BS EN IEC 61400-21-1:2019+A11:2020

BSI Standards Publication

Wind energy generation systems

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

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National foreword

This British Standard is the UK implementation of EN IEC 61400-21-1:2019+A11:2020. It is derived from IEC 61400-21-1:2019. It supersedes BS EN IEC 61400-21-1:2019, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/88, Wind turbines.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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Date	Text affected
31 December 2020	Implementation of CENELEC amendment A11:2020: addition of supersession information to European foreword

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

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(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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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- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2022-06-24

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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)

Foreword to amendment A11

This document (EN IEC 61400-21-1:2019/A11:2020) has been prepared by CLC/TC 88 "Wind turbines".

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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	-	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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WIND ENERGY GENERATION SYSTEMS –

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

FOREWORD

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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;

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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.

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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.

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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.

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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]

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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

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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

$$S_n = \sqrt{3} U_n I_n \text{ at } Q = 0$$

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 $I_n = \frac{P_n}{\sqrt{3} U_n}$

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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

$$SCR = \frac{S_k}{S_n}$$

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
$k_u(\psi_k)$
normalized measure of the voltage change due to a switching operation of the wind turbine:

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

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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.

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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 $A e^{j\theta_0}$ 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 $\underline{X}_{L1}$, $\underline{X}_{L2}$ and $\underline{X}_{L3}$ are the complex expressions of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

Note 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 $\underline{U}_{L1} = Ue^{j\theta}$, $\underline{U}_{L2} = Ue^{j(\theta+4\pi/3)}$ and $\underline{U}_{L3} = Ue^{j(\theta+2\pi/3)}$ then $\underline{U}_1 = (Ue^{j\theta} + e^{j2\pi/3}\,Ue^{j(\theta+4\pi/3)} + e^{j4\pi/3}\,Ue^{j(\theta+2\pi/3)})/3 = (Ue^{j\theta} + Ue^{j\theta} + Ue^{j\theta})/3 = Ue^{j\theta}$.

[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 $\underline{U}_{L1} = Ue^{j\theta}$, $\underline{U}_{L2} = Ue^{j(\theta+4\pi/3)}$ and $\underline{U}_{L3} = Ue^{j(\theta+2\pi/3)}$ then $\underline{U}_2 = (Ue^{j\theta} + e^{j4\pi/3}\,Ue^{j(\theta+4\pi/3)} + e^{j2\pi/3}\,Ue^{j(\theta+2\pi/3)})/3 = Ue^{j\theta}\,(1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

[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:

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

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

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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.

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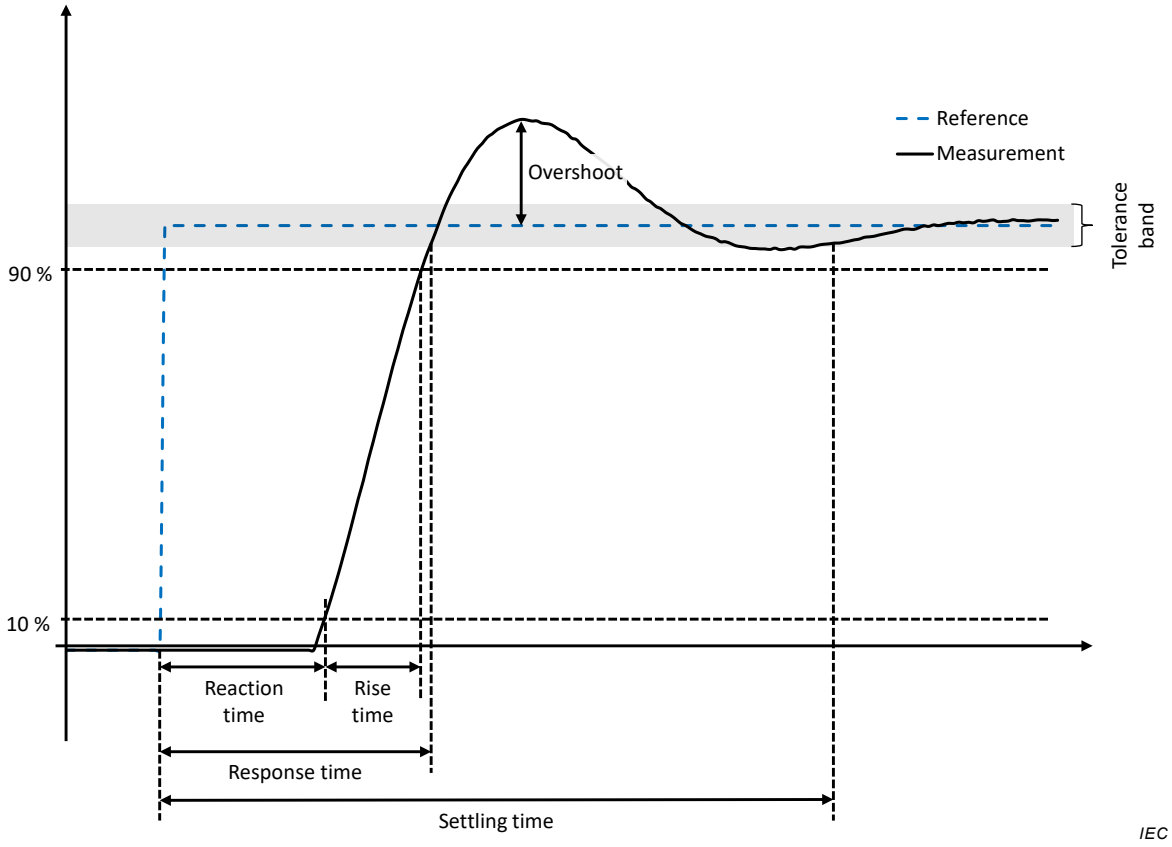

Figure 1 – Example of step response

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.

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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

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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

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4 Symbols and units

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

$\frac{\Delta U_{dyn}}{U_n}$	maximum permitted voltage change (%)
ψ_k	network impedance phase angle (°)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (°)
β	exponent associated with summation of harmonics
$c(\psi_k)$	flicker coefficient for continuous operation
d	relative voltage change (%)
E_{PIti}	long-term flicker emission limit
E_{Psti}	short-term flicker emission limit
f_g	nominal grid frequency (50 Hz or 60 Hz)
$f_{inertia,\ recovery}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{inertia,\ trigger}$	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
$I_{h,i}$	h'th order harmonic current distortion of i'th wind turbine (A)
$i_m(t)$	measured instantaneous current (A)
I_n	nominal current (A)
IUF	current unbalance factor
$k_f(\psi_k)$	flicker step factor
k_i	ratio of maximum inrush current and nominal current
$k_u(\psi_k)$	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)

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$Pr(c<x)$	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

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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.

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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

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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.

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- 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.

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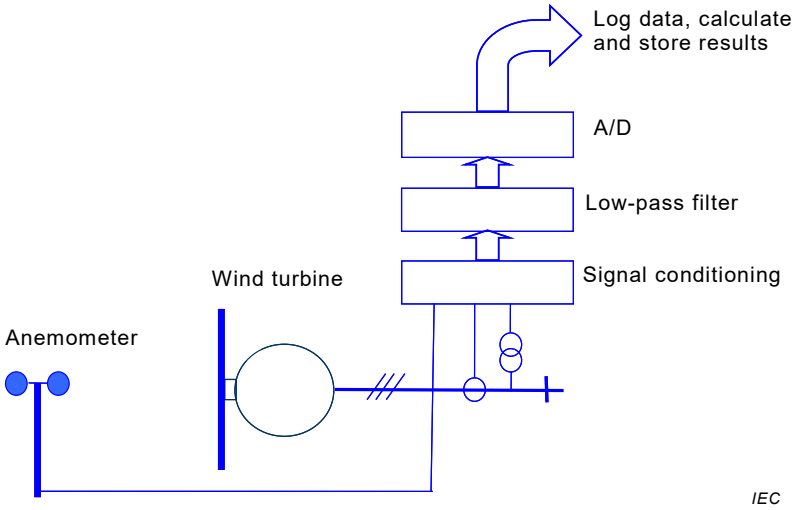

Figure 2 – Measurement system description including the most significant components

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

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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.

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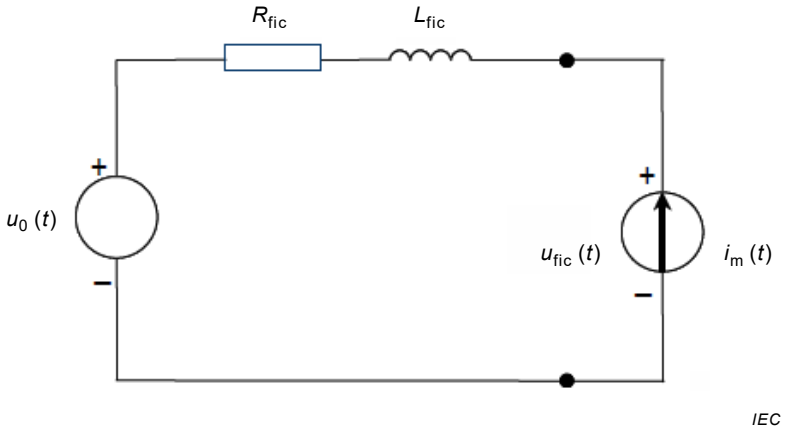

Figure 3 – Fictitious grid for simulation of fictitious voltage

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):

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

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:

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

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).

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

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:

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

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:

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

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 $0{,}05 \leq k \leq 5{,}0$, 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.

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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 $u_{\text{fic}}(t)$.
2) The voltage time-series of $u_{\text{fic}}(t)$ shall be input to the flicker algorithm in compliance with IEC 61000-4-15 to give one flicker emission value $P_{\text{st,fic}}$ 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):

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

where

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

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

Finally, the flicker coefficient $c(\psi_{\text{k}})$ shall be determined as the 95$^{\text{th}}$ 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$^{\text{th}}$ 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.

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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_{10m} of the switching operation within a 10-minute period.
- The maximum number N_{120m} of the switching operation within a 2-hour period.
- The flicker step factor $k_f(\psi_k)$ for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.
- The voltage change factor $k_u(\psi_k)$ 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_{10m} and N_{120m} 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_{10m} = 10 and N_{120m} = 120;
- wind turbine start-up at nominal active power: N_{10m} = 1 and N_{120m} = 12;
- the worst case of switching between generators: N_{10m} = 10 and N_{120m} = 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_{10m} and N_{120m} are typically provided by the manufacturer, whereas $k_f(\psi_k)$ and $k_u(\psi_k)$ 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 $k_u(\psi_k)$, and the flicker step factor $k_f(\psi_k)$ 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.

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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.

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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.

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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):

$$\mathrm{THC} = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_n} \times 100 \tag{9}$$

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.

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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.

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