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TECHNICAL SPECIFICATION

colour inside

Grid code compliance assessment methods for grid connection of wind and PV power plants

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GRID CODE COMPLIANCE ASSESSMENT METHODS FOR GRID CONNECTION OF WIND AND PV POWER PLANTS

FOREWORD

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IEC TS 63102 has been prepared by subcommittee SC 8A: Grid integration of renewable energy generation, of IEC technical committee TC 8: System aspects of electrical energy supply. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
8A/80/DTS	8A/86/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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- reconfirmed,
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GRID CODE COMPLIANCE ASSESSMENT METHODS FOR GRID CONNECTION OF WIND AND PV POWER PLANTS

1 Scope

This technical specification highlights recommended technical methods of grid code compliance assessment for grid connection of wind and PV power plants as the basic components of grid connection evaluation. The electrical behaviour of wind and PV power plants in this technical specification includes frequency and voltage range, reactive power capability, control performance including active power based control and reactive power based control, fault ride through capability and power quality.

Compliance assessment is the process of determining whether the electrical behaviour of wind and PV power plants meets specific technical requirements in grid codes or technical regulations. The assessment methods include compliance testing, compliance simulation and compliance monitoring. The input for compliance assessment includes relevant supporting documents, testing results and validated simulation models, and continuous monitoring data. The scope of this technical specification only covers assessment methods from a technical aspect; processes related to certification are not included.

This technical specification is applicable to wind and PV power plants connected to the electrical power grid.

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 60050-415:1999, *International Electrotechnical Vocabulary – Part 415: Wind turbine generator systems*

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

IEC 62934, *Grid integration of renewable energy generation – Terms and definitions*

3 Terms, definitions, abbreviations and subscripts

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61400-21-1, IEC 60050-415, IEC 62934 and the following apply.

ISO and IEC also maintain terminological database 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

3.1.1
compliance monitoring
monitoring activity with the purpose of demonstrating the continuous compliance with the required specifications throughout the lifetime of the power plant

3.1.2
compliance simulation
simulation activity with the purpose of demonstrating the compliance with the required specifications, especially where testing is not applicable or risk of damaging the facility exists

3.1.3
controller hardware in the loop testing
CHIL testing
testing method for the subject controller based on physical and digital real-time simulation

Note 1 to entry: A simulation model is used to build the external real-time testing environment. Then a closed loop test system is composed of the simulation model and embedded physical controller under test.

3.1.4
grid code
document that recommends practices or procedures for the activities of connection, management, planning, development and maintenance of the electrical transmission and distribution grid, as well as dispatching and metering, etc.

3.1.5
grid code compliance
demonstration that the electrical behaviours of power plants satisfy specific technical requirements in grid codes or technical regulations

3.2 Abbreviations and subscripts

3.2.1 Abbreviations

The following abbreviations are used in this document:

CHIL	controller hardware in the loop
CIGRE	International Council on Large Electric Systems
CT	Current Transformer
DB	Dead Band
FACTS	Flexible Alternating Current Transmission Systems
HVDC	High Voltage Direct Current
OF	Over Frequency
OVRT	over-voltage ride-through
PCS	power conditioning system
PV	photovoltaic
POC	point of connection
PQ	active power and reactive power
SCR	short circuit ratio
STATCOM	static synchronous compensator
TS	technical specification
UF	Under Frequency
UVRT	under-voltage ride-through
VT	Voltage Transformer

3.2.2 Subscripts

F	fault
meas	measured value
max	maximum
min	minimum
n	nominal
Omax	maximum value of over voltage fault
poc-s	produced by the grid
poc-c	produced by the power plant
ref	reference value
s	variable of grid
sa	phase A of grid
sb	phase B of grid
sc	phase C of grid
Umin	minimum value of under voltage fault

4 Symbols and units

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

I_{poc}	tested results of the current at POC (A)
$I_{\mathrm{poc\text{-}s}}$	harmonic currents produced by the grid (A)
$I_{\mathrm{poc\text{-}c}}$	harmonic currents produced by the power plant (A)
I_{s}	equivalent current of the grid
I_{c}	equivalent current of the plant
P	active power of the power plant (W)
P_{n}	active power rated value (W)
P_{meas}	active power measured value (pu)
P_{lt}	maximum long-term flicker
P_{lt0}	maximum background long-term flicker
P_{ltRE}	maximum long-term flicker caused by power plant
Q	reactive power of the power plant (Var)
Q_{ref}	reactive power reference value (pu)
Q_{meas}	reactive power measured value (pu)
Q_{max}	maximum reactive power at POC (Var)
Q_{min}	minimum reactive power at POC (Var)
S_{k}	short circuit power (VA)
U_{n}	rated value of voltage at POC (V)
U_{s}	voltage of the grid (V)
U_{sa}	phase A voltage of the grid (V)
U_{sb}	phase B voltage of the grid (V)
U_{sc}	phase C voltage of the grid (V)
U_{max}	maximum voltage under normal operation at POC (V)
U_{min}	minimum voltage under normal operation at POC (V)

U_{Umin}	minimum value under voltage according to gird codes (V)
U_{Omax}	maximum value over voltage according to gird codes (V)
U_{poc}	tested results of the voltage at POC (V)
Z_{c}	equivalent impedance of the power plant (Ω)
Z_{F}	equivalent fault impedance (Ω)
Z_{s}	equivalent impedance of the grid (Ω)
Z_{sa}	phase A equivalent impedance of the grid (Ω)
Z_{sb}	phase B equivalent impedance of the grid (Ω)
Z_{sc}	phase C equivalent impedance of the grid (Ω)

5 General specifications

5.1 General

Technical requirements of wind and PV power plants for connecting to the grid were given in the grid codes, such as operating area, active power control, reactive power control, fault ride through, etc. Some existing IEC standards like IEC 61400-21 (all parts) and IEC 61400-27 (all parts) specify the measurement procedures, modelling and validation methods of electrical characteristics for wind turbines and wind power plants. This technical specification will specify the compliance assessment methods of the electrical behaviours stipulated in the grid codes.

5.2 Type tested units – Wind turbines and PV inverters

Type tested units are a series of wind turbines or PV inverters that have a common design, materials and major components, subject to a common manufacturing process and uniquely described by specific values or ranges of values of machine parameters and design conditions. The definition of a type tested unit is dependent on the characteristics being assessed and should be agreed by all stakeholders. Type testing is usually performed only once per type in order to prove the general capability for all units of this type.

5.3 Projects – Wind and PV power plants

Wind or PV power plants are usually built clustering many units and jointly connecting them to the grid. For these, a project based assessment needs to be performed. This means using results from the type tested assessment, but taking the site-specific parameters into account.

5.4 Compliance assessment methods

In general, methods of project based compliance assessment can be classified into three general categories:

- testing, including field testing and controller hardware in the loop (CHIL) testing;
- simulation;
- monitoring.

NOTE Annex A includes detailed information and recommendations for monitoring.

Normally for each electrical behaviour there is more than one compliance assessment method. The selection of assessment methods should be carried out by system operators taking into consideration the following factors:

- the technology of the project, including whether the performance is likely to drift or degrade over a particular time-frame;
- experience with the particular generation technology, including manufacturer's advice;
- the connection point arrangement;

- an assessment of the risks and costs of different testing methods, including consideration of the relative size of the plant;
- the availability and location of testing equipment, monitoring/metering equipment and other necessary facilities.

Table 1 gives an overview of recommended assessment methods for different electrical behaviors.

Table 1 – Overview of assessment methods

		Field testing	CHIL	Simulation	Monitoring
Operating area	Frequency range				x
	Voltage range			x	x
	Reactive power capability			x	x
Control performance		x	x		x
Fault ride through				x	x
Power quality		x			
x: recommended assessment methods.					

6 Operating area

6.1 General

As the frequency and voltage of the power system are not constant, the wind and PV power plants need to be capable of being operated continuously or for certain durations within specified frequency and voltage ranges required by the grid codes. Reactive power capability is also required to help maintain the system voltage and fulfil reactive power demand of the grid. The operating area is generally focused on steady state conditions. For compliance assessment of transient behaviour during grid faults, see Clause 8.

Assessment of the operating area is the assessment of appropriate equipment rating. This rating assessment for power plants should be based on the units and the additional equipment installed in the plant. This assessment can be undertaken in the planning phase based on related documentation and load flow simulations. The continuous compliance should be monitored as well. Field testing at the wind or PV power plant level is not recommended for confirmation of the entire frequency and voltage area since this testing can endanger both grid and plant safety. However, field testing could be conducted to confirm reactive power capability and a limited range within the frequency or voltage area.

6.2 Frequency range

6.2.1 Documentation

Related documentation should be provided in the planning phase declaring the frequency range of units and additional equipment installed in the power plant. For the units and additional equipment, specification or manufacturer declarations should be submitted.

6.2.2 Method 1: Monitoring

The POC of the power plant and main equipment within the plant should be monitored and assessed continuously. For the evaluation of power plant operability with decreased or increased grid frequency, the protection settings at POC should be documented.

6.3 Voltage range

6.3.1 Documentation

Corresponding documentation should be provided in order to prove the voltage operational range of units and additional equipment are installed in the power plant. For each component under assessment, specification or manufacturer declarations should be submitted.

For additional equipment installed in the power plant, documentation of those components should be provided. Documentation may include, but should not be limited to rating plate data, environmental assumptions and corresponding calculations.

6.3.2 Method 1: Simulation

The voltage range of power plants is referred to the POC. All terminals of the units and main equipment within the plant should be assessed (e.g. transformers, reactive power compensation devices). This can be achieved by load flow simulation, during which corresponding assumptions should be made for the worst realistic cases at all terminals. Dynamic simulation (with base frequency domain 50 Hz/60 Hz RMS simulation) can help confirm the withstand time of wind and PV power plants capability to voltages in the voltage area. Modelling and model validation procedure can refer to IEC 61400-27-1 and IEC 61400-27-2.

6.3.3 Method 2: Monitoring

The POC of the power plant and main equipment within the plant should be monitored and assessed continuously. For the evaluation of power plant operability with decreased or increased grid voltage, the protection settings at POC should be documented.

6.4 Reactive power capability

6.4.1 Documentation

For wind power plants, tests for reactive power capability should be performed for each type of wind turbine according to IEC 61400-21-1. When each PCS device is individually equipped with a voltage detection device and reactive power control function, it is sufficient to perform a verification test for that function at the manufacturer's factory or testing laboratory, making field testing optional. Alternatively, corresponding type test reports can be assessed if they have been performed in the past. The scope of required testing depends on grid codes. If no type tests exist, corresponding tests should be performed instead.

If the plant contains reactive power compensation devices, corresponding documentation should be provided declaring their reactive power capability. For STATCOM, the available operation modes should be listed and clarified in detail. Corresponding type test reports, specification or manufacturer declarations should be submitted.

6.4.2 Method 1: Simulation

Before simulation, the reactive power capability of unit models should be configured according to IEC 61400-27-1 based on type testing results. The maximum and minimum reactive power capability of the power plant should be verified with load flow calculations, which are determined by the capability of the units and other components like cables, transformers and compensation devices.

Simulation procedure of maximum reactive power capability:

- Set all units to the appropriate control mode with the reference value equal to the maximum operation voltage, or set all units to reactive power control mode with the reference values equal to the maximum reactive power.
- Execute a sequence of load flow simulations with varying active power levels.

Simulation procedure of minimum reactive power capability:

- Set all units to the appropriate control mode with the reference value equal to the minimum operation voltage, or set all units to reactive power control mode with the reference values equal to the minimum reactive power.
- Execute a sequence of load flow simulations with varying active power levels.

The maximum and minimum operation voltage is based on the voltage range of continuous operation in 6.3. For low active power level (e.g. P < 10 %P_n), if reactive power capability were not required in grid codes, then relevant simulation scenarios are not mandatory. The simulation results can be summarized as a PQ-diagram including both the grid code requirements and the plant capability (see Figure 1 as an example).

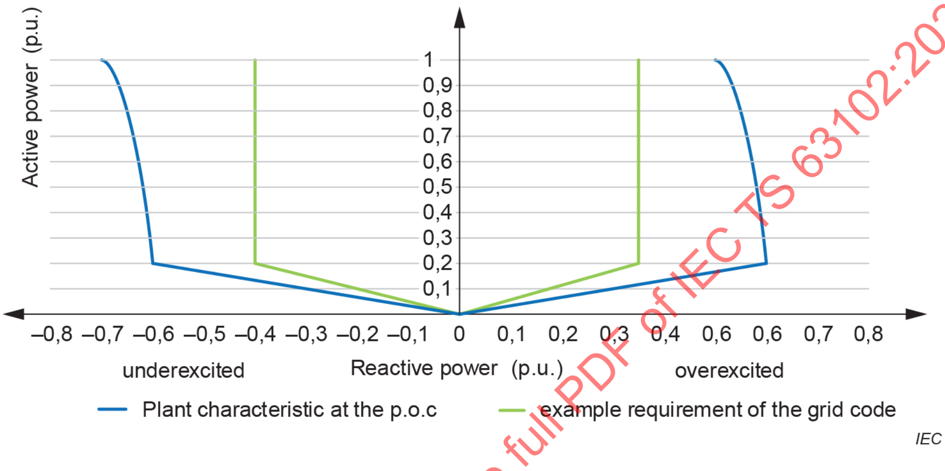

Figure 1 – An example of PQ diagram

6.4.3 Method 2: Monitoring

The reactive power at the plant POC should be monitored and assessed continuously.

7 Control performance

7.1 General

Grid codes require power plants to be properly controlled keeping power systems in balance and stable condition. Depending on grid codes, the active power outputs of power plants could be controlled by either active power or grid frequency variation settings. This kind of control performance is named active power based control. Meanwhile the control reference of reactive power could be selected from either reactive power, grid voltage or power factor settings, and the related control performance is named reactive power based control.

Control performance assessment intends to assess the functionality and controllability of plants in both normal and dynamic operation states. The electrical behaviour can be directly tested in pre-commercial operation phase if permitted by system operators. Some special test cases should be performed by CHIL, due to the unchangeable grid frequency and safe range of voltage. The control performance of power plants can also be assessed and monitored during commercial operation.

7.2 Active power based control

7.2.1 Documentation

Specification or manufacturer declarations of plant controllers should be submitted.

7.2.2 Method 1: Plant field testing

The active power at POC can be measured with variant control references such as set point and ramp rate. In order to assess frequency control performance, variant frequency signals can be injected into the plant controller to simulate a grid frequency incident. During plant field testing the injected system frequency should be manipulated within certain frequency operation range according to grid codes, normally including Under-Frequency (UF) range, Dead-Band (DB) range, and Over-Frequency (OF) range. The testing procedure should refer to IEC 61400-21-2[1].

Plant field testing should meet the following conditions:

- The available active power output of power plant should be at least 50 % of rated power.
- The plant active power production at POC and control reference signal should be monitored and documented continuously at the same time.
- The plant active power production, grid frequency at POC and control reference signal should be monitored and documented at the same time, when the frequency control is performed.
- If a grid meter is used for the measurement, the sampling frequency of grid meter output should be at least 10 Hz.
- If no grid meter is used, the measurements should be obtained by CT/VT sensors, and the sampling frequency of measurements should be at least 1 kHz.
- During a field test, all measurements signals should be time stamped, in order to assess the plant control timing related performance, for instance, rise time.
- The testing results should be reported as 0,1 s average data.

The contents of plant field testing include:

- active power ramp rate test;
- active power set point test;
- frequency control test (variant frequency signals injected into the plant controller to simulate a grid frequency incident).

Results of plant field testing should be presented in the following form:

- Figure: time series of active power set point value and measured active power output in the ramp rate test, see Figure 2.
- Figure: time series of control reference and measured active power output in the set point test, see Figure 3.
- Figure: time series of adjustment response of injected frequency test, see Figure 4.

[1] Under preparation. Stage at the time of publication: IEC/CCDV 61400-21-2:2021.

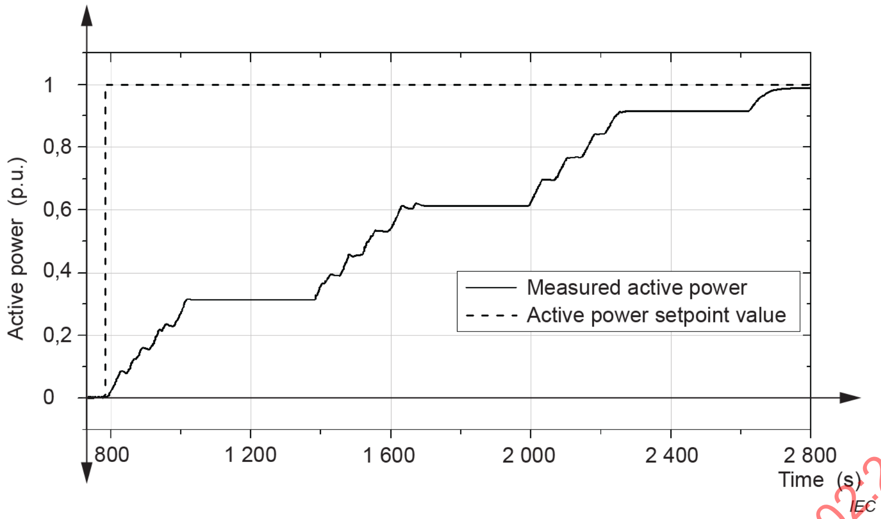

Figure 2 – Example of figure for active power ramp rate test

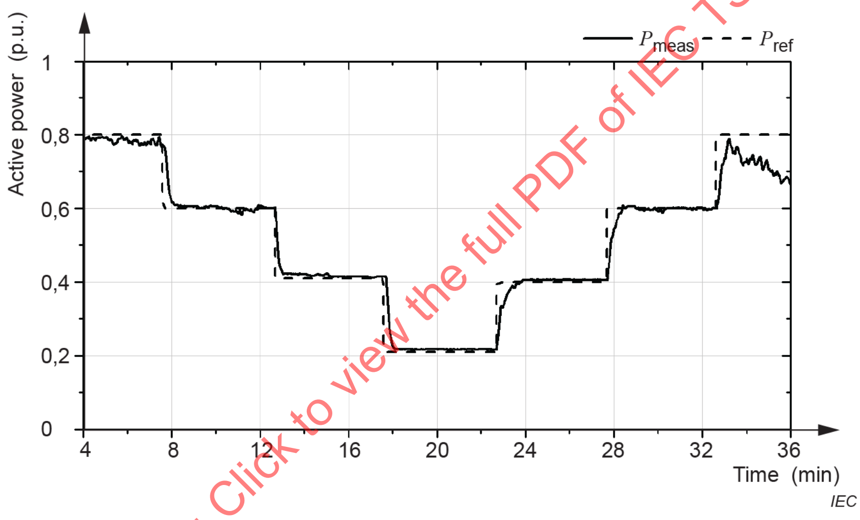

Figure 3 – Example of figure for set point test of active power

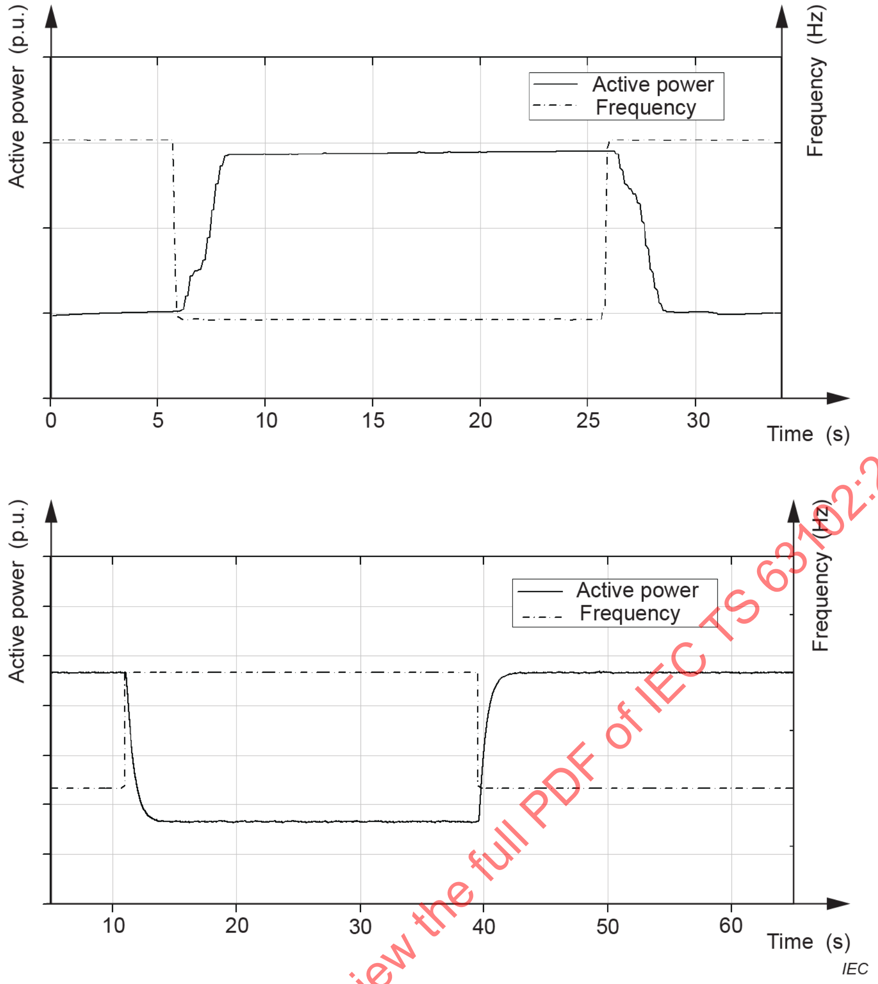

Figure 4 – Example of figure for frequency control test

- Table: Maximum variation value in 10 min and 1 min of active power in the ramp rate test, see Table 2. It can be calculated by using sliding window in the test data.
- Table: Control settling time, overshoot as percentage of reference and static error for each control reference in the set point test, see Table 3. The calculation method of performance index described in Annex D.
- Table: Control response time, control settling time, active power before and after the injected frequency disturbance and static error in the frequency control test, see Table 4. Performance indexes are described in Annex D.

The performance index and cases for compliance assessment listed in Table 2~Table 4 should be determined according to the situation in different countries.

Table 2 – Example table for maximum variation value of active power

Cases	**Maximum variation value in 10 min** (MW)	**Maximum variation value in 1 min** (MW)
Normal operation		
Start-up		
Stop		

Table 3 – Example of table for performance index of set point test

Set value of active power [(P/P_n) p.u.]	Control settling time (s)	Overshoot (%)	Tolerance band (%)
0,8 → 0,6			
0,6 → 0,4			
0,4 → 0,2			
0,2 → 0,4			
0,4 → 0,6			
0,6 → 0,8			

Table 4 – Example of table for performance index of frequency control response

Cases	Control response time (s)	Control settling time (s)	Active power before disturbance (p.u.)	Active power after disturbance (p.u.)	Tolerance band (%)
50 Hz → 50,2 Hz (Active power derating to 0,2 p.u ~ 0,3 p.u.)					
50 Hz → 50,2 Hz (Active power 0,2 p.u ~ 0,3 p.u. without derating)					
50 Hz → 50,2 Hz (Active power derating to 0.5~0.9 p.u.)					
50 Hz → 50,2 Hz (Active power 0.5~0.9p.u. without derating)					
50 Hz → 49,8 Hz (Active power derating to 0.2 p.u ~ 0.3 p.u.)					
50 Hz →49,8 Hz (Active power 0.2 p.u. ~ 0.3 p.u. without derating)					

7.2.3 Method 2: Monitoring

The plant active power production at POC should be measured, while the control reference signal should be monitored continuously at the same time.

If frequency control is required, the plant frequency at POC should be measured simultaneously, while the control reference signal should be monitored continuously at the same time.

7.2.4 Method 3: CHIL testing

CHIL is generally used for active power based control strategy testing. In CHIL testing environment, the plant controller should be hardware based. Except that, the power plant should be a simulation model with at least one generation unit, as well as the external grid. The testing procedure can refer to IEC 61400-21-2.

CHIL testing should meet following conditions:

- The available active power output of the power plant should be equal to the rated power.
- Simulated frequency variation (upward and downward) should be obtained in the external grid model.
- The testing results should be reported as 0,1 s average data.

The contents of CHIL testing include:

- frequency control functionality;
- coordination functionality of active power set point and frequency control.

Results of CHIL test should be presented in the following form:

- Figure: Time series of simulated frequency variation, active power reference and measured active power output, see Figure 5.

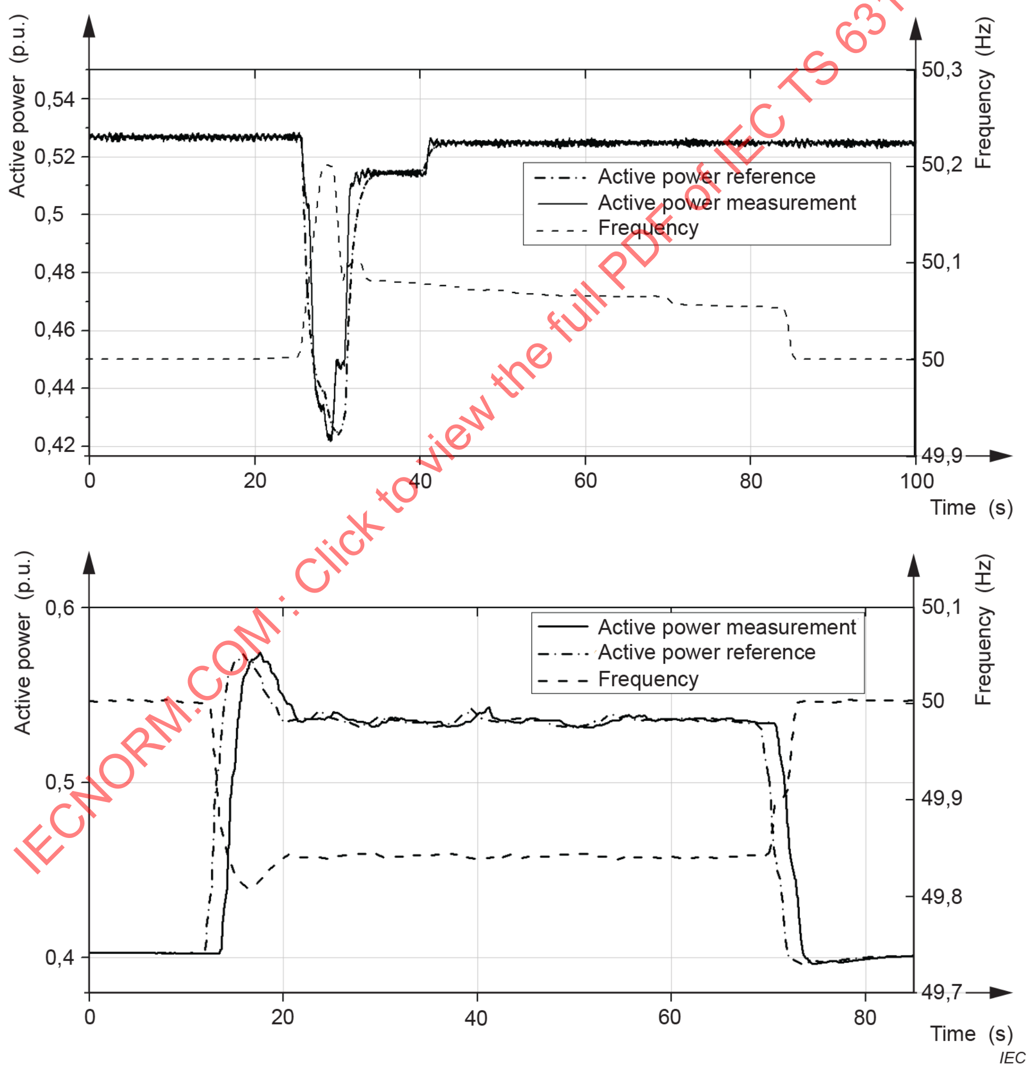

Figure 5 – Example of figure for frequency control test with simulated frequency variation

- Table: functionality assessment of frequency control, see Table 4.
- Table: frequency step value, active power set point and measured active power output in the coordination functionality test, see Table 5. This test should be performed in the active power de-rating mode. If frequency control is activated firstly, active power set point control should be activated during the period of frequency control.

The cases listed in Table 5 and Table 6 can be adjusted according to the situation in different countries.

Table 5 – Example of table for functionality test of frequency control

Cases	Functionality of frequency control
Disturbance upward of frequency (Active power derating to 0,2 p.u ~ 0,3 p.u.)	☐Yes ☐NO
Disturbance upward of frequency (Active power derating to 0,5 p.u ~ 0,9 p.u.)	☐Yes ☐NO
Disturbance downward of frequency (Active power derating to 0.,2 p.u ~ 0,3 p.u.)	☐Yes ☐NO
Disturbance downward of frequency (Active power derating to 0,5 p.u ~ 0,9 p.u.)	☐Yes ☐NO

Table 6 – Example of table for coordination functionality of active power set point and frequency control

Cases	Frequency step (Hz)	Active power set-point (p.u.)	Measured active power output (p.u.)	Functionality of coordination
UF+ active power set point increase	50 → 49,8			☐Yes ☐NO
UF+ active power set point decrease	50 → 49,8			☐Yes ☐NO
OF+ active power set point increase	50 → 50,2			☐Yes ☐NO
OF+ active power set point decrease	50 → 50,2			☐Yes ☐NO
active power set point increase+ UF	50 → 49,8			☐Yes ☐NO
active power set point decrease+ UF	50 → 49,8			☐Yes ☐NO
active power set point increase+ OF	50 → 50,2			☐Yes ☐NO
active power set point decrease+ OF	50 → 50,2			☐Yes ☐NO

- Documentation of controller identification, software version and hardware should be included.
- Used model should be described in the report, including but not limited to modelling approaches, topology and simulation environment.

The real-time model guidelines for power plant modelling and setup are described in Annex B.

7.3 Reactive power based control

7.3.1 Documentation

Specification or manufacturer declarations of plant controllers and reactive power compensation devices should be submitted.

7.3.2 Method 1: Plant field testing

The reactive power at POC can be measured with variant control reference such as set point. Plant field testing should meet following conditions:

- During plant field testing, control set points should be within the reactive power capability area defined in 6.4.
- The available active power output of power plant should be at least 50 % of rated power.
- Control reference should be monitored. Also the grid voltage and active power should be measured simultaneously.
- If a grid meter is used for the measurement, then the sampling frequency of grid meter output should be at least 10 Hz.
- If no grid meter is used, the measurements should be obtained by CT/VT sensors, and the sampling frequency of measurements should be at least 1 kHz.
- The testing results should be reported as 0,1 s average data.

The contents of plant field testing include:

- Reactive power set point test.
- Voltage set point test.

Results of plant field testing should be presented in the following form:

- Figure: Time series of reactive power reference, measured reactive power and active power output (reactive power control mode), see Figure 6.
- Figure: Time series of voltage reference, measured voltage at POC, measured reactive power and active power (voltage control mode), see Figure 7.

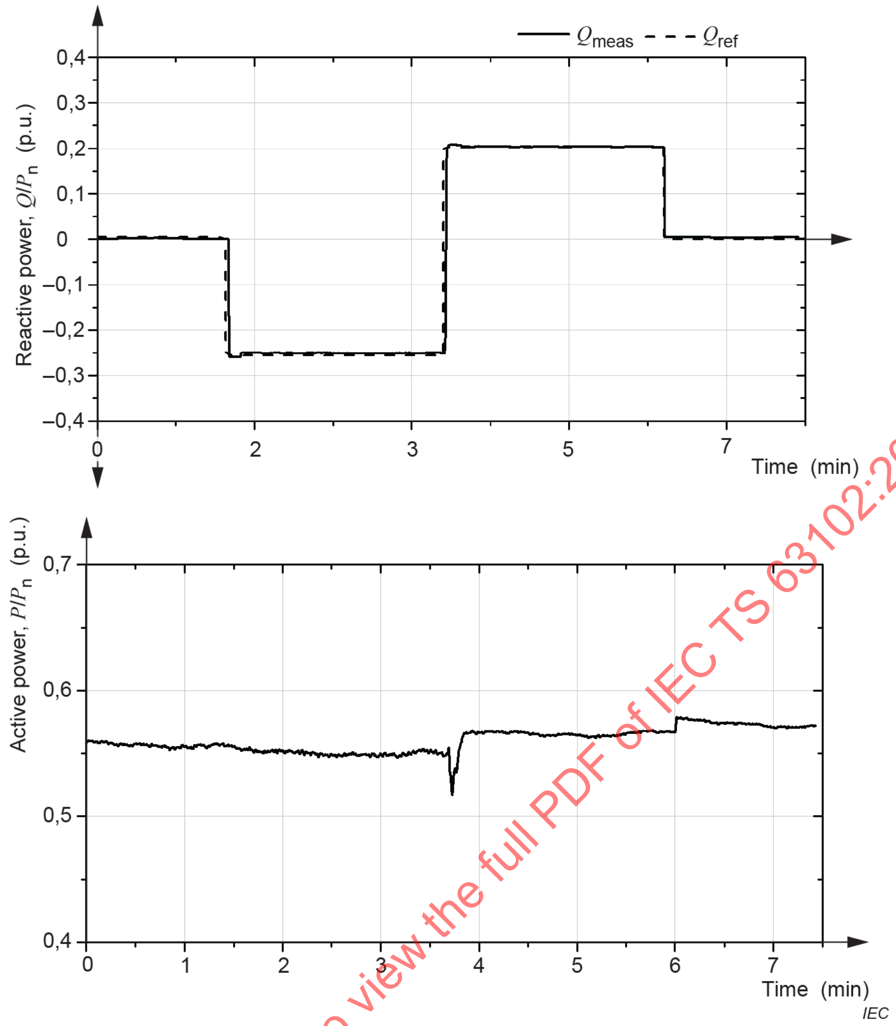

Figure 6 – Example figure for set point control of reactive power as control reference (reactive power control mode)

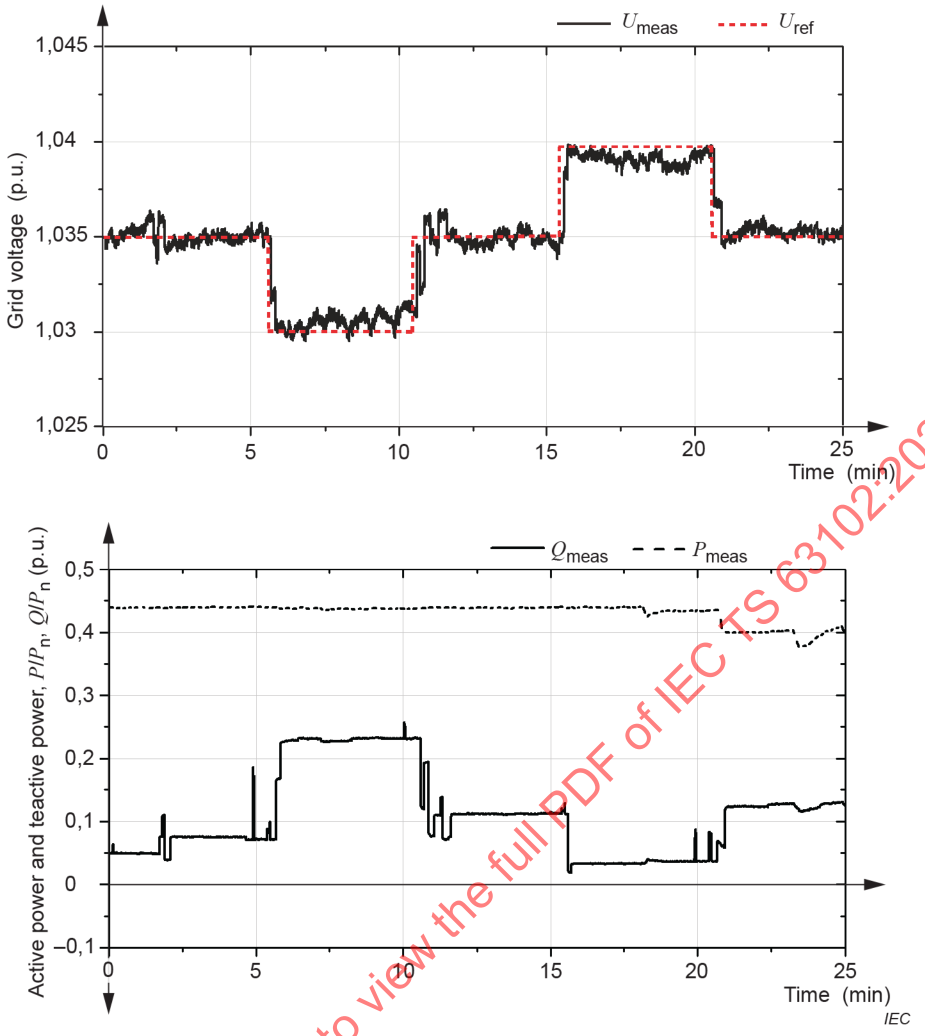

Figure 7 – Example of figure for set point control of voltage as control reference (voltage control mode)

- Table: Control settling time and static error should be listed in the set point control test under the reactive power and voltage control mode, see Table 7 and Table 8.

Performance indexes are described in Annex D. The performance index and cases for compliance assessment listed in Table 7 and Table 8 can be adjusted according to the situation in different countries.

Table 7 – Example of table for reactive power control testing

Set value of reactive power [(Q/P_n) p.u.]	Control settling time (s)	Tolerance band (%)
0		
-0.25		
0.25		
0		

Table 8 – Example of table for voltage control testing

Set value of voltage [p.u.]	Control settling time (s)	Tolerance band (%)
1.0		
0.996		
1.0		
1.004		
1.0		

7.3.3 Method 2: Monitoring

The control reference signal, grid voltage, active power and reactive power at POC should be monitored and assessed continuously.

7.3.4 Method 3: CHIL testing

CHIL is generally used for reactive power based control strategy testing. In CHIL testing environment, the plant controller should be hardware-based. Except that, the power plant should be a simulation model with multiple generation units, as well as the external grid. The testing procedure should refer to IEC 61400-21-2.

CHIL testing should meet following conditions:

- A fixed grid voltage (infinite bus) or a given SCR ratio and R/X ratio (infinite bus and impedance) should be modelled in the external grid.
- The testing results should be reported as 0.1 s average data.

The contents of CHIL testing include:

- Voltage control (Q(U)-characteristic) test.

The results of controller hardware in loop testing should be presented in the following form:

- Figure: Time series of voltage set value in the external grid (U_{set}), measured POC voltage and measured output of reactive power, see Figure 8.

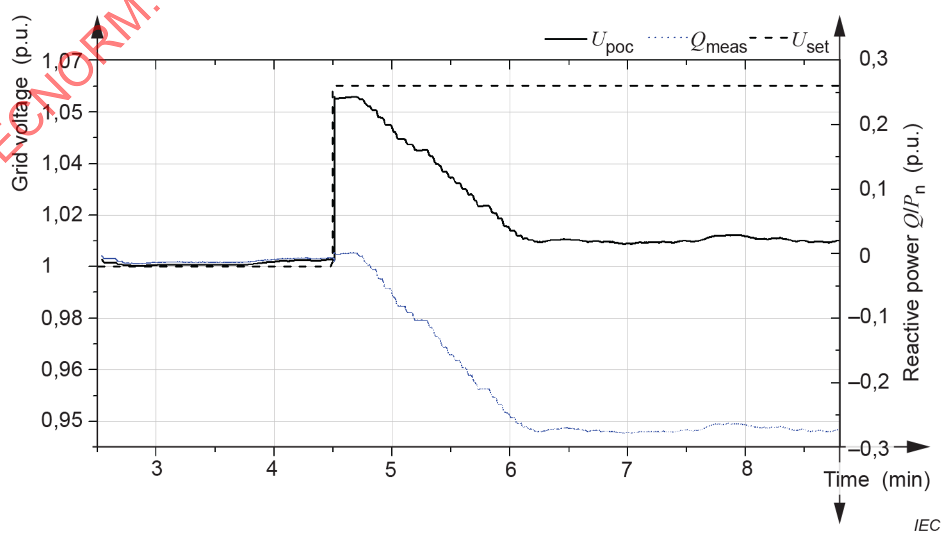

Figure 8 – Example of figure for voltage control test

The cases listed in Table 9 can be adjusted according to the situation in different countries.

Table 9 – Example of table for voltage control test

Set value of voltage in the external grid (p.u.)	Measured POC voltage (p.u.)	Measured reactive power output (Q/P_n)	Functionality of power factor control
1,00→ 1,05	1,05		☐Yes ☐NO
	1,04		
	1,03		
	1,02		

- Documentation of the controller identification, software version and hardware should be included.
- Used model should be described in the report, including but not limited to modelling approaches, topology and simulation environment.

The real-time model guidelines for power plant modelling and setup are described in Annex B.

8 Fault ride through

8.1 General

In a power system, faults could cause high current as well as under/over voltage leading to equipment damage and even blackout events. Therefore, protection devices are used to detect abnormal states and isolate faults. In order to achieve successful protection, generators must remain connected to the power system, to provide extra current during the fault and to maintain system power balance after the fault clearance.

The behaviour of power plant during faults should be assessed based on the fault ride through capability of wind turbines or PV inverters, which can be proved by type testing or other accepted methods with grid codes. Plant level simulation should be used, while field testing is not recommended as a routine assessment method.

8.2 Documentation

Corresponding documentation should be provided in planning phase declaring their fault ride through capability of units. For wind power plants, fault ride through capability tests should be performed for each type of wind turbine according to IEC 61400-21-1. For PV power plants, under voltage ride through capability tests should be performed for each type of power inverter according to IEC TS 62910, and over voltage ride through capability tests of power inverters can refer to the corresponding procedure and testing methods of IEC 61400-21-1. Other evidence including type test reports and simulations reports should be verified according to the grid codes.

If the plant contains reactive power compensation devices, corresponding documentation should be provided declaring their fault ride through capability or the designed reaction to the faults. Corresponding documentation about the plant controller should be provided if units can continuously respond to the control reference from the plant controller during faults. Testing reports, design reports or type test reports of other key devices including protection devices should be submitted and verified.

8.3 Method 1: Simulation

The detailed model of wind and PV power plants should be developed, including wind turbines/PV inverters, transformers, cables, overhead lines, STATCOM and other auxiliary equipment depending on the power plants condition. The wind power plants should be modelled according to IEC 61400-27-1. Before simulation, the wind turbine model should be validated according to IEC 61400-27-2. For PV power plants, modelling and unit model validation procedure can refer to IEC 61400-27-1 and IEC 61400-27-2.

The grid model can be aggregated as a voltage source and equivalent short-circuit impedance at POC of power plant. The minimum short-circuit power is used for short-circuit impedance calculation. The layout of grid model with symmetrical fault and 2-phase unsymmetrical fault are shown as Figure 9 and Figure 10.

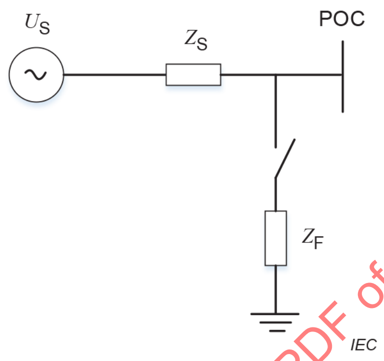

Figure 9 – Layout of grid with symmetrical fault

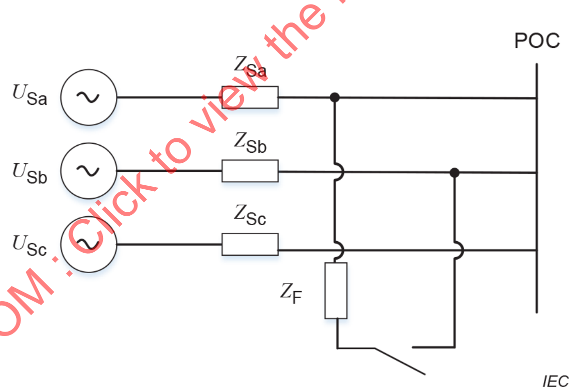

Figure 10 – Layout of grid with unsymmetrical fault

Simulation scenarios should be defined according to grid codes and specific standards of system operators. In general, conditions like different pre-fault operation modes, grid fault types and under/over voltage levels should be considered. Among every combination of the above conditions, only credible contingency events should be included in compliance assessment. This TS only recommends the minimal set of worst simulation cases. More cases should be considered according to grid codes and specific standards from system operators. The credible contingency events should include the following conditions:

- rated power P_n at POC;
- maximum voltage U_{max} and minimum voltage U_{min} at POC referring to 6.3;
- maximum reactive power Q_{max} and minimum reactive power Q_{min} at POC referring to 6.4;
- minimum under voltage U_{Umin} according to grid codes;
- maximum over voltage U_{Omax} according to grid codes.

Table 10 shows a recommended scenario of pre-fault operation modes. Table 11 shows a recommended scenario of grid fault types and under/over voltage levels. Unbalance faults in Table 11 are optional for system operators. The scenarios of specific project should be decided based on grid code requirements. The fault duration and control modes for each scenario should refer to grid code requirements. The parameters of the external grid should be set based on actual conditions.

Table 10 – Recommended scenario of pre-fault operation modes

Number	Fault ride through	Active power at POC	Voltage at POC	Reactive power at POC
	Under voltage	P_n	U_n	0
			U_n	Q_{max}
			U_{max}	0
			U_{max}	Q_{min}
	Over voltage		U_n	0
			U_n	Q_{min}
			U_{min}	0
			U_{min}	Q_{max}

Table 11 – Recommended scenario of grid fault types and under/over voltage levels

Number	Fault ride through	grid fault types	under/over voltage levels
1.	Under voltage	3-phase	U_{Umin}
2.		3-phase	45 % – 60 % U_n
3.		3-phase	70 % – 80 % U_n
4.		3-phase	$U_{min} - 0.5 \times (U_n - U_{min})$
5.		2-phase	U_{Umin}
6.		2-phase	70 % – 80 % U_n
7.	Over voltage	3-phase	U_{omax}
8.		3-phase	$U_{max} + 0.5 \times (U_{max} - U_n)$

The simulation procedure of fault ride through is the following:

- Set models of all units and external grid according to the simulation scenario.
- Execute a sequence of transient simulation with varying grid faults.
- Data recording time of simulation results should start 1 s before the fault and end at least 5 s after active power fully restored.
- Voltage, current and power at POC and each unit terminal should be recorded.
- Examining continuous operation capability of each unit through comparing unit protection thresholds and voltage variations.

The fault ride through characteristics should be presented in the following form:

- Table: Response time and settling time of reactive current at POC, steady-state reactive current during fault at POC, recovery time of active power after fault at POC.

Table 12 – Example table for fault ride through simulation results

Scenario No.	Response time of reactive current at POC (s)	Settling time of reactive current at POC (s)	Steady-state reactive current during fault at POC (p.u.)	Recovery time of active power after fault clearance at POC (s) (Under voltage)
1.				
2.				
…				

- Response time of reactive current is defined as the elapsed time from when the fault happens until the first time that the reactive current enters the predefined tolerance band of the target value. It is described in Annex D.
- Settling time of reactive current is defined as the elapsed time from fault happens until the reactive current continuously stays within the predefined tolerance band of the average reactive current during fault. It is described in Annex D.
- Steady-state reactive current during fault is defined as the average value of reactive current from the end of settling time until the fault clearance.
- Recovery time of active power after fault is defined as the time from the fault clearance until active power fluctuates continuously within the predefined tolerance band. It is defined as Figure 11.

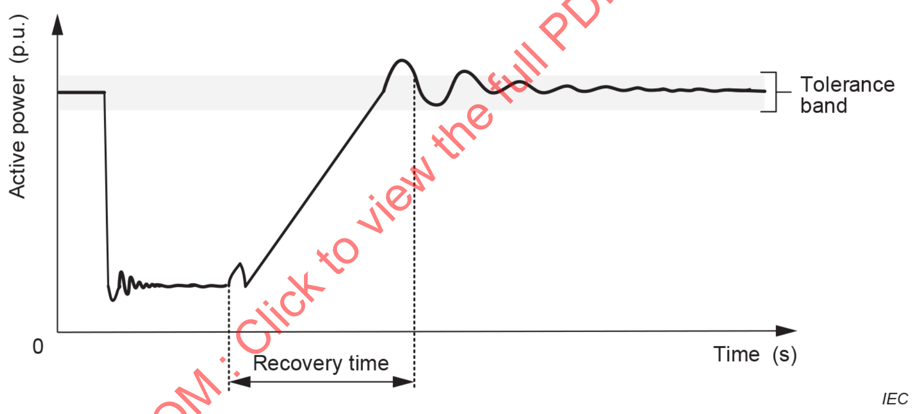

Figure 11 – Example of active power recovery

Plots of each simulation scenario should be presented as time series of the following variables:

- positive sequence voltage at POC;
- positive sequence reactive current, or negative sequence reactive current if required by grid codes at POC;
- positive sequence active power and reactive power at POC.

Positive sequence voltage, reactive current, active power and reactive power at the unit terminal which has the maximum or minimum electrical distance from POC are recommended to be plotted.

8.4 Method 2: Monitoring

Voltage, active power, reactive current and reactive power of the POC of power plant should be monitored and assessed continuously. If units can continuously respond to the control reference from plant controller during faults, the control reference signal at POC should be monitored and assessed continuously.

9 Power quality

9.1 General

Based on the requirement of grid codes, power quality at the POC of wind and PV power plants should be assessed and documented. In the planning phase of wind and PV power plants, simulation based on unit type testing can be used to assess the impact of power quality on power grid. In the pre-commercial operation phase, plant field testing can be carried out.

9.2 Current harmonics and inter-harmonics

9.2.1 Documentation

For wind power plants, type testing results of each wind turbines for current harmonics and inter-harmonics assessment should be provided, and the type testing should be carried out in accordance with IEC 61400-21-1. For PV power plants, power inverters can be tested using the same procedure and testing methods of IEC 61400-21-1. Measurement procedures for harmonics and inter-harmonics can refer to IEC 61400-21-2.

9.2.2 Method 1: Plant Field testing

Current harmonics and inter-harmonics at the POC of wind and PV power plants can be directly tested in pre-commercial operation phase. The results of plant field testing should meet following conditions:

- During plant field testing period at least 90 % of generation units in the wind and PV power plant should be in operation.
- For wind power plants in low wind speed areas and PV power plants in low irradiance areas, the maximum active power bin can be set to a lower value based on a wind/irradiance testing report in one year period.

The harmonic current of wind and PV power plants can be influenced by grid background noise. Thus, in order to determine the exclusive harmonic current produced by the power plant, the impedance values of the grid and the power plant are needed.

Figure 12 gives the equivalent circuit of the grid and the power plant. Then, according to the Kirchhoff voltage and current laws, the harmonic currents produced by the grid and the power plant can be calculated as

$$\begin{cases} I_{\text{poc-s}} = \left(\dfrac{U_{\text{poc}}}{Z_{\text{s}}} - I_{\text{poc}}\right)\dfrac{Z_{\text{s}}}{Z_{\text{s}} + Z_{\text{c}}} \\ I_{\text{poc-c}} = \left(\dfrac{U_{\text{poc}}}{Z_{\text{c}}} + I_{\text{poc}}\right)\dfrac{Z_{\text{c}}}{Z_{\text{s}} + Z_{\text{c}}} \end{cases} \tag{1}$$

where

U_{poc} and I_{poc}	refer the tested results of the voltage and current at POC,
Z_{s} and Z_{c}	refer to the equivalent impedance of the grid and the power plant,
$I_{\text{poc-s}}$ and $I_{\text{poc-c}}$	refer to the harmonic currents produced by the grid and the power plant, respectively.

Therefore, based on the aforementioned calculations, the harmonic current produced by the power plant can be assessed without the influence of grid background harmonics.

Annex C gives a recommended harmonic simulation method for wind and PV power plants.

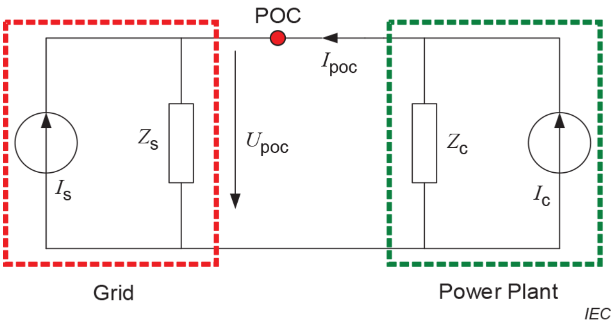

Figure 12 – Equivalent circuit of the grid and the power plant

9.3 Flicker

9.3.1 Documentation

For wind power plants, type testing results of each wind turbines flicker assessment should be provided, and the type testing should be carried out in accordance with IEC 61400-21-1. For PV power plants, power inverters should be tested using the same procedure and testing methods of IEC 61400-21-1.

Power system operators are in charge of providing the minimum, typical and maximum short circuit power S_k and the corresponding grid impedance angle at the POC of wind and PV power plant.

9.3.2 Method 1: Plant field testing

Voltage variation at the POC of wind and PV power plants can be directly tested in pre-commercial operation phase. The results of plant field testing should meet the following conditions:

- During plant field testing period, at least 90 % generation units in the wind and PV power plant should be in operation.
- For wind power plants in low wind speed areas and PV power plant in low irradiance areas, the maximum active power bin can be set to a lower value based on a wind/ irradiance testing report in one year period.
- Maximum long-term flicker P_{lt} should be stated.
- Maximum background long-term flicker P_{lt0} should be stated.

The maximum long-term flicker caused by wind and PV power plant (P_{ltRE}) are calculated according to grid codes. If there is no requirement, Equation (2) is a reference of how it should be done.

$$P_{ltRE} = \sqrt[3]{P_{lt}^3 - P_{lt0}^3} \qquad (2)$$

Annex A
(informative)

Monitoring of electrical performance of wind and PV power plants

A.1 Overview

Monitoring the electrical performance of wind and PV power plants is one of three categories of compliance assessment methods. It is intended to continuously guarantee grid code compliance in the whole life time of wind and PV power plants. This informative annex is mainly focused on monitoring that is based on permanent measurement devices installed in wind and PV power plants, such as grid meter and SCADA, through which continuous operation data is obtained and assessed.

Periodical field testing can be used as a method of monitoring, and the corresponding testing scenarios could be limited to a small percentage of common scenarios. The testing conditions and results can refer to corresponding subclauses of this technical specification.

A.2 Responsibilities

Operators of wind and PV power plants should be responsible for reporting any potential factors that may affect compliance with the grid codes. This may include, for example reporting the need for replacement or refurbishment of equipment, operational incidents or failures, and serious events. Undue delay of reporting such requirements should be avoided. System operators should be responsible for reporting of changes of grid equipment and new installed electricity generating and consuming facilities.

A.3 Basic principles

During monitoring, usually no extra effort is expected beyond measuring and storing data related to the value to be monitored. In general, it should be performed during normal operation or it should be triggered automatically when faults occur. Monitoring requirements should be specified in each case:

- signals to be monitored;
- monitoring period and averaging principles of the data should be measured and stored;
- Events that should trigger the monitoring including the measurement and signal details regarding this event.

At the end of the monitoring period, the data needs to be:

- time synchronized to a common reference time;
- safely stored with back-up, independent from power source availability;
- summarized in a monitoring report to be detailed in the text of this technical specification. The monitoring period may be longer than the report.

A.4 Monitoring signals

Table A.1 shows the recommended signals for wind and PV power plant monitoring.

Table A.1 – Monitoring signals

Numbe r	Signal group	Signal description	Type of data
1.	General	Grid disconnection at POC	Status
2.		Operational incidents or failures, and serious events	Tag
3.	Frequency range	Frequency at POC	Metering
4.		Active power at POC	Metering
5.	Voltage range	Voltage at POC	Metering
6.		Reactive power at POC	Metering
7.	Reactive power capability	Voltage at POC	Metering
8.		Active power at POC	Metering
9.		Reactive power at POC	Metering
10.	Active power based control	Control mode	Status
11.		Ramp rate	Set-point
12.		Requested active power at POC	Set-point
13.		Active power supplied at POC	Metering
14.		Requested frequency area at POC	Set-point
15.		Frequency at POC	Metering
16.	Reactive power based control	Control mode	Status
17.		Requested voltage range at reference point	Set-point
18.		Voltage at reference point	Metering
19.		Requested reactive power at POC	Set-point
20.		Reactive power import/export at POC	Metering
21.		Requested power factor at POC	Set-point
22.		Power factor at POC	Metering
23.	Fault ride through	Voltage at POC	Metering
24.		Current at POC	Metering

A.5 Monitoring hardware

In general, there are two types of monitoring hardware:

- grid meters;
- extra monitoring devices used to obtain signals controllers, from current- and voltage transducers (CTs and VTs) which are built-in at the substation or generating unit.

The two hardware options should be separated. For example, for compliance testing, separate devices could be used which will be directly connected to CTs and VTs, at the relevant sampling frequency (e.g. 2 kHz). Such devices are needed as the current controller cannot store large amounts of data for long periods of time. For monitoring, the controller or the grid meter can be used.