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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINES –

Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines

FOREWORD

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International Standard IEC 61400-21 has been prepared by IEC technical committee 88: Wind turbines.

This second edition cancels and replaces the first edition published in 2001. It constitutes a technical revision.

The main changes with respect to the previous edition are additions of the topics listed below:

- Current interharmonics and higher frequency components (<9 kHz)
- Response to voltage dip
- Active power control
- Reactive power control
- Protection and reconnection time

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

FDIS	Report on voting

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

Annexes A, B and C are for information only.

The committee has decided that the contents of this publication will remain unchanged until xxxx. At this date, the publication will be

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- withdrawn;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

INTRODUCTION

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency and accuracy in the presentation, testing and assessment of power quality characteristics of grid connected wind turbines (WTs). The standard has been prepared with the anticipation that it would be applied by:

- the WT manufacturer striving to meet well-defined power quality characteristics;
- the WT purchaser in specifying such power quality characteristics;
- the WT operator who may be required to verify that stated, or required power quality characteristics are met;
- the WT planner or regulator who must 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 component testing organization in evaluating the power quality characteristics of the wind turbine type;
- the planner or regulator of the electric network who must be able to determine the grid connection required for a WT.

This standard provides recommendations for preparing the measurements and assessment of power quality characteristics of grid connected WTs. The standard will benefit those parties involved in the manufacture, installation planning, obtaining of permission, operation, utilization, testing and regulation of WTs. The measurement and analysis techniques recommended in this standard 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 standard presents measurement and analysis procedures expected to provide consistent results that can be replicated by others.

WIND TURBINES –

Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines

1 Scope

This part of IEC 61400 includes:

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

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 standard only requires wind turbine types intended for PCC at MV or HV to be tested and characterized as specified in this standard.

The measured characteristics are valid for the specific configuration and operational mode of the assessed wind turbine only. Other configurations, including altered control parameters that cause the wind turbine to behave differently with respect to power quality, require separate assessment.

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

The procedures for assessing compliance with power quality requirements are valid for wind turbines with PCC at MV or HV in power systems with fixed frequency within ±1 Hz, and sufficient active and reactive power regulation capabilities and sufficient load to absorb the wind power production. In other cases, the principles for assessing compliance with power quality requirements may still be used as a guide.

This standard is for testing of wind turbines, though it contains information that may also be useful for testing of wind farms.

NOTE 1 This standard uses the following terms for system voltage:

– 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 $U_n > 35$ kV.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 61400. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 61400 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60034-1, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60044-1, *Instrument transformers – Part 1: Current transformers*

IEC 60050(161), *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

IEC 60050(393), *International Electrotechnical Vocabulary (IEV) – Chapter 393: Nuclear instrumentation: Physical phenomena and basic concepts*

IEC 60050(415), *International Electrotechnical Vocabulary* (*IEV*) *– Chapter 415: Wind turbine generator systems*

IEC 60186, *Voltage transformers*
Amendment 1 (1988)
Amendment 2 (1995)

IEC 60688, *Electrical measuring transducers for converting a.c. electrical quantities to analogue or digital signals*

IEC 61000-4-7, *Electromagnetic compatibility* (*EMC*) *– Part 4: Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

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

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC product standard including specific test methods*

3 Definitions

For the purpose of this part of IEC 61400, the following definitions apply.

3.1
continuous operation (for wind turbines)
normal operation of the wind turbine excluding start-up and shutdown operations

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

[IEV 415-03-05]

3.3
flicker coefficient for continuous operation (for wind turbines)
a normalized measure of the flicker emission during continuous operation of the wind turbine:

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

where

$P_{st,fic}$ is the flicker emission from the wind turbine on the fictitious grid;

S_n is the rated apparent power of the wind turbine;

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

NOTE The flicker coefficient for continuous operation is the same for a short-term (10 min) and long-term period (2 h).

3.4
flicker step factor (for wind turbines)
a normalized measure of the flicker emission due to a single switching operation of the wind turbine:

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

where

T_p is the measurement period, 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 flicker emission from the wind turbine on the fictitious grid;

S_n is the rated apparent power of the wind turbine;

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

3.5
maximum measured power (for wind turbines)
that power (with a specified averaging time) which is observed during continuous operation of the wind turbine

3.6
network impedance phase angle
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.

3.7
normal operation (for wind turbines)
fault free operation complying with the description in the wind turbine manual

[IEV 393-08-12, modified]

3.8
operational mode (for wind turbines)
operation according to control setting, e.g. voltage control mode, frequency control mode, reactive power control mode, active power control mode, etc.

3.9
output power (for wind turbines)
electric active power delivered by the wind turbine at its terminals

[IEV 415-04-02, modified]

3.10
point of common coupling (PCC)
point of a power supply network, electrically nearest to a particular load, at which other loads are, or may be, connected

NOTE 1 These loads can be either devices, equipment or systems, or distinct customer's installations.

NOTE 2 In some applications, the term “point of common coupling” is restricted to public networks.

[IEV 161-07-15, modified]

3.11
power collection system (for wind turbines)
electrical system that collects the power from a wind turbine and feeds it into an electrical supply network

[IEV 415-04-06, modified]

3.12
rated apparent power (for wind turbines)
the apparent power from the wind turbine while operating at rated current and nominal voltage and frequency:

$$S_n = \sqrt{3} U_n I_n$$

where

U_n is the nominal voltage;

I_n is the rated current.

3.13
rated current (for wind turbines)
maximum continuous electric output current which a wind turbine is designed to achieve under normal operating conditions

3.14
rated power (for wind turbines)
maximum continuous electric output power which a wind turbine is designed to achieve under normal operating conditions

[IEV 415-04-03, modified]

3.15
rated wind speed (for wind turbines)
wind speed at which a wind turbine's rated power is achieved

[IEV 415-03-04, modified]

3.16
standstill (for wind turbines)
condition of a wind turbine that is stopped

[IEV 415-01-15, modified]

3.17
start-up (for wind turbines)
transitional state of a wind turbine between standstill and power production

3.18
switching operation (for wind turbines)
start-up or switching between generators

3.19
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

[IEV 415-03-25]

3.20
voltage change factor (for wind turbines)
a normalized measure of the voltage change due to a switching operation of the wind turbine:

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

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 rated apparent power of the wind turbine;

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

NOTE The voltage change factor k_u is similar to k_i being the ratio between the maximum inrush current and the rated 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.

3.21
wind turbine (WT)
system which converts kinetic wind energy into electric energy

3.22
wind turbine terminals
a point being a part of the WT and identified by the WT supplier at which the WT may be connected to the power collection system

4 Symbols and units

In this standard, the following symbols and units are used.

$\frac{\Delta U_{dyn}}{U_n}$	maximum permitted voltage change (%)
ψ_k	network impedance phase angle (degrees)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (degrees)
β	exponent associated with summation of harmonics
$c(\psi_k)$	flicker coefficient for continuous operation
d	relative voltage change (%)
E_{Plti}	long-term flicker emission limit
E_{Psti}	short-term flicker emission limit
$f_{m,i}$	frequency of occurrence of flicker coefficient values within the i'th wind speed bin
f_{over}	over-frequency protection level
f_{under}	under-frequency protection level
$f_{y,i}$	frequency of occurrence of wind speeds within the i'th wind speed bin
h	harmonic order
$I_{h,i}$	h'th order harmonic current distortion of i'th wind turbine (A)
$i_m(t)$	measured instantaneous current (A)
I_n	rated current (A)
$k_f(\psi_k)$	flicker step factor
k_i	ratio of maximum inrush current and rated current
$k_u(\psi_k)$	voltage change factor
L_{fic}	inductance of fictitious grid (H)
N_{10}	maximum number of one type of switching operations within a 10 min period
N_{120}	maximum number of one type of switching operations within a 120 min period
N_{bin}	total number of wind speed bins between v_{cut-in} and 15 m/s
n_i	ratio of the transformer at the i'th wind turbine
N_m	total number of measured flicker coefficient values
$N_{m,i}$	number of measured flicker coefficient values within the i'th wind speed bin
$N_{m,i,c<x}$	number of flicker coefficient values less than x within the i'th wind speed bin
N_{wt}	number of wind turbines
$P_{0,2}$	maximum measured power (0,2-second-average value) (W)
P_{60}	maximum measured power (60-second-average value) (W)
P_{600}	maximum measured power (600-second-average value) (W)
P_{lt}	long-term flicker disturbance factor
P_n	rated power of wind turbine (W)
$Pr(c<x)$	accumulated distribution of c
P_{st}	short-term flicker disturbance factor
$P_{st,fic}$	short-term flicker disturbance factor at fictitious grid
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	rated apparent power of wind turbine (VA)
THC	Total harmonic current distortion (% of I_n)
T_p	transient time period of a switching operation (s)
$u_0(t)$	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_n	nominal phase-to-phase voltage (V)
U_{under}	under-voltage protection level
U_{over}	over-voltage protection level
v_a	annual average wind speed (m/s)
v_{cut-in}	cut-in wind speed (m/s)
v_i	mid-point of the i'th wind speed bin
w_i	weighting factor for the i'th wind speed bin
X_{fic}	reactance of fictitious grid (Ω)

5 Abbreviations

The following abbreviations are used in this standard.

A/D converter	analogue to digital converter
HV	high voltage
LV	low voltage
MV	medium voltage
PCC	point of common coupling
RMS	root mean square
SCADA	supervisory control and data acquisition
THC	total harmonic current distortion
WT	wind turbine

6 Wind turbine power quality characteristic parameters

6.1 General

This clause gives the quantities that shall be stated for characterizing the power quality of a wind turbine. 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 assumed to be from the wind turbine and to the grid.

6.2 Wind turbine specification

1 6.2.1 Rated data

The rated data of the wind turbine shall be specified, including P_n, S_n, U_n and I_n.

NOTE The rated data are used only for normalizing purposes in this standard.

2 6.2.2 Electrical drive-train data

3 The generator main data shall be specified, including number of pole pairs, stator, rotor and
4 magnetizing impedances.

5 For wind turbines equipped with power electronic converters, the converter data shall be
6 specified, including applicable current limits, time constants and protective function set
7 points.

8 6.2.3 Mechanical drive-train data

The mechanical drive train main data shall be specified, including turbine and generator inertia, effective shaft stiffness (or eigenfrequency of mechanical drive train with locked generator shaft) and gearbox ratio.

6.3 Voltage fluctuations

The voltage fluctuations (flicker and voltage changes) imposed by the wind turbine shall be characterized as described in 6.3.1 and 6.3.2.

6.3.1 Continuous operation

The wind turbine flicker coefficient for continuous operation, $c(\psi_k, v_a)$ shall be stated as the 99th percentile for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85° in a table for four different wind speed distributions with annual average wind speed v_a = 6 m/s, 7,5 m/s, 8,5 m/s and 10 m/s respectively. The 10 min average values of the wind speed shall be assumed to be Rayleigh distributed (see note). The annual average wind speed refers to the hub height of the wind turbine.

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 set-point control shall be set to Q=0. If other operational mode is used, this shall be clearly stated.

NOTE The Rayleigh distribution is a probability distribution that commonly fits the annual wind speed distribution. The Rayleigh distribution may be described by:

$$F(v) = 1 - \exp\left(-\frac{\pi}{4} \left(\frac{v}{v_a} \right)^2 \right)$$

where

$F(v)$ is the Rayleigh cumulative probability distribution function for the wind speed;

v_a is the annual average wind speed at hub height;

v is the wind speed.

6.3.2 Switching operations

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 rated wind speed.

c) The worst case of switching between generators (applicable only to wind turbines with more than one generator or a generator with multiple windings). See also note 1.

For each of the above types of switching operations, the values of the parameters below shall be stated (see also notes 2 and 3):

1) The maximum number N_{10} of the switching operation within a 10 min period.

2) The maximum number N_{120} of the switching operation within a 2 h period.

3) The flicker step factor $k_f(\psi_k)$ for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.

4) The voltage change factor $k_u(\psi_k)$ for the network impedance phase angles ψ_k = 30°, 50°, 70° and 85°.

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 set-point control shall be set to Q=0. If other operational mode is used, this shall be clearly stated.

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} and N_{120} may be based on manufacturers information, whereas $k_f(\psi_k)$ *and* $k_u(\psi_k)$ should be measured and computed.

NOTE 3 Depending on the control system of the wind turbine, the maximum number of the switching operation within a 2 h period may be less than twelve times the maximum number of the switching operation within a 10 min period.

6.4 Current harmonics, interharmonics and higher frequency components

For a wind turbine with a power electronic converter (see notes 1, 2 and 3), the wind turbine's emission of current harmonics, interharmonics and higher frequency components during continuous operation shall be stated (see note 4).

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 power bins 10, 20, … , 100 % of P_n.

The individual harmonic current components shall be specified as subgrouped values for frequencies up to 50 times the fundamental grid frequency, and the total harmonic current distortion shall be stated as derived from these.

The interharmonic current components shall be specified as subgrouped values for frequencies up to 2 kHz in accordance to IEC 61000-4-7 (Annex A).

The higher frequency current components shall be specified as subgrouped values for frequencies between 2 and 9 kHz in accordance to IEC 61000-4-7 (Annex B).

The current harmonics, interharmonics and higher frequency components shall be stated for the wind turbine operating with reactive power as close as possible to zero, i.e. if applicable the reactive set-point control shall be set to Q=0. If other operational mode is used, this shall be clearly stated.

NOTE 1 Harmonic emissions have been reported from a few installations of wind turbines with induction generators but without power electronic converters. There is however no agreed procedure for measurement of harmonic emissions from induction machines. Further, there is no known instance of customer annoyance or damage to equipment due to harmonic emissions from such wind turbines. This standard therefore does not require measurement of harmonic emissions from such wind turbines.

NOTE 2 The synchronous generator generates a voltage with a waveform depending on the shape of the magnetic field in the air-gap and the regularity of its stator winding. For a wind turbine with a synchronous generator directly connected to the grid, the waveform should according to 8.3 comply with the requirements in 8.9 of IEC 60034-1. Then the wind turbine will only emit very limited harmonic and interharmonic currents, and hence this standard therefore does not require specification of these.

NOTE 3 Harmonics are considered harmless as long as the duration is limited to a short period of time. Experience with “soft-start” power electronic units in wind turbines has not generally shown that the short-duration harmonic emissions cause problems. Hence, this standard does not require specification of short-duration harmonics caused by wind turbine start-up or other switching operations.

NOTE 4 The latest version IEC 61000-4-7 describes measurement and grouping methods for harmonic, interharmonic (up to 2 kHz) and higher frequency components (2-9 kHz).

6.5 Response to voltage dips

The response of the wind turbine to the voltage dips specified in Table 1 shall be stated for the wind turbine operating at 20 and 100 % of P_n. The stated response shall include time-series of active power, reactive power and voltage at wind turbine terminals for the time shortly prior to the voltage dip and until the effect of the voltage dip has abated, but also the wind turbine operational mode shall be specified.

Table 1 – Specification of voltage dips. The specified magnitudes, duration and shape are for the voltage dip occurring when the wind turbine under test is not connected.

<table>
<tr><th>Case</th><th>Magnitude of voltage phase to ground (pu)</th><th>Duration (s)</th><th>Shape</th></tr>
<tr><td>VD1 – symmetrical three phase voltage dip</td><td>0,90</td><td>0,4</td><td>‾‾‾|__|‾‾‾</td></tr>
<tr><td>VD2 – symmetrical three phase voltage dip</td><td>0,50</td><td>0,4</td><td>‾‾‾|__|‾‾‾</td></tr>
<tr><td>VD3 – two phase voltage dip</td><td>0,90</td><td>0,4</td><td>‾‾‾|__|‾‾‾</td></tr>
<tr><td>VD4 – two phase voltage dip</td><td>0,50</td><td>0,4</td><td>‾‾‾|__|‾‾‾</td></tr>
</table>

NOTE 1 The test is basically for providing a basis for wind turbine numerical simulation model validation. Optional tests may however be carried out and reported for assessing compliance with specific grid code requirements to wind turbine fault ride through capabilities.

NOTE 2 A voltage dip may cause a wind turbine to cut-out for many reasons, not only related to the electrical drive train but also due to mechanical vibrations or ancillary system low voltage capabilities. It is therefore a point of doing the test on the complete wind turbine rather than relaying on drive train testing only.

NOTE 3 A voltage dip is strictly a drop in voltage below 0,9 pu of nominal voltage

6.6 Active Power

6.6.1 Maximum measured power

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, $P_{0,2}$.

6.6.2 Ramp rate limitation

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 available and measured active power output during operation at a ramp rate value of 10 % of rated power per minute for a test period of 10 minutes.

The test results shall be reported as 0,2 sec average data.

6.6.3 Set-point control

The ability of the wind turbine to operate in active power set-point control mode shall be characterized by test results presented in a graph. The graph shall show available and measured active power output during operation at set point values being adjusted from 100 % down to 20 % of rated power in steps of 20 % with 2 min operation at each set-point value, i.e. according to Figure 1.

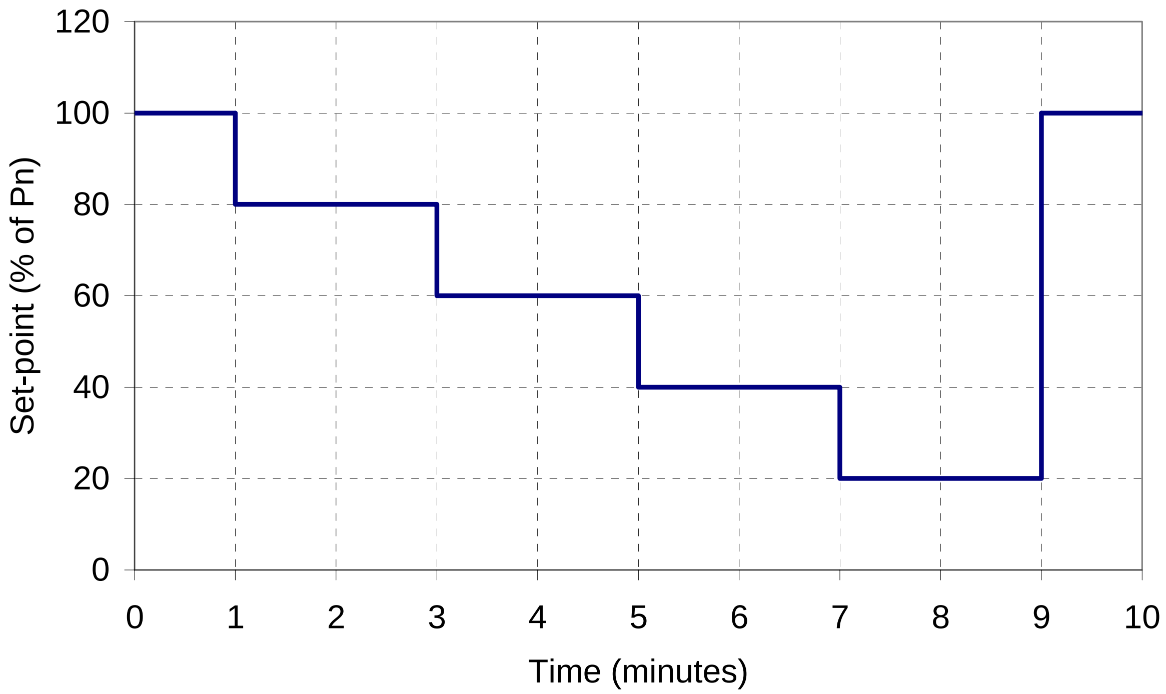

Figure 1 – Adjustment of active power set-point

The test results shall be reported as 0,2 sec average data.

NOTE The ability of a wind turbine to participate in an automatic frequency control scheme is closely linked to its ability to operate in active power set-point control mode. Participation in automatic frequency control can for instance be achieved through the SCADA system of a modern wind farm that may continuously update the active power set-point of the individual wind turbines to achieve a requested frequency response.

6.7 Reactive Power

6.7.1 Reactive power capability

The capability of the WT concerning the maximum inductive reactive power and the maximum capacitive reactive power of the WT shall be specified in a table as 10 min average values as a function of the 10 min average output power for 0, 10, ... 90, 100 % of the rated power.

6.7.2 Set-point control

The reactive power set-point control shall be described by a table and a graph as follows:

The table shall show measured reactive power at reactive set point value = 0 for operation at 0, 10, 20, ... 100 % active power output. The active and reactive power shall be 1 min average values.

The graph shall show measured reactive power during step change of reactive power set-point from 0 to maximum inductive value (according to 6.7.1) and back to 0 again at approximately 50 % active power output, i.e. the set-point is adjusted as illustrated in Figure 2. The active power output shall be 1 min average values, and reactive power shall be 0,2 sec average data.

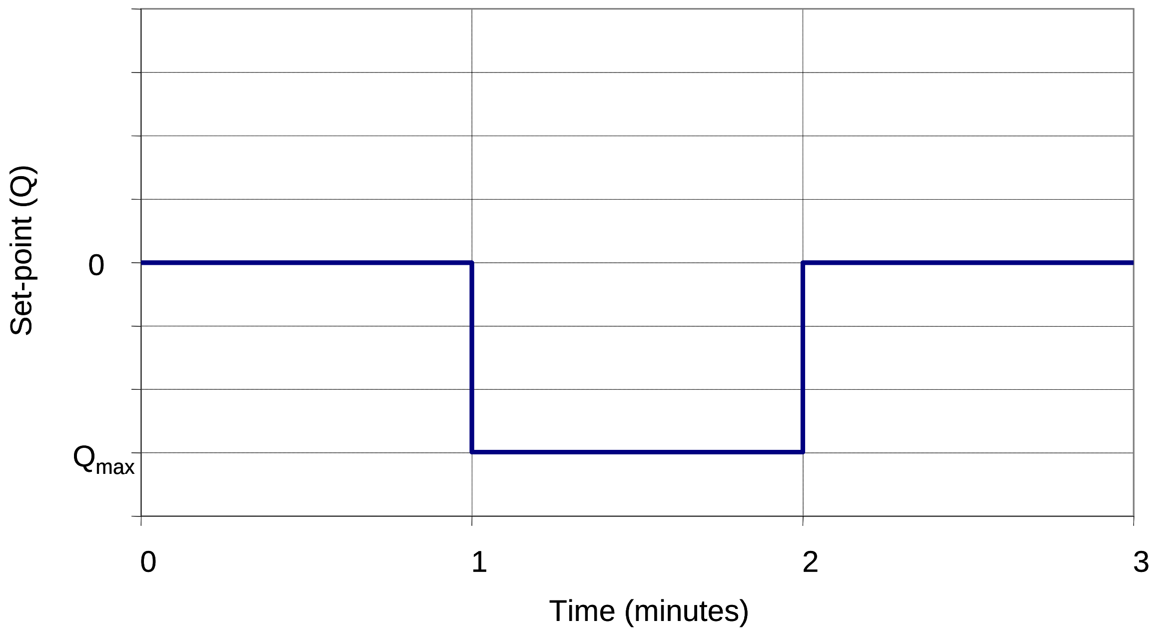

Figure 2 – Adjustment of reactive power set-point

NOTE The ability of a wind turbine to participate in an automatic voltage control scheme is closely linked to its ability to operate in reactive power set-point control mode. Participation in automatic voltage control can for instance be achieved through the SCADA system of a modern wind farm that may continuously update the reactive power set-point of the individual wind turbines to achieve a requested voltage response.

6.8 Grid Protection

The disconnection levels and disconnection times of the WT shall be determined for over- and under-voltage and over- and under-frequency.

The disconnection level is the voltage or frequency that causes the wind turbine to disconnect.

The disconnection time is the time duration from start of the under-/over- voltage or frequency and until the wind turbine has disconnected.

6.9 Reconnection time

The reconnection time after the wind turbine has been disconnected due 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 in 10 seconds, 1 minute and 10 minutes respectively. 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.

7 Test procedures

Subclause 7.1 gives general information about the validity of the measurements, required test conditions and equipment. Subclauses 7.2 – 7.9 state the required measurements to be taken to determine the power quality characteristic parameters of the assessed wind turbine.

7.1 General

The measurement procedures are valid for single wind turbines with a three-phase grid connection.

The measurements aim in general to verify the characteristic power quality parameters for the full operational range of the assessed wind turbine. Measurements are however not required for wind speeds above 15 m/s (see note 1). This is because requiring measurements at higher wind speeds would normally give a significant longer measurement period due to the rare appearance of higher wind speeds, and are not expected to give significantly better verification of the characteristic power quality parameters of the assessed wind turbine. See also note 2.

The measured characteristics are valid for the specific configuration of the assessed wind turbine only. Other configurations, including altered control parameters, that cause the wind turbine to behave differently with respect to power quality, require separate assessment. See also note 3.

NOTE 1 If measurements are taken above 15 m/s, they can be omitted. If they are included however, the applied wind speed range should be stated in the test report.

NOTE 2 Inclusion of measurements above 15 m/s may improve the accuracy of the determined flicker coefficient, and for some wind turbine design give greater maximum measured power (0,2 s average). Aiming for a balance between cost and accuracy however, inclusion of measurements above 15 m/s is not required. If measurements above 15 m/s are included, this will improve confidence in the results of the procedures of 8.3 for high-wind speed sites.

NOTE 3 Some wind turbine designs include a built-in transformer. The measurements of the electrical characteristics should be made at the wind turbine terminals. It is up to the WT supplier to define the wind turbine terminals to be at the lower-voltage or higher-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. Thus, separate assessment is not required if the transformer output voltage is changed, except that rated voltage and current must be updated.

7.1.1 Test conditions

The following test conditions are required (see note 1).

- The wind turbine shall be connected directly to the MV-network through a standard transformer with rated power at least corresponding to the apparent power at P_{mc} 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 must be measured during the test, and test data possibly sampled during periods with inappropriate grid frequency must be excluded.
- The voltage shall be within ±5 % of its nominal value measured as 10 min average data at the wind turbine terminals. If the voltage is known to be very stable and well within the above requirement, which would commonly be the case if the wind turbine is connected to a very strong grid, this need not be assessed any further. Otherwise, the voltage must be

measured during the test, and test data possibly sampled during periods with inappropriate voltage must be excluded.

- The voltage unbalance factor shall be less than 2 % measured as 10 min data at the wind turbine terminals. The voltage unbalance factor may be determined as described in IEC 61800-3, clause B.3. 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 must be measured during the test, and test data possibly sampled during periods with inappropriate voltage unbalance factor must be excluded.
- During the measurement for the determination of the flicker coefficient in normal operation, see chapter 7.8.2, the voltage flicker according to IEC 61000-4-15 at the terminal of the wind turbine shall be reported. (see also note in section 7.3)
- 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. See also note 2.

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 turbulence intensity shall be stated based on sector-wise identification of obstacles and terrain variations or based on wind speed measurements.

NOTE 1 The specified conditions are required to achieve reliable test results, and should not be confused with conditions for reliable grid connection and operation of wind turbines.

NOTE 2 The maximum measured power may for some wind turbine designs to some degree depend on the air density. Hence, the maximum measured power determined following the procedure in 7.4 and measured at a site with low air density may 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.

7.1.2 Test equipment

The description of the measurements assumes application of a digital data acquisition system with elements as illustrated in Figure 3.

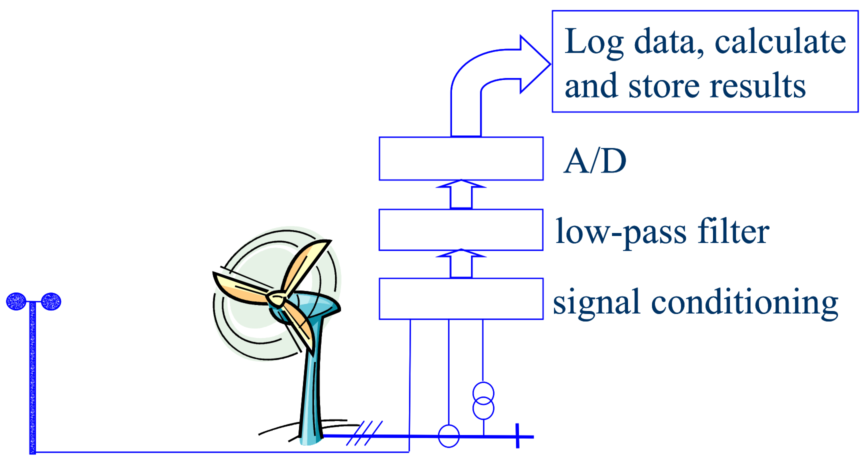

Figure 3 – Assumed elements of measurement system

The anemometer, voltage transducers (transformers) and current transducers (transformers) are the required sensors of the measurement system. The signal conditioning is for connecting these to the low-pass filter that are required for anti-aliasing. The analogue to digital conversion (A/D) shall be of at least 12 bit resolution, i.e. to maintain the required measurement accuracy. See Table 2 for specification of equipment accuracy.

Table 2 – Specification of requirements for measurement equipment

Equipment	Required accuracy	Compliance with standard
Voltage transformers	class 1,0	IEC 60186
Current transformers	class 1,0	IEC 60044-1
Anemometer	±0,5 m/s	–
Filter + A/D converter + data acquisition system	1 % of full scale	–

The digital data acquisition system is assumed to log, calculate and store results as specified in the subsequent clauses. General guidance for calculation of RMS voltage, active and reactive power in a system as outlined in Figure 3 is given in Appendix C. This requires a sample rate of at least 5 kHz per channel of the voltage and current signals. For measurement of harmonics (higher frequency components) the minimum sample rate must be at least 20 kHz per channel.

The wind speed signal shall be sampled with at least 1 Hz (according to IEC 61400-12-1).

Ideally, a hub-height anemometer located at a position unaffected by wind turbine blockage or wind turbine wakes should be applied for measuring the wind speed. A position 2,5 rotor diameters upstream will generally give good definition. Alternatively, hub-height wind speed can be estimated from lower level measurement or from corrected nacelle wind speed measurement possibly in conjunction with power measurements and knowledge of the power curve. Either way, uncertainties due to anemometer location should not exceed ± 1 m/s.

7.2 Wind turbine specification

Based on manufacturer's information, the wind turbine specifications as outlined in section 6.2 shall be stated.

7.3 Voltage fluctuations

As stated in 7.1.1, the wind turbine under test shall be connected to an MV-network. The MV-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. The aim is however to achieve test results which are independent of the grid conditions at the test site. To accomplish this, this standard 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 7.3.1. The additional measurement procedures for voltage fluctuations are separated into procedures for continuous operation (see 7.3.2) and switching operations (see 7.3.3). 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 may be an influence of the measured current of the wind turbine on these voltage fluctuations, imposed by other sources, which may also have influence on the simulated voltage fluctuations on the fictitious grid. But this effect is relatively small and does not justify changing the procedure for determining the voltage fluctuations and flicker.

7.3.1 Fictitious grid

The phase diagram of the fictitious grid is shown in figure 2.

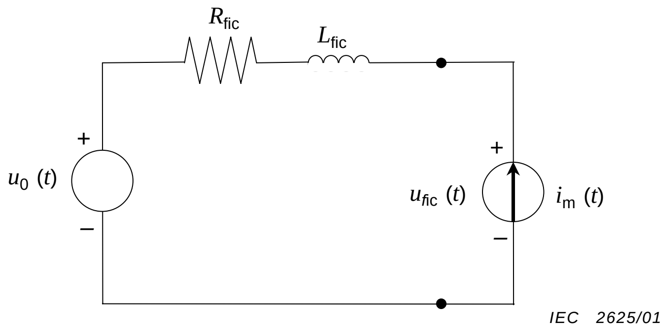

Figure 4 – Fictitious grid for simulation of fictitious voltage

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 $u_{fic}(t)$ according to:

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

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) $u_0(t)$ must 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:

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

where U_n is the r.m.s. value of the nominal voltage of the grid.

The electrical angle of the fundamental of the measured voltage may be described by equation 3.

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

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:

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

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

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

A proper ratio between $S_{k,fic}$ and S_n must be used to assure that the applied flickermeter algorithm or instrument gives P_{st} values that are well within the measurement range required in IEC 61000-4-15. Because the intention of the procedure described in IEC 61000-4-15 is to determine if a specific fluctuating voltage causes flicker, the procedure in IEC 61000-4-15 does not treat small voltage fluctuations very accurately. To obtain simulated voltage fluctuations within the flickermeter range, this standard suggests as a guide to use a ratio of 50 between $S_{k,fic}$ and S_n, though it is the responsibility of the assessor to select the appropriate ratio. The actual ratio selected will not affect the resulting coefficients as long as the selected ratio does not bring the instrument outside its valid range.

7.3.2 Continuous operation

The flicker coefficient $c(\psi_k, v_a)$ shall be determined so it can be stated according to 6.3.1. This shall be done by measurement and simulation.

This subclause gives the detailed procedure, whereas an informative outline is provided in clause B.1.

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. See also note 1.
b) Measurements shall be taken so that at least fifteen 10 min time-series of instantaneous voltage and current measurements (five tests and three phases) are collected for each 1 m/s wind speed bin between cut-in wind speed and 15 m/s. Here, the wind speed is measured as 10 min-average values.
c) The wind speed shall be measured according to 7.1.2.
d) Switching operations are excluded except such as switching of capacitors that occur during continuous operation of the wind turbine.

The measurements shall be taken with a measurement set-up as specified in Figure 3, and by applying voltage and current transformers and an anemometer with specifications according to Table 2. The cut-off frequency of the voltage and current measurements shall be at least 400 Hz. See note 2.

The measurements must be treated to determine the flicker coefficient of the wind turbine as a function of the network impedance phase angle and wind speed distribution. This shall be done repeating the following procedure for each of the network impedance phase angles and wind speed distributions specified in 6.3.1.

First, the flicker coefficient for each set of 10 min 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 $u_{fic}(t)$.

2) The 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 10 min time-series.

3) The flicker coefficient shall be determined for each of the calculated flicker emission values by applying:

$$c(\psi_k) = P_{st,fic} \cdot \frac{S_{k,fic}}{S_n} \tag{6}$$

where

S_n is the rated apparent power of the wind turbine;

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

See also note 3.

Secondly, a weighting factor shall be determined for each wind speed bin to scale the measured frequency of occurrence of the flicker coefficients to correspond with the assumed wind speed distribution. The procedure for finding the weighting factor is described in steps 4) to 6) below.

4) As specified in 6.3.1, the assumed frequency of occurrence $f_{y,i}$ of wind speeds within the i'th wind speed bin shall correspond to a Rayleigh distribution, i.e.:

$$f_{y,i} = \exp\left(-\frac{\pi}{4} \cdot \left(\frac{v_i - 0{,}5}{v_a}\right)^2\right) - \exp\left(-\frac{\pi}{4} \cdot \left(\frac{v_i + 0{,}5}{v_a}\right)^2\right) \tag{7}$$

where

v_i is the midpoint of the i'th wind speed bin;

v_a is the assumed annual average wind speed.

5) The actual frequency of occurrence $f_{m,i}$ of measured flicker coefficients within the i'th wind speed bin is given by:

$$f_{m,i} = \frac{N_{m,i}}{N_m} \tag{8}$$

where

$N_{m,i}$ is the number of flicker coefficient values measured within the i'th wind speed bin;

N_m is the total number of flicker coefficient values.

6) The weighting factor shall be determined for each 1 m/s wind speed bin between $v_{cut\text{-}in}$ and 15 m/s by inserting calculated values of $f_{y,i}$ and $f_{m,i}$ in the equation below:

$$w_i = \frac{f_{y,i}}{f_{m,i}} \tag{9}$$

Finally, the weighted accumulated distribution of the measured flicker coefficient values shall be found, and the flicker coefficient $c(\psi_k, v_a)$ shall be determined as the 99th percentile of this distribution (see notes 4 and 5). The procedure for this is given in steps 7) to 8) below:

7) The weighted accumulated distribution of the flicker coefficient values is given by:

$$\Pr(c < x) = \frac{\sum_{i=1}^{N_{\text{bin}}} w_{\text{i}} \cdot N_{\text{m,i,c<x}}}{\sum_{i=1}^{N_{\text{bin}}} w_{\text{i}} \cdot N_{\text{m,i}}} \tag{10}$$

where

$N_{\text{m,i,c<x}}$ is the number of flicker coefficient values less than or equal to the value *x* within the i'th wind speed bin;

N_{bin} is the total number of wind speed bins.

8) The flicker coefficient shall be determined as the 99th percentile of the weighted accumulated distribution of the flicker coefficient values. This shall be done by calculating $\Pr(c<x)$ and reading the 99th percentile from that.

The above procedure steps 4) to 8) are further illustrated in clause B.3.

The long-term flicker emission can, according to IEC 61000-3-7, be calculated as the cubic average of 12 consecutive short-term values. Considering that the flicker emission from a wind turbine is a function of the wind speed, and that wind conditions are likely to persist for a 2 h period, 12 consecutive short-term values are likely to be equal. Hence, for wind turbines the long-term flicker emission coefficient becomes equal to the short-term value.

NOTE 1 If the phase-to-neutral voltages are not available, the phase-to-phase voltages must be measured and the phase-to-neutral voltages calculated from the measured phase-to-phase voltages. The phase-to-neutral voltages may be calculated from measured phase-to-phase voltages according to the equations below:

$$u_1 = \frac{u_{12} - u_{31}}{3}$$

$$u_2 = \frac{u_{23} - u_{12}}{3}$$

$$u_3 = \frac{u_{31} - u_{23}}{3}$$

where

u_1, u_2 and u_3 are the instantaneous phase-to-neutral voltages;

u_{12}, u_{31} and u_{23} are the instantaneous phase-to-phase voltages.

NOTE 2 The flicker algorithm described in IEC 61000-4-15 generates the RMS value of $u_{\text{fic}}(t)$, and then cuts off variations faster than 35 Hz. Still a minimum cut-off frequency of 400 Hz, corresponding to a minimum sampling frequency of 800 Hz is required for flicker measurements of continuous operation in this standard. Test calculations have shown that this sampling frequency is necessary to obtain consistent results. A lower sampling frequency will reduce the accuracy of the electrical angle of the fundamental of the measured voltage $\alpha_{\text{m}}(t)$.

NOTE 3 The formula defining the flicker coefficient is further explained in B.4.1.

NOTE 4 The 99th percentile is applied as flicker emission limits usually relate to this percentile.

NOTE 5 As stated in 6.3.1, $c(\psi_{\text{k}},v_{\text{a}})$ shall be determined for v_{a} = 6 m/s, 7,5 m/s 8,5 m/s and 10 m/s respectively. Further, as stated in this subclause, measurements are only required up to 15 m/s. Assuming the wind speed to be Rayleigh distributed, it can be calculated that 15 m/s corresponds to the 99th percentile for v_{a} = 6 m/s, and a further 96 %, 91 % and 83 % for v_{a} = 7,5 m/s, 8,5 m/s and 10 m/s respectively. Hence, although $c(\psi_{\text{k}},v_{\text{a}})$ is determined according to this subclause as the 99th percentile of the data set, it may represent lower percentiles for Rayleigh distributed wind speed distributions with v_{a} = 7,5 m/s, 8,5 m/s and 10 m/s. This is further explained in clause B.3. It is however judged that the uncertainty of the actual percentiles do not justify requiring measurements at higher wind speeds to expand the data set to ensure 99th percentiles also for v_{a} = 7,5 m/s, 8,5 m/s and 10 m/s, as this would often dramatically increase the required testing period. It is however open for users of this standard to agree to include measurements above 15 m/s in order to improve the accuracy of $c(\psi_{\text{k}},v_{\text{a}})$ for v_{a} > 6 m/s.

7.3.3 Switching operations

Based on manufacturer's information, the maximum number of switching operations, N_{10} and N_{120} shall be determined for each type of switching operation specified in 6.6.2a), 6.6.2b) and 6.6.2c). In the event that the wind turbine manufacturer cannot provide these numbers, or the manufacturer cannot provide sufficient specification of the wind turbine control system to support the provided numbers, the following shall be assumed:

- N_{10} = 10 and N_{120} = 120 for 6.6.2a) and 6.6.2c);
- N_{10} = 1 and N_{120} = 12 for 6.6.2b).

Measurements and subsequent 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 6.3.2a), 6.3.2b) and 6.3.2c).

This subclause gives the detailed procedure, whereas an informative outline is provided in clause B.2.

Whereas 6.3.2a) and 6.3.2b) each specify a switching at a specific wind speed, it is the task of the assessor to identify the conditions of 6.3.2c). This may be done by assessment of the wind turbine design, or if this does not give sufficient evidence, measurements must be taken to identify the conditions for 6.3.2c). See also note 1 in 6.3.2.

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. See also note 2 in 7.3.2;

b) the measurements must 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, each case should be performed five times;

d) the wind speed shall be measured according to 7.1.2. It is required that the 10 min average wind speed during the switching operation is within a range of ±2 m/s of the required wind speed.

The measurements shall be taken with a measurement set-up as specified in Figure 3, and by applying voltage and current transformers and an anemometer with specifications according to Table 2. The cut-off frequency of the voltage and current measurements shall be at least 1 500 Hz (see note 1). As a guide, for wind turbines applying soft-starters or other effective limitation of the inrush currents, the current transformers should be rated two to four times the rated current. For wind turbines without any inrush current limitation, as a guide, the current transformers should be rated 10 to 20 times the rated current of the wind turbine.

The measurements shall be treated 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 $u_{fic}(t)$.

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 according to its definition below.

$$k_f(\psi_k) = \frac{1}{130} \cdot \frac{S_{k,fic}}{S_n} \cdot P_{st,fic} \cdot T_p^{0,31} \quad (11)$$

See also note 2.

4) The voltage change factor $k_u(\psi_k)$ shall be determined according to the definition below.

$$k_u(\psi_k) = \sqrt{3} \cdot \frac{U_{fic,max} - U_{fic,min}}{U_n} \cdot \frac{S_{k,fic}}{S_n} \qquad (12)$$

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.

See also note 3.

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

NOTE 1 The cut-off frequency should be at least 1 500 Hz to ensure that the fluctuating harmonics due to “soft-start” power electronics are correctly included in the voltage change factors and flicker step factors. See also note 2 in 7.3.2.

NOTE 2 The formula defining the flicker step factor is deducted from IEC 61000-3-3 as explained in B.4.2.

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

7.4 Current harmonics, interharmonics and higher frequency components

This subclause is relevant only for wind turbines with a power electronic converter.

The emission of current harmonics, interharmonics and higher frequency components from the wind turbine during continuous operation shall be measured so that these can be stated in accordance with in section 6.4.

The results shall be based on observation times of 10 minutes for each power bin, i.e. 10, 20, …, 100 % of P_n as stated in section 6.4, and shall be for situations with minimum distortion from the grid. The measurement procedure shall be suitable for wind turbines, i.e. where the magnitude of the current harmonics produced can be expected to change over the periods of a few seconds.

Measurements, which are clearly influenced by grid background noise, can be excluded.

At least nine 10 min time-series of instantaneous current measurements (three tests and three phases) shall be collected for each 10% power bin.

The measurements and grouping of the spectral components shall be performed according to IEC 61000-4-7. The accuracy class I as defined in IEC 61000-4-7 shall be applied.

The 10-cycle window for 50 Hz and 12-cycle window for 60 Hz systems is recommended. The window size shall be stated in the data sheet.

Harmonic currents below 0,1 % of the rated current for any of the harmonic orders need not be reported.

The DFT (Discrete Fourier Transform) is applied to each of 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.

The harmonic current components for frequencies up to 50 times the fundamental grid frequency shall be subgrouped as given in Section 5.6 of IEC 61000-4-7.

The total harmonic current distortion (THC) shall be calculated according to

$$THC = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_n} \cdot 100 \qquad (13)$$

where

I_h is the subgrouped rms current harmonic of harmonic order h;

I_n is the rated current of the wind turbine.

The interharmonic current components below 2 kHz shall be subgrouped in accordance to IEC 61000-4-7 Annex A (equations A3 and A4 for 50 and 60 Hz systems respectively).

The higher frequency components, i.e. the 2-9 kHz current components, shall be measured and grouped according to IEC 61000-4-7 Annex B (equation B1). The output of raw DFT shall be grouped in bands of 200 Hz.

For each frequency band and for each 10 % power bin the maximum subgrouped current harmonic, interharmonic and higher frequency component of the three phases and of the collected measurements shall be reported.

7.5 Response to temporary voltage dip

The response of the wind turbine to the temporary voltage dips specified in Table 1, section 6.5, shall be measured. The stated response shall include time-series of active power, reactive power and voltage at wind turbine terminals for the time shortly prior to the voltage dip and until the effect of the voltage dip has abated. The wind turbine operational mode and ten-minute average wind speed shall be specified.

The active power, reactive power and voltage shall be given for each line period (50 or 60 Hz), and shall be measured as positive sequence fundamentals – see Annex C.

The test shall be carried out for the wind turbine operating at both 20 and 100 % of rated power.

The test can be carried out using the set-ups outlined in Figure 3. The voltage dips are created by a short-circuit emulator that connects the three or two phases to ground via an impedance, or connecting the three or two phases together through an impedance.

The voltage magnitudes specified in Table 1 may be affected by the wind turbine operation, but are defined for the wind turbine not connected to set up outlined in Figure 3.

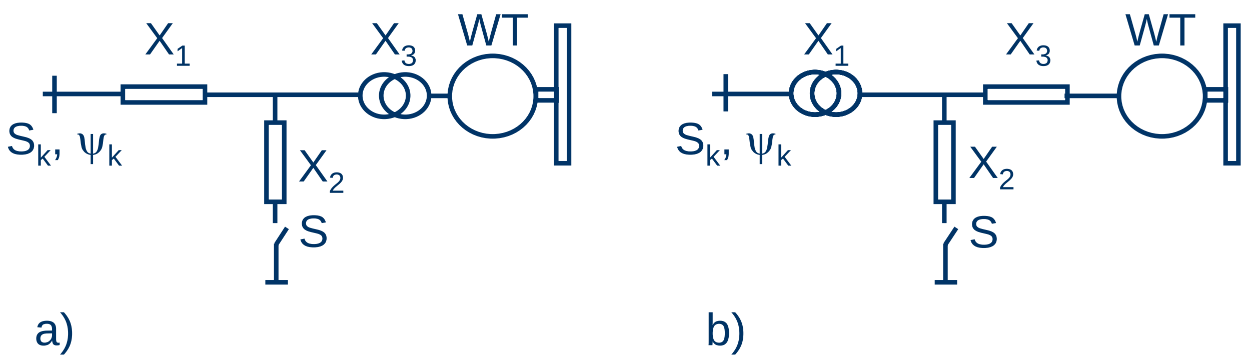

Figure 5 – System with short circuit emulator for testing wind turbine response to temporary voltage dip. The short circuit emulator can be connected at either the high (fig a) or low (fig b) voltage side of the wind turbine transformer.

The reactance X_1 is for limiting the effect of the short-circuit on the up-stream grid. The size of the reactance approximates that of the wind turbine transformer, i.e. X_1 may be 5-10 % of the transformer base impedance.

$$Z_b = \frac{U_n^2}{S_n} \qquad (14)$$

The voltage dip is created by connecting the reactance X_2 by the switch S. The size of X_2 shall be adjusted to give the voltage magnitudes U (in pu) specified in Table 1 within +/- 0.05 pu when the wind turbine is not connected.

$$X_2 \approx X_1 \frac{U}{1-U} \qquad (15)$$

The switch S shall be able to accurately control the time between connection and disconnection of X2, and for all three or two phases. The switch can be e.g. a mechanical circuit breaker or a power electronic device.

The voltage drop and rise time shall be less than 50 ms without the wind turbine connected (this depends on the connected grid). The duration of the dip shall be 400 ms, i.e. from closing to opening of the switch S.

The reactance X_3 is either the wind turbine transformer or a reactance of the same size, i.e. X_3 may be 5-10 % of the transformer base impedance.

NOTE The test shall be carried out at 20 % of rated power to get response at the most probable operational mode (assuming common wind conditions), and at 100 % of rated power to get the response at tougher conditions.

7.6 Active Power

7.6.1 Maximum measured power

The maximum measured power shall be measured as a 600-second-average value, P_{600}, a 60-second-average value, P_{60} and as a 0,2-second-average value, $P_{0,2}$ applying the following procedure:

- measurements shall be sampled during continuous operation only;
- the power shall be measured at the WT terminals;
- measurements shall be taken so that at least five 10 min time-series of power are collected for each 1 m/s wind speed bin between cut-in wind speed and 15 m/s.
- the wind speed is measured as 10 min average values and according to 7.1.2;
- the measured data shall be inspected and erroneous data shall be deleted;
- the measured power shall be transferred to 0,2-second-average data and 60-second-average data by block averaging;
- $P_{0,2}$ shall be determined as the highest valid 0,2-second-average value recorded during the measurement period;
- P_{60} shall be determined as the highest valid 60-second-average value recorded during the measurement period.
- P_{600} shall be determined as the highest valid 600-second-average value recorded during the measurement period.

The measurements shall be taken with a measurement set-up as specified in Figure 3, and by applying voltage and current transformers, and an anemometer with specifications according to Table 2.

As a guide, the full-scale range for measuring the current may be two times the rated current of the wind turbine.

7.6.2 Ramp rate limitation

The ramp rate limitation shall be tested so that it can be characterized according to 6.6.2. The following procedure shall be applied:

- The wind turbine shall be started from stand still.
- The ramp rate shall be set to 10 % of rated power per minute.
- The test shall be carried out until 10 min after the wind turbine has connected to the grid.
- The available active power output shall during the whole test be at least 50 % of rated power.
- The active power shall be measured at the WT terminals.
- The test results shall be reported as 0,2 sec average data.

The measurements shall be taken with a measurement set-up as specified in Figure 3 and by applying anemometer, voltage and current transformers with specifications according to Table 2.

The available active power output shall be read from the control system of the wind turbine, or if the wind turbine control system does not facilitate this, an approximate value can be used based on measured wind speed combined with the power curve of the wind turbine.

7.6.3 Set point control

The active power set point control shall be tested so that it can be characterized according to 6.6.3. The following procedure shall be applied:

- The test shall be carried out during a test period of 10 min.
- Ramp rate limitation shall be deactivated during the test to ensure fastest possible response.
- The set point signal shall be reduced from 100 % to 20 % in steps of 20 % with 2 min operation at each set point value, i.e. according to Figure 1.
- The available active power output shall during the whole test be at least 90 % of rated.
- The active power shall be measured at the WT terminals.
- The test results shall be reported as 0,2 sec average data.

The measurements shall be taken with a measurement set-up as specified in Figure 3 and by applying anemometer, voltage and current transformers with specifications according to Table 2.

The available active power output shall be read from the control system of the wind turbine, or if the wind turbine control system does not facilitate this, an approximate value can be used based on measured wind speed combined with the power curve of the wind turbine.

7.7 Reactive Power

7.7.1 Reactive power capability

The maximum inductive reactive power and the maximum capacitive reactive power shall be measured so that it can be stated according to section 6.7.1.

- For the measurement of the maximum inductive reactive power the wind turbine shall be set to the operation mode, which gives the maximum inductive reactive power in the whole power range.
- For the measurement of the maximum capacitive reactive power the wind turbine shall be set to the operation mode, which gives the maximum capacitive reactive power in the whole power range.

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

- Measurements shall be sampled during continuous operation only.
- The active and reactive power shall be measured at the WT terminals.
- Measurements shall be taken so that at least 30 one minute time-series of active and reactive power are collected at each 10 % power bin.
- The sampled data shall be transferred to 1 min. average data by applying block averaging for each 1 min. period.
- The 1 min. average data shall be sorted according to the method of bins so that the reactive power can be specified in a table for 0, 10, ...90, 100% of rated power. Here 0, 10, ...90, 100% are the midpoints of active power bins.

The measurements shall be taken with a measurement set-up as specified in Figure 3 and by applying voltage and current transformers with the specifications according to Table 2.

7.7.2 Set point control

The reactive power control by set point value shall be measured so that it can be stated according to 6.7.2.

For the measurement at a set point of reactive power = 0, the following procedure shall be applied:

- measurements shall be sampled during continuous operation only;
- the active and reactive power shall be measured at the WT terminals;
- measurements shall be taken so that at least 30 one minute time-series of active and reactive power are collected at each 10 % power bin;
- the sampled data shall be transferred to 1 min. average data by applying block averaging for each 1 min. period.
- the 1 min. average data shall be sorted according to the method of bins so that the reactive power can be specified in a table for 0, 10, ...90, 100% of rated power. Here 0, 10, ...90, 100% are the midpoints of active power bins.

For the measurement during the step change of reactive power the following procedure shall be applied:

- measurements shall be sampled during continuous operation only;
- the active and reactive power shall be measured at the WT terminals;
- the active power output shall be at approximately 50 % of rated power;
- the sampled data for reactive power shall be 0.2 sec. average data
- the set point of reactive power shall be varied according to Figure 2
- the measured reactive power shall be shown in a graph as 0.2 sec. data together with the set point value of reactive power.

The measurements shall be taken with a measurement set-up as specified in Figure 3 and by applying voltage and current transformers with the specifications according to Table 2.

7.8 Grid Protection

The protection levels and the disconnection times of the WT shall be determined concerning over- and under-voltage and over- and under-frequency. Therefore a separate 3 phase voltage supply, which is variable in voltage and frequency, is fed into the control of the WT. Due to safety reasons the measurements concerning the grid protection are performed while the generator of the wind turbine is not in operation.

The following procedure shall be applied for the determination of the protection levels:

- Under-voltage protection level, U_{under}:
  The voltage of the separate 3 phase voltage supply shall be decreased in all three phases from 100 % of nominal voltage at nominal frequency in steps of 1% of nominal voltage until the WT disconnects. Each step shall take at minimum 20 sec.
- Over-voltage protection level, U_{over}:
  The voltage of the separate 3 phase voltage supply shall be increased in all three phases from 100 % of nominal voltage at nominal frequency in steps of 1% of nominal voltage until the WT disconnects. Each step shall take at minimum 20 sec.
- Under-frequency protection level, f_{under}:
  The frequency of the separate 3 phase voltage supply shall be decreased from 100 % of nominal frequency at nominal voltage in steps of 0.1 Hz until the WT disconnects. Each step shall take at minimum 20 sec.
- Over-frequency protection level, f_{over}:
  The frequency of the separate 3 phase voltage supply shall be increased from 100 % of nominal frequency at nominal voltage in steps of 0.1 Hz until the WT disconnects. Each step shall take at minimum 20 sec.

For the determination of the disconnection times the following procedure shall be applied:

- The disconnection time of the wind turbine shall be determined from the data sheet of the wind turbine or by a measurement of the disconnection time.
- The disconnection time is the time duration from the beginning of the voltage step until the wind turbine has disconnected.
- Under-voltage:
  A voltage step from nominal voltage to U_{under} –5 % of nominal voltage shall be given to the circuit breaker of the WT by the separate voltage supply.
- Over-voltage:
  A voltage step from nominal voltage to U_{over} +5 % of nominal voltage shall be given to the circuit breaker of the WT by the separate voltage supply.
- Over-frequency:
  A frequency step from nominal frequency to f_{over} +1 Hz shall be given to the circuit breaker of the WT by the separate voltage supply.
- Under-frequency:
  A frequency step from nominal frequency to f_{under} -1 Hz shall be given to the circuit breaker of the WT by the separate voltage supply.

7.9 Reconnection time

The reconnection time shall be tested so that it can be characterized according to section 6.9. The following procedure shall be applied:

- The test shall be carried out 3 times with different grid failure times as specified in section 6.9.
- The average wind speed shall be greater than 10 m/s during the reconnection time.

- The grid should be made unavailable to the wind turbine by opening a breaker in the grid, typically the MV breaker connecting the wind turbine to the power collection system. 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 the breaker. The breaker would normally have to be operated manually, and the tester should ensure that the grid failure time is as specified within a tolerance of ± 1 second.
- The active power shall be measured at the WT terminals.
- The voltage shall be measured at the WT terminals.
- The test results shall be reported based on 0,2 sec average data of the power and voltage. Based on the measured power and voltage, the reconnection time is determined from the time when the voltage returns ($U > 0.9 \times U_n$) to the time where wind turbine starts producing power again ($P > 0$).

The measurements shall be taken with a measurement set-up as specified in Figure 3 and by applying voltage and current transformers with the specifications according to Table 2

8 Assessment of power quality

8.1 General

This clause 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 this clause may still be used as a guide.

The methods for assessing compliance with power quality requirements are valid for wind turbines with PCC at MV or HV in power systems with fixed frequency within ±1 Hz, and sufficient active and reactive power regulation capabilities and sufficient load to absorb the wind power production. In other cases, the principles for assessing compliance with power quality requirements may still be used as a guide.

8.2 Voltage fluctuations

The flicker emissions from a wind turbine installation must be limited to comply with the flicker emission limits as specified in equation 15 and equation 16 below.

$$P_{\mathrm{st}} \le E_{\mathrm{Psti}} \tag{16}$$

$$P_{\mathrm{lt}} \le E_{\mathrm{Plti}} \tag{17}$$

where

P_{st} and P_{lt} are the short and long-term flicker emissions from the wind turbine installation;

E_{Psti} and E_{Plti} are the short and long-term flicker emission limits for the relevant PCC.

Further, the relative voltage change due to a wind turbine installation must be limited in accordance with equation 17 below.

$$d \le \frac{\Delta U_{\mathrm{dyn}}}{U_{\mathrm{n}}} \tag{18}$$

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 61000-3-7.

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.

8.2.1 Continuous operation

The 99th percentile flicker emission from a single wind turbine during continuous operation shall be estimated applying equation 18 below.

$$P_{\mathrm{st}} = P_{\mathrm{lt}} = c(\psi_{\mathrm{k}}, v_{\mathrm{a}}) \cdot \frac{S_{\mathrm{n}}}{S_{\mathrm{k}}} \quad (19)$$

where

$c(\psi_k, v_a)$ is the flicker coefficient of the wind turbine for the given network impedance phase angle, ψ_k at the PCC, and for the given annual average wind speed, v_a at hub-height of the wind turbine at the site;

S_n is the rated 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 and v_a at the site, may be found from the table of data produced as a result of the measurements described in 7.3.2 by applying linear interpolation.

In case more wind turbines are connected to the PCC, the flicker emission from the sum of them can be estimated from equation 19 below.

$$P_{\mathrm{st}\Sigma} = P_{\mathrm{lt}\Sigma} = \frac{1}{S_{\mathrm{k}}} \cdot \sqrt{\sum_{i=1}^{N_{\mathrm{wt}}} \left(c_{\mathrm{i}}(\psi_{\mathrm{k}}, v_{\mathrm{a}}) \cdot S_{\mathrm{n,i}}\right)^2} \quad (20)$$

where

$c_i(\psi_k, v_a)$ is the flicker coefficient of the individual wind turbine;

$S_{n,i}$ is the rated apparent power of the individual wind turbine;

N_{wt} is the number of wind turbines connected to the PCC.

8.2.2 Switching operations

The flicker emission due to switching operations of a single wind turbine shall be estimated applying equation 20 and equation 21 below.

$$P_{\mathrm{st}} = 18 \cdot N_{10}^{0{,}31} \cdot k_{\mathrm{f}}(\psi_{\mathrm{k}}) \cdot \frac{S_{\mathrm{n}}}{S_{\mathrm{k}}} \quad (21)$$

$$P_{\mathrm{lt}} = 8 \cdot N_{120}^{0{,}31} \cdot k_{\mathrm{f}}(\psi_{\mathrm{k}}) \cdot \frac{S_{\mathrm{n}}}{S_{\mathrm{k}}} \quad (22)$$

where $k_f(\psi_k)$ is the flicker step factor of the wind turbine for the given ψ_k at the PCC. See also note 1.

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 7.3.3 by applying linear interpolation.

In case more wind turbines are connected to the PCC, the flicker emission from the sum of them can be estimated from equation 22 and equation 23 below.

$$P_{\mathrm{st}\Sigma} = \frac{18}{S_{\mathrm{k}}} \cdot \left(\sum_{i=1}^{N_{\mathrm{wt}}} N_{10,\mathrm{i}} \cdot \left(k_{\mathrm{f,i}}(\psi_{\mathrm{k}}) \cdot S_{\mathrm{n,i}}\right)^{3{,}2} \right)^{0{,}31} \quad (23)$$

$$P_{\mathrm{lt}\Sigma} = \frac{8}{S_{\mathrm{k}}} \cdot \left(\sum_{i=1}^{N_{\mathrm{wt}}} N_{120,\mathrm{i}} \cdot \left(k_{\mathrm{f,i}}(\psi_{\mathrm{k}}) \cdot S_{\mathrm{n,i}}\right)^{3{,}2} \right)^{0{,}31} \quad (24)$$

where

$N_{10,i}$ and $N_{120,i}$ are the number of switching operations of the individual wind turbine within a 10 min and 2 h period respectively;

$k_{f,i}(\psi_k)$ is the flicker step factor of the individual wind turbine;

$S_{n,i}$ is the rated power of the individual wind turbine. See also note 2.

If there is an overall control system associated with the wind turbine installation that limits the total number of switching operations, adequate account should be taken to include the effect of this.

The relative voltage change due to a switching operation of a single wind turbine shall be estimated applying equation 24 below.

$$d = 100 \cdot k_u(\psi_k) \cdot \frac{S_n}{S_k} \tag{25}$$

where

d is the relative voltage change in %;

$k_u(\psi_k)$ 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 7.3.3 by applying linear interpolation.

In case 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 20 and equation 21 may be deduced from B.4.2 applying an observation period of 600 s and 7 200 s respectively.

NOTE 2 Equation 22 and equation 23 may be deduced as equation 20 and equation 21, 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.

8.3 Harmonics

The harmonic currents shall be limited to the degree needed to avoid unacceptable harmonic voltages at the PCC.

A wind turbine with an induction generator directly connected to the electricity system (i.e. without a power electronic converter) is not expected to cause any significant harmonic distortion. Hence, this standard does not require any further assessment of these. For a wind turbine with a directly connected synchronous generator (i.e. without a power electronic converter), the requirements of IEC 60034-1 of irregularities of waveform shall be met. Then the wind turbine will only give a very limited emission of harmonic currents, and hence this standard does not require any further assessment of these. For a wind turbine with a power electronic converter, the applicable limits for emission of harmonics should be found by applying the guidance given in IEC 61000-3-6.

IEC 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 applying equation 25 below:

$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left(\frac{I_{h,i}}{n_i} \right)^{\beta}} \tag{26}$$

where

N_{wt} is the number of wind turbines connected to the PCC;

$I_{h\Sigma}$ is the h'th order harmonic current distortion at the PCC;

n_i is the ratio of the transformer at the i'th wind turbine;

$I_{h,i}$ is the h'th order harmonic current distortion of the i'th wind turbine;

β is the exponent given in Table 3.

If the wind turbines are equal and their converters' line commutated, the harmonics are likely to be in phase and $\beta = 1$ shall be used for all harmonic orders.

Table 3 – Specification of exponents according to IEC 61000-3-6

Harmonic order	β
h < 5	1,0
5 ≤ h ≤ 10	1,4
h > 10	2,0

Equation 25 does not take account of the use of transformers with different vector groups that may cancel out particular harmonics. If this is the case, adequate account should be taken to include the effect of this.

Annex A
(informative)

Sample report format

This sample report format gives a suggested format for reporting the results of tests for characterizing the power quality parameters of a wind turbine.

REPORT ON RESULTS OF WIND TURBINE POWER QUALITY TESTS

The reported characteristics are valid for the specific configuration of the assessed wind turbine only. Other configurations, including altered control parameters, that cause the wind turbine to behave differently with respect to power quality, require separate assessment.

Name of test organization	
Report number	
Wind turbine type designation	
Wind turbine manufacturer	
Serial number of wind turbine tested	

The wind turbine identified above has been tested in accordance with IEC 61400-21. General wind turbine data are given below:

Wind turbine type (horizontal/vertical axis)	
Number of blades	
Rotor diameter (m)	
Hub height (m)	
Blade control (pitch/stall)	
Speed control (fixed/two-speed/variable)	
Generator type and rating(s) (kW)	
Frequency converter type and rating (kVA)	
Reactive compensation type and rating (kvar)	
Identification of wind turbine terminals	

This test report is accompanied by the documents specified below.

Type of information	**Document name and date**
Description of the tested wind turbine, including settings of control parameters	
Description of test site and grid connection	
Description of test equipment	
Description of test conditions	
Note of exceptions to IEC 61400-21	

Author	
Checked	
Approved	
Date of issue	

Characteristic parameters that are determined otherwise than outlined in IEC 61400-21 are marked. This includes parameters that are calculated instead of measured. The document(s) with exceptions to IEC 61400-21 describes the alternative procedure(s) that has been applied.

The resulting characteristic parameters are stated below.

A.1 Wind turbine specifications

A.1.1 Rated data

Rated power, P_n (kW)	
Rated wind speed, v_n (m/s)	
Rated apparent power, S_n (kVA)	
Rated current, I_n (A)	
Rated voltage, U_n (V)	
Rated frequency, f_n (Hz)	

A.1.2 Electrical drive-train data

A.1.2.1 Generator data

This table is an example for a wound rotor induction generator.

Rated power, P_n (kW)	
Rated apparent power, S_n (kVA)	
Rated current, I_n (A)	
Rated voltage, U_n (V)	
Rated frequency, f_n (Hz)	
Generator inertia, J_g (kg·m^2)	
Stator to rotor turn-ratio	
Rated speed (RPM)	
Number of pole pairs, p	
Stator resistance, R_S (ohm)	
Stator leakage reactance, X_S (ohm)	
Rotor leakage reactance, X_R (ohm)	
Magnetizing reactance, X_M (ohm)	
Magnetizing resistance, R_M (ohm)	
Rotor resistance, R_R (ohm)	

A.1.2.2 Power electronic converter data

For wind turbines equipped with power electronic converters, the converter data shall be specified, including e.g. converter type, rated power, switching frequency, applicable current limits, time constants and protective function set points.

A.1.3 Mechanical drive-train data

The equivalent shaft stiffness is for a 2 inertia representation of the turbine – generator mechanical drive train.

Turbine inertia, J_t (kg·m^2)	
Equivalent shaft stiffness, k (Nm/rad)	
Gearbox ratio, n_g	

A.2 Voltage fluctuations

A.2.1 Continuous operation

The operational mode of the wind turbine during the test was:

Reactive set-point control, Q=0
Other mode:

Network impedance phase angle, ψ_k (deg.)	**30**	**50**	**70**	**85**
Annual average wind speed, v_a (m/s)	**Flicker coefficient, $c(\psi_k, v_a)$**			
6,0				
7,5				
8,5				
10,0				

A.2.2 Switching operations

The operational mode of the wind turbine during the test was:

Reactive set-point control, Q=0
Other mode:

Case of switching operation	**Start-up at cut-in wind speed**			
Max number of switching operations, N_{10}				
Max number of switching operations, N_{120}				
Network impedance phase angle, ψ_k (deg.)	**30**	**50**	**70**	**85**
Flicker step factor, $k_f(\psi_k)$				
Voltage change factor, $k_u(\psi_k)$				

Case of switching operation	**Start-up at rated wind speed**			
Max number of switching operations, N_{10}				
Max number of switching operations, N_{120}				
Network impedance phase angle, ψ_k (deg.)	**30**	**50**	**70**	**85**
Flicker step factor, $k_f(\psi_k)$				
Voltage change factor, $k_u(\psi_k)$				

Case of switching operation	**Worst case switching between generators**
Max number of switching operations, N_{10}	

Max number of switching operations, N_{120}				
Network impedance phase angle, ψ_k (deg.)	**30**	**50**	**70**	**85**
Flicker step factor, $k_f(\psi_k)$				
Voltage change factor, $k_u(\psi_k)$				

A.3 Current harmonics, interharmonics and higher frequency components

This clause is only relevant for wind turbines with a power electronic converter.

The emission of current harmonics, interharmonics and higher frequency components from the wind turbine is specified for in percent of I_n for operation of the wind turbine within the power bins 10, 20, … , 100 % of P_n.

The operational mode of the wind turbine during the test was:

Reactive set-point control, Q=0
Other mode:

A.3.1 Harmonics

P_{bin} (%)	10	20	30	40	50	60	70	80	90	100
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										
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41										
42										
43										
44										
45										
46										
47										
48										
49										
50										
THC (%)										

A.3.2 Interharmonics

P_{bin} (%)	10	20	30	40	50	60	70	80	90	100
f (Hz)	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										
875/1050										
925/1110										
975/1170										
1025/1230										
1075/1290										
1125/1350										
1175/1410										
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1325/1590										
1375/1650										
1425/1710										
1475/1770										
1525/1830										
1575/1890										
1625/1950										
1675										
1725										
1775										
1825										
1875										
1925										
1975										

A.3.3 Higher frequency components

P_{bin} (%)	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
f (kHz)	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										
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7,9										
8,1										
8,3										
8,5										
8,7										
8,9										

A.4 Response to voltage dips

Wind turbine operational mode:

Test conditions:

Figure A.1 Time-series of measured voltage dip when the wind turbine under test is not connected. Case VD1-VD4.

Test results at 20 % of P_n:

Figure A.2 Time-series of measured positive sequence fundamental active power. Case VD1-VD4.

Figure A.3 Time-series of measured positive sequence fundamental reactive power. Case VD1-VD4.

Figure A.4 Time-series of measured positive sequence fundamental voltage at wind turbine terminals. Case VD1-VD4.

Test results at 100 % of P_n:

Figure A.5 Time-series of measured positive sequence fundamental active power. Case VD1-VD4.

Figure A.6 Time-series of measured positive sequence fundamental reactive power. Case VD1-VD4.

Figure A.7 Time-series of measured positive sequence fundamental voltage at wind turbine terminals. Case VD1-VD4.

A.5 Active power

A.5.1 Maximum measured power

600 s average value

Measured value, P_{600} (kW)	
Normalized value, $p_{600} = P_{600} / P_n$	

60 s average value

Measured value, P_{60} (kW)	
Normalized value, $p_{60} = P_{60} / P_n$	

0,2 s average value

Measured value, $P_{0,2}$ (kW)	
Normalized value, $p_{0,2} = P_{0,2} / P_n$	

A.5.2 Ramp rate limitation

Wind turbine operational mode: Ramp rate limitation set to 10 % of rated power per minute

Figure A.8 Time-series of available and measured active power output.

A.5.3 Set-point control

Wind turbine operational mode: Active power set-point control mode

Figure A.9 Time-series of active power set-point values, available power and measured active power output.

A.6 Reactive power

A.6.1 Reactive power capability

Wind turbine operational mode: Reactive power set-point control mode

Active power (% of rated)	0	10	20	30	40	50	60	70	80	90	100
Max inductive reactive power (kvar)											
Max capacitive reactive power (kvar)											

A.6.2 Set-point control

Wind turbine operational mode: Reactive power set-point control mode

Reactive power set point = 0 kvar:

Active power (% of rated)	0	10	20	30	40	50	60	70	80	90	100
Reactive power (kvar)											

Reactive power set point step change:

Figure A.9 Time-series of reactive power set-point values and measured reactive power.

Figure A.10 Time-series of active power during test (shall be approximately 50 % of rated).

A.7 Grid protection

	Tripping level	Tripping time (s)
Over-voltage		
Under-voltage		
Over-frequency		
Under-frequency		

A.8 Reconnection time

Duration of grid failure	10 s	1 minute	10 minutes
Reconnection time (s)			

Annex B
(informative)

Voltage fluctuations and flicker

B.1 Continuous operation

The measurement and assessment procedures for flicker during continuous operation are shown in figure B.1. It is illustrated in figure B.1 that the measurement procedure is rather comprehensive, whereas the assessment procedure is fairly simple.

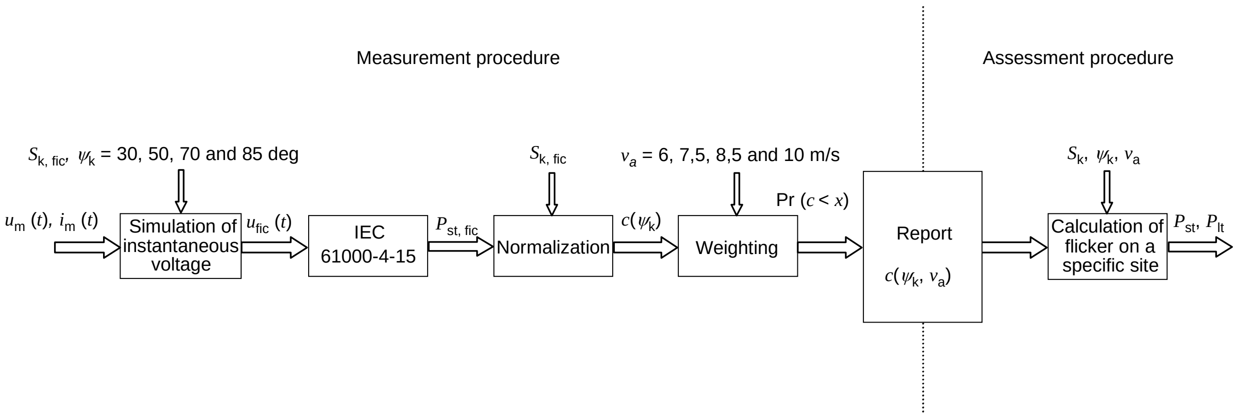

Figure B.1 – Measurement and assessment procedures for flicker during continuous operation of the wind turbine

The illustration of the measurement procedure in figure B.1 is as follows:

a) a number of voltage and current time-series $u_m(t)$ and $i_m(t)$ are measured, distributed over the wind speed interval from cut-in wind speed to 15 m/s;

b) each set of measured time-series 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;

c) 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 $P_{st,fic}$;

d) 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 $S_{k,fic}$;

e) for each network impedance phase angle ψ_k, the weighting procedure then calculates the weighted accumulated distribution functions of the flicker coefficients, $Pr(c<x)$, assuming four different wind speed distributions. $Pr(c<x)$ represents the distribution of flicker coefficients that would have been obtained if the measurements had been performed on a site with Rayleigh distributed wind speeds of mean v_a;

f) for each accumulated distribution, the 99 % percentile $c(\psi_k, v_a)$ of the flicker coefficient is then reported.

The assessment procedure specifies how the reported flicker coefficients can be used to estimate the flicker emission from a single wind turbine or a group of wind turbines operating continuously on any specified site.

B.2 Switching operations

The measurement and assessment procedures for switching operations are shown in figure B.2. These procedures specify how to measure and assess voltage changes as well as flicker. It is seen that the measurement procedure is rather comprehensive, and that the assessment procedure is fairly simple.

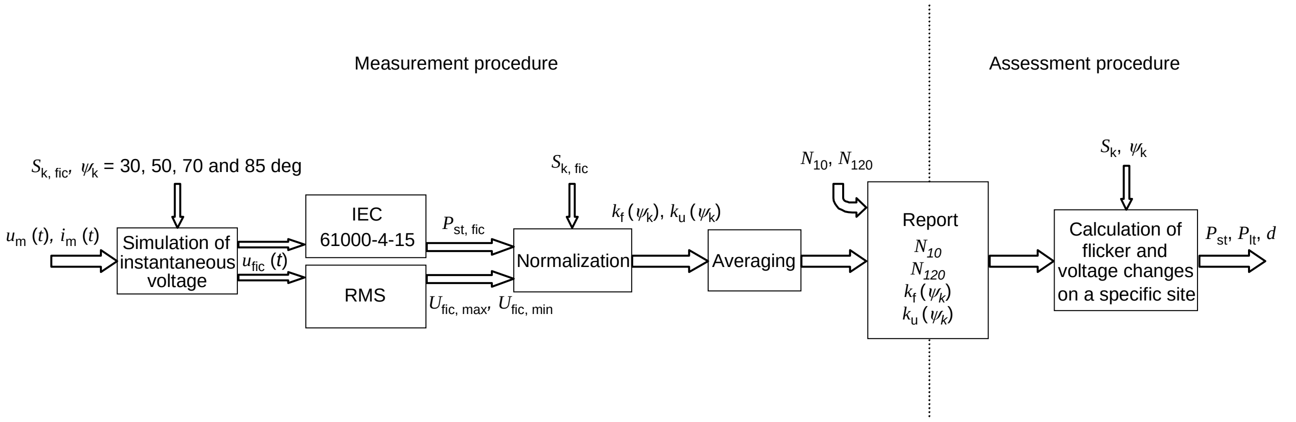

Figure B.2 – Measurement and assessment procedures for voltage changes and flicker during switching operations of the wind turbine

The measurement procedure for switching operations is as follows:

a) a number of voltage and current time-series $u_m(t)$ and $i_m(t)$ are measured for each of the specified types of switching;

b) each set of measured time-series 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;

c) 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 r.m.s. value $U_{fic,min}$;

d) 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 $k_u(\psi_k)$;

e) for each network impedance phase angle ψ_k, the measured flicker step factors and voltage change factors are then averaged;

f) the averaged flicker step factors and voltage change factors then reported together with the maximum number N_{10} of the switching operation within a 10 min period and the maximum number N_{120} of the switching operation within a 120 min period, for each type of switching operation.

The assessment procedure for switching operations specifies how to estimate the flicker emission and voltage changes from switching operations on any specified site, using the reported flicker step factors and voltage change factors. Methods are given for a single wind turbine as well as a group of wind turbines

B.3 Weighting of flicker coefficients

The following example illustrates the weighting procedure, which is used in this standard to derive the flicker coefficients $c(\psi_k, v_a)$ for four different wind speed distributions. The determination of the flicker coefficient is only shown for the network impedance phase angle ψ_k = 50°. The same procedure must be performed for the other network impedance phase angles 30°, 70° and 85°.

Figure B.3 shows a set of measured flicker coefficients $c(\psi_k)$ as a function of wind speed for the network impedance phase angle ψ_k = 50°.

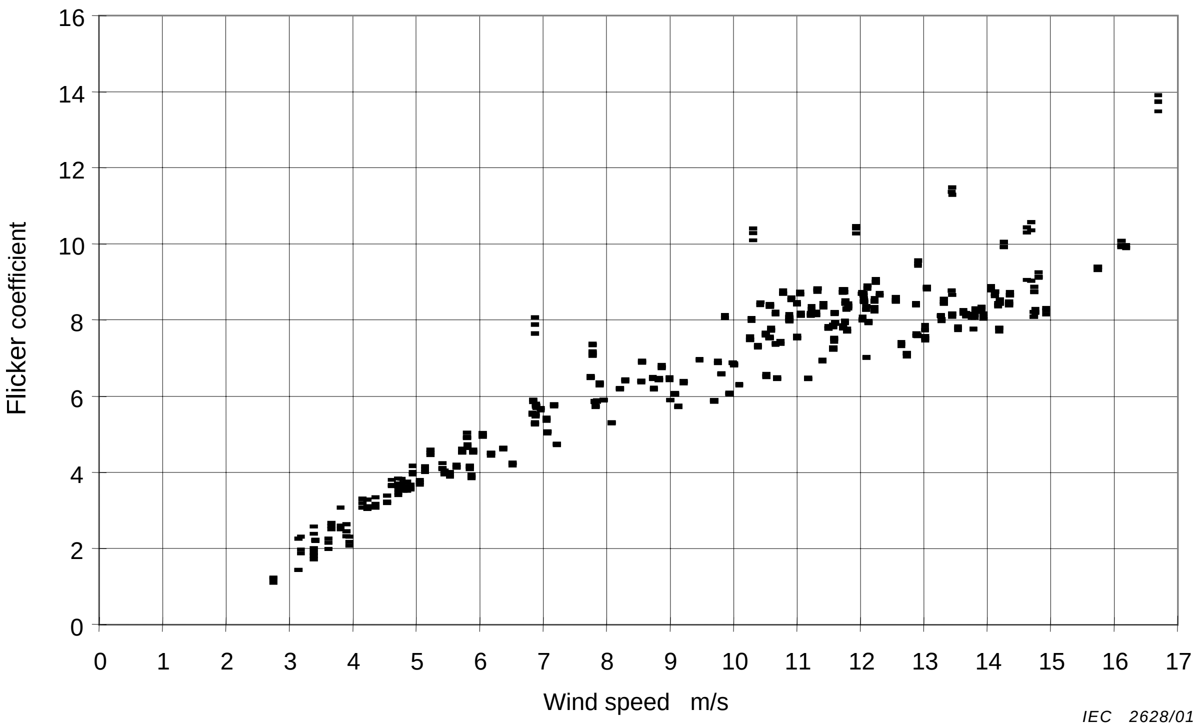

Figure B.3 – Flicker coefficient as a function of wind speed

Using these flicker coefficients to obtain a resulting flicker coefficient $c(\psi_k,v_a)$ for each wind speed distribution, the following steps are performed:

- classification of the flicker coefficients $c(\psi_k)$ in 1 m/s bins of the wind speed;
- determination of the number of measurements in each wind speed bin;
- determination of the weighting factor w_i for each wind speed bin;
- determination of the weighted accumulated distribution $Pr(c<x)$;
- determination of the 99th percentile, which gives the flicker coefficient $c(\psi_k,v_a)$.

The cut-in wind speed of the WT is, in this example, v_{cut-in} = 3 m/s. Few measurements were performed at wind speeds below cut-in wind speed and at wind speeds above 15 m/s. These measurements are not taken into account. Only the measurements above cut-in wind speed and below 15 m/s are used for the determination of the flicker coefficient $c(\psi_k,v_a)$.

Table B.1 shows the wind speed bins, the number of measurements of each bin, the relative frequency of occurrence of measured flicker coefficients $f_{m,i}$ for each wind speed bin and the Rayleigh distribution, $f_{y,i}$ for annual average wind speed v_a = 6 m/s, 7,5 m/s, 8,5 m/s and 10 m/s.

Table B.1 – Number of measurements $N_{m,i}$ and frequency of occurrence of $f_{m,i}$ and $f_{y,i}$ for each wind speed bin in the range from cut-in wind speed to 15 m/s

Wind speed bin range m/s	**Number of measurements** $N_{m,i}$	$f_{m,i}$ %	$f_{y,i}$ % **6 m/s**	$f_{y,i}$ % **7,5 m/s**	$f_{y,i}$ % **8,5 m/s**	$f_{y,i}$ % **10 m/s**
3 – <4	30	5,38	11,64	8,21	6,64	4,98
4 – <5	36	6,45	12,57	9,44	7,83	6,02
5 – <6	45	8,06	12,37	10,04	8,59	6,80

6 – <7	33	5,91	11,26	10,04	8,91	7,32
7 – <8	42	7,53	9,58	9,53	8,83	7,56
8 – <9	33	5,91	7,67	8,65	8,41	7,56
9 – <10	33	5,91	5,80	7,52	7,74	7,34
10 – <11	69	12,37	4,15	6,29	6,88	6,93
11 – <12	87	15,59	2,82	5,07	5,94	6,39
12 – <13	60	10,75	1,82	3,95	4,97	5,75
13 – <14	45	8,06	1,11	2,97	4,05	5,07
14 – <15	45	8,06	0,65	2,16	3,21	4,37
Total N_m	558					

The weighting factor, w_i, is the ratio between the frequency of occurrence of the wind speeds $f_{y,i}$ and the relative frequency of occurrence of measured flicker coefficients $f_{m,i}$. Table B.2 gives the weighting factor, w_i, for each wind speed bin.

Table B.2 – Weighting factor w_i for each wind speed bin

Wind speed bin range (m/s)	w_i 6 m/s	w_i 7,5 m/s	w_i 8,5 m/s	w_i 10 m/s
3 – <4	2,165	1,527	1,236	0,927
4 – <5	1,949	1,464	1,214	0,933
5 – <6	1,533	1,245	1,065	0,843
6 – <7	1,904	1,698	1,507	1,237
7 – <8	1,273	1,267	1,173	1,005
8 – <9	1,297	1,462	1,423	1,278
9 – <10	0,980	1,272	1,308	1,241
10 – <11	0,335	0,509	0,557	0,561
11 – <12	0,181	0,325	0,381	0,410
12 – <13	0,169	0,367	0,463	0,535
13 – <14	0,138	0,368	0,502	0,628
14 – <15	0,081	0,267	0,398	0,542

The total sum of the weighting factor for each bin multiplied by the number of measurements for that is given in table B.3.

Table B.3 – Total sum of weighting factor multiplied by number of measurements for all wind speed bins

v_a (m/s)	6,0	7,5	8,5	10,0
$\sum_{i=1}^{N_{bin}} w_i \cdot N_{m,i}$	454,40	467,99	457,64	424,60

In the next step, the measurements are sorted according to the flicker coefficients $c(\psi_k)$. This is illustrated in table B.4 where the upper row gives the maximum value of all of the flicker coefficients $c(\psi_k)$ in the wind speed range 3 m/s to 15 m/s. The maximum of the flicker coefficients $c(\psi_k)$ is the 100 percentile, that means the weighted accumulated distribution factor $Pr(c< 11{,}495) = 1{,}0$. Subsequent rows of table B.4 are completed by subtracting the weighting factor for the relevant measurement (from table B.2) divided by the total sum of weighting factors (from table B.3), from the figure in the previous row.

Table B.4 – Weighted accumulated distribution of the flicker coefficients $Pr(c<x)$ for each wind speed distribution

Sorted flicker coefficients	Corresponding wind speed m/s	$Pr(c<x)$ **6 m/s**	$Pr(c<x)$ **7,5 m/s**	$Pr(c<x)$ **8,5 m/s**	$Pr(c<x)$ **10 m/s**
11,495	13,4	1,0000	1,0000	1,0000	1,0000
11,379	13,4	0,9997	0,9992	0,9989	0,9985
11,298	13,4	0,9994	0,9984	0,9978	0,9970
10,584	14,6	0,9991	0,9976	0,9967	0,9956
10,472	11,9	0,9989	0,9971	0,9958	0,9943
10,444	14,6	0,9985	0,9964	0,9950	0,9933
10,418	11,9	0,9983	0,9958	0,9941	0,9920
10,418	10,3	0,9979	0,9951	0,9933	**0,9911**
10,364	14,6	0,9972	0,9940	0,9921	0,9898
10,308	14,6	0,9970	0,9935	0,9912	0,9885
10,286	10,3	0,9968	0,9929	**0,9903**	0,9872
10,280	11,9	0,9961	0,9918	0,9891	0,9859
10,104	10,3	0,9957	0,9911	0,9883	0,9849
10,059	14,2	0,9950	**0,9900**	0,9871	0,9836
9,931	14,2	0,9948	0,9894	0,9862	0,9823
:		:	:	:	:
8,882	12,9	0,9906	0,9788	0,9713	0,9620
8,858	12,9	**0,9902**	0,9780	0,9703	0,9608
8,846	12,1	0,9898	0,9772	0,9693	0,9595
8,836	11,3	0,9895	0,9765	0,9683	0,9582
8,831	12,1	0,9891	0,9758	0,9674	0,9573

The relevant 99th percentiles are marked by bold types in table B.4. These 99th percentiles give the flicker coefficients $c(\psi_k,v_a)$ for the network impedance phase angle of 50° for the measurement report, as shown in table B.5.

Table B.5 – Resulting flicker coefficient in continuous operation

ψ_k degrees	**30**	**50**	**70**	**85**
v_a m/s	**Flicker coefficient**			
6,0		8,9		
7,5		10,1		
8,5		10,3		
10,0		10,4		

The reported flicker coefficients are the 99th percentile of the values in the wind speed interval from cut-in wind speed to 15 m/s, though not necessarily for the complete wind speed interval from zero to infinity.

The uncertainty introduced by the limited measurement interval is illustrated in table B.6. Using the accumulated distribution functions for the Rayleigh distributions, the first three rows show the probabilities that wind speed is below, within or above the specified measurement interval from 3 m/s to 15 m/s. In the best case, all flicker coefficients outside the measurement interval are below the 99th percentile inside the measurement interval. In that case, the reported percentile actually corresponds to the best case percentile in table B.6. In the worst case, all the flicker coefficients in the wind speed interval above 15 m/s are greater than the 99th percentile inside the measurement interval. In that case, the reported percentile corresponds to the worst case percentile in table B.6. It is seen that the actual percentage of the reported percentile is quite uncertain for the wind speed distributions with high values of the annual mean wind speeds. The uncertainty can be reduced to any desired level by increasing the upper limit of the measurement interval above 15 m/s. This will, however, often dramatically increase the required testing period and thereby the cost of the measurements.

Table B.6 – Probabilities and percentiles for different wind speeds

v_a (m/s)	6,0	7,5	8,5	10,0
$Pr(v<3\text{m/s})$ (%)	17,8	11,8	9,3	6,8
$Pr(3\text{m/s}< v <15\text{m/s})$ (%)	81,4	83,9	82,0	76,1
$Pr(v>15\text{m/s})$ (%)	0,7	4,3	8,7	17,1
Best case percentile (%)	99,2	99,2	99,2	99,2
Worst case percentile (%)	98,4	94,8	90,5	82,2
NOTE The first three rows show the probabilities that wind speed is below, within or above the specified measurement interval from 3 m/s to 15 m/s. From these probabilities, the possible interval of the actually measured percentiles are given by the last two rows.				

B.4 Deduction of definitions

B.4.1 Flicker coefficient

The simulated flicker $P_{\mathrm{st,fic}}$ value will depend on the short-circuit power of the grid, $S_{\mathrm{k,fic}}$, and the angle of the grid impedance, ψ_k. $P_{\mathrm{st,fic}}$ is approximately inversely proportional to $S_{\mathrm{k,fic}}$, whereas the relation between $P_{\mathrm{st,fic}}$ and ψ_k depends on the wind turbine type. Therefore, the flicker coefficient, $c(\psi_k)$, is defined so that:

$$P_{\mathrm{st,fic}} = c(\psi_k) \cdot \frac{S_n}{S_{\mathrm{k,fic}}} \tag{B.1}$$

where S_n is the rated apparent power of the wind turbine.

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

$$c(\psi_k) = P_{\mathrm{st,fic}} \cdot \frac{S_{\mathrm{k,fic}}}{S_n} \tag{B.2}$$

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 the present standard. 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

$$d_{max} = k_f(\psi_k) \cdot \frac{S_n}{S_{k,fic}} \cdot 100 \tag{B.3}$$

where d_{max} is the equivalent voltage step in percentage of rated voltage.

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

$$t_f = 2{,}3 \cdot d_{max}^{\;3{,}2} \tag{B.4}$$

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

$$P_{st,fic} = \left(\frac{\sum t_f}{T_p} \right)^{1/3{,}2} \tag{B.5}$$

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

$$P_{st,fic} = 100 \cdot k_f(\psi_k) \cdot \frac{S_n}{S_{k,fic}} \cdot \left(\frac{2{,}3}{T_p} \right)^{1/3{,}2} \tag{B.6}$$

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

$$k_f(\psi_k) = \frac{S_{k,fic}}{100 \cdot S_n} \cdot \left(\frac{T_P}{2{,}3} \right)^{1/3{,}2} \cdot P_{st,fic} \tag{B.7}$$

The observation time, T_P, in equation B.7 is the length of the simulated voltage time series 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

$$\Delta u = k_u(\psi_k) \cdot \frac{S_n}{S_{k,fic}} \tag{B.8}$$

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

$$k_u(\psi_k) = \sqrt{3} \cdot \frac{U_{fic,max} - U_{fic,min}}{U_n} \cdot \frac{S_{k,fic}}{S_n} \tag{B.9}$$

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.

1

Annex C
(informative)

Measurement of active power, reactive power and voltage

This annex gives the recommended procedure to calculate active power, reactive power and RMS voltage based on measurement of instantaneous voltages and currents.

The measurement of active and reactive power is well defined when the voltages and currents in the system are sinusoidal and balanced. Several ways to measure active and reactive power are in common use for this kind of situation.

For a three-phase system a two wattmeter method is often used.

1 $$P_{\mathrm{ave}} = \frac{1}{T}\int_0^T \left(P_1 + P_2\right)\mathrm{d}t = \frac{1}{T}\int_0^T \left(u_{\mathrm{ab}} i_{\mathrm{a}} + u_{\mathrm{cb}} i_{\mathrm{c}}\right)\mathrm{d}t \qquad \text{(C.1)}$$

2 $$Q_{\mathrm{ave}} = \frac{1}{T}\int_0^T \sqrt{3}\left(P_2 - P_1\right)\mathrm{d}t = \frac{1}{T}\int_0^T \sqrt{3}\left(u_{\mathrm{cb}} i_{\mathrm{c}} - u_{\mathrm{ab}} i_{\mathrm{a}}\right)\mathrm{d}t \qquad \text{(C.2)}$$

3 where

T	is the period of the fundamental grid frequency;
P_1	is the power measured by wattmeter 1;
P_1	is the power measured by wattmeter 2;
u_{ab}, u_{cb}	are the instantaneous values of the phase-to-phase voltages
i_a, i_c	are the instantaneous values of the phase a and c currents.

4

For single-phase systems the reactive power is usually measured by delaying the voltage signal by 90 degrees.

5 $$Q_{\mathrm{ave}} = \frac{1}{T}\int_0^T u\left(t - \frac{T}{4}\right) i(t)\,\mathrm{d}t \qquad \text{(C.3)}$$

Naturally three-phase reactive power can be measured by three such single-phase measurements as well.

Further, the average three-phase reactive power can be calculated by using instantaneous reactive power formula

6 $$Q_{\mathrm{ave}} = \frac{1}{T}\int_0^T \frac{1}{2\sqrt{3}}\left[3\,u_{\mathrm{bc}}\, i_{\mathrm{a}} + \left(u_{\mathrm{ab}} - u_{\mathrm{ca}}\right)\left(i_{\mathrm{b}} - i_{\mathrm{c}}\right)\right]\mathrm{d}t \qquad \text{(C.4)}$$

However, a voltage dip is transitory in nature. Thus the voltages and currents are non-sinusoidal and may contain dc components. Moreover, the voltages and currents are highly unbalanced when the dip is caused by single or two-phase faults. Thus the methods presented above may then give quite different reactive power values. The active power is affected as well. The situation is worst when the voltages are unbalanced.

Thus it is important that active and reactive powers are based on the positive sequence of the fundamental voltage and current components at least in unbalanced voltage dip case. There are several advantages when this definition is used:

g) The positive sequence of the fundamental is the one that produces torque in the rotating machines. The negative sequence and the harmonics only cause losses;

h) In many cases reactive current is specified instead of the reactive power. Using positive sequence of the fundamental the reactive current component can be calculated explicitly. The same applies to the power factor;

i) 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 the similar way.

In order to measure the positive sequence of the fundamental of the voltages and currents a multichannel datalogger with high sampling rate is needed (typically at least 5 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 prevent phase errors. Moreover, the amplitude error due to the anti-aliasing filter should be negligible at the fundamental frequency.

When phase voltages and currents are measured, the fundamental's Fourier coefficients are first calculated over one fundamental cycle *T* (equation shown here only for phase a voltage u_a; other phase voltages and currents are calculated similarly)

$$u_{a,\cos} = \frac{2}{T}\int_{t-T}^{t} u_a(t)\cos(2\pi f_1 t)\,dt \qquad (C.5)$$

$$u_{a,\sin} = \frac{2}{T}\int_{t-T}^{t} u_a(t)\sin(2\pi f_1 t)\,dt \qquad (C.6)$$

where f_1 is the frequency of the fundamental.

The effective value of this fundamental phase voltage is

$$U_{a1} = \sqrt{\frac{u_{a,\cos}^2 + u_{a,\sin}^2}{2}} \qquad (C.7)$$

The voltage and current vector components of the fundamental positive sequence are calculated using

$$u_{1+,\cos} = \frac{1}{6}\left[2u_{a,\cos} - u_{b,\cos} - u_{c,\cos} - \sqrt{3}\left(u_{c,\sin} - u_{b,\sin}\right)\right] \qquad (C.8)$$

$$u_{1+,\sin} = \frac{1}{6}\left[2u_{a,\sin} - u_{b,\sin} - u_{c,\sin} - \sqrt{3}\left(u_{b,\cos} - u_{c,\cos}\right)\right] \qquad (C.9)$$

$$i_{1+,\cos} = \frac{1}{6}\left[2i_{a,\cos} - i_{b,\cos} - i_{c,\cos} - \sqrt{3}\left(i_{c,\sin} - i_{b,\sin}\right)\right] \qquad (C.10)$$

$$i_{1+,\sin} = \frac{1}{6}\left[2i_{a,\sin} - i_{b,\sin} - i_{c,\sin} - \sqrt{3}\left(i_{b,\cos} - i_{c,\cos}\right)\right] \tag{C.11}$$

The active and reactive powers of the fundamental positive sequence are then

$$P_{1+} = \frac{3}{2}\left(u_{1+,\cos} i_{1+,\cos} + u_{1+,\sin} i_{1+,\sin}\right) \tag{C.12}$$

$$Q_{1+} = \frac{3}{2}\left(u_{1+,\cos} i_{1+,\sin} - u_{1+,\sin} i_{1+,\cos}\right) \tag{C.13}$$

and the effective phase-to-phase voltage of the fundamental positive sequence is

$$U_{1+} = \sqrt{\frac{3}{2}\left(u_{1+,\sin}^2 + u_{1+,\cos}^2\right)} \tag{C.14}$$

The effective active and reactive currents of the fundamental positive sequence are

$$I_{P1+} = \frac{P_{1+}}{\sqrt{3}U_{1+}} \tag{C.15}$$

$$I_{Q1+} = \frac{Q_{1+}}{\sqrt{3}U_{1+}} \tag{C.16}$$

The power factor of the fundamental positive sequence is

$$\cos\varphi_{1+} = \frac{P_{1+}}{\sqrt{P_{1+}^2 + Q_{1+}^2}} \tag{C.17}$$

These calculations can be performed in a spreadsheet program or using a special computer program. A new value of the reactive and active power should be calculated at least once in every fundamental period using the latest data.

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