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DESIGN QUALIFICATION AND TYPE APPROVAL OF INVERTERS FOR GRID-CONNECTED OPERATION OF PHOTOVOLTAIC POWER GENERATORS

DUTCH GUIDELINES

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Abstract

In the Netherlands and worldwide, the installation of grid-connected PV-systems is rapidly gaining pace and volume. This makes the need for regulations of the requirements of grid-connected PV inverters urgent.

This document lays down requirements and recommendations for the design qualification and type approval of inverters for grid-connected operation of photovoltaic power generators with a current up to and including 16 A per phase for single or three phase power conditioners (max. 11 kVA) feeding into the utility low-voltage mains. Inverters up to 5 kVA can be single-phase connected, and only a minimum level of protection is required. Islanding prevention is considered to be implemented with sufficient safety and at low costs by using a window for grid voltage and frequency, as well as the frequency shift method.

The document addresses the design of grid connected PV-inverters with regard to performance, electromagnetic compatibility (EMC), safety, utility interface protection and reliability. It describes the applicable standards for the design as well as for the experimental verification of a number of aspects related to the items above mentioned.

This document can be used by manufacturers in the design process, by testing institutes for research and development and by certification bodies for type approval.

Preface

This document has been written to provide input as the Dutch Guidelines firstly to the National Committee NEC 82, and secondly also to the International Committee TC 82 (WG 3) of the International Electrotechnical Commission (IEC) and CENELEC.
At various phases of the editing process, this document was presented to the members of the NEC 82, for comments and for their suggestions on the structure and implementation of this document.

Key Words

PV inverters, Guideline of PV inverters, Energy efficiency, Maximum power point efficiency, performance

CONTENTS

1. SCOPE AND OBJECTIVE

This document specifies requirements and recommendations for the design qualification and type approval of inverters for grid-connected operation of photovoltaic power generators with a current up to and including 16 A per phase for single or three phase power conditioners (max. 11 kVA) feeding into the utility low-voltage mains.

The document addresses the design of grid connected PV-inverters with regard to performance, electromagnetic compatibility (EMC), safety, utility interface protection and reliability. It describes the applicable standards for the design as well as for the experimental verification of a number of aspects related to the above mentioned items.

This document may be used by manufacturers in the design process, by testing institutes for research and development and by certification bodies for type approval.

2. PROCEDURE FOR TYPE APPROVAL

The type approval of the PV inverter shall be carried out in compliance with the criteria as described in Annex A. The manufacturer must provide the exact values of the inverter's specifications in tabular form to the testing institute before testing of the particular inverter type begins.

For some PV inverters it is possible to provide more power than their rated output power for a short time. If a PV inverter operates at a level above its specified rated power value for a short time, the PV inverter must be tested up to this level of the available power value. This operating level can be up to 120% of the rated output power.

For grid-connected inverters it is important to measure maximum power point tracking (MPPT) performance under varying outdoor conditions using a PV array. Outdoor measurements have the advantage that the actual (MPPT) behaviour can be observed with the real PV array thus avoiding potentially unrealistic simulation of the interactions between the MPPT and PV array simulator.

The test procedures shall be in compliance with the annexes of this document.

3. DEFINITIONS

3.1 PV Inverter

A power converter transforming DC voltage and current of the PV generator into single-phase or multi-phase AC voltage and current.

3.2 Rated value

A specified value for the electrical, thermal, mechanical and environmental quantities assigned by the manufacturer to define the operating conditions under which a PV inverter is expected to give satisfactory service.

3.3 Rated DC current

The maximum DC current specified by the manufacturer as the basis of rating.

3.4 Rated DC voltage

The maximum DC voltage specified by the manufacturer as the basis of rating.

3.5 Open-circuit voltage under standard test conditions (U_{oc_STC})

The open circuit voltage of a PV module, string or array under STC.

3.6 Short-circuit current under standard test conditions (I_{sc_STC})

The output current of a photovoltaic device in short-circuit condition.

3.7 Input voltage operating range

Input DC voltage range in which the power conditioner operates in a stable way.

3.8 MPPT-input voltage range

The range of input voltage in which the inverter's MPP-tracker adequately follows the MPP.

3.9 Output voltage

The r.m.s. AC voltage between the output terminals.

3.10 Output current

The r.m.s. AC current from the output terminals.

3.11 Output power (W)

The active power (the sum of the power of the fundamental frequency components of voltage, current and power) from the output terminals

3.12 Rated continuous output power

The rated continuous output power $P_{rat,AC}$ of PV inverter shall be regarded as the rating which defines the output power which can be taken from the inverter under continuous operation without exceeding any of the limitations of established standards (which apply to various components of a PV inverter unit) or incurring structural failure.

3.13 Rated output current

The maximum output current specified by the manufacturer as the basis of rating.

3.14 Rated output voltage

The maximum output voltage specified by the manufacturer as a basis for rating.

3.15 Stand-by loss

For a utility interactive power conditioner, this is the active and reactive power drawn from the utility grid when the power conditioner is in stand-by mode.

3.16 Energy efficiency

The ratio of output energy to input energy during an identified period.

3.17 Maximum Power Point Tracking (MPPT)

A control strategy whereby the power conditioner input power is always at or near the maximum power point of the PV array

3.18 MPPT energy efficiency

The fraction of actual energy from the PV array to the maximum available energy at the MPP within the measurement interval T_M

3.19 STC (**S**tandard **T**est **C**onditions)

1000 W/m^2 perpendicular irradiance in the plane of module, module temperature 25°C and a spectral distribution of irradiance according to Air Mass 1.5.

4. NORMATIVE REFERENCES

IEC 68-2-2	1974	Basic environmental testing procedures. Part 2: Tests-Tests B: Dry heat
IEC 68-2-3	1984	Basic environmental testing procedures. Part 2. Tests-Test Ca: Damp head, steady state.
IEC 146-1-1	1991	Semiconductor converters-General requirements and line commutated converters. Part 1-1: Basic requirements
IEC 146-1-2	1991	Semiconductor converters-General requirements and line commutated converters. Part 1-2: Application guide
IEC 1215	1993	Crystalline silicon terrestrial photovoltaic(PV) modules-Design qualification and type approval.
IEC 60335	1995	Safety of household and similar electrical appliances
IEC 60529	1989	Degrees of protection provided by enclosures (IP Code)
IEC 60950	1991	Safety of information technology equipment incl. electrical business equipment (installation rules)
IEC 61000	1990	Description of the environment-Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems
IEC 61140	1997	Protection against electric shock-Common aspects for installation and equipment
IEC 61173	1992	Overvoltage protection for photovoltaic (PV) power generating systems
IEC 61277	1995	Terrestrial photovoltaic (PV) power generating systems-General and guide
IEC 61683	1998	Procedures for measuring the efficiency of power conditioners used in photovoltaic systems(Draft)
IEC 61723	1998	Safety guidelines for grid connected photovoltaic (PV) systems mounted on buildings (Draft)
IEC 61727	1995	Photovoltaic (PV) systems-Characteristics of the utility interface
IEC 61728	1998	Safety test procedures for utility grid connected photovoltaic inverters (Draft)
IEC 61836	1997	Solar photovoltaic systems-Terms and symbols (APUB)
PNW 82-188	1998	Certification and accreditation program for photovoltaic (PV) components and systems-Guidelines for a total quality system (1998, NWIP)
PNW 82-210	1998	Balance-of-system components for photovoltaic systems-Design qualification and type approval (1998, NWIP)
UL 1741	1997	(Safety) Standard for static inverters and charge controllers for use in photovoltaic power systems
EN 50160	1995	Voltage characteristics of electricity supplied by public distribution systems
EN 55014	1993	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus-Part 1: Emission-Product family standard-Part 2: Immunity-Product family standard
EN 50081-1	1992	EMC; generic emission standard; Part 1: residential, commercial and light industry.
EN 60555	1994	Reactions in power supply grids, caused through domestic appliances and similar electrical installations-Part 1: Terms and definitions Part 2: Harmonics
TAD	1994	Technische aansluitvoorwaarden decentrale electriciteits productie-eenheden (technical terms of connection to the public network for local production units)
EnergieNed /1/	1996	Model aansluitvoorwaarden elektriciteit (model of requirements for electricity connection)
EnergieNed /2/	1997	Model aanvullende voorwaarden decentrale opwekkers

	laagspanningsniveau (supplementary conditions for decentralised generators low-voltage level)
EnergieNed /3/ 1997	Richtlijnen voor toelaatbare harmonische stromen, geproduceerd door apparatuur met een vermogen groter dan 11 kVA (guidelines for tolerated harmonic currents, produced by appliances with a nominal power above 11 kVA
EnergieNed /4/ 1998	Aanvullende richtlijnen voor de elektrische installatie van netgekoppelde PV-systemen (regulations for electrical installation of grid-connected PV-systems)
EnergieNed /5/ 1993	Model veiligheidsinstructie laagspanningsaanleg (safety instructions for low voltage installations)
EnergieNed /6/ 1993	Beschrijving kwaliteit laagspanning (description of low voltage quality)

5. DESIGN REQUIREMENTS

5.1 Performance

5.1.1 Energy efficiency

The static and the dynamic energy efficiency shall be part of the inverter's specifications and shall be determined in compliance with annex B1.

5.1.2 Stand-by loss

The stand-by loss is the consumption of utility active and reactive power when the power conditioner is not operating at zero insolation but is under stand-by condition. The stand-by loss shall be part of the inverter's specifications and shall be determined in compliance with annex B2.

5.1.3 Start-up and shut-down DC input voltage and power

The start-up and shut-down power is defined as the available DC-power at which the inverter starts and stops respectively, producing AC-power. The hysteresis of the DC input voltage lower limit shall be determined. The start-up and shutdown power shall be part of the inverter's specifications and shall be determined in compliance with annex B3.

5.1.4 Maximum Power Point (MPP)-efficiency

The maximum power point efficiency is a measure for the inverter's ability to operate the PV-array in its maximum power point. The MPP-efficiency includes deviations from the MPP due to non-ideal behaviour of the tracking algorithm and due to the 100 Hz ripple in the DC power in the case of a single-phase electric system. The static and the dynamic maximum power point efficiency shall be part of the inverter's specifications and shall be determined in compliance with annex B4.

5.1.5 MPP-tracking range

The MPP-tracking range shall be part of the inverter's specifications and shall be determined in compliance with annex B5.

5.1.6 Field measurements (outdoors)

In addition to testing the MPP tracking in the laboratory, outdoor measurements are necessary to assess the MPP tracker performance of the inverter. The MPP tracker performance should be measured under various irradiance conditions, when the power delivered to the grid is up to 120% of the rated output power of the inverter. The MPP tracking shall be part of the inverter's specifications and shall be determined in compliance with annex B6.

5.2 Electromagnetic compatibility (EMC)

The inverter shall meet the requirements of IEC 61000-x-x and its amendments. The assessment of the inverter's EMC aspects shall be performed by an accredited laboratory complying with the standard EMC procedures. Guidance in the assessment of the EMC aspects can be found in the IEC-61000-x-x and EN 50081-1 documents.

5.3 Safety

The inverter type shall comply with EN 60950 and its amendments. An accredited laboratory according to their in-house procedures must perform the assessment of the inverter's safety aspects. The in-house procedures may contain requirements additional to the above mentioned standard. Guidance in the assessment of the safety aspects can be found in the working draft IEC TC82/210/NP (August 1998) or its succeeding IEC-documents.

5.4 Utility interface protection

5.4.1 Islanding protection

Islanding is defined as a continuation of the inverter operation after a disconnection or failure of the grid. The inverter must provide adequate protection against islanding. In the Netherlands the protection shall be based on a continuous check of the voltage and frequency window at the inverter's output. The minimum criteria, are given in 'Supplementary Conditions for Decentralised Generators Low-Voltage level'; EnergieNed /2/, August 1997.
The inverter's voltage and frequency protection are tested according to the test procedure given in annexes C1 and C2.

5.4.2 Power factor

The power factor shall be part of the inverter's specifications and shall be determined in compliance with annex C3. In the Netherlands, the requirement concerning the power factor is laid down in 'Supplementary Conditions for Decentralised Generators Low-Voltage level'; EnergieNed /2/, August 1997. This document states that the power factor shall be 0.9 or higher at 'actual operating conditions'. The requirement is considered to be unnecessarily restrictive at low power levels. For this reason the 'actual operating conditions' are relaxed in this Draft Dutch guideline for PV-inverters to 'power levels higher than the inverter's power, averaged over its operational period'. As a guidance this level is 25% of the inverter's rated output power.

5.5 Reliability

The inverter's specifications shall state the rated output power and the range of temperature and humidity conditions for the inverter. It is not compulsory to state the MTTF (Mean Time To Failure) in the inverter specifications. The reliability of the inverter shall be tested, using the specified data as boundary conditions, according to annex D.

ANNEX A: TYPE APPROVAL CRITERIA

The following points will be checked and tests will be carried out as necessary to establish if an inverter can be classified as an “approved inverter for photovoltaic power generators” according to the “Dutch Guidelines for Design qualification and Type approval of inverter’s for grid connected operation of photovoltaic power generators”.

The EMC, Safety and Utility interface protection of the PV inverter shall be checked for compliance with international (IEC), European (EN) or national standards (NEN) and recommendations. The following table can be used to identify equipment specifications, which are not covered by official standards and therefore require additional verification.

The performance and reliability shall be checked and shall be part of the inverter’s specifications and must be determined in compliance with annexes B1-6.

Function	Standard/Specification	Reference
Performance		
Energy Efficiency	“Procedures for measuring the efficiency of PV- inverters”	IEC 61683, Draft (1998)
Stand-by loss	Specifications of the inverter	
Start-up and shut-down power		
MPP-efficiency		
MPP-tracking range		
EMC		
Harmonics	“ Electromagnetic Compatibility (EMC)-Limits”	IEC 61000-3-2 (1995)
Radiofrequency emission	“Generic emission standard (EMC)”	EN 50081-1 (1992)
Electrostatic discharge(ESD) immunity	“Electrostatic discharge immunity (EMC)”	IEC 61000-4-2 (1995)
Electromagnetic fields immunity	“Radiated electromagnetic fields immunity ”	IEC 61000-4-3 (1995)
Radio-frequency immunity	“Conducted radio frequency…. (EMC)”	IEC 61000-4-6 (1996)
Electrical fast transients immunity(EFT)	“Electrical fast transient/burst (EMC)”	IEC 61000-4-4 (1995)
Surge immunity	“Surge immunity test (EMC)”	IEC 61000-4-5 (1995)
Low-frequency disturbances immunity	“Voltage dips and voltage variations…(EMC)”	IEC 61000-4-11 (1994)
Safety		
Safety of equipment	“Safety of information technology equipment” “Balance of system components for PV systems”	EN 60950 (1991), IEC 82-210 PNW (1998)
Utility interface protection		
Islanding	“Supplementary conditions for decentralised generators low voltage level”	EnergieNed/2/ (8/1997)
Power factor		
Reliability	Specifications of the inverter	

ANNEX B: PERFORMANCE TEST PROCEDURES

In the following sections the test procedures specified are based on the use of a PV- simulator as a power supply for the inverter under test. The PV-simulator is an analogue or numerically driven device with a DC-output power that follows the IV-characteristic of a normal PV-array. In the test procedures reference is made to ‘the available power’ which is defined as the DC output power of the PV-simulator at its maximum power point. Since the available power is not necessarily equal to the input power of the inverter, the available power value cannot be measured at the inverter’s input. Instead the available power shall be determined using the IV-characteristic of the PV simulator. The IV-characteristic of the PV simulator shall be determined by calibration, both stationary and non-stationary, using for example a (variable) dump load or an IV-tracer.
The exact shape of the simulated IV-characteristic has not been prescribed for practical reasons. However, the testing institute shall reveal the IV-characteristic of its PV-simulator to enable the client to match the inverter's settings to the PV-simulator if desired. The relevance of this clause becomes evident when testing the maximum power point efficiency of inverters that relate the maximum power point voltage to the (periodically measured) open circuit voltage.
The PV simulator shall be able to follow the IV-characteristic of a PV-array with sufficient speed in relation to the dynamic behaviour of the inverter (such as the 100 Hz ripple in the case of a 1-phase inverter and the inverter’s MPPT-algorithm).

B1. Energy efficiency

The static energy efficiency is measured in compliance with the procedure for grid connected inverters described in Draft IEC 61683. Additionally the dynamic energy efficiency is measured at an averaged available power equal to the inverter's rated output power. This averaged available power has a sine-wave shaped modulation with a fixed frequency of 10 mHz and various amplitudes. The test values for the available power amplitude are 10, 20, 30, 40 and 50% of the rated output power. The averaging period of the tests per power amplitude value is at least 10 minutes.

B2. Stand-by loss

Stand-by loss shall be measured in compliance with the procedure for grid connected inverters described in Draft IEC 61683. Both active and reactive power shall be measured.

B3. Start-up and shut-down DC input voltage and power

The start-up and shutdown DC input voltage and power of the inverter shall be measured with a quasi static increasing and decreasing available power. The increase and decrease is performed in steps of 1% of the available power with a duration of 10s. The measurement for start-up power shall begin at the lowest DC input voltage.

The measurements shall be performed at a simulated DC voltage value equal to the lower limit and repeated at the upper limit of the inverter’s DC-voltage range. The values of the start-up and shutdown power are the lowest P_{DC}-values at which the inverter produces output power.

B4. MPP-efficiency

B4.1. General.

The MPP-efficiency is defined by the following formula.

$$\eta_{MPP} = 100 \frac{\int_0^{T_a} P_{DC}(t)dt}{\int_0^{T_a} P_{MPP}(t)dt}$$

in which:

η_{MPP}	= MPP-efficiency (%)
T_a	= averaging period (s)
$P_{DC}(t)$	= instantaneous input power to the inverter (kW)
$P_{MPP}(t)$	= instantaneous MPP power (kW)
t	= time (s)

The input power of the inverter is measured using a real-power measuring device capable of measuring DC-power with a ripple of 100 Hz.

B4.2 Measurement procedure

Both the static MPP-efficiency (in which the power at MPP is stationary during each averaging period) and the dynamic MPP-efficiency (in which the power at MPP is non-stationary during each averaging period) shall be measured. The measurements shall be performed at available power values from 0 % to 100 % (including start-up) in steps up to the inverter's rated power. The averaging intervals are at least 10 s for the static measurements and at least 120 s for the dynamic measurements dependent on the MPP algorithms of the inverter. The static and dynamic measurements are performed at a U_{DC}-value equal to the inverter's rated input voltage.

The dynamic measurements are performed with stepwise shaped variations of at most $0,25.P_{rat, AC}$ superimposed on the averaged $0,5.P_{rat, AC}$ with test amplitudes and with test frequencies up to 1 Hz.

B5. MPP-tracking range

The MPP-tracking range shall be measured in 25 quasi-static steps of simulated U_{DC}-values from 0 V to the maximum voltage level given in the inverter's specifications. The steps shall have a duration of at least 10 s dependent on the MPP algorithms of the inverter. The available power is at each step equal to the inverter's rated output power. The MPP-tracking range is determined as the voltage range at which the MPP-efficiency is higher than 0.95 times the static MPP-efficiency obtained according to annex B4 at 100 % of the rated power.

B.6 Field measurements (outdoors)

In addition to checking the MPPT performance indoors, outdoor measurements are necessary to assess the maximum power point tracker performance of the particular inverter type. Outdoor measurements have the advantage that the actual MPPT behaviour can be observed with the real PV array, so that potentially unrealistic interactions between the MPPT an PV array simulator can be avoided.

The voltage V and I at the inverter input are continuously measured at a high sampling speed, typically 1 kHz.

By studying plots of power and voltage over time it can be determined whether the MPP is correctly tracked.

ANNEX C: TESTPROCEDURES FOR THE UTILITY INTERFACE PROTECTION

C1. Voltage and frequency protection set points

The voltage and frequency limits at which the inverter stops operating are measured using a grid simulator with variable voltage and frequency control and with a DC-power supply at the inverter's rated input voltage and at least at 10 % of the inverter's rated power.
During the measurements the inverter operation shall be detected by measuring the inverter's output current. The following measurements shall be performed:

C1.1 Undervoltage

The undervoltage cut-out shall be measured at the nominal grid frequency and with a grid voltage slowly sloping from the nominal voltage downwards. The undervoltage value is the lowest value of the voltage during inverter operation. By decreasing the voltage starting from the nominal value, upon shutdown of the inverter and increasing the voltage again, the hysteresis of the lower voltage limit shall be determined.

C1.2 Overvoltage

The overvoltage limit shall be measured at the nominal grid frequency and with a grid voltage slowly sloping from the nominal voltage upwards. The overvoltage value is the highest value of the voltage during inverter operation. The upper limit of the voltage 'window' shall be determined by slowly increasing and decreasing the grid voltage as described above.

C1.3 Underfrequency

The underfrequency shall be measured at the nominal grid voltage and with a frequency slowly sloping downwards starting from the nominal grid frequency. The underfrequency is the lowest value of the frequency during inverter operation. By decreasing the frequency starting from the nominal value of 50 Hz and, upon shutdown of the inverter, increasing the frequency again, the hysteresis of the lower frequency limit shall be determined.

C1.4 Overfrequency

The overfrequency shall be measured at the nominal grid voltage and with a frequency slowly sloping upward starting from the nominal grid frequency. The overfrequency is the highest value of the frequency during inverter operation. The upper limit of the frequency 'window' shall be determined by slowly increasing and decreasing the grid frequency as described above.

C2. Voltage and frequency protection response times

The response times of the overvoltage and undervoltage protection shall be measured for a stepwise change of the voltage. The response times are measured as the time lapse between the application of the step and the shut down of the inverter. The values of the applied stepwise disturbances are given below.

C2.1 Undervoltage

The voltage shall be stepwise decreased from the nominal voltage to 90 % of the measured undervoltage setpoint.

C2.2 Overvoltage

The voltage shall be stepwise increased from the nominal voltage to 110 % of the measured overvoltage setpoint.

C2.3 Underfrequency

The frequency is decreased from the nominal grid frequency to 1 Hz below the measured underfrequency setpoint.

C2.4 Overfrequency

The frequency shall be increased from the nominal grid frequency to 1 Hz above the measured overfrequency setpoint.

C3. Power factor

The power factor of the inverter's output is defined by the following formula.

$$PF = \frac{\int_0^{T_a} u(t) \cdot i(t)\, dt}{\sqrt{\int_0^{T_a} u(t)^2\, dt \cdot \int_0^{T_a} i(t)^2\, dt}}$$

in which:

PF	= power factor (-)
T_a	= averaging period (s)
u	= output voltage (V)
i	= output current (A)
t	= time (s)

The power factor shall be measured with a power analyser or a set of power, current and voltage meters at a number of stationary values of the available power. The available power values are 0-100 % in steps of 10 % of the inverter's rated power. The averaging period for each condition is at least 1s. The measurements shall be performed with a U_{DC} equal to 90% of the inverter's rated input voltage.

ANNEX D: RELIABILITY TEST PROCEDURE

The purpose of this test is primarily to permit the observation of the effects of high humidity at constant temperature over a prescribed period. The test procedure is in compliance with IEC 68-2-3. The reliability test is based on a batch of 5 specimens of the inverter type. At the begining and at the end of the test period the specimen shall be inspected visually and shall be checked electrically and mechanically. Each specimen shall operate at the upper limit of the specified temperature and humidity range, stated in the inverter's specifications, with an available power value adequate to the inverters rated output power. The temperature and relative humidity in the working space can be maintained at 40°C and 95% respectively. The duration of each test shall be not less than 4 days and not more than 10 days. The inverter type does not pass the reliability test procedure if one or more of the 5 specimens stops producing its nominal output power during the complete test period.