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**Wind energy generation systems –
Part 21-2: Measurement and assessment of electrical characteristics – Wind
power plants**

**Systèmes de génération d'énergie éolienne –
Partie 21-2: Mesurage et évaluation des caractéristiques électriques – Centrales
éoliennes**



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WIND ENERGY GENERATION SYSTEMS –

**Part 21-2: Measurement and assessment of electrical characteristics –
Wind power plants**

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The language used for the development of this International Standard is English.

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INTRODUCTION

This part of IEC 61400 defines a uniform method that will ensure the measurement, testing and assessment of the electrical characteristics of grid connected wind power plants. These characteristics include: power quality aspects, control characteristics such as power control, reactive power control, voltage control, frequency control, fault ride-through behaviour, as well as grid protection testing.

The measurements and assessment refer to the point of connection (POC) of the power plant. The procedure describes standardized methods, which will allow the developer as well as system operators (e.g. transmission system operators (TSOs) and distribution system operators (DSOs)) to analyze the fulfilment of the grid connection rules with respect to the above-mentioned characteristics.

This document includes the following aspects:

- definition and specification of the quantities to be determined for characterizing the electrical characteristics of grid connected power plants;
- measurement and test procedures for quantifying the electrical characteristics of a power plant;
- measurement and test procedures of the power plant controller;
- procedures and methods for the estimation of electrical capabilities, using results from each of the wind turbine measurements to assess compliance with electrical connection requirements on power plant level;
- test and measurement procedures that can be used as a reference, for example commissioning tests for existing or newly connected power plants;
- procedures for measurement and fault recording for the validation and verification of wind power plant simulation models as described in IEC 61400-27-1 and IEC 61400-27-2.

These measurement procedures are valid for power plants, including the power plant controller (PPC) and other connected equipment necessary for the operation of the power plant. The measurement procedures are valid for any size of power plant connected to the POC with a single interface.

The results of the measurements and assessment of the power plant's electrical characteristics can be used as input for the verification of the electrical simulation models for wind power plants as described in IEC 61400-27-2.

Any aspects described in this document can be tested and reported individually, and it is not mandatory to perform all of the described tests and measurements.

The validation of control functions on the power plant is a combination of the performance of the individual power generation units (PGUs), any additional plant components, the communication system and the PPC.

The control performance of the power plant can be proved by a combination of performance tests on site and functionality tests carried out on a hardware-in-the-loop (HIL) setup.

The validation tests for the control performance are therefore divided into two parts:

- 1) performance tests
- 2) functionality tests

Functionality tests can be carried out either on a specific test setup (HIL test) or on site.

Performance tests, which are site-dependent, are done at each specific site under the specific site conditions and provide together with the functionality tests the complete control performance of the power plant.

Additional tests and measurements may be carried out and reported on for more detailed assessment of simulation models and compliance with specific grid code requirements.

As the described tests can be used for the validation of other renewable power plants, this document uses the following generic abbreviations:

- PGU: power generation unit as an abbreviated term for a wind turbine
- PP: power plant as the abbreviated term for wind power plant

WIND ENERGY GENERATION SYSTEMS –

Part 21-2: Measurement and assessment of electrical characteristics – Wind power plants

1 Scope

This part of IEC 61400 defines and specifies the quantities that are determined to characterize the electrical characteristics of grid-connected power plants (PPs).

This document defines the measurement and test procedures for quantifying the electrical characteristics as basis for the verification of compliance of PPs, including:

- power quality aspects,
- steady state operation,
- dynamic response (undervoltage and overvoltage fault ride-through),
- disconnection from grid (grid protection),
- control performance.

This document defines a uniform functionality test and measurement procedure for the power plant controller (PPC), as a basis for the unit test of the power plant controller.

This document defines the procedures for assessing compliance with electrical connection requirements, including the aggregation methods for power quality aspects such as voltage variations, flicker, harmonics and interharmonics.

This document defines the procedures for measurement and fault recording, for example for the verification of power plant electrical simulation models in relation to undervoltage and overvoltage ride-through events.

These measurement procedures are valid for power plants, including the power plant controller and other connected equipment, necessary for the operation of the power plant. The measurement procedures are valid for any size of power plant connected to the point of connection (POC) at one connection point.

The procedures for assessing and verifying the compliance with grid connection requirements are valid for power plants in power systems with fixed frequency and a sufficient short-circuit power.

Out of the scope of this document are:

- evaluation of several power plants, i.e. the control by a cluster management of several power plants (PPs) or evaluation where the power plant is connected to several connection points;
- compliance test and performance requirements, including pass or fail criteria;
- specific component test and validation of the PP equipment (switchgear, cables, transformers, etc.), which are covered by other IEC standards;
- wind power plant model validation, as defined in IEC 61400-27-2;
- load flow calculation methods and load flow study guidelines;
- test and measurement of the communication interface and system of the PP as defined in the IEC 61400-25 series.

NOTE For the purposes of this document, the following terms for system voltage apply, based on IEC 60038:

- low voltage (LV) refers to $100\text{ V} < U_n \leq 1\text{ kV}$;
- medium voltage (MV) refers to $1\text{ kV} < U_n \leq 35\text{ kV}$;
- high voltage (HV) refers to $35\text{ kV} < U_n \leq 230\text{ kV}$;
- extra high voltage (EHV) refers to $U_n > 230\text{ kV}$.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60038, *IEC standard voltages*

IEC 60255-121:2014, *Measuring relays and protection equipment – Part 121: Functional requirements for distance protection*

IEC 60255-127:2010, *Measuring relays and protection equipment – Part 127: Functional requirements for over/under voltage protection*

IEC 60255-151:2009, *Measuring relays and protection equipment – Part 151: Functional requirements for over/under current protection*

IEC 60255-181:2019, *Measuring relays and protection equipment – Part 181: Functional requirements for frequency protection*

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

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

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

IEC 61400-21-1:2019, *Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines*

IEC 61400-27-1, *Wind energy generation systems – Part 27-1: Electrical simulation models – Generic models*

IEC 61400-27-2, *Wind energy generation systems – Part 27-2: Electrical simulation models – Model validation*

IEC 61869-2, *Instrument transformers – Part 2: Additional requirements for current transformers*

IEC 61869-3, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

IEC/IEEE 61850-9-3, *Communication networks and systems for power utility automation – Part 9-3: Precision time protocol profile for power utility automation*

3 Terms and definitions

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

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

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

3.1

additional plant components, pl.

additional equipment necessary for the operation and grid compliance performance of the power generation unit or power plant

EXAMPLE: Capacitor banks, reactive power compensation devices, shunt reactors, static var compensations (SVCs), storage systems, etc.

3.2

available active power

predicted instantaneous active power from the PP, taking into account the available power of each of the PGUs, additional storage equipment, power losses in the collector grid, etc.

Note 1 to entry: The available active power at the PCC is typically provided from the SCADA system.

3.3

available reactive power

predicted instantaneous reactive power from the PP, taking into account the PGUs' capability, compensation equipment, transformers, etc.

Note 1 to entry: The available reactive power at the PCC is typically provided from the SCADA system.

3.4

compliance test

procedure to verify if a characteristic or a property complies with the stated requirements

[SOURCE: IEC 60050-192:2015, 192-09-02]

3.5

component

smallest unit where all necessary functions are available in the unit and which cannot be divided into smaller parts without losing the primary function

Note 1 to entry: Examples for wind turbine components: generators, transformers, switchgear, gearboxes and converters.

3.6

component test

test on a single component, whose necessary functions and required behaviour are not dependent on other components or systems (e.g. the protection device, if this is an independent unit)

Note 1 to entry: A test done on component level shall be valid for all turbine variants where the same component is applied.

3.7

continuous operation

normal operation of the power plant excluding start-up and shut-down of the complete power plant

3.8**disconnection time**

time duration from exceeding a predefined disconnection level until the physical disconnection of the power generation unit (PGU) or power plant (PP) from the grid

3.9**droop**

ratio of the per-unit change in frequency to the per-unit change in nominal active power

$$droop = \frac{\Delta f / f_g}{\Delta P / P_n} \quad (1)$$

[SOURCE: IEC 60050-603:1986, 603-04-08, modified – used “droop” instead of “droop of a set” in the term, and formula changed.]

3.10**fault ride-through****FRT**

ability of a power generation unit or power plant to stay connected during faults in the grid

3.11**flicker coefficient for continuous operation**

normalized measure of the flicker emission during continuous operation of the power generation unit or power plant

$$c(\psi_k) = P_{st, fic} \times \frac{S_{k, fic}}{S_n} \quad (2)$$

where

$P_{st, fic}$ is the short-term flicker severity from the PGU or PP on the fictitious grid

S_n is the nominal apparent power of the PGU or PP

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

3.12**flicker step factor**

normalized measure of the flicker emission due to a single switching operation of the PGU

$$k_f(\psi_k) = \frac{1}{130} \times \frac{S_{k, fic}}{S_n} \times P_{st, fic} \times T_p^{0,31} \quad (3)$$

where

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

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

S_n is the nominal apparent power of the PGU

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

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

3.13

functionality

ability to perform a specified operation performed by a component or subsystem and a software program

Note 1 to entry: The activity of performing a function normally employs a system of displays, controls and instrumentation.

3.14

functionality test

measurement or test carried out to determine the functionality of the component or system against selected parameters as defined in this document

3.15

hardware-in-the-loop-simulation

HIL

simulation method that allows a hardware under test to interact in a closed loop with a real-time simulation model

Note 1 to entry: In this document the simulation includes electrical emulation of sensors, control signals and actuators, where the electrical emulations act as the interface between the embedded hardware of the power plant controller and the power plant is simulated under the tests.

3.16

installed capacity

sum of the declared ratings for the installed PGUs in the PP

3.17

maximum voltage change

d_{max}

maximum absolute voltage change during an observation period.

Note 1 to entry: For detailed information about the calculation of d_{max} , see IEC 61000-4-15.

3.18

negative sequence component of the fundamental

<for a three-phase system with phases L1, L2 and L3> one of the three symmetrical sequence components which exists only in an unsymmetrical three-phase system of sinusoidal quantities and which is defined by the following complex mathematical expression::

$$\underline{X}_2 = \frac{1}{3} \left(\underline{X}_{L1} + \underline{a}^2 \underline{X}_{L2} + \underline{a} \underline{X}_{L3} \right) \quad (4)$$

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

Note 1 to entry: Negative sequence voltage or current components can be significant only when the voltages or currents, respectively, are unbalanced. For example, if phase voltage phasors are symmetrical $\underline{U}_{L1} = \underline{U}e^{j\theta}$, $\underline{U}_{L2} = \underline{U}e^{j(\theta+4\pi/3)}$ and $\underline{U}_{L3} = \underline{U}e^{j(\theta+2\pi/3)}$ then $\underline{U}_2 = (\underline{U}e^{j\theta} + e^{j4\pi/3} \underline{U}e^{j(\theta+4\pi/3)} + e^{j2\pi/3} \underline{U}e^{j(\theta+2\pi/3)})/3 = \underline{U}e^{j\theta} (1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

[SOURCE: IEC 60050-448:1995, 448-11-28, modified – clarified the $\underline{a}$ operator and note added.]

3.19**network impedance phase angle**

phase angle of the network short-circuit impedance:

$$\psi_k = \arctan(X_k/R_k) \quad (5)$$

where

X_k is the network short-circuit reactance

R_k is the network short-circuit resistance

3.20**nominal apparent power**

apparent power from the power plant while operating at nominal current and nominal voltage and frequency:

$$S_n = \sqrt{3}U_n I_n \text{ at } Q = 0 \quad (6)$$

where

U_n is the nominal voltage at the POC of the PP

I_n is the nominal current at the POC of the PP

3.21**nominal current**

nominal value I_n of the power plant current, which is calculated from the nominal active power

P_n and the nominal voltage U_n according to $I_n = \frac{P_n}{\sqrt{3}U_n}$

Note 1 to entry: I_n is mainly used for the normalization of the results and the p.u. calculations.

3.22**nominal active power**

P_n

nominal value of the power plant active power agreed between the grid operator and the plant owner

Note 1 to entry: P_n is typically used for the normalization of the results and as the base value for the p.u. calculations (active, reactive, apparent power etc.).

3.23**normal operation**

fault free operation as defined by the power plant specification

3.24**operational mode**

settable mode of operation, for example voltage control mode, frequency control mode, reactive power control mode, active power control mode, etc.

3.25 overshoot

difference between the maximum measured value of the response and the steady state final value

Note 1 to entry: See Figure 1.

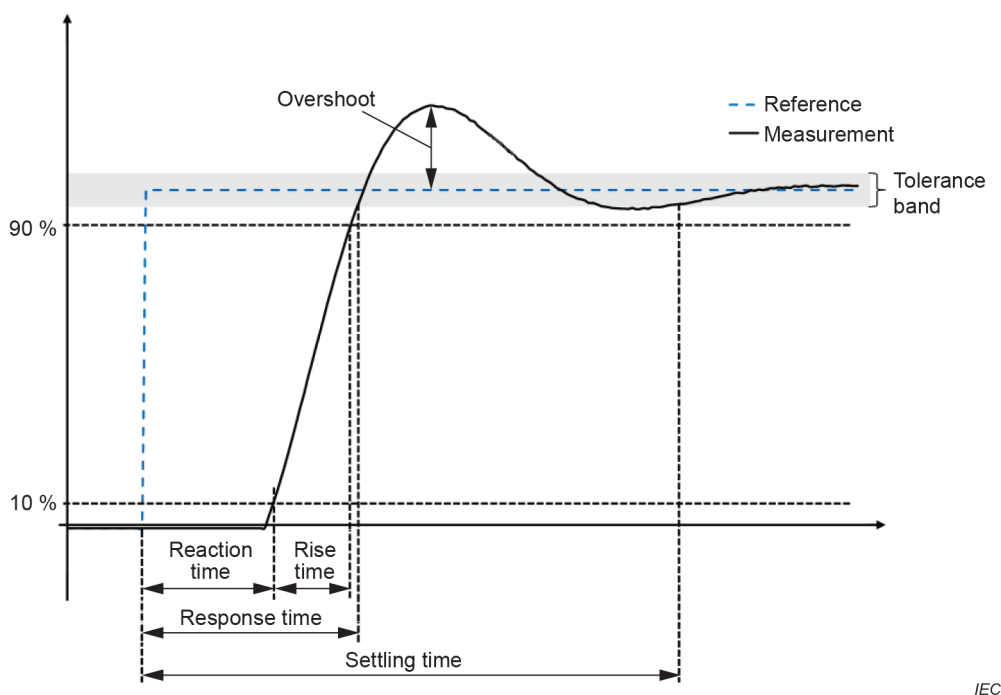


Figure 1 – Example of step response

3.26 overvoltage ride-through OVRT

ability of a PGU or PP to stay connected during voltage swells

3.27 percentile

value of a variable below which a certain percentage of observations fall

3.28 performance

steady state and dynamic fulfilment according to the specification of the complete system in relation to the defined parameters

3.29 performance test

measurements and tests carried out to determine the performance of the power plant at a given site against selected parameters as defined in this document to archive an intended function

3.30 plant owner

natural or legal entity owning a power plant and responsible for the connection agreement with the regulatory authority/system operator

3.31 point of connection POC

agreed point in the electric power system where the power plant is connected and is obliged to fulfil the requirements

3.32 positive sequence component of the fundamental

<for a three-phase system with phases L1, L2 and L3> one of the three symmetrical sequence components which exists in symmetrical and unsymmetrical three-phase system(s) of sinusoidal quantities and which is defined by the following complex mathematical expression:

$$\underline{X}_1 = \frac{1}{3} (\underline{X}_{L1} + a \underline{X}_{L2} + a^2 \underline{X}_{L3}) \quad (7)$$

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

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

[SOURCE: IEC 60050-448:1995, 448-11-27, modified – clarified the a operator and note added.]

3.33 power bin

consecutive, non-overlapping intervals of the power plant active power measured at the power plant terminals

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

3.34 power collection system

electrical system that collects the power from power generation units and feeds it into an electrical supply network

[SOURCE: IEC 60050-415:1999, 415-04-06, modified – “wind turbine generator system” replaced with “power generation units”.]

3.35 power generation unit PGU

smallest set of equipment that can generate electrical energy and feed the electricity into an electric power network

EXAMPLE: Wind turbines, which use wind energy as the primary source of energy and convert this into electrical energy.

3.36 power plant PP

power station comprising one or more power generating units, additional plant components, tap changers, plant control, etc.

3.37**power plant controller****PPC**

device that includes all the control functions necessary for the operation of the power plant

3.38 **Q capability**

reactive power capability of a power plant, including the collector grid and contribution of reactive power compensation devices, etc., up to the POC

Note 1 to entry: Q capability can vary depending on the output power of the PP and the voltage at the POC.

3.39**ramp-down time**

time taken for the measured value to decrease from 90 % to 10 % of the step change

3.40**reaction time**

elapsed time from the setpoint step change to when the measured value reaches 10 % of the step change

Note 1 to entry: See Figure 1.

3.41**recovery time**

elapsed time between the end of the inertia event and the point in time when the active power enters the predefined tolerance band around the pre-event active power value for the last time

3.42**response time**

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

Note 1 to entry: See Figure 1.

Note 2 to entry: If the target value is not provided during events, the steady state value can be used.

3.43**rise time**

elapsed time from when the measured value reaches 10 % of the step change until the measured value reaches 90 % of the step change

Note 1 to entry: See Figure 1.

3.44**settling time**

elapsed time from the start of the step change or start of event until the observed value enters the predefined tolerance band of the target value for the last time

Note 1 to entry: See Figure 1.

Note 2 to entry: If the target value is not provided during events, the steady state value can be used instead.

3.45**short-circuit apparent power**

product of the current in the short circuit at a point of a system and a conventional voltage, generally the operating voltage

[SOURCE: IEC 60050-601:1985: 601-01-14]

3.46**short-circuit ratio****SCR**

ratio of the short-circuit apparent power S_k to the nominal power S_n

$$SCR = \frac{S_k}{S_n} \quad (8)$$

3.47**start of event**

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

Note 1 to entry: The stimulus can be a reference signal or a disturbance.

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

3.48**static error**

deviation between the obtained values (observed or measured) and a requested reference value (or setpoint value)

EXAMPLE 1: If the measured value is greater than the setpoint value, the static error or deviation shall have a positive value.

EXAMPLE 2: If the measured value is less than the setpoint value, the static error or deviation shall have a negative value.

3.49**steady state**

system state obtained when the settling time has expired

3.50**substation**

part of an electrical system confined to a given area, mainly including terminations of transmission or distribution lines, electrical switchgear, protection, control and SCADA equipment, buildings and transformers

Note 1 to entry: The substation can be qualified according to the designation of the system of which it forms a part, for example switching station (transmission system), distribution substation, 400 kV or 20 kV substation.

[SOURCE: IEC 60050-601:1985, 601-03-02, modified – “protection, control and SCADA equipment” has been added and the second part of the definition has been removed.]

3.51**sub-system**

system which consists of several components or elements, which are directly related to each other

3.52**sub-system test**

test on a sub-system, whose necessary functions and required behaviour are not dependent on other components or systems.

Note 1 to entry: Tests done on a sub-system are valid for all turbine variants, where the same sub-system is applied.

3.53**synthetic inertia**

response of a power generating unit or power plant active power production as a function of time after a sudden change in the grid frequency

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

3.54**time-series**

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

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

3.55**tolerance band**

acceptable deviation range of the measured signal from the defined target value

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

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

3.56**unbalance factor**

in a three-phase system, the degree of unbalance expressed by the ratio $|\underline{X}_2/\underline{X}_1|$ (in percent) between the values of the negative sequence component X_2 and the positive sequence component X_1 of voltage or current

[SOURCE: IEC 60050-614:2016, 614-01-33, modified – operator X added and RMS values removed.]

3.57**undervoltage ride-through****UVRT**

ability of a power generating unit or power plant to stay connected during voltage dips

3.58**validation**

confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled

Note 1 to entry: In relation to this document, the defined test & measurement procedures are validation procedures as the validation is based on experimental data in relation to an intended use.

Note 2 to entry: In this document the defined tests procedures etc. are validation tests, as the IS does not verify that specific requirements are met.

[SOURCE: IEC 60050-192:2015, 192-01-18, modified – the notes have been removed and new notes added.]

3.59**verification**

confirmation, through the provision of objective evidence, that specified (system) requirements have been fulfilled

Note 1 to entry: In relation to this document the measurement results can be used to assess conformity of the PP to a specified requirement, for example to verify that the PP fulfils for example specific grid code requirements.

3.60 voltage change

d_c

maximum steady state voltage change during an observation period

Note 1 to entry: For detailed information about the calculation of d_c , see IEC 61000-4-15.

3.61 voltage change factor

normalized measure of the voltage change due to a switching operation of the power generating unit:

$$k_u(\psi_k) = \sqrt{3} \times \frac{U_{\text{fic,max}} - U_{\text{fic,min}}}{U_n} \times \frac{S_{k,\text{fic}}}{S_n} \quad (9)$$

where

$U_{\text{fic,min}}$ and $U_{\text{fic,max}}$ 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 at the PGU terminals

S_n is the nominal apparent power of the PGU

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

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

3.62 voltage dip

limited duration non-periodic sudden decrease of the power supply network's voltage amplitude and associated phase changes

3.63 voltage swell

limited duration non-periodic sudden increase of the power supply network's voltage amplitude above its nominal value and associated phase changes

3.64 wind turbine WT

system which converts kinetic wind energy into electrical energy

[SOURCE: IEC 60050-415:1999, 415-01-01, modified – “into another form of energy” replaced with “electrical energy”.]

3.65**zero sequence component of the fundamental**

<for a three-phase system with phases L1, L2 and L3> one of the three symmetrical sequence components which exists only in an unsymmetrical three-phase system of sinusoidal quantities and which is defined by the following complex mathematical expression:

$$\underline{X}_0 = \frac{1}{3}(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3}) \quad (10)$$

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

[SOURCE: IEC 60050-448:1995, 448-11-29]

4 Symbols and abbreviated terms

For the purposes of this document, the following symbols and abbreviated terms are used.

4.1 Symbols

$\frac{\Delta U_{\text{dyn}}}{U_n}$	maximum permitted voltage change (%)
ψ_k	network impedance phase angle (°)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (°)
β	exponent associated with summation of harmonics
$c(\psi_k)$	flicker coefficient for continuous operation
d	relative voltage change (%)
d_c	steady state voltage change
d_{max}	maximum voltage change
E_{Plti}	long-term flicker emission limit
E_{Psti}	short-term flicker emission limit
f_g	nominal grid frequency (50 Hz or 60 Hz)
$f_{\text{inertia, recovery}}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{\text{inertia, trigger}}$	frequency threshold where the turbine shall start boosting active power (Hz)
f_{over}	overfrequency protection / control activation level (Hz)
f_{under}	underfrequency protection / control activation level (Hz)
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	nominal current (A)
IUF	current unbalance factor
$k_f(\psi_k)$	flicker step factor

k_i	ratio of maximum inrush current and nominal current
$k_u(\psi_k)$	voltage change factor
L_{fic}	inductance of fictitious grid (H)
n_i	ratio of the transformer at the i^{th} wind turbine
N_m	total number of measured flicker coefficient values
N_{wt}	number of wind turbines
P	active power (W)
$P_{\text{available}}$	available active power (W)
P_{capacity}	installed capacity of the PP including additional plant components (W)
P_{lt}	long-term flicker severity
P_n	nominal active power of the power plant (W)
$Pr(c < x)$	accumulated distribution of c
P_{st}	short-term flicker severity
$P_{\text{st,fic}}$	short-term flicker severity at fictitious grid
POC	point of connection
Q	reactive power (var)
R_{fic}	resistance of fictitious grid (Ω)
$RoCoF$	rate of change of frequency
S_k	short-circuit apparent power of grid (VA)
$S_{k,\text{fic}}$	short-circuit apparent power of the fictitious grid (VA)
S_n	nominal apparent power of a PP (VA)
T_p	transient time period of a switching operation (s)
U	phase-to-phase voltage (V)
$u_0(t)$	instantaneous phase-to-neutral voltage of an ideal voltage source (V)
$u_{\text{fic}}(t)$	instantaneous phase-to-neutral voltage simulated at fictitious grid (V)
$U_{\text{fic,max}}$	maximum phase-to-neutral voltage at fictitious grid (V)
$U_{\text{fic,min}}$	minimum phase-to-neutral voltage at fictitious grid (V)
U_n	nominal phase-to-phase voltage (V)
U_{under}	undervoltage protection level (V)
U_{over}	overvoltage protection level (V)
U_{pre}	pre-fault voltage (V)
UUF	voltage unbalance factor
X_{fic}	reactance of fictitious grid (Ω)

4.2 Abbreviated terms

A/D converter	analog-to-digital converter
CAP	capacitor
DFAG	doubly-fed asynchronous generator (often referred to as a doubly-fed induction generator (DFIG), but it is not operated as an induction generator when the rotor current is controlled)
DFT	discrete Fourier transformation
DSO	distribution system operator
DUT	device under test
EHV	extra-high voltage
FRT	fault ride-through
HIL	hardware in the loop
HV	high voltage
HVDC	high voltage direct current
HW	hardware
LV	low voltage
MV	medium voltage
OVRT	overvoltage ride-through
PGU	power generation unit
PP	power plant
POC	point of connection
PPC	power plant controller
RCVD	resistive capacitive voltage divider
RMS	root mean square
RoCoF	rate of change of frequency
SCADA	supervisory control and data acquisition
SLD	single line diagram
STATCOM	STATic synchronous COMpensator
SVC	static var compensation
SW	software
THC	total harmonic current distortion
TSO	transmission system operator
UVRT	undervoltage ride-through
WT	wind turbine

5 Power plant specifications

The nominal data of the power plant (referring to the POC) shall be specified, including P_n , U_n , and the agreed performance. The following minimum information shall be stated as part of the documentation:

- nominal active power P_n ;
- agreed reactive power;
- nominal voltage U_n and the agreed voltage range;

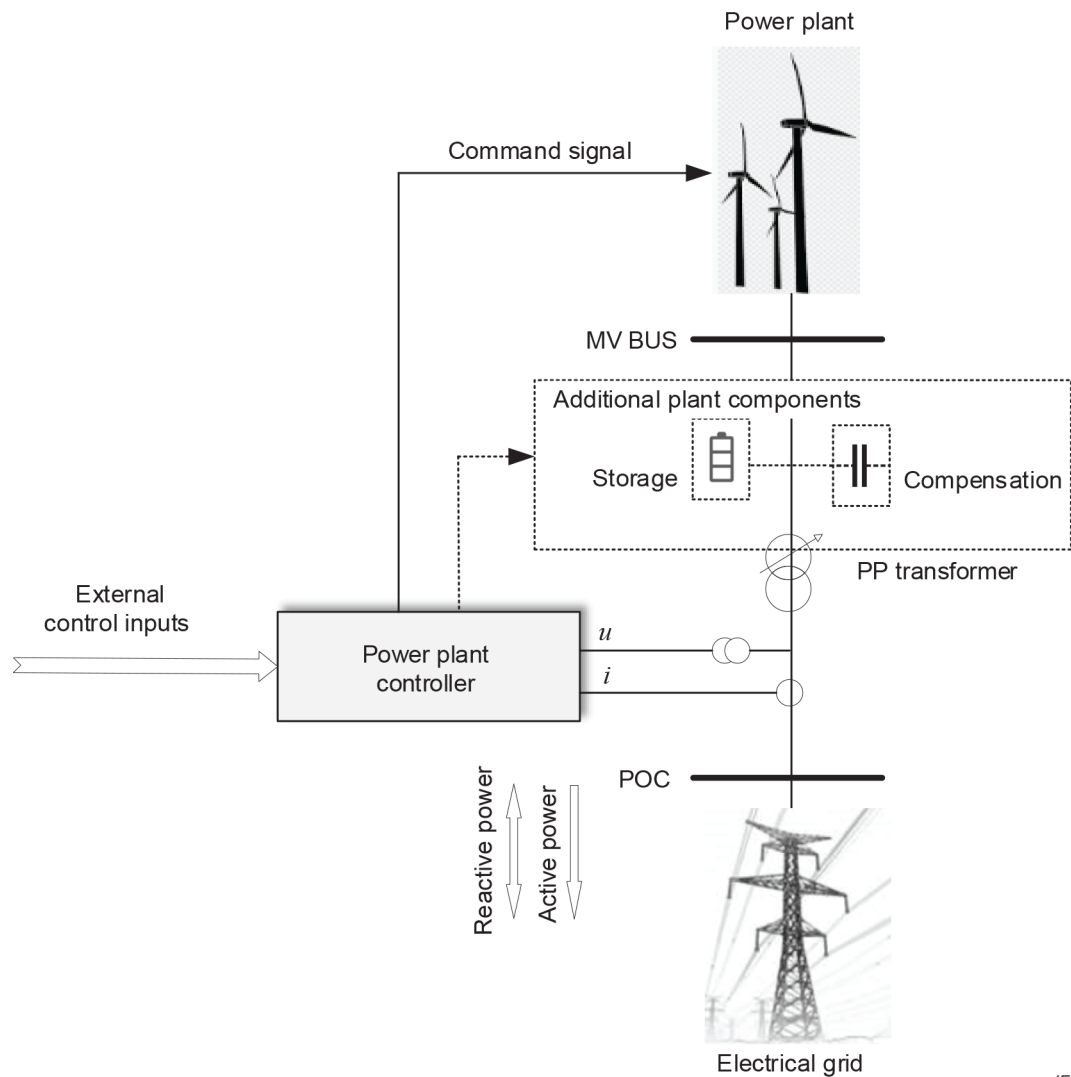
- PGU types, manufacturer and number of PGU;
- PPC type and manufacturer;
- SCADA system type and manufacturer;
- additional equipment in the PP (CAP-banks, STATCOM, etc.);
- single line diagram (SLD), including the collector grid and additional plant components, for example compensation equipment, grid connection points, tie lines, transformer/substation, etc.;
- agreed grid code requirements
- available control functions, agreed control functions, settings (droop, Q_{base} , slope, etc.);
- signal list and required signals for the exchange with the system operator and the plant owner;
- protection settings (overvoltage, undervoltage, overfrequency, etc.) for the PGU and the PP at the time of commissioning for the installed protection devices.

For further details, see 6.2. A template of the specification documentation is outlined in Annex A.

NOTE The nominal data are used only for normalizing purposes in this document.

The agreed reactive power can be defined as a PQ -chart, power factor, QU -chart, etc.

The substation transformer, cable data, etc., are relevant for the simulation model and model validation as defined in IEC 61400-27-1 and IEC 61400-27-2.



IEC

Figure 2 – Example of a PP setup

Figure 2 shows a schematic overview of a PP, including the PGUs, the PPC, the grid interface to the POC, the control interface, as well as potential additional plant components of the PP.

Compliance of the PP can depend on additional equipment, for example the reactive power capability of the PGUs is not sufficient to be compliant, and compensation equipment is needed in the form of a STATCOM (or CAP-bank), or the synthetic inertia response depends on a battery storage system and therefore additional equipment should be included in the test.

The component level test of additional equipment is not part of this document.

6 Overall test and documentation requirements

6.1 General

Clause 6 defines the overall test conditions, monitoring and reporting requirements necessary for the assessment of the electrical characteristics of a PP, as well as the overall measurement equipment. A sample report format is given in Annex A.

This document only considers PPs with one single POC for the measurements and analysis.

The typical setup is to have a number of feeders in the PP, that are all feeding into one (wind farm) substation transformer. The POC will typically be the HV side of the same transformer.

Generator sign convention shall be used, i.e. the positive direction of the power flow is defined to be from the generator to the grid. If the PP is replaced with a resistor and an inductor, both active and reactive power will be negative (see 61400-21-1:2019, Annex C).

Table 1 gives an overview of the measurements according to this document at the POC and the required conditions for performing each of these tests and measurements. Additional details about the operating and test conditions are defined in the respective clauses or subclauses of this document.

Table 1 – Overview of measurements and their requirements

Subclause		Conditions				Comments (see specific subclause for details)
		$P_{\text{capacity}} > 90 \% P_n^a$	$P_{\text{available}} > 50 \% P_n$	$P_{\text{available}} > 80 \% P_n$	Test level	
Power quality aspects						
7.2.2	Flicker	X			PP	Continuous recording ^b
7.2.3	Rapid voltage changes due to Switching operations	X		X	PP	
7.2.4	Harmonics, interharmonics and higher frequency components	X			PP	Continuous recording ^b
Steady state operation						
7.3.2	Unbalance	X			PP	Continuous recording ^b
Dynamic performance						
7.4.1	Fault ride-through capability				PGU	Fault recording / event logging
Disconnection from grid						
7.5.3	PP level – Grid protection				Subsystem / Component	
7.5.4	PGU level – Grid protection				Subsystem / Component	
Control performance						
Performance test						
8.2.2	Active power control	X	X		PP	
8.2.3	Controlled shutdown	X	X		PP	
8.2.4	Synthetic inertia	X	X	X	PP	One test shall be performed with $P_{\text{avail}} > 25 \% P_n$
8.2.5	Reactive power control	X	X		PP	
8.2.6	Reactive power capability	X		X	PP	

Subclause		Conditions				Comments (see specific subclause for details)
		$P_{\text{capacity}} > 90 \% ^a$	$P_{\text{available}} > 50 \% P_n$	$P_{\text{available}} > 80 \% P_n$	Test level	
Functionality test						
8.3.2	Active power ramp rate limitation	(X)	(X)		HIL	
8.3.3	Priority of setpoints	(X)	(X)		HIL	
8.3.4	Frequency control	(X)	(X)		HIL	
8.3.5	Reactive power ramp rate limitation	(X)	(X)		HIL	
8.3.6	Voltage control $Q(U)$	(X)	(X)		HIL	
8.3.7	Power factor control	(X)	(X)		HIL	
8.3.8	Communication error / Fallback scenarios	(X)			HIL	
Assessment of power quality						
9.2	Voltage fluctuations				PGU	Based on calculations from IEC 61400-21-1
9.2.2	Continuous operation				PGU	Based on calculations from IEC 61400 -21-1
9.2.3	Switching operations				PGU	Based on calculations from IEC 61400-21-1
9.3	Harmonics, interharmonics and higher frequency components				PGU	Based on calculations from IEC 61400-21-1
X: Strongly recommended						
(X): Recommended in certain cases (see Annex C)						
^a $P_{\text{capacity}} > 90 \%$ –more than 90 % of installed capacity of PP equipment are in normal operation.						
^b Continuous measurements are done for all power ranges or given time intervals.						

6.2 Test conditions, monitoring and reporting requirements

The following test conditions are required and shall be measured and reported as part of the test procedure.

Test and measurement results shall be excluded or clearly marked, if they cannot be obtained under the required test conditions or if the external influence on the test results cannot be avoided.

Grid and test conditions

- The voltage level shall be inside the agreed voltage range, measured as 10 min average data at the POC. If nothing is stated in the connection agreement, the voltage range shall be inside the voltage level as defined in IEC 60038, typically $\pm 10 \%$ of the nominal voltage.
- The grid frequency shall be inside the agreed frequency range measured as 0,2 s average values at the POC. If nothing is stated, the frequency shall be within $\pm 0,2 \%$ of the nominal frequency.

- c) The voltage unbalance factor shall be less than 2 % measured as 10 min average data at the POC. The voltage unbalance factor shall be determined as described in IEC 61000-4-30. It is defined as the ratio of the negative sequence to the positive sequence components of the voltage.
- d) The total harmonic distortion of the voltage, including all harmonics up to the order of 50, shall comply with IEC TR 61000-3-6 measured as 10 min average data at the POC, while the plant is not generating (background noise).
- e) The environmental conditions (temperature, altitude, etc.) shall comply with the plant owner's requirements for the power plant.
Normally 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.

Monitoring and reporting requirements

- 1) The short-circuit ratio SCR, defined as the ratio of the short-circuit apparent power to the nominal power of the PP, as well as the grid impedance (complex value), shall be stated in the report.
- 2) The number of turbines in operation as well as the additional plant components during the test and measurements shall be stated in the report.
- 3) The operational state and operational limits of the plant during the different tests and measurements shall be clearly stated in the report and shall be within the required levels and operational states as defined in the corresponding subclauses.
- 4) The status of the online tap-changer of the main transformer should be monitored during the measurements, if it influences the results.
- 5) A single-line-diagram (SLD), including the collector grid, compensation equipment, grid connection points as well as any transformers or substations, shall be stated in the test report.
- 6) The test report shall include the following additional information:
 - plant owner;
 - site name and address;
 - name of responsible grid operator / grid owner;
 - name of system operator / system responsible;
 - nominal voltage;
 - nominal frequency;
 - nominal active power, export capacity, installed capacity and technical minimum;
 - reactive power capability, export capacity, installed capacity and technical minimum;
 - PGU types, manufacturer and number of PGUs;
 - PPC type and manufacturer;
 - SCADA system type and manufacturer;
 - available control functions and agreed control functions and performance;
 - list of signals including system operator signals and plant owner signals;
 - protection settings (overvoltage, undervoltage, overfrequency, etc.), for the PGU and the PP at the time of commissioning for the installed protection devices.

An example template for the test report is given in Annex A.

All measured data and time series, etc., shall be available in electronic form.

6.3 Test conditions in the case of external influences

Measurements that are clearly influenced by external influences, for example from a neighbouring power plant connected to the same substation, shall be done in a way where the influence is minimized.

EXAMPLE Voltage control where two PPs are connected to the same substation and the reactive power response of the single park can be very different from what is expected, due to the interaction with the other PP. In this case the best solution for doing this test is to have the PP under test in voltage control mode and to set any other PP on the same POC in the reactive power control mode with a fixed setpoint to minimize the influence from the other PP.

For power quality measurements, it is important to consider whether the measurements can be influenced by background noise. See IEC 61400-21-1:2019, Annex D, for methods to distinguish between background noise and real harmonic emission.

6.4 Test and measurement equipment

6.4.1 General

The equipment for performing the measurements at the POC level will require different characteristics depending on the quantities being measured.

Considering control of active or reactive power, existing measurement equipment at the power plant substation will be sufficient if they provide the requested values and precision.

However, with regard to power quality aspects, equipment with specific characteristics are required in accordance with 6.4.3.

In both cases, the time stamp shall be included in order to be able to synchronize the different signals and setpoints that can be recorded from other devices or the SCADA system. The time stamp will be included as indicated in IEC 61000-4-30. The precision shall comply with IEC/IEEE 61850-9-3.

6.4.2 Voltage, current and power calculations

The active and reactive power values, as well as the positive, negative and zero sequence components of the active and reactive current, and the power factor and voltages, can be calculated based on the measured instantaneous phase voltages and currents, as defined in IEC 61400-21-1:2019, Annex C.

6.4.3 Measurement equipment

The accuracy of the measurement equipment shall be stated in the measurement report.

The sampling rate for measurements of harmonics up to the 50th harmonic shall be at least 12 kHz.

Interharmonics and higher frequency components shall be measured with a sampling rate of at least 40 kHz in order to ensure that frequency components up to 9 kHz can be measured.

Measurement equipment for power quality should comply with the defined accuracy of class A in accordance with IEC 61000-4-30.

If existing equipment on the HV side is used, the precision and frequency characteristic shall be stated. If voltage and current transformers are used, they shall comply with class 1,0.

- Current transformer shall comply with IEC 61869-2.
- Voltage transformers shall comply with IEC 61869-3.

An overview of different voltage and current measurement devices, their typical application range bandwidth and their limitations is given in Annex D.

6.4.4 Existing measurement equipment for power control tests

In order to verify the active and reactive power control, the existing measuring equipment at the power plant substation may be used. The measuring equipment shall provide the requested data and values as defined in the respective subclause. The minimum update rate is 10 Hz. The control setpoints obtained by the SCADA system shall be synchronized appropriately with the time-stamps of the measurements.

To verify the measurement precision and to calculate the measurement uncertainties, the necessary data of the existing measurement system at the PP shall be provided.

6.4.5 Optional measurements

- Wind speed:

This document does not consider the wind speed data mandatory information to be included in the proposed report shown in Annex A. However, the wind speed data can be added to the measurements by using the data from the SCADA system for documenting the measurements adding statistical information. This would be possible only if the signals have been synchronized appropriately as indicated above.

- Neighbouring power plants:

This document does not consider the influence or power production from neighbouring PPs as mandatory information. However, the influence of the neighbouring power plant can be added to the measurements as additional documentation.

6.5 Functional and performance test

The method for assessing the behaviour of the PP depends mainly on the voltage level at the POC, the influence of the PP on the electricity grid in relation to the size of the PP, the installed capacity of the PP and the short-circuit level.

The validation of control functions on the PP is a combination of the performance of the individual PGUs, any additional plant components, the communication system and the PPC.

The control performance of the PP can be proved by combining performance tests on site with functionality tests carried out on a hardware-in-the-loop (HIL) setup, including a simulator.

The validation tests are therefore divided into two parts:

- 1) Performance tests – site specific tests including the PPC defined in 8.2.
- 2) Functionality tests – specific test rig (HIL test) or site specific tests including the PPC, defined in 8.3.

Functionality tests can be performed on a specific test setup (HIL test) or on site.

Performance tests are site dependent (e.g. number of turbines, cabling, grid behaviour, etc.) and there are many variables that could influence the results. Therefore, it is necessary that these tests are done at each specific site.

Functionality tests are not site dependent and allow to test these functionalities in a generic way on a test rig (HIL test). Functionalities can include ramp rate, setpoint handling, frequency control, voltage control, fallback scenarios, etc. See 8.3 and Table 1.

Performance tests and functionality tests, provide the complete control performance of the PP. The test procedures for the different tests are defined in Clause 8.

Annex C gives guidelines for which tests and assessment methods (measurements, simulation validation, functionality tests, etc.) are recommended for the performance validation of the PP, depending on the size of the PP, the short-circuit level and the voltage level at the POC.

6.6 Power plant controller

6.6.1 General

Subclause 6.6 describes the generic test setup for PPC control tests.

6.6.2 Definition and requirements

Figure 3 (reactive power control) and Figure 4 (active power control) show the general structure of a PPC within a PP.

For the external communication (e.g. setpoint values from the system operator) to the PP, an interface is applied. This interface transmits the external control setpoint to the PPC. The interface converts the external interface protocol to the internal communication protocol in the PPC.

The external control inputs are fed into the actual control core via the corresponding function blocks ($Q(P)$, $Q(U)$, etc.). The controller calculates and sends a command signal at the output to the controlling element/system (PP). The controlling element changes its output quantity, measured at the grid connection point POC.

The measured grid voltage and current at the POC are converted into the relevant electrical values (P , Q , f , $\cos \phi$, etc.) used in the park controller. These variables correspond to the actual values at the POC and are available in the controller.

NOTE Most SCADA/PPC systems store the internal data, for example the relevant setpoint and actual variables values. These data can be used as the measured data for the test method described here if they fulfil the requirements in 6.6.4. Alternatively, the data from an external measurement system (see 6.6.4) could be used for the analysis of the results.

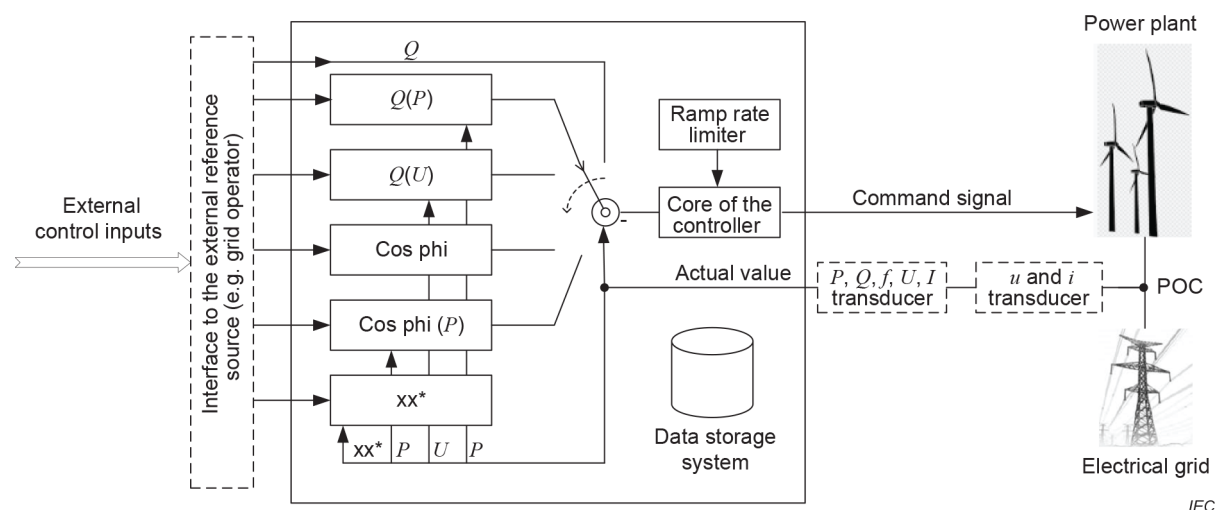
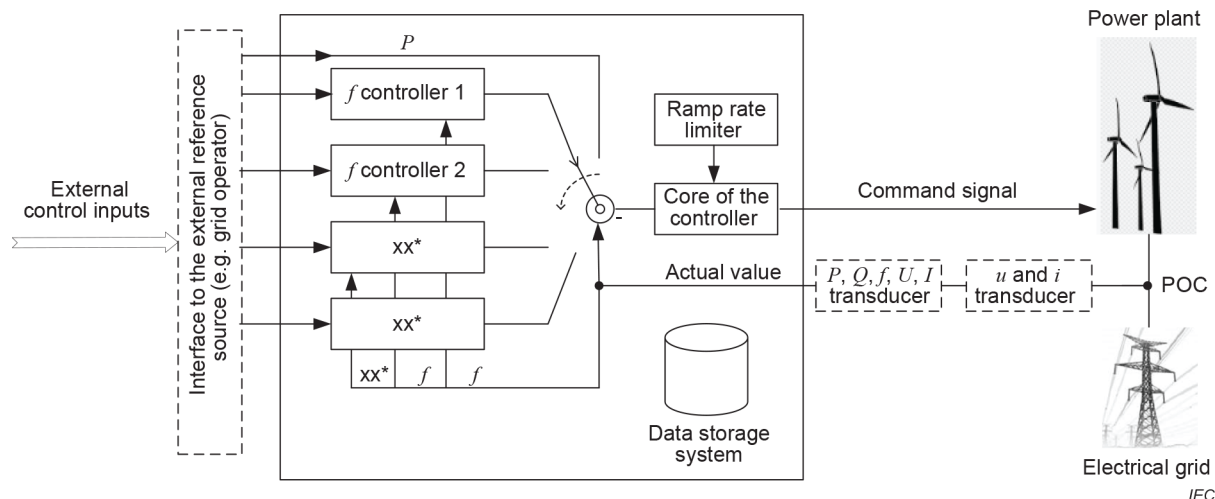


Figure 3 – General structure of a PPC for reactive power control within a power plant



*: placeholder for other control strategies

Figure 4 – General structure of a PPC for active power control within a power plant

6.6.3 Measurement points

The PPC has two inputs and one output at the system boundary, where it is necessary to perform the measurements. Examples of these boundaries are illustrated in Figure 3 and Figure 4 by the solid line. The dashed line interface, and any transducers or any other components not shown could be also part of the PPC. The precise setup has to be declared by the plant owner and documented as part of the test report.

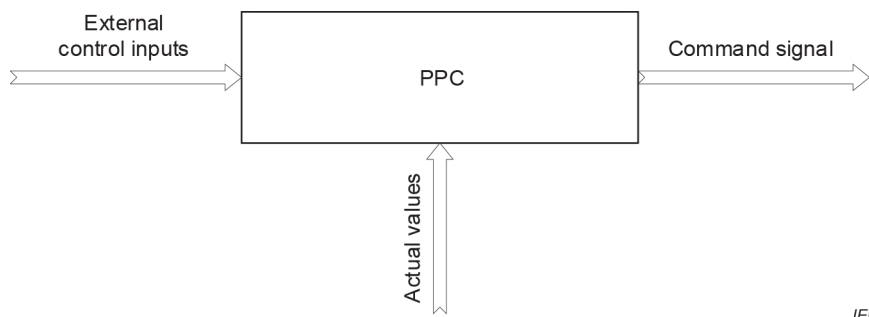
Inputs

- a) external control inputs (setpoints)
- b) actual values (measured feedback values)

Output

- c) command signals (setpoints to the PGUs)

It is required to measure the inputs a) and b) to show the functionality behaviour. In addition, it is recommended to measure the output c) to have a control signal available and to have the input and output of the simulated PP and electrical grid (see Figure 5). The delay time between the external control input and the command signal can also be measured.

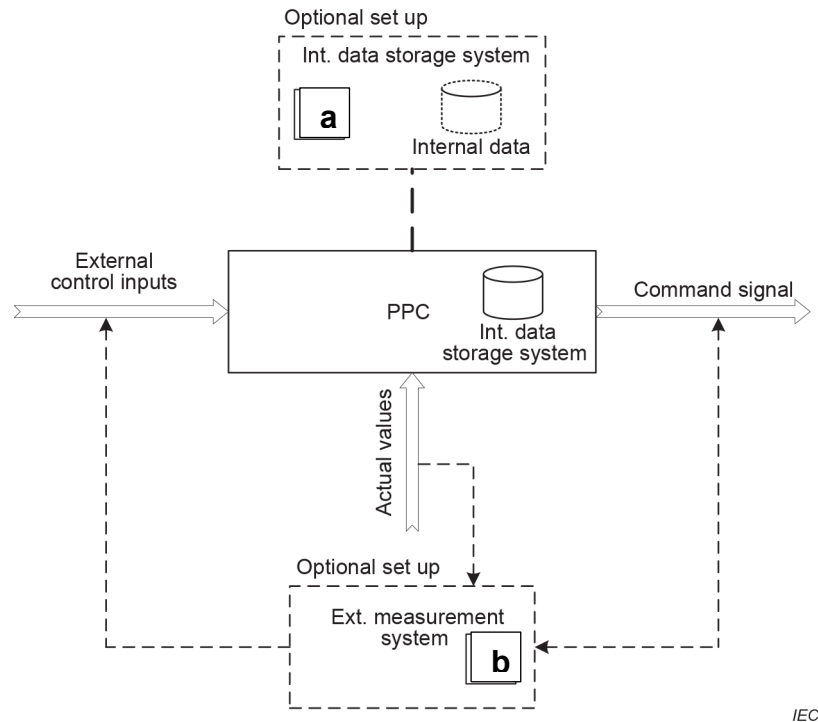


IEC

Figure 5 – Illustration of the PPC as a black box with in- and outputs

6.6.4 Measurement data

The requested data can be measured by specific measurement devices (external measurement system) or the PPC/SCADA system (internal data) according to Figure 6, if the requested values and parameters are as defined in 6.4 and as specified in 8.3.



IEC

Key

- a (optional): located physically outside the PPC
- b connection to an external measurement system)

Figure 6 – Illustration of the PPC with the internal system data

6.6.5 Test setup

Subclause 6.6.5 gives a more specific description of the test setup, which is a combination of:

- the PPC as HIL,
- the simulation of the electrical grid,
- the simulation of the PP,
- the simulation/ emulation of the measurement system (U , I , P , Q , f , etc.),
- the source of the external control values.

The device under test (DUT), including the HW and SW, is embedded in the test setup. The PPC shall consist of the original technical setup inside the boundary (see Figure 3 and Figure 4), just as it would be within a real PP.

The test setup itself shall be designed to show the functional behaviour of the PPC.

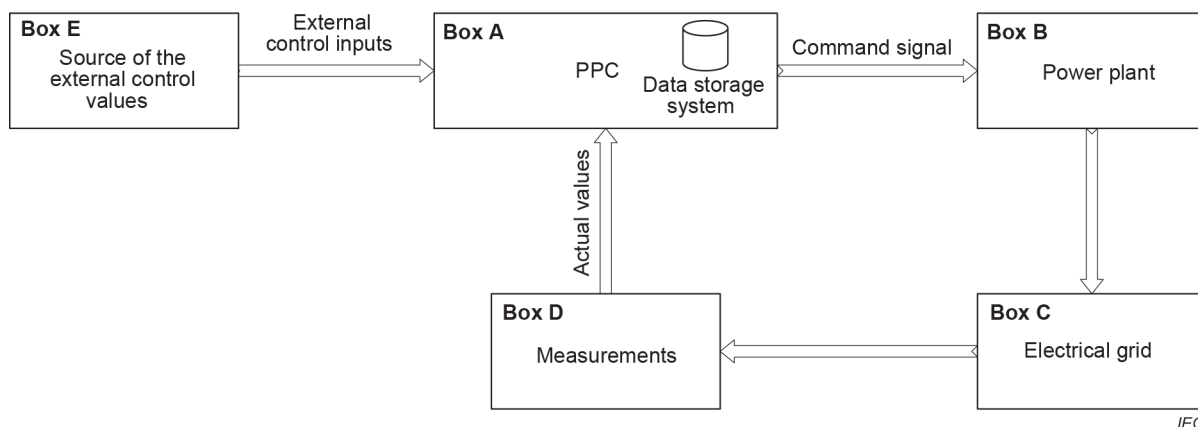


Figure 7 – Illustration of a complete test setup

Table 2 describes the HIL setup including the boxes A to E in Figure 7 in more detail. The HIL setup consists of simulation methods that allow a hardware under test of the PPC to interact in a closed loop with a real-time simulation model, including electrical simulation/emulation of sensors, control signals and setpoint control. The measurement data setup from the PPC is shown in Figure 6.

Table 2 – Description and general requirements of the HIL test functional

Box	Item
A	PPC: The PPC (DUT) in the HIL shall consist of the same technical setup (hardware and software) defined by the manufacturer as that in use in a PP.
B	Power plant: The simulation of the PP operating on the simulated electrical grid shall react on the command signals from the PPC. The PP shall represent the different P and Q control functions and the limitations of the PGU/PP. The PP model can be an aggregated simulation model of the PGUs, representing at least one PGU (e.g., as defined in the IEC 61400-27-1).
C	Electrical grid: Simulation or emulation of the electrical grid including configurable SCR ratio and impedance phase angle (X/R ratio). The electrical grid shall be able to simulate different grid faults, including voltage and frequency events.
D	Measurements: Simulation or emulation of the measurement system including, the calculation of RMS values, frequency measurements and scaling of CT and VT signals.
E	Source of external control values: Setpoints for the PPC as requested, for example from the grid operator. The setpoints can be generated automatically or manually for the different functionality tests.

6.6.6 Documentation

For the test results defined in 8.3, the following documentation is required:

- description of PPC; type, model, SW-version and manufacturer;
- description of the test setup – HIL setup;
- limitation of test setup (e.g. constant wind, SCR, which could influence the test results);
- external control interface; type, sampling rate, data format, etc.;
- measurement setup (internal or external measurements); sample rate, signal interface type, data format, etc.;
- update/sampling rates and time delays from box E to box A, from box A to box B and from box D to box A (according to Figure 7).

7 Measurement and test of electrical characteristics

7.1 General

Clause 7 defines the test and measurements procedures in relation to the electrical capabilities of the PP at the POC. The defined procedures are closely related to the tests specified in IEC 61400-21-1, where the measurements are defined for a single PGU and measured at the terminals of the PGU.

If nothing else is stated, the general requirements for the test equipment and test conditions according to Clause 6 apply.

7.2 Power quality aspects

7.2.1 General

Subclause 7.2 defines the test and measurement procedures in relation to the power quality aspects of the PP at the POC.

7.2.2 Flicker during continuous operation

7.2.2.1 Overview

The aim of the measurement is the determination of voltage flicker at the POC of the PP during continuous operation.

7.2.2.2 Test setup and test conditions

The general requirements of this document for the test equipment and test conditions apply as described in Clause 6.

The following additional specific conditions are required:

- Background voltage flicker shall be as low as possible. Voltage flicker should comply with the limits of IEC 61000 (all parts). In the selected period, the typical wind speeds for the specific site shall appear.

7.2.2.3 Test and measurement procedure

Measurements shall be performed for at least 1 week with normal business activity, but preferably for more than 3 weeks. The measuring period should include some part of the period of expected maximum flicker levels. It is recommended that at least five 10 min periods are collected within the measuring period for each power bin up to 80 % of the nominal power of the PP.

The flicker effect of switchings of single PGUs can be considered as continuous operation of the PP and is already included in the measurement of flicker, as long as the measurement period is at least 1 week.

Measurements shall be performed with the reactive power setting equal to the typical setting for the site. Measurements with further settings are optional.

Flicker and rapid voltage change $d_{\max}$ and d_c in accordance with IEC 61000-4-15 shall be determined with one of the following methods:

a) Fictitious grid (option 1)

Measurement of currents and voltages at the POC of the complete PP and application of the method of the fictitious grid of IEC 61400-21-1:2019, 8.2.2, using the actual grid impedance at the POC to calculate the flicker (P_{st} and P_{lt}), voltage change $d_{\max}$ and the steady state voltage change d_c of the PP at the POC.

b) Direct voltage measurement (option 2)

Measurement of voltages at the POC. Determination of voltage flicker (P_{st} and P_{lt}) and $d_{\max}$ and d_c .

Due to the fact that the voltage flicker measurement is influenced by background flicker, it is essential to determine the background flicker levels as described below.

NOTE In case of high background flicker, the method of the fictitious grid (option 1) can be used, which minimizes the influence of the background flicker on the measured flicker of the PP.

Flicker background level:

- Flicker background levels should be measured without the PP in operation (preferably over 1 week or more).
- The measurement period should be of sufficient duration to obtain typical flicker background levels in different grid situations that coincide with the operation of the PP.
- Measurements can be carried out before or after commissioning of the PP.

7.2.2.4 Documentation

- For normal operation of the PP, including the switchings of the single PGUs: reporting of P_{st} and P_{lt} values and rapid voltage changes of the PP at the POC:
 - For P_{st} , the 10 min 95 % and 99 % probability value of the complete measurement period shall be reported.
 - For P_{lt} , the 95 % probability value of the complete measurement period shall be reported.
 - For the maximum voltage change $d_{\max}$ and the steady state voltage change d_c the 95 % and 99 % probability values of the complete measurement period shall be reported.
- For the measurement of the flicker background level: reporting of the P_{st} and P_{lt} values and rapid voltage changes at the POC:
 - For P_{st} , the 10 min 95 % and 99 % probability value of the complete measurement period shall be reported.
 - For P_{lt} , the 95 % probability value of the complete measurement period shall be reported.
 - For the maximum voltage change $d_{\max}$ and the steady state voltage change d_c , the 95 % and 99 % probability values of the complete measurement period shall be reported.

7.2.3 Rapid voltage changes due to switching operations

7.2.3.1 Overview

The aim of these measurements is to determine the voltage change and flicker P_{st} values at the POC of the PP during switching operations.

7.2.3.2 Test setup and test conditions

The general requirements of this document for the test equipment and test conditions in accordance with Clause 6 apply.

Further specific conditions are required:

- Background voltage flicker shall be as low as possible. Voltage flicker should comply with the limits of the IEC 61000 series.

7.2.3.3 Test and measurement procedure

The following switching operations shall be performed:

- PP starting/stopping;
- energizing transformers (optional; it can be of importance for some PPs or systems);
- reactive power compensation units at the PP level.

Switching operations include start-up and shut-down.

Voltage change and flicker shall be determined with one of the following methods:

a) Fictitious grid (option 1)

Measurement of currents and voltages at the POC of the complete PP and application of the method of the fictitious grid of 61400-21-1:2019, 8.2.2, using the actual grid impedance at the POC to calculate the voltage flicker P_{st} , and d_{max} and d_c of the PP at the POC during the switching.

b) Direct voltage measurement (option 2)

Measurement of voltages at the POC. Determination of voltage flicker P_{st} and d_{max} and d_c .

Measurements shall be performed with the reactive power setting equal to the typical setting for the site. Measurements with further settings are optional.

It is recommended to perform three switching operations (at least one) for each type of switching.

7.2.3.4 Documentation

For each type of switching:

- Reporting of maximum voltage change d_{max} and the steady state voltage change d_c .
- Reporting of the maximum flicker P_{st} value.

If more than one switching is taken for the same type of switching, then the average result values of d_{max} , d_c and flicker P_{st} shall be reported.

7.2.4 Harmonics

7.2.4.1 Overview

The aim of this measurement is to determine the voltage and current harmonics at the POC of the PP during continuous operation.

NOTE Additional explanations are given in Annex B.

7.2.4.2 Test setup and test conditions

The general requirements of this document for the test equipment and test conditions according to Clause 6 apply.

The measurement period shall include data covering the typical power range for the site in question.

The bandwidth of the measurement transducers shall cover the harmonic range of interest. The voltage and current transducers used for this type of measurement should comply with the requirements given in IEC 61000-4-30. The measurement sensors should be capable of measuring the frequency components (i.e. harmonics and interharmonics) of interest.

There should be agreement on the transducers used for the specific test campaign. In new PPs, adequate transducers should be installed. Inductive VTs bandwidth is limited for HV installations, which is why RCVDs can be more a feasible solution.

7.2.4.3 Test and measurement procedure

The following procedure shall be applied:

- The current and voltage harmonic, interharmonic and higher frequency distortion during continuous operation shall be stated.
- The harmonic components shall be grouped as described in IEC 61400-21-1.
- 10 min aggregation and 3 s aggregation are performed using the square root of the arithmetic mean of the squared 10-cycle (for a 50 Hz power system) or 12-cycle window values (for a 60 Hz power system) for each harmonic.
- Measurements shall be performed for normal operation of the PP over a certain period of time (minimum 1 week with normal business activity, preferably at least 3 months). The measuring period should include some part of the period of expected maximum harmonic levels. It is recommended that at least five 10 min periods are collected within the measuring period for each power bin up to 80 % of the nominal power of the PP.
- Measurements shall be performed with the reactive power setting equal to the typical setting for the site. Measurements with further settings are optional.
- The 10 min 95th percentile and the 99th percentile of each harmonic order, interharmonics and higher frequency component shall be calculated for every week of measurement. The maximum 95th and 99th percentile of the weekly values shall be selected from the entire period.
- The 3 s 99th percentile of each harmonic order, interharmonics and higher frequency component shall be calculated for every day of measurement. The maximum 99th percentile of the daily values shall be selected for each week.
- Maximum values for each week of measurement can be also reported, if requested.

Additional tests of background noise shall be performed:

- Measurements shall be taken over a certain period of time (preferably 1 week or more), where the PP is not in operation. Measurements could be done before and/or after commissioning of the PP.
- The harmonic voltages, interharmonics and higher frequency components shall be analyzed as described above for normal operation of the PP.

NOTE For more investigations of background noise, the procedures given in IEC 61400-21-1:2019, Annex D, can be followed.

7.2.4.4 Documentation

Reporting for the normal operation of the PP in tables:

- The 95 % and 99 % percentile for each week of the measurement and the maximum 95 % and 99 % percentile of the weekly values for the complete measurement period of harmonic voltages and harmonic currents (integer harmonics, interharmonics and higher frequency components).
- Harmonic results shall be presented as 10 min (both 95 % and 99 %) and 3 s aggregated values (only 99 %).

Reporting for the background noise in tables:

- The 95 % and 99 % percentile for each week of the measurement and the maximum 95 % and 99 % percentile of the weekly values for the complete measurement period of harmonic voltages (integer harmonics, interharmonics and higher frequency components).
- Harmonic results shall be presented as 10 min (both 95 % and 99 %) and 3 s aggregated values (only 99 %).

7.3 Steady state operation

7.3.1 General

Subclause 7.3 defines the measurement procedures for the steady state operation of the PP, which are not dependent on the control functions of the power plant.

7.3.2 Unbalance

7.3.2.1 Overview

The aim of the measurement is to determine the unbalance factor in the PP fed-in current.

7.3.2.2 Test setup and test conditions

The general requirements of this document for the test equipment and test conditions according to Clause 6 apply.

7.3.2.3 Test and measurement procedure

The measurement procedure and data from 7.2.2 shall be used for the analysis and reporting.

Measurements shall be performed for at least 1 week with normal business activity, preferably for more than 3 weeks. It is recommended that at least five 10 min periods are collected within the measuring period for each power bin up to 80 % of the nominal power of the PP.

The current unbalance factor (IUF) and voltage unbalance factor (UUF) shall be calculated as 10 min aggregated values using the square root of the arithmetic mean of the squared 10-cycle (for 50 Hz power systems) or 12-cycle window values (for 60 Hz power systems), as defined in IEC 61000-4-30, from each measured record using the following formulae:

$$IUF = \frac{I_2}{I_1} \cdot 100 \% \quad (11)$$

$$UUF = \frac{U_2}{U_1} \cdot 100 \% \quad (12)$$

where:

I_1 is the 10-cycle or 12-cycle window positive sequence current, in accordance with IEC 61400-21-1:2019, Annex C;

I_2 is the 10-cycle or 12-cycle window negative sequence current, in accordance with IEC 61400-21-1:2019, Annex C;

U_1 is the 10-cycle or 12-cycle window positive sequence voltage, in accordance with IEC 61400-21-1:2019, Annex C;

U_2 is the 10-cycle or 12-cycle window negative sequence voltage, in accordance with IEC 61400-21-1:2019, Annex C.

The active power positive sequence system component is calculated as a 10 min arithmetic mean value.

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

7.3.2.4 Documentation

The measured 10 min values of the current and voltage unbalance and the active power positive sequence system component are represented as an IUF-P diagram and a UUF-P diagram.

The measurement results shall be presented as 95 % percentile values of the current and voltage unbalance of the complete measurement period.

7.4 Dynamic performance

7.4.1 Undervoltage and overvoltage ride-through (UVRT and OVRT) capability

Subclause 7.4 describes the measurement and event recording procedures to validate and verify the dynamic performance of the PP during grid faults (fault ride-through capabilities of the PP). The described procedures and documentation requirements for the event logging and/or fault recording of a PP as basis for the PP simulation and model validation are defined in IEC 61400-27-2.

The test of the fault ride-through capabilities of each wind turbine is not part of this document, as this is defined in the IEC 61400-21-1. The method of wind turbine and wind power plant simulation and model validation is defined in IEC 61400-27-1 and IEC 61400-27-2.

NOTE 1 Typically the FRT tests are only performed on a single WT, but the described FRT test procedures in IEC 61400-21-1 can be used as well to verify the performance of the WPP.

NOTE 2 The recommended validation procedures for the fault ride-through capability are described further in Annex C.

7.4.2 Test setup and test conditions

The fault recording or event monitoring shall be performed at the POC of the PP and can be done by specific measurement devices or the SCADA system, if the requested values and parameters are as defined in 6.4 and as specified in 7.4.3.

7.4.3 Test and measurement procedure

The measurement devices, connected to the voltage and current transducers at the POC, should be adjusted to record the signals mentioned below in the case of a voltage dip or swell. The thresholds for the events have to comply with the undervoltage and overvoltage ride-through requirements of the dedicated grid code. According to those requirements the trigger and return values, as well as the duration for the recording, shall be configured.

Table 3 defines the signals to be recorded or calculated during the assessment process.

Table 3 – List of recorded signals

Signal name (example) ^b	Signal description	Minimum sampling rate	Unit ^a
i_{1_inst} , i_{2_inst} , i_{3_inst}	Instantaneous phase currents at POC	2 kHz	A
u_{1_inst} , u_{2_inst} , u_{3_inst}	Instantaneous phase voltages at POC	2 kHz	kV
P_control_mode	Active power control mode	10 Hz	
P_setpoint external	Active power setpoint from external source	10 Hz	MW
P_setpoint internal	Active power setpoint from internal source	10 Hz	MW
Q_control_mode	Active Q_control mode: Q-control U-control φ -control	10 Hz	
PF_setpoint	Power factor control setpoint	10 Hz	°
U_setpoint	Voltage control setpoint	10 Hz	kV
Q_setpoint	Reactive power setpoint	10 Hz	Mvar
PGU_available	Percentage of wind turbines available for active power production	10 Hz	%
Optional			
wind_speed	Wind speed from met-mast or as average from turbine measurements	10 Hz	m/s
P_available	Available active power production of wind farm	10 Hz	MW
^a The units should be based on SI units, for example MW, kW, W, etc. ^b Signal naming can vary.			

Table 4 defines the minimum electrical values to be calculated during the assessment process.

Table 4 – List of electrical signals to be monitored for the evaluation of events

Name	Description	Unit
I_1 , I_2 , I_3	RMS phase currents at POC	p.u.
U_1 , U_2 , U_3	RMS phase voltages at POC	p.u.
$I_{d, pos}$	Positive sequence active current at POC	p.u.
$I_{q, pos}$	Positive sequence reactive current at POC	p.u.
$I_{d, neg}$	Negative sequence active current at POC	p.u.
$I_{q, neg}$	Negative sequence reactive current at POC	p.u.
U_{pos}	Positive sequence voltage	p.u.
U_{neg}	Negative sequence voltage	p.u.
P	Positive sequence active power at POC	MW
Q	Positive sequence reactive power at POC	Mvar
S	Apparent power at POC	MVA
f	Grid frequency	Hz

All parameters in Table 4 shall be calculated with an average time of one line period, and the update rate of the parameters shall be no more than a half line period.

NOTE The line period is 20 ms for 50 Hz and 16,67 ms for 60 Hz,

7.4.4 Documentation

To be able to compare the results of the fault recording with the simulation models as described in IEC 61400-27-1 and 61400-27-2, the following measured and calculated values shall be available, in addition to the general reporting requirements as described in 6.2:

- time series of instantaneous three-phase currents and voltages at the POC;
- time series of positive and negative sequence of the active and reactive current;
- time series of positive and negative sequence of the active and reactive power;
- time series of positive and negative sequence grid voltage at the POC;
- grid frequency, measured as 0,2 s average value at the POC;
- type of fault and number of faulted phases;
- magnitude and duration of the fault or event;
- operational modes and operational limits of the PGU and the PP;
- number of turbines and external equipment in operation and actual configuration of the PP plant;
- setpoints of the PP from the grid operator and plant owner;
- short-circuit level and impedance angle at the POC at the time of the event.

The following additional information is optional:

- average wind speed for the PP;
- available active and reactive power.

The time series shall, at a minimum, consist of data, measurements and calculation values from 10 s before the fault (pre-fault) and 30 s after the fault clearance (post-fault).

The requested signals, data and time series of the measured values of the event shall be synchronized to each other and time stamped with a precision as defined in 6.4.

The data shall be electronically available as well as documented as defined in Annex A.

Figure 8 shows some examples of time series for reactive and active current during a fault ride-through event at the POC.

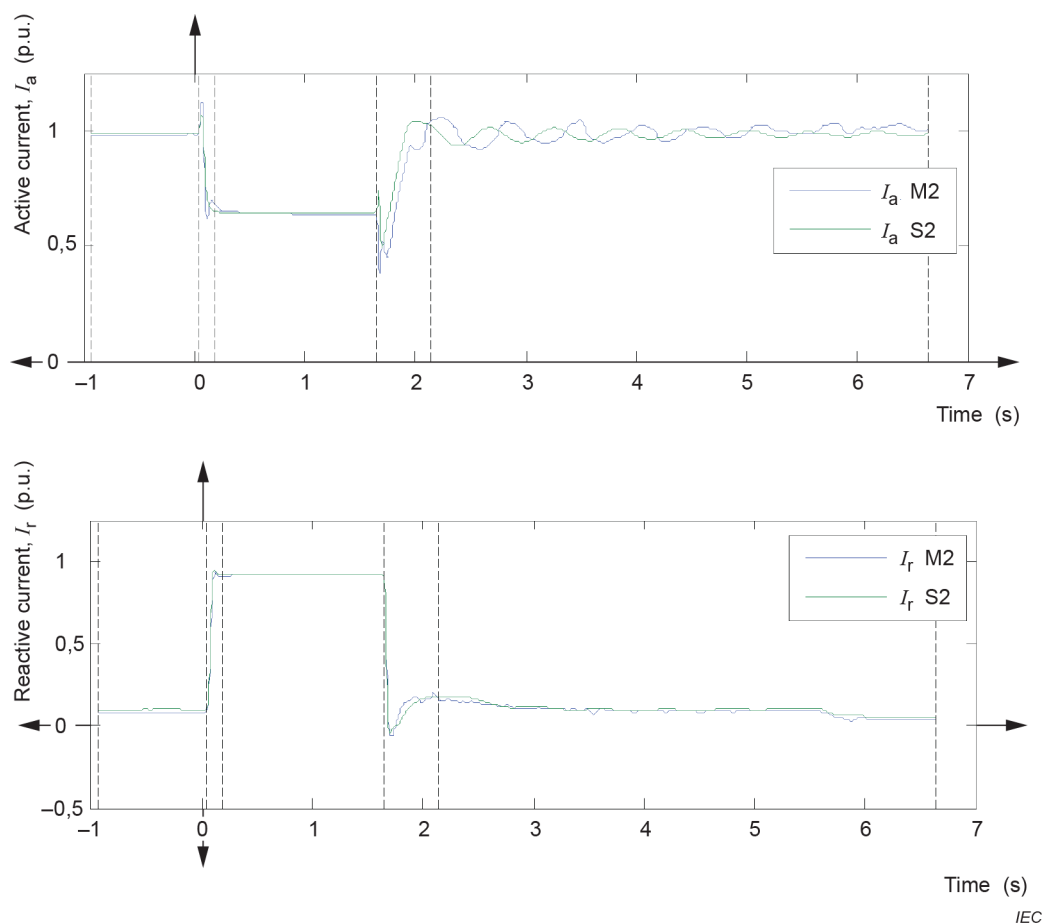


Figure 8 – Example of time series for the active and reactive current measured (M) and simulated (S) active and reactive current [1]¹

7.5 Disconnection from grid

7.5.1 Grid protection

The aim of the grid protection test is to demonstrate the correct function of the grid protection devices' ability to disconnect from the grid if the current, voltage or frequency exceeds a given limit for a given time.

The actual protection settings shall be made available before the grid protection testing.

The voltage measuring principle (either phase-to-phase or phase-to-neutral), along with the scope of testing (single-phase, two-phase or three-phase testing), shall be agreed upon before commencing testing.

All required pickup values and time delays shall be determined for all overcurrent, overvoltage, undervoltage, overfrequency and underfrequency protective devices associated with the PGU or PP.

The protection tests described in 7.5 are required for commissioning.

Due to safety reasons, these measurements concerning the grid protection should be performed while the PGU/PP is not in operation.

¹ Numbers in square brackets refer to the Bibliography.

7.5.2 Requirements of test devices

The grid protection test shall be carried out using a separate test system, which is able to inject currents, voltages and varying frequencies. The accuracy of the current, voltage and frequency of the current source and voltage source will be ensured by the accuracy of the measurement system.

For measurement and test technology (without current and voltage transformers), compliance with the following measurement uncertainties is required (see Table 5):

Table 5 – Maximum measurement uncertainties for the grid simulator

	Max. measurement uncertainties
Voltage (fundamental)	$\leq 0,5 \% U_n$
Current (fundamental)	$\leq 0,5 \% I_n$
Frequency	$\leq 0,01 \% f_n$

Current and voltage transformers shall correspond at least to class 1 in accordance with IEC 61869-3 (for voltage transformers) and in accordance with IEC 61869-2 (for current transformers).

The traceability of the measured values to international standards shall be established by calibrating the measurement technology and the transducers.

7.5.3 Grid protection test – PP level

7.5.3.1 Basic grid protection devices

The following protection devices are typically installed in the substation at the POC: voltage, frequency and overcurrent protection.

Additionally, a distance protection relay may be installed if the PPC is on the high voltage level.

7.5.3.2 Test procedure for grid protection devices

For voltage and frequency protection, the test procedure shall be carried out in accordance with IEC 60255-127:2010, Clause 6, for over- and undervoltage protection and IEC 60255-181:2019, Clause 6, for frequency protection. Alternatively, the procedure as defined in the IEC 61400-21-1 shall be used for the evaluation of the protection functions.

For over- and undercurrent protection, the test procedure in accordance with IEC 60255-151:2009, Clause 6, shall be applied.

For distance protection, the test procedure in accordance with IEC 60255-121:2014, Clause 6, shall be applied.

7.5.3.3 Documentation of the test procedure and results

The documentation of the test procedure and results shall be in accordance with:

- 1) IEC 60255-127:2010, Clause 7, for over- and undervoltage protection;
- 2) IEC 60255-181:2019, Clause 7, for frequency protection;
- 3) IEC 60255-151:2009, Clause 7, for over- and undercurrent protection;
- 4) IEC 60255-121:2014, Clause 7, for distance protection.