IEC TS 63106-1

Edition 1.0 2020-11

TECHNICAL SPECIFICATION

Simulators used for testing of photovoltaic power conversion equipment – Recommendations – Part 1: AC power simulators

IEC TS 63106-1:2020-11(en)

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Simulators used for testing of photovoltaic power conversion equipment – Recommendations –
Part 1: AC power simulators

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SIMULATORS USED FOR TESTING OF PHOTOVOLTAIC POWER CONVERSION EQUIPMENT – RECOMMENDATIONS –

Part 1: AC power simulators

FOREWORD

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a Technical Specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 63106-1, which is a Technical Specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Specifications based on the following documents:

Draft TS	Report on voting
82/1731/DTS	82/1776A/RVDTS

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

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

A list of all parts in the IEC 63106 series, published under the general title *Simulators used for testing of photovoltaic power conversion equipment – Recommendations*, can be found on the IEC web site.

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

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- withdrawn,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

INTRODUCTION

The objective of this document is to establish terminology, and create a framework for, and provide guidance regarding the electrical performance of AC power simulators used to test utility interactive photovoltaic (PV) power conversion equipment (PCE) for compliance with grid interconnection standards.

It serves as a generalized guideline for the development of AC power simulators used within a test and evaluation system for PV PCEs.

Testing laboratories are responsible for selecting the appropriate test items and procedures as well as defining the required performance for adequate evaluation of utility interactive PV PCEs, considering utility power requirements, local codes and regulations.

Utility interactive PCEs are used not only for PV, but also for various distributed generation technologies such as wind power, battery energy storage, engine co-generation or fuel cells. Some of the recommendations in this document may be similar and applicable for AC simulators used to test these other generation technologies, but they are not intended to supersede testing requirements found in related IEC standards.

This document may be used in conjunction with regional or national grid standards and codes, such as:

a) European level utility interaction requirements such as:

   EN 50549-1:2019,

   EN 50549-2:2019.

b) German FGW TG3.

c) UL1741 supplement SA, SRD-UL-1741-SA-V1.1.

d) IEEE 1547-2003, IEEE1547a (Amendment 1) -2014 and IEEE1547.1-2005.

e) IEEE 1547-2018 and IEEE 1547.1-2020.

SIMULATORS USED FOR TESTING OF PHOTOVOLTAIC POWER CONVERSION EQUIPMENT – RECOMMENDATIONS –

Part 1: AC power simulators

1 Scope

The purpose of this part of IEC 63106 is to provide recommendations for Low Voltage (LV) AC power simulators used for testing utility interactive photovoltaic power conversion equipment (PCE).

NOTE Low Voltage refers to 1 000 Va.c. and less.

The AC power simulators connect to the AC output power port of a PCE under test and simulate the utility grid by generating comparable AC voltage.

The AC power simulators can be used to test a PCE's utility interaction characteristics, including protection, ride through, immunity and power quality. The requirements and procedures are specified in IEC standards and local utility grid requirements, selected by the network operator, utility, or authority having jurisdiction.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes recommendations 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 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and :instrumentation, for power supply systems and equipment connected thereto*
IEC 61000-4-7:2002/AMD1:2008

IEC TS 61836:2016, *Solar photovoltaic energy systems – Terms, definitions and symbols*

IEC TS 62910:2020, *Utility-interconnected photovoltaic inverters – Test procedure for under voltage ride-through measurements*

IEC TS 63106-2, *Simulators used for testing of photovoltaic power conversion equipment – recommendations – Part 2: DC power simulators*

IEC TS 63217:–[1], *Utility-interconnected photovoltaic (PV) inverters – Test procedure of high-voltage ride-through measurements*

3 Terms, definitions and abbreviated terms

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

[1] Under preparation. Stage at the time of publication: ACD.

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
AC power simulator
system or device able to source and/or absorb AC power, for use in testing of PCE

Note 1 to entry: This document includes a real utility grid, where appropriate, as well as synthetic sources as rotating machines or power converters.

3.2
power conversion equipment
PCE
electrical device converting one form of electrical power to another form of electrical power with respect to voltage, current, frequency, phase and the number of phases

[SOURCE: IEC 62109-1:2010, 3.66]

3.3
port
particular interface of the PCE with external circuits

Note 1 to entry: see Figure 1 for examples of ports.

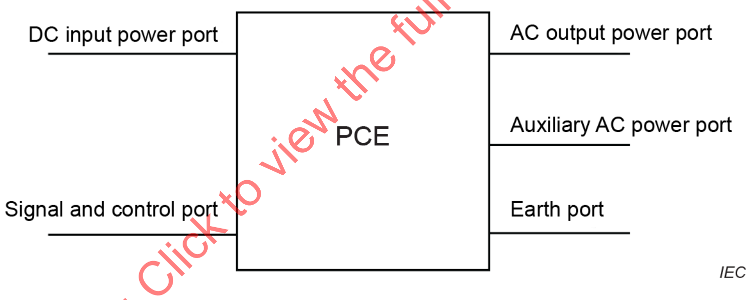

Figure 1 – Examples of ports

3.4
equipment under test
EUT
PCE that is tested by connecting and supplying DC and AC power to each port

3.5
AC output power port
port used to connect to a public low voltage AC mains power distribution network or other low voltage AC mains installation

3.6
DC input power port
port used to connect the PCE to a low voltage DC photovoltaic power generating sub-system

3.7
distributed generation
DG
decentralized power generation system that is connected to the utility grid in a distributed manner

3.8
low voltage
LV
set of voltage levels used for the distribution of electricity

[SOURCE: IEC 60050-601:1985, 601-01-26, modified to delete upper limit voltage]

3.9
high voltage
HV
set of upper voltage levels used in power system for bulk transmission of electricity

[SOURCE: IEC 60050-601:1985, 601-01-27]

3.10
medium voltage
MV
any set of voltage levels lying between low and high voltage

[SOURCE: IEC 60050-601:1985, 601-01-28]

3.11
type test
conformity test made on one or more items representative of the production

[SOURCE: IEC 60050-151:2001, 151-16-16]

3.12
OVRT
over voltage ride through for utility failure durability of operation

3.13
UVRT
under voltage ride through for utility failure durability of operation

3.14
OFRT
over frequency ride through for utility failure durability of operation

3.15
UFRT
under frequency ride through for utility failure durability of operation

3.16
ROCOF
rate of change of power system frequency in Hz/s in the transient period

4 PCE types with respect to AC voltage levels and grid interconnection

In this document, utility interconnected voltage or capacity categories are not specified. PCE based DG may be connected to the utility in any of the voltage ranges described below:

a) High voltage transmission or sub-transmission line connection.
b) Medium voltage distribution line connection.
c) Low voltage distribution line connection, including PCEs for residential use and micro inverter or module integrated electronics.

Figure 2 shows examples of DG systems connected to the utility grid.

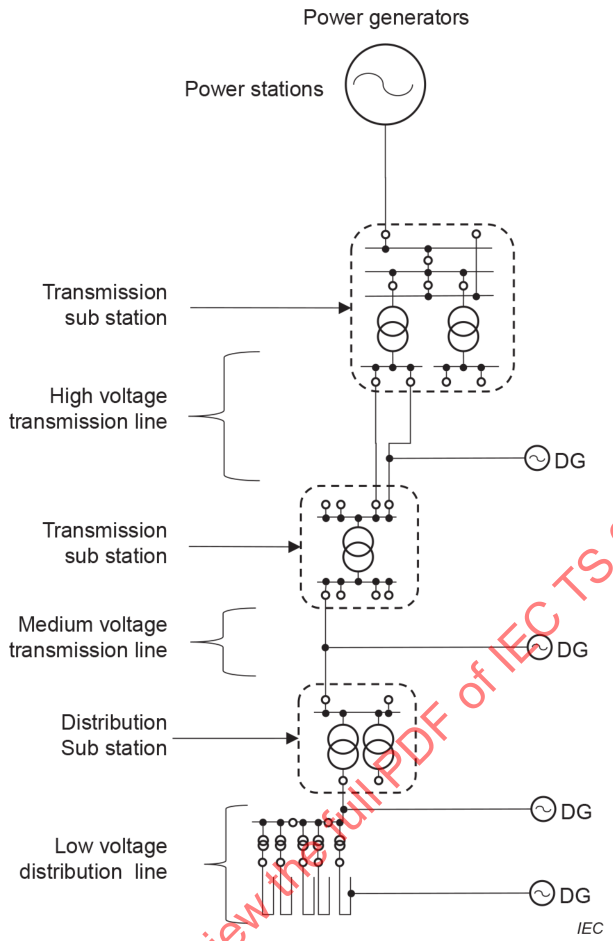

Figure 2 – Example of connection of DG systems to utility grid

Utility-interactive PCEs typically have AC voltage outputs in the range of 100 V to 1 000 V, determined by the input DC voltage window of the PCE or the input voltage from a DC/DC converter. Connections to the utility grid at higher voltages require the use of step-up transformers. Therefore, an upper limit of 1 000 Va.c. for the AC voltage range of a PCE test system is sufficient.

5 Test setup for utility interactive PCEs

5.1 General

In order to realize valid and reproducible testing, the AC power source shall be appropriate for the test being performed. This may mean utilizing an actual power grid, an AC power generator or an electronic AC power simulator depending on the needs of the specific test under consideration. In this document, recommendations of AC power simulators for a wide range of typical utility interconnection tests are described.

Similarly, the DC power source shall be appropriate for the test being performed. This may mean utilizing an actual PV array output, a conventional power supply, or an electronic PV power simulator depending on the needs of the specific test under consideration. Recommendations for DC power simulators are addressed in IEC TS 63106-2.

NOTE Hardware in the loop (HIL) or software to control the voltage and frequency at the EUT output port point by detecting output power (active and reactive) and calculating the voltage and frequency or phase properties by given utility network model with simulated generators and line impedances are discussed and developed. They are not used for type certification tests but still have potential usefulness in the future for testing the performance of multiple DGs in combination with a smart grid.

5.2 Test setup examples for utility interaction test

5.2.1 General

The test system shall be able to simulate steady state and transient utility grid conditions with respect to AC voltage, frequency, line impedance, load, and other conditions as required for the testing. Figure 3 illustrates basic configuration examples for the EUT test system. Here, EUT is the utility interactive PV PCE under test. A DC power simulator is connected to the DC input power port. An AC power simulator is connected to the AC output power port, with other optional impedance and load equipment.

Figure 3 shows only the main power line connections to DC port, AC port in both sides. An earth line may be shared between DC side and AC side devices.

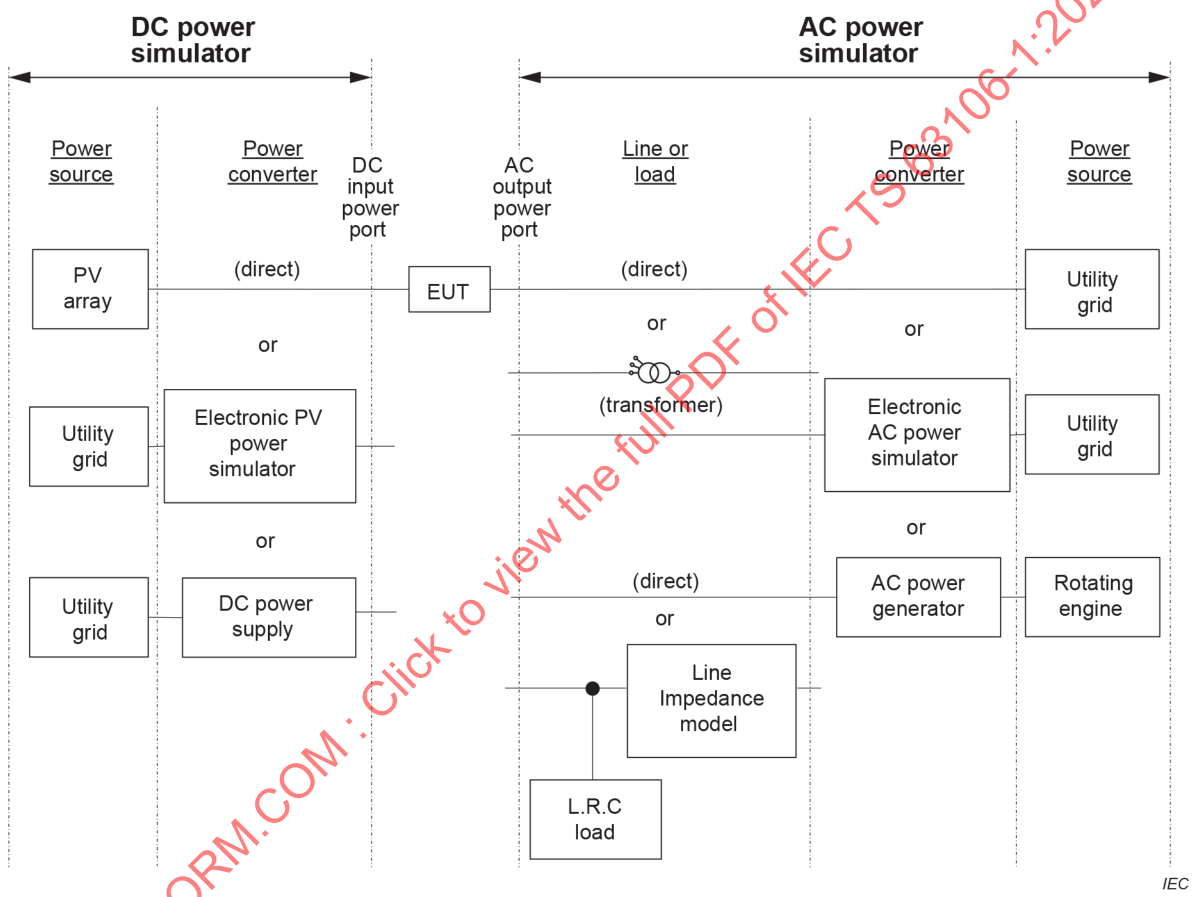

Figure 3 – Examples of fundamental setup of EUT test system

5.2.2 Types of AC power simulator systems

5.2.2.1 General

AC power simulator systems may consist of one or more of the following types of equipment: in 5.2.2 through 5.2.4. Other approaches are possible depending on the test(s) under consideration. As different tests have different power simulator needs, it may be required or optional for a facility to have more than one type of AC power simulator.

The internal resistance of an AC power simulator including connections to the EUT so measured at the EUT AC output power port should be designed referring the real-world distribution and transmission line impedance, for attaining the reasonable test result for power qualities, as harmonics, DC injection, or flicker tests.

5.2.2.2 Utility grid

A simple utility grid connection may be used for certain tests. The utility grid used shall have the right nominal voltage and frequency, appropriate impedance and harmonic distortion levels, and the ability to source or sink adequate active or reactive power for the test(s) under consideration.

5.2.2.3 Utility grid and transformer with tap changer

A transformer with tap changer can change the output voltage of the AC power simulator but only in discrete steps. Some types can be switched under load while others require the transformer to be de-energized before switching. Quick transfer of voltage is realized by using a semiconductor switch for the tap changer. Some types will cause a momentary loss of voltage to the EUT while others do not. These characteristics need to be taken into account when considering this technique for an AC power simulator.

5.2.2.4 Electronic AC power simulator

An electronic AC power simulator uses power electronics to create or modify AC grid voltage. Electronic AC power simulators may be composed of an AC to DC conversion stage followed by a DC to AC conversion stage. Other approaches such as waveform simulation with power amplification are possible. Electronic AC power simulators provide a wide range of capabilities for testing including continuous control of the output AC voltage, phase, and frequency. The electronic AC power simulator provides testing voltage conditions for voltage swells (OVRT) and sag (UVRT) on 1,2 or all 3 phases, and for some types, arbitrary waveform generation. The electronic AC power simulator provides testing frequency conditions for frequency rise (OFRT) and frequency drop (UFRT).

Electronic AC power simulators are typically categorized for three different product groups based on size, including micro PCE, string PCE and central PCE. The fundamental output characteristics of the electronic AC power simulators may depend on the testing power level and the control of switching devices and circuits. For small scale PCE's testing, linear power amplification configurations are well-suited for precise output voltage control. For large scale applications, chopper circuits with bi-directional control are typically used to reduce heat dissipation. For a back-to-back system consisting of a chopper converter and inverter circuit configuration, the output voltage harmonic distortion components are absorbed with sufficient AC filter circuit.

5.2.2.5 Rotating engine and AC power generator

A rotating engine coupled to an AC power generator provides a controllable source isolated from the utility grid. This provides a source independent of utility grid conditions and able to be used at remote sites of PV installations in addition to laboratories. Motor-driven generator systems are capable of continuous control of AC voltage and frequency. Such systems are limited to creating only symmetrical variations (all three phases vary in the same manner).

5.2.3 Load

5.2.3.1 General

For some testing, it is required or important to control the impedance as seen by the EUT. This can be inherent impedance of the AC power simulator, or additional local active or reactive loads or line impedances may be needed.

5.2.3.2 Inherent impedance

All types of AC power simulators have an inherent impedance as seen by the EUT. This impedance is complex and can impact the results of many types of grid interconnection testing. It is important to characterize this impedance, and in some cases compensate for it or alter it through external means.

5.2.3.3 RLC load

An RLC load is used in parallel to the EUT for:

a) Anti-islanding tests that require control over active and reactive power, load balance, and the resonant load quality factor (Q-factor).

NOTE 1 RLC load details for anti-islanding can be found in standards such as IEC 62116 and IEEE 1547.1 .

NOTE 2 In addition to RLC loads, induction motors may be used as a load model. Such motors have tendency to prevent frequency transition with power running and regeneration modes for anti-islanding tests.

NOTE 3 Electronic loads have the capability to simulate the passive RLC elements needed for anti-islanding tests, and in some cases may be regenerative, thus reducing the power consumption of the test system. However, the use of electronic loads in anti-islanding testing is not currently accepted by most standards.

b) Absorbing and dampening active and reactive power flow to the AC power simulator in case it is not capable of absorbing reverse power flow from EUT.

5.2.4 Line impedance

A line impedance may be connected in series between the EUT and AC power simulator depending on the need of the selected test. Examples of the purposes of the line impedance are:

a) An impedance representing distribution line or transmission line inductance and resistance.
b) With by-passing or connecting the impedance in series to line, to make voltage fluctuations at the AC output power port of the EUT intentionally for LVRT test.
c) A blocking impedance to prevent the direct application of surge test voltage to the AC power source system, or to suppress short circuit current from the AC power source system to the short circuit point, preventing system apparatus failure by surge voltage or short circuit current.

6 General recommendations for AC power simulators

6.1 General

6.1.1 Overview

An AC power simulator is permitted to be used as the utility AC power source system. In this clause, test items conducted with AC power simulators, and general recommendations relevant to each of them are described.

All of the recommendations allow for variations based on need of the simulator.

6.1.2 AC main connections

The AC power simulator's phase and neutral supply connections should be compatible with the local country code and standards, and with the EUT.

6.1.3 Output transformer

The output transformer is supplied by EUT testing applicant to adjust AC output voltage, if required.

6.1.4 Number of phases and voltage range

The AC power simulator provides the correct number of phases and conductors for the EUT.

The AC power simulator is able to operate across a voltage range that accommodates the UVRT and OVRT tests required based on the nominal voltage of the EUT.

For UVRT test, refer to IEC TS 62910:2020.

For OVRT test, refer to IEC TR 63217.

6.1.5 Frequency ranges supplied to EUT

Considering that PV PCEs are installed in all global regions, testing at both 50 Hz and 60 Hz is desirable.

The AC power simulator shall be able to operate across a frequency range that accommodates the OFRT and UFRT.OFRT tests based on the nominal frequency of the EUT.

6.1.6 Voltage stability and accuracy

The AC simulator shall be able to operate at voltage set points with an accuracy as specified by the interconnection standards being tested.

The stability of the voltage may also be important for some tests and may be specified by the test standards.

6.1.7 Frequency stability and accuracy

The AC power simulator shall be able to operate at frequency set points with an accuracy as specified by the interconnection standards being tested.

The stability of the frequency may also be important for some tests and may be specified by the test standards.

6.1.8 AC output voltage harmonic distortion

The typical AC output voltage harmonic distortion requirement is indicated in Table 1.

The interconnection standards may have different requirements.

The voltage harmonics are measured before the EUT is connected.

U1 is the fundamental component of the rated output voltage.

Table 1 – Typical maximum harmonic voltage distortion (as per IEC 61000-4-7:2002)

Harmonic number	% of U1
3	0,9
5	0,4
7	0,3
9	0,2
2 to 10 (even harmonics)	0,2
11 to 40	0,1

It is important to test the output power quality, see independent standards and documents per each local requirement.

Total harmonic distortion value may also be specified by independent interconnection standards for each region of power system.

6.1.9 Signal interface for hardware in the loop

As an optional function, an interface may be included to allow the AC power simulator to be controlled by a Real Time Digital Simulator/Hardware in the Loop Simulator, so that testing capabilities can be extended to specific voltage-frequency profiles or scenarios.

6.1.10 Durability against impulse test voltage

Surge voltage is induced to the AC output power port and DC input power port of the EUT during normal rated or reduced power operation. The AC power simulator should be durable against the impulse test voltages at the EUT AC output power port or DC input power port, either line to line or line to ground.

NOTE Impulse voltage and wave forms may be referenced from standards such as IEC 61000-4-4, IEC 61000-4-5, IEC 61643-11, IEEE C62.45, or IEEE C62.41.2.

6.1.11 Other requirements for test properties

6.1.11.1 General

The requirements shown below are to be confirmed for the test(s) under consideration.

6.1.11.2 AC phase-to-neutral voltage balance

The AC output phase-to-neutral voltage balance for a three-phase system is specified as per test requirement.

6.1.11.3 AC output phase control range and accuracy

The AC phase timing accuracy of the change and recovery of voltage or frequency are specified as per test requirement.

6.1.11.4 AC phase displacement to voltage balance

The AC output phase displacement to voltage balance is specified as per test requirement.

6.1.11.5 AC output voltage/frequency step change rate

The AC output voltage/frequency step change rate are specified as per test requirement.

6.2 AC power simulator performance and characteristics

Characteristics and performance of an AC power simulator are important for each specific test. The desired characteristics are indicated in Table 2 through Table 23. Refer to local or national grid connection codes for detailed specific requirements.

The characteristics recommended in Table 2 through Table 23 should be maintained over the full range of conditions as applicable for the test specification.

NOTE 1 Test items for utility interactive PCEs are based on IEC TS 62786-1:2017, where requirements are developed under close relationship with EN 50549 series. PCEs requirements for active and reactive power output functions are developed reflecting the local utility experience and studies in UL1741SA, IEEE 1547.1, and FGW PART3 (TG3) in parallel.

NOTE 2 Abbreviations used in the tables are: P for active power, Q for reactive power, S for apparent power, PF for power factor, OV for over voltage, UV for under voltage, OF for over frequency, UF for under frequency, Iq for reactive current and ROCOF for rate of change of frequency.

**Table 2 – Grid qualification/Requalification –
In-range voltage before connection/reconnection**

Short description of test	Before the EUT connection and injecting energy into the AC power simulator, the AC voltage is raised or lowered from below or above the interconnection voltage range threshold at which the EUT output switch should close and then start generation. Typically, not required to be done at full power and often signal injection methods are allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC voltage	- RMS voltage continuously variable across a range that covers the interconnection voltage thresholds of all relevant standards, typically requiring ± 20 % around V_{nom}. - for interconnection voltage tests, need to be able to ramp V_{rms}		
Steady frequency and phase	- During the voltage ramps, the frequency and phase shall remain unchanged.		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Voltage not variable
Utility grid and transformer	None		Voltage not variable
Utility grid, transformer, and tap changer	Partial	Tap changer can do step changes for interconnection voltage testing.	Interconnection voltage testing with ramp or small steps is required.
Electronic AC power simulator	Good	Able to program V_{rms} ramps and small step changes, while holding frequency and phase steady. For signal injection a small simulator may be used.	
Rotating AC power generator	Partial	Able to control to create V_{rms} ramps	Steadiness of frequency may be marginal. Unable to create defined step changes.

Table 3 – Grid qualification/Requalification – In-range frequency before connection/reconnection

Short description of test	Before the EUT connection and injecting energy into the AC power simulator, the AC frequency is raised or lowered from below or above the interconnection frequency range threshold that the EUT output switch should close and then start generation. Typically, not required to be done at full power and often signal injection methods are allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC frequency	- Frequency continuously variable across a range that covers the interconnection frequency thresholds of all relevant standards, typically requiring ± 10 % around F_{nom}. - for interconnection frequency tests, need to be able to ramp frequency.		
Steady frequency and phase	- During the frequency ramps, the voltage shall remain unchanged and no phase jump.		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Frequency not variable
Utility grid and transformer	None		Frequency not variable
Utility grid, transformer, and tap changer	None		Frequency not variable
Electronic AC power simulator	Good	Able to program frequency ramps and small step changes, while holding voltage steady. For signal injection a small simulator may be used.	
Rotating AC power generator	Partial	Able to control to create frequency ramps	Steadiness of voltage may be marginal. Unable to create defined small step changes.

Table 4 – Power capability: Nameplate P, Q, S under normal and near-normal grid conditions

Short description of test	After the connection to the AC power simulator, the EUT input is raised to the rated maximum power point of the PV array to check that the EUT is operating at rated output active power under normal and near-normal grid conditions. EUT operation set point or grid voltage is adjusted, to check that the EUT is operating at rated output reactive and apparent power as designed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Steady AC voltage	- During the power capability tests, the voltage shall remain unchanged. - For voltage deviation to reactive power tests, need to be able to adjust voltage.		
Steady frequency and phase	- During the power capability tests, the frequency and phase shall remain unchanged.		
Power	- Simulator power shall cover EUT active, reactive and apparent power rating. The power is injected into the AC power simulator or consumed by parallel loads, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Partial	Able to absorb the active and reactive power.	Voltage not variable
Utility grid and transformer	Partial	Able to absorb the active and reactive power.	Voltage not variable
Utility grid, transformer, and tap changer	Good	Able to absorb the active and reactive power. Voltage variable.	Voltage tap adjustment to the setpoint is needed for the voltage change by reactive current with the transformer impedance.
Electronic AC power simulator	Good	Able to program the voltage steadily.	The power is absorbed into the AC power simulator or consumed by parallel loads
Rotating AC power generator	Partial	Able to adjust voltage.	Voltage adjustment for voltage rise by reactive current and AC power generator impedance is needed. The power is absorbed into the AC power generator or consumed by parallel loads

Table 5 – Power capability: Limitation of P/Q/S/PF by setpoint

<table>
<tr><td>Short description of test</td><td colspan="3">After the connection to the AC power simulator, the EUT input is raised to the rated maximum power point of photovoltaic array to check that the EUT is operating at limited set point output P under normal and near-normal grid conditions. EUT operation set point is adjusted, to check that the EUT is operating at rated output reactive, apparent power and power factor as designed. Sometimes, photovoltaic array I-V curve has a maximum power point exceeding the EUT rated input power. In that case, EUT is checked to operate at rated output power.</td></tr>
<tr><td>Important AC power simulator attributes for this specific test</td><td colspan="3">Important aspects of the simulator attribute</td></tr>
<tr><td>Steady AC voltage</td><td colspan="3">- During the limitation by setpoint- tests, the voltage shall remain unchanged.
- For voltage deviation to reactive power under the setpoint tests, need to be able to adjust voltage.</td></tr>
<tr><td>Steady frequency and phase</td><td colspan="3">- During the limitation by setpoint- tests, the frequency and phase shall remain unchanged.</td></tr>
<tr><td>Power</td><td colspan="3">- Simulator power shall cover EUT active, reactive and apparent power rating. The power is injected into the AC power simulator or consumed by parallel loads, allowing a range of techniques.</td></tr>
<tr><td></td><td>Usability</td><td>Capabilities and benefits</td><td>Drawbacks</td></tr>
<tr><td>AC utility grid</td><td>Partial</td><td>Able to absorb the active and reactive power.</td><td>Voltage not variable</td></tr>
<tr><td>Utility grid and transformer</td><td>Partial</td><td>Able to absorb the active and reactive power.</td><td>Voltage not variable</td></tr>
<tr><td>Utility grid, transformer, and tap changer</td><td>Good</td><td>Able to absorb the active and reactive power.
Voltage variable.</td><td>Voltage tap adjustment to the setpoint is needed for the voltage change by reactive current with the transformer impedance.</td></tr>
<tr><td>Electronic AC power simulator</td><td>Good</td><td>Able to program the voltage steadily.</td><td>The power is absorbed into the AC power simulator or consumed by parallel loads.</td></tr>
<tr><td>Rotating AC power generator</td><td>Partial</td><td>Able to adjust voltage.</td><td>Voltage adjustment for voltage rise by reactive current and AC power generator impedance is needed.
The power is absorbed into the AC power generator or consumed by parallel loads</td></tr>
</table>

Table 6 – Power capability: Ramp rate or soft start time-developing magnitude by set rate

Short description of test	Before the AC connection, the EUT input irradiance parameter is raised to the I-V characteristic with rated maximum power point of photovoltaic array. The AC power simulator is operated with nominal voltage and frequency. Then, EUT is started by manual command or automatic sequence to check that the EUT starts operation at the expected ramp rate or soft start rate.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Steady AC voltage	- During the ramp rate or soft start tests, the voltage shall remain unchanged.		
Steady frequency and phase	- During the ramp rate or soft start tests, the frequency and phase shall remain unchanged.		
Power	- Simulator power shall cover EUT active, reactive and apparent power rating. The power is injected into the AC power simulator or consumed by parallel loads, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Good	Able to absorb the active and reactive power.	
Utility grid and transformer	Good	Able to absorb the active and reactive power.	
Utility grid, transformer, and tap changer	Good	Able to absorb the active and reactive power. Voltage variable.	
Electronic AC power simulator	Good	Able to program voltage steady.	
Rotating AC power generator	Good	Able to adjust voltage.	

**Table 7 – Grid protection tests –
AC over-voltage (OV) and under-voltage (UV) trip tests**

Short description of test	With the EUT injecting energy into the AC power simulator, the AC voltage in all phases (symmetrical) or on one or two phases (asymmetrical) is raised or lowered far enough above or below the nominal interconnection voltage that the EUT's grid OV or UV protection should trip, in a specified time. Typically, not required to be done at full power and often signal injection methods are allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC voltage	- RMS voltage continuously variable across a range that covers the voltage disconnection thresholds of all relevant standards, typically requiring ± 20 % around V_{nom}; - for trip magnitude tests, need to be able to ramp V_{rms}; - for trip time tests, need to be able to implement a step change of V_{rms} by a defined amount.		
Steady frequency and phase	- During the voltage ramps and step changes the frequency and phase shall remain unchanged.		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques.		
Usability of AC Power Simulator Types	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Voltage not variable
Utility grid and transformer	None		Voltage not variable
Utility grid, transformer, and tap changer	Partial	Tap changer can do step changes for trip time testing	Not able to be used for trip magnitude testing due to inability to ramp
Electronic AC power simulator	Good	Able to program V_{rms} ramps and step changes, while holding frequency and phase steady. For signal injection, a very small simulator may be used.	
Rotating AC power generator	Partial	Able to control to create V_{rms} ramps.	Steadiness of frequency may be marginal Unable to create defined step changes

Table 8 – Grid protection tests: OF/UF trips

Short description of test	With the EUT injecting energy to the AC power simulator, the AC frequency is raised or lowered far enough above or below the nominal interconnection frequency that the EUT's grid OF or UF protection should trip, in a specified time. Typically, not required to be done at full power and often signal injection methods are allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC frequency	- Frequency continuously variable across a range that covers the frequency disconnection thresholds of all relevant standards, typically requiring ±10 % around F_{nom}. - For trip frequency tests, need to be able to ramp Frequency. - For trip time tests, need to be able to implement a step change of frequency by a defined step. - For application for specific islands, OF/UF trip threshold in connection with frequency ride-through area is as wide as ± 15 %, which is 60 Hz at the rated to 50 Hz at the bottom.		
Steady voltage	- During the frequency ramps and step changes the voltage shall remain unchanged.		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Frequency not variable
Utility grid and transformer	None		Frequency not variable
Utility grid, transformer, and tap changer	None		Frequency not variable
Electronic AC power simulator	Good	Able to program frequency ramps and step changes, while holding voltage steady. For signal injection a very small simulator may be used.	
Rotating AC power generator	Partial	Able to control to create frequency ramps.	Steadiness of frequency may be marginal Unable to create defined step changes

Table 9 – Grid protection tests: Anti-islanding

<table>
<tr><td>Short description of test</td><td colspan="3">With the EUT injecting energy to the AC power simulator and L-C-R loads, the AC voltage and frequency are set to nominal values. EUT generation and load consumption powers are adjusted to be balanced and designated near-balanced points.
Then AC power simulator is switched off, EUT and the load make an islanding situation.
Typically, not required to be done at full power and often signal injection methods are allowed.
- For the PCE with grid-support functions with active and reactive power control by PCE terminal AC voltage or frequency, anti-islanding test is conducted with and without the functions.
- For the PCE with voltage and frequency ride thorough functions, anti-islanding test is conducted with the functions.</td></tr>
<tr><td>Important AC power simulator attributes for this specific test</td><td colspan="3">Important aspects of the simulator attribute</td></tr>
<tr><td>Steady AC frequency</td><td colspan="3">- For adjusting the reactive and active power before the islanding situation by switching off the AC power simulator, frequency shall remain unchanged.</td></tr>
<tr><td>Steady voltage</td><td colspan="3">- For adjusting the reactive and active power before the islanding situation by switching off the AC power simulator, voltage shall remain unchanged.</td></tr>
<tr><td>Power</td><td colspan="3">- Simulator power may be a small percentage of EUT rated output, allowing a range of techniques.</td></tr>
<tr><td>R-L-C load</td><td colspan="3">- R-L-C load shall be adjustable to make active and reactive power flow balance between the EUT output and the power system.
- According to the test requirement, L and C load capacities are chosen to make designated L-C resonance strength at system frequency to disturb the islanding detection.
-For regional requirements, induction motor is used combined with R-L-C load that have characteristic to prevent frequency transition with power running and regeneration properties instead of L-C load resonance method.</td></tr>
<tr><td></td><td>Usability</td><td>Capabilities and benefits</td><td>Drawbacks</td></tr>
<tr><td>AC utility grid</td><td>Good</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Utility grid and transformer</td><td>Good</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Utility grid, transformer, and tap changer</td><td>Good</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Electronic AC power simulator</td><td>Good</td><td>Able to program frequency and voltage steady</td><td></td></tr>
<tr><td>Rotating AC power generator</td><td>Good</td><td></td><td>Steadiness of frequency may be marginal</td></tr>
</table>

Table 10 – Grid protection tests: ROCOF trips

Short description of test	With the EUT injecting energy to the AC power simulator, the AC frequency is quickly raised or lowered with a designated inclination in a specified time. Typically, not required to be done at full power and often signal injection methods are allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC frequency	- Frequency stepwise or linearly variable across a range that covers the ROCOF disconnection thresholds of all relevant standards, typically requiring under ± 3 Hz/s. - For trip time tests, need to be able to implement a step or linear change of frequency with time by a defined inclination.		
Steady voltage	- During the frequency changes, the voltage shall remain unchanged		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Frequency not variable
Utility grid and transformer	None		Frequency not variable
Utility grid, transformer, and tap changer	None		Frequency not variable
Electronic AC power simulator	Good	Able to program frequency linear and step changes, while holding voltage steady. For signal injection a very small simulator may be used.	
Rotating AC power generator	Partial	Able to control to create frequency quick change but may be non-linear.	Steadiness of frequency may be marginal Unable to create defined step changes

Table 11 – Grid protection tests: Open phase

Short description of test	With the EUT injecting energy to the AC power simulator, a selected single-phase line in multi-phase system of the EUT output is switched-off. The remaining two-phase lines are energized. Typically, not required to be done at full power and often lower as 5 % of rated output power is allowed.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC frequency	Before and after the single-phase line disconnection, the AC power simulator shall supply the rated frequency to operate the EUT at the specified power level		
Steady voltage	Before and after the single-phase line disconnection, the AC power simulator shall supply the rated voltage to operate the EUT at the specified power level.		
Power	- Simulator power may be a small percentage of EUT rated output, allowing a range of techniques		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Good		Frequency not variable
Utility grid and transformer	Good		Frequency not variable
Utility grid, transformer, and tap changer	Good		Frequency not variable
Electronic AC power simulator	Good	Able to program frequency and voltage steady	
Rotating AC power generator	Good		

Table 12 – Power quality tests: Current harmonics, inter-harmonics, THDi

<table>
<tr><td>Short description of test</td><td colspan="3">With the EUT injecting energy to the AC power simulator, the AC frequency and voltage is kept steady. Typically, required to be done at full and reduced power.
The connection cable and AC power simulator absorb the 2_{nd} to 40_{th}, and higher order of harmonics, and not produce voltage harmonics.
As real grid has impedance depend on its configuration and length by the installation site, impact to line voltage harmonics is estimated and evaluated by system operator or by line impedance data.</td></tr>
<tr><td>Important AC power simulator attributes for this specific test</td><td colspan="3">Important aspects of the simulator attribute</td></tr>
<tr><td>Steady AC frequency</td><td colspan="3">- During the inter-harmonics test, frequency shall remain unchanged.</td></tr>
<tr><td>Steady voltage</td><td colspan="3">- During the inter-harmonics test, voltage shall remain unchanged.</td></tr>
<tr><td>Low voltage harmonics distortion</td><td colspan="3">- During the inter-harmonics test, voltage harmonics components and THDi shall be low.
- Voltage harmonic distortion for AC power simulator is measured and evaluated, as the background noise for the test, when the EUT is not connected.</td></tr>
<tr><td>Power capacity</td><td colspan="3">- AC power simulator power shall be the same or larger than EUT rated output.</td></tr>
<tr><td></td><td>Usability</td><td>Capabilities and benefits</td><td>Drawbacks</td></tr>
<tr><td>AC utility grid</td><td>Partial</td><td>Select low distortion, clean voltage waveform time-period, such as midnight</td><td>Frequency not variable</td></tr>
<tr><td>Utility grid and transformer</td><td>Partial</td><td>Select low distortion, clean voltage waveform time-period, such as midnight</td><td>Frequency not variable</td></tr>
<tr><td>Utility grid, transformer, and tap changer</td><td>Partial</td><td>Select low distortion, clean voltage waveform time-period, such as midnight</td><td>Frequency not variable</td></tr>
<tr><td>Electronic AC power simulator</td><td>Good</td><td>Able to program the voltage stable</td><td></td></tr>
<tr><td>Rotating AC power generator</td><td>Partial</td><td>Able to control the frequency unchanged</td><td>Low harmonic distortion of voltage may be marginal depending on the generator output capacity</td></tr>
</table>

Table 13 – Power quality tests: Flicker (continuous)

Short description of test	With the EUT injecting energy to the AC power simulator, the AC frequency and voltage is kept steady. This test is confirming that the AC voltage flicker is under the required values with referred standards. Typically, the test is required to be done at full power. Voltage flicker test result is treated as for reference which is field-dependent.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Steady AC frequency	- During the flicker test, frequency shall remain unchanged.		
Steady voltage	- During the flicker test, voltage shall remain unchanged.		
Low voltage harmonics distortion	- During the flicker test, voltage flicker and harmonics components shall be low.		
Power	- AC power simulator power capacity shall be the same or larger than EUT rated output.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Partial	Select low distortion, clean voltage waveform period, such as midnight	Frequency not variable
Utility grid and transformer	Partial	Select low distortion, clean voltage waveform period, such as midnight	Frequency not variable
Utility grid, transformer, and tap changer	Partial	Select low distortion, clean voltage waveform period, such as midnight	Frequency not variable
Electronic AC power simulator	Partial	Able to program the frequency stable	
Rotating AC power generator	Partial	Able to control the frequency unchanged	Low harmonic distortion of voltage may be marginal depending on the generator output capacity

Table 14 – Power quality tests: Current inrush (at connection switch close)

<table>
<tr><td>Short description of test</td><td colspan="3">Before injecting energy to the AC power simulator, the AC frequency and voltage is kept steady. Three phases of voltage are kept balanced. Connection switch to the grid placed inside or outside of the EUT is closed to see the inrush current waveform with peak, time to peak, and defined cycle period-RMS. If output transformer is installed inside of the EUT, it is required to be measured at the utility side of the transformer to determine the inrush current at the switch closing.</td></tr>
<tr><td>Important AC power simulator attributes for this specific test</td><td colspan="3">Important aspects of the simulator attribute</td></tr>
<tr><td>Steady AC frequency</td><td colspan="3">- During the current inrush test, frequency shall remain unchanged.</td></tr>
<tr><td>Steady voltage</td><td colspan="3">- Before the test, the voltage should be the EUT nominal voltage, except some standards may require testing at high end of the line voltage range.
- During the inrush, some voltage dip will occur depending on line impedance. The standards may specify the line impedance for this test.</td></tr>
<tr><td>voltage balance</td><td colspan="3">- During the current inrush test, three phase voltages relative angle and amplitude are balanced.</td></tr>
<tr><td>Power</td><td colspan="3">- AC power simulator power capacity shall be the same or larger than EUT rated output.</td></tr>
<tr><td></td><td>Usability</td><td>Capabilities and benefits</td><td>Drawbacks</td></tr>
<tr><td>AC utility grid</td><td>Good</td><td>Able to supply natural inrush current of the EUT</td><td>Frequency not variable</td></tr>
<tr><td>Utility grid and transformer</td><td>Good</td><td>Able to supply natural inrush current of the EUT</td><td>Frequency not variable</td></tr>
<tr><td>Utility grid, transformer, and tap changer</td><td>Good</td><td>Able to supply natural inrush current of the EUT</td><td>Frequency not variable</td></tr>
<tr><td>Electronic AC power simulator</td><td>Good</td><td>Almost able to supply natural inrush current of the EUT, but it depends on the AC power simulator capacity rating</td><td></td></tr>
<tr><td>Rotating AC power generator</td><td>Good</td><td>Able to supply natural inrush current of the EUT</td><td>Compatibility with 50/60 Hz may be marginal depending on the generator</td></tr>
</table>

Table 15 – Power quality tests: Current imbalance

Short description of test	With the EUT injecting energy to the AC power simulator, the AC frequency and voltage is kept steady. Three phases of voltage are kept valanced. Current imbalance is measured. Typically, required to be done at full and reduced power.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Steady frequency	- During the current imbalance test, frequency shall remain unchanged.		
Steady voltage	- During the current imbalance test, voltage shall remain unchanged.		
voltage valance	- During the current imbalance test, three phase voltages relative angle and amplitude are balanced.		
Power	- AC power simulator power capacity shall be the same or larger than EUT rated output.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Partial	Select balanced voltage waveform period, such as midnight	Frequency not variable
Utility grid and transformer	Partial	Select balanced voltage waveform period, such as midnight	Frequency not variable
Utility grid, transformer, and tap changer	Partial	Select balanced voltage waveform period, such as midnight	Frequency not variable
Electronic AC power simulator	Good	Able to program the valanced three phase voltage	
Rotating AC power generator	Partial	Able to supply valanced voltage waveform	may be marginal depending on the generator

Table 16 – Power quality tests: Transient OV on load dump

Short description of test	With the EUT injecting energy into the AC power simulator, the connection to the simulator is suddenly opened, which tends to cause a transient overvoltage on the EUT output terminals. In many standards the magnitude and duration of that overvoltage transient are subject to limits. This test may also require a resistive load between the EUT and the AC simulator if the simulator cannot sink load current, or if the test requires a residual load level after the connection to the simulator is opened.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Steady AC frequency	Before disconnection, the simulator shall supply the correct frequency to operate the EUT at the specified power level		
Steady voltage	Before disconnection, the simulator shall supply the correct voltage to operate the EUT at the specified power level		
R-Load	- R-load shall be adjustable to the required values for load dump test - R-load shall withstand the estimated peak voltage and power during the test		
Power	- AC power simulator power capacity shall be the same or larger than EUT rated output.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	Good	With switches to open the AC power simulator and to change the R-load capacity	
Utility grid and transformer	Good	With switches to open the AC power simulator and to change the R-load capacity	
Utility grid, transformer, and tap changer	Good	With switches to open the AC power simulator and to change the R-load capacity	
Electronic AC power simulator	Good	With switches to open the AC power simulator and to change the R-load capacity	
Rotating AC power generator	Good	With switches to open the AC power simulator and to change the R-load capacity	

Table 17 – Grid support tests: UV/OV ride-through with/without Iq injection

Short description of test	With the EUT injecting energy to the AC power simulator, the AC voltage is quickly dipped below or raised above the normal operating range on one, two and phases (symmetrical), for a defined period of time, and then come back into the normal operation range. The EUT should be able to remain connected, continue to inject reactive current, depending on the grid code requirements, and then resume normal operation after the simulated UV/OV event. 100 % or 90 % or output is required.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC voltage	- Ability to create one, two, or all phases voltage dip or rise, with defined transition time. - Ability to hold the dip or rise voltage for the defined period. - Ability to return to normal voltage range with defined transition time.		
Voltage phase behaviour	- During the UV/OVRT event, AC voltage phase to phase angles shall change in a manner that simulates the behaviour seen by the EUT when a fault occurs on the distribution or transmission network (see IEC TS 62910:2020).		
Impedance	- During the UV/OVRT event, for testing to grid codes that require continued reactive current injection, the impedance of the AC power simulator and connection cable to the EUT shall be low enough to maintain the voltage dip level within acceptable tolerances.		
Usability of AC power simulator types	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Voltage not variable
Utility grid and transformer	None		Voltage not variable
Utility grid, transformer, and tap changer	None	Tap changer can do voltage changes.	
Electronic AC power simulator	Good	Able to program V_{rms} with step changes with phase to phase angle changes, while holding the frequency steady.	
Rotating AC power generator	Partial		Steadiness of frequency may be marginal Unable to create defined step changes

Table 18 – Grid support tests: UF/OF ride-through

<table>
<tr><td>Short description of test</td><td colspan="3">With the EUT injecting energy to the AC power simulator, the AC frequency falls / rises from the normal operating range, for a defined period of time, and then come back to the normal operation range. The EUT should be able to remain connected, continue to inject active power, depending on the grid code requirements, and then resume normal operation after the simulated UF/OF event.</td></tr>
<tr><td>Important AC power simulator attributes for this specific test</td><td colspan="3">Important aspects of the simulator attribute</td></tr>
<tr><td>Variable frequency with time</td><td colspan="3">- Ability to create frequency falls and rises, with defined inclination with time
- Ability to hold the low or high frequency for the defined period
- Ability to return to normal frequency with defined inclination with time</td></tr>
<tr><td>Stable voltage</td><td colspan="3">- During the UF/OF ride through test, voltage shall remain unchanged</td></tr>
<tr><td>Power</td><td colspan="3">- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques</td></tr>
<tr><td></td><td>Usability</td><td>Capabilities and benefits</td><td>Drawbacks</td></tr>
<tr><td>AC utility grid</td><td>None</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Utility grid and transformer</td><td>None</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Utility grid, transformer, and tap changer</td><td>None</td><td></td><td>Frequency not variable</td></tr>
<tr><td>Electronic AC power simulator</td><td>Good</td><td>Able to program frequency linear and step changes, while holding voltage steady.
For signal injection a small simulator may be used.</td><td></td></tr>
<tr><td>Rotating AC power generator</td><td>Partial</td><td>Able to control to create frequency quick change but may be on-linear.</td><td>Steadiness of frequency may be marginal
Unable to create defined step changes</td></tr>
</table>

Table 19 – Grid support tests: ROCOF ride-through

Short description of test	With the EUT injecting energy to the AC power simulator, the AC frequency is quickly raised or lowered with a designated linear inclination in a specified time. Typically, not required to be done at full power but main circuit should be energized.		
Important AC power simulator attributes for this specific test	Important aspects of the simulator attribute		
Variable AC frequency	- Frequency quick and linearly variable across a range that covers the ROCOF disconnection thresholds of all relevant standards, typically requiring under ± 3 Hz/s. - For trip time tests, need to be able to implement a linear change of frequency by a defined inclination.		
Steady voltage	- During the frequency changes, the voltage shall remain unchanged.		
Power	- Simulator power may be signal level, or a small percentage of EUT rated output, allowing a range of techniques.		
	Usability	Capabilities and benefits	Drawbacks
AC utility grid	None		Frequency not variable
Utility grid and transformer	None		Frequency not variable
Utility grid, transformer, and tap changer	None		Frequency not variable
Electronic AC power simulator	Good	Able to program frequency linear and step changes, while holding voltage steady. For signal injection a very small simulator may be used.	
Rotating power generator	Partial	Able to control to create frequency change but may be non-linear.	Unable to create defined quick changes