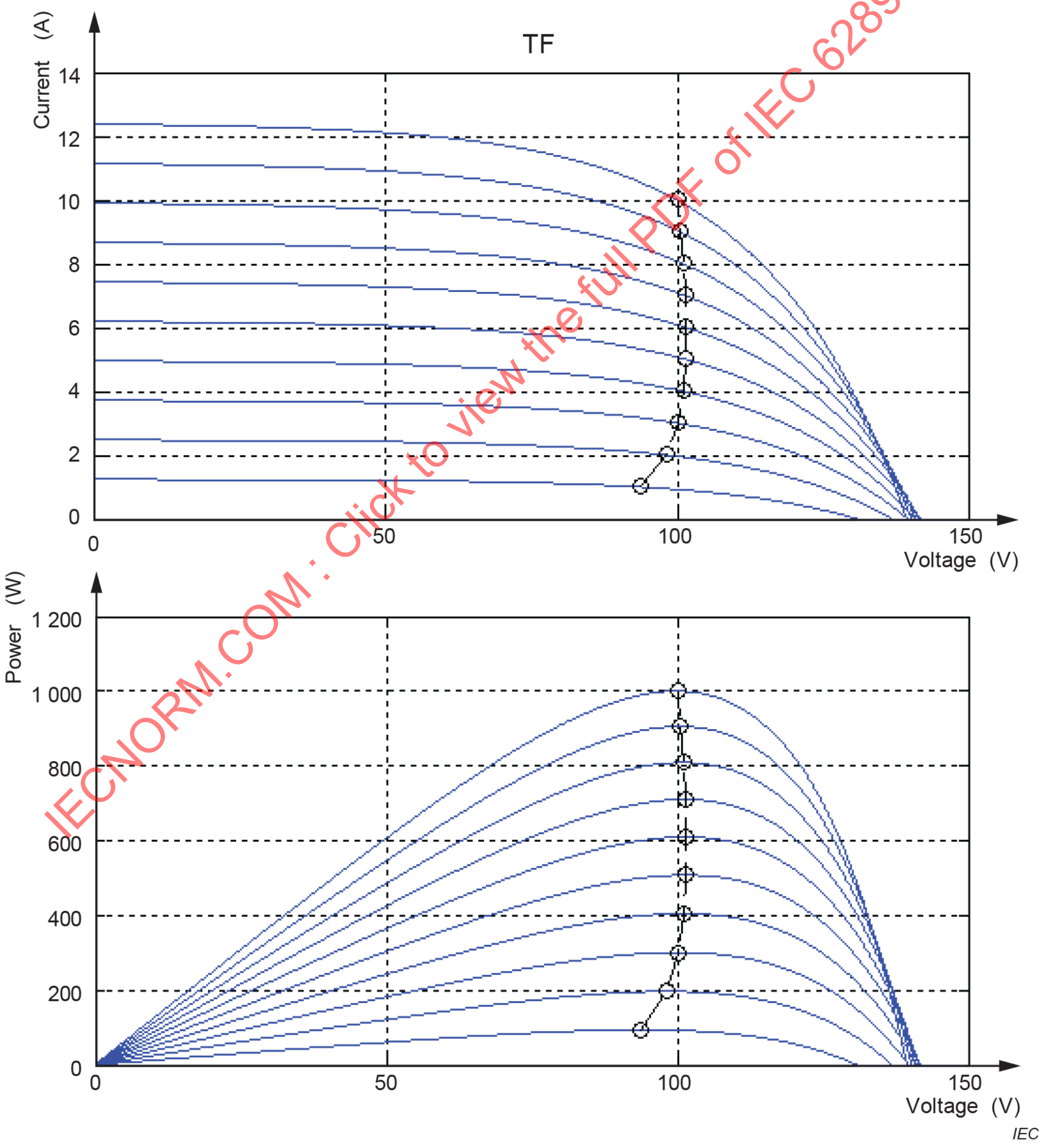


Figure C.2 – Irradiation-dependent V-I- and V-P characteristic of a thin-film PV generator

Table C.3 – MPP-values obtained with the TF-PV mode

G W/m²	V_{MPP} V	P_{MPP} W
50	88,8	44,4
100	93,9	93,9
200	98,2	196,6
300	100,2	300,7
500	101,5	507,9
750	101,3	759,8
1 000	100	1 000,3

C.2 Alternative PV generator model for MPPT performance tests

Other models of the PV generator characteristics like the 1-diode model or the 2-diode can be used as well. The characteristics should preferably fulfil the technology dependent parameters according to Table A.1. If the model cannot fulfil the requirements of Table A.1 the achieved Technology dependent parameters have to be stated and the used model should be stated together with its parameters.

Example: cSi-PV generator with 1-diode model:

$$I_{PV} = I_{ph} - I_0 \left(e^{\frac{V_{PV}+I_{PV}R_S}{mV_T}} - 1 \right) - \frac{V_{PV}+I_{PV}R_S}{R_P} \quad (C.15)$$

where

$I_{ph} = I_{ph,STC} \cdot \frac{G}{G_{STC}}$ and

$I_0 = C_0\, T_{PV}{}^3\, e^{-\frac{E_g}{kT_{PV}}}$ and

$V_T = \frac{kT_{PV}}{e_0}$

where

I_{PV} is the module current in A;

I_0 is the diode saturation current in A;

I_{ph} is the photo current (source current) in A;

V_{PV} is the module voltage in V;

V_T is the temperature voltage in V;

E_g is the bandgap in eV;

R_S is the serial resistance in Ω;

R_P is the parallel resistance in Ω;

T_{PV} is the module temperature in K;

G is the irradiance in W/m²;

C_0 is the coefficient of diode saturation current in A/K^3;

m is the diode factor;

e_0 is the elementary charge (1,602 × 10^{-19} C);

k is the Boltzmann constant (1,381 × 10^{-23} J/K).

For the application of the 1-diode model for the crystalline technology, the following parameters can be applied:

– C_0 = 101,668 A/K^3;
– m = 1,113;
– R_s = 47,731 mΩ;
– R_p = 11,173 Ω;
– the photo current at G_{STC} amounts to I_{ph} = 1 A;
– the band gap amounts to 1,1 eV.

With these parameters, a standard PV cell is obtained that fulfils the requirements of Table A.1. By parallel or serial interconnections of the standard cell, PV generators of arbitrary size can be configured.