Spanish standard

UNE-EN IEC 61400-21-1

June 2021

Wind energy generation systems

Part 21-1: Measurement and assessment of electrical characteristics

Wind turbines

This standard has been prepared by the Technical Committee CTN 206 *Electrical energy production* the Secretariat of which is held by UNE.

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UNE-EN IEC 61400-21-1

Wind energy generation systems
Part 21-1: Measurement and assessment of electrical characteristics
Wind turbines

Sistemas de generación de energía eólica. Parte 21-1: Medida y evaluación de las características eléctricas. Aerogeneradores.

Systèmes de génération d'énergie éolienne. Partie 21-1: Mesurage et évaluation des caractéristiques électriques. Éoliennes.

This standard is the official English version of EN IEC 61400-21-1:2019, which adopts IEC 61400-21-1:2019.

This standard was published as UNE-EN IEC 61400-21-1:2021, which is the definitive Spanish version.

The remarks to this document must be sent to:

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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN IEC 61400-21-1

July 2019

ICS 27.180

English Version

Wind energy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines (IEC 61400-21-1:2019)

Systèmes de génération d'énergie éolienne - Partie 21-1: Mesurage et évaluation des caractéristiques électriques - Éoliennes
(IEC 61400-21-1:2019)

Windenergieerzeugungsanlagen - Teil 21-1: Messung und Bewertung der elektrischen Kennwerte - Windenergieanlagen
(IEC 61400-21-1:2019)

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Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

Ref. No. EN IEC 61400-21-1:2019 E

European foreword

The text of document 88/711/FDIS, future edition 1 of IEC 61400-21-1, prepared by IEC/TC 88 "Wind energy generation systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 61400-21-1:2019.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2020-03-24
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2022-06-24

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 61400-21-1:2019 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61400-27-1:2015 NOTE Harmonized as EN 61400-27-1:2015 (not modified)

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 61000-3-2	2014	Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)	EN 61000-3-2	2014
IEC 61000-3-3	-	Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current < 16 A per phase and not subject to conditional connection	EN 61000-3-3	-
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	EN 61000-4-7	2002
+ A1	2008		+ A1	2009
IEC 61000-4-15	2010	Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications	EN 61000-4-15	2011
IEC 61000-4-30	-	Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods	EN 61000-4-30	-
IEC 62008	-	Performance characteristics and calibration methods for digital data acquisition systems and relevant software	EN 62008	-
IEC/TR 61000-3-6	-	Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems	-	-
IEC/TR 61000-3-7:2008	-	Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems	-	-
IEC/TR 61000-3-14	-	Electromagnetic compatibility (EMC) - Part 3-14: Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems	-	-
IEC/TR 61869-103	2012	Instrument transformers - The use of instrument transformers for power quality measurement	-	-

IEC 61400-21-1

Edition 1.0 2019-05

INTERNATIONAL STANDARD

NORME INTERNATIONALE

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Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines

Systèmes de génération d'énergie éolienne – Partie 21-1: Mesurage et évaluation des caractéristiques électriques – Éoliennes

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IEC 61400-21-1

Edition 1.0 2019-05

INTERNATIONAL STANDARD

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Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines

Systèmes de génération d'énergie éolienne – Partie 21-1: Mesurage et évaluation des caractéristiques électriques – Éoliennes

INTERNATIONAL
ELECTROTECHNICAL
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ICS 27.180 ISBN 978-2-8322-6761-5

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61400-21-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This first edition cancels and replaces the second edition of 61400-21 published in 2008. This edition constitutes a technical revision.

This edition includes the following new items with respect to 61400-21:

a) frequency control measurement;
b) updated reactive power control and capability measurement, including voltage and cos φ control;
c) inertia control response measurement;
d) overvoltage ride through test procedure;
e) updated undervoltage ride through test procedure based on Wind Turbine capability;

f) new methods for the harmonic assessment.

Parts of the assessments related to the wind power plant evaluation are moved to Annex E, as they will be replaced by IEC 61400-21-2, *Measurement and assessment of electrical characteristics – Wind power plants*.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/711/FDIS	88/716/RVD

Full information on the voting for the approval of this International Standard 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 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

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.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 61400 provides a uniform methodology that will ensure consistency and accuracy in reporting, testing and assessment of electrical characteristics of grid connected wind turbines (WTs). The electrical characteristics include wind turbine specifications and capabilities, voltage quality (emissions of flicker and harmonics), under- and overvoltage ride-through response, active power control, frequency control, voltage control, and reactive power control, grid protection and reconnection time.

This part of IEC 61400 has been prepared with the anticipation that it would be applied by:

– the WT manufacturer, striving to meet well-defined electrical characteristics;
– the WT purchaser, in specifying such electrical characteristics;
– the WT operator, who may be required to verify that stated, or required electrical characteristics are met;
– the WT planner or regulator, who has to be able to accurately and fairly determine the impact of a WT on the voltage quality to ensure that the installation is designed so that voltage quality requirements are respected;
– the WT certification authority or testing organization, in evaluating the electrical characteristics of the wind turbine type;
– the planner or regulator of the electric network, who has to be able to determine the grid connection required for a WT.

This part of IEC 61400 provides recommendations for preparing the measurements and assessment of electrical characteristics of grid connected WTs. This document will benefit those parties involved in the manufacture, installation planning, obtaining of permission, operation, usage, testing and regulation of WTs. The measurement and analysis techniques, recommended in this document, should be applied by all parties to ensure that the continuing development and operation of WTs are carried out in an atmosphere of consistent and accurate communication.

This part of IEC 61400 presents measurement and analysis procedures expected to provide consistent results that can be replicated by others. Any selection of tests can be done and reported separately.

WIND ENERGY GENERATION SYSTEMS –

Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines

1 Scope

This part of IEC 61400 includes:

- definition and specification of the quantities to be determined for characterizing the electrical characteristics of a grid-connected wind turbine;
- measurement procedures for quantifying the electrical characteristics;
- procedures for assessing compliance with electrical connection requirements, including estimation of the power quality expected from the wind turbine type when deployed at a specific site.

The measurement procedures are valid for single wind turbines with a three-phase grid connection. The measurement procedures are valid for any size of wind turbine, though this part of IEC 61400 only requires wind turbine types intended for connection to an electricity supply network to be tested and characterized as specified in this part of IEC 61400.

The measured characteristics are valid for the specific configuration and operational mode of the assessed wind turbine product platform. If a measured property is based on control parameters and the behavior of the wind turbine can be changed for this property, it is stated in the test report. Example: Grid protection, where the disconnect level is based on a parameter and the test only verifies the proper functioning of the protection, not the specific level.

The measurement procedures are designed to be as non-site-specific as possible, so that electrical characteristics measured at for example a test site can be considered representative for other sites.

This document is for the testing of wind turbines; all procedures, measurements and tests related to wind power plants are covered by IEC 61400-21-2.

The procedures for assessing electrical characteristics are valid for wind turbines with the connection to the PCC in power systems with stable grid frequency.

NOTE

For the purposes of this document, the following terms for system voltage apply:

– Low voltage (LV) refers to $U_n \leq 1$ kV;

– Medium voltage (MV) refers to 1 kV < $U_n \leq 35$ kV;

– High voltage (HV) refers to 35 kV < $U_n \leq 220$ kV;

– Extra high voltage (EHV) refers to $U_n > 220$ kV.

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 61000-3-2:2014, *Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase*

IEC 61000-3-3, *Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limits of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current < 16 A per phase and not subject to conditional connection*

IEC TR 61000-3-6, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC TR 61000-3-7, *Electromagnetic compatibility (EMC) – Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems*

IEC TR 61000-3-14, *Electromagnetic compatibility (EMC) – Part 3-14: Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems*

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 61000-4-15:2010, *Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications*

IEC 61000-4-30, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*

IEC TR 61869-103:2012, *Instrument transformers – The use of instrument transformers for power quality measurement*

IEC 62008, *Performance characteristics and calibration methods for digital data acquisition systems and relevant software*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1
continuous operation
normal operation of the wind turbine excluding switching operations

3.2
cut-in wind speed
lowest wind speed at hub height at which the wind turbine starts to produce power

[SOURCE: IEC 60050-415:1999, 415-03-05]

3.3
disconnection time
time duration from exceeding a predefined disconnection level until the physical disconnection of the wind turbine from the grid

3.4
flicker coefficient for continuous operation
$c(\psi_k)$
normalized measure of the flicker emission during continuous operation of the wind turbine

$$c(\psi_k) = P_{st,fic} \times \frac{S_{k,fic}}{S_n}$$

where

$P_{st,fic}$ is the short-term flicker severity from the wind turbine on the fictitious grid;

S_n is the nominal apparent power of the wind turbine;

$S_{k,fic}$ is the short-circuit apparent power of the fictitious grid

3.5
flicker step factor
$k_f(\psi_k)$
normalized measure of the flicker emission due to a single switching operation of the wind turbine

$$k_f(\psi_k) = \frac{1}{130} \times \frac{S_{k,fic}}{S_n} \times P_{st,fic} \times T_p^{0,31}$$

where

T_p is the measurement period in seconds, long enough to ensure that the transient of the switching operation has abated, though limited to exclude possible power fluctuations due to turbulence;

$P_{st,fic}$ is the short-term flicker severity from the wind turbine on the fictitious grid;

S_n is the nominal apparent power of the wind turbine;

$S_{k,fic}$ is the short-circuit apparent power of the fictitious grid

Note 1 to entry: The short-term flicker severity $P_{st,fic}$ is here evaluated over the time period T_p.

3.6
maximum measured power
highest measured value of active power (with a specified averaging time) that is observed during continuous operation of the wind turbine

3.7
network impedance phase angle
ψ_k
phase angle of network short-circuit impedance

$$\psi_k = \arctan(X_k / R_k)$$

where

X_k is the network short-circuit reactance;

R_k is the network short-circuit resistance

3.8
normal operation
fault free operation according to the description in the wind turbine manual

3.9
operational mode
operation according to control setting, for example voltage control mode, frequency control mode, reactive power control mode, active power control mode, etc.

3.10
output power
electric active power delivered by the wind turbine at its terminals

[SOURCE: IEC 60050-415:1999, 415-04-02, modified – "at any time by a wind turbine generator system" has been replaced by "by the wind turbine at its terminals"]

3.11
point of common coupling
PCC
point of a power supply network, electrically nearest to a particular load, at which other loads may be connected

Note 1 to entry: These loads can be devices, equipment or systems, or distinct customer's installations.

Note 2 to entry: In some applications, the term "point of common coupling" is restricted to public networks.

Note 3 to entry: This note applies to the French language only.

[SOURCE: IEC 60050-161:1990, 161-07-15, modified – "are, or may be" has been replaced by "may be".]

3.12
power collection system
electrical system that collects the power from a wind turbine and feeds it into an electrical supply network

[SOURCE: IEC 60050-415:1999, 415-04-06, modified – "generator system" has been deleted and "a network step-up transformer or electrical loads" has been replaced by " an electrical supply network".]

3.13
nominal apparent power
S_n
apparent power from the wind turbine while operating at nominal current and nominal voltage and frequency

$$S_\mathrm{n} = \sqrt{3} U_\mathrm{n} I_\mathrm{n} \text{ at } Q = 0$$

where

U_n is the nominal voltage;

I_n is the nominal current

3.14
nominal current
nominal value I_n of wind turbine current, which are calculated from nominal active power P_n and nominal voltage U_n according to $I_\mathrm{n} = \dfrac{P_\mathrm{n}}{\sqrt{3} U_\mathrm{n}}$

3.15
nominal active power
nominal value of wind turbine active power, which is stated by the manufacturer and is used as a per-unit base for all powers (active, reactive, apparent)

3.16
Q capability
reactive power capability of a wind turbine, which is measured from the capability curve or by a site-specific test or defined by the manufacturer

3.17
nominal wind speed
wind speed at which a wind turbine’s nominal active power is achieved

[SOURCE: IEC 60050-415:1999, 415-03-04, modified – the term defined "rated wind speed" has been changed to "nominal wind speed".]

3.18
standstill
condition of a wind turbine that is stopped

[SOURCE: IEC 60050-415:1999, 415-01-15, modified – "wind turbine generator system" has been changed to "wind turbine"]

3.19
start-up
transitional state of a wind turbine between standstill and power production

3.20
short-circuit ratio
SCR
ratio of the short circuit apparent power S_{k} to the nominal power S_{n}

$$SCR = \frac{S_{\mathrm{k}}}{S_{\mathrm{n}}}$$

3.21
switching operation
start-up or shutdown of the wind turbine, or switching between generators in the wind turbine

3.22
turbulence intensity
ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

[SOURCE: IEC 60050-415:1999, 415-03-25]

3.23
voltage change factor
$k_{\mathrm{u}}(\psi_{\mathrm{k}})$
normalized measure of the voltage change due to a switching operation of the wind turbine:

$$k_{\mathrm{u}}(\psi_{\mathrm{k}}) = \sqrt{3} \times \frac{U_{\mathrm{fic,max}} - U_{\mathrm{fic,min}}}{U_{\mathrm{n}}} \times \frac{S_{\mathrm{k,fic}}}{S_{\mathrm{n}}}$$

where

$U_{fic,min}$ and $U_{fic,max}$	are the minimum and maximum one period RMS value of the phase-to-neutral voltage on the fictitious grid during the switching operation;
U_n	is the nominal phase-to-phase voltage;
S_n	is the nominal apparent power of the wind turbine;
$S_{k,fic}$	is the short-circuit apparent power of the fictitious grid.

Note 1 to entry: The voltage change factor k_u is similar to k_i being the ratio between the maximum inrush current and the nominal current, though k_u is a function of the network impedance phase angle. The highest value of k_u will be numerically close to k_i.

3.24
wind turbine
WT
system that converts kinetic wind energy into electric energy

Note 1 to entry: This note applies to the French language only.

3.25
wind turbine terminals
point that is part of the WT and identified by the WT manufacturer as a point at which the WT may be connected to the power collection system

3.26
voltage dip
limited duration non-periodic sudden decrease of the power supply network’s voltage magnitude and associated change of its phase

Note 1 to entry: In some articles, publications, etc. the expression "voltage sags" is used for the same event.

3.27
voltage swell
limited duration non-periodic sudden increase of the power supply network’s voltage magnitude above its nominal value and associated change of the phase of the voltage

3.28
fault ride through
FRT
ability of a wind turbine or wind power plant to stay connected during faults in the grid

Note 1 to entry: This note applies to the French language only.

3.29
undervoltage ride through
UVRT
ability of a wind turbine or wind power plant to stay connected during voltage dips

Note 1 to entry: In some publications, the expression "low voltage ride through (LVRT)", is used for the same event.

Note 2 to entry: This note applies to the French language only.

3.30
overvoltage ride through
OVRT
ability of a wind turbine or wind power plant to stay connected during voltage swells

Note 1 to entry: In some publications, the expression "high voltage ride through (HVRT)", is used for the same event.

Note 2 to entry: This note applies to the French language only.

3.31
phasor
representation of a sinusoidal quantity by a complex quantity whose argument is equal to the initial phase and whose modulus is equal to the root-mean-square value or to the amplitude

Note 1 to entry: For a quantity $a(t) = A\sqrt{2}\cos(\omega t + \theta_0) = A_m\cos(\omega t + \theta_0)$ the phasor is either $Ae^{j\theta_0}$ or $A_m e^{j\theta_0}$.

Note 2 to entry: A phasor can also be represented graphically.

[SOURCE: IEC 60050-131:2002, 131-11-26, modified – "integral" has been deleted, "or to the amplitude" has been added, and the first note has been modified]

3.32
positive sequence component of the fundamental
for a three-phase system with phases L1, L2 and L3, the symmetrical sinusoidal three-phase set of voltages or currents having positive frequency equal to the fundamental frequency. The positive sequence component is defined by the following complex mathematical expression:

$$\underline{X}_1 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{a}\underline{X}_{L2} + \underline{a}^2\underline{X}_{L3}\right)$$

where $\underline{a} = e^{j2\pi/3}$ is the 120-degree operator, and X_{L1}, X_{L2} and X_{L3} are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

Note 1 to entry: In a balanced harmonic-free system, only positive sequence component of the fundamental exists. For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} = Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_1 = (Ue^{j\theta} + e^{j2\pi/3}\,Ue^{j(\theta+4\pi/3)} + e^{j4\pi/3}\,Ue^{j(\theta+2\pi/3)})/3 = (Ue^{j\theta} + Ue^{j\theta} + Ue^{j\theta})/3 = Ue^{j\theta}$.

[SOURCE: IEC 60050-448:1995, 448-11-27, modified – the term and the definition have been modified and Note 1 to entry has been added.]

3.33
negative sequence component of the fundamental
for a three-phase system with phases L_1, L_2 and L_3, the symmetrical sinusoidal three-phase set of voltages or currents having negative frequency the absolute value of which is equal to the fundamental frequency

Note 1 to entry: The negative sequence component is defined by the following complex mathematical expression:

$$\underline{X}_2 = \frac{1}{3}\left(\underline{X}_{L_1} + \underline{a}^2\underline{X}_{L_2} + \underline{a}\underline{X}_{L_3}\right)$$

where a = $e^{j2\pi/3}$ is the 120-degree operator, and $\underline{X}_{L1}$, $\underline{X}_{L2}$ and $\underline{X}_{L3}$ are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors.

Note 2 to entry: Negative sequence voltage or current components may be significant only when the voltages or currents, respectively, are unbalanced. For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} = Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_2 = (Ue^{j\theta} + e^{j4\pi/3}\,Ue^{j(\theta+4\pi/3)} + e^{j2\pi/3}\,Ue^{j(\theta+2\pi/3)})/3 = Ue^{j\theta}\,(1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

[SOURCE: IEC 60050-448:1995, 448-11-28, modified – The term and the definition have been modified and two notes to entry added.]

3.34
zero-sequence component of the fundamental
for a three-phase system with phases L1, L2 and L3, the in-phase sinusoidal voltage or current component having the fundamental frequency and equal amplitude in each of the phases

Note 1 to entry: The zero-sequence component is defined by the following complex mathematical expression:

$$\underline{X}_0 = \frac{1}{3}\left(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3}\right)$$

where $\underline{X}_{L1}$, $\underline{X}_{L2}$ and $\underline{X}_{L3}$ are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

[SOURCE: IEC 60050-448:1995, 448-11-29, modified – the term and the definition have been modified and the note to entry added.]

3.35
unbalance factor
in a three-phase system, the degree of unbalance expressed by the ratio $\left|\underline{X}_2/\underline{X}_1\right|$ (in percent) between the values of the negative sequence component $\underline{X}_2$ and the positive sequence component $\underline{X}_1$ of voltage or current

[SOURCE: IEC 60050-614:2016, 614-01-33, modified – The symbols have been added.]

3.36
control interface
point that is part of the WT and identified by the WT supplier as a point at which the WT may be connected to the power plant control system

3.37
wind power plant
power station comprising one or more wind turbines, auxiliary equipment and plant control

3.38
assessor
body accredited to do the assessment

3.39
time-series
record consisting of the numerical values of a time varying signal's equidistant samples

Note 1 to entry: Samples may represent a measured signal or data processed from the measured values.

3.40
short-circuit apparent power
S_k
product of the current in the short circuit at a point of a system and a conventional voltage, generally the operating voltage

3.41
percentile
value of a variable below which a certain percent of observations fall

3.42
synthetic inertia
wind turbine or wind power plant active power production as a function of time after a sudden change in the grid frequency

Note 1 to entry: The expression "synthetic inertia" are in some publications also defined as "virtual inertia", "fast frequency response", "inertia control". In this document, we use the term "synthetic inertia" for this functionality.

3.43
static error
deviation between the obtained values compared to a requested reference value

3.44
response time
elapsed time from the start of a step change or start of event until the observed value first time enters the predefined tolerance band of the target value

Note 1 to entry: See Figure 1.

3.45
settling time
elapsed time from the start of a step change event until the observed value continuously stays within the predefined tolerance band of the target value

Note 1 to entry: See Figure 1.

3.46
rise time
time from when the observed value reaches 10 % of the step change until the observed value reaches 90 % of the step change

Note 1 to entry: See Figure 1.

3.47
overshoot
difference between the maximum value of the response and the steady-state final value

Note 1 to entry: See Figure 1.

3.48
reaction time
elapsed time from test command issued until the change in amplitude reaches 10 % of the measured output variable of the step height

Note 1 to entry: See Figure 1.

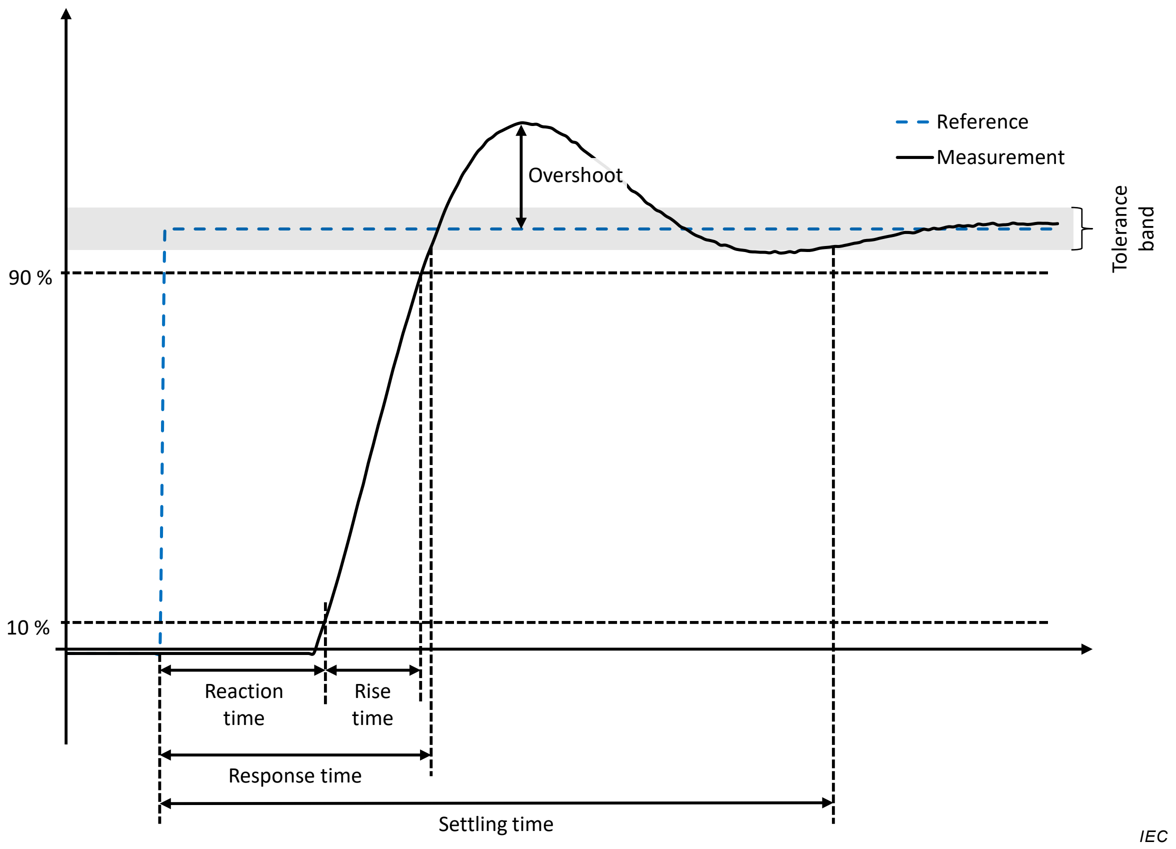


Figure 1 – Example of step response

3.49
ramp-down time
time during which the measured value decreases from 90 % to 10 % of the target value

3.50
recovery time
time from end of the event after which the measured value is continuously within the predefined tolerance band around the start value before the event

3.51
steady state
status of the system obtained when the settling time has expired

3.52
tolerance band
acceptable deviation range of the measured signal from the defined target value

Note 1 to entry: The steady-state target value is usually defined to be equal to the observed signal's reference value or the value towards which the observed signal is converging after the event.

Note 2 to entry: Default tolerance band is defined to be ±10 % of the nominal value if nothing else is stated.

3.53
start of event
time instant where the stimulus value deviates for the first time outside its defined stimulus tolerance band

Note 1 to entry: Stimulus may be a reference signal or a disturbance.

Note 2 to entry: Default stimulus tolerance band is defined to be ±10 % of the stimulus increment and centred on the value the stimulus had before the event.

3.54
wind turbine product platform
turbines sharing the same mechanical platform, electrical system and main drive train components

Note 1 to entry: These turbines are part of the same turbine platform (family) and the differences are typical of the IEC 61400-1 wind classes; they are designed for with the corresponding rotor diameter and nominal power.

Note 2 to entry: Other examples of turbines from the same platform are e.g. wind turbines with different wind turbine transformer primary side voltage ratings, wind turbines with different rotor diameters, etc. See also Annex F.

3.55
component test
test on a single component, where all necessary functions and performance for the test are available in the component and are not dependent on other components/systems (e.g. the protection device, if this an independent unit)

Note 1 to entry: Test done on component level is valid for all turbine variants, where the component is used.

3.56
sub-system
portion of a system that fulfils a specific function, consisting of several components/elements, which are directly related to each other and are directly interacting for the defined function

3.57
sub-system test
test on a sub-system, where all necessary functions and performance for the test are available in the sub-system and are not dependent on other components or systems

Note 1 to entry: Test done on a sub-system is valid for all turbine variants, where the sub-system is used.

3.58
available active power
predicted instantaneous active power from the turbine, either based on the power curve and measured wind speed or as an output from the turbine controller, where more parameters are taken into the calculation

3.59
power factor
under periodic conditions, ratio of the absolute value of the active power P to the apparent power S:

$$PF = \frac{P}{S} \quad PF = \frac{|P|}{S}$$

Note 1 to entry: Under sinusoidal conditions, the power factor is the absolute value of the active factor.

[SOURCE: IEC 60050-131:2002, 131-11-46]

3.60
ramp rate
gradient of ramp during a given period

3.61
reference value
target value that a control system aims to reach

3.62
active power bin
consecutive, non-overlapping intervals of WT active power measured at WT terminals

Note 1 to entry: The bins (intervals) are equal size from 0 %, 10 %, 20 %, … , 100 % of P_n. 0 %, 10 %, 20 %, … , 100 % are the bin midpoints.

3.63
fictitious grid
representation of an ideal phase-to-neutral voltage source with the instantaneous value $u_0(t)$, in series with a defined grid resistance R and grid inductance L

Note 1 to entry: The fictitious grid is used for the normalization of flicker measurements.

3.64
field measurement
measurements performed on a wind turbine or wind power plant installation on a given site

3.65
field test
tests to validate and measure the performance of a wind turbine or wind power plant installation on a given site

3.66
wind speed bin
groups of 10- or 1-minute average measurements into bins based on the average wind speed

4 Symbols and units

In this part of IEC 61400, the following symbols and units are used.

$\frac{\Delta U_{\mathrm{dyn}}}{U_{\mathrm{n}}}$	maximum permitted voltage change (%)
ψ_{k}	network impedance phase angle (°)
$\alpha_{\mathrm{m}}(\mathrm{t})$	electrical angle of the fundamental of the measured voltage (°)
β	exponent associated with summation of harmonics
$c(\psi_{\mathrm{k}})$	flicker coefficient for continuous operation
d	relative voltage change (%)
E_{Plti}	long-term flicker emission limit
E_{Psti}	short-term flicker emission limit
f_{g}	nominal grid frequency (50 Hz or 60 Hz)
$f_{\mathrm{inertia,\ recovery}}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{\mathrm{inertia,\ trigger}}$	frequency threshold where the turbine shall start boosting active power (Hz)
f_{sim}	frequency reference value
f_{over}	over-frequency protection level
f_{under}	under-frequency protection level
h	harmonic order
HW	hardware
$I_{\mathrm{h,i}}$	h'th order harmonic current distortion of i'th wind turbine (A)
$i_{\mathrm{m}}(t)$	measured instantaneous current (A)
I_{n}	nominal current (A)
IUF	current unbalance factor
$k_{\mathrm{f}}(\psi_{\mathrm{k}})$	flicker step factor
k_{i}	ratio of maximum inrush current and nominal current
$k_{\mathrm{u}}(\psi_{\mathrm{k}})$	voltage change factor
L_{fic}	inductance of fictitious grid (H)
N_{10m}	maximum number of one type of switching operations within a 10 min period
N_{120m}	maximum number of one type of switching operations within a 120 min period
n_{i}	ratio of the transformer at the i'th wind turbine
N_{m}	total number of measured flicker coefficient values
N_{wt}	number of wind turbines
P	active power (W)
$P_{0,2}$	maximum measured active power (0,2 s average value) (W)
P_{60}	maximum measured active power (60 s average value) (W)
P_{600}	maximum measured active power (600 s average value) (W)
PF	power factor
P_{lt}	long-term flicker severity
P_{n}	nominal active power of wind turbine (W)

$Pr(c<x)$	accumulated distribution of c
P_{st}	short-term flicker severity
$P_{st,fic}$	short-term flicker severity at fictitious grid
Q	reactive power (var)
R_{fic}	resistance of fictitious grid (Ω)
S_k	short-circuit apparent power of grid (VA)
$S_{k,fic}$	short-circuit apparent power of the fictitious grid (VA)
S_n	nominal apparent power of wind turbine (VA)
SW	software
THC	total harmonic current distortion (% of I_n)
T_p	transient time period of a switching operation in seconds (s)
U	phase-to-phase voltage (V)
$u_0(t)$	instantaneous phase-to-neutral voltage of an ideal voltage source (V)
$u_{fic}(t)$	instantaneous phase-to-neutral voltage simulated at fictitious grid (V)
$U_{fic,max}$	maximum phase-to-neutral voltage at fictitious grid (V)
$U_{fic,min}$	minimum phase-to-neutral voltage at fictitious grid (V)
U_{min}	minimum phase-to-phase voltage the turbine can ride through in p.u.
U_{max}	maximum phase-to-phase voltage the turbine can ride through in p.u.
U_n	nominal phase-to-phase voltage (V)
U_{under}	undervoltage protection level
U_{UVRC}	the difference between U_n of the WT and U_{min} in p.u. (undervoltage range capability).
U_{OVRC}	the difference between U_{max} and U_n of the WT in p.u. (overvoltage range capability).
U_{over}	overvoltage protection level
U_{pre}	prefault voltage; calculated as 0,2 s average value measured from 10 s before the event to start of the event.
$v_{cut\text{-}in}$	cut-in wind speed (m/s)
X_{fic}	reactance of fictitious grid (Ω)
Z_1	impedance for limiting the effect of the short-circuit on the upstream grid (Ω)
Z_2	impedance between phases or to ground during short-circuit (Ω)

5 Abbreviated terms

The following abbreviated terms are used in this document.

A/D converter	analogue to digital converter
DFAG	doubly fed asynchronous generator
	Often referred to as a doubly-fed induction generator (DFIG), but it is not operated as an induction generator when the rotor current is controlled.
DFT	discrete fourier transform
HV	high voltage
LV	low voltage

MV	medium voltage
RMS	root mean square
RoCoF	rate of change of frequency
SCADA	supervisory control and data acquisition
THC	total harmonic current distortion
WT	wind turbine

6 Wind turbine specification

The nominal data of the wind turbine (referred to the wind turbine terminals) shall be specified, including P_n, S_n, U_n, I_n and, where applicable, undervoltage and overvoltage ride through profiles, reactive power capability profile and control values.

Based on manufacturer's information, the wind turbine specifications as outlined in Annex A shall be stated.

NOTE The nominal data are only used as base for the p.u. calculations in this document.

7 Test conditions and test systems

7.1 General

Clause 7 gives the testing fundamentals that are necessary for the assessment of the electrical characteristics of a wind turbine, i.e. test validity (7.3), test conditions (7.4) and test equipment (7.5). A sample report format is given in Annex A.

Generator sign convention shall be used, i.e. the positive direction of the power flow is defined to be from the generator to the grid. If the wind turbine is replaced with a resistor and an inductor, both active and reactive power will be negative (see Annex C).

7.2 Overview of required test levels

Table 1 gives an overview of the required and optional test levels for the different tests and measurements as described in Clause 8. Optional tests and measurements may be carried out and reported for more detailed assessment of simulation models and compliance with specific grid codes. A test is not required at all, if a wind turbine does not provide the corresponding functionality. In some cases a test or measurement (or part of it) would be acceptable on a lower system level, if certain conditions are met which are then provided in Clause 8. For some tests and measurements, a different system level than stated as "required" would be acceptable, too. These cases are marked as "optional" in the following overview and would replace the test on the "required" system level.

Table 1 – Overview of required test levels

Clause	Test	Component test	Sub-system Test	Field measurement – Wind turbine level	Field measurement – Wind power plant
Power Quality Aspects					
8.2.2	Flicker			S	O
8.2.3	Switching operations			S	O
8.2.4	Harmonics, interharmonics and higher frequency components		C	S	O
Steady-State Operation					
8.3.3	Maximum power			S	O
8.3.4	Reactive power characteristic (Q=0)		S	O	O
8.3.5	Reactive power capability		S	O	O
8.3.6	Voltage dependency of PQ diagram		S	O	O
8.3.7	Unbalance factor		S	O	O
Control Performance					
8.4.2	Active power control		C	S	O
8.4.3	Active power ramp rate limitation		C	S	O
8.4.4	Frequency control		S	O	O
8.4.5	Synthetic inertia			S	O
8.4.6	Reactive power control		S	O	O
Dynamic Performance					
8.5.2	Fault ride-through capability		C	S	O
Grid Protection					
8.6.2	Grid protection	S	O	O	O
8.6.4	Reconnection time			S	O
8.6.3	Rate of change of frequency RoCoF (df/dt)	S	O	O	O
S: Suggested minimum measurement / test level					
C: Conditional measurement / test level, if certain conditions are fulfilled (details in corresponding clause)					
O: Optional measurement / test level, if the function is available on other level than required as a minimum					

7.3 Test validity

Measurements are required in order to validate theoretical analysis and numerical simulations as well as electrical performance. Appropriate measurements as well as data processing are crucial in wind turbine evaluation and comparison with expected theoretical assumptions.

The measured characteristics are valid for the wind turbine product platform. Some wind turbine designs include a built-in transformer. The measurements of the electrical characteristics shall be made at the wind turbine terminals. It is up to the wind turbine manufacturer to define the wind turbine terminals to be at the low-voltage or high-voltage side of the transformer. Changing the transformer from one output voltage to another is not expected to cause the wind turbine to behave differently with respect to power quality characteristics. Thus, separate assessment is not required, if the transformer output voltage is changed and if the assessment has been previously done at other MV levels or at the low-voltage side of the wind turbine transformer, except that nominal voltage and current shall be updated. The considerations given in Annex F shall be taken into account.

NOTE Measuring voltage and current on the low- or high-voltage side of transformer has an influence on harmonic measurement results. However, it is still up to the manufacturer to define the "WT terminals". When transferring test results to other turbines of one product platform, the test validity applies for the same side of the transformer. If necessary, an additional measurement could be done at a specific site in accordance with this document.

The location of the wind turbine terminals (being the measurement point) and the specific configuration of the assessed wind turbine including the relevant control parameter settings shall be clearly stated in the test report (Annex A).

Any selection of tests can be done and reported separately. This means that all parts in this document can be tested and reported individually and it is not mandatory to perform all the described test and measurements procedures.

Optional tests and measurements (for example pitch angle and rotational speed) may be carried out and reported for more detailed assessment of simulation models and compliance with specific grid code requirements.

Type testing one turbine which is part of a product platform shall be considered sufficient to cover the entire turbine product platform, provided that a documented risk assessment is carried out according to Annex F to determine which type tests are valid and which tests need to be repeated on the rest of the turbine product platform.

7.4 Test conditions

The following test conditions are required and shall be measured and reported as part of the test procedure. Any test data measured during periods not complying with the given test conditions shall be excluded.

- The wind turbine shall be connected directly to the network through a standard transformer (i.e. equal or electrically comparable to a transformer to be used in other applications than the prototype measurement) with nominal apparent power at least corresponding to the nominal apparent power of the assessed wind turbine.
- The total harmonic distortion of the voltage including all harmonics up to the order of 50 shall be less than 5 % measured as 10 min average data at the wind turbine terminals while the wind turbine is not generating. The total harmonic distortion of the voltage may be determined by measurement prior to testing the wind turbine.
- The grid frequency measured as 0,2 s average data shall be within ±1 % of the nominal frequency, and the rate of change of the grid frequency measured as 0,2 s average data shall be less than 0,2 % of the nominal frequency per 0,2 s. If the grid frequency is known to be very stable and well within the above requirements, which would commonly be the case in a large interconnected power system, this need not be assessed any further. Otherwise, the grid frequency shall be measured during the test.
- The voltage shall be within ±10 % of its nominal value measured as 10 min average data at the wind turbine terminals.
- The voltage unbalance factor shall be less than 2 % measured as 10 min data at the wind turbine terminals. The voltage unbalance factor shall be determined as described in IEC 61000-4-30 where the voltage unbalance factor is defined as ratio of positive and negative sequence component of the voltage. If the voltage unbalance factor is known to be well within the above requirement, it need not be assessed any further. Otherwise, the voltage unbalance factor shall be measured during the test.
- The environmental conditions shall comply with the manufacturer's requirements for the instruments and the wind turbine. Commonly, this does not call for any online measurements of the environmental conditions, though it is required that these are described in general terms as part of the measurement report.

- Tests may be prepared at any turbulence intensity and at any short-circuit ratio, but conditions (average turbulence intensity, short-circuit apparent power and network impedance angle) shall be stated as part of the test report/certificate.
- The characteristics shall be stated for the wind turbine operating with reactive power as close as possible to zero, i.e. if applicable, the reactive reference value shall be set to Q = 0, unless stated differently in the corresponding clause of a specific test. If any other operational mode is used, this shall be clearly stated in the report.
- Various operational modes could be taken into consideration. Please note that various operational modes can be characterized by different frequency response of the turbine control system affecting the electrical characteristics, therefore it is recommended to specify if the operation mode was changed during the assessment process and exclude invalid data. It is the manufacturer's responsibility to define if changes in the operational mode will change the measured electrical characteristics. A guideline to evaluate the influence of design changes is given in Annex F.
- Electromagnetic influence on the measurement should be avoided. Therefore, it is recommended that all measurement equipment shall have an EMC class that meets at least the expected level of electromagnetic emission in the wind turbine.
- The temperature variation regarding the calibration uncertainties of the measurement equipment shall not exceed the limits specified by the equipment manufacturer. The data acquisition device shall meet the requirements given in IEC 62008 in terms of performance characteristics and calibration methods.

NOTE 1 The specified conditions above are required to achieve reliable test results and should not be interpreted as conditions for a reliable grid connection and operation of wind turbines.

NOTE 2 The maximum measured power depends for some wind turbine designs to some degree on the air density. Hence, the maximum measured power determined following the procedure in 8.3.3 and measured at a site with low air density can be less than at a site with higher air density. It is, however, found that the uncertainty introduced by not specifying a limited air density range cannot justify the cost of additional equipment and procedures associated with this.

7.5 Test equipment

The measurement equipment should be carefully adjusted in order to record electrical characteristics of interest with acceptable accuracy and precision. The description of the measurements assumes application of a digital data acquisition system with elements as illustrated in Figure 2.

The anemometer, voltage transducers and current transducers are the required sensors of the measurement system. The signal conditioning is for connecting these to the low-pass filter that is required for anti-aliasing. See Table 2 for the specification of equipment accuracy. The transducers shall meet the requirements given in IEC 61869-103.

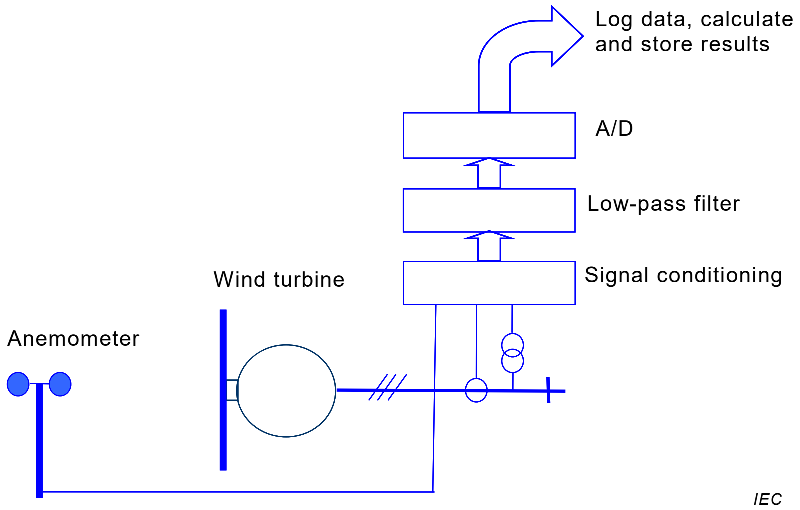


Figure 2 – Measurement system description including the most significant components

Table 2 defines the overall required accuracies for the measurement equipment, if there are no specific requirements mentioned in the specific subclauses.

Table 2 – Specification of requirements for measurement equipment

Equipment	Required accuracy
Voltage transducers	Class 1,0
Current transducers	Class 1,0
Anemometer	±1 m/s
Filter + A/D converter + data acquisition system	1 % of full scale
Frequency	10 mHz

The digital data acquisition system is assumed to log, calculate and store results as specified in the subclauses of Clause 8. General guidance for calculation of RMS voltage, active and reactive power in a system as outlined in Figure 2 is given in Annex C. This requires a sample rate of at least 2 kHz per channel of the voltage and current signals. For measurements of harmonics, interharmonics and higher frequency components, the sampling rate should be chosen in accordance with the established rules of signal analysis such that frequency components up to 9 kHz inclusive can be measured. It has to be guaranteed that the frequency response of the transducers is linear up to 9 kHz.

The minimum signal bandwidth for measurements of flicker shall be 1 500 Hz. See also the note in 7.5.

The wind speed signal shall be sampled with at least 1 Hz, the measurement from the corrected nacelle anemometer can be used.

Alternatively, a hub-height anemometer located at a position unaffected by wind turbine blockage or wind turbine wakes can be applied for measuring the wind speed. A position 2,5 rotor diameter upstream would generally give good definition. As another alternative, hub-height wind speed can be estimated from lower level measurement possibly in conjunction with power measurements and knowledge of the power curve.

The measurement equipment configuration including sensors bandwidth, cable shielding, anti-aliasing filter cut-off frequency, A/D converter resolution and sample rate, should be adjusted in order to measure all expected frequency components with sufficient amplitude and phase angle accuracy.

Other signals needed in the test are reference values and available active power. Reference values shall be read by the measurements system either via network connection, serial or analogue values. The available active power can be calculated from the measured wind speed signal, which is converted into an active power signal according to the observation of active power against wind speed (see 8.3.2). Alternatively, the available active power output shall be provided by the control system of the wind turbine.

8 Measurement and test of electrical characteristics

8.1 General

The electrical characteristics to be measured and tested consist of five different categories of tests: power quality, steady-state operation, control performance, dynamic performance and disconnection from grid. These five categories cover all aspects needed to evaluate the performance of the turbine against requirements given in the grid code.

8.2 Power quality aspects

8.2.1 General

Subclause 8.2 covers the classical power quality terms with respect to flicker during normal operation, flicker and voltage change during switching operations and current harmonics under different operational conditions.

8.2.2 Flicker during continuous operation

8.2.2.1 Description

The network will normally have other fluctuating loads that may cause significant voltage fluctuations at the wind turbine terminals where the test measurements are taken. Moreover, the voltage fluctuations imposed by the wind turbine will depend on the characteristics of the grid e.g. the short-circuit power and impedance angle. The aim is, however, to achieve test results that are independent of the grid conditions at the test site. To accomplish this, IEC 61400-21-1 specifies a method that uses current and voltage time-series measured at the wind turbine terminals to simulate the voltage fluctuations on a fictitious grid with no source of voltage fluctuations other than the wind turbine (see NOTE).

The application of the fictitious grid is further described in 8.2.2.2 and in Annex B. The measurement procedures for voltage fluctuations are separated into procedures for continuous operation and switching operations. This separation reflects that the flicker emission from a wind turbine has the character of stochastic noise during continuous operation, whereas the flicker emission and voltage changes during switching operations have the character of a number of time-limited, non-coincident events.

NOTE Although the specified method to simulate the voltage fluctuations on a fictitious grid avoids the direct influence of the real voltage fluctuations of the grid at the measurement point on flicker, there can be an influence of these voltage fluctuations, imposed by other sources, on the measured current from the wind turbine. This in turn may influence the simulated voltage fluctuations on the fictitious grid. However, this effect is relatively small and does not justify changing the procedure for determining the flicker coefficient.

8.2.2.2 Procedure

The following procedure is used to measure flicker.

Fictitious grid

The phase diagram of the fictitious grid is shown in Figure 3.

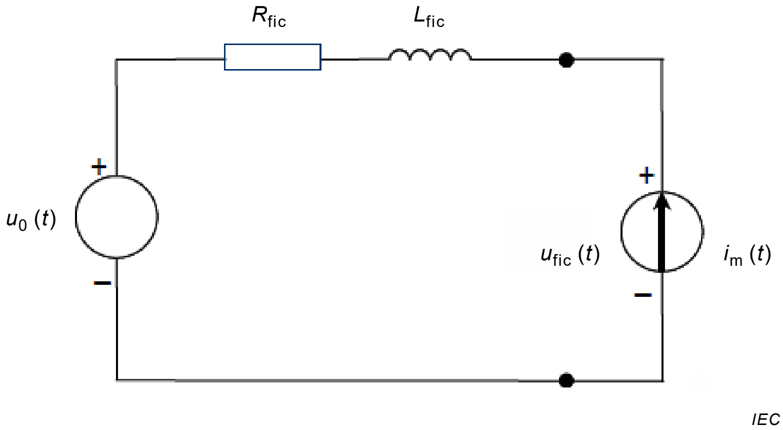


Figure 3 – Fictitious grid for simulation of fictitious voltage

The fictitious grid is represented by an ideal phase-to-neutral voltage source with the instantaneous value $u_0(t)$ and a grid impedance given as a resistance R_{fic} in series with an inductance L_{fic}. The wind turbine is represented by the current generator $i_m(t)$, which is the measured instantaneous value of the line current. This simple model gives a simulated voltage with the instantaneous value $u_{fic}(t)$ in accordance with Equation (1):

$$u_{fic}(t) = u_0(t) + R_{fic} \times i_m(t) + L_{fic} \times \frac{di_m(t)}{dt} \qquad (1)$$

The ideal voltage source $u_0(t)$ can be generated in different ways. But two properties of the ideal voltage should be fulfilled:

a) the ideal voltage should be without any fluctuations, i.e. the flicker on the voltage should be zero;

b) $u_0(t)$ shall have the same electrical angle $\alpha_m(t)$ as the fundamental of the measured voltage. This ensures the phase angle between $u_{fic}(t)$ and $i_m(t)$ is correct, provided that $|u_{fic}(t) - u_0(t)| << |u_0(t)|$.

To fulfil these properties, $u_0(t)$ is defined as:

$$u_0(t) = \sqrt{\frac{2}{3}} \times U_n \times \sin(\alpha_m(t)) \qquad (2)$$

where U_n is the RMS value of the nominal voltage of the grid.

The electrical angle of the fundamental of the measured voltage may be described by Equation (3).

$$\alpha_m(t) = 2\pi \times \int_0^t f(t)dt + \alpha_0 \qquad (3)$$

where

$f(t)$ is the frequency (that may vary over time);

t is the time since the start of the time-series;

α_0 is the electrical angle at t = 0.

R_{fic} and L_{fic} shall be selected to obtain the appropriate network impedance phase angle ψ_k applying Equation (4) below:

$$\tan(\psi_k) = \frac{2\pi \times f_g \times L_{fic}}{R_{fic}} = \frac{X_{fic}}{R_{fic}} \tag{4}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz).

The three-phase short-circuit apparent power of the fictitious grid is given by Equation (5) below:

$$S_{k,fic} = \frac{U_n^2}{\sqrt{R_{fic}^2 + X_{fic}^2}} \tag{5}$$

A proper short-circuit ratio $S_{k,fic}/S_n$ shall be used to ensure that the applied flicker meter algorithm or instrument gives P_{st} values that are well within the measurement range required in IEC 61000-4-15. A class F1 flicker meter for low measurement uncertainties shall be used. Due to the magnitude of the P_{st} values involved in the flicker characterization of the wind turbines, the flicker meter shall specify the working range in the performance testing (rectangular voltage changes and performance testing, Table 5 of IEC 61000-4-15:2010) as the lowest and highest k-value for which the corresponding value $P_{st,k}$ is within ±5 %. This part of IEC 61400 suggests using the measurement range $0{,}05 \le k \le 5{,}0$, though it is the responsibility of the assessor to select the appropriate short-circuit ratio $S_{k,fic}/S_n$ for the available measurement range.

NOTE It should be taken into account that, in one hand, larger voltage fluctuations can be obtained by decreasing the short-circuit ratio. On the other hand, if the short-circuit ratio becomes too small, the mean RMS value of $u_{fic}(t)$ will deviate significantly from the RMS value of $u_0(t)$, which will influence the relative voltage changes because the absolute voltage changes are normalised with a different mean value. To obtain simulated voltage fluctuations within the flicker meter range, a short-circuit ratio $S_{k,fic}/S_n$ between 20 and 50 is recommended.

Flicker coefficient during continuous operation

The wind turbine flicker coefficient for continuous operation, $c(\psi_k)$ shall be stated as the 95th percentile for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85° in tables for operation of the wind turbine within the active power bins 0 %, 10 %, 20 %, … , 100 % of P_n. 0 %, 10 %, 20 %, … , 100 % are the bin midpoints. The measurements shall be based on observation times of 10 minutes for each data set.

The flicker coefficient $c(\psi_k)$ shall be determined so it can be stated in accordance with Annex A. This shall be done by measurement and simulation.

The detailed procedure is provided here, whereas an informative outline is provided in Annex B.

The following measurements shall be performed:

a) The three instantaneous line currents and the three instantaneous phase-to-neutral voltages shall be measured at the wind turbine terminals. If the phase-to-neutral voltages are not available, the phase-to-phase voltages shall be measured and the phase-to-neutral voltages calculated from the measured phase-to-phase voltages. The phase-to-neutral voltages shall be calculated in accordance with Annex C.

b) Measurements shall be taken so that at least seven, 10-minute data sets of instantaneous voltage and current measurements (seven tests and three phases equal to 21 time series) are collected for each 10 % power bin. If more than these twenty-one time series are collected for a power bin, then all of the time series shall be used.

c) The wind speed should be measured optionally in accordance with 8.3.2.

d) Switching operations such as start-up and shut-down of the wind turbine are excluded.

The voltage flicker during the test shall be reported. The voltage flicker shall be measured at the wind turbine terminals and according to IEC 61000-4-15.

The measurements shall be taken with a measurement set-up and by applying voltage and current transducers with specifications in accordance with 7.5. The cut-off frequency of the voltage and current measurements shall be at least 1 500 Hz.

The measurements shall be treated to determine the flicker coefficient of the wind turbine as a function of the network impedance phase angle and its active power bin. This shall be done by repeating the following procedure for each of the network impedance phase angles and power bins.

First, the flicker coefficient for each set of 10-minute measured voltage and current time-series shall be determined. The procedure for this is given in steps 1) to 3) below.

1) The measured time-series shall be combined with Equation (1) to give voltage time-series of $u_{\mathrm{fic}}(t)$.
2) The voltage time-series of $u_{\mathrm{fic}}(t)$ shall be input to the flicker algorithm in compliance with IEC 61000-4-15 to give one flicker emission value $P_{\mathrm{st,fic}}$ on the fictitious grid for each 10-minute time-series.
3) The flicker coefficient shall be determined for each of the calculated flicker emission values by applying Equation (6):

$$c(\psi_{\mathrm{k}}) = P_{\mathrm{st,fic}} \times \frac{S_{\mathrm{k,fic}}}{S_{\mathrm{n}}} \tag{6}$$

where

S_{n} is the nominal apparent power of the wind turbine;

$S_{\mathrm{k,fic}}$ is the short-circuit apparent power of the fictitious grid.

Finally, the flicker coefficient $c(\psi_{\mathrm{k}})$ shall be determined as the 95$^{\mathrm{th}}$ percentile for each power bin and for each phase angle of the fictitious grid, and represented in a table, as in Table 4.

The long-term flicker severity can, in accordance with IEC TR 61000-3-7, be calculated as the cubic average of 12 consecutive short-term values. The flicker measurement will be done over the full range of active power capability. Seven 10-minute datasets at each power bin are used for the evaluation of the flicker behaviour. With this method, the long-term flicker severity becomes equal to the short-term value, which is a conservative approach.

NOTE 1 The formula defining the flicker coefficient is further explained in B.4.1.

NOTE 2 The 95$^{\mathrm{th}}$ percentile is applied as the flicker emission limit.

8.2.2.3 Documentation

Flicker from continuous operation shall be documented in a table and graphs, as defined, for example, in Annex A.

- Flicker coefficients as function of the impedance angle ψ_{k} for all power bins
- Graphs of the voltage flicker P_{st} and flicker coefficients against the active power.

8.2.3 Flicker and voltage change during switching operations

8.2.3.1 General

Switching operation covers flicker generated by start, stop and switching between generators of the turbine.

8.2.3.2 Description

The characteristics shall be stated for the following types of switching operations:

a) wind turbine start-up at cut-in wind speed;

b) wind turbine start-up at nominal active power;

c) the worst case of switching between generators (applicable only to wind turbines with more than one generator or a generator with multiple windings).

For each of the above types of switching operations, the values of the parameters below shall be stated:

- The maximum number $N_{10\text{m}}$ of the switching operation within a 10-minute period.
- The maximum number $N_{120\text{m}}$ of the switching operation within a 2-hour period.
- The flicker step factor $k_\text{f}(\psi_\text{k})$ for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.
- The voltage change factor $k_\text{u}(\psi_\text{k})$ for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.

Based on manufacturer's information, the maximum number of switching operations, $N_{10\text{m}}$ and $N_{120\text{m}}$ shall be determined for each type of switching operation. In the event that the wind turbine manufacturer cannot provide these values, or the manufacturer cannot provide sufficient specification of the wind turbine control system to support the provided values, the following shall be assumed:

- wind turbine start-up at around cut-in wind speed: $N_{10\text{m}}$ = 10 and $N_{120\text{m}}$ = 120;
- wind turbine start-up at nominal active power: $N_{10\text{m}}$ = 1 and $N_{120\text{m}}$ = 12;
- the worst case of switching between generators: $N_{10\text{m}}$ = 10 and $N_{120\text{m}}$ = 120.

NOTE 1 The worst case of switching between generators is in the context of flicker step factor defined as the switching operation that gives the highest flicker step factor, and in the context of voltage change factor defined as the switching operation that gives the highest voltage change factor.

NOTE 2 The parameters $N_{10\text{m}}$ and $N_{120\text{m}}$ are typically provided by the manufacturer, whereas $k_\text{f}(\psi_\text{k})$ and $k_\text{u}(\psi_\text{k})$ are measured and calculated.

NOTE 3 Depending on the control system of the wind turbine, the maximum number of switching operations within a 2-hour period can be less than twelve times the maximum number of switching operations within a 10-minute period.

8.2.3.3 Procedure

Measurements, simulations and calculations shall be prepared to determine the voltage change factor $k_\text{u}(\psi_\text{k})$, and the flicker step factor $k_\text{f}(\psi_\text{k})$ for each type of switching operation specified in 8.2.3.2.

The measurement should be taken under normal operational conditions; if it's not possible, it can be measured by manually controlling the WT.

The detailed procedure is provided here, whereas an informative outline is provided in Clause B.2.

Whereas 8.2.3.2 a) and 8.2.3.2 b) each specify switching at a specific wind speed, it is the task of the assessor to identify the conditions of 8.2.3.2 c). This may be done by assessment of the wind turbine design, or if this does not give sufficient evidence, measurements shall be taken to identify the conditions for 8.2.3.2 c). See also NOTE 1 in 8.2.3.2.

To determine the voltage change factor $k_u(\psi_k)$, and the flicker step factor $k_f(\psi_k)$, the following measurements shall be prepared:

a) the three instantaneous line currents and the three instantaneous phase-to-neutral voltages shall be measured at the wind turbine terminals;

b) the measurements shall be taken for a period, T_p, long enough to ensure that the transient of the switching operation has abated, though limited to exclude possible power fluctuations due to turbulence;

c) in order to ensure that the results of the measurements are representative of the normal average conditions, at least five time series shall be evaluated;

d) the wind speed shall be measured in accordance with Clause 7. The 1-minute average wind speed during the switching operation shall be within a range of ±2 m/s of the required wind speed.

The measurements shall be taken with a measurement set-up and by applying voltage and current transducers and an anemometer with specifications in accordance with Clause 7. The cut-off frequency of the voltage and current measurements shall be at least 1 500 Hz.

NOTE For wind turbines applying soft-starters or other effective limitation of the inrush currents, the current transducers should be nominal two to four times the nominal current. For wind turbines with converter systems, the rating of the current transducers can be in general below 2 times rated current. For wind turbines without any inrush current limitation, as guidance, the current transducers should be nominal 10 to 20 times the nominal current of the wind turbine.

The measurements shall be used to determine the voltage change factor and the flicker step factor. This shall be done applying the following procedure.

1) The measured time-series shall be combined to give voltage time-series of $u_{fic}(t)$, in accordance with 8.2.2.2

2) The simulated voltage time-series of $u_{fic}(t)$ shall be input to the flicker algorithm in compliance with IEC 61000-4-15 to give one flicker emission value $P_{st,fic}$ on the fictitious grid for each time-series of $u_{fic}(t)$. This will result in 15 values of $P_{st,fic}$ for each case, i.e. five tests and three phases.

3) The flicker step factor $k_f(\psi_k)$ shall be calculated in accordance with Equation (7).

$$k_f(\psi_k) = \frac{1}{130} \times \frac{S_{k,fic}}{S_n} \times P_{st,fic} \times T_p^{0,31} \tag{7}$$

4) The voltage change factor $k_u(\psi_k)$ shall be determined in accordance with Equation (8).

$$k_u(\psi_k) = \sqrt{3} \times \frac{U_{fic,max} - U_{fic,min}}{U_n} \times \frac{S_{k,fic}}{S_n} \tag{8}$$

where

$U_{fic,min}$ is the minimum one period RMS value of the voltage on the fictitious grid during the switching operation;

$U_{fic,max}$ is the maximum one period RMS value of the voltage on the fictitious grid during the switching operation.

5) The flicker step factor and the voltage change factor shall be determined as the average result of the 15 values.

NOTE 1 The formula defining the flicker step factor is deduced from IEC 61000-3-3 as explained in B.4.2.

NOTE 2 The flicker coefficient $P_{st,fic}$ is here evaluated over the time period T_p.

NOTE 3 The formula defining the voltage change factor is further explained in B.4.3.

8.2.3.4 Documentation

The following parameters have to be reported in, for example, a table as described in Annex A:

- flicker step factor,
- voltage change factor,

as a function of the impedance phase angle, for all measured cases.

Furthermore, time series of the voltage, current, active and reactive power shall be documented in a graph for one switching event in each case.

8.2.4 Harmonics, interharmonics and higher frequency components

8.2.4.1 General

The emission of current harmonics, interharmonics and higher frequency components during continuous operation shall be stated.

8.2.4.2 Description

It is recommended to measure the voltage harmonics: additionally, see Annex D.2.1 and IEC TR 61400-21-3[1].

The voltage and current transducers used for this kind of measurements should comply with the requirements given in IEC 61000-4-30. It should be ensured that the measurement sensors are capable of measuring the frequency components (i.e. harmonics and interharmonics) of interest.

Frequencies outside the measurement range of the instrument shall be attenuated as described in IEC 61000-4-7 so they don't affect the measurement results.

The values of the individual current components (harmonics, interharmonics and higher frequency components) and the total harmonic current distortion shall be given in tables in percentage of I_{n} and for operation of the wind turbine within the active power bins 0, 10, 20, ... , 100 % of P_{n}. 0, 10, 20, ... , 100 % are the bin midpoints.

The individual harmonic current components shall be specified as sub grouped values for frequencies up to 50 times the fundamental grid frequency in accordance with Equation 9 of 5.6, Figure 6 in IEC 61000-4-7:2002/AMD1:2008 and the total harmonic current distortion shall be stated as derived from these.

The interharmonic current components below 2 kHz shall be sub-grouped in accordance with Annex A of IEC 61000-4-7:2002/AMD1:2008.

The higher frequency components, i.e. the 2 to 9 kHz current components, shall be measured and grouped in accordance with Annex B of IEC 61000-4-7:2002/AMD1:2008 (Equation (B.1)). The output of raw DFT shall be grouped in bands of 200 Hz.

10-minute aggregation is performed using the square root of the arithmetic mean of the squared 10-cycle (for a 50 Hz power system) resp. 12-cycle window values (for a 60 Hz power system) for each harmonic as further described in Annex D and reported for each active power bin. The measurement procedure shall be suitable for wind turbines, i.e. where the

1 Under preparation. Stage at the time of publication: IEC DTR 61400-21-3:2018.

magnitude of the current harmonics produced can be expected to change over the periods of a few seconds.

If current harmonics, interharmonics or higher frequency components are clearly influenced by background distortion, then the measured values of the current harmonics, interharmonics or higher frequency components can be reduced by the amount related with the background distortion. If the harmonics are reduced, a description of the method used in determining the background distortion reduction (simulations, comparative measurements, etc.) should be included in the measurement report. See Annex D for further details. If the amount of reduction cannot be defined:

a) a note about the possible influence of the background distortion can be added to the affected harmonics, interharmonics and higher frequency components in the report;

   or

b) the harmonic model in accordance with IEC TR 61400-21-3 can be used, in order to calculate the harmonic contribution.

8.2.4.3 Procedure

Measurements shall be taken so that at least seven, 10-minute data sets of instantaneous voltage and current measurements (seven tests and three phases equal to 21 time series) are collected for each 10 % power bin. If more than these twenty-one time series are collected for a power bin, then all of the time series shall be used.

The 10-cycle window for 50 Hz and 12-cycle window for 60 Hz power systems is recommended. The window size shall be stated in the test report (see Annex A).

Harmonic currents below 0,1 % of I_{n} for any of the harmonic orders need not be reported.

NOTE Harmonic levels below 0,1 % are typical below the measurement accuracy and may be considered as measurement noise and should not be reported.

The DFT is applied to each of the measured currents with rectangular weighting, i.e. no special weighting function (Hanning, Hamming, etc.) shall be applied to measured time-series. The active power shall be evaluated over the same time window as the harmonics. It is recommended to perform measurements without synchronization and later adjust the sample rate during post-processing or to exclude measurement data in cases when the synchronization is lost.

The THC distortion for each 10-cycle window for 50 Hz and 12-cycle window for 60 Hz shall be calculated in accordance with Equation (9):

$$\mathrm{THC} = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_{\mathrm{n}}} \times 100 \qquad (9)$$

where

I_h is the sub grouped RMS current harmonic of harmonic order h;

I_{n} is the nominal current of the wind turbine.

The 10-minute square root of the arithmetic mean of the squared 10-cycle (for 50 Hz power systems) or 12-cycle (for 60 Hz power systems) window values of each frequency band (i.e. each sub-grouped harmonic, interharmonic, higher frequency current component and THC) shall be calculated for each 10-minute time-series.

NOTE 1 Harmonics are considered harmless as long as the duration is limited to a short period of time. Hence, this document does not require specification of short-duration harmonics caused by wind turbine start-up or other switching operations.

NOTE 2 IEC 61000-4-7:2002/AMD1:2008, Subclause 5.6 is on voltage harmonics. This grouping procedure is still recommended for assessing the current harmonics of a fluctuating source like wind turbines.

NOTE 3 It is recommended to measure harmonic voltage in accordance with Annex D. The harmonic voltage measurements can furthermore be used for the harmonic model validation as defined in IEC TR 61400-21-3.

8.2.4.4 Documentation

The emission of current harmonics, interharmonics and higher frequency components shall be documented in tables and graphs as shown, for example, in Annex A. The following parameters have to be measured and reported:

- 95^{th} percentile of current harmonics;
- 95^{th} percentile of current interharmonics;
- 95^{th} percentile of the higher frequency current components.

8.3 Steady-state operation

8.3.1 General

The steady-state operation subclause consists of measurements of active power against wind speed, maximum power, and reactive power capability.

8.3.2 Observation of active power against wind speed

8.3.2.1 Description

The aim is to illustrate the power production against the wind speed, during the power quality measurement period.

NOTE It is not necessary to perform an additional measurement campaign for this test as the data from 8.2.2 can be used for the analysis and reporting.

8.3.2.2 Procedure

The measured wind speed and active power shall be processed into 10-minute block average values. During the measurement, the data shall be recorded continuously.

Measurements shall be taken so that at least seven 10-minute data sets of instantaneous voltage and current measurements are collected for each 10 % power bin.

8.3.2.3 Documentation

The following parameters have to be documented and reported:

- the active power of the wind turbine (WT) shall be displayed as a function of the wind speed as shown, for example, in Figure 4.
- The number of measured 10-minute time series of active power per wind speed bin shall be represented as shown in Table 3 or as shown in Figure 6;
- The number of measured 10-minute data sets of active power per power bin as shown, for example, in Figure 5 or Table 4.

Table 3 – Number of 10-min time-series per wind speed bin

Wind speed bin: [m/s]	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	…
Total number of data sets:														

Table 4 – Number of measurements per power bin (10 min average)

Power bin [% of P_n]	-5 to 5	5 to 15	15 to 25	25 to 35	35 to 45	45 to 55	55 to 65	65 to 75	75 to 85	85 to 95	95 to 105
Total number of datasets											

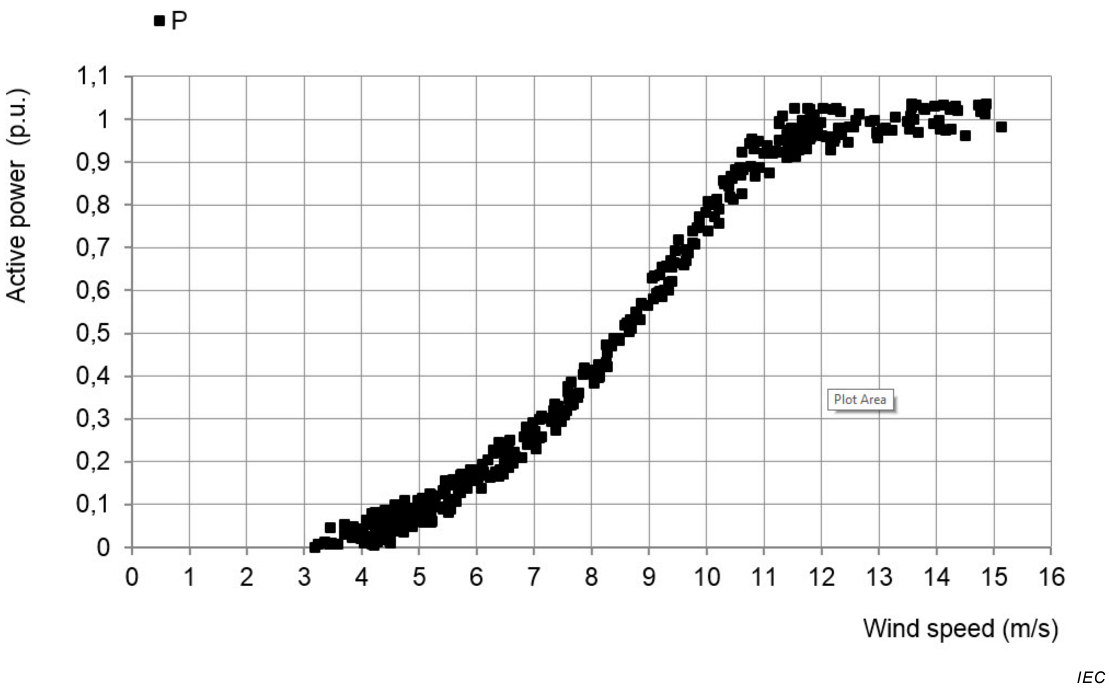


Figure 4 – Active power as a function of the wind speed (example)

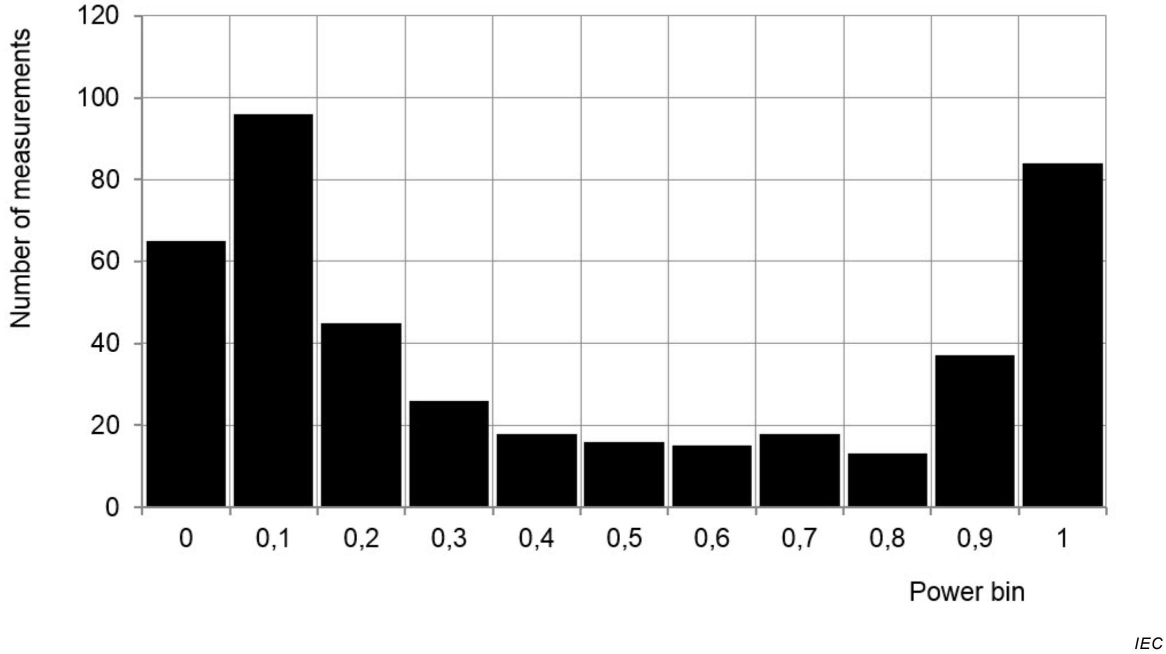


Figure 5 – Number of measurements in power bins (example)

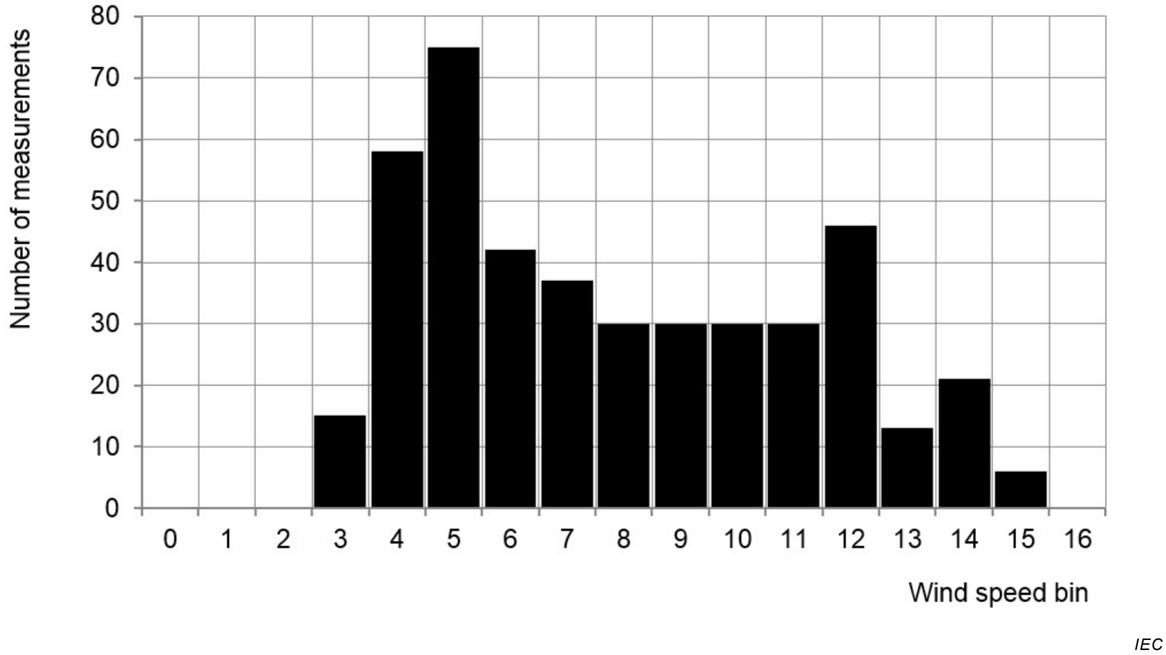


Figure 6 – Number of measurements in wind speed bins (example)

8.3.3 Maximum power

8.3.3.1 Description

The aim of the test is to show that the specified value of the active power output is kept independent from the averaging time. Data recorded from the test at 8.2.2 can be used.

The maximum measured power of the wind turbine shall be specified as a 600 s average value, P_{600}, a 60 s average value, P_{60} and as a 0,2 s average value, $P_{0,2}$. The maximum active power peaks are determined from each of the different averaging intervals.

8.3.3.2 Procedure

The maximum power shall be measured so that it can be specified in accordance with 8.3.3.1 as a 600 s average value, P_{600}, a 60 s average value, P_{60}, and as a 0,2 s average value, $P_{0,2}$, applying the following procedure:

- measurements shall be sampled during continuous normal operation only;
- the active power shall be measured at the WT terminals;
- measurements shall be taken, so that at least seven 10-minute time series in each power bin are collected;
- the measured power shall be transferred to 60 s average data and to 600 s average data by block averaging;
- $P_{0,2}$ shall be determined as the highest valid 0,2 s average value recorded during the measurement period;
- P_{60} shall be determined as the highest valid 60 s average value recorded during the measurement period;
- P_{600} shall be determined as the highest valid 600 s average value recorded during the measurement period;
- the total number of 10- minute data sets of the entire measurement campaign, from which the highest average values have been selected, shall be represented in a table (in accordance with Table 5).

As guidance, the full-scale range for measuring the current may be two times the nominal current of the wind turbine.

8.3.3.3 Documentation

The following parameters have to be calculated and documented:

- $P_{0,2}$,
- P_{60},
- P_{600},

including the number of datasets.

The results of the measured values of active power shall be represented in a table as shown in Table 5 .

Table 5 – Measured maximum active power values

Active power P_x	$P_{0.2}$	P_{60}	P_{600}
Measured active power [kW]			
Normalized active power [p.u.]			
Total number of 10-min. data sets			

8.3.4 Reactive power characteristic (Q = 0)

8.3.4.1 Description

The aim of this measurement is to determine reactive power characteristic of the WT for a reference value of Q = 0. Data recorded for 8.2.2 can be used for the analysis and reporting.

8.3.4.2 Procedure

The measurements can be carried out either in an open area test site or on a test bench. The test setup shall reflect the design envelope of the WT. The measuring devices and their accuracies shall satisfy the requirements of 7.5.

The WT shall be set to the operation mode with a reactive power reference value of 0.

The following procedure shall be applied:

- measurements shall be sampled during continuous operation only;
- the active and reactive power shall be calculated according to Annex C based on the voltages and currents at the WT terminals;
- the power factor shall be calculated according to Annex C based on the voltages and currents at the WT terminals;
- measurements shall be taken so that at least seven 1-minute time-series of active and reactive power are collected at each 10 % power bin;
- the sampled data shall be transferred into 1-minute block average values.

8.3.4.3 Documentation

The following parameters shall be documented and reported as e.g. described in Annex A:

- the measured reactive power as a function of active power (10 % bin classification);
- the measured power factor as a function of active power (10 % bin classification).

8.3.5 Reactive power capability

8.3.5.1 Description

The aim of this measurement is to determine the under- and overexcited reactive power capability of the WT as a function of the active power output.

8.3.5.2 Procedure

The measurements shall be performed in a field test or at a test bench.

The capability of the WT concerning the maximum underexcited reactive power and the maximum overexcited reactive power of the WT shall be measured as 1-minute block average values as a function of the 1 minute average active output power for all power bins.

Reactive power reference values:

- for the measurement of the maximum underexcited reactive power, the WT shall be given a reference value high enough to show the maximum underexcited reactive power capability in the active power range;
- for the measurement of the maximum overexcited reactive power, the WT shall be given a reference value high enough to show the maximum overexcited reactive power capability in the active power range.

For each of the two reactive powers setting modes, the following procedure shall be applied:

- measurements shall be sampled during continuous operation only;
- the active and reactive power shall be calculated in accordance with Annex C based on the voltages and currents at the WT terminals;
- the power factor shall be calculated in accordance with Annex C based on the voltages and currents at the WT terminals;
- measurements shall be taken so that at least seven 1-minute time-series of active and reactive power are collected at each 10 % power bin for field test measurements;
- measurements shall be taken so that at least one 1-minute time-series of active and reactive power are collected at each 10 % power bin for sub- system tests;
- the sampled data shall be transferred into 1-minute block average values.

8.3.5.3 Documentation

The following parameters shall be documented and reported as described, for example, in Annex A:

- the measured reactive power as a function of active power (10 % bin classification);
- the measured power factor as a function of active power (10 % bin classification);
- the measured PQ diagram, including the measured voltage shall be reported as illustrated in Figure 7.

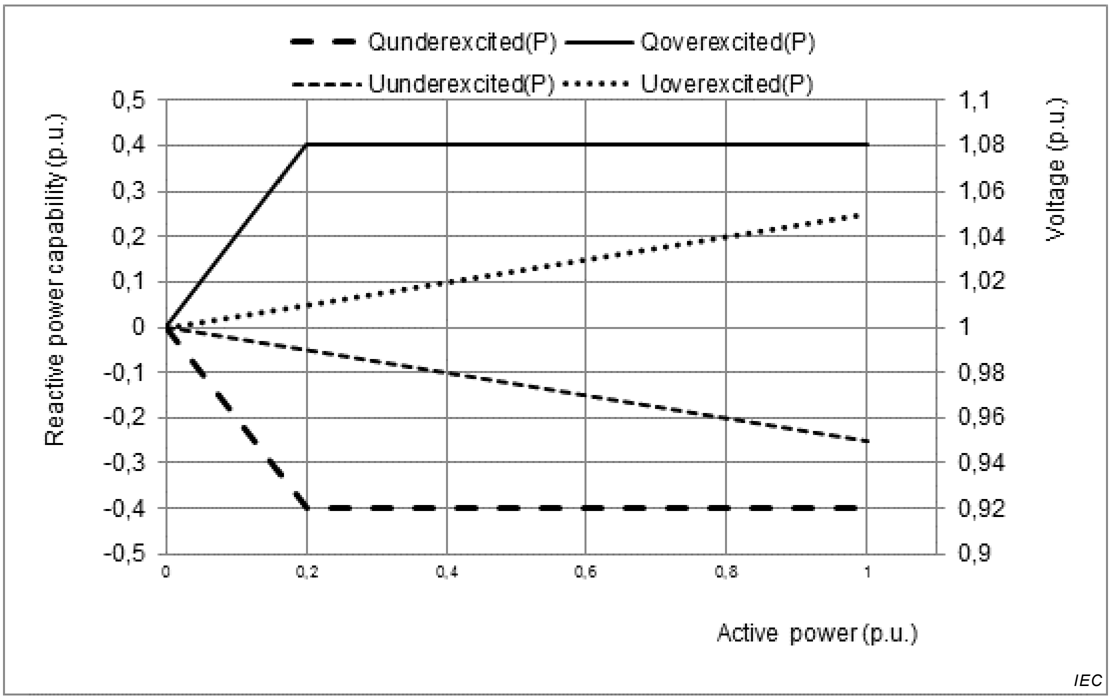


Figure 7 – Example of PQ capability diagram for a given voltage at WT level

8.3.6 Voltage dependency of PQ diagram

8.3.6.1 Description

The dependency to the voltage variations at the WT terminals should be documented according to the manufacturer's specification. The PQ diagram should be repeated for the maximum and minimum continuous operation voltage for the wind turbine according to the manufacturer's specification. To be able to adjust the voltage to cover the operation range of the wind turbine, it is recommended to perform a sub-system test of generator and converter on a test-bench, if it is not feasible to test in a field test.

8.3.6.2 Procedure

Requirements for the voltage dependency of P(Q)-characteristic measurement in a field test:

The results shall be reported in the form of a PQ diagram clearly indicating the voltage dependency or in separated diagrams (see Figure 7 as example).

Requirements for the voltage dependency of P(Q)-characteristic measurement in a test bench test:

The test-bench should have a variable power supply and the sub-system under test shall consist of all the components that influence the reactive power capability.

Procedure for sub-system test:

- select active power reference value inside the active power bin;
- run the generator at the r/min corresponding to the active power reference value;
- set the reactive power reference value to maximum underexcited or overexcited;
- adjust the input voltage to the desired level;
- record at least one 1-minute time series at the active power bin;
- repeat the procedure for all power bins.

8.3.6.3 Documentation

The following parameters shall be documented and reported as described, for example, in Annex A:

- the measured reactive power as a function of active power (10 % bin classification);
- the measured power factor as a function of active power (10 % bin classification);
- the measured PQ diagrams, including the measured voltage at different voltage levels shall be reported as illustrated in Figure 7.

8.3.7 Unbalance factor

8.3.7.1 Description

The aim of the measurement is to determine the unbalance factor in the wind turbine fed-in current. The measurement data from 8.2.2 can be used for the analysis and reporting.

8.3.7.2 Procedure

Current unbalance factor IUF is calculated as 1-minute aggregated values using the square root of the arithmetic mean of the squared 10-cycle (for 50 Hz power systems) resp. 12-cycle window values (for 60 Hz power systems), as defined in IEC 61000-4-30 from each measured record using the following equation:

$$IUF = \frac{I_2}{I_1} \cdot 100\ \%$$

where:

I_1 is the 10-cycle or 12-cycle window positive sequence current, in accordance with Annex C;

I_2 is the 10-cycle or 12-cycle window negative sequence current, in accordance with Annex C.

Active power positive sequence system component is calculated as 1-minute arithmetic mean.

The data are grouped into 10 % active power bins. Only measurement data where the active power are above or equal to 10 % of P_N are used. The aggregated values of the current and voltage positive and negative phase sequence system components, current unbalance and active power positive phase sequence system component are calculated for each active power bin.

8.3.7.3 Documentation

The measured 1-minute values of the current unbalance and the active power positive sequence system component are represented as an IUF-P diagram.

The measurement results shall be presented in a table as mean values of each power bin, as defined, for example, in Annex A. The maximum current unbalance factor as a 1-minute value shall be explicitly given.

8.4 Control performance

8.4.1 General

Control performance is the ability of the turbine to follow a given reference value for active or reactive power or to control the power based on the grid frequency.

8.4.2 Active power control

8.4.2.1 Description

The ability of the wind turbine to operate in active power control mode shall be characterized for various reference values given by the control interface. The aim of this test is to determine the response of the WT to reference commands regarding the static error, the rise time and the settling time of active power, for both steady-state conditions and under dynamic response conditions. An exemplary tabular representation of the test results is given in Annex A.

8.4.2.2 Procedure

Static error test

For the test of the static error, the following test procedure is recommended: a reference value shall request active power reduction from 1,00 p.u. to 0,20 p.u. in steps of 0,20 p.u. with at least 2-minute operation at each reference value in accordance with Figure 8. The static error and the settling time shall be determined in accordance with 3.43.

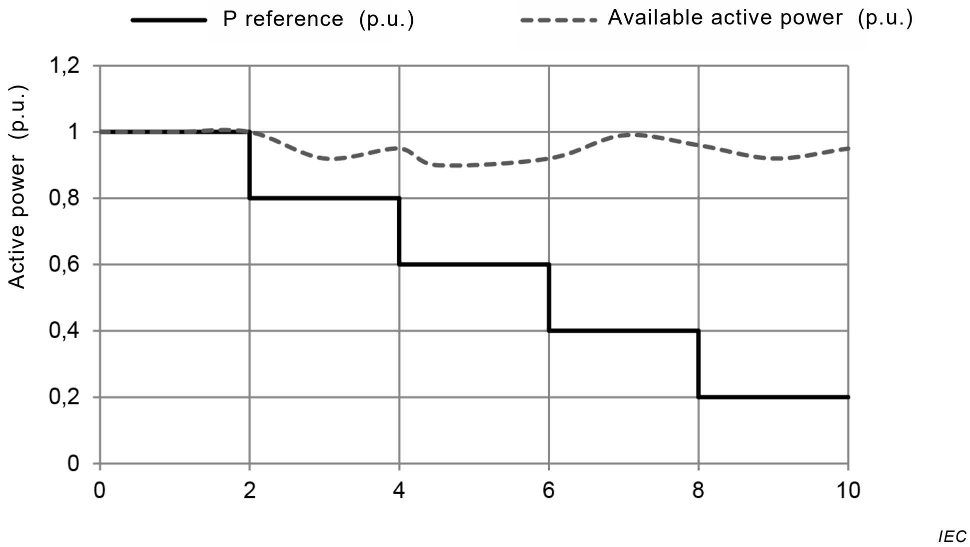


Figure 8 – Adjustment of active power reference value

The calculation of the 1-minute block-average values for the test report shall be carried out after steady state is reached. The time of steady state will be defined as the last 1 minute at each step.

- The absolute static error of the active power shall be measured.
- The wind speed should be such that the available active power output of the WT is at least 0,1 p.u. higher than the targeted reference value, but not less than 0,5 p.u. during the entire test procedure. For the reference value of 1,0 p.u. the WT shall operate with nominal active power.
- The test has to be carried out continuously, i.e. it is not allowed to connect disjoint measurements. A control interface shall be used.
- The sampled data for the active power shall be one fundamental period average data.

Dynamic response test

This test will be used to determine the dynamic behaviour of the WT by observing the step response characteristics (i.e. settling time, ramp-down time, reaction time). The test shall be carried out by a step with a minimum step size of 0,4 p.u. of the nominal active power according to Figure 9.

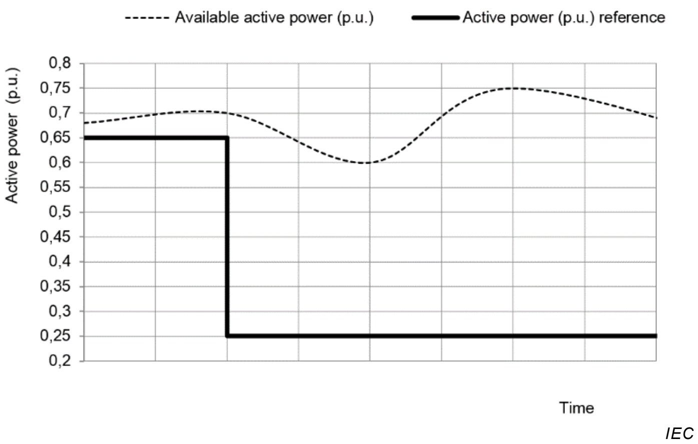


Figure 9 – Example of active power response step

- The tolerance band is ±0,05 p.u. for the calculation of the settling time.
- The sampled data for active power shall be calculated over one fundamental period (average data).

Ramp rate limitations shall be deactivated during the test. If this is not possible, the ramp rate limitation has to be adjusted to the highest value (that causes the fastest reaction of the WT).

8.4.2.3 Documentation

The following parameters shall be documented and reported as described, for example, in Annex A.

Test Static error:

The test results shall be reported as 0,2 s average data and calculated in accordance with Annex C.

The graph shall show available active power, measured active power output and the given reference values, during operation at reference values being adjusted from 1,0 p.u. down to 0.2 p.u. of nominal active power in steps of 0,2 p.u.

NOTE The available active power can be calculated from the measured wind speed signal, which is converting into an active power signal according to the observation of active power against wind speed (see 8.3.2). Alternatively, the available active power output could be provided by the control system of the wind turbine.

For the evaluation of the static error the reference value, the actual value and the difference between the reference value and the actual value as 1-minute average data shall be represented as shown in Table 6.

Table 6 – Accuracy of the active power control values

Active power step [p.u.]	Requested reference value		Actual value		Max absolute static error	
	[kW]	P/P_n [p.u.]	[kW]	P/P_n [p.u.]	[kW]	P/P_n [p.u.]
1,00						
0,80						
0,60						
0,40						
0,20						

Test dynamic response:

Response time information (rise time, reaction time and settling time) as well as the time instant for the reference value command change at every step shall be recorded in a table in accordance with Table 7, together with the corresponding time series.

Table 7 – Results from the active power reference test

Active power reference P/P_n [p.u.]		Settling time [s]	Rise time [s]	Reaction time [s]	Time instant of reference command
Starting point	Second point				

The measured active power shall also be shown in a graph as one fundamental period data together with the reference value of the active power.

Furthermore, a description of the implementation of the reference values shall be reported together with the interface description.

8.4.3 Active power ramp rate limitation

8.4.3.1 Description

The aim of this measurement is to show the capability of the WT to follow given active power gradients, with positive and negative ramp rate, during the following operational states:

- start-up, normal stop and start up after grid disconnection;
- normal operation (with positive and negative ramp rate).

NOTE The test "after grid disconnection" shows that the WT does not "forget" the ramp rate settings after loss of voltage, after tripping or after restart of the WT.

The manufacturer shall declare the possible settings (reference values or setting range) of the ramp rates of the WT. The tests shall be adapted to the possible settings of the ramp rates of the WT.

8.4.3.2 Procedure

The wind speed shall be high enough for active power production higher than 0,7 p.u. for the entire test.

Data should be recorded from 10 s before the ramp rate command and until steady state condition is reached.

At the beginning of the test, the WT shall be operated in normal operation mode. The active power of the WT can be set to an adequate start value above 0,5 p.u. of the nominal active power. Then the following two tests with different ramp rates shall be performed.

Test 1 (slow ramp rate), e.g. +/- 10 % P_n /minute

Test 2 (fast ramp rate), e.g. +/- 2 % P_n /s

The test shall be carried out with at least P = 0,2 p.u. of the nominal active power between each reference value.

For the tests of the ramp rate at start-up and normal stop the data recorded for 8.2.3 can be used for the evaluation.

For the ramp rate calculation after start-up after grid disconnection, the recorded data from 8.6.4 can be used.

8.4.3.3 Documentation

The ability of the wind turbine to operate in ramp rate limitation control mode shall be characterized by test results presented in a graph. The graph shall show the available and measured active power output during the operational state. Figure 10 gives an example of a step with a negative ramp rate and of a step with a positive ramp rate. The steps are achieved by switching the WT from one reference value to another reference value and back.

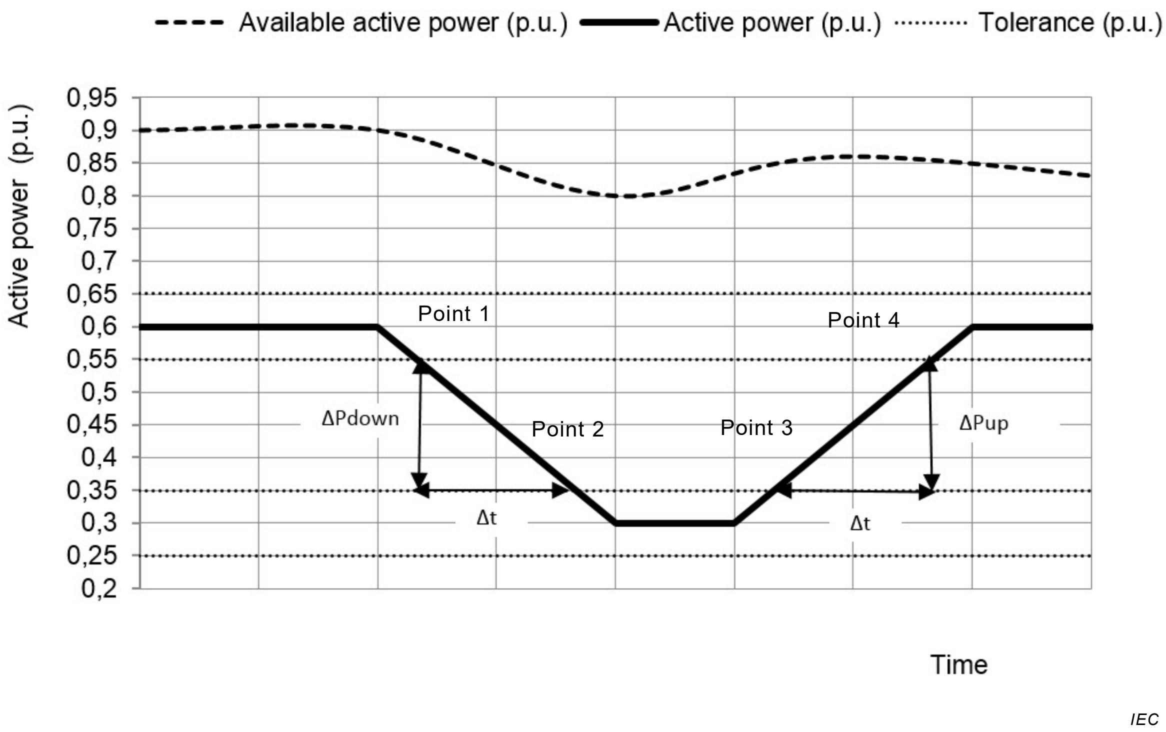


Figure 10 – Example of available active power and active power in ramp rate limitation modefigue

The positive and negative active power gradient shall be calculated from the 0,2 s average of the measured active power from respectively two different points during the ramp rate activation (point 1 and point 2 for the calculation of the negative gradient and point 3 and point 4 for the calculation of the positive gradient, in accordance with Figure 10.

Table 8 – Active power ramp rate calculation

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			
Point 3			
Point 4			

- Requested and measured ramp rate characteristic shall be given in the test report in accordance with Table 8.
- The available and measured active power output shall be represented in a graph in accordance with Figure 10.
- A declaration of the ramp rate setting procedure by the manufacturer shall be described in the test report.

The test results shall be reported as 0,2 s average data and calculated in accordance with Annex C.

8.4.4 Frequency control

8.4.4.1 Description

With this test, the active power reduction as a function of the grid overfrequency shall be measured and documented.

NOTE The defined frequency test includes only over frequency and no under frequency tests, as the described procedure only validate the functionality of the frequency control and not the real performance in relation to frequency changes. Furthermore, this control functionality is mainly performed on the Wind Power Plant level.

The wind turbine frequency dependent active power control capability shall be declared by the manufacturer in terms of: deadband, slope and release conditions (see Figure 11 and Table 9 as an example).

8.4.4.2 Procedure

The procedure to test frequency control involves pairs of frequency and active power which begin from a starting point at "First measurement point" to the maximum possible frequency reference value at "step max" and back to the starting point "Step release control" according to the chosen function of the controller. The following tests verify the control capability of the WT to perform a frequency dependent power control, with a given gradient.

It is up to the WT manufacturer to define the kind of control function that shall be tested. The number of frequency steps and frequency values is variable and depends on the control function to be tested.

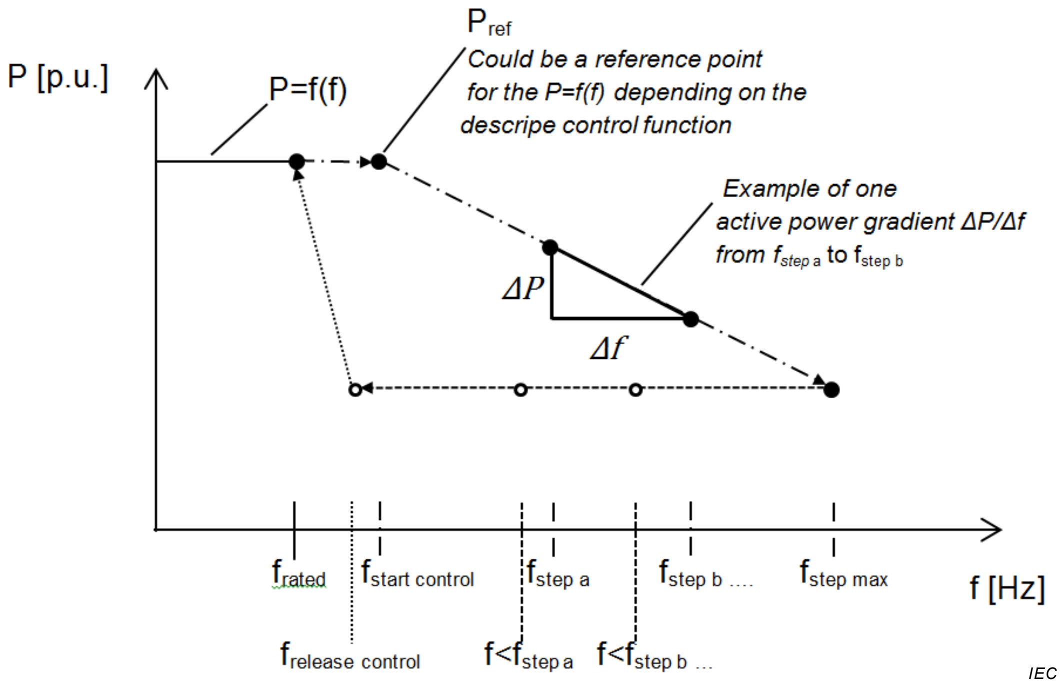


Figure 11 – Example of an active power control function P=f(f), with the different measurement points and related steps of frequency

- The test shall be performed at two different power levels, at
  a) P > 0,8 p.u.
  b) P between 0,25 p.u. and 0,5 p.u.
- Each frequency step should be held for at least 30 seconds.
- If the controller allows different settings concerning the response time or the delay time for the frequency-dependent active power reduction, then the fastest possible setting has to be chosen.

For the test itself, one of the following procedures shall be used:

a) Changing the limits of the wind turbine frequency control by adjusting the nominal frequency in the control unit. This test can only be used if the frequency change can be applied to a running wind turbine.

b) Provide an internal or external input at the control unit to add a frequency reference value offset to the nominal frequency. The software shall be adapted to calculate a resulting frequency (nominal frequency + offset signal) and to react to this signal. For this test, also the additional offset shall be measured.

c) The test can be performed as a sub-system test. The sub-system that is tested shall consist of at least the WT controller and a suitable grid simulator/test bench.

The grid protection settings of the WT shall not be changed during the test.

8.4.4.3 Documentation

The test results shall be reported in accordance with Annex A and consist of:

- The measurement set up has to be described, including the used procedure a), b) or c).
- The measured frequency together with the reference signal has to be documented. The active power output of the wind turbine as block average time values (0,2 s) and the available active power have to be documented.
- The active power and the frequency change over time shall be presented in the report.
- If the test is carried out by changing the nominal frequency, the timing of the adjustment of the nominal frequency change has to be documented. The results of the test "frequency increase at nominal active power" have be documented in a table. This includes the measured frequency and active power and the calculated active power gradient.
- The active power gradient between two consecutive measurement points shall be determined by calculation of $\Delta P/\Delta f$, as can be seen in Figure 11 as an example.
- The results of the test "frequency increase at partial power" have to be documented in a table. This includes the measured frequency and active power and the calculated active power gradient.
- The active power shall be plotted over the frequency increase. Frequency increase is the difference between the measured frequency and the nominal frequency of wind turbine.
- For nominal as well as for partial power, an average gradient of active power shall be calculated and reported based on the determined gradients given in Table 9.

Every change of parameter shall be documented.

Table 9 – Example of Settings for the frequency dependent active power function

Step of the Measurement	Measured Grid frequency [Hz]	Frequency reference [Hz]	Measured Active power [p.u.]	Active power gradient [p.u./Hz]
First measurement point	f_{rated}	-----		-----
Step start control				
Step $f_{\text{step a}}$				
Step $f_{\text{step b}}$				
Step max				
Step $f < f_{\text{step b}}$				
Step $f < f_{\text{step a}}$				
Step release control				

According to 8.4.4.1, the frequency control function should be declared by the manufacturer and clearly described.

8.4.5 Synthetic inertia

8.4.5.1 Description

The aim of this test is to document the wind turbine ability to support the grid by providing additional active power in the case of under frequency events in the power system.

8.4.5.2 Procedure

The control response of the wind turbine to fast grid frequency changes shall be performed for the wind turbine operating during continuous operation at:

a) partial load between 0,25 P_n and 0,5 P_n,

b) above 0,8 P_n, and

c) above nominal wind speed (or wind turbine with reduced active power reference) with the power factor of 1.

For a) and b), the wind turbine shall not be operated with reduced active power output (derated turbine). To operate the wind turbine with reduced active power reference is acceptable during the synthetic inertia test part c).

The stated response shall include results from at least 2 tests for each case, a), b) and c), by time-series of active power, and frequency reference value f_{sim} at the wind turbine terminals as well as wind speed for the time shortly prior to the active power rise until the active power recovery phase of the wind turbine.

The measurement consists of 3 intervals of active power output behaviour: power boost, steady state and ramp-down. For the start of the power boost interval, the frequency f_{sim} has to drop or rise from the reference signal and the synthetic inertia capability chart for the turbine specification to be verified by the synthetic inertia tests.

The active power shall be given for each line period (50 Hz or 60 Hz), and shall be reported as positive sequence fundamentals – see Annex C. The frequency reference value (as 0,2 s block average value) and the active power are the minimum values that need to be reported, as shown in Figure 9, for example.

The test can be carried out using for instance a direct activation signal in the WT control, a suitable grid simulator, or a lookup-table to apply the frequency reference value f_{sim} to the wind turbine frequency control system.

To show the synthetic inertia capability of the WT the manufacturer must ensure that the inertia functionality is enabled and other functionalities which might also cause a reaction to grid frequency changes (like grid protection settings, RoCof functionality) do not interfere.

8.4.5.3 Documentation

All turbine-specific inertia setting parameters, test conditions and measured values shall be stated in the report in accordance with Table A.35.

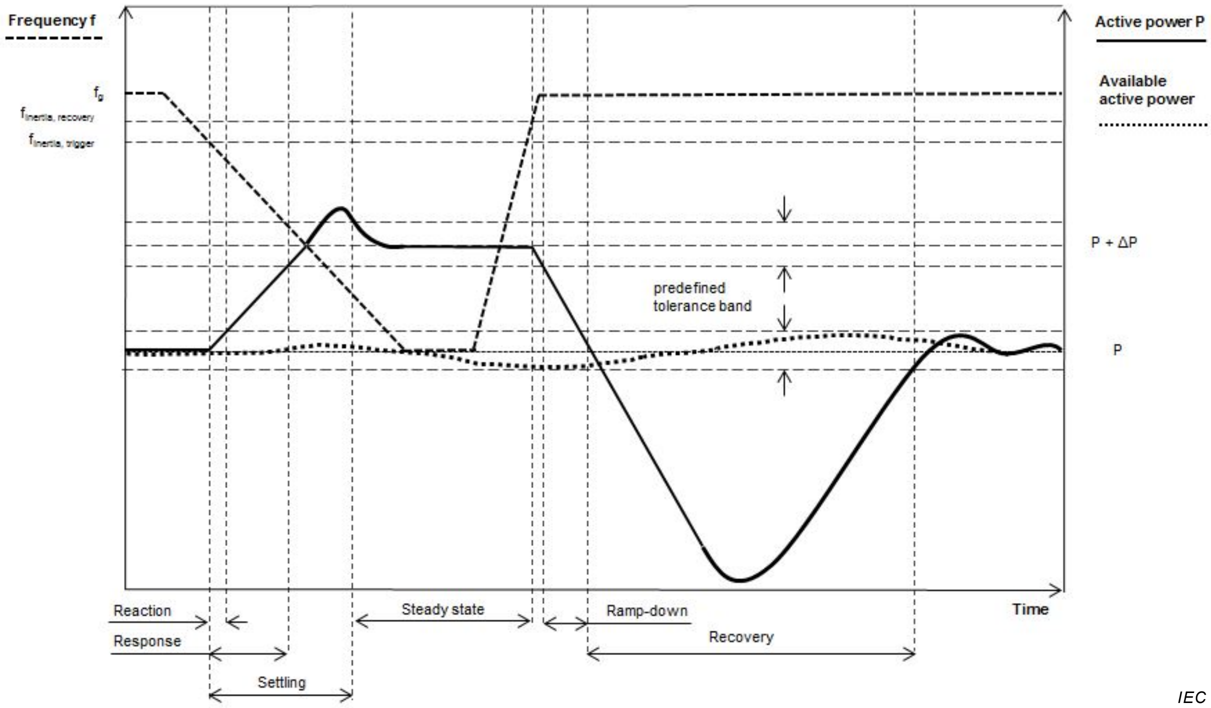


Figure 12 – Synthetic inertia – definitions

The stated response shall include time-series of active power and frequency reference value f_{sim} at the wind turbine terminals as well as wind speed for the time shortly prior to the active power rise and until the active power recovery phase of the wind turbine (see Figure 12). Typically, 5 s prior to the start of the synthetic inertia event to show if the wind speed drops or rises and at least 5 s post the recovery time.

8.4.6 Reactive power control

8.4.6.1 Description

The aim of this test is to determine the response of the WT to reference commands regarding the static error, the rise time and the settling time of reactive power using either reactive power, voltage or cos φ reference values, depending on the wind turbine control system as specified by the manufacturer. For exemplary tabular representation of the test results, see Annex A.

8.4.6.2 Procedure

- Measurements shall be sampled during continuous operation only.
- The active and reactive power shall be measured at the WT's terminals.
- The active power during the entire control test shall be in the range where the WT can reach its maximum reactive power.
- The sampled data for reactive power shall be one fundamental period's average data.
- The measured reactive power shall be shown in a graph as one fundamental period data together with the reference value of reactive power.

Static error test

The reference of reactive power shall be varied, in accordance with Figure 13. The calculation of the 1 min block-average values for the test report shall be carried out after steady state is reached during the last minute of each step period.

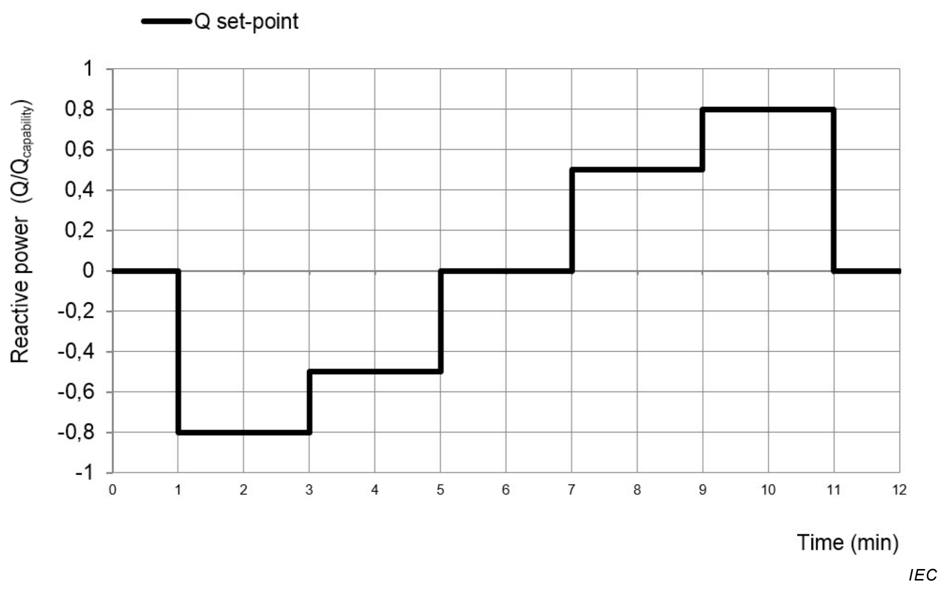


Figure 13 – Test for static error

Dynamic response test

This test will be used to determine the dynamic behaviour of the WT by observing the step response characteristics (i.e. settling time, rise time, reaction time).

To test the dynamic response of the WT, reactive power should be switched to 0,8 p.u. overexcited mode of operation of the Q_capability, then to 0,8 p.u. underexcited mode of Q_capability of the wind turbine, as shown in Figure 14. The active power during the entire dynamic response test shall be in the range where the WT can reach its maximum reactive power.

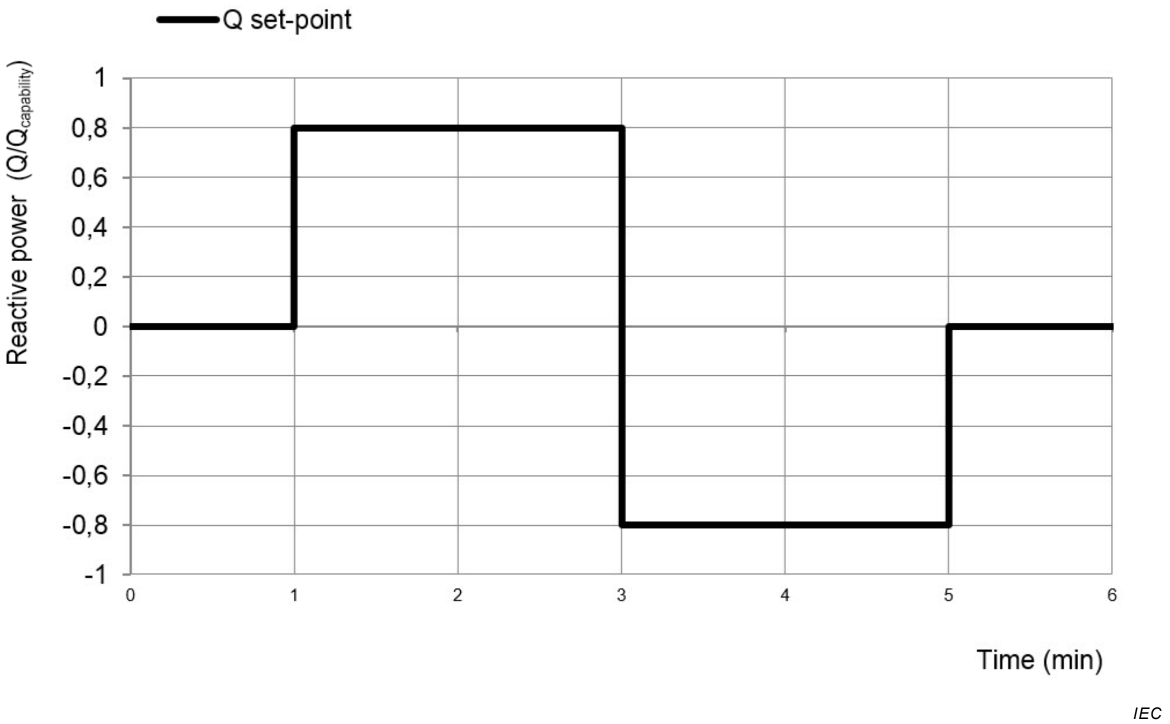


Figure 14 – Test of dynamic response (example)

8.4.6.3 Documentation

Measurement results shall be documented as follows, as shown in Table 10 and Table 11:

<u>Static error test</u>

- The differences from the reference values shall be provided in kvar and p.u. for the reactive power.
- Description of the sequence of reactive power control corresponding to the references, especially the implementation of the reference values shall be described.
- The network voltage during the measurements shall be provided in the report as the 1-minute average value for all reference values.
- The interface used for reference values shall be reported.

<u>Dynamic response test</u>

- Response time information (rise time, reaction time and settling time) as well as the time instant for the reference value command change at every step shall be recorded in accordance with Table A.38.
- Description of the sequence of reactive power control corresponding to the reference values, especially the implementation of the reference values, shall be described.
- The network voltage during the measurements shall be provided in the report as 1-minute average value for all reference values.
- The interface used for reference values shall be reported.

Table 10 – Test for static error

Reactive power step $Q/Q_{capability}$ [p.u.]	Voltage	Reference value		Measured value		Static error	
	U [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]
-0,8							
-0,5							
0							
0,5							
0,8							

Table 11 – Test for dynamic response

Reactive power reference value (p.u.)	From 0 to 0,8 (overexcited)	From 0,8 (overexcited) to 0,8 (underexcited)	From 0,8 (underexcited) to 0
Settling time (s)			
Rise time (s)			
Reaction time (s)			
Time instant of reference command			

8.5 Dynamic performance

8.5.1 General

Subclause 8.5 describes the measurement procedures to demonstrate the fault ride through capabilities of the WT and to provide measurement data for the simulation model validation.

8.5.2 Fault ride-through capability

8.5.2.1 Description

The following tests are to evaluate the wind turbine capabilities in relation to undervoltage and overvoltage events imposed on the WT terminals.

The test is intended to verify the wind turbine response to undervoltage and overvoltage events (due to e.g. grid faults, switching operations) and providing a basis for wind turbine numerical simulation model validation. Optional tests and measurements at different operational conditions (e.g. reactive power operation mode) may be carried out and reported for more detailed assessment of simulation models and compliance with specific grid code requirements.

8.5.2.2 Procedure

The response of the wind turbine to the undervoltage and overvoltage events in accordance with the turbine manufacturer's specifications shall be measured.

The stated response shall include time-series of:

- positive and negative sequence voltage,
- positive and negative sequence currents,
- active power,
- reactive power,

- active current,
- reactive current,
- wind speed or available power.

Positive sequence and negative sequence values shall be calculated in accordance with Annex C.

All measurements per unit are referred to the nominal values.

Length of the time-series is defined as from stable conditions prior to the voltage dip or swell and until the effect of the undervoltage or overvoltage event has abated. Typically, 10 s prior and 10 s post fault.

The wind turbine operational mode shall be specified.

The test shall be carried out for the wind turbine operating at a) between 0,25 p.u. and 0,5 p.u. and b) above 0,9 p.u. of the nominal active power.

The test can be carried out using the voltage division principle, schematically shown in Figure 15 (for undervoltage events), or by a suitable AC grid simulator in a test bench, or other suitable test system (able to perform the requested voltage events).

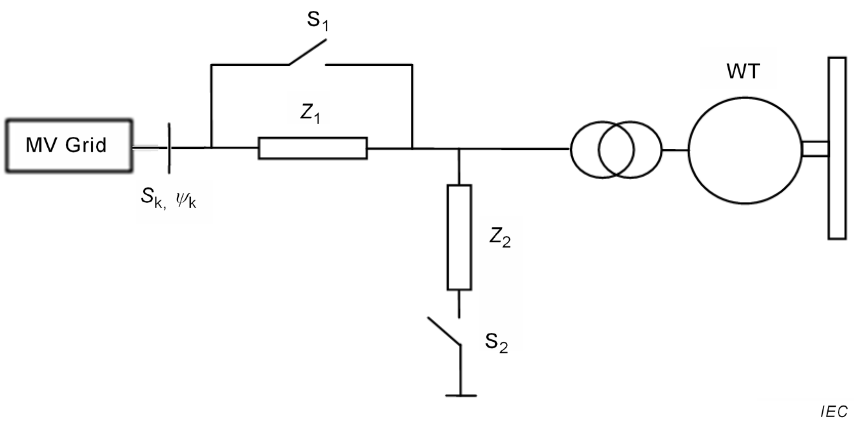


Figure 15 – Example UVRT test equipment

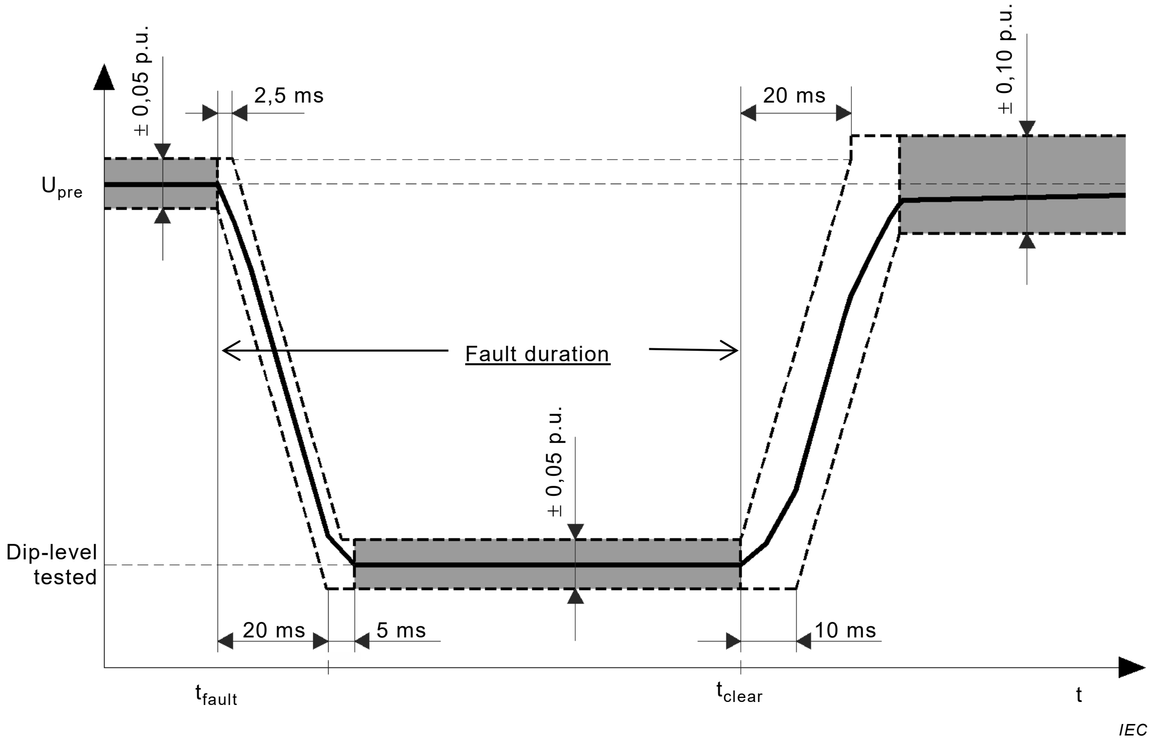
The impedance Z_1 is for limiting the effect of the short-circuit for the up-stream grid. A by-pass connection of Z_1 may be applied prior and after the dip by operating S_1. Operating the by-pass switch S_1 should be timed so to prevent interference with the test.

The undervoltage event is created by connecting the impedance Z_2 by the switch S_2. The size of Z_2 shall be adjusted to give the voltage magnitudes specified for the test, when the wind turbine is not connected. The detailed test system and test conditions shall be documented in the test report.

The switch S_2 shall be able to accurately control the time between connection and disconnection of Z_2, and for all three or two phases. The switch should be e.g. a mechanical circuit breaker or a power electronic device. The voltage magnitudes specified for the test may be affected by the wind turbine operation but are defined for the wind turbine not connected to the setup outlined in Figure 15. Without the wind turbine connected, the undervoltage event shall be within the shape indicated in Figure 16. The duration of the dip can be measured on the voltage waveform at the output terminals of the test equipment, alternatively the duration time can be measured e.g. on the current through the switch S_2.

The number of tests and operational modes needs to be defined and described by the manufacturer in order to document the turbine's capability. It is recommended to test at four different undervoltage levels:

- minimum voltage the turbine can ride through U_{min},
- U_{min} + 0,2 p.u. of the under voltage range capability U_{UVRC},
- U_{min} + 0,5 p.u. U_{UVRC} and
- U_{min} + 0,75 p.u. U_{UVRC}.



NOTE The tolerance of the voltage is stated as per unit of the prefault voltage. Figure 16 shows that there is a tolerance band of total 7,5 ms around the positive sequence voltage for the dip and a tolerance of 10 ms for the voltage recovery on the positive sequence voltage. The most important values for evaluation of the fault performance is the fault duration and the dip level as indicated in the figure.

Figure 16 – Tolerances of the positive sequence voltage for the undervoltage event with disconnected WT under test

For tests of the overvoltage capability of the wind turbine, the actual measured values of voltage, overvoltage duration and tolerances shall be stated in the report.

It is up to the manufacturer to define the overvoltage event capability chart for the turbine specification to be verified by an overvoltage test. At least two different levels should be tested one at maximum voltage and one event at 50 % to 80 % of the overvoltage range capability.

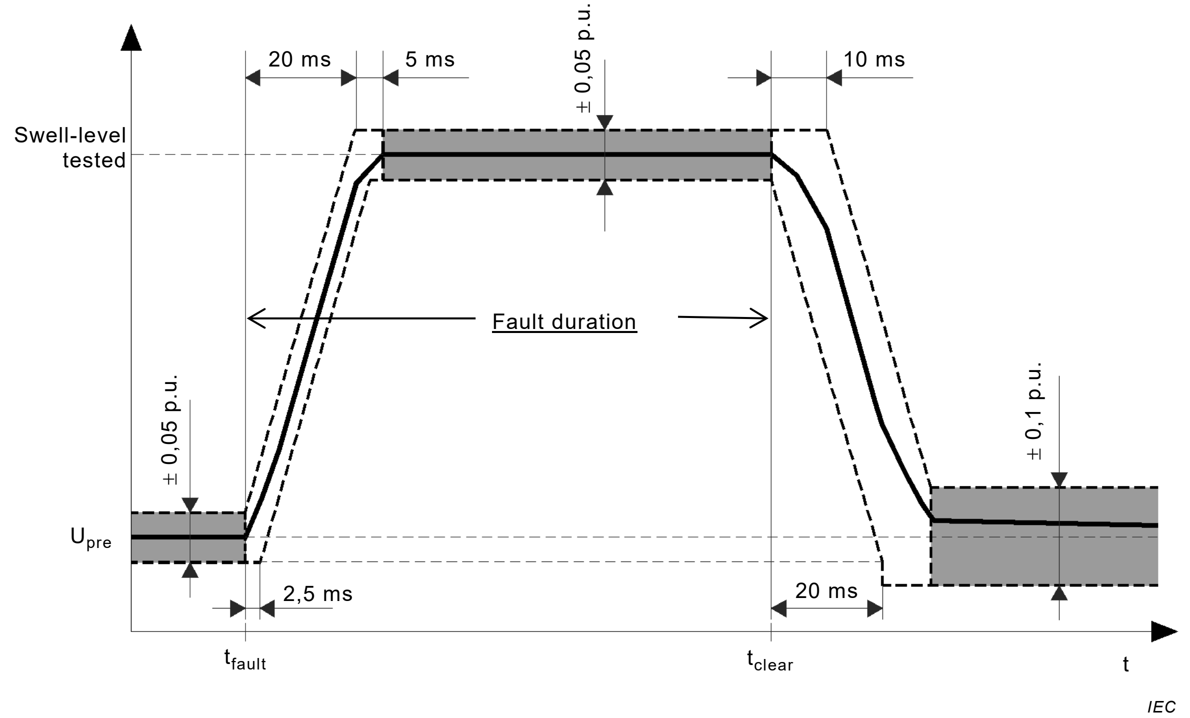


Figure 17 – Tolerance of positive sequence overvoltage event

Examples of possible test equipment that can support overvoltage events:

- capacitor based test unit;
- autotransformer or a bypass transformer system;
- converter system (AC grid simulator).

As an example, a capacitor-based OVRT test unit is shown in Figure 18. The overvoltage event can be created by connecting the three or two phases together via an impedance consisting of a capacitor C_L and a resistor R_d in series, or connecting the three or two phases to ground via an impedance consisting of a capacitor C_L and a resistor R_d in series. This way, overvoltage scenarios in grids (e.g. load shedding, Ferranti effect) can be emulated.

As also described above for the UVRT test unit, the effect of the test sequence for the up-stream grid is limited by the impedance X_{SR}, and at the same time does not significantly affect the transient response of the wind turbine. A by-pass connection of X_{SR} (S_1) may be applied prior and after the voltage swell that is initiated by operating S_2.

The overvoltage event can be created by connecting the impedance consisting of C_L and R_d by circuit breaker S_2. The values of X_{SR}, C_L and R_d can be adjusted in order to give the voltage magnitudes specified for the test, when the wind turbine is not connected.

The circuit breakers S_1 and S_2 shall be able to accurately control the duration of the voltage swell. The switch could be, for example, a mechanical circuit breaker or a power electronic device.

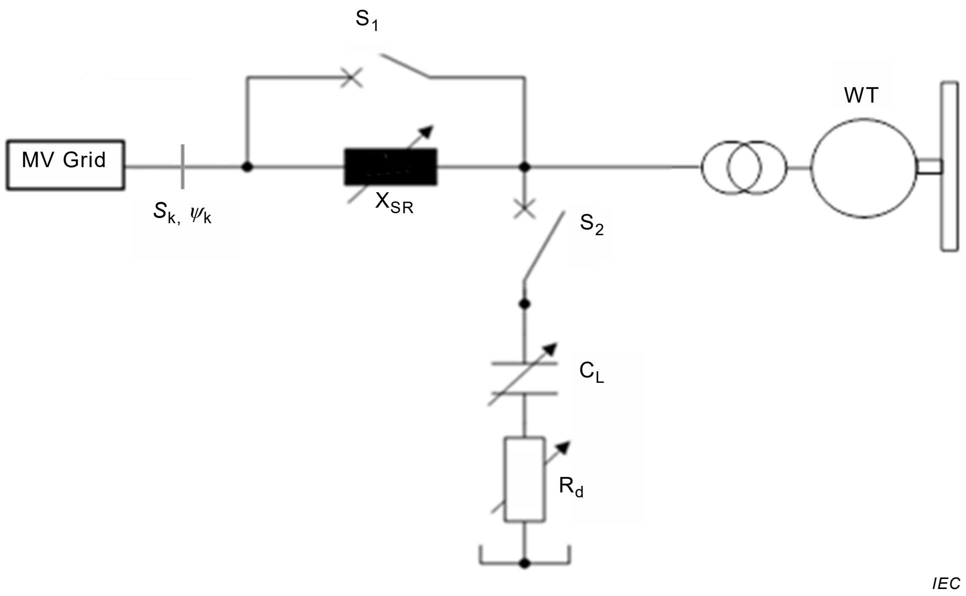


Figure 18 – Example OVRT capacitor test unit

8.5.2.3 Undervoltage events

Response to undervoltage events shall be done as a field test to demonstrate the ride-through capability of the entire turbine. Field test can be complemented by a test bench test, where for example different operation modes, different grid codes settings or different components can be verified.

The capability of the wind turbine to handle undervoltage events shall be demonstrated for the wind turbine operating in the full load and partial load range. Partial load can be done with a down regulated turbine (de-rating or curtailed). At least two dips of the partial load tests shall be done under normal operational conditions (without derating/curtailed). Test conditions shall be stated in the report.

It is up to the manufacturer to define the number of the voltage levels in the undervoltage capability chart for the turbine specification to be verified by undervoltage test. See Figure 19 as an example.

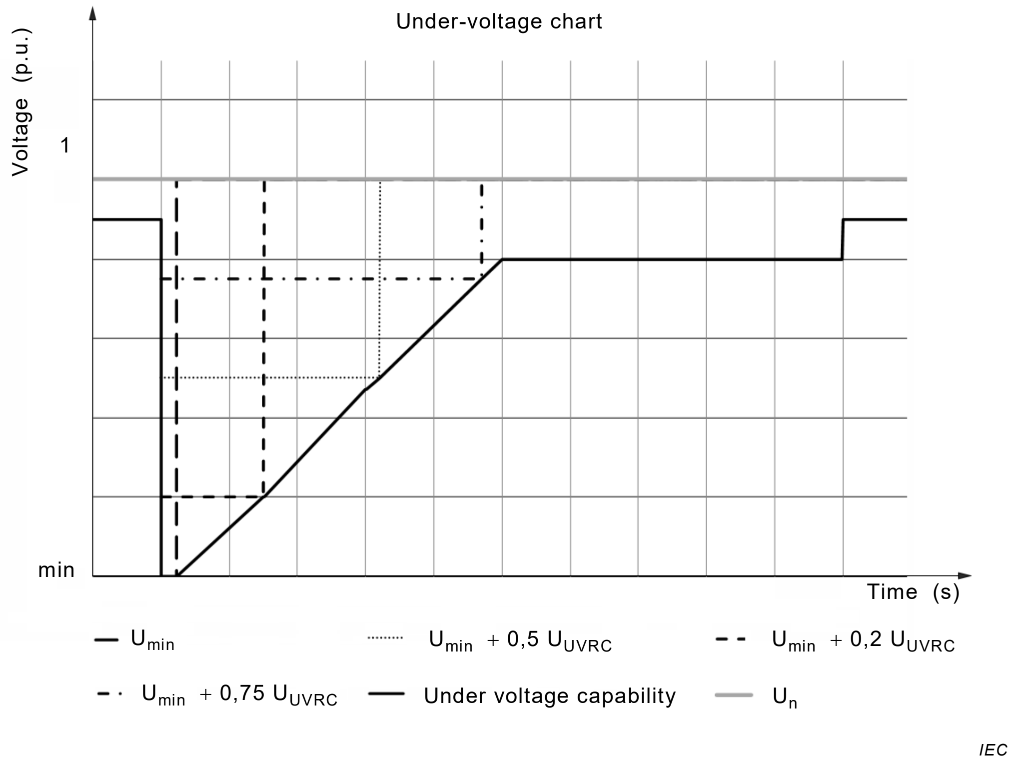


Figure 19 – Example of an undervoltage test chart

Table 12 – Example of undervoltage events

Case	Magnitude of voltage phase to phase (fraction of voltage immediately before the under- or overvoltage event) [p.u.]	(according to capability curve) [ms]
VD1 – symmetrical three-phase undervoltage	$U_{\text{min}}{}^{+0,05U_\text{n}}_{-0}$	
VD2 – symmetrical three-phase undervoltage	$(U_{\text{min}} + 0{,}2\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	
VD3 – symmetrical three-phase undervoltage	$(U_{\text{min}} + 0{,}5\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	
VD4 – symmetrical three-phase undervoltage	$(U_{\text{min}} + 0{,}75\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	
VD5 – two-phase undervoltage	$U_{\text{min}}{}^{+0,05U_\text{n}}_{-0}$	
VD6 – two-phase undervoltage	$(U_{\text{min}} + 0{,}2\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	
VD7 – two-phase undervoltage	$(U_{\text{min}} + 0{,}5\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	
VD8 – two-phase undervoltage	$(U_{\text{min}} + 0{,}75\ U_{\text{UVRC}}) \pm 0{,}05\ U_{\text{n}}$	

Table 12 shows the specified magnitudes and durations for the undervoltage event occurring when the wind turbine under test is not connected.

The stated response shall include at least results from one test of each case by time-series of active power, reactive power, active current, reactive current and voltage at the wind turbine terminals for at least 1 s prior to the undervoltage event and until the effect of the voltage dip has been stabilized (typically 10 s after fault clearance). The other test results shall be electronically available. Each different setting for the test equipment shall be documented by a reference undervoltage event measured without the turbine operating

NOTE The exact duration of the dips is given by the manufacturer's capability chart

The reporting needs to run from at least 1 s prior to the fault until at least 10 s after the fault or until the effect of the voltage dip has been stabilized. The U_{pre} needs to be calculated 10 s prior to the fault.

8.5.2.4 Overvoltage events

Response to overvoltage events shall be done as a field test to demonstrate the ride-through capability of the entire turbine. These tests can be complemented by a test bench test, where for example different operation modes, different grid code settings or different components can be verified.

The capability of the wind turbine to handle overvoltage events shall be demonstrated for the wind turbine operating in the full load and partial load range. Partial load can be done with a down regulated turbine (de-rating or curtailed). At least two swells of the partial load tests shall be done under normal operating conditions (without derating/curtailed). Test conditions shall be stated in the report.

The number of tests and operational modes need to be defined and described by the manufacturer in order to document the turbine's capability.

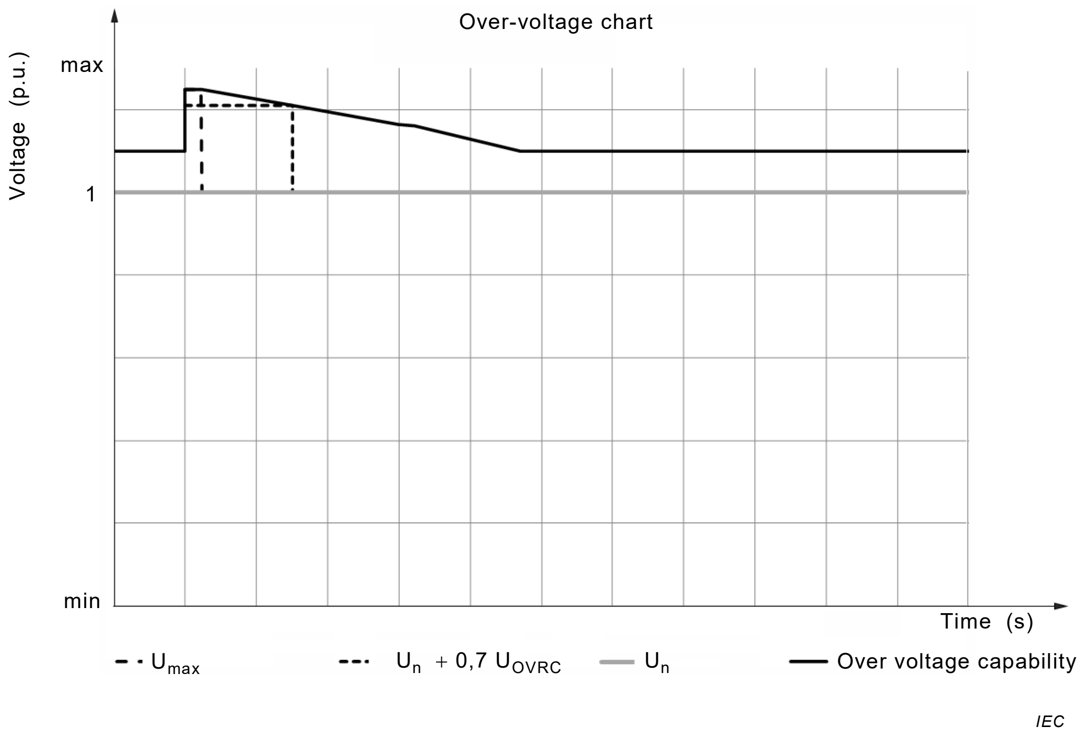


Figure 20 – Example of an overvoltage capability curve

Table 13 – Example of overvoltage tests

Case	Magnitude of voltage phase to phase (fraction of voltage immediately before the under- or overvoltage event) [p.u.]	Duration (according to capability curve) [ms] [a]
VD9 – symmetrical three-phase overvoltage	$U_{max}\ {}^{+0}_{-0,05\ U_n}$	
VD10 – symmetrical three-phase overvoltage	$(U_n + 0,7\ U_{OVRC}) \pm 0,05\ U_n$	
The reporting needs to run from at least 1s prior until at least 10 s after the fault or until the effect of the voltage swell has been stabilized. The U_{pre} needs to be calculated 10 s prior to the fault. [a] The exact duration of the swells read from the manufacturer's capability chart.		

Table 13 shows the specified magnitude and duration for the overvoltage event occurring when the wind turbine under test is not connected.

The stated response shall include at least results from one test of each case by time-series of active power, reactive power, active current, reactive current and voltage at the wind turbine terminals for at least 1 s prior to the overvoltage event and until the effect of the overvoltage event has been stabilized. The other test results shall be electronically available. Each different setting for the test equipment must be documented by a reference overvoltage event measured without the turbine operating.

8.5.2.5 Documentation

Undervoltage event

For undervoltage events, the following properties shall be stated and reported:

- test setup (test with complete turbine or at a test bench),
- operational mode of turbine,
- depending on the test device all different test states and the test sequence,
- t_{fault}, fault duration and t_{clear}
- trip /no trip of the turbine under test,
- tolerance band,
- response time of the measured reactive and active current [ms]
  - during undervoltage event
  - after undervoltage event,
- settling times of the reactive and active current [ms]:
  - during undervoltage event
  - after undervoltage event,
- measured steady state reactive current and active current and calculated active and reactive power
  - before the dip, measured as average in steady state [p.u.]
  - injection during dip, measured as average in steady state [p.u.]
  - after the dip measured as average in steady state [p.u.],
- active power response time after fault, measured from the time the voltage is back above 0,9 p.u. to the time the active power is back to the pre-fault active power level minus 0,1 p.u. of the nominal power.

For voltage dips below 5 % of the remaining voltage, only the absolute value of the current needs to be reported.

Overvoltage event

For overvoltage events, the following properties shall be stated:

- test setup (test with complete turbine or at a test bench),
- operationel mode of turbine,
- depending on the test device all different test states and the test sequence,
- t_{fault}, fault duration and t_{clear}
- trip/no trip of the turbine under the test,
- response time of the measured reactive and active current [ms]
  - during the overvoltage event
  - after the overvoltage event,
- settling times of the reactive and active current [ms]
  - during the overvoltage event
  - after the overvoltage event,
- measured steady state reactive current and active current and calculated active and reactive power
  - before the swell, measured as average in steady state [p.u.]
  - injection during swell, measured as average in steady state [p.u.]
  - after the swell measured as average in steady state [p.u.],
- active power response time after the overvoltage event measured from the time the voltage is inside the tolerance band (Figure 17) to the time the active power is back to the pre-fault active power level +/- 0,1 p.u of the nominal power[ms].

Documentation examples are given in Annex A.

8.6 Disconnection from grid

8.6.1 General

Subclause 8.6 describes the measurement and test procedures to validate the function of the different grid protection systems in the WT as well as the reconnection procedures.

8.6.2 Grid protection

8.6.2.1 General

The test of the grid protection is not intended to document specific protection levels and times, but to demonstrate the functionality of the grid protection and it can follow a given setting.

The test can be performed on the turbine level, the subsystem level, if the grid protection is realized by a separate unit, like a separate grid protection relay or on a hardware in the loop test of the protection system of the WT.

Owing to safety reasons, these measurements concerning the grid protection are performed while the generator of the wind turbine is not in operation.

8.6.2.2 Description

The aim of this test is to demonstrate the turbine ability to disconnect from the grid if the voltage or frequency for a given time exceeds a given limit. With the default settings of disconnection levels and disconnection times, the actual disconnection levels and disconnection times of the WT shall be determined for over- and undervoltage and over- and under-frequency.

This shall be done using a suitable external voltage supply, which is variable in voltage and frequency, and fed into the control system of the WT or into the protection device. The accuracy of voltage and frequency of the voltage source will be ensured by the accuracy of the measurement system.

The default protection levels and disconnection times of the WT controller shall be specified by the manufacturer.

The manufacture specifies if the over- and undervoltage tests are performed as a phase-to-ground voltage on all three phases together, phase-to-ground on single phase or phase-to-phase.

8.6.2.3 Procedure

The functions in Table 14 with the given parameter settings shall be tested.

Table 14 – Grid protection tests

Test No.	Function	Reference value of the grid protection device		Test procedure for determination of				
				accuracy of the protective level			release time	
		Protective level	Release time	Starting point of the test	Step size	Duration of each step	Step from	Step to
1	Overvoltage U>	Default level	Default time	Default Level – 2 % U_n	0,5 % U_n	1,5 × reference value of release time, min. 1 s	Default level – 2 % U_n	Default level + 2 % U_n
2	Overvoltage U>> (if available)	Default level	Default time	Default Level – 2 % U_n	0,5 % U_n	1,5 × reference value of release time, min. 1 s	Default level – 2 % U_n	Default level + 2 % U_n
3	Undervoltage U<	Default level	Default time	Default Level + 2 % U_n	-0,5 % U_n	1,5 × reference value of release time, min. 1 s	Default level – 2 % U_n	Default level + 2 % U_n
4	Undervoltage U<< (if available)	Default level	Default time	Default Level + 2 % U_n	-0,5 % U_n	1,5 × reference value of release time, min. 1 s	Default level – 2 % U_n	Default level + 2 % U_n
5	Over frequency f>	Default level	Default time	Default Level – 0,2 Hz	0,05 Hz	1,5 × reference value of release time, min. 1 s	Default level – 1 Hz	Default level + 1 Hz

Test No.	Function	Reference value of the grid protection device		Test procedure for determination of				
				accuracy of the protective level			release time	
		Protec-tive level	Release time	Starting point of the test	Step size	Duration of each step	Step from	Step to
6	Under frequency *f*<	Default level	Default time	Default Level + 0,2 Hz	−0,05 Hz	1,5 × reference value of release time, min. 1 s	Default level + 1 Hz	Default level - 1 Hz

One of the following procedures (step ramp or pulse ramp) shall be applied for the determination of the protection levels. The duration of each of the following steps should be at least 1,5 times the reference value of the release time, but minimum 1 s. If the WT disconnects already during the first step, then the test should start at nominal voltage or the nominal frequency.

The step ramp can be applied for testing of slow overvoltage *U*> and undervoltage *U*< and for overfrequency *f*> and underfrequency *f*<. For the testing of fast overvoltage *U*>> and fast undervoltage *U*<< the pulse ramp can be applied, to avoid tripping of the grid protection, during the slow under- and overvoltage protection tests.

Step ramp:

1) Start ramp at the starting point of the test, as defined in Table 14 and Figure 21.
2) Decrease or increase level with the step size and the duration of the step, as given in Table 14 and Figure 21 until the grid protection trips.
3) The level, where the grid protection trips, gives the measured protection level.

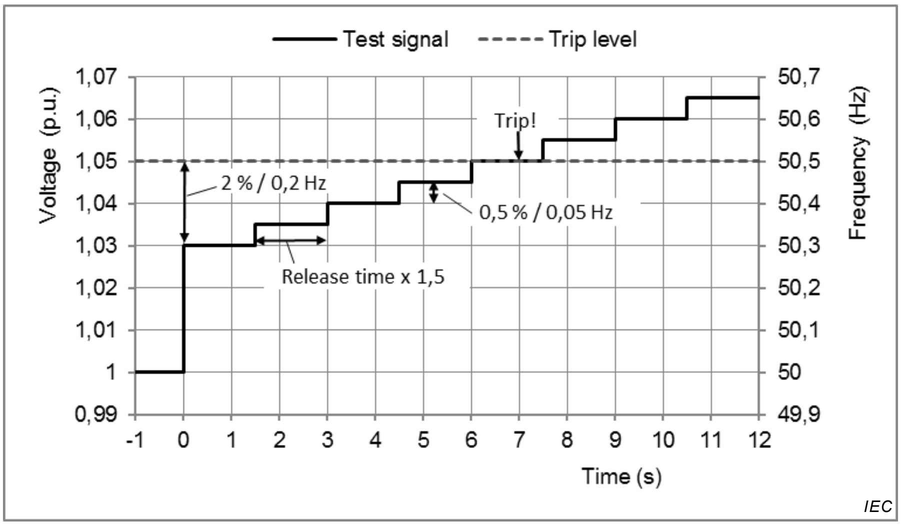


Figure 21 – Example of step ramp for overvoltage or frequency testing

Pulse ramp:

1) Start at the nominal value, as given in Table 14 and Figure 22.
2) Step to the starting point of the test, as defined in Table 14 and Figure 22 with the duration of the step, as given in Table 14 and Figure 22.
3) Step back to the nominal value, as given in Table 14 and Figure 22.

4) Step to the next level by increasing or decreasing with a step size and a duration as given in Table 14 and Figure 22.

5) Repeat the steps 3 and 4 until the grid protection trips.

The level, where the grid protection trips, gives the measured protection level.

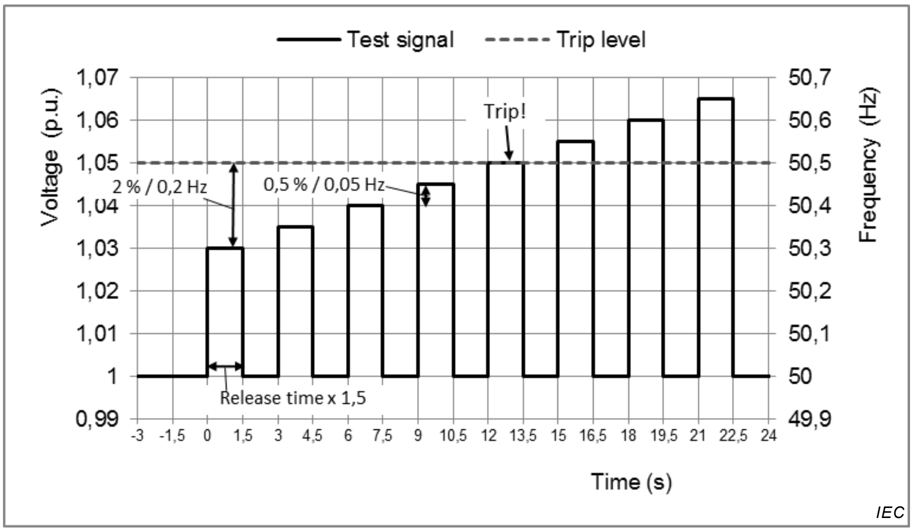


Figure 22 – Example of pulse ramp for over voltage or frequency testing

Release time of the grid protection device:

For the determination of the release time of the grid protection device, the following test procedure shall be applied.

A step from the level, given in Table 14 and Figure 23, shall be given to the grid protection device. Owing to this step, the grid protection device should trip. The release time of the grid protection device is the time from the step until the grid protection device trips.

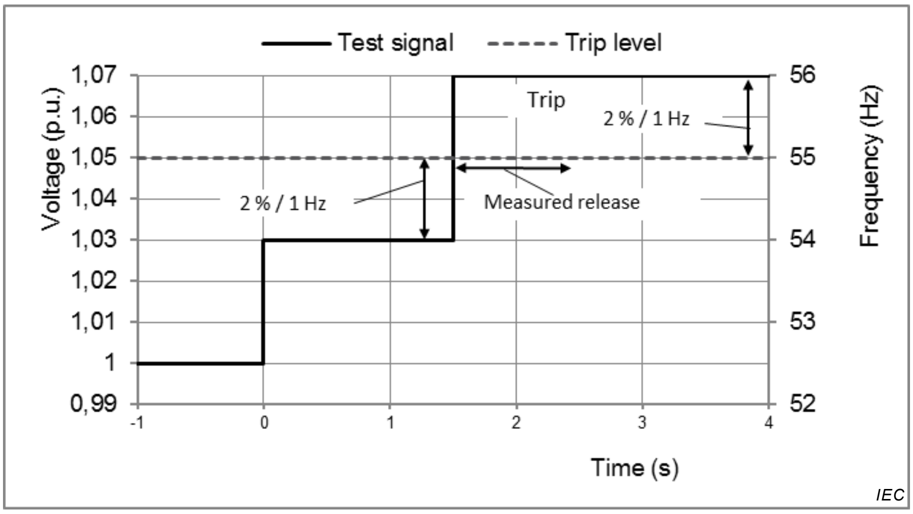


Figure 23 – Example of the test levels to determine the release time

Testing of the complete trip circuit:

To demonstrate the function of the complete trip circuit, one test shall be carried out at the WT during normal wind turbine operation.

The protection of the WT is tripped by either altering one of the limit values for under- / overvoltage or under-/ over frequency, or another suitable means. The operating time of the circuit breaker and of the auxiliary relays (if available) is determined by measurement of the trip or other applicable signals.

If a manufacturer's test report is available for the circuit breaker and/or the auxiliary relays containing details of the release times, determination of these times of the circuit breaker and/or auxiliary relays by measurements may be omitted.

8.6.2.4 Documentation

The following parameters have to be reported in, for example, a table as described in Annex A:

- reference value of the protection level and release time;
- measured protection level and release time.

8.6.3 Test of rate of change of frequency RoCoF (df/dt) protection device

8.6.3.1 Description

The rate of change of frequency protection is mainly used to detect islanding. The turbine behavior during grid events that cause a fast change of frequency in a short time frame shall be tested. The turbine protection shall trip when an excessive frequency derivative is encountered.

The test is not intended to document specific protection levels and times, but to demonstrate the functionality of the protection. The test can be performed on the turbine level or on the subsystem level, while the wind turbine is stopped.

With the given settings of disconnection levels and disconnection times, the actual disconnection levels and disconnection times of the WT shall be determined for the $\mathrm{d}f/\mathrm{d}t$ protection.

8.6.3.2 Procedure

The test sequence consists of a rapid change of the frequency typically in the range of 0,1 Hz/s to 2 Hz/s starting from the nominal frequency.

The RoCoF test is made using a $\mathrm{d}f/\mathrm{d}t$ value specified by the turbine manufacturer.

The test can be made for example with a grid simulator, able to control the frequency, within the required range and with the required dynamic.

The test shall be carried out by:

1) determination of the protection level, by:

   increasing or decreasing input frequency of RoCoF at the constant rate of change of frequency ($\mathrm{d}f/\mathrm{d}t$) from rated frequency. The test is repeated until the protection device trips, while increasing the test slop ($\mathrm{d}f/\mathrm{d}t$) condition 0,1 Hz/s steps;

2) determination of the protection time, by:

   increasing or decreasing input frequency of RoCoF at the constant rate of change of frequency ($\mathrm{d}f/\mathrm{d}t$) 0,2 Hz/s higher than the trip level from rated frequency and measure the release time.

The functionality of the wind turbine RoCoF protection system and the disconnection time is tested with both positive and negative frequency derivatives at a level that is above the df/dt protection's disconnection level. The test should be performed at a reference value which is within the over- and underfrequency limits.

8.6.3.3 Documentation

The following parameters have to be reported in, for example, a table as described in Annex A:

- reference value of the protection level and release time;
- measured protection level and release time.

8.6.4 Reconnection test

8.6.4.1 Description

The aim of the reconnection time test is to show that the turbine automatically reconnects after a grid fault regardless of the length of the fault as well as that the power is ramped up following a predefined ramp rate.

The reconnection time after the wind turbine has been disconnected owing to a grid failure shall be characterized by test results presented in a table. The table shall show the reconnection time after the grid has failed for 10 seconds, 1 minute and 10 minutes, as well as the ramp rate. The reconnection time is the time from the instant when the grid is available on the wind turbine terminals to the instant when the wind turbine starts to produce power.

8.6.4.2 Procedure

The following procedure shall be applied:

- The test shall be carried out once for each of the 3 grid failure times specified in 8.6.4.1.
- The average wind speed shall be greater than the start-up wind speed during the reconnection time.
- The grid should be made unavailable to the wind turbine by opening an applicable breaker in the grid. This breaker will typically be the MV breaker connecting the wind turbine to the power collection system. The opening of the breaker shall be done while the wind turbine is in normal production. The grid should be made available again to the wind turbine by closing the breaker.
- The failure time is the time between opening and closing of the breaker. The breaker would normally be operated manually and it has to be ensured that the grid failure time is as specified within a tolerance of ±10 % of the failure time.
- The reconnection time is determined from the time when the voltage returns to its normal level (between 0,9 and 1,1 p.u.) to the time where the wind turbine starts producing power again (P > 0).
- The active power and voltage shall be measured at the WT terminals.
- The ramp rate is measured from the 0,1 p.u. up to 0,4 p.u. based on the active power production.

8.6.4.3 Documentation

The following parameters have to be reported in, for example, Table A.46 and graphs as described in Annex A. The test results shall be reported based on 0,2 s average data of the measured active power and voltage:

- reconnection time;
- ramp rate during start-up.

Annex A
(informative)

Reporting

A.1 Overview

The following template includes the minimum required information for the reporting of the results. Formatting of the tables and the graphs is exemplary.

A.2 General

Table A.1 – General report information

Report:		***Sheet:***		***page 1 of --***
Wind turbine type designation:			*Serial number:*	
Wind turbine manufacturer:				
Description of the tested wind turbine, including settings of control parameters:	*Document name and date*			
Description of the test site and grid connection:				
Description of the test equipment (complete list of equipment used with specifications, serial numbers etc.):				
Note of exceptions				
Name and address of test organisation:				
Author:		*Checked:*		
Date of issue:		*Approved:*		

Table A.2 – General data

Number of blades:		*Speed control (fixed/2speed/variable):*	
Rotor diameter [m]:		*Speed range [rpm]:*	
Hub height [m]:		*Wind turbine type (doubly fed / full converter / direct coupled / others):*	
Blade control (pitch/stall):		*Generator type and rating: [kW]:*	
Cut-in wind speed [m/s]:		*Grid side converter type and rating [kVA]:*	
Description of FRT profile (voltage levels, trigger signal, hysteresis, control strategy):	*UVRT:*		
	OVRT:		
Reactive power capability profile:			
Special features:			

Table A.3 – Nominal data

Nominal active power , Pn:[kW]		*Nominal apparent power, Sn: [kVA]*	
Nominal wind speed, vn:[m/s]		*Nominal current, In: [A]*	
Nominal voltage, Un: [V]		*Nominal frequency, fn [Hz]*	

Table A.4 – Test conditions

Transformer apparent power (MVA)	
Measurement point (i.e. MV/LV side)	
Voltage THD (up to 50th order)	
Frequency variations (0,2 s average data)	
Frequency rate of change (0,2 s average data)	
Slow voltage variations (10 min average data)	
Voltage unbalance factor (IEC 61000-4-30)	
Average turbulence intensity	
Network short-circuit apparent power	
Network impedance angle	
Environmental conditions	
Information on EMC of the measurement equipment	
Temperature variation during the test within manufacturer's specifications of the measurement equipment	
Data acquisition device compliance with IEC 62008 in terms of performance characteristics and calibration methods	

A.3 Power quality aspects

Flicker (see 8.2.2):

Table A.5 – Flicker coefficient per power bin (95th percentile)

	P_{bin} [% of P_n]											
ψ_k [°]	0	10	20	30	40	50	60	70	80	90	100	Max.
30°												
50°												
70°												
85°												
Number of 10-min data sets												
Period of measurements												
Operational mode (reactive control Q=0 / others)												

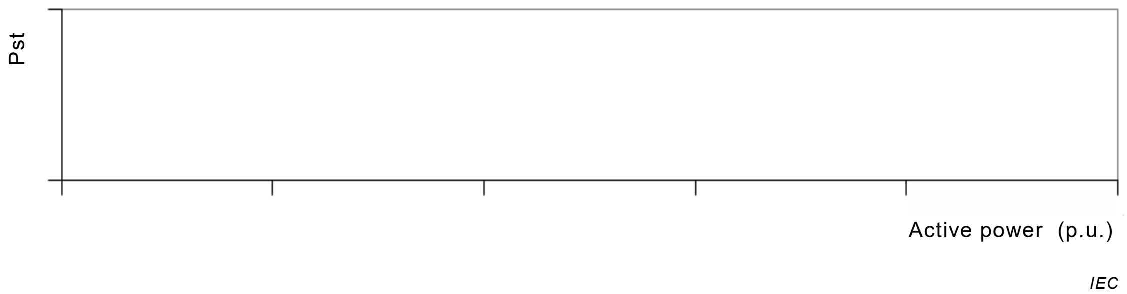


Figure A.1 – Voltage flicker P_{st} vs. active power

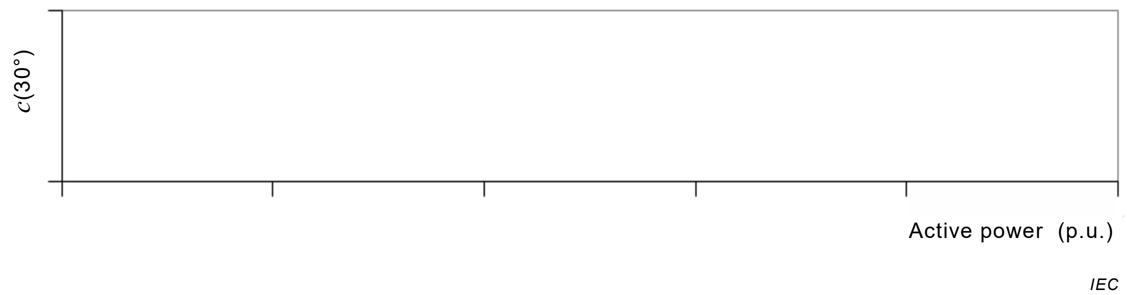


Figure A.2 – Flicker coefficient c(30°) vs. active power

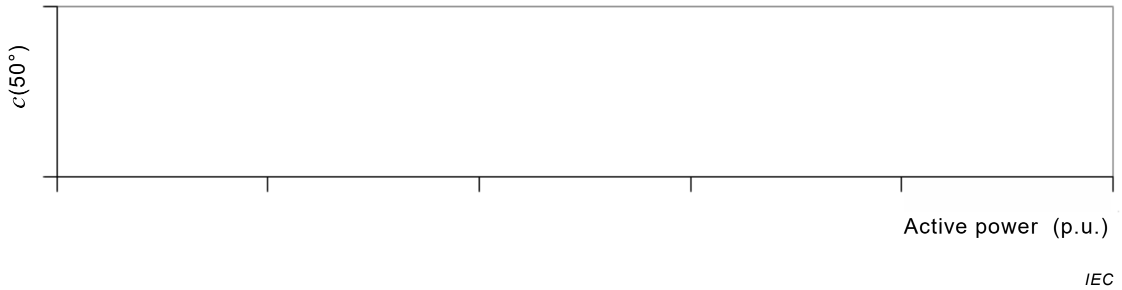


Figure A.3 – Flicker coefficient c(50°) vs. active power

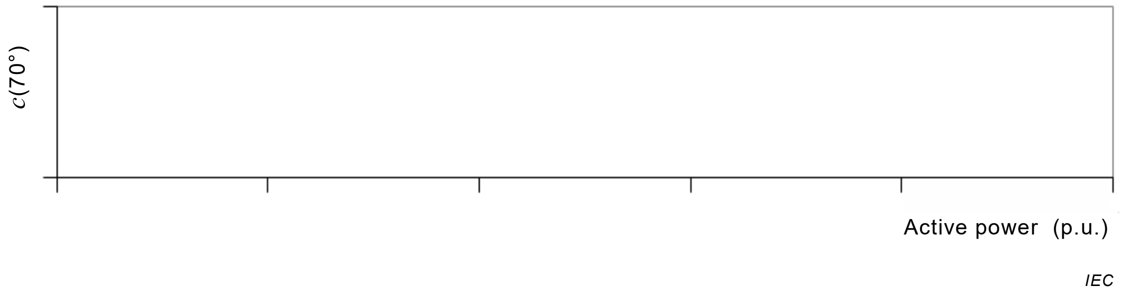


Figure A.4 – Flicker coefficient c(70°) vs. active power

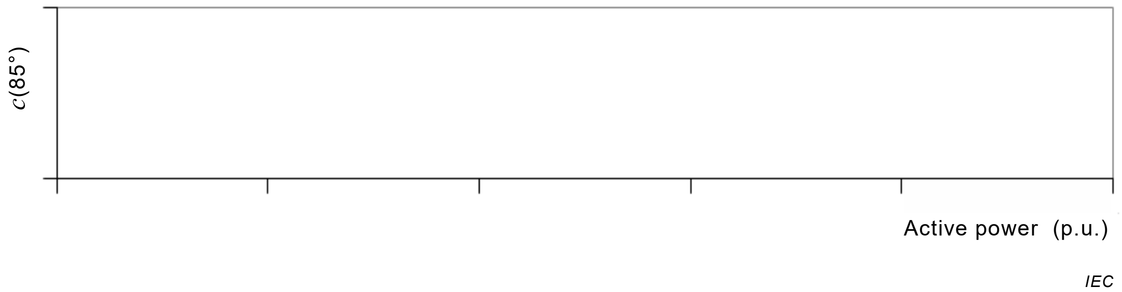


Figure A.5 – Flicker coefficient c(85°) vs. active power

Switching operations (see 8.2.3)

Table A.6 – Start-up at cut in wind speed

Case of switching operation:	*Start-up at cut in wind speed*			
Operational mode for switchings (reactive control Q=0 / others)				
Number of switching operations performed				
Period of measurements				
Wind speed range (min, max)				
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

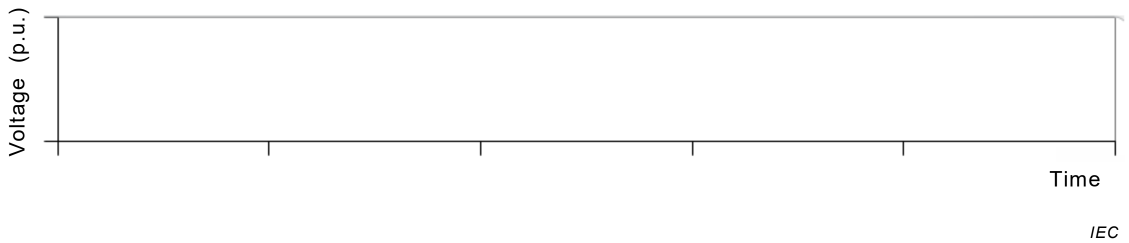


Figure A.6 – Time series of 3-phase voltages as RMS of start-up at the wind speed of ... m/s

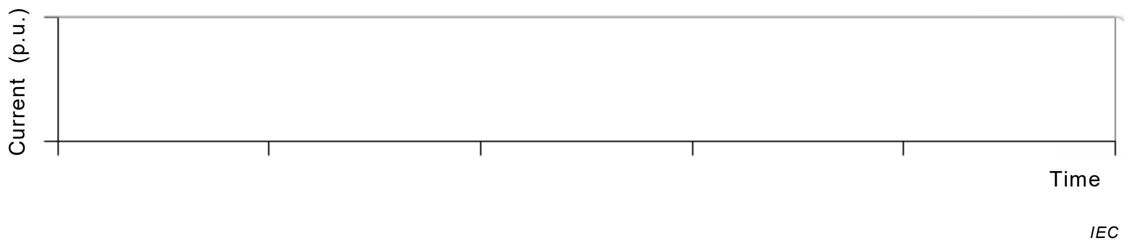


Figure A.7 – Time series of 3-phase currents as RMS of start-up at the wind speed of ... m/s

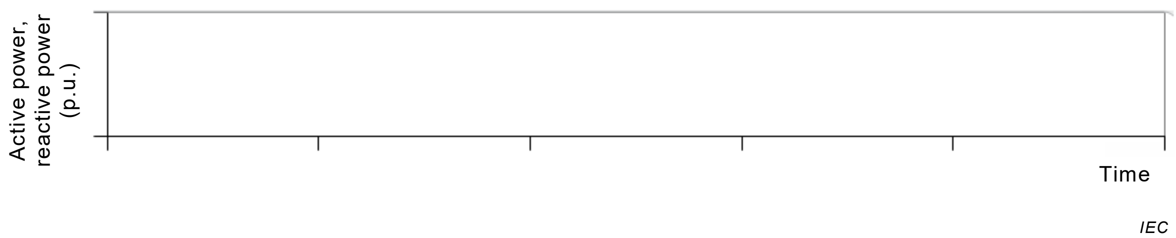


Figure A.8 – Time series of active and reactive power of start-up at the wind speed of ... m/s

Table A.7 – Start-up at nominal active power

Case of switching operation:	***Start-up at nominal active power***			
Operational mode for switchings (reactive control Q=0 / others)				
Number of switching operations performed				
Period of measurements				
Wind speed range (min, max)				
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

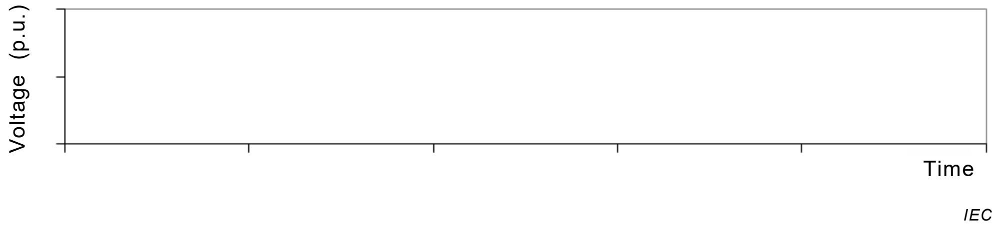


Figure A.9 – Time series of 3-phase voltages as RMS of start-up at nominal active power

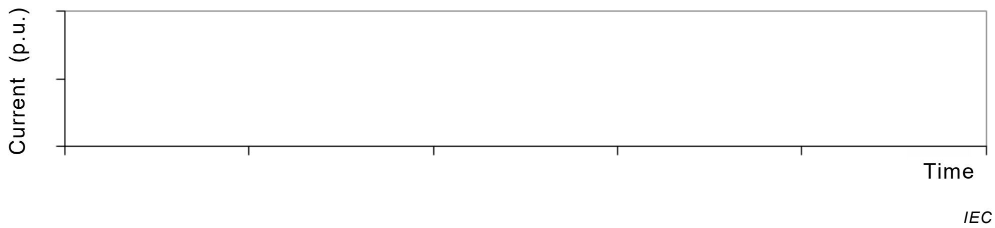


Figure A.10 – Time series of 3-phase currents as RMS of start-up at nominal active power

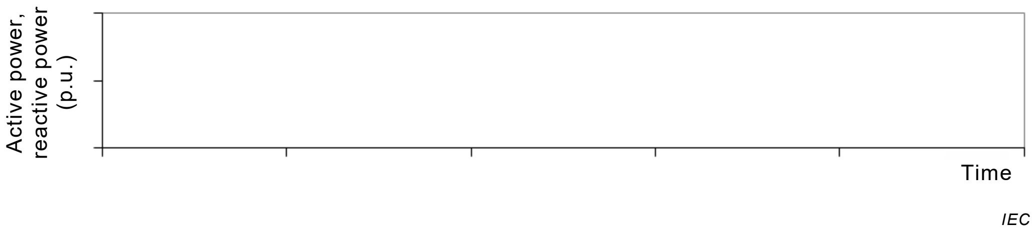


Figure A.11 – Time series of active and reactive power of start-up at nominal active power

Table A.8 – Worst-case switching between generators

Case of switching operation:	***Worst-case switching between generators:***			
Operational mode for switchings (reactive control Q=0 / others)				
Number of switching operations performed				
Period of measurements				
Wind speed range (min, max)				
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

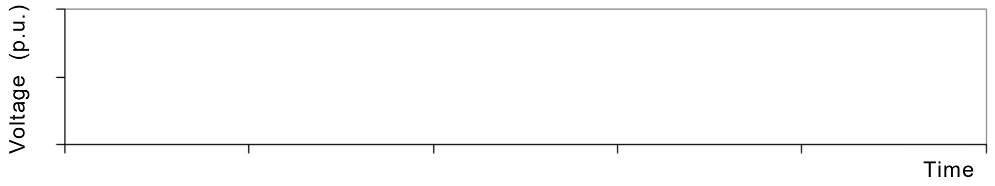


Figure A.12 – Time series of 3-phase voltages as RMS of change from generator stage 1 to stage 2

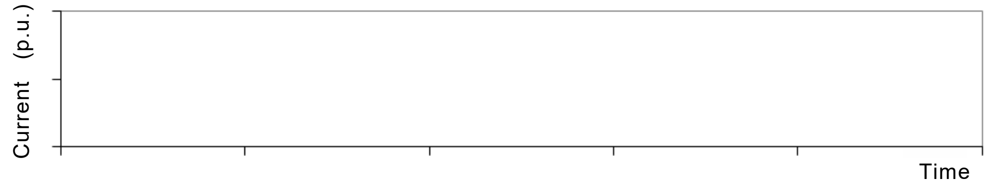


Figure A.13 – Time series of 3-phase currents as RMS of change from generator stage 1 to stage 2

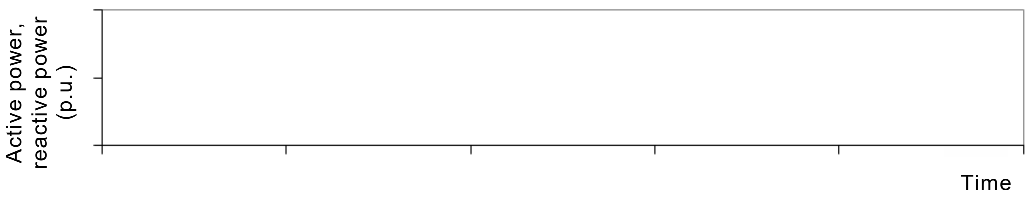


Figure A.14 – Time series of active and reactive power of change from generator stage 1 to stage 2

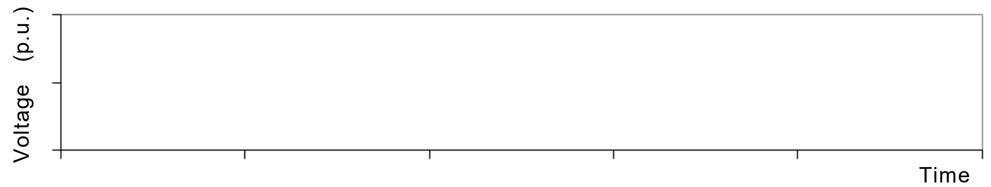


Figure A.15 – Time series of 3-phase voltages as RMS of change from generator stage 2 to stage 1

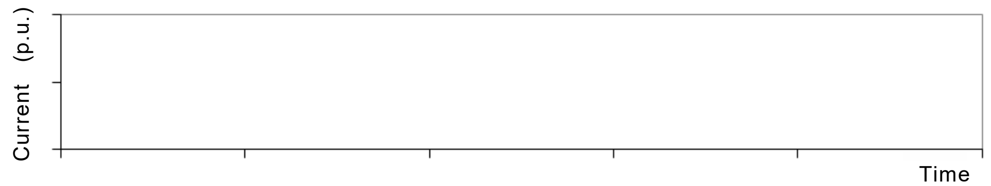


Figure A.16 – Time series of 3-phase currents as RMS of change from generator stage 2 to stage 1

Figure A.17 – Time series of active and reactive power of change from generator stage 2 to stage 1

Harmonics currents (see 8.2.4):

Table A.9 – General test information

Power bin: (% of P_n)	0	10	20	30	40	50	60	70	80	90	100
Number of 10-min data sets											
Period of measurements											
Operational mode during the test (reactive control Q=0 / others)											
Time window size used in the analysis of harmonics (cycles or ms)	*Integer harmonics*										
	Interharmonics										
	Higher frequency components										
Description of possible influence of the background distortion and of the method used for the reduction of harmonics (in case harmonics are reduced)											

Integer harmonic currents:

Table A.10 – 95th percentile of 10-min harmonic magnitudes per power bin

P_{bin} (%)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**Max.**
H	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**	**I_h (%)**
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	Max.
H	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
16												
17												
18												
19												
20												
21												
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42												
43												
44												
45												
46												
47												
48												
49												
50												
THC (%)												

Interharmonic currents:

Table A.11 – 95th percentile of 10-min harmonic magnitudes per power bin

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	Max.
f (Hz)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
75/90												
125/150												
175/210												
225/270												
275/330												
325/390												
375/450												
425/510												
475/570												
525/630												
575/690												
625/750												
675/810												
725/870												
775/930												
825/990												
875/1 050												
925/1 110												
975/1 170												
1 025/1 230												
1 075/1 290												
1 125/1 350												
1 175/1 410												
1 225/1 470												
1 275/1 530												
1 325/1 590												
1 375/1 650												
1 425/1 710												
1 475/1 770												
1 525/1 830												
1 575/1 890												
1 625/1 950												
1 675												
1 725												
1 775												
1 825												
1 875												
1 925												
1 975												

Higher frequency components:

Table A.12 – 95th percentile of 10-min harmonic magnitudes per power bin

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	Max.
f (kHz)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
2,1												
2,3												
2,5												
2,7												
2,9												
3,1												
3,3												
3,5												
3,7												
3,9												
4,1												
4,3												
4,5												
4,7												
4,9												
5,1												
5,3												
5,5												
5,7												
5,9												
6,1												
6,3												
6,5												
6,7												
6,9												
7,1												
7,3												
7,5												
7,7												
7,9												
8,1												
8,3												
8,5												
8,7												
8,9												

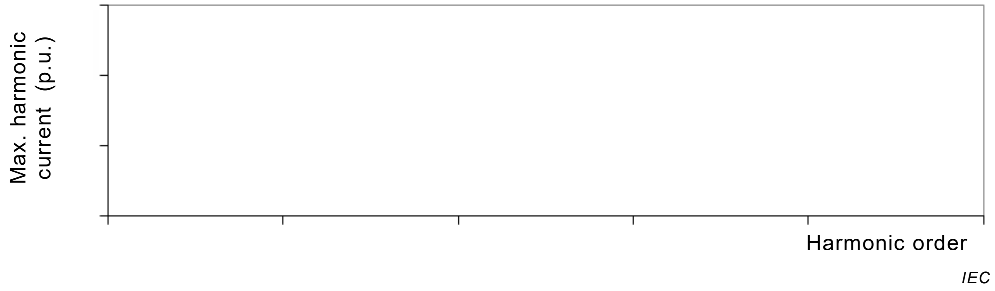


Figure A.18 – Max. of the 95th percentiles of integer harmonic currents vs. harmonic order

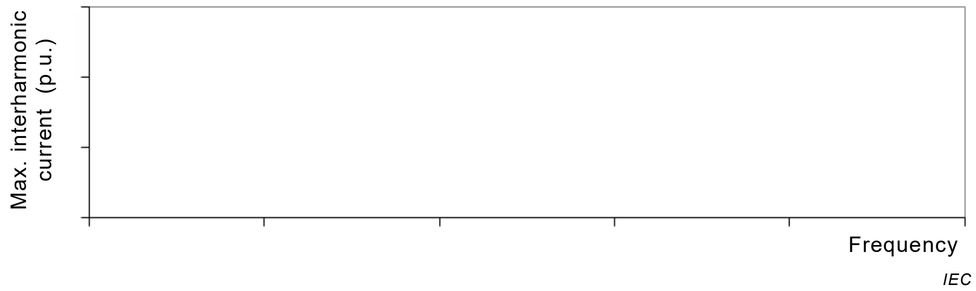


Figure A.19 – Max. of the 95th percentiles of interharmonic currents vs. frequency

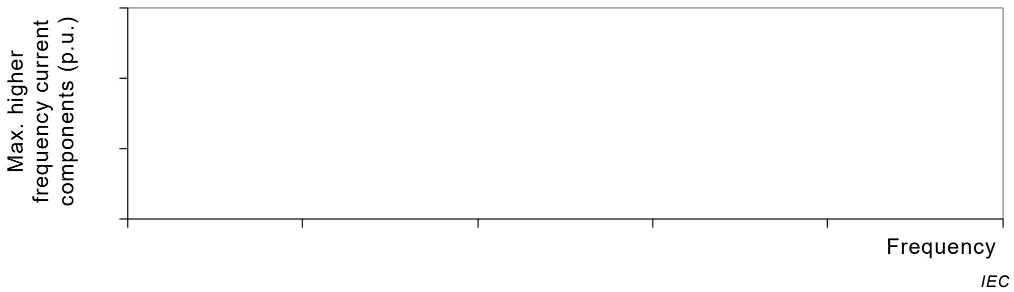


Figure A.20 – Max. of the 95th percentiles of higher frequency current components vs. frequency

A.4 Steady-state operation

Observation of active power against wind speed (see 8.3.2):

Table A.13 – Active power against wind speed (see 8.3.2)

Wind speed bin: [m/s]	*1-2*	*2-3*	*3-4*	*4-5*	*5-6*	*6-7*	*7-8*	*8-9*	*9-10*	*10-11*	*11-12*	*12-13*	*13-14*	…
Total number of data sets:														

Table A.14 – Measurement data set

Period of measurements											
Power bin: [% of P_n]	-5 to 5	5 to 15	15 to 25	25 to 35	35 to 45	45 to 55	55 to 65	65 to 75	75 to 85	85 to 95	95 to 105
Total number of 10 min data sets:											

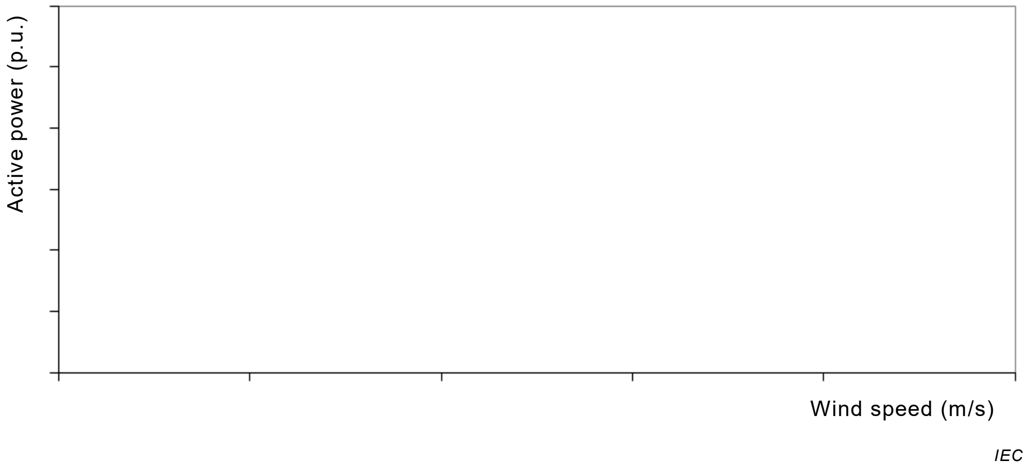


Figure A.21 – Active power as a function of the wind speed

Maximum power (see 8.3.3):

Table A.15 – Maximum active power

Active power P_x	$P_{0.2}$	P_{60}	P_{600}
Averaging time [s]	0,2	60	600
Measured active power [kW]			
Normalized active power [p.u.]			
Total number of data sets			

Reactive power characteristic at Q = 0 (see 8.3.4):

Table A.16 – Reactive power characteristic

Period of measurements					
P_{bin} (%)	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1 min data sets
0					
10					
20					
30					
40					
50					
60					
70					
80					
90					
100					

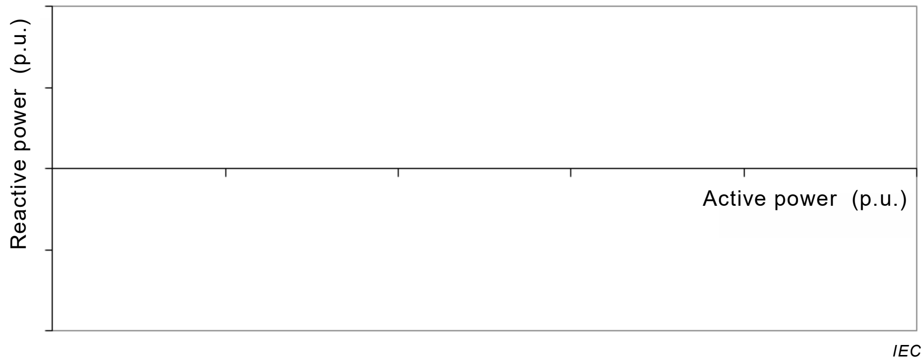


Figure A.22 – Reactive power vs. active power

Reactive power capability (see 8.3.5):

Table A.17 – PQ-diagram

Period of measurements										
P_{bin} (%)	underexcited					overexcited				
	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1-min data sets	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1 min data sets
0										
10										
20										
30										
40										
50										
60										
70										
80										
90										
100										

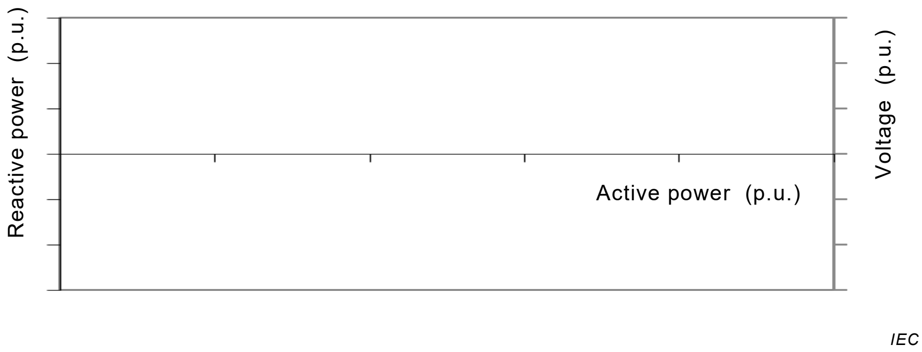


Figure A.23 – PQ-Diagram

Voltage dependency PQ diagram (see 8.3.6):

Table A.18 – PQ-diagram at maximum voltage

Period of measurements										
P_{bin} (%)	underexcited					overexcited				
	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1-min data sets	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1 min data sets
0										
10										
20										
30										
40										
50										
60										
70										
80										
90										
100										

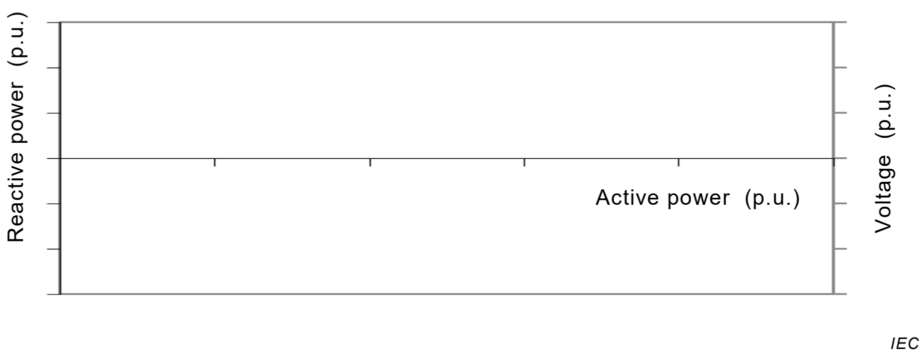


Figure A.24 – PQ-Diagram

Table A.19 – PQ-diagram at minimum voltage

Period of measurements										
P_{bin} (%)	underexcited					overexcited				
	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1-min data sets	P [kW]	Q [kvar]	cos(φ) [-]	U_1 [V]	Number of 1 min data sets
0										
10										
20										
30										
40										
50										
60										
70										
80										
90										
100										

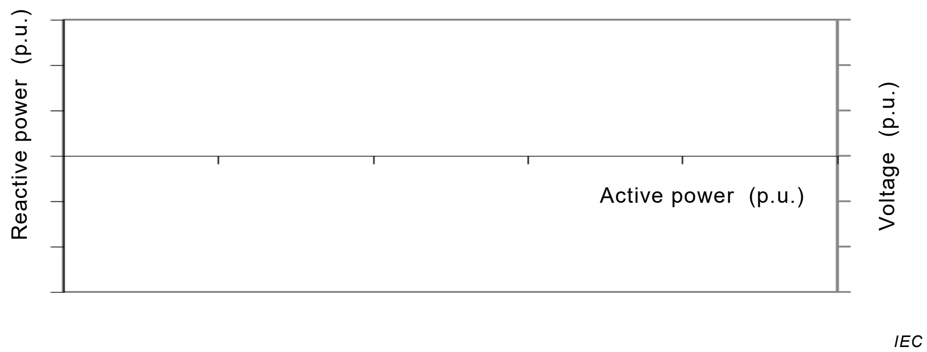


Figure A.25 – PQ-Diagram

Current unbalance factor (see 8.3.7):

Table A.20 – P-IUF$_i$ diagram

Period of measurements											
Power bin: [% of P_n]	10	20	30	40	50	60	70	80	90	100	Max.
Mean IUFi [%]											
Max IUFi [%]											

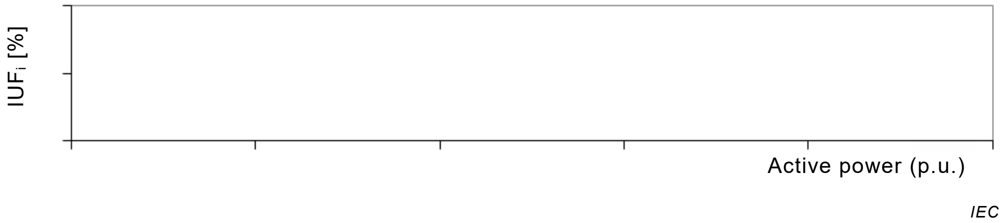


Figure A.26 – Mean 1-min current unbalance factor over active power

Active power control (see 8.4.2):

Table A.21 – General test information

Period of measurements	
Operational mode of the wind turbine during the test (active power control mode/others)	

Table A.22 – Static error

Active power step P/P_n [p.u.]	Requested reference value		Actual value		Max absolute static error	
	[kW]	P/P_n [p.u.]	[kW]	P/P_n [p.u.]	[kW]	P/P_n [p.u.]
1,00						
0,80						
0,60						
0,40						
0,20						

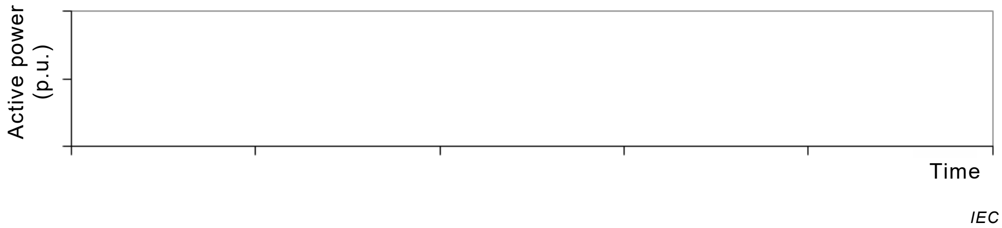


Figure A.27 – Time-series of active power reference values, available power and measured active power output during active power control for the evaluation of the static error

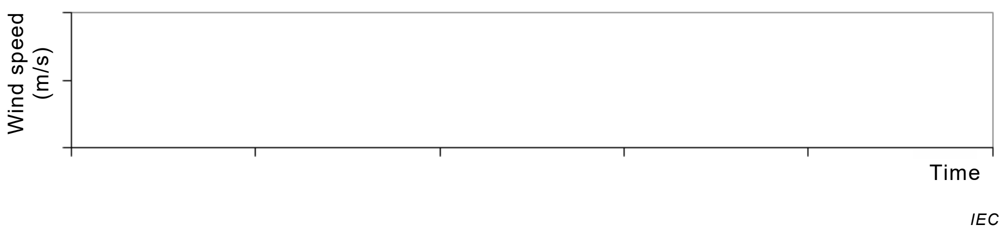


Figure A.28 – Time-series of measured wind speed during active power control during the test of the static error

Table A.23 – Dynamic response

Dynamic response active power reference P/P_n [p.u.]		Settling time [s]	Ramp-down time [s]	Reaction time [s]	Time instant of reference command
Starting point	Second point				

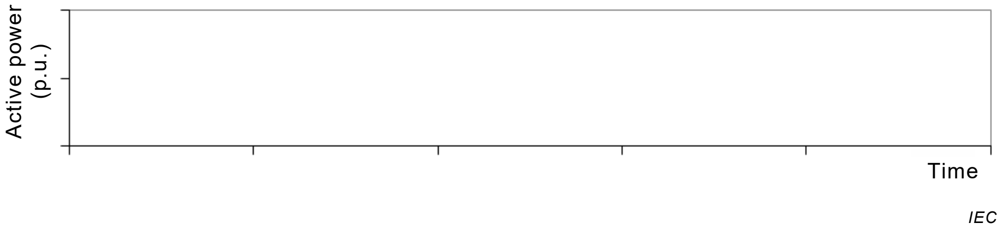


Figure A.29 – Time-series of active power reference values, available power and measured active power output during active power control for the evaluation of the settling time

Active power ramp rate limitation (see 8.4.3):

Normal start-up

Table A.24 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Ramp rate [% of nominal active power per minute]	
Declaration of the possible reference values for ramp rate (given by the manufacturer)	

Table A.25 – Active power ramp rate calculation at start-up

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			
Point 3			
Point 4			

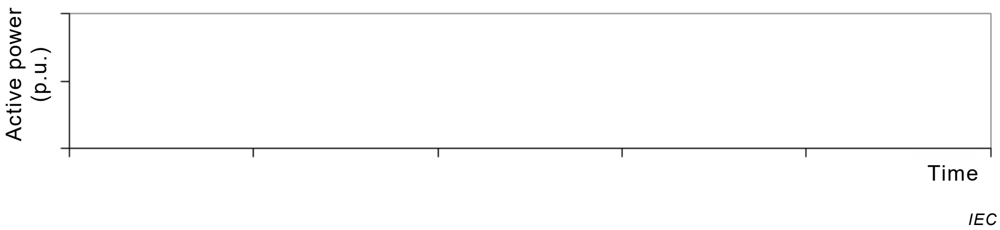


Figure A.30 – Time-series of available and measured active power output during ramp rate limitation

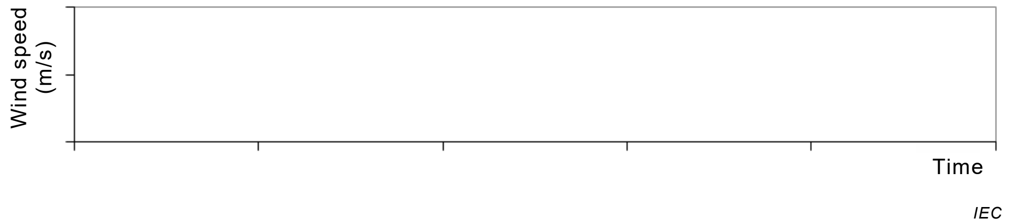


Figure A.31 – Time-series of measured wind speed during ramp rate limitation

Start-up after grid disconnection (in case a reconnection test is performed)

Table A.26 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Ramp rate [% of nominal active power per minute]	
Declaration of the possible reference values for ramp rate (given by the manufacturer)	

Table A.27 – Active power ramp rate limitation at start-up

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			
Point 3			
Point 4			

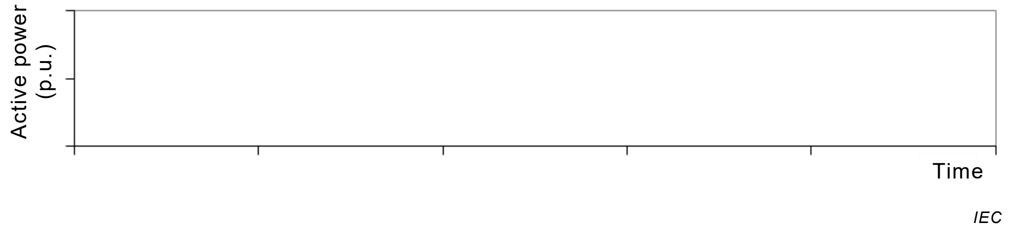


Figure A.32 – Time-series of available and measured active power output during ramp rate limitation

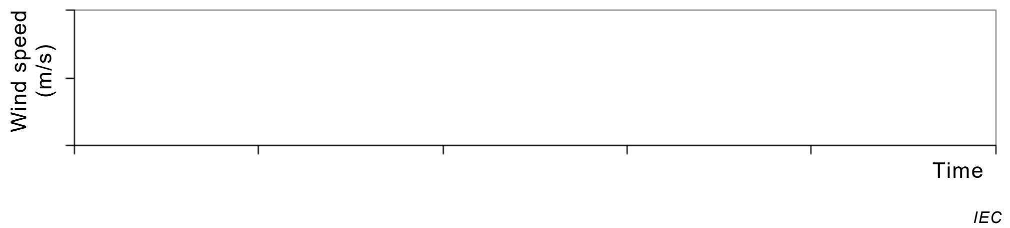


Figure A.33 – Time-series of measured wind speed during ramp rate limitation

Normal stop (see 8.4.3)

Table A.28 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Ramp rate [% of nominal active power per minute]	
Declaration of the possible reference values for ramp rate (given by the manufacturer)	

Table A.29 – Active power ramp rate limitation at normal stop

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			
Point 3			
Point 4			

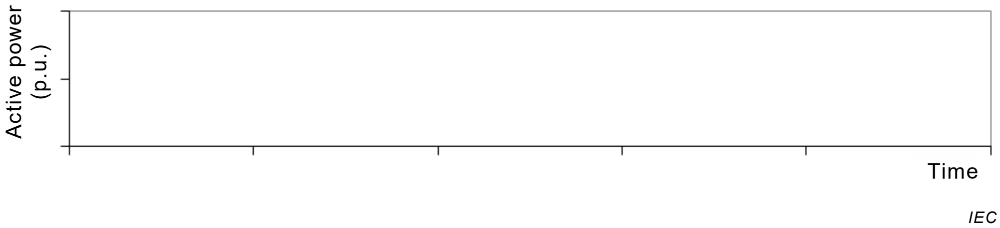


Figure A.34 – Time-series of available and measured active power output during ramp rate limitation

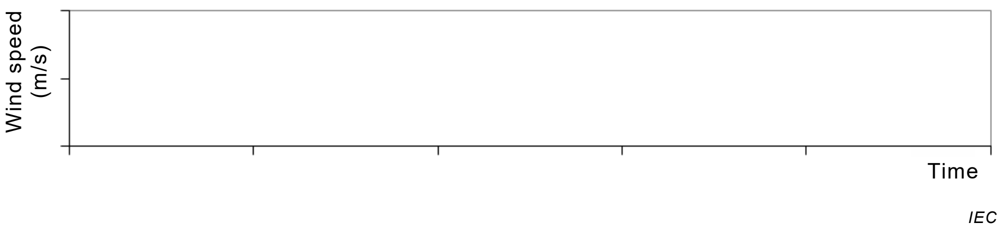


Figure A.35 – Time-series of measured wind speed during ramp rate limitation

Normal operation (see 8.4.3)

Table A.30 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Ramp rate [% of nominal active power per minute]	
Declaration of the possible reference values for ramp rate (given by the manufacturer)	

Table A.31 – Active power ramp rate limitation in normal operation

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			
Point 3			
Point 4			

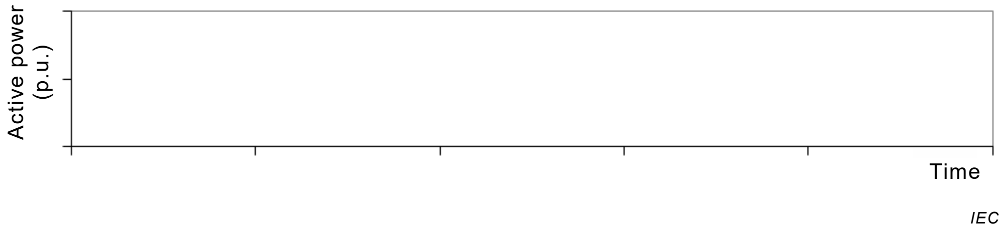


Figure A.36 – Time-series of available and measured active power output during ramp rate limitation

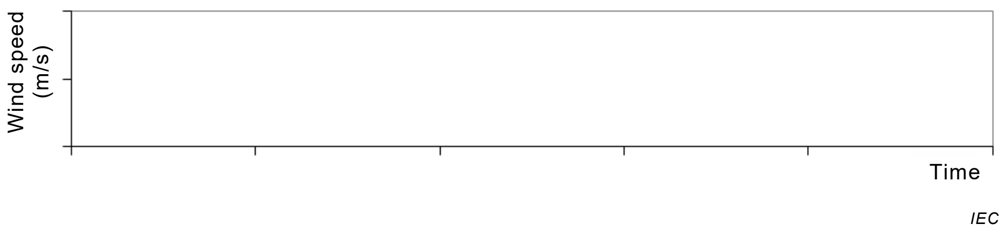


Figure A.37 – Time-series of measured wind speed during ramp rate limitation

Frequency control (see 8.4.4):

Table A.32 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Used procedure	
Frequency control function (declared by the manufacturer)	

Table A.33 – Test at 0,25 × P_n < P < 0,5 × P_n

STEP OF THE MEASUREMENT	MEASURED GRID FREQUENCY [Hz]	FREQUENCY REFERENCE [Hz]	MEASURED ACTIVE POWER [p.u.]	ACTIVE POWER GRADIENT [p.u./Hz]
First measurement point	f_{rated}	-----		-----
Step start control				
Step $f_{\text{step a}}$				
Step $f_{\text{step b}}$				
Step max				
Step f < $f_{\text{step b}}$				
Step f < $f_{\text{step a}}$				
Step release control				

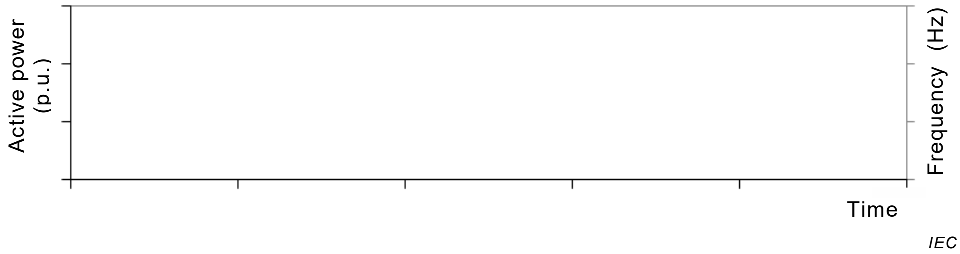


Figure A.38 – Time-series of available power, measured active power and reference value of the grid frequency change

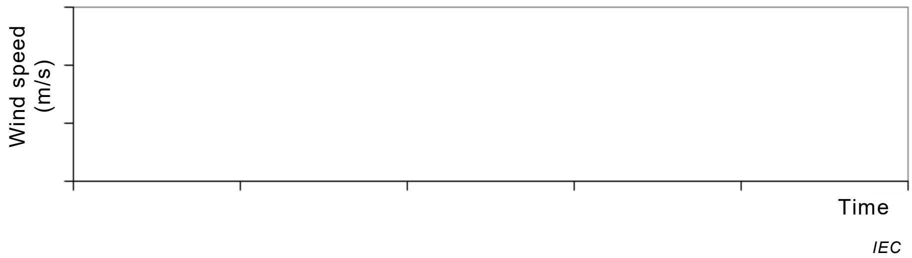


Figure A.39 – Time-series of measured wind speed

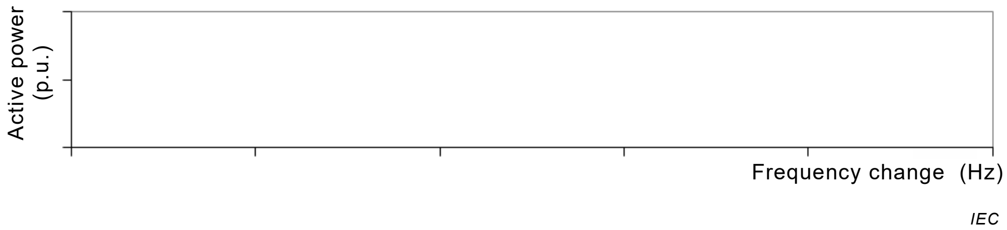


Figure A.40 – Measured active power over frequency change

Table A.34 – Test at P > 0,8 x P_n

STEP OF THE MEASUREMENT	MEASURED GRID FREQUENCY [Hz]	FREQUENCY REFERENCE [Hz]	MEASURED ACTIVE POWER [p.u.]	ACTIVE POWER GRADIENT [p.u./Hz]
First measurement point	f_{rated}	-----		-----
Step start control				
Step $f_{step\ a}$				
Step $f_{step\ b}$				
Step max				
Step $f < f_{step\ b}$				
Step $f < f_{step\ a}$				
Step release control				

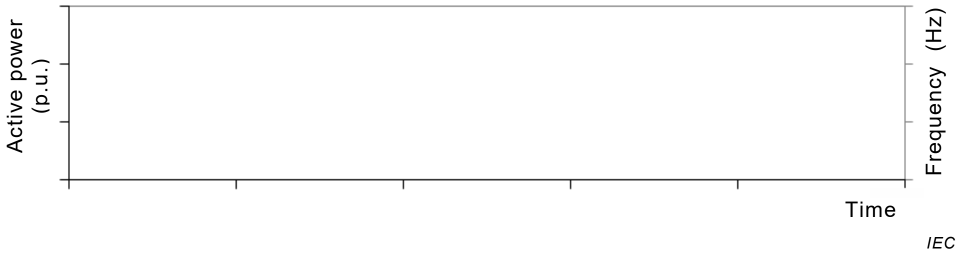


Figure A.41 – Time-series of available power, measured active power and reference value of the grid frequency change

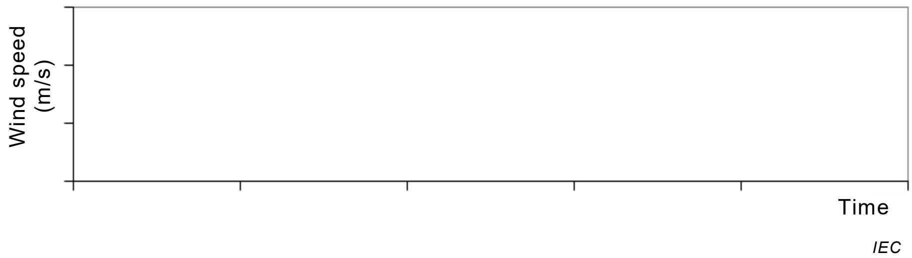


Figure A.42 – Time-series of measured wind speed

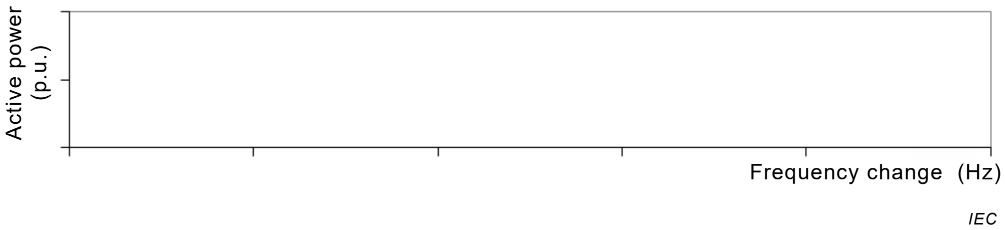


Figure A.43 – Measured active power over frequency change

Synthetic inertia (see 8.4.5)

Table A.35 – Synthetic inertia results

Period of measurements						
Operational mode of the wind turbine during the test						
Active power range resp. wind speed range	**$0,25 \times P_n < P < 0,5 \times P_n$**		**$P > 0,8 \times P_n$**		**$v > v_n$**	
Test number	1	2	3	4	5	6
Default active power boost ΔP [kW]						
Gradient of active power boost dP/dt [kW/s]						
Response time [ms]						
Settling time [ms]						
Steady state time [ms]						
Ramp-down time [ms]						
$f_{\text{inertia, trigger}}$ [Hz]						
$f_{\text{inertia, recovery}}$ [Hz]						
Recovery time [ms]						

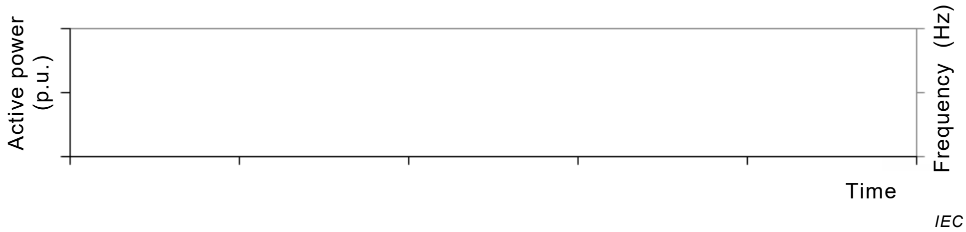


Figure A.44 – Test 1, time-series of available power, measured active power and reference value of the grid frequency for $0,25 \times P_n < P < 0,5 \times P_n$

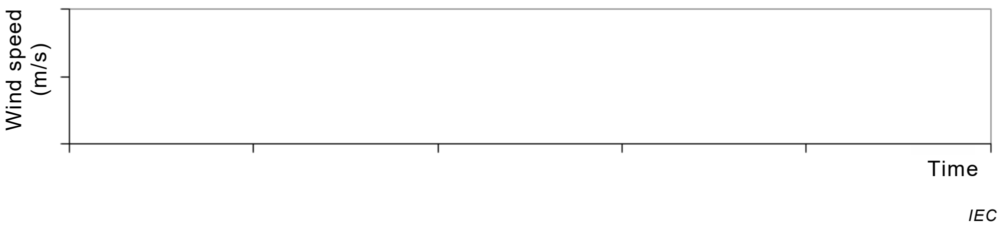


Figure A.45 – Test 1, time-series of wind speed for $0,25 \times P_n < P < 0,5 \times P_n$

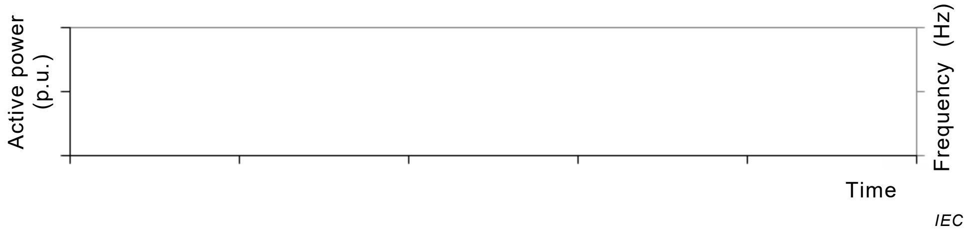


Figure A.46 – Test 2, time-series of available power, measured active power and reference value of the grid frequency for 0,25 × P_n < P < 0,5 × P_n

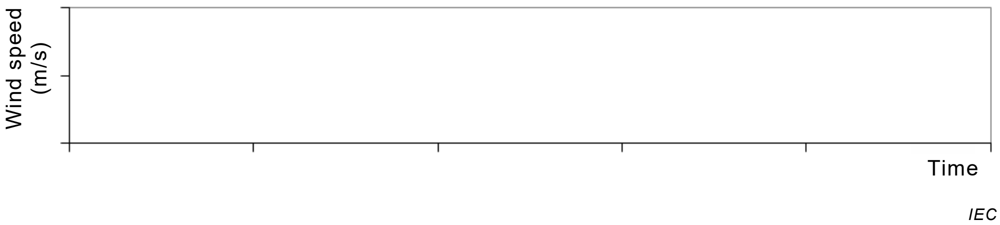


Figure A.47 – Test 2, time-series of wind speed for 0,25 × P_n < P < 0,5 × P_n

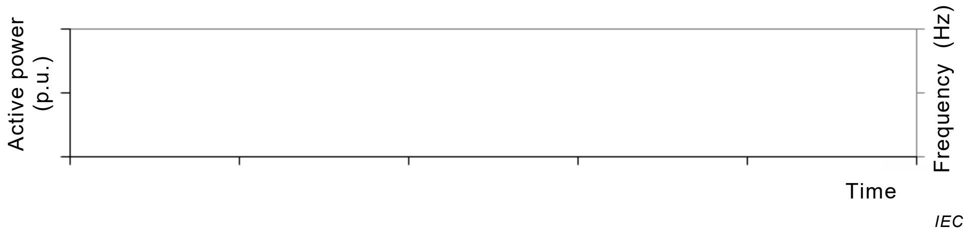


Figure A.48 – Test 3, time-series of available power, measured active power and reference values of the grid frequency for P > 0,8 × P_n

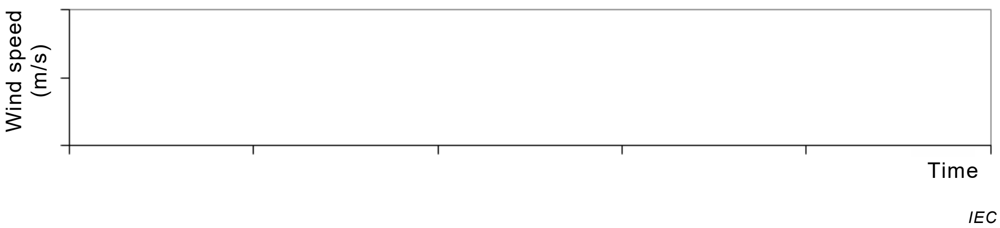


Figure A.49 – Test 3, time-series of wind speed for P > 0,8 × P_n

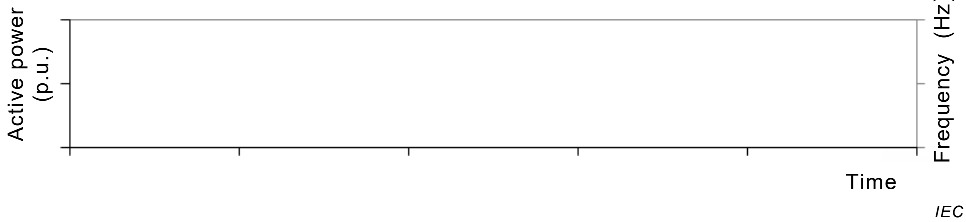


Figure A.50 – Test 4, time-series of available power, measured active power and reference value of the grid frequency for P > 0,8 × P_n

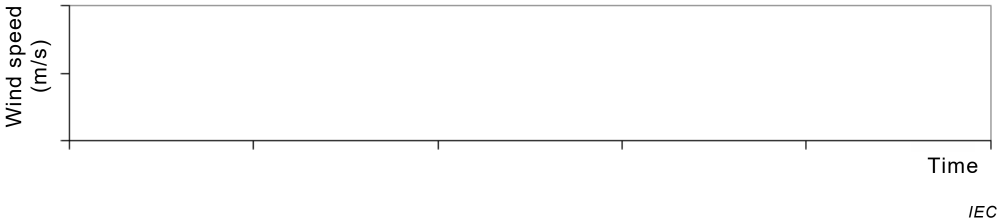


Figure A.51 – Test 4, time-series of wind speed for P > 0,8 × P_n

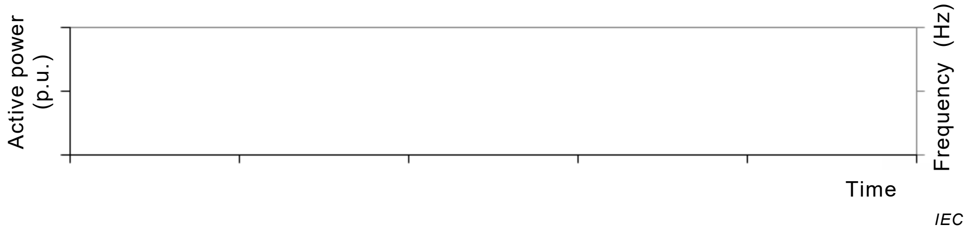


Figure A.52 – Test 5, time-series of available power, measured active power and reference value of the grid frequency for v > v_n

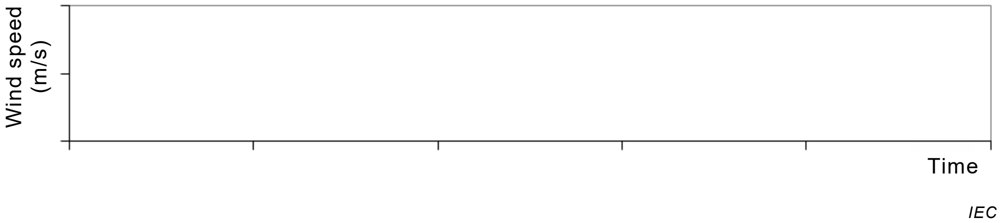


Figure A.53 – Test 5, time-series of wind speed for v > v_n

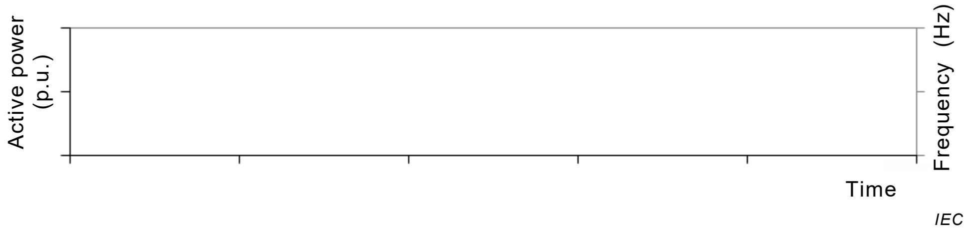


Figure A.54 – Test 6, time-series of available power, measured active power and reference value of the grid frequency for v > v_n

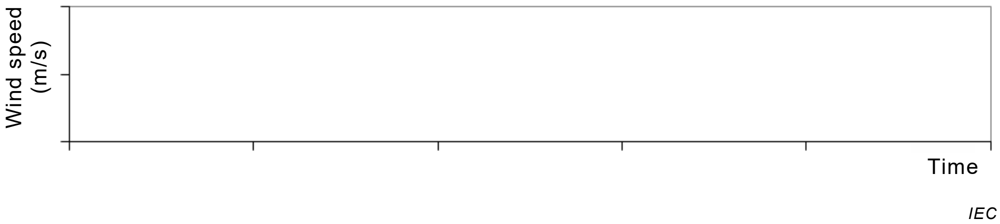


Figure A.55 – Test 6, time-series of wind speed for v > v_n

Reactive power control (see 8.4.6)

Table A.36 – General test information

Period of measurements	
Operational mode of the wind turbine during the test	
Interface used	

Table A.37 – Static error

Reactive power step $Q/ Q_{capability}$ [p.u.]	Voltage	Reference value		Measured value		Static error	
	U [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]	[kvar]	$Q/ Q_{capability}$ [p.u.]
-0,8							
-0,5							
0							
0,5							
0,8							

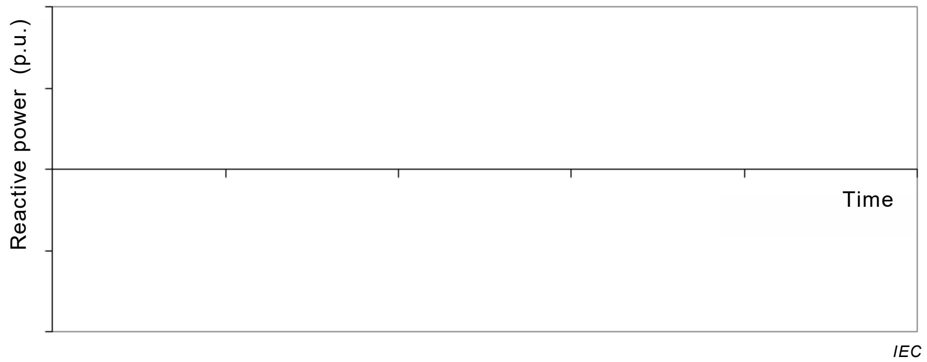


Figure A.56 – Time-series of reactive power reference values and measured reactive power during the test of reactive power control

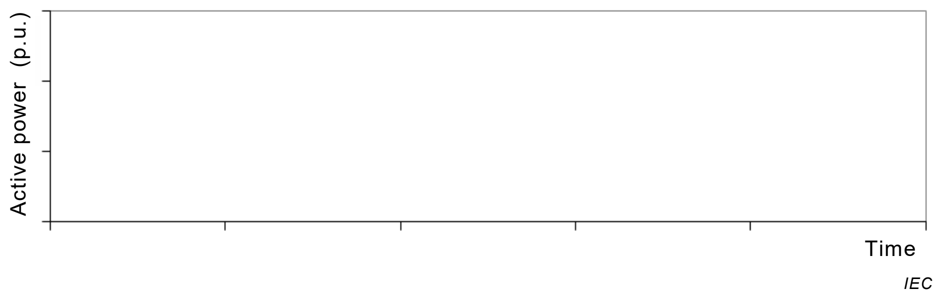


Figure A.57 – Time-series of active power during the test of reactive power control

Table A.38 – Dynamic response

Reactive power reference (p.u.)	From 0 to 0,8 (overexcited)	From 0,8 (overexcited) to 0,8 (underexcited)	From 0,8 (underexcited) to 0
Settling time (s)			
Rise time (s)			
Reaction time (s)			
Time instant of reference command			

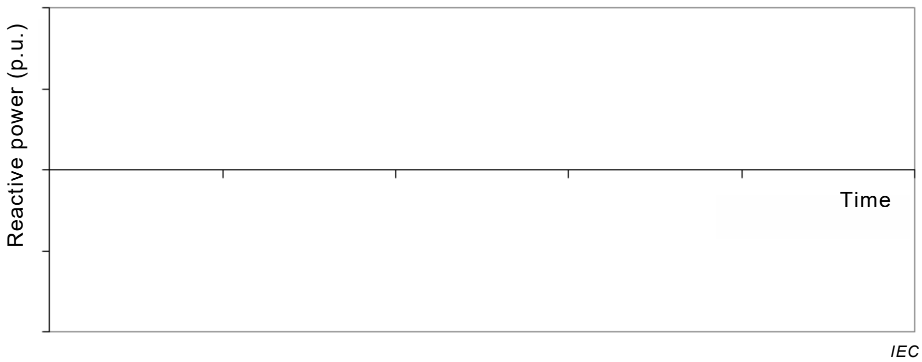


Figure A.58 – Time-series of reactive power reference values and measured reactive power during the test of reactive power dynamic response

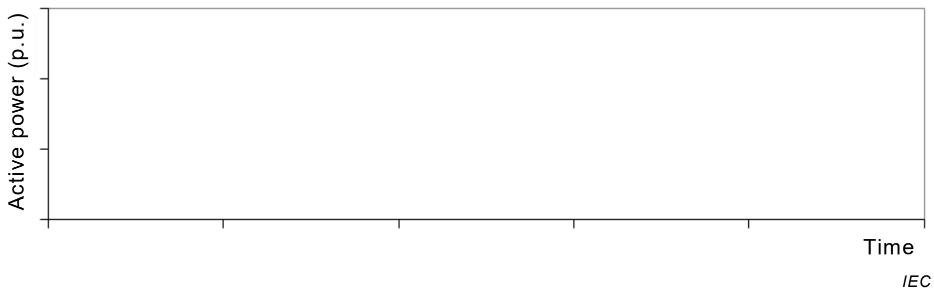


Figure A.59 – Time-series of active power during the test of reactive power dynamic response

A.5 Dynamic performance (see 8.5)

Table A.39 – Results for tests where the WT is not connected

	No.	Parameter description	Parameter	Unit
General	1	Number of test		-
	2	Date		[MM/DD/YYYY]
	3	Time		[hh:mm:ss]
	4	Three phase / two phase voltage dip/swell		-
	5	Series impedance X1		[Ω]
	6	Series impedance R1		[Ω]
	7	Short-circuit impedance X2		[Ω]
	8	Short-circuit impedance R2		[Ω]
	9	Time of entrance of voltage dip/swell (t_{fault})		[s]
	10	Time of clearance of voltage dip/swell (t_{clear})		[s]
	11	Duration of the voltage dip/swell (measured from test)		[s]
	12	Magnitude of pos. sequence of voltage dip/swell (measured from test)		[p.u.]
	13	Magnitude of neg. sequence of voltage dip/swell (measured from test)		[p.u.]
Before voltage dip/swell	14	Steady state voltage (U_{pre})		[p.u.]
During voltage dip/swell	15	Steady state voltage		[p.u.]
	16	Response time of voltage		[s]
	17	Settling time of voltage		[s]
After voltage dip/swell	18	Steady state voltage		[p.u.]
	19	Response time of voltage		[s]
	20	Settling time of voltage		[s]

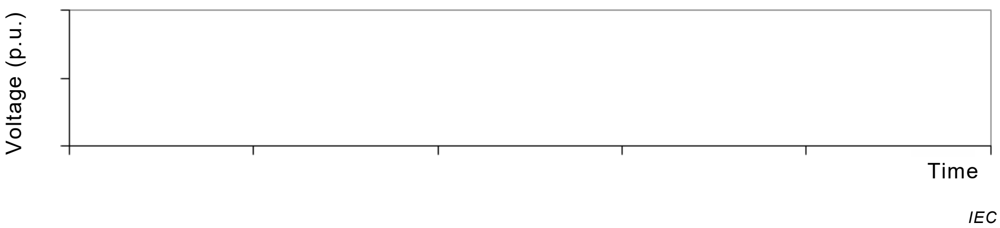


Figure A.60 – Wave shape of 3-phase voltages during entrance of voltage dip/swell when the WT under test is not connected

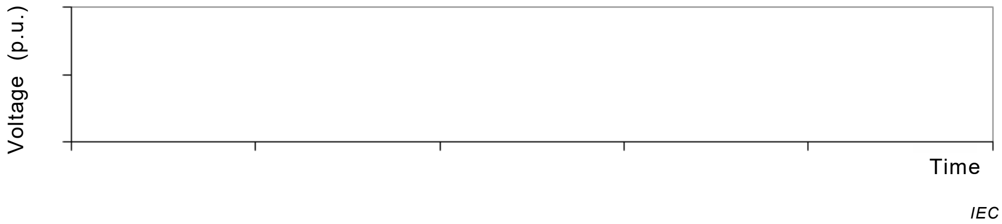


Figure A.61 – Wave shape of 3-phase voltages during clearance of voltage dip/swell when the WT under test is not connected

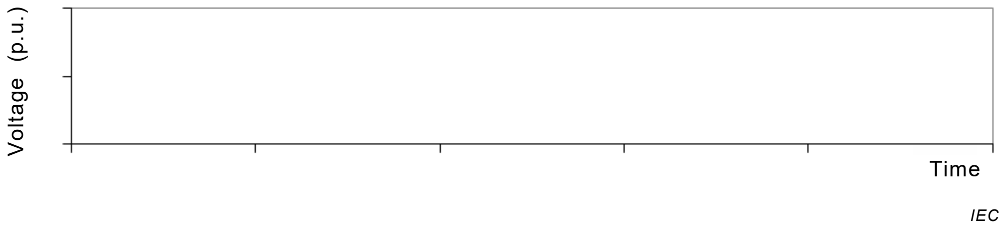


Figure A.62 – 3-phase voltages as RMS (1 line period) during the test when the WT under test is not connected

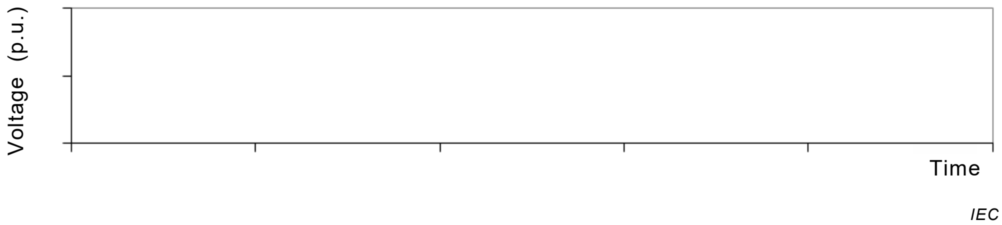


Figure A.63 – Positive sequence voltage during the test when the WT under test is not connected

Table A.40 – Results for tests where the WT is connected

	No.	Parameter description	Parameter	Unit
General	1	Number of test		-
	2	Date		[MM/DD/YYYY]
	3	Time		[hh:mm:ss]
	4	Operational mode of WT		-
	5	Active power range		[p.u.]
	6	Three phase / two phase voltage dip/swell		-
	7	Wind speed or available power		[m/s] or [p.u.]
	8	WT tripped (Y/N)		
	9	Time of entrance voltage dip/swell		[s]
	10	Time of clearance voltage dip/swell		[s]
	11	Duration of the voltage dip/swell (measured from the test)		[s]
	12	Magnitude of pos. sequence of voltage dip/swell (measured from test)		[p.u.]
	13	Magnitude of neg. sequence of voltage dip/swell (measured from test)		[p.u.]
	14	Tolerance band		[p.u.]
Before voltage dip/swell	15	Steady-state voltage (U_{pre})		[p.u.]
	16	Steady-state active power		[p.u.]
	17	Steady-state reactive power		[p.u.]
	18	Steady-state active current		[p.u.]
	19	Steady-state reactive current		[p.u.]
During voltage dip/swell	20	Steady-state voltage		[p.u.]
	21	Steady-state active power		[p.u.]
	22	Steady-state reactive power		[p.u.]
	23	Steady-state active current		[p.u.]
	24	Steady-state reactive current		[p.u.]
	25	Response time of active current		[s]
	26	Response time of reactive current		[s]
	27	Settling time of active current		[s]
	28	Settling time of reactive current		[s]
After voltage dip/swell	29	Steady-state voltage		[p.u.]
	30	Steady-state active power		[p.u.]
	31	Steady-state reactive power		[p.u.]
	32	Steady-state active current		[p.u.]
	33	Steady-state reactive current		[p.u.]
	34	Response time of active current		[s]
	35	Response time of reactive current		[s]
	36	Settling time of active current		[s]
	37	Settling time of reactive current		[s]
	38	Active power response time		[s]

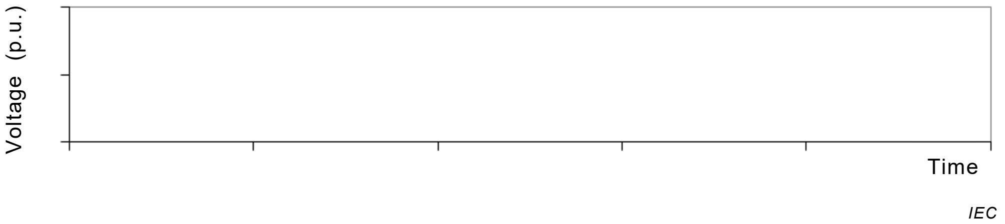


Figure A.64 – Wave shape of 3-phase voltages during entrance of the voltage dip/swell when the WT under test is connected

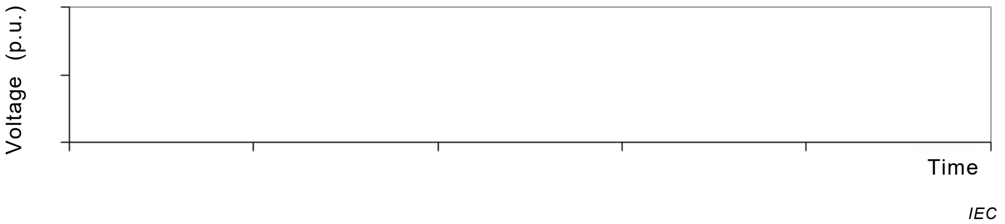


Figure A.65 – Wave shape of 3-phase voltages during clearance of the voltage dip/swell when the WT under test is connected

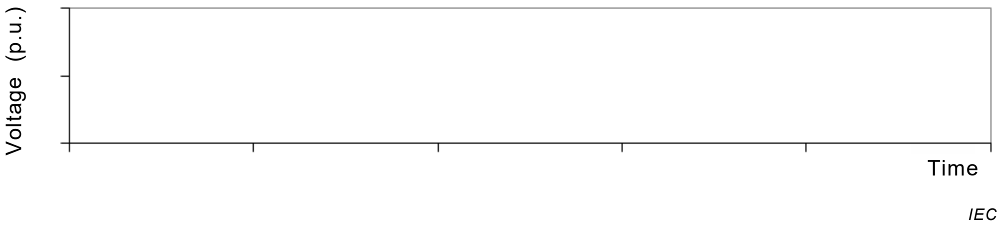


Figure A.66 – 3-phase voltages as RMS (1 line period) during the test when the WT under test is connected

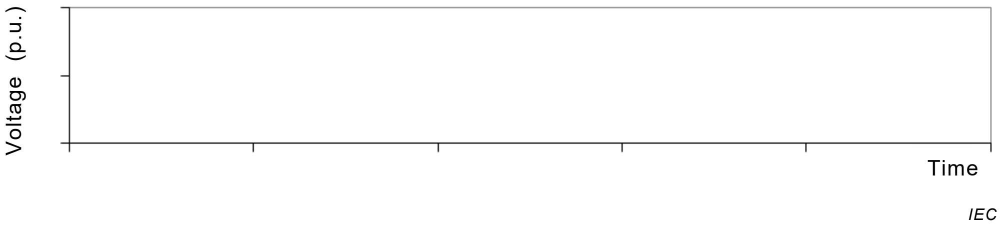


Figure A.67 – Positive and negative sequence fundamental voltage during the test when the WT under test is connected

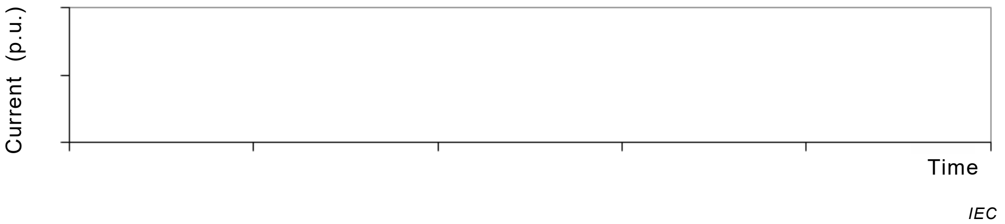


Figure A.68 – 3-phase currents as RMS (1 line period) during the test when the WT under test is connected

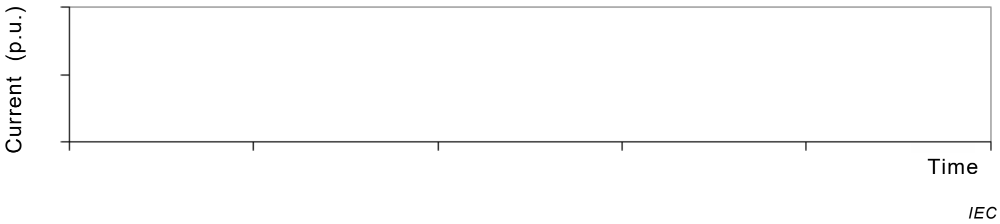


Figure A.69 – Pos. and neg. sequence fundamental current during the test when the WT under test is connected

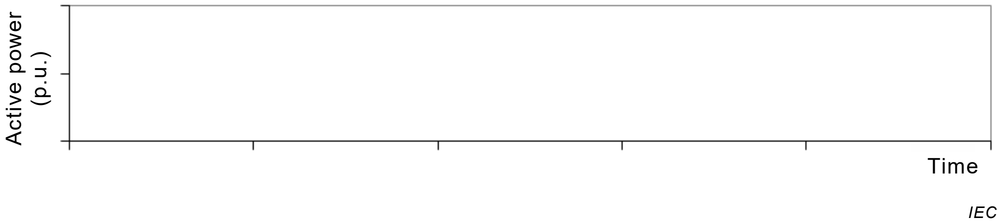


Figure A.70 – Pos. sequence fundamental active power during the test when the WT under test is connected.

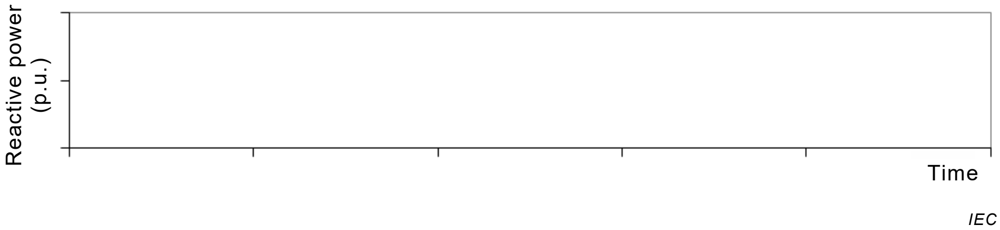


Figure A.71 – Pos. sequence fundamental reactive power during the test when the WT under test is connected

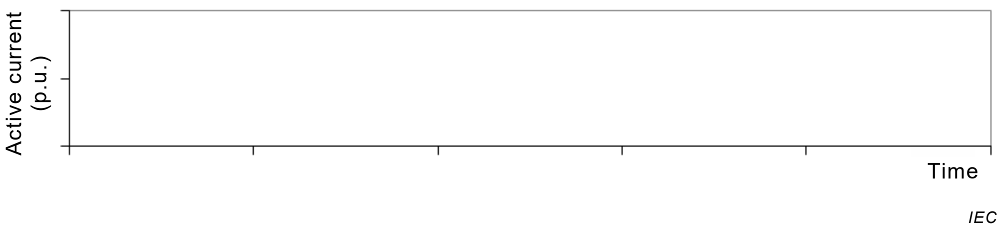


Figure A.72 – Pos. sequence fundamental active current during the test when the WT under test is connected

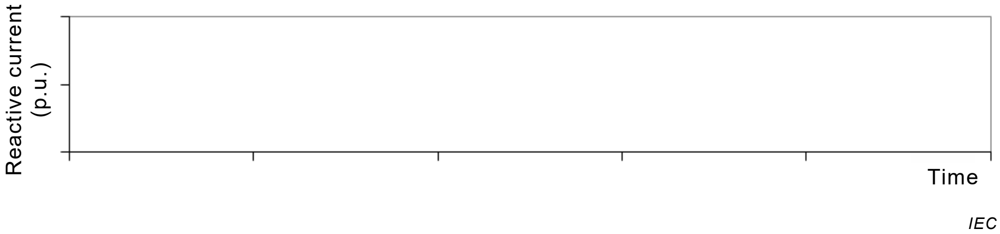


Figure A.73 – Pos. sequence fundamental reactive current during the test when the WT under test is connected

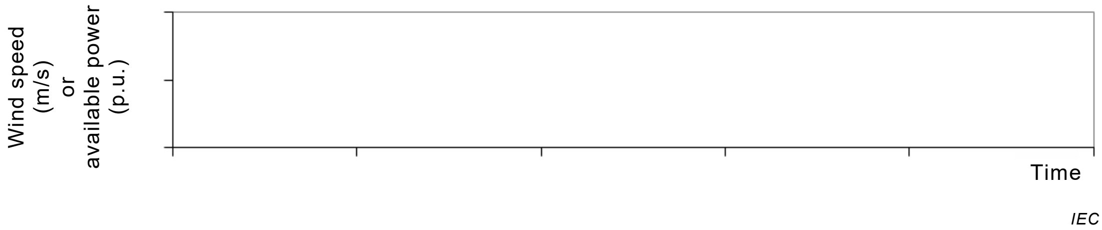


Figure A.74 – Wind speed or available power during the test when the WT under test is connected

A.6 Disconnection from grid (see 8.6)

Grid protection (see 8.6.2):

Table A.41 – Voltage protection

Test No.	Function	Reference value of the grid protection device		Measured value	
		Protective level [p.u.]	Release time [s]	Protective level [p.u.]	Disconnection time [s]
1	Overvoltage U>				
2	Overvoltage U>> (if available)				
3	Undervoltage U<				
4	Undervoltage U<< (if available)				

Table A.42 – Frequency protection

Test No.	Function	Reference value of the grid protection device		Measured value	
		Protective level [Hz]	Release time [s]	Protective level [Hz]	Disconnection time [s]
5	Overfrequency f>				
6	Underfrequency f<				

Table A.43 – Complete trip circuit test

Complete trip circuit test successful		YES ☐	NO ☐
	Time [ms]	**By measurement**	**By manufacturer certificate**
Operating time of circuit breaker		☐	☐

Rate of change of frequency (8.6.3):

Table A.44 – RoCoF test results

Test No.	Reference value		Measured value	
	df/dt disconnection level [p.u.]	**Release time [s]**	**df/dt disconnection level [p.u.]**	**Disconnection time [s]**

Table A.45 – RoCoF test information

Period of measurement	
Method used	
Operational mode of the wind turbine	

Reconnection test (8.6.4):

Table A.46 – Reconnection test results

Period of measurements			
Duration of grid failure [s]	**10**	**60**	**600**
Actual measured duration of grid failure [s]			
Reconnection time [s]			
Ramp rate reference values (given by the manufacturer)			
Measured ramp rate [% of nominal active power per minute]			
Operational mode of the wind turbine during the tests			

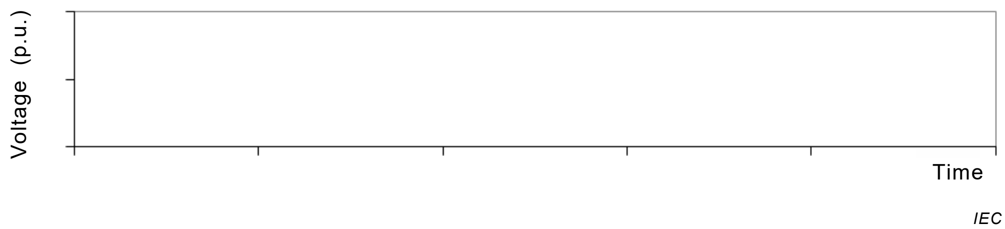


Figure A.75 – Voltage during the reconnection test of 10 s

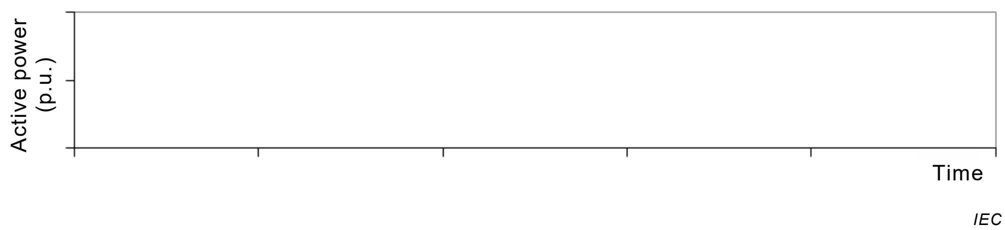


Figure A.76 – Active power during the reconnection test of 10 s, including the recovery

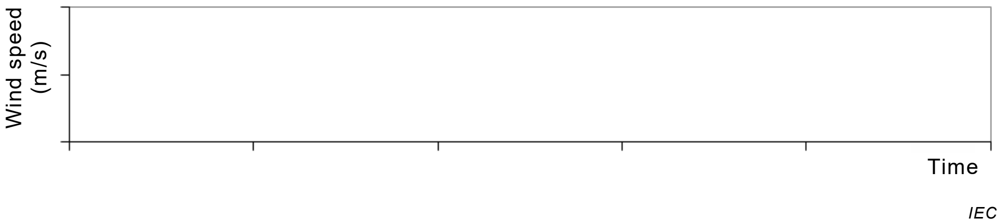


Figure A.77 – Time-series of measured wind speed during the reconnection test of 10 s

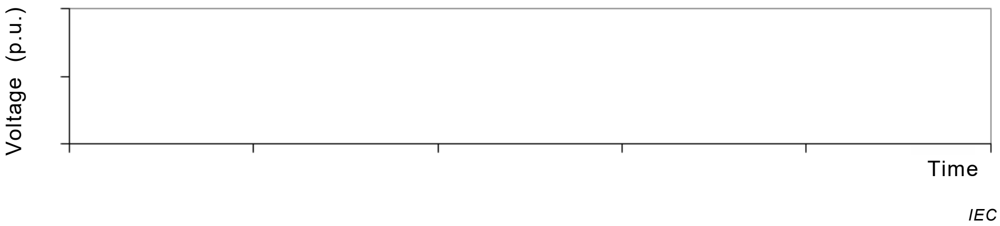


Figure A.78 – Voltage during the reconnection test of 60 s

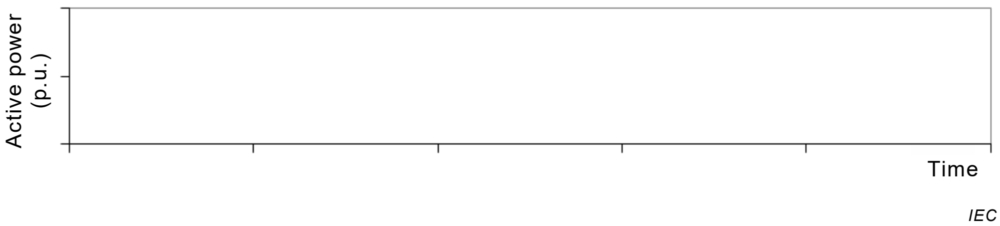


Figure A.79 – Active power during the reconnection test of 60 s, including the recovery

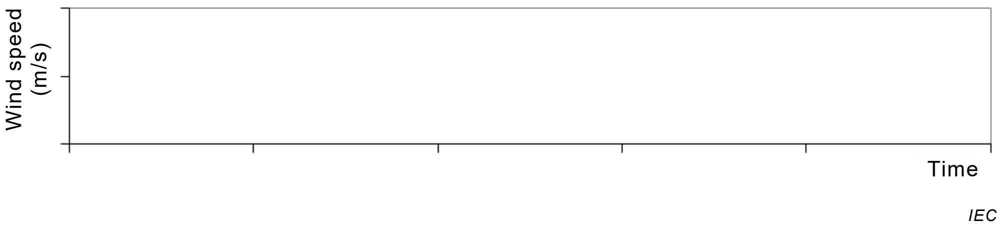


Figure A.80 – Time-series of measured wind speed during the reconnection test of 60 s

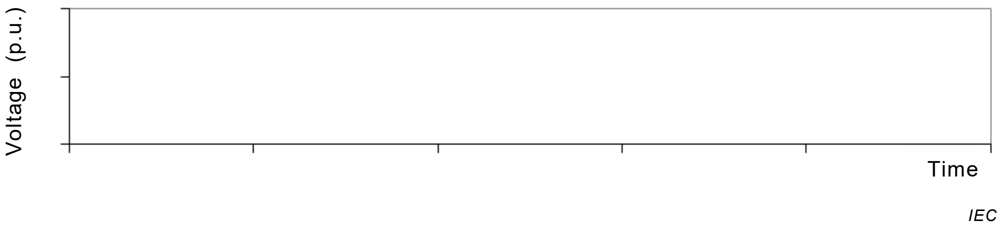


Figure A.81 – Voltage during the reconnection test of 600 s

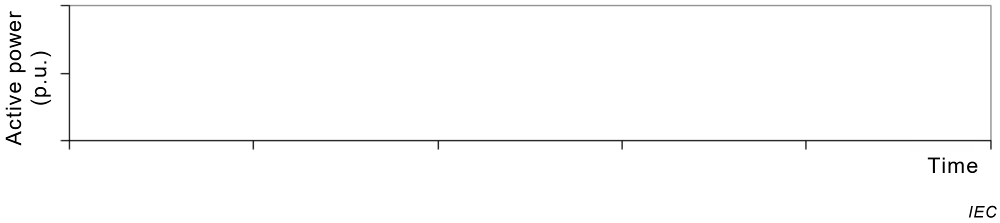


Figure A.82 – Active power during the reconnection test of 600 s including the recovery

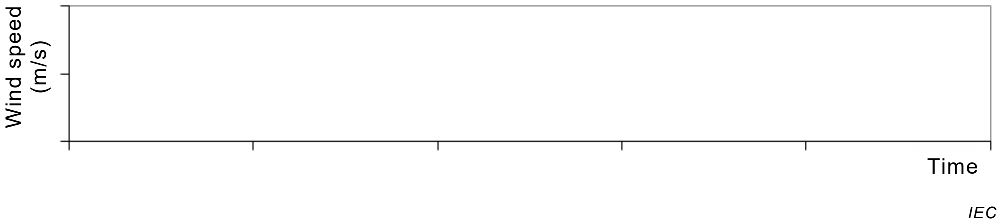


Figure A.83 – Time-series of measured wind speed during the reconnection test of 600 s

Annex B
(informative)

Voltage fluctuations and flicker

B.1 Continuous operation

The comprehensive measurement procedure for flicker during continuous operation of the wind turbine is shown in Figure B.1.

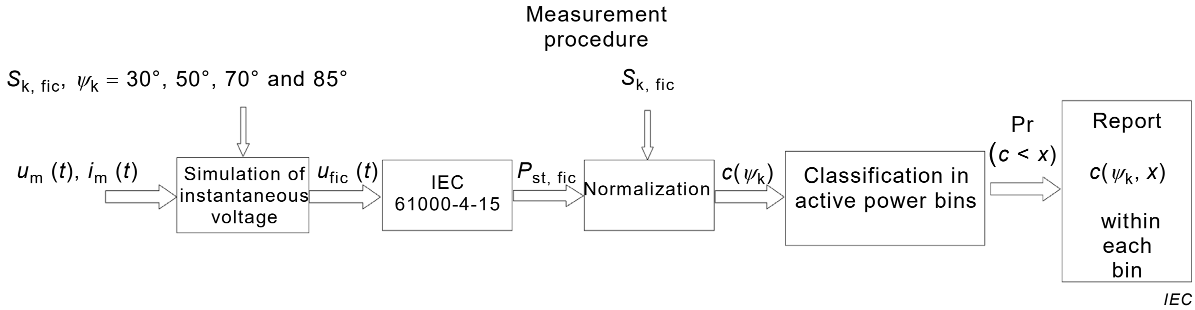


Figure B.1 – Measurement procedure for flicker during continuous operation of the wind turbine

The measurement procedure, illustrated in Figure B.1, is as follows:

1) A number of voltage and current time-series values, $u_m(t)$and $i_m(t)$, are measured at the PCC, distributed over the active power operation intervals from 0 % to 100 % of P_n.
2) Each set of measured time-series values is used as input to simulate the voltage fluctuations, $u_{fic}(t)$ on a fictitious grid with an appropriate short-circuit apparent power $S_{k,fic}$ and for four different network impedance phase angles, ψ_k.
3) Each simulated instantaneous voltage time-series $u_{fic}(t)$ is then used as input to the voltage flicker algorithm described in IEC 61000-4-15 to generate the flicker emission value $P_{st,fic}$.
4) Each $P_{st,fic}$ value is normalized to a flicker coefficient $c(\psi_k)$, which is in principle independent of the selected short-circuit apparent power $S_{k,fic}$.
5) For each network impedance phase angle ψ_k, the classification procedure sorts the calculated flicker coefficients, $c(\psi_k)$, within the active power bins 0 %, 10 %, 20 %,… , 100 % of P_n where 0 %, 10 %, 20 %,… , 100 % are the bin midpoints.
6) For each power bin, the accumulated distribution functions of the flicker coefficients is calculated, $Pr(c<x)$. This function represents the distribution of flicker coefficients that would have been obtained if the wind turbine operation had been operated in the corresponding interval of percentage of P_n.
7) For each accumulated distribution, the 95 % percentile $c(\psi_k,$ 95 %) of the flicker coefficient is then reported.

B.2 Switching operations

The comprehensive measurement procedure for switching operations – voltage changes as well as flicker – is shown in Figure B.2.

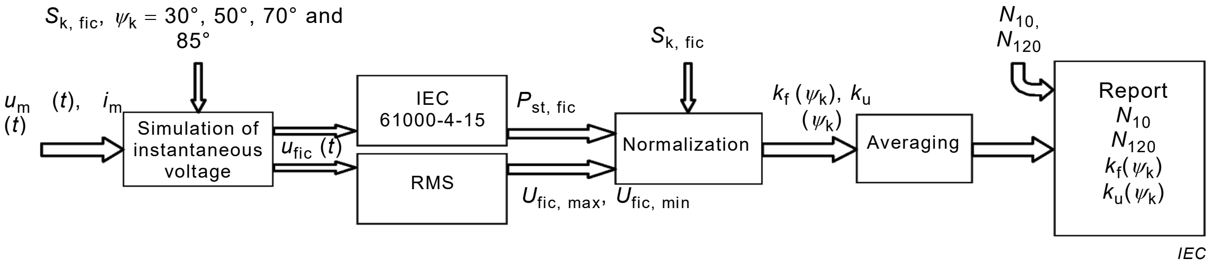


Figure B.2 – Measurement procedure for voltage changes and flicker during switching operations of the wind turbine

The measurement procedure for switching operations is as follows:

1) A number of voltage and current time-series values, $u_m(t)$ and $i_m(t)$, are measured for each of the specified types of switching events as described in 8.2.3.2.
2) Each set of measured time-series values is used as input to simulate the voltage fluctuations, $u_{fic}(t)$ on a fictitious grid with an appropriate short-circuit apparent power $S_{k,fic}$ and for four different network impedance phase angles, ψ_k.
3) Each simulated instantaneous voltage time-series $u_{fic}(t)$ is then used as input to the voltage flicker algorithm described in IEC 61000-4-15 to generate the flicker emission value $P_{st,fic}$ and as input to an RMS calculation algorithm to identify the maximum one period RMS value $U_{fic,max}$ and the minimum one period RMS value $U_{fic,min}$. The measurements shall be taken for a period, T_p, long enough to ensure that the transient of the switching operation has abated, though limited to exclude possible power fluctuations due to turbulence.
4) Each $P_{st,fic}$ value is normalized to a flicker step factor $k_f(\psi_k)$, and each voltage change $U_{fic,max} - U_{fic,min}$ is normalized to a voltage change factor $k_u(\psi_k)$.
5) For each network impedance phase angle ψ_k, the measured flicker step factors and voltage change factors are then averaged.
6) The averaged flicker step factors and voltage change factors are then reported together with the maximum number N_{10m} of the switching operation within a 10 min period and the maximum number N_{120m} of the switching operation within a 120 min period, for each type of switching operation.

B.3 Verification test of the measurement procedure for flicker

B.3.1 General

The overall response from the voltage and current time-series values, $u_m(t)$ and $i_m(t)$, to the flicker coefficient, which is the output of the "Normalization" block indicated in Figure B.1, can be verified using sinusoidal signals and sinusoidal modulations that give rise to predetermined $c(\psi_k)$ values.

The framework of these tests should be based on the following example using the parameters of wind turbine shown in Table B.1.

Table B.1 – Nominal values of the wind turbine used in the verification tests

Symbol	Value	Units
S_n	3	MVA
U_n	12	KV
I_n	144	A

It is recommended to use the same sampling frequency for the verification tests as it is used for the standard flicker tests in accordance with 8.2.2, the length of the test signals should be 600 s.

For all the tests presented in par. B.3.1, B.3.2, B.3.3 and B.3.4 the input current, $i_m(t)$, shall be the same: a sinusoidal signal with sinusoidal fluctuations characterized by the relative current changes, $\Delta I/I$, and the modulating frequency, f_m. The input current can be written as follows:

$$i_m(t) = \sqrt{2} \times I_n \times \left(1 + \frac{\Delta I}{I} \times \frac{1}{100} \times \frac{1}{2} \times \sin(2\pi f_m t)\right) \times \sin(2 \cdot \pi \cdot f_g \cdot t) \tag{B.1}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz).

For any input voltage signal, $u_m(t)$, based on a sinusoid with the same frequency and phase angle of $i_m(t)$ described in Equation (B.1) and for the cases of relative current changes, $\Delta I/I$, modulating frequency, f_m, and network impedance phase angles, ψ_k,described in Table B.2 and Table B.3 (for short-circuit ratio $S_{k,fic}/S_n$ 20 or 50, respectively), the observed flicker coefficient $c(\psi_k)$ should be 2,00 with a tolerance of ±5 %.

Table B.2 – Input relative current fluctuation, $\Delta I/I$, for flicker coefficient $c(\psi_k)$ = 2,00 ± 5 % when $S_{k,fic}$ = 20·S_n

f_m (Hz)	Current fluctuation $\Delta I/I$ for 50 Hz systems (%)				Current fluctuation $\Delta I/I$ for 60 Hz systems (%)			
	ψ_k = 30°	ψ_k = 50°	ψ_k = 70°	ψ_k = 85°	ψ_k = 30°	ψ_k = 50°	ψ_k = 70°	ψ_k = 85°
0,5	8,031	10,401	17,860	49,537	8,466	10,965	18,830	52,248
1,5	3,618	4,684	8,029	21,924	3,813	4,938	8,469	23,270
8,8	0,833	1,064	1,712	3,192	1,072	1,374	2,252	4,554
20,0	2,294	2,773	3,748	4,731	3,212	3,958	5,644	7,711
25,0	3,335	3,901	4,892	5,686	4,763	5,726	7,640	9,488
33,3	6,648	7,330	8,289	8,881	8,189	9,395	11,348	12,760
40,0					13,725	15,132	17,111	18,335

Table B.3 – Input relative current fluctuation, $\Delta I/I$, for flicker coefficient $c(\psi_k)$ = 2,00 ± 5 % when $S_{k,fic}$ = 50·S_n

f_m (Hz)	Current fluctuation $\Delta I/I$ for 50 Hz systems (%)				Current fluctuation $\Delta I/I$ for 60 Hz systems (%)			
	ψ_k = 30°	ψ_k = 50°	ψ_k = 70°	ψ_k = 85°	ψ_k = 30°	ψ_k = 50°	ψ_k = 70°	ψ_k = 85°
0,5	7,891	10,457	18,916	62,928	8,319	11,025	19,944	66,419
1,5	3,555	4,709	8,500	27,463	3,747	4,964	8,967	29,270
8,8	0,819	1,068	1,793	3,437	1,053	1,380	2,366	5,005
20,0	2,254	2,775	3,833	4,807	3,155	3,966	5,808	7,899
25,0	3,275	3,897	4,965	5,737	4,678	5,730	7,802	9,627
33,3	6,526	7,300	8,340	8,910	8,040	9,376	11,479	12,844
40,0					13,472	15,071	17,218	18,396

B.3.2 Fictitious grid performance testing

The intention of the test is to verify the simulation and resolution of the fictitious grid, paying special attention to the derivative of the input current signal, $i_m(t)$.

The simulated input voltage signal, $u_m(t)$, can be written as follows:

$$u_m(t) = \sqrt{\frac{2}{3}} \times U_n \times \sin(2 \cdot \pi \cdot f_g \cdot t) \tag{B.2}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz).

The simulated input current signal, $i_m(t)$, is described in Equation (B.1), and in Table B.2 or Table B.3 (for short-circuit ratio $S_{k,fic}/S_n$ 20 or 50, respectively).

The observed flicker coefficient $c(\psi_k)$ should be 2,00 with a tolerance of ±5 %.

B.3.3 Distorted u_m(t) voltage with multiple zero crossings

The intention of the test is to verify the procedure for generating the ideal voltage source $u_0(t)$ of the fictitious grid, based on a distorted input voltage signal, $u_m(t)$, with multiple zero crossings. The distorted voltage $u_m(t)$ consists of the fundamental voltage and the harmonic levels according to Table B.4. All harmonics have a 180° phase shift with respect to the 50 Hz/60 Hz fundamental – i.e. have a negative going zero crossing when the fundamental has a positive going zero crossing. This distorted voltage is then sinusoidally modulated at 8,8Hz with a relative amplitude of 0,25 %. The voltage signal $u_m(t)$ can be written as follows:

$$\begin{aligned} u_m(t) = \sqrt{\frac{2}{3}} \times U_n \times \left(1 + 0{,}25 \times \frac{1}{100} \times \frac{1}{2} \times \sin(2 \cdot \pi \cdot 8{,}8 \cdot t)\right) \times \\ \left(\sin(2 \cdot \pi \cdot f_g \cdot t) + \Sigma_\nu U_\nu \times \frac{1}{100} \times \sin(2 \cdot \pi \cdot \nu \cdot f_g \cdot t + \pi)\right) \end{aligned} \tag{B.3}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz), and U_v is described in Table B.4.

Table B.4 – Test specification for distorted voltage with multiple zero crossings

Harmonic order ν	**3**	**5**	**7**	**9**	**11**	**13**	**17**	**19**	**23**	**25**	**29**	**31**
U_v **– % of** U_n	5	6	5	1,5	3,5	3,0	2,0	1,76	1,41	1,27	1,06	0,97

The simulated input current signal, $i_m(t)$, is described in Equation (B.1), and in Table B.2 or Table B.3 (for short-circuit ratio $S_{k,fic}/S_n$ 20 or 50, respectively).

The observed flicker coefficient $c(\psi_k)$ should be 2,00 with a tolerance of ±5 %.

B.3.4 Distorted $u_m(t)$ voltage with inter-harmonic modulation

The intention of the test is to verify the procedure for generating the ideal voltage source $u_0(t)$ of the fictitious grid, based on a distorted input voltage signal, $u_m(t)$, that is modulated with inter-harmonic frequencies that are related to flicker. The distorted voltage $u_m(t)$ can be written as follows:

$$u_m(t) = \sqrt{\frac{2}{3}} \times U_n \times \left(1 + 3 + \frac{1}{100} \times \frac{1}{2} \times \sin(2 \cdot \pi \cdot f_v \cdot t)\right) \times \sin(2 \cdot \pi \cdot f_g \cdot t) \tag{B.4}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz).

The test is divided into 60 different cases. The modulating frequency f_v is increased in steps of 0,5 Hz, starting at the minimum modulating frequency of 0,5 Hz, and reaching the maximum modulating frequency of 30 Hz.

The simulated input current signal, $i_m(t)$, is described in Equation (B.1), and in Table B.2 or Table B.3 (for short-circuit ratio $S_{k,fic}/S_n$ 20 or 50, respectively) for all the cases.

The observed flicker coefficient $c(\psi_k)$ should be 2,00 with a tolerance of ±5 %.

B.3.5 Slow frequency changes

The intention of the test is to verify the procedure of generating the ideal voltage source $u_0(t)$ of the fictitious grid, based on a distorted input voltage signal, $u_m(t)$, that shows slow frequency changes in the fundamental frequency, reaching deviations of 0,05 Hz. The fundamental frequency of the grid can be written as follows:

$$f(t) = f_g + 0{,}05 \times \sin\left(2 \cdot \pi \cdot \frac{1}{60} \cdot t\right) \quad \text{(B.5)}$$

where f_g is the nominal grid frequency (50 Hz or 60 Hz).

And the distorted voltage $u_m(t)$ can be written as follows:

$$u_m(t) = \sqrt{\frac{2}{3}} \times U_n \times \left(1 + 0{,}25 \times \frac{1}{100} \times \frac{1}{2} \times \sin(2 \cdot \pi \cdot 8{,}8 \cdot t)\right) \times \sin\left(2 \cdot \pi \int_0^t f(t)\,\mathrm{d}t\right) \quad \text{(B.6)}$$

The simulated input current signal, $i_m(t)$, is described as follows:

$$i_m(t) = \sqrt{2} \times I_n \times \left(1 + \frac{\Delta t}{I} \times \frac{1}{100} \times \frac{1}{2} \times \sin(2 \cdot \pi \cdot f_m \cdot t)\right) \times \sin\left(2 \cdot \pi \cdot \int_0^t f(t)\,\mathrm{d}t\right) \quad \text{(B.7)}$$

where the relative current changes, $\Delta I/I$, modulating frequency, f_m, and network impedance phase angles, ψ_k, are described in Table B.2 or Table B.3 (for short-circuit ratio $S_{k,fic}/S_n$ 20 or 50, respectively).

The observed flicker coefficient $c(\psi_k)$ should be 2,00 with a tolerance of ±5 %.

B.4 Deduction of definitions

B.4.1 Flicker coefficient

The simulated flicker $P_{st,fic}$ value will depend on the short-circuit power of the grid, $S_{k,fic}$, and the angle of the grid impedance, ψ_k. $P_{st,fic}$ is approximately inversely proportional to $S_{k,fic}$, whereas the relation between $P_{st,fic}$ and ψ_k depends on the wind turbine type.

Therefore, the flicker coefficient, $c(\psi_k)$, is defined so that:

$$P_{st,fic} = c(\psi_k) \times \frac{S_n}{S_{k,fic}} \quad \text{(B.8)}$$

Where S_n is the nominal apparent power of the wind turbine.

Hence, the flicker coefficient $c(\psi_k)$ becomes:

$$c(\psi_k) = P_{st,fic} \times \frac{S_{k,fic}}{S_n} \tag{B.9}$$

B.4.2 Flicker step factor

IEC 61000-3-3 defines an analytical method to assess flicker, based on a voltage change and a form factor. The form factor, F = 1, corresponds to a stepwise voltage change. That method is used to define the flicker step factor, $k_f(\psi_k)$, in accordance with IEC 61000-3-3. The flicker step factor is defined so that it can be used to calculate an equivalent voltage step, which has the same flicker severity as the switching operation. The formal definition is:

$$d_{max} = k_f(\psi_k) \times \frac{S_n}{S_{k,fic}} \times 100 \tag{B.10}$$

Where d_{max} is the equivalent voltage step in percentage of nominal voltage.

Applying the IEC 61000-3-3 analytical method, a voltage step, d_{max}, gives the flicker impression time, t_f, according to

$$t_f = 2{,}3 \times {d_{max}}^{3{,}2} \tag{B.11}$$

and this flicker impression time gives the flicker severity, $P_{st,fic}$, according to

$$P_{st,fic} = \left(\frac{\sum t_f}{T_p} \right)^{1/3{,}2} \tag{B.12}$$

in an observation period, T_p. With a single flicker impression time, t_f, as above:

$$P_{st,fic} = 100 \times k_f(\psi_k) \times \frac{S_n}{S_{k,fic}} \times \left(\frac{2{,}3}{T_p} \right)^{1/3{,}2} \tag{B.13}$$

Using this result, the flicker step factor, $k_f(\psi_k)$, can be defined as:

$$k_f(\psi_k) = \frac{S_{k,fic}}{100 \times S_n} \times \left(\frac{T_P}{2{,}3} \right)^{1/3{,}2} \times P_{st,fic} \tag{B.14}$$

The observation time, T_P, in Equation (B.14) is the length of the simulated voltage time-series expressed in seconds.

B.4.3 Voltage change factor

The relative voltage change, Δu, due to switching operations will depend on the short-circuit power of the grid, $S_{k,fic}$, and the angle of the network impedance ψ_k. Δu is approximately inversely proportional to $S_{k,fic}$, whereas the relation between Δu and ψ_k depends on the technology of the wind turbine. Therefore, the voltage change factor, $k_u(\psi_k)$, is defined according to:

$$\Delta u = k_u(\psi_k) \times \frac{S_n}{S_{k,fic}} \tag{B.15}$$

Inserting the simulated voltage change on the grid with the short-circuit power of the grid, $S_{k,fic}$, the voltage change factor can then be determined by:

$$k_u(\psi_k) = \sqrt{3} \times \frac{U_{fic,max} - U_{fic,min}}{U_n} \times \frac{S_{k,fic}}{S_n} \tag{B.16}$$

where $U_{fic,max}$ and $U_{fic,min}$ are the maximum and minimum values respectively of the simulated phase-to-neutral voltage, $u_{fic}(t)$, on the fictitious grid.

Annex C
(normative)

Measurement of active power, reactive power and voltage

C.1 General

Annex C gives the procedures for the calculation of the fundamental frequency positive, negative and zero sequence components for the active power, reactive power, active current, reactive current, power factor (active factor/cos φ/displacement factor) and voltage based on the measured instantaneous phase voltages and currents.

Presenting quantities by their fundamental frequency positive, negative and zero sequence components provides clear definitions even in the case of an unbalanced and distorted power system. The reasons for calculating at least the positive sequence components are:

a) The positive sequence of the fundamental is the one that produces useful torque in rotating machines.

b) In many cases, reactive current is specified instead of the reactive power. Using the positive sequence of the fundamental, the reactive current component can be calculated explicitly even in the case of an unbalanced and distorted power system. The same applies to the active factor.

c) Many power system simulators use only the positive sequence of the fundamental. Thus, for easy verification of the simulations, the measurements should be presented in a similar way.

C.2 Generator convention of the signs

The positive direction of instantaneous phase voltages u_a, u_b and u_c and currents i_a, i_b and i_c are shown in Figure C.1. An overexcited generator feeding resistive and inductive load in the grid as shown in Figure C.1 has both its active power P and reactive power Q positive. Moreover, the active and reactive current components are also positive.

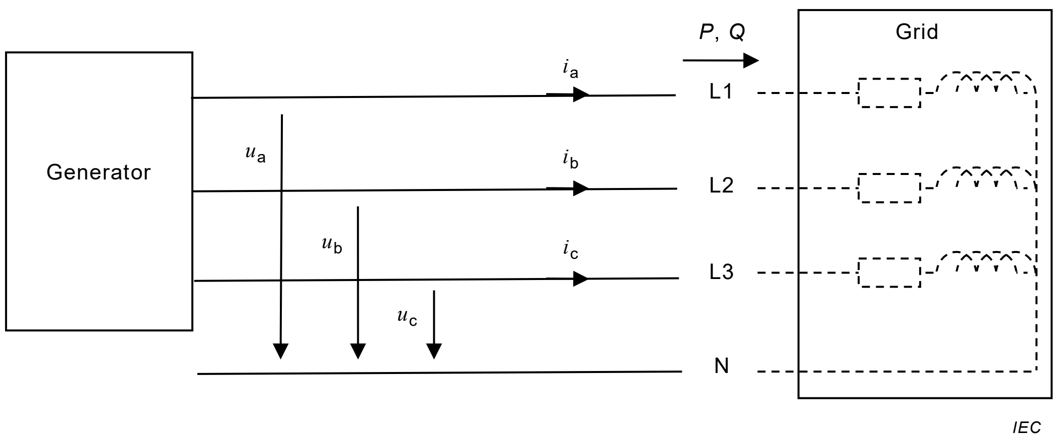


Figure C.1 – Positive directions of active power, reactive power, instantaneous phase voltages and instantaneous phase currents with generator convention

This kind of sign convention is called generator convention. Figure C.2 shows examples of the power phasor diagrams for the generator convention. Operation in the motoring quadrants 2 and 3 is related with the own consumption of the turbine when it is stopped but it may also take place at low wind speeds.

NOTE As other sign conventions such as consumer convention exists, extra care is needed when requirements and data are exchanged with the parties involved.

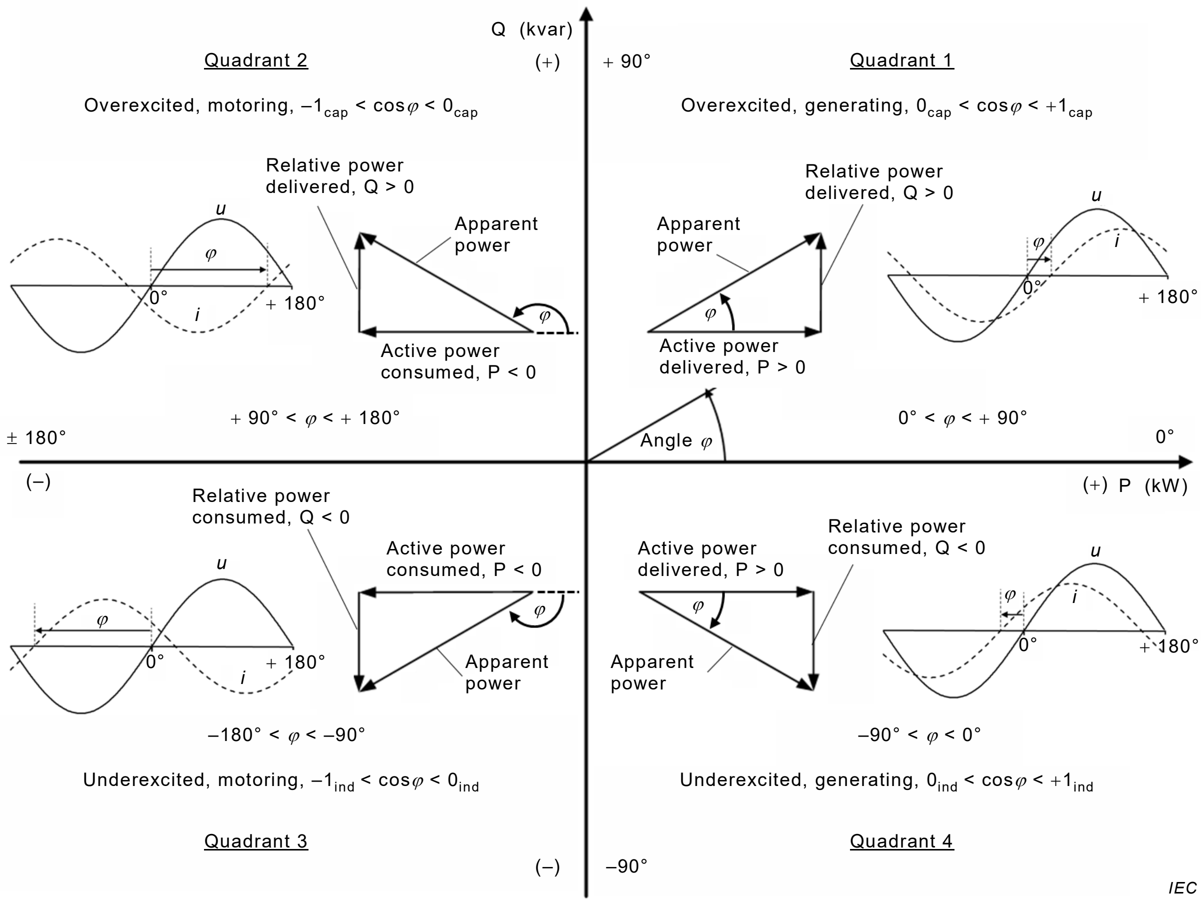


Figure C.2 – Examples of the power phasor diagrams of the generator convention in each quadrant with respective instantaneous phase voltage and current

C.3 Calculation of positive, negative and zero sequence quantities

C.3.1 Phasor calculations

Zero, positive and negative sequence components denoted by subscripts 0, 1 and 2, respectively, are defined using phasors. For the voltages:

$$\underline{U}_0 = U_0 e^{j\theta_0} = U_{0,\mathrm{Re}} + jU_{0,\mathrm{Im}} = \frac{1}{3}\left(\underline{U}_a + \underline{U}_b + \underline{U}_c\right) \tag{C.1}$$

$$\underline{U}_1 = U_1 e^{j\theta_1} = U_{1,\mathrm{Re}} + jU_{1,\mathrm{Im}} = \frac{1}{3}\left(\underline{U}_a + \underline{a}\,\underline{U}_b + \underline{a}^2\underline{U}_c\right) \tag{C.2}$$

$$\underline{U}_2 = U_2 e^{j\theta_2} = U_{2,\mathrm{Re}} + jU_{2,\mathrm{Im}} = \frac{1}{3}\left(\underline{U}_a + \underline{a}^2\underline{U}_b + \underline{a}\,\underline{U}_c\right) \tag{C.3}$$

where $\underline{a} = e^{j2\pi/3}$ is the 120-degree operator. The current components $\underline{I}_0$, $\underline{I}_1$ and $\underline{I}_2$ are defined similarly.

For example, if the phase voltage phasors are symmetrical $\underline{U}_a = U e^{j\theta}$, $\underline{U}_b = U e^{j(\theta - 2\pi/3)}$ and $\underline{U}_c = U e^{j(\theta + 2\pi/3)}$ then only the positive sequence component is non-zero:

$$\underline{U}_0 = \left(U e^{j\theta} + U e^{j(\theta - 2\pi/3)} + U e^{j(\theta + 2\pi/3)} \right) \Big/ 3 = U e^{j\theta} \left(1 + e^{-j2\pi/3} + e^{j2\pi/3} \right) \Big/ 3 = 0 \qquad \text{(C.4)}$$

$$\underline{U}_1 = \left(U e^{j\theta} + e^{j2\pi/3} U e^{j(\theta - 2\pi/3)} + e^{j4\pi/3} U e^{j(\theta + 2\pi/3)} \right) \Big/ 3 = \left(U e^{j\theta} + U e^{j\theta} + U e^{j\theta} \right) \Big/ 3 = U e^{j\theta} \qquad \text{(C.5)}$$

$$\underline{U}_2 = \left(U e^{j\theta} + e^{j4\pi/3} U e^{j(\theta - 2\pi/3)} + e^{j2\pi/3} U e^{j(\theta + 2\pi/3)} \right) \Big/ 3 = U e^{j\theta} \left(1 + e^{j2\pi/3} + e^{j4\pi/3} \right) \Big/ 3 = 0 \qquad \text{(C.6)}$$

The apparent power of the positive sequence component is

$$S_1 = \left| \underline{S}_1 \right| = \left| 3 \underline{U}_1 \underline{I}_1^* \right| \qquad \text{(C.7)}$$

Where the superscript * means complex conjugate of the phasor. The active and reactive powers of the positive sequence component are:

$$P_1 = \mathrm{Re}\left\{ \underline{S}_1 \right\} \qquad \text{(C.8)}$$

$$Q_1 = \mathrm{Im}\left\{ \underline{S}_1 \right\} \qquad \text{(C.9)}$$

The active and reactive currents of the positive sequence component are:

$$I_{P1} = \frac{P_1}{3 \left| \underline{U}_1 \right|} \qquad \text{(C.10)}$$

$$I_{Q1} = \frac{Q_1}{3 \left| \underline{U}_1 \right|} \qquad \text{(C.11)}$$

The power factor of the positive sequence is:

$$PF = \frac{P_1}{\sqrt{P_1^2 + Q_1^2}} \qquad \text{(C.12)}$$

If the reactive power is positive, the power factor is overexcited according to the sign convention and indicated with subscript cap after the numerical value, for example $\cos \varphi_1 = 0{,}95_{\text{cap}}$. If the reactive power is negative, the power factor is underexcited and indicated with subscript ind after the numerical value.

As all calculation is based on the fundamental frequency component and contribution from harmonics is disregarded, the power factor, displacement factor, active factor and $\cos \varphi_1$ have the same value.

The zero and negative sequence quantities are calculated similarly to Equations (C.7) to (C.12).

The definitions above require the magnitude and phase of the phasors to be known. This is difficult especially during voltage dips due to harmonics and variation of magnitudes and phases. Thus a method based on Fourier analysis is used that suits for calculation of the time series of the components and their active and reactive powers.

For the analysis the instantaneous phase, voltages and currents have to be measured using a multichannel datalogger or measuring instrument having high sampling rate (greater or equal to 2 kHz per channel). The analogue anti-aliasing filter (low pass filter) should have the same frequency response in all voltage and current inputs in order to minimize the errors in the phase shifts between voltages and currents. Moreover, the amplitude error due to the anti-aliasing filter should be negligible at the fundamental frequency.

If there is no neutral and the instantaneous phase-to-phase voltages are measured instead of the phase to neutral voltages, the phase voltages used in the calculation can be obtained from the phase-to-phase voltages using:

$$u_{\mathrm{a}}(t) = \frac{u_{\mathrm{ab}}(t) - u_{\mathrm{ca}}(t)}{3} \tag{C.13}$$

$$u_{\mathrm{b}}(t) = \frac{u_{\mathrm{bc}}(t) - u_{\mathrm{ab}}(t)}{3} \tag{C.14}$$

$$u_{\mathrm{c}}(t) = \frac{u_{\mathrm{ca}}(t) - u_{\mathrm{bc}}(t)}{3} = -u_{\mathrm{a}}(t) - u_{\mathrm{b}}(t) \tag{C.15}$$

The following characteristics can be performed in a spreadsheet or using a computer program or measurement instruments. New values for the components should be calculated at instants $t_{\mathrm{calc}} = n\ \Delta t_{\mathrm{calc}}$ where Δt_{calc} is the calculation interval that should be less or equal to the half cycle of the fundamental and n is an integer.

The calculation starts by calculation of the fundamental's Fourier coefficients over one fundamental period $T = 1/f_{(1)}$ in accordance with Equations (C.16) and (C.17) where $f_{(1)}$ is the frequency of the fundamental and t_{calc} is the instant for which the calculations are made. Because the measured variable is represented by sampled values, a suitable numerical integration method is used in the calculation. The equations are shown here only for the phase a fundamental voltage phasor $U_{\mathrm{a}(1)}$ components. Phasor components for phase b and c voltages and the three phase currents are calculated similarly.

$$U_{\mathrm{a}(1),\mathrm{Re}} = +\frac{\sqrt{2}}{T} \int_{t_{\mathrm{calc}}-T}^{t_{\mathrm{calc}}} u_{\mathrm{a}}(t) \cos(2\pi f_{(1)} t)\, \mathrm{d}t \tag{C.16}$$

$$U_{\mathrm{a}(1),\mathrm{Im}} = -\frac{\sqrt{2}}{T} \int_{t_{\mathrm{calc}}-T}^{t_{\mathrm{calc}}} u_{\mathrm{a}}(t) \sin(2\pi f_{(1)} t)\, \mathrm{d}t \tag{C.17}$$

The effective value of phase a fundamental voltage is:

$$U_{a(1)} = \sqrt{U_{a(1),Re}^2 + U_{a(1),Im}^2} \tag{C.18}$$

This is also the magnitude of the corresponding phasor. The phase of the phasor is:

$$\arg \underline{U}_{a(1)} = \begin{cases} \arctan \dfrac{U_{a(1),Im}}{U_{a(1),Re}} & \text{when } U_{a(1),Re} \geq 0, U_{a(1),Im} \neq 0 \\ \arctan \dfrac{U_{a(1),Im}}{U_{a(1),Re}} + \pi & \text{when } U_{a(1),Re} < 0, U_{a(1),Im} \geq 0 \\ \arctan \dfrac{U_{a(1),Im}}{U_{a(1),Re}} - \pi & \text{when } U_{a(1),Re} < 0, U_{a(1),Im} < 0 \\ 0 & \text{when } U_{a(1),Re} = 0, U_{a(1),Im} = 0 \end{cases} \tag{C.19}$$

The phasors for the voltages and currents obtained in the way described above can be used to calculate the zero, positive and negative sequence components using Equations (C.1), (C.2) and (C.3). However, this requires complex number calculations that are often not easy to do by a computer and thus the phasor component-based equations in C.3.2 to C.3.4 are used instead.

C.3.2 Calculation of the positive sequence quantities using phasor components

Instead of applying (C.2) the voltage and current phasor components of the fundamental positive sequence can be calculated using:

$$U_{(1)1,Re} = \frac{1}{6}\left[2U_{a(1),Re} - U_{b(1),Re} - U_{c(1),Re} + \sqrt{3}\left(U_{c(1),Im} - U_{b(1),Im}\right)\right] \tag{C.20}$$

$$U_{(1)1,Im} = \frac{1}{6}\left[2U_{a(1),Im} - U_{b(1),Im} - U_{c(1),Im} + \sqrt{3}\left(U_{b(1),Re} - U_{c(1),Re}\right)\right] \tag{C.21}$$

$$I_{(1)1,Re} = \frac{1}{6}\left[2I_{a(1),Re} - I_{b(1),Re} - I_{c(1),Re} + \sqrt{3}\left(I_{c(1),Im} - I_{b(1),Im}\right)\right] \tag{C.22}$$

$$I_{(1)1,Im} = \frac{1}{6}\left[2I_{a(1),Im} - I_{b(1),Im} - I_{c(1),Im} + \sqrt{3}\left(I_{b(1),Re} - I_{c(1),Re}\right)\right] \tag{C.23}$$

The active and reactive powers of the fundamental positive sequence are then:

$$P_{(1)1} = 3\left(U_{(1)1,Re}I_{(1)1,Re} + U_{(1)1,Im}I_{(1)1,Im}\right) \tag{C.24}$$

$$Q_{(1)1} = 3\left(U_{(1)1,Im}I_{(1)1,Re} - U_{(1)1,Re}I_{(1)1,Im}\right) \tag{C.25}$$

The effective value of the phase voltage of the fundamental positive sequence is:

$$U_{(1)1} = \sqrt{U_{(1)1,\text{Re}}^2 + U_{(1)1,\text{Im}}^2} \tag{C.26}$$

The effective active and reactive currents of the fundamental positive sequence are:

$$I_{P(1)1} = \frac{P_{(1)1}}{3U_{(1)1}} \tag{C.27}$$

$$I_{Q(1)1} = \frac{Q_{(1)1}}{3U_{(1)1}} \tag{C.28}$$

NOTE The active and reactive currents obtained by equations (C.27) and (C.28) are generally not equal to the current phasor components obtained from equations (C.22) and (C.23) because the real and imaginary axis coordinate system of the phasors is defined by the t_{calc} instant of the Fourier analysis.

The power factor of the fundamental positive sequence is:

$$PF_1 = \frac{P_{(1)1}}{\sqrt{P_{(1)1}^2 + Q_{(1)1}^2}} \tag{C.29}$$

C.3.3 Calculation of the negative sequence quantities using phasor components

Instead of applying (C.3), the voltage and current phasor components of the fundamental negative sequence can be calculated using:

$$U_{(1)2,\text{Re}} = \frac{1}{6}\left[2U_{a(1),\text{Re}} - U_{b(1),\text{Re}} - U_{c(1),\text{Re}} - \sqrt{3}\left(U_{c(1),\text{Im}} - U_{b(1),\text{Im}}\right)\right] \tag{C.30}$$

$$U_{(1)2,\text{Im}} = \frac{1}{6}\left[2U_{a(1),\text{Im}} - U_{b(1),\text{Im}} - U_{c(1),\text{Im}} - \sqrt{3}\left(U_{b(1),\text{Re}} - U_{c(1),\text{Re}}\right)\right] \tag{C.31}$$

$$I_{(1)2,\text{Re}} = \frac{1}{6}\left[2I_{a(1),\text{Re}} - I_{b(1),\text{Re}} - I_{c(1),\text{Re}} - \sqrt{3}\left(I_{c(1),\text{Im}} - I_{b(1),\text{Im}}\right)\right] \tag{C.32}$$

$$I_{(1)2,\text{Im}} = \frac{1}{6}\left[2I_{a(1),\text{Im}} - I_{b(1),\text{Im}} - I_{c(1),\text{Im}} - \sqrt{3}\left(I_{b(1),\text{Re}} - I_{c(1),\text{Re}}\right)\right] \tag{C.33}$$

The active and reactive powers of the fundamental negative sequence are then:

$$P_{(1)2} = 3\left(U_{(1)2,\text{Re}} I_{(1)2,\text{Re}} + U_{(1)2,\text{Im}} I_{(1)2,\text{Im}}\right) \tag{C.34}$$

$$Q_{(1)2} = 3\left(U_{(1)2,\text{Im}} I_{(1)2,\text{Re}} - U_{(1)2,\text{Re}} I_{(1)2,\text{Im}}\right) \tag{C.35}$$

The effective value of the phase voltage of the fundamental negative sequence is:

$$U_{(1)2} = \sqrt{U_{(1)2,\mathrm{Re}}^2 + U_{(1)2,\mathrm{Im}}^2} \tag{C.36}$$

The effective active and reactive currents of the fundamental negative sequence are:

$$I_{\mathrm{P}(1)2} = \frac{P_{(1)2}}{3U_{(1)2}} \tag{C.37}$$

$$I_{\mathrm{Q}(1)2} = \frac{Q_{(1)2}}{3U_{(1)2}} \tag{C.38}$$

NOTE The active and reactive currents obtained by Equations (C.37) and (C.38) are generally not equal to the current phasor components obtained from Equations (C.32) and (C.33) because the real and imaginary axis coordinate system of the phasors is defined by the $t_{\text{calc instant}}$ of the Fourier analysis.

The power factor of the fundamental negative sequence is

$$PF_2 = \frac{P_{(1)2}}{\sqrt{P_{(1)2}^2 + Q_{(1)2}^2}} \tag{C.39}$$

C.3.4 Calculation of the zero sequence quantities using phasor components

When there is a neutral conductor in the measured system zero sequence components may exist. Instead of applying equation (C.1), the voltage and current phasor components of the fundamental zero sequence can be calculated using:

$$U_{(1)0,\mathrm{Re}} = \frac{1}{3}\left(U_{\mathrm{a}(1),\mathrm{Re}} + U_{\mathrm{b}(1),\mathrm{Re}} + U_{\mathrm{c}(1),\mathrm{Re}}\right) \tag{C.40}$$

$$U_{(1)0,\mathrm{Im}} = \frac{1}{3}\left(U_{\mathrm{a}(1),\mathrm{Im}} + U_{\mathrm{b}(1),\mathrm{Im}} + U_{\mathrm{c}(1),\mathrm{Im}}\right) \tag{C.41}$$

$$I_{(1)0,\mathrm{Re}} = \frac{1}{3}\left(I_{\mathrm{a}(1),\mathrm{Re}} + I_{\mathrm{b}(1),\mathrm{Re}} + I_{\mathrm{c}(1),\mathrm{Re}}\right) \tag{C.42}$$

$$I_{(1)0,\mathrm{Im}} = \frac{1}{3}\left(I_{\mathrm{a}(1),\mathrm{Im}} + I_{\mathrm{b}(1),\mathrm{Im}} + I_{\mathrm{c}(1),\mathrm{Im}}\right) \tag{C.43}$$

The active and reactive powers of the fundamental zero sequence are then:

$$P_{(1)0} = 3\left(U_{(1)0,\mathrm{Re}} I_{(1)0,\mathrm{Re}} + U_{(1)0,\mathrm{Im}} I_{(1)0,\mathrm{Im}}\right) \tag{C.44}$$

$$Q_{(1)0} = 3\left(U_{(1)0,\mathrm{Im}} I_{(1)0,\mathrm{Re}} - U_{(1)0,\mathrm{Re}} I_{(1)0,\mathrm{Im}}\right) \tag{C.45}$$

The effective value of the phase voltage of the fundamental zero sequence is:

$$U_{(1)0} = \sqrt{U_{(1)0,\mathrm{Re}}^2 + U_{(1)0,\mathrm{Im}}^2} \tag{C.46}$$

The effective active and reactive currents of the fundamental zero sequence are:

$$I_{\mathrm{P}(1)0} = \frac{P_{(1)0}}{3U_{(1)0}} \tag{C.47}$$

$$I_{\mathrm{Q}(1)0} = \frac{Q_{(1)0}}{3U_{(1)0}} \tag{C.48}$$

NOTE The active and reactive currents obtained by Equations (C.47) and (C.48) are generally not equal to the current phasor components obtained from Equations (C.42) and (C.43) because the real and imaginary axis coordinate system of the phasors is defined by the t_{calc} instant of the Fourier analysis.

The power factor of the fundamental zero sequence is:

$$PF_0 = \frac{P_{(1)0}}{\sqrt{P_{(1)0}^2 + Q_{(1)0}^2}} \tag{C.49}$$

Annex D
(informative)

Harmonic evaluation

D.1 General

The harmonic current emission of a wind turbine can be influenced by e.g.:

- harmonic grid background distortion,
- resonances in the grid,
- short circuit power at the grid connection point.

The aim of this evaluation is to be able to report the harmonic emission of a wind turbine independent from the above influences as much as possible. Thus, it may be necessary to identify other influences on the harmonic emission of the wind turbine and possibly exclude these influences.

The above-mentioned influences are dependent on the wind turbine type, on the grid configuration and situation at the site of the measured wind turbine and on the actual grid background harmonic voltage distortions during the measurements. Thus, it is still not possible to give a generic procedure, how to identify the influences and how to exclude them.

In Clause D.2, various analysis methods and additional measurement procedures are given, which may help to identify the influences on the harmonic emission.

D.2 General analysis methods

D.2.1 General

In Clause D.2, general harmonic analysis methods are presented. By application of these analysis methods, it should be easier to determine whether the harmonic measurements of wind turbine are affected by the background harmonic distortion or not.

D.2.2 Harmonic voltages

Harmonic voltages can be measured and analysed like harmonic currents, as given in 8.2.4. Additionally, the harmonic voltage angle can be determined as it is described in D.2.2.

D.2.3 Harmonic phase angles and magnitudes

The harmonic phase angle can help to identify the direction of a harmonic current flow or to find out if a harmonic current is synchronised to the grid fundamental frequency. As harmonic groups and subgroups do not contain the phase, the harmonic components without grouping calculated from the 10-cycle or 12-cycle waveforms have to be used in the analysis. There are two different phase angles, which can be analysed:

– Phase angle of the spectral component α_h, that is, the angle between the harmonic current component (or harmonic voltage component) and the fundamental phase voltage defined in Figure D.1 and Equation (D.1).

$$y_h(t) = c_h \sin\left(h\omega_1 t + \alpha_h\right) \tag{D.1}$$

– Harmonic phase angle between the harmonic current component and the corresponding harmonic voltage component, $\varphi_{\mathrm{h}} = \alpha_{\mathrm{Uh}} - \alpha_{\mathrm{Ih}}$. From this, the cos φ_{h} of the harmonic can also be calculated. Harmonic phase angle indicates the direction of the harmonic current flow. In practical cases, this phase angle is often −90° or +90°, which means inductive or capacitive current flow, respectively. Phase angle close to 180°means that the WT is absorbing energy from the grid harmonic. As the typical grid impedance is mainly inductive, the harmonic phase angles in the range from + 120° to + 270° (= −90°) usually tend to decrease the voltage distortion.

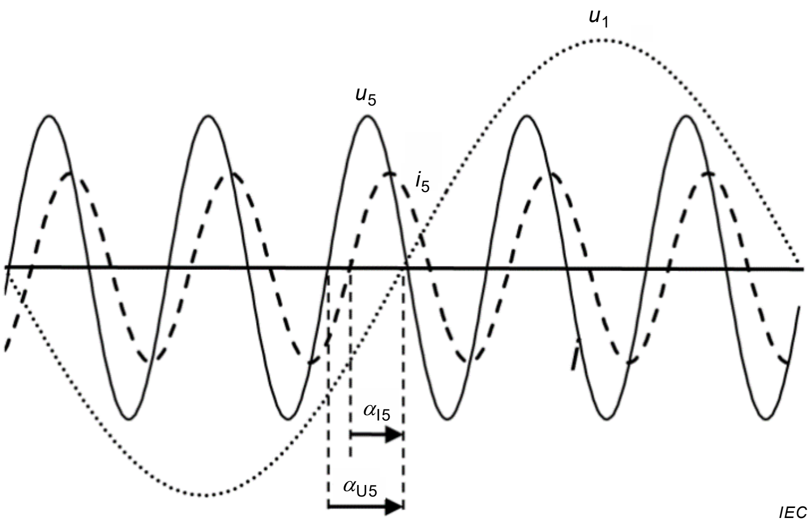


Figure D.1 – Definition of the phase angles of the spectral line in generator convention – (5th harmonic with αI5 = + 120° and αU5 = + 170°shown as an example, thus 5th harmonic phase angle is φ5 = + 170° − 120° = + 50°)

NOTE The sign convention used for the voltages and currents is the generator convention as defined in Annex C. If the phase angle of a harmonic current spectral line varies in a wide range, it indicates that the harmonic current does not relate with the fundamental voltage.

As the magnitude and the phase angle of the spectral components may vary largely between discrete Fourier transform (DFT) windows, aggregation is often needed.

The magnitude aggregation is done using the square root of the arithmetic mean of the squared input values (i.e. RMS) in accordance with Equation (D.2).

$$C_h = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\underline{C}_{h,i}\right|^2} \qquad \text{(D.2)}$$

where n is the number of aggregated DFT windows, $C_{h,i}$ is the complex value of the h-th harmonic from the estimated spectrum from each of i-th 10-cycle or 12-cycle window and C_{h} is the aggregated h-th harmonic magnitude. Possible grouping of the spectral components can be performed according to IEC 61000-4-7.

The prevailing phase angle of the spectral component is described by Equation (D.3).

$$\alpha_{h,ave} = \arctan\left(\frac{\sum_{i=1}^{n} Im\left[\underline{C}_{h,i}\right]}{\sum_{i=1}^{n} Re\left[\underline{C}_{h,i}\right]}\right) \qquad \text{if } \sum_{i=1}^{n} Re\left[\underline{C}_{h,i}\right] \geq 0$$

$$\alpha_{h,ave} = \pi + \arctan\left(\frac{\sum_{i=1}^{n} Im\left[\underline{C}_{h,i}\right]}{\sum_{i=1}^{n} Re\left[\underline{C}_{h,i}\right]}\right) \qquad \text{if } \sum_{i=1}^{n} Re\left[\underline{C}_{h,i}\right] < 0 \tag{D.3}$$

The 10-cycle values can be aggregated over the following intervals:

– 150-cycle interval for 50 Hz nominal or 180-cycle interval for 60 Hz,
– 10-min interval,
– 2 h interval.

In some applications, other time intervals (e.g. 10 s, 1 min) may be useful. These other time intervals, if used, should be obtained with the same aggregation method (e.g. a 1-min time interval, if used, should be implemented using a method that is analogous to the 10-minute aggregation method). See also NOTE 1.

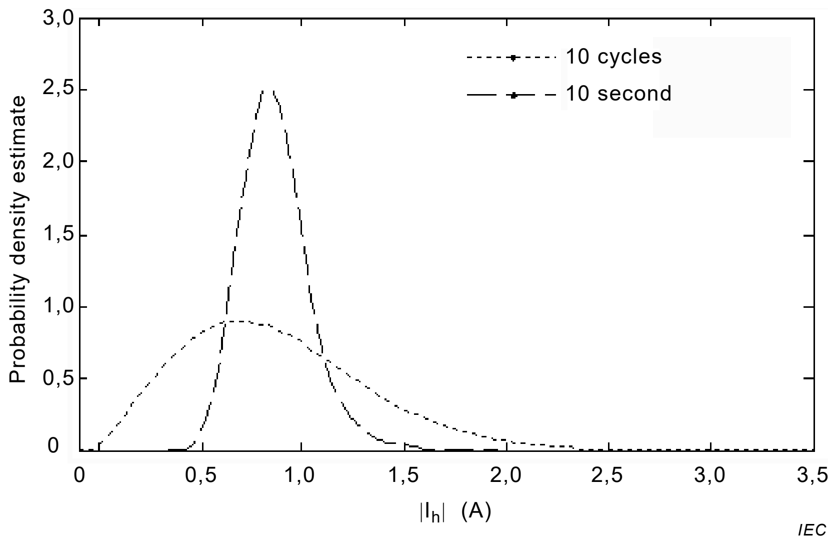


Figure D.2 – Comparison of harmonic amplitude aggregation (dotted) no aggregated amplitude directly from DFT with 10-cycle window, (dashed) 10-second aggregation

As it can be seen in Figure D.2, additional aggregation can change the distribution of measured harmonics as well sample statistics such as percentiles, maximum values, etc.

The randomness of the prevailing phase angle can be estimated from the prevailing angle ratio expressed by Equation (D.4).

$$PAR = \frac{\left|\sum_{i=1}^{n} \underline{C}_{h,i}\right|}{\sum_{i=1}^{n} \left|\underline{C}_{h,i}\right|} = \frac{\left|\sum_{i=1}^{n} \left(a_{h,i} + \mathrm{j}b_{h,i}\right)\right|}{\sum_{i=1}^{n} \left|a_{h,i} + \mathrm{j}b_{h,i}\right|} \tag{D.4}$$

where $\underline{C}_{h,i}$ is the complex spectral component from DFT, and $a_{h,i}$ and $b_{h,i}$ are the real and imaginary components of the complex spectral component of the i-th window, respectively.

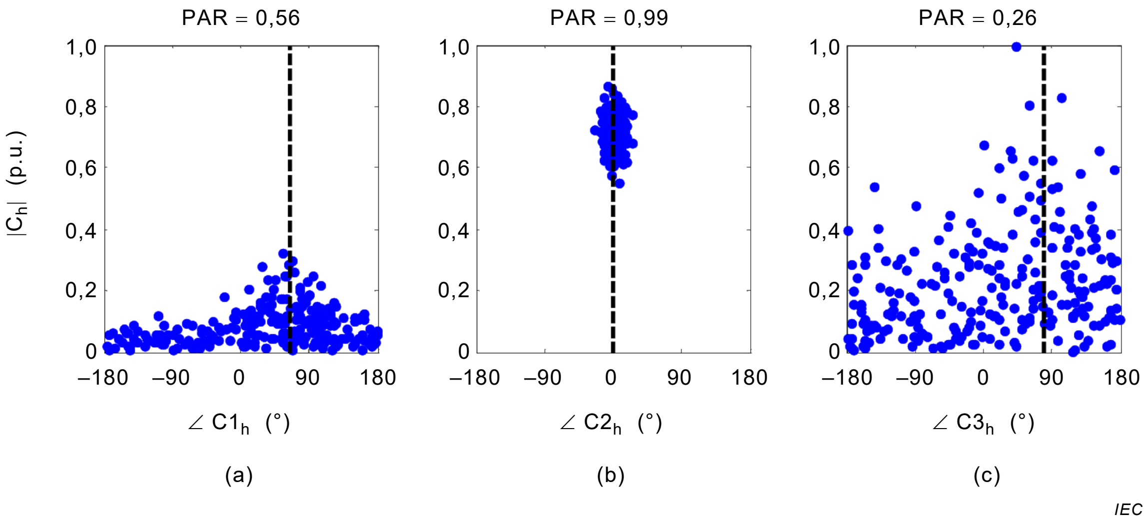
If the prevailing angle ratio is close to unity, it means that there is not significant variation of the harmonic angle during the analysed interval. On the contrary, the harmonic can be considered to have a random phase angle if the prevailing ratio is less than 0,3. Notice, however, that uncertainties in the measurement system or data processing also affect the prevailing angle ratio especially when the harmonic magnitude is low.

In order to evaluate the measurement uncertainty also harmonic phase angle evaluation might be very useful. The distribution of harmonic angles obtained directly from DFT can give an overview about the measurement system accuracy. For small harmonic magnitudes (e.g. close to the expected measurement system accuracy), it is expected that the probability density function will tend to be uniform. This can be evaluated either by investigation of the histogram or assessment of such statistics as mean, min, max, median, skewness, kurtosis, etc. See also NOTE 2.

The prevailing angle ratio expressed in Equation (D.4) can also be helpful in the assessment of the measurement system uncertainties.

If the prevailing angle ratio is close to unity it means that there is not significant variation of the harmonic angle during the analysed interval. If the value is much lower than 1 it means that the angle variation can be caused either by uncertainties, significant changes in the analysed system or lack of analysed harmonic phase lock to the fundamental frequency. If the prevailing angle ratio is low and the harmonic amplitude is low, the estimated harmonic component can be significantly affected by uncertainties in measurements or data processing. Please note that the prevailing angle ratio is one of supplementary indices and cannot give absolute judgement about the system uncertainties.

In Figure D.3 (a), it can be seen how the prevailing angle ratio can indicate harmonics significantly affected by the measurement system uncertainties. Of course, the magnitude should be evaluated simultaneously.



Key

(a) a harmonic C1 with small magnitude affected by the measurement system uncertainties

(b) correctly estimated harmonic C2 with fix phase

(c) frequency component at harmonic frequency which is not linked to the power system fundamental frequency

Figure D.3 – Comparison of the prevailing angle ratio (PAR)

NOTE 1 Phase angle aggregation is not specified in any of the standards concerning the quality of power. Therefore, another aggregation approach sometimes can be seen taking into consideration magnitude as well as phase aggregation as complex values where amplitude and angle are aggregated together or complex unity vectors with angles directly from DFT where phase angle is aggregated separately. However, this approach is not considered in this document.

NOTE 2 If the harmonic component of interest is not linked to the power system fundamental frequency, the phase angle also can behave randomly. Thus, it is of great importance to evaluate the phase angle together with the harmonic magnitude.

D.2.4 Statistical analysis

Shorter measurement intervals, e.g. 3 s or 1 min intervals will increase the number of measurement intervals and thus can lead to a better statistical analysis. Further information may be given by a more detailed statistical analysis within each power bin. The average value, 95 percentile, but also the maximum and minimum value and the standard deviation could be analysed for each power bin.

D.2.5 Sample rate adjustment

In IEC 61000-4-7, it is stated that before application of DFT, the samples in the time window are often weighted by multiplying them with a special symmetrical function (i.e. windowing function). However, for periodic signals and synchronous sampling, it is preferable to use a rectangular weighting window, which multiplies each sample by unity.

The synchronous sampling can be obtained in two possible ways: before data acquisition (on-line) and after data acquisition (off-line). It is recommended to perform sample rate adjustment during off-line processing. For frequency components that are multiple integers of the power system frequency, the sample rate should be adjusted to the power system fundamental component f_0.

NOTE In Fourier decomposition, it is assumed that the waveform is a stationary time-series. However, in real life this is not always the case therefore various stationarity tests (e.g. reverse arrangement test) can be done before the Fourier decomposition and results where the stationarity assumption is violated should be flagged.

D.2.6 Determination of background harmonic voltage distortion

A group of procedures are described in the following clauses, which could help to determine if certain harmonic level is affected by the background distortion.

The following points 1 to 8 provide aid in considering and evaluating harmonics (the methods used here shall be documented in the test report):

1) diurnal variations of the harmonic voltage and current,
2) shutting down neighbouring WT or loads,
3) harmonics of current and voltage over power,
4) filters,
5) measuring at a standard source,
6) harmonics power flow + voltage measurement, phase angle,
7) voltage harmonics with and without operation of the tested wind turbine,
8) measurements at different sites.

D.2.7 Diurnal variations of the harmonic voltage and current

If a harmonic displays a clear diurnal variation, this is a clear indication of bias. WT behaviour is exclusively dependent on the primary energy supply and not on the time of day (does not apply to PV systems). If the harmonics display no diurnal pattern, this does not necessarily mean that these harmonics are not subject to bias. The voltage quality at the WT connection point can be impaired by loads and neighbouring WTs (see D.4.2).

Test procedure:

To estimate the influence of diurnal variations on background distortion, the following values have to be investigated:

– voltage harmonics and current harmonics measured at the wind turbine terminals,
– wind turbine active power.

The measurement has to be done during continuous operation of the wind turbine. In contrast to the harmonic measurement as described in Subclause 8.2, this measurement requires at least twenty-one (minimum) 10-min time-series of measurement data for each 10 % power bin because it is necessary to show the voltage and current harmonics over the course of some days. To reduce the number of measurement data and save storage space on the measurement device, it is recommended to record only a 10-cycle window for each second. Since the typical power consumption in the grid is different on the weekend than it is on a working day, it is recommended to perform this measurement at least during one complete week.

Documentation:

To investigate the diurnal variations, the active power, voltage harmonics and current harmonics have to be plotted over the measurement time. If there is a correlation between the course of current harmonics and voltage harmonics over the time, this is an indication of background harmonics. This assumption would be assisted even more if at the same time the active power of the wind turbine shows no correlation with the current harmonics and voltage harmonics.

Probably, the most obvious results in terms of diurnal variations can be expected for the harmonics that are typically influenced by the grid characteristic, namely the 5th, 7th and 11th harmonics.

D.2.8 Shutting down neighbouring WT or loads

The harmonic distortion in the grid is influenced by neighbouring power generating units (PGU) and loads. To minimise the influence of background distortion on measurement results, it can be helpful to shut down the sources of interference during the measurement.

Note that shutting down PGUs or loads in the neighbourhood will change the grid impedance seen from the wind turbine under test, which will influence the harmonic emission.

Test procedure:

– Analyse the grid topology.
– Identify sources of interference.
– If possible, shut down the sources of interference for the harmonic measurement of the wind turbine under test.

Documentation:

– Analysis of the grid topology has to be documented.
– Documentation about which sources of interference were shut down during the harmonic measurement.

D.2.9 Harmonics of current and voltage over power

It appears practical to investigate the power dependency together with the diurnal pattern. If a strong power dependency of individual harmonic currents can be recognised it is often interpreted as an indication that the measured WT feeds in the harmonic current (assuming it is not a phenomenon as described in D.4.4).

Additional consideration of the associated harmonic voltage can be useful for interpretation. However, incorrect interpretations are still possible due to the complex interaction between the source of a harmonic interference and the grid distortion. For example, if both the harmonic current and the associated harmonic voltage increase with WT output, this may mean that the WT imposes a current and the voltage reacts accordingly.

However, the current may also be the result of a voltage imposed externally. There is an additional problem of possible superimposed dependence on output and time of day, which was addressed in D.4.1.

Test procedure:

Additional measurement data are not needed.

Documentation:

Generally the typical grid harmonics 3rd, 5th, 7th and 11th will be present in a scatter plot (harmonic value vs. the active power). If the measurements suppose that other harmonics are derived from the electrical grid, they should be plotted in the same place.

D.2.10 Filters switching

Filters shall be switched on and off on a WT at standstill to determine the grid harmonic distortion level. The filters on some WT types are cut-in depending on the power output. An indication of external network influence can be obtained by separate filter cut-in on a stopped WT if the neighbouring WT continues to provide power to the grid while measuring. The measured harmonics are employed as the basis for background distortions. Increased uncertainty shall be taken into consideration here if the measurement period is limited to a certain power range. In addition, the frequency response of the harmonics filter shall be taken into consideration and documented.

Test procedure:

Harmonic measurement in normal operation of the wind turbine.

A complete measurement campaign can be performed in accordance with 8.2.4. If the harmonic voltages and the harmonic phase angles were not recorded during this measurement campaign, then a further measurement campaign over a minimum of 2 hours can be performed, where also the harmonic voltages and the phase angles are recorded.

Harmonic measurements, where only the filter is switched on. The generator and the inverter are disconnected.

A measurement campaign of harmonic currents, harmonic voltages and harmonic phase angles for a time period of 2 hours can be performed. In the case of different background harmonic distortion, the measurement should be repeated.

Harmonic measurement of the own consumption of the wind turbine. The generator, the inverter and the filter are disconnected.

In general, the own consumption of the wind turbine cannot be switched off during the previous measurement campaign B. Thus, a separate measurement of harmonic currents, voltages and phase angles for a time period of 20 minutes should be taken at the own consumption of the wind turbine.

Each harmonic order shall be analyzed separately.

If the harmonic phase angles give no clear value, that means they are distributed from 0° to 360°, then the harmonic currents can only be reduced geometrically.

Otherwise the harmonic currents can be reduced with regard of the harmonic phase angle by a complex calculation:

Documentation:

The harmonic currents, voltages and phase angles of all harmonic orders can be shown in diagrams. The resulting harmonic currents can be given in a table.

D.2.11 Measuring at a standard source

The use of a standard source probably only makes economic sense for smaller WT.

Background distortion can be minimized by using an AC source. The AC source shall have enough capacity to feed the wind turbine and should fulfil the THD specifications as described in IEC 61000-3-2. In this case, it can be assumed that the background distortion has only low or no influence on the harmonic current emission of the wind turbine.

D.2.12 Harmonics power flow + voltage measurement, phase angle

The power flow indicates the direction of the harmonics and serves as a point of orientation. A change in the harmonic power flow direction indicates that grid bias may be present. In addition, vector resolution of the currents can provide an indication of the scatter and direction of the harmonics. Direction identification is hindered due to the low level and absent correlation between current and voltage in the high-frequency components.

In general, the phase angles between the harmonic currents and voltages are in the range of 90° inductive or 90° capacitive. This is owing to the impedances of the harmonic filter of the wind turbine or the impedance of the grid (e.g. wind turbine transformer). If the phase angles are in the range of 0° or 180°, then it can be assumed that there is a resonance at this frequency.

Test procedure:

Additionally, to the determination of the sub-grouped current harmonics and interharmonics, the following results can be determined and documented:

– ungrouped current harmonics, interharmonics and higher frequencies,
– ungrouped voltage harmonics, interharmonics and higher frequencies.

From these ungrouped current and voltage spectra, the magnitudes and phase angles can be determined for every bandwidth.

With the information of the current and voltage phase angles, additional identification of the power flow can be given by further calculations of the phase angle as described in D.2.2:

– Harmonic phase angle between the harmonic current component and the corresponding harmonic voltage component $\phi h = \alpha Uh - \alpha Ih$, calculated for each 10-/12-cycle window and aggregated applying prevailing angle calculation method,
– prevailing angle $\alpha_{h,ave}$,
– prevailing angle ratio PAR.

Documentation:

An overview of the harmonic currents and voltages as well as the different calculations of the phase angles lead to an interpretation of the power flow direction.

As the phase angle of the spectral components may vary largely between discrete Fourier transform (DFT) windows, aggregation is needed. Aggregation intervals for various applications are described in D.2.2.

The aggregation method and used intervals of the calculated parameters should be additionally described.

Table D.1 shows the results for one phase. If results may vary over all phases, possible documentation over all phases should be considered.

Table D.1 – Example of measurements results presentation

Frequency	**Current harmonic**			**Voltage harmonic**			**Harmonic phase angle**
[Hz]	Magnitude [A]	Prevailing angle [°]	PAR	Magnitude [V]	Prevailing angle [°]	PAR	ϕ_h [°]
....							

D.2.13 Voltage harmonics with and without operation of the tested wind turbine

The evaluation of the voltage harmonics gives a possibility to see the effect with and without operational turbine. This method is not possible in relation to measured current. Voltage harmonics with and without operation of the tested wind turbine indicate the influence of the tested turbine to distortion in the grid. If some of the measured voltage harmonics are higher when the turbine is disconnected, it can be concluded that the harmonic currents of the tested turbine at these harmonic frequencies are reducing the grid voltage distortion. In order to find out if the reduction of harmonic voltage is due to emission of harmonic currents with harmonic voltage reducing phase shift or by filtering effect (either by hardware filters or by control system), the measurement should be repeated different times of the day and turbine power in order to find out if the harmonic current depends on the harmonic voltage level when the turbine is shut down.

To show a reproducible effect, it is recommended to measure it at different test sites.

Test procedure:

a) Measure voltage and current harmonics and their phase shifts when the turbine is operating. The measurement is preferably done at the low-voltage side of the turbine transformer. If the turbine is such that there is no single low voltage winding the measurement has to be done in the medium voltage side. The voltage distortion levels may be artificially increased during the measurement by extra series inductance, for example, the series inductance of the UVRT tester. The thermal rating of such inductor, if used, has to be taken into account for defining the duration of the measurement where the turbine is operating.

b) Disconnect the turbine and measure the voltage harmonics immediately after that.

c) This measurement should be done for:

  – different times of the day,

  – different power bins (e.g. 10 %, 30 %, 70 % and 100 %),

  – different test sites.

Documentation:

d) Presentation of the voltage harmonics with and without operational test turbine.

e) Table of the maximum, minimum and average deviation of the voltage harmonics, at the different measurement situations, with and without operational test turbine.

D.2.14 Measurements at different sites

Harmonic measurements at different sites, but at the same type of wind turbine can lead to different results owing to varying background distortion level and resonance effects. They can help to identify the background distortion and can support the verification of harmonic models.

If harmonic measurements at one site are more influenced by background distortion than at another side, those measurement results can be used, where the influence from the background distortion is less.

D.2.15 Harmonic model

The wind turbine harmonic assessment can be also done based on wind turbine harmonic model evaluation. The model can be developed based on measurement data obtained and processed in accordance with that described above as well as sophisticated simulation tools. The model would describe the harmonic behaviour of a wind turbine in theory excluding influence of a distorted grid to which the wind turbine is connected.

Requirements for the wind turbine harmonic model:

– The wind turbine harmonic model describes the wind turbine's harmonic behaviour without influence of the external network.
– The wind turbine harmonic model correctly represents the wind turbine reaction to background harmonic voltages in the connection grid.
– The wind turbine harmonic model can be applied in conventional harmonic assessment studies.

It is up to the wind turbine manufacturer how the harmonic development is done and how the model validation process should be performed. The model can be used in order to evaluate the background distortion impact on the measurement process.

Further detailed information about harmonic model including, description, format and validation can be found in IEC TR 61400-21-3.

D.3 Determination of harmonic amplitude affected by space harmonics at DFAG systems

Space harmonics are frequency components that can be observed in measurements of DFAG systems. The source for space harmonics is the non-ideal magnetic flux density in the air gap of the generator. The frequency of these components changes according to the rotational speed of the generator. Therefore, space harmonics are interharmonics with changing frequencies. If the space harmonic frequency is close to a harmonic frequency, it affects the determination of the real harmonics. In this case, grouping in accordance with IEC 61400-4-7 increases the calculated amplitudes for harmonics out of the DFT.

An indication for the influence gives the analysis of the sidebands ±5 Hz beside the harmonic frequency. If the amplitude of one of the sidebands is higher than the amplitude of the harmonic itself, it is not justified by Parseval’s theorem. In this case, grouping should not be applied. In fact, this is a conservative approach because the calculated harmonic amplitude is still increased by the space harmonic.

Another possibility is the calculation of the critical working points out of the measurement of the rotational speed of the generator. It is useful to calculate the frequencies at which the space harmonics can be expected at a given speed. With the synchronous speed N_{sync} and the current speed of the generator N, the slip s can be determined by Equation (D.5).

$$s = \frac{N_{\mathrm{sync}} - N}{N_{\mathrm{sync}}} \tag{D.5}$$

The frequency of the space harmonic f_{SH} can be determined with the knowledge of the slip s and the fundamental power system frequency f_{o} according to Equation (D.6).

$$f_{\mathrm{SH}} = 6n \cdot (1 - s) \cdot f_{\mathrm{o}} \pm f_{\mathrm{o}} \qquad n \in \mathrm{N} \tag{D.6}$$

If the frequency of the space harmonic f_{SH} is in the range of f_{h} ± 7,5 Hz not grouping could give additional information to complement grouped harmonics that are calculated and reported in accordance with Annex A. The range of ± 7,5 Hz is carefully chosen with respect to the spectral leakage effect. As mentioned above, this is still a conservative approach for determination of the relative harmonic magnitude.

Annex E
(informative)

Assessment of power quality of wind turbines and wind power plants

E.1 General

This Annex gives methods for estimating the power quality expected from a wind turbine or a group of wind turbines when deployed at a specific site, and to allow the results to be compared to requirements in other IEC publications.

If electricity network operators and regulatory authorities apply their own requirements in place of or in addition to IEC standards, the principles of Annex E may still be used as guidance.

The methods for assessing compliance with power quality requirements are valid for wind turbines with PCC at LV, MV or HV in power systems with fixed frequency within ±1 Hz, and sufficient active and reactive power regulation capabilities. In other cases, the principles for assessing compliance with power quality requirements may still be used as guidance.

E.2 Voltage fluctuations

E.2.1 General

The flicker emissions from a wind turbine installation should be limited to comply with the flicker emission limits as specified in Equation (E.1) and Equation (E.2) below.

$$P_{\mathrm{st}} \leq E_{\mathrm{Psti}} \tag{E.1}$$

$$P_{\mathrm{lt}} \leq E_{\mathrm{Plti}} \tag{E.2}$$

where

P_{st} and P_{lt} are the short-term and long-term flicker severities from the wind turbine installation;

E_{Psti} and E_{Plti} are the short- and long-term flicker emission limits for the relevant PCC.

Furthermore, the relative voltage change due to a wind turbine installation should be limited in accordance with Equation (E.3) below.

$$d \leq \frac{\Delta U_{\mathrm{dyn}}}{U_{\mathrm{n}}} \tag{E.3}$$

where

d is the relative voltage change due to a switching operation of a wind turbine installation;

$\frac{\Delta U_{\mathrm{dyn}}}{U_{\mathrm{n}}}$ is the maximum permitted voltage change.

Recommended methods for assessing the flicker emission limits and the maximum permitted voltage change for installations at medium and high voltage levels are given in IEC TR 61000-3-7, and for installations at low voltage levels are given in IEC TR 61000-3-14.

The procedure given in the subsequent subclauses is recommended for assessing the flicker emission and the relative voltage change due to a wind turbine installation.

E.2.2 Continuous operation

The 95th percentile flicker emission from a single wind turbine during continuous operation should be estimated by applying Equation (E.4) below.

$$P_{st} = P_{lt} = c(\psi_k) \times \frac{S_n}{S_k} \tag{E.4}$$

where

$c(\psi_k)$ is the flicker coefficient of the wind turbine for the given network impedance phase angle, ψ_k, at the site (PCC);

S_n is the nominal apparent power of the wind turbine;

S_k is the short-circuit apparent power at the PCC.

The flicker coefficient of the wind turbine for the actual ψ_k at the site may be found from the worst case of the table of data produced as a result of the measurements described in 8.2.2, by applying linear interpolation.

If more wind turbines are connected to the PCC, the flicker emission from the sum of them can be estimated from Equation (E.5) below.

$$P_{st\Sigma} = P_{lt\Sigma} = \frac{1}{S_k} \times \sqrt{\sum_{i=1}^{N_{wt}} \left(c_i(\psi_k) \times S_{n,i}\right)^2} \tag{E.5}$$

where

$c_i(\psi_k)$ is the flicker coefficient of the individual wind turbine;

$S_{n,i}$ is the nominal apparent power of the individual wind turbine;

N_{wt} is the number of wind turbines connected to the PCC.

E.2.3 Switching operations

The flicker emission due to switching operations of a single wind turbine should be estimated by applying Equation (E.6) and Equation (E.7) below.

$$P_{st} = 18 \times N_{10m}^{0,31} \times k_f(\psi_k) \times \frac{S_n}{S_k} \tag{E.6}$$

$$P_{lt} = 8 \times N_{120m}^{0,31} \times k_f(\psi_k) \times \frac{S_n}{S_k} \tag{E.7}$$

where $k_f(\psi_k)$ is the flicker step factor of the wind turbine for the given ψ_k at the PCC.

The flicker step factor of the wind turbine for the actual ψ_k at the site may be found from the table of data produced as a result of the measurements described in 8.2.3 by applying linear interpolation.

If more wind turbines are connected to the PCC, the flicker emission from the sum of them can be estimated from Equation (E.8) and Equation (E.9) below.

$$P_{\mathrm{st}\Sigma} = \frac{18}{S_\mathrm{k}} \times \left(\sum_{i=1}^{N_\mathrm{wt}} N_{10\mathrm{m,i}} \times \left(k_{\mathrm{f,i}}(\psi_\mathrm{k}) \times S_{\mathrm{n,i}} \right)^{3,2} \right)^{0,31} \tag{E.8}$$

$$P_{\mathrm{lt}\Sigma} = \frac{8}{S_\mathrm{k}} \times \left(\sum_{i=1}^{N_\mathrm{wt}} N_{120\mathrm{m,i}} \times \left(k_{\mathrm{f,i}}(\psi_\mathrm{k}) \times S_{\mathrm{n,i}} \right)^{3,2} \right)^{0,31} \tag{E.9}$$

where

$N_{10\mathrm{m,i}}$ and $N_{120\mathrm{m,i}}$ are the number of switching operations of the individual wind turbine within a 10 min and 2 h period respectively;

$k_{\mathrm{f,i}}(\psi_\mathrm{k})$ is the flicker step factor of the individual wind turbine;

$S_{\mathrm{n,i}}$ is the nominal apparent power of the individual wind turbine.

If there is an overall control system associated with the wind turbine installation that limits the total number of switching operations, adequate measures should be taken to include the effect of this.

The relative voltage change due to a switching operation of a single wind turbine should be estimated by applying Equation (E.10) below:

$$d = 100 \times k_\mathrm{u}(\psi_\mathrm{k}) \times \frac{S_\mathrm{n}}{S_\mathrm{k}} \tag{E.10}$$

where

d is the relative voltage change in %;

$k_\mathrm{u}(\psi_\mathrm{k})$ is the voltage change factor of the wind turbine for the given ψ_k at the PCC.

The voltage change factor of the wind turbine for the actual ψ_k at the site may be found from the table of data produced as a result of the measurements described in 8.2 by applying linear interpolation.

If more wind turbines are connected to the PCC, it is still not likely that even two of them will perform a switching operation at the same time. Hence, no summation effects need to be taken into account to assess the relative voltage change of a wind turbine installation consisting of multiple wind turbines.

NOTE 1 Equation (E.6) and Equation (E.7) can be deduced from B.4.2 by applying an observation period of 600 s and 7 200 s respectively.

NOTE 2 Equation (E.8) and Equation (E.9) can be deduced from Equation (E.6) and Equation (E.7), though including in the summation the number of wind turbines connected to the PCC. The summation is justified because the transient part of a switching operation, i.e. the part that significantly contributes to the flicker emission, is normally of a short duration.

E.3 Current harmonics, interharmonics and higher frequency components

The harmonic currents should be limited to the degree needed to avoid unacceptable harmonic voltages at the PCC.

The applicable limits for emission of harmonics may be found by applying the guidance given in IEC TR 61000-3-6 and IEC TR 61000-3-14.

IEC TR 61000-3-6 gives guidance for summation of harmonic current distortion from loads. Applying this, the harmonic current at the PCC due to a wind turbine installation with a number of wind turbines may be estimated by applying Equation (E.11) below:

$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left(\frac{I_{h,i}}{n_i} \right)^{\beta}} \qquad \text{(E.11)}$$

where

N_{wt} is the number of wind turbines connected to the PCC;

$I_{h\Sigma}$ is the hth order harmonic current distortion at the PCC;

n_i is the ratio of the transformer at the ith wind turbine;

$I_{h,i}$ is the hth order harmonic current distortion of the ith wind turbine;

β is an exponent with a numerical value to be selected from Table E.1 and the points below.

Table E.1– Specification of exponents in accordance with IEC TR 61000-3-6

Harmonic order	β
$h < 5$	1,0
$5 \leq h \leq 10$	1,4
$h > 10$	2,0

If the wind turbines are equal and their converters' line commutated, the harmonics are likely to be in phase and $\beta = 1$ should be used for all harmonic orders.

Equation (E.11) does not take into account the use of transformers with different vector groups that may cancel out particular harmonics. If this is the case, adequate measures should be taken to include the effect of this.

Equation (E.11) can also be applied for current interharmonics and higher frequency components. As current interharmonics and higher-frequency components are assumed to be uncorrelated, it is recommended to use $\beta = 2$ in Equation (E.11) for summation of these.

NOTE It is also possible to use harmonic load flow calculations to consider the effects of wind park equipment such as cables, additional capacitor banks, additional filters. The summation law can be used similarly with taking the individual contributions of each wind turbine effective at the PCC as a result of a harmonic load flow calculation. A guidance to build these harmonic models is given in IEC TR 61400-21-3. These models can then be used to calculate the overall harmonic contribution from a wind power plant.

Annex F
(informative)

Guidelines for the transferability of test results to different turbine variants in the same product platform

This guideline is intended to enable the possibility to share applicable tests results across turbines from the same product platform and thereby allowing for a possible reduction of the total number of tests.

The overall structure of the major component block is shown in Figure F.1. If changes to a given block is not affecting a given test listed in Table F.1, a new test is not required for this item.

Example: a change to the aerodynamics, like a bigger rotor, does not affect the harmonics, so a new harmonic measurement is not needed, but it does influence the flicker, so this test has to be repeated.

Type testing of one turbine that is part of a product platform can be considered sufficient to cover the entire turbine product platform, provided that a documented risk assessment is carried out to determine which type tests are valid and which tests need to be repeated on the rest of the turbine product platform.

In this respect, turbines are considered to be part of a turbine product platform if the type, the main components and its control schemes are the same. Power rating inside a product platform may vary, but typically by not more than ±25 %.

The risk assessment should consist of a thorough review of the changes that have been made between the respective turbines under investigation to identify the validity and transferability of particular test results.

A product platform typically consists of turbines for different site conditions. Inside such a product platform, up-rating or upgrading of equipment or particular parts of the wind turbines within the product platform may have occurred. Such changes could include, for example, the introduction of a new gearbox, changing the blades (or their length), change in tower height. Such changes to the mechanical parts of the turbine will typically not have a significant impact on the electrical performance of the wind turbine generator.

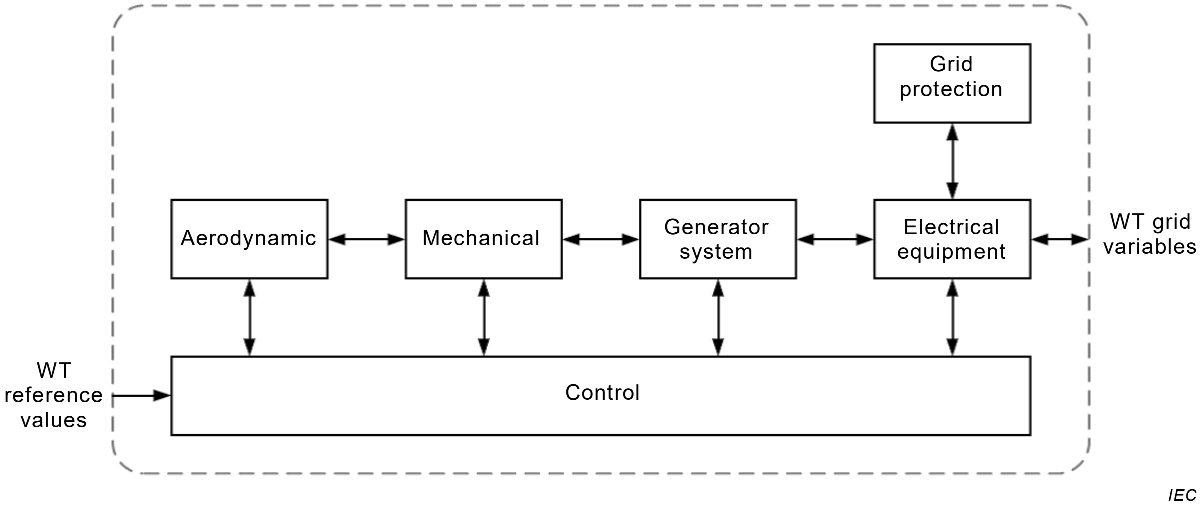
If it can be reasoned that the changes that have been implemented pose no significant risk of changing the electrical performance of the unit, then there is no need to perform new tests and measurements on the wind turbine with the changes. In these cases, the measurement and test results can be adapted to the other wind turbines within the product platform.

The following 4 major turbine types are considered:

- Type 1: Asynchronous generators directly connected to the grid,
- Type 2: Variable rotor resistance asynchronous generator,
- Type 3: Doubly fed asynchronous generator,
- Type 4: Connected to the grid through a full-scale power converter.

The risk assessment can be different depending on the type of turbine.

A generic turbine can be represented by a block diagram, as shown in Figure F.1.



Definition of blocks:

- Aerodynamic: blades, pitch system, rotor,
- Mechanical: gearbox, drivetrain,
- Generator system: generator, converter,
- Electrical equipment: transformer, cap. banks, filter, aux. supply, circuit breaker, cables,
- Grid protection: grid protection function,
- Control: control SW, converter SW, pitch control, controller HW type.

Figure F.1 – Block diagram for generic wind turbine (source IEC 61400-27-1)

Assuming the tested functions are within the capability of the turbine and no hardware limits are met, Table F.1 shows what blocks are influencing the performance measured and thereby giving the risk that a change will make a test invalid to transfer between turbines.

Table F.1– Main components influencing the electrical characteristics of the WT

Subclause	Test	Typical affected by:
8.2.2	Flicker	The following components affect flicker: Aerodynamic: both the rotor size and the rotation speed Control: software where the power controller is directly affecting the flicker. Electrical equipment: AUX supply can have an effect, if big loads are switched in and out.
8.2.3	Switching operations	The following components affect flicker under switching operations: Control: the ramp rate in the power controller is directly affecting the switching operations
8.2.4	Harmonics Interharmonics and higher frequency components	The following components affect harmonics: Electrical equipment: for Type 3 and 4: The converter is the source of harmonics and the filters, as they are designed to minimize harmonics. Control: for Type 3 and 4: where the line side converter may be damping harmonics.
8.4.2	Power control	The following components affect power control: Control: power-control software is directly controlling the power.
8.4.3	Ramp rate Limitation	The following components affect ramp rate: Control: the software controlling the ramp rate.
8.4.4	Frequency Control	The following components affect frequency control: Control: the frequency-control software.
8.4.5	Synthetic Inertia response	The following components affect inertia response: Aerodynamic: the rotor is where the energy is stored that is used for inertia Generator system, electrical equipment and control: Reaction depends primary on the control software, but also generator and converter have an influence on the performance.
8.4.6	Reactive power control	The following components affect reactive power control: Control: software controlling the converter and generator. Electrical equipment and generator system: this test is showing the limitations in the converter and generator. For wind turbines of type I and type II, the capacitor banks used for the reactive power compensation, can affect the reactive power control.
8.3.3	Maximum power	The following components affect maximum power: Control: for type 4: software where the power control. Aerodynamics, electrical equipment and generator system: for type 1 and 2 turbines, the fluctuations from the wind may give rise to power fluctuation and peaks.
8.3.5	Reactive power capability	The following components affect reactive power capability: Control: software where the power and reactive power control is controlled. Electrical equipment and generator system: the reactive power capability should show the capability of the hardware: generator, converter, filters, transformer, capacitor banks, etc.
8.5.2.3	Undervoltage events	The following components affect voltage dip: Control: the voltage dip shall be handled in the control software. Electrical equipment: the converter is the main responsible in performance of the turbine in a UVRT event. Depending on the type of turbine, the generator also has some influence on the UVRT performance.
8.5.2.4	Overvoltage events	The following components affect voltage swells: Same as for voltage dips
8.6.2	Grid protection	The following components affect grid protection: Grid protection: this is handled in this block, but also the electrical equipment is involved as the breakers are part of the chain.

Subclause	Test	Typical affected by:
8.6.4	Reconnection time	The following components affect reconnection time: Electrical equipment: as the UPS and AUX supply has start-up, but also the control as the re-start and boot-up of controller is important here.
8.6.3	RoCof	The following components affect RoCof: Same as the grid protection

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