Deliverable 3.6: Report with the compliance test procedures for DR and VSC connected WPPs

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Total number of authors:
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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Göksu, Ö., Saborío-Romano, O., Cutululis, N. A., Blasco-Gimenez, R., Bernal-Perez, S., Martinez-Turegano , J., Xu, L., Li, R., Zeni, L., Kocewiak, . H., El-Khatib, W. Z., Brantl, C., Kahlen, C., Scheffer, J., Zanner, M., Abdalrahman, A., He, W., Harson, A., & Abeyasekera , T. (2018). *Deliverable 3.6: Report with the compliance test procedures for DR and VSC connected WPPs*. PROMOTion - Progress on Meshed HVDC Offshore Transmission Networks.

Deliverable 3.6:
Report with the compliance test procedures for DR and VSC connected WPPs

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This result is part of a project that has received funding form the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

DOCUMENT INFO SHEET

Document Name:	PROMOTioN Deliverable Report with the compliance test procedures for DR and VSC connected WPPs
Responsible partner:	FGH
Work Package:	WP 3
Work Package leader:	DTU
Task:	3.3 Compliance evaluation procedure
Task lead:	FGH

DISTRIBUTION LIST

PROMOTioN WP3 partners , European Commission

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DOCUMENT HISTORY

Version	Date	Main modification	Author
1	08.10.2018		

WP Number	WP Title	Person months	Start month	End month
WP3	Wind Turbine – Converter Interaction	256.8	3	42

Deliverable Number	Deliverable Title	Type	Dissemination level	Due Date
D3.6	Report with the compliance test procedures for DR and VSC connected WPPs	Report		

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Work Package 3 and deliverable 3.6 involve a large number of partners and contributors. The names of the partners, who contributed to the present deliverable, are presented in the following table.

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LIST OF DEFINITIONS / ABBREVIATIONS

Term	Meaning
WPP	Wind Power Plant
WT	Wind Turbine
FEC	Front-End Converter
OWF	Offshore Wind Farm
VSC	Voltage Source Converter
DR	Diode Rectifier
DRU	Diode Rectifier Unit
Radial grid	Grid that does not contain a loop
Point-to-Point	(Inter) connection between two points
OTS	Offshore Transmission System
WFG	Wind Farm Group
TSO	Transport (onshore) System Operator
MOG	Meshed Offshore Grid
Multi Terminal	More than two stations
SAC	Synchronised AC
DRSAC	Diode Rectifier and Synchronised AC
ISL	Island Operation
PGU	Power Generating Unit
FSM	Frequency Sensitive Mode
Cluster	See Figure 2-3 D3.1
Sub-cluster	
Cluster Controller (CLC)	
Master Controller (MC)	
Offshore HVDC Conv. (OFC)	
Onshore HVDC Conv. (ONC)	

Content

1. INTRODUCTION / EXECUTIVE SUMMARY

The PROMOTioN Work Package 3 (WP3) “Wind Turbine – Converter Interaction” has three main objectives;
1. to specify functional requirements to OWFs, focusing on DRU-HVDC connection
2. to identify and specify general control algorithms for WTs and OWFs, focusing on DRU-HVDC connection
3. to define and demonstrate compliance evaluation procedures by simulations and tests

This report summarises the results of Task 3.3 “Compliance evaluation procedure”.

In Task 3.1 operational and system stability related requirements for DRU connected OWFs have been specified, mainly in Deliverable 3.1. In Task 3.2 control algorithms and simulation test cases for DRU connected OWFs have been specified, mainly in Deliverable 3.2. Based on these simulation test cases simulation results for DRU connected OWFs have been given in Deliverable 3.4 and 3.5. Hereby, in this Deliverable 3.6, evaluation procedures for compliance of the DRU connected OWFs to the requirements specified in Deliverable 3.1 are the main focus. The following step is application of the specified compliance test procedures in the succeeding Task 3.4, mainly in Deliverable 3.7.

In WP3 and also in this report, the main focus has been set on DRU-HVDC connection, since the VSC-HVDC connection is seen as a proven technology of today. Nevertheless, VSC-HVDC is still being investigated throughout the work package when there is room for further developments. In Task 3.2 of WP3, VSC-HVDC control strategies are being studied as state of the art and detailed requirement analysis for VSC-HVDC is being performed in WP1, which encompasses requirements for all components in the PROMOTioN project.

Section 2 of this report contains a description of requirements on wind turbines (WT) and wind power plants (WPP) that are in focus of compliance evaluation procedures.

In section 3 validation procedures for open models and manufacturer black-box simulation models are described.

Procedures for simulation-based compliance evaluations are described in section 4.

It should be noted that the simulation model validation procedures and compliance test procedures for certain functions (that are listed below) apply for VSC-connected OWPP as well.

The functions for which the specified compliance test procedures apply for both DRU and VSC connected OWPPs are:

- Active Power Production (section 4.1.1)
- Dynamic Active Power Control (section 4.1.3)
- Harmonics (section 4.2)
- Offshore Voltage-/Reactive Power Behaviour (section 4.3.4)
- Offshore AC Symmetrical / Asymmetrical Faults (section 4.4)
- Frequency Support (section 4.5.1)
- Onshore Power Oscillation Damping (section 4.5.2)

Compliance evaluation procedures are also being handled in WP11 in D11.4 “Report with recommendations to best practice for compliance evaluation”.

2. COMPLIANCE TEST REQUIREMENTS

2.1. COMPLIANCE TEST REQUIREMENTS FOR WIND TURBINES (WT)

Detailed functional requirements to OWFs connected to DRU-HVDC, including detailed specifications for WTG and OWF models are described in D3.1 “Detailed functional requirements to WPPs” with the aim to provide input for Task 3.3 and D3.6.

IEC 61400-21 “Measurement and assessment of power quality characteristics of grid-connected wind turbines” provides a uniform methodology that ensures consistency and accuracy in the presentation, testing and assessment of characteristics of grid connected wind turbines (WTs). Requirements related to power quality characteristics include wind turbine specifications, voltage quality (emissions of flicker and harmonics), voltage drop response, power control (control of active and reactive power), grid protection and reconnection time.

IEC 61400-21 includes:

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

According to IEC 61400-21, the procedures for assessing compliance with power quality requirements are valid for wind turbines with PCC at MV or HV in power systems with fixed frequency within ±1 Hz, and sufficient active and reactive power regulation capabilities. In other cases, the principles for assessing compliance with power quality requirements may still be used as guidance.

FGW technical guideline TR3 describes the determination of the electrical characteristics of power generating units and systems in medium-, high- and extra-high voltage grids in detail. FGW technical guideline TR8 specifies the assessment and certification of electrical characteristics of wind turbines and wind power plants.

2.2. COMPLIANCE TEST REQUIREMENTS FOR WIND POWER PLANTS (WPP)

In D3.1 “Detailed functional requirements to WPPs” OWF functional requirements include

- operational ranges (voltage range, frequency range, harmonics)
- controllers during normal operation; response times
- fault-ride-through for offshore AC, DC, and onshore AC faults
- ancillary services (frequency support, power oscillation damping, etc.) provision to onshore AC grids
- power quality (primarily harmonics) & harmonic compatibility (harmonic acceptance)
- simulation models (model interface, control modes)

On the one hand, this document refers to the requirements of D3.1 and other deliverables. On the other hand, it refers to requirements based on standards and grid codes. Other requirements have been developed within the project.

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In the following sections, the requirements with regard to the characteristics that are in focus of compliance evaluation are described. Requirements on simulation models are described in detail in section 3 of this document.

2.2.1 ACTIVE POWER PRODUCTION

Requirements:

Requirements are specified in ENTSO-E HVDC (see also D3.1, section 3.4.1):

The OWF shall be capable of maximizing the active power delivered to shore respecting the following limitations:

a) Available wind (power curve shall not be diminished).
b) Operator limitations (e.g. curtailment signal from the onshore power system operator due to onshore power system transmission constraints)
c) Intended transmission system limitations.
d) Unintended transmission system limitations.
e) Operational range violations.
f) Frequency support (activation via OWF controller)

2.2.2 STEADY STATE ACTIVE POWER CONTROL

Requirements:

Requirements are specified in D3.1, section 3.4.2:

The OWF shall be capable of balancing the active power production with the active power transmitted to shore by changing the active power flow in the transmission system.

a) In operational mode DR, the OWF shall modify the AC voltage magnitude at the diode rectifier terminals in such way that the desired (e.g. the available wind power) active power flow in the diode rectifier is established. This means that the OWF has to adjust reactive power infeed in order to control active power flow and stabilize system frequency.
b) In operational modes SAC and UAC, the OWF shall modify the AC voltage phase angle at the (offshore) connection point in such way that the power flow is modified in the desired way (e.g. the available wind power is transferred). At the same time additional requirements for the voltage magnitude control / reactive power injection need to be applied ("standard OWF controller")
c) In operational modes DRSAC and DRUAC different operational concepts are possible depending on the concrete system configuration. In any case it is beneficial if the OWF supports active power flow through the DRU and dc line by injection of reactive power. Different secondary control strategies may involve OWF, HVDC onshore station or HVDC offshore station to guarantee proper power sharing between AC and DC lines or OWF and AC sources. The optimization of offshore AC voltage may additionally require active control of tap changers.

If the system is in operational mode DRSAC and is operated in parallel with an umbilical cable, coordination must be done much faster in order to keep frequency synchronism and limit thermal stress in the cable. This

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can be achieved by the onshore HVDC station or OWF. In the latter case a feedback representing the power flow in the AC system/source should be available, and the OWF shall control the feedback towards zero.

2.2.3 DYNAMIC ACTIVE POWER CONTROL

Requirements:

When the system is synchronized with an external AC, it should be possible to control the active and reactive power flow through the external AC link. The system will start synchronized with an external AC grid and the active/reactive power references will vary within the nominal range. The system should react to that variation keeping all magnitudes in normal operating range.

To support normal operation, the OWF shall be capable of ramping active power from one set point to another (considering the limitations as stated in D3.1 3.4.1) within 10 seconds.

2.2.4 ACTIVE POWER RECOVERY

Requirements:

During an event which causes unintended transmission capability limitation, the system should be protected to avoid any damage to equipment. Appropriate system control also needs to be in place to ensure maximum power transmission and fast system recovery. In some cases, the offshore wind power could be continuously transferred through the DRU-HVDC but with limited capacity, depending on the specific fault types.

The OWF shall be capable of returning the active power from a limited operating point to the pre-event active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s.

Active Power oscillations shall be acceptable provided that:

(1) the total Active Energy delivered during the period of the oscillations is at least that which would have been delivered if the Active Power was constant,
(2) the oscillations are adequately damped,
(3) limitations of the transmission system are regarded.

2.2.5 ISLAND SUPPORT (NO HVDC OR AC CONNECTION)

A) Island Operation

Requirements:

Requirements are specified in ENTSO-E NC RFG (see also D3.1, section 3.4.5):

The OWF shall support a temporary islanding of the offshore AC system for minimum 20 seconds. It is understood that this can only be achieved as long as there is sufficient energy available (wind, kinetic, alternative power source at the offshore AC network, etc.).

The following requirements shall be fulfilled:

(i) power-generating modules shall be capable of taking part in island operation if required by the relevant system operator in coordination with the relevant TSO and:

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  a. the frequency limits for island operation shall be those established in accordance with point (a) of Article 13(1) of ENTSO-E NC RFG,
  b. the voltage limits for island operation shall be those established in accordance with Article 15(3) or Article 16(2) of ENTSO-E NC RFG, where applicable;

(ii) power-generating modules shall be able to operate in FSM (Frequency Sensitive Mode) during island operation, as specified in point (d) of paragraph 2 of ENTSO-E NC RFG.

In the event of a power surplus, power-generating modules shall be capable of reducing the active power output from a previous operating point to any new operating point within the P-Q-capability diagram. In that regard, the power-generating module shall be capable of reducing active power output as much as inherently technically feasible, but to at least 55 % of its maximum capacity

B) Black Start Capability

Requirements:

Requirements are specified for synchronous power-generating modules in ENTSO-E RFG. These requirements are considered applicable here, as well.

The following requirements shall be fulfilled:

(i) a power-generating module with black start capability shall be capable of starting from shutdown without any external electrical energy supply within a time frame specified by the relevant system operator in coordination with the relevant TSO

(ii) a power-generating module with black start capability shall be able to synchronise within the frequency limits laid down in point (a) of Article 13(1) of ENTSO-E RFG and, where applicable, voltage limits specified by the relevant system operator or in Article 16(2) of ENTSO-E RFG

(iii) a power-generating module with black start capability shall be capable of automatically regulating dips in voltage caused by connection of demand

(iv) a power-generating module with black start capability shall:

- be capable of regulating load connections in block load,
- be capable of operating in LFSM-O (Limited FSM – Overfrequency) and LFSM-U (Limited FSM – Underfrequency), as specified in point (c) of paragraph 2 and Article 13(2) of ENTSO-E RFG,
- control frequency in case of overfrequency and underfrequency within the whole active power output range between minimum regulating level and maximum capacity as well as at houseload level,
- be capable of parallel operation of a few power-generating modules within one island,
- control voltage automatically during the system restoration phase

2.2.6 HARMONICS

Requirements:

The OWF MV collector system shall comply with IEC 61000-2-4 compatibility requirements.

To determine relevant harmonic values for wind turbines a testing method in line with the IEC standard is specified in FGW TR3.

2.2.7 FREQUENCY ENVELOPE

Requirements:

When the OWF is connected to a diode rectifier only, then the frequency shall be maintained within the frequency vs. time envelope specified in the following table. This is a DRU solution specific requirement, not based on any grid code specification. The narrow frequency ranges are needed to assure optimal filter design and operation.

Table: Frequency control performance requirements according to D3.1

Frequency Range	Time period for operation
49.875 - 50.125 Hz	Unlimited
49.00 – 51.00 Hz	500ms

Note: When the OWF is connected via an AC connection, then the frequency is defined by the onshore grid, and no independent frequency control of the OWF can be achieved. Frequency will be calculated using a 500ms window, with the corresponding interpolation calculation.

2.2.8 STEADY STATE FREQUENCY CONTROL

Requirements:

When the OWF is connected to a diode rectifier only, then the frequency shall be controlled towards a set point (Zero steady state error).

2.2.9 DYNAMIC FREQUENCY CONTROL

Requirements:

When the OWF is connected to a diode rectifier only, then the frequency shall be controlled to a new set point with a rise time of less than 3 seconds from the point where the set point is received by the OWF. (This is DRU solution specific requirement)

2.2.10 OFFSHORE VOLTAGE-/REACTIVE POWER BEHAVIOUR

A) VOLTAGE ENVELOPE

Requirements:

The OWF voltage shall be maintained within the normal operating range which is 90-110% of the rated voltage. (In line with the [ENTSO-E NC HVDC Article 40 Annex VII]):

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Table: Minimum time periods for which a DC-connected power park module shall be capable of operating for different voltages deviating from a reference 1 pu value without disconnecting from the network where the voltage base for pu values is from 110 kV to (not including) 300 kV.

Voltage Range	Time period for operation
0,85 pu – 0,90 pu	60 minutes
0,90 pu – 1,10 pu	Unlimited
1,10 pu – 1,118 pu	Unlimited, unless specified otherwise by the relevant system operator, in coordination with the relevant TSO.
1,118 pu-1,15 pu	To be specified by the relevant system operator, in coordination with the relevant TSO.

Table: Minimum time periods for which a DC-connected power park module shall be capable of operating for different voltages deviating from a reference 1 pu value without disconnecting from the network where the voltage base for pu values is from 300 kV to 400 kV (included).

Voltage Range	Time period for operation
0,85 pu – 0,90 pu	60 minutes
0,90 pu – 1,05 pu	Unlimited
1,05 pu – 1,15 pu	To be specified by the relevant system operator, in coordination with the relevant TSO. Various sub-ranges of voltage withstand capability can be specified.

B) REACTIVE POWER/CURRENT CAPABILITIES

Requirements:

The OWF shall support the reactive power/current which is required to maintain the voltage within the normal operating range and to transfer active power into the OTS.

Note: It is expected that the offshore electrical system is designed to respect the reactive capabilities of the WTG, and that start-up/shut-down is coordinated in a way which considers that WTGs can only provide reactive support after they have been started up.

C) STEADY STATE VOLTAGE/REACTIVE POWER CONTROL

Requirements:

When the OWF is not connected via the HVDC (No HVDC power flow), it shall be possible to control the WTG output voltage/reactive power in such way to:

- Support the OTS in controlling the voltage magnitude at the interface between OWF and OTS.
- Avoid any unnecessary reactive power flow between WTGs in the OWF to prevent overloading of collector cabling etc. (This applies in all modes of operation).

Note: When power is being transmitted via the HVDC connection, the voltage at the OTS/OWF interface cannot be controlled independently of the active power flow in the HVDC.

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2.2.11 OFFSHORE FAULT-RIDE-THROUGH

Requirements:

OWF shall be capable of staying connected to the network and continuing to operate stably after the (offshore) power system has been disturbed by secured faults. That capability shall be in accordance with the voltage against time profile at the connection point. The voltage-against-time-profile shall express lower and upper limits of the actual course of the phase-to-phase voltages on the network voltage level at the offshore connection point during a fault, as a function of time before, during and after the fault.

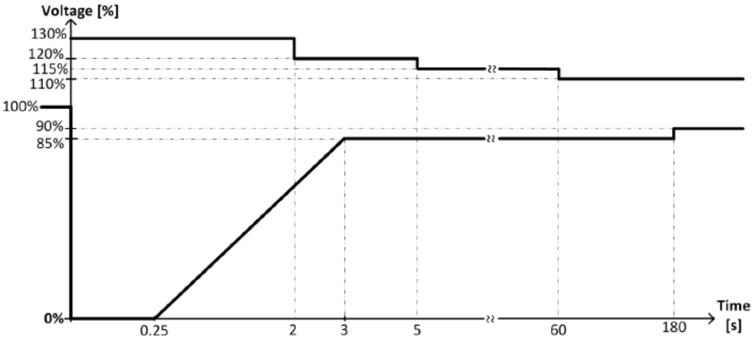

Figure 1: Voltage-time profile for offshore AC faults

Fault current requirements shall cover

- symmetrical (3-phase to ground) and asymmetrical (1-phase to ground fault, phase-phase, phase-phase to ground) AC offshore faults
- all related system configurations such as; DR (only diode rectifier connection), SAC (e.g. only umbilical cable), DRSAC (diode rectifier and umbilical cable)
- whole range (e.g. 5%-100%) of power generation level (e.g. including cases with low wind and/or few WTs are in operation).

It is important to note that the voltage-time profile in **Error! Reference source not found.** is originating from classical (onshore) power system response, where the voltage ramp might take time. This profile is expected to be observed when there is connection (umbilical cable) to the onshore AC system. For the offshore AC faults, when there is no connection to the onshore AC (i.e. DR state) the voltage profile will depend on the response of the WTGs. For instance, the voltage ramp up might be quite faster than the one shown in **Error! Reference source not found.**. However, it is also important to note that DRU-connected WTGs would possibly be tested against DRU connection, rather than a voltage-profile.

2.2.12 OFFSHORE AC FAULT CURRENT INJECTION

Requirements:

OWF shall be capable of providing fast fault current (start within 20ms after fault detection) at the connection point either by:

- ensuring the supply of the fast fault current at the OWF connection point, or

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- measuring voltage deviations at the terminals of the individual WTs of the OWF and providing a fast fault current at the terminals of WTs. [ENTSO-E NC HVDC, article 38] [ENTSO-E NC RfG Article 20 (2)]

OWF shall also be capable of delivery of additional reactive current supporting voltage retention. The ratio between the provided fault current and amount of voltage dip shall be adjustable with the range of 2-10.

2.2.13 OFFSHORE AC FAULT RECOVERY

Requirements:

The OWF shall be capable of returning the active power from a limited operating point to the pre-fault active power level minus 10% (e.g. 100% -10% = 90%) with a ramp rate of 200%/s. Active Power oscillations shall be acceptable provided that:

(1) the total Active Energy delivered during the period of the oscillations is at least that which would have been delivered if the Active Power was constant,
(2) the oscillations are adequately damped,
(3) limitations of the transmission system are regarded.

It is important to note that the recovery here is defined for post-fault recovery after offshore faults. This requirement is similar to the requirement on active power recovery, where the recovery has been defined for recovery after unintended transmission system limitation.

2.2.14 FREQUENCY RESPONSE

Requirements:

OWF shall be capable of receiving an onshore frequency signal (measured at the onshore synchronous area and sent by the onshore converter or OWF-OTS Coordinator).

OWFs connected via HVDC systems which connect to more than one control area should be capable of delivering coordinated frequency control which will be separately specified.

OWFs that are directly connected to onshore synchronous area (for instance via AC offshore interconnection to an AC-connected OWF) will respond without need for communication.

2.2.15 ONSHORE POWER OSCILLATION DAMPING BEHAVIOUR

Requirements:

OWF shall have the capability to modulate its active power output for a sinusoidal waveform in the frequency range 0.3 Hz to 2 Hz with a magnitude of 0.1pu.

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3. VALIDATION PROCEDURES FOR SIMULATIONS

3.1. REQUIREMENTS ON MODELS FOR COMPLIANCE EVALUATION

ENTSO-E RFG specifies compliance testing (chapter 4) and compliance simulations (chapter 7) for offshore power park modules. ENTSO-E HVDC specifies compliance testing (chapter 2) and compliance simulations (chapter 3) for HVDC systems. Equipment certificates may be used instead of tests or simulations.

Compliance evaluation of OWF shall be conducted by means of simulations based on models of all relevant components**:**

(i) Wind turbine (WT) model

The WT model must describe characteristics of

- Active power generation
- Reactive power generation
- Fault detection
- Fault behavior

The model should have been validated against tests as specified in IEC 61400-21. Both a generic WT model block diagram and examples of simplifications are shown and described in section 5 of deliverable D3.1. Detailed specifications for WT models and their documentation can also be found in FGW TR 4 [5].

(ii) Model of OWF Transformers

Standard models of transformers can be used. They must include

- Series resistance
- Leakage inductance
- Transmission ratio
- Main inductivity at power frequency
- Winding configuration
- Neutral point treatment

(iii) Model of power cables within the OWF

Standard models can be used. They should include resistance, inductance, capacitance per length

(iv) Models of active/passive compensation systems

- Compensation systems should be described by their discrete components

(v) Model of DC-link and external grid to which the OWF is connected

(vi) Model/documentation of OWF control

Detailed specifications for models and their documentation as well as detailed information on simulations (time-dependent and time-independent) can be found in FGW TR 4.

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It should be stated that for IEC 61400-27-1 which specifies a model validation procedure refers to RMS models while for several compliance evaluation processes described in this report – e.g. harmonics, DRU, black start capability - harmonic models or EMT models are required.

In these cases, both harmonic and small signal stability studies will use the frequency and operating point dependent Norton (or Thevenin) models of all the system elements (WTs, cables, DRUs, umbilical cable, etc.). Whereas DRU, transformer and cable models are passive systems, WT harmonic models depend on the particular control being used. As particular WT controls might not be accessible or accessible as black-box models, closed loop harmonic models should be provided for different generation levels by the relevant manufacturer/developer. EMT simulations might be used to validate the harmonic models by the manufacturer or by other parties if black-box or detailed WT models are available. WT harmonic models should consider the complete GSC WT control, GSC converter and GSC passive elements (filters, transformer, etc.).

3.2. VALIDATION PROCEDURE FOR OPEN MODELS AND MANUFACTURER BLACK BOX SIMULATION MODELS

A simulation model is a representation of a real equipment. The main aim of simulation models is to emulate the behaviour of the real equipment, especially when subjected to disturbance, such as a power system fault. Several simplifications are implemented in models to determine the response of the model within a specified frequency, voltage range, or time interval. These simplifications always result in reduced accuracy. In this sense, simulation model response needs to be compared with real experiments, alternatively previously validated models. The use of real events data to validate a detailed EMT wind turbine model in a first step and then this validated EMT model is used to validate a simplified RMS model for power system stability is proposed. Due to the recent development and publication of the IEC 61400-27-1 generic models, there is a need to validate them with respect to particular vendor models. In this line, one common validation procedure is defined in the German FGW TR4.

Two validation types depending on the input to the simulation model have been defined in the IEC 61400-27 working group.

- Playback: In a classical playback method, the specific wind turbine Type is modelled and voltage signal, u, is played-back as input to the simulation model. The response of the other signals, such as currents and power are used for validation purposes. However, the DRU-connected WTs are grid forming WTs that create the voltage for the offshore AC grid, where the DRU is connected. The DRU behaves similar to a voltage-dependent load, which draws power with a dependency on the offshore AC voltage level, the DC link voltage level, and DRU characteristics. Hence, it is not straightforward to apply the classical playback method to grid forming DRU-connected WTs. In case of grid forming DRU-connected WTs, a new playback method has to be applied, where both the voltage and also the current is played-back as input to the simulation model. It should be noted that the played-back voltage cannot be the voltage at the controlled terminals of the grid forming WT (as this voltage is being generated by the WT itself). The played-back voltage shall be the voltage at the DRU terminals and the net-

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work between the DRU and WTs (e.g. the collector network) has to be modelled, which implies that the new playback method is a blend between the classical playback method and full grid simulation.

- Full grid simulation: both the specific wind turbine Type and the equivalent grid and the interface between the wind turbine and the network are modelled.

The playback validation approach is recommended by IEC guidelines.

Once the generic IEC model simulations and the corresponding vendor model simulations have been performed, the resulting signals are filtered by a 15 Hz low pass filter. In fact, bandwidths between 0.1 Hz and 10 Hz are typical for equipment models commonly used for power system stability simulations.

The purpose of IEC61400-27 is to establish a standard procedure for the validation of a WPP simulation model referring to tests on the WPP concerned.

The validation procedure applies to fundamental frequency simulation models. The validation process must be on the WPP simulation models that are defined in IEC61400-27, as well. The validation process can also be used for other fundamental frequency wind turbine models such as manufacturer or project specific models.

The validation procedure specified in IEC61400-27 and recommended in this document is based on tests according to IEC61400-21 that are also specified in FGW TR3 [6].

For model validation, the following general specifications must be considered:

- The validation procedure must include at least the following WPP function characteristics:
    - validation of the behaviour of the simulation model at tested voltage dips;
    - validation of the behaviour of the simulation model during tested jump changes in the reference values;
    - validation of the network protection functions of the simulation model.
- Model and test must refer to the same WPP terminals to ensure that measurements and simulations refer to the same point. According to IEC 61400-21, the WPP terminals specified by the manufacturer, and that may be the low voltage side of the WPP transformer or) the high voltage side of the WPP transformer.
- In accordance with the validation procedure, simulated positive sequence values must be validated against measured positive sequence values. If models include negative sequence values, those must be evaluated against measurements, as well.
- The validation procedure focuses on
    - Voltage dips
    - Change of reference point / set points
    - Network protection

  For these cases, necessary measurement data, simulation set-up and results are specified.
- A test plan must be drawn up for each measurement performed during the validation.
- The results of the validation process must be:
    - time series of measured and simulated fundamental frequency quantities;
    - time series of errors between simulated and measured fundamental frequency currents and voltages;

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  - the mean error, the mean absolute error and the largest error in windows of voltage dips before the fault condition, during the fault condition and after the fault condition;
  - the measured and simulated response time, rise time and settling time of reference point changes;
  - the measured and simulated protection level and the measured and simulated shutdown times of the network protection;
  - the specification of the scope of the validated simulation model.
- The sampling of information and data for visualization must be done with a sampling time of 10 ms or better. The visualization of the measured and simulated data must be in accordance with IEC 61400-21 if the positive and negative sequence or zero system are required.
- To calculate the deviation between simulated and measured values, a common time base can be set up for the two records. This can be done by time synchronization, decimation or interpolation of the sampled values.
- All observed high frequency phenomena of electromagnetic origin which are persisting for less than e.g. one period, must be neglected, since they are not specified within the scope of the simulation models.
- If a measured value does not have an associated simulated value, an interpolated (error-) value can be used.
- The measured, processed and simulated values must be given as related values, where, the nominal value of the apparent power and the nominal voltage at the measuring point are used as the basis for the calculation of the related parameters.

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4. PROCEDURES FOR SIMULATION BASED COMPLIANCE EVALUATIONS

In deliverable D3.1 a set of requirements for DRU connected OWF is given as a basis for the control and compliance procedure development. Both DRU specific operational requirements and power system stability requirements are considered in D3.1. The operational requirements aim at fundamental functional operation of the OWF when connected to the DRU, while the stability requirements aim at support to the offshore and onshore grids, especially in case of disturbances (e.g. faults, frequency drops). In this report, procedures for simulation-based compliance evaluation of WPPs´ behaviour concerning the requirements specified in D3.1 are described. For each case, the overall aim, the general requirements that must be met and the compliance evaluation methodology is given.

4.1. ACTIVE POWER CONTROL BEHAVIOUR

4.1.1 ACTIVE POWER PRODUCTION

Aim:
Evaluation of active power production

Compliance Evaluation
Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components (see section 3.1).

Simulations:
For the evaluation of power tracking with varying wind each WT model will be provided by a variable wind speed and corresponding active power reference. The equivalent wind speed sent to each WT model will follow a Kaimal distribution with a given average wind speed and turbulence intensity. The wind speeds for each WT will not be correlated and wind farm layout effects will not be considered.
For the evaluation of the reaction to set point and curtailment signals in the simulations the OWF controller is commanded to ramp down/up the active power delivered by the WTs. OWF controller sends the active power set-point command to individual WTs. It should not be assumed that the ramp up/down command sent from the OWF controller arrives to all the WTs at the same time.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.5.

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For each one of the test cases, the functional requirements will be evaluated and a quantitative or qualitative result will be tabulated. In each case, quantitative and qualitative results will be compared with the considered functional requirements.

4.1.2 STEADY STATE ACTIVE POWER CONTROL

Aim:
Evaluation of steady state active power control of OWF

Compliance Evaluation
Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components (see section 3.1).

Simulations:
For the evaluation of power tracking with varying wind each WT model will be provided by a variable wind speed and corresponding active power reference. The equivalent wind speed sent to each WT model will follow a Kaimal distribution with a given average wind speed and turbulence intensity. The wind speeds for each WT model will not be correlated and wind farm layout effects will not be considered. Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.5.
For each one of the test cases, the functional requirements will be evaluated and a quantitative or qualitative result will be tabulated. In each case, quantitative and qualitative results will be compared with the considered functional requirements.
Optimal power tracking error will also be evaluated and tabulated for each one of the considered cases.
In each case, the quantitative and qualitative results will be compared with the related functional requirements.

4.1.3 DYNAMIC ACTIVE POWER CONTROL

Aim:
Evaluation of dynamic active power control of OWF

Compliance Evaluation
Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components (see section 3.1).

Simulations:
Initially, the system will be simulated as synchronized and transmitting active power to the on-shore AC grid via umbilical cable and via HVDC link. Then, new active power references will be set.
Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.8.

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For each one of the tests the functional requirements will be evaluated and a quantitative or qualitative result will be tabulated. In each case, quantitative and qualitative results will be compared with the considered functional requirements.

4.1.4 ACTIVE POWER RECOVERY

Aim:

Evaluation of active power recovery of OWF

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components (see section 3.1).

Simulations:

The following cases should be investigated:

(1) During a close symmetrical fault with small short-circuit impedance, the AC terminal voltage of the MMC is decreased to around zero and it is impossible to export power to the AC grid. The DC voltage of the HVDC link needs to be properly regulated by the MMC to reduce the imported power through the DRUs and alleviate system overvoltage.

(2) During a remote symmetrical fault with significant short-circuit impedance, considerable AC terminal voltage is still available at the MMC terminal. Thus, the power transfer should be continued and controlled in the range of the remaining capacity of the MMC, which is in proportional to the remaining AC grid voltage.

(3) During an asymmetrical onshore AC fault, the AC terminal voltage of the MMC is unbalanced. In addition to the positive sequence component, the negative sequence components also need to be properly controlled (e.g. for suppressing power oscillation). The energy balancing (i.e. submodules per arm, upper and lower arms, and phase-to-phase) is also required to ensure satisfactory operation of the MMC under asymmetrical AC fault conditions.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.3.1.

For each one of the test cases, EMT simulation results will be provided and will be evaluated against the functional requirements

4.1.5 ISLAND SUPPORT (NO HVDC OR AC CONNECTION)

A) Island Operation

Aim:

Evaluation of capability of OWF to take part in island operation

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Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components (see section 3.1). ENTSO-E RFG specifies general requirements for island operation simulation. Paragraphs 3 and 5 of Article 54 as well as in paragraphs 4, 5 and 7 of Article 55 shall apply to any offshore power park module.

Simulations:

With regard to the island operation simulation the following requirements shall apply:

(i) the power-generating module's performance during island operation referred to in the conditions set out in point (b) of Article 15(5) shall be demonstrated

(ii) the simulation shall be deemed successful if the power-generating module reduces or increases the active power output from its previous operating point to any new operating point within the P-Q-capability diagram within the limits of point (b) of Article 15(5), without disconnection of the power-generating module from the island due to over- or underfrequency.

More specific, the following cases should be investigated (D3.2, section 4.2.3):

(i) Intentional islanding

The system will start completely energised and transmitting active power either via HVDC Link (DR mode). Then, order of intentional islanding is given. Therefore, the power transmission has to be stopped and, at the end of the procedure, the off-shore system will remain completely disconnected from the onshore grid. The OWF should be capable of maintaining offshore voltage and frequency in that final state, island.

(ii) Re-synchronisation to external AC from island mode

The system will start in island mode controlling offshore grid voltage and frequency. It should be possible to re-synchronise with the onshore grid via umbilical, for example if there is no longer available wind power. At the end of the procedure, the system must remain synchronised with the external AC grid and manage the active and reactive power flow through umbilical.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.3.

B) Black Start Capability

Aim:

Evaluation of black start capability of OWF

Compliance Evaluation:

Compliance evaluation will follow black start tests are specified in general in ENTSO-E RFG and ENTSO-E HVDC.

According to ENTSO-E RFG, with regard to the black start capability test the following requirements shall apply:

(i) For power-generating modules with black start capability, this technical capability to start from shut down without any external electrical energy supply shall be demonstrated;

(ii) The test shall be successful if the start-up time is kept within the time frame set out in point (iii) of Article 15(5)(a) in ENTSO-E RFG.

According to ENTSO-E HVDC, with regard to the black start capability test the following requirements shall apply:

(i) the HVDC system shall demonstrate its technical capability to energise the busbar of the remote AC substation to which it is connected, within a time frame specified by the relevant TSO, according to Article 37(2)
(ii) the test shall be carried out while the HVDC system starts from shut down
(iii) the test shall be deemed passed, provided that the following conditions are cumulatively fulfilled:
    a. the HVDC system has demonstrated being able to energise the busbar of the remote AC-substation to which it is connected;
    b. the HVDC system operates from a stable operating point at agreed capacity, according to the procedure of Article 37(3).

A more detailed black start test procedure for generating units and stations is defined in the UK Grid code (Operating code 5.7).

4.2. HARMONICS

4.2.1 EVALUATION OF HARMONICS

HARMONIC COMPATIBILITY REQUIREMENTS

Aim:

Evaluation of harmonic compatibility requirements

Compliance Evaluation

Testing method

The harmonics are measured compliant with IEC 61000-4-7:2002. Accuracy class I in accordance with the IEC 61000-4-7:2002 definition must be adopted. The measurements must be based on observation times of 10 min for each active power bin and be determined where there is a minimum level of grid background distortion. Measurements that are clearly influenced by any level of background distortion in the grid must be excluded.

The midpoints of the active power bins are at 0 %, 10 %, 20 %, …, 100 % Pn. At least three records consisting of 3-phase measurements of both current and voltage must be recorded for each bin.

As a deviation to IEC 61000-4-7, the error is with reference to the PGU's (Power Generating Unit, wind turbine in this case) rated current In and not the rated current range of the measurement device. The metrological resolution of the relative proportions of the harmonic currents must be ≤ 0.05 % of In. As a minimum, the grid-side currents and phase-neutral voltages shall be measured.

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Analysis method

Notes on the reduction of harmonics values in the case of grid background distortion are given FGW TR3, as well. The following specifications relate to both the harmonic currents and the harmonic voltages. The measurements as well as the grouping methods of the spectral component used must comply to IEC 61000-4-7:2002. The analyses of integer harmonics and inter-harmonics up to the 50th order must be synchronised with the grid frequency. Analyses of the higher frequency components from 2 kHz to 9 kHz do not need to be synchronised.

For a 50 Hz power system analysis of records in windows of 10 periods is recommended. A 200 ms window can also be applied for the higher frequency components.

The discrete Fourier transform (DFT) must be applied to each measured current using a rectangular window. The active power must be determined for the same time window as the harmonics.

Harmonic subgroups corresponding to the IEC 61000-4-7:2002 definition in the chapter titled 'Assessment of voltage harmonic subgroups' chapter are determined from the integer multiples of the fundamental frequency and the two neighbouring spectral lines and are referred to here as harmonics. The root mean square is formed from all 3 spectral lines and referenced to the PGU's rated value. These harmonics are determined up to the 50th order.

Centred inter-harmonic subgroups corresponding to the IEC 61000-4-7:2002 definition in the chapter titled 'Assessment of voltage harmonic subgroups' are determined from the spectral lines remaining from determination of the harmonics and are referred to here as inter-harmonics. The number of spectral lines varies with the bandwidth of the spectral lines. The root mean square is formed from all spectral lines and referenced to the PGU's rated value. These inter-harmonics are determined up to the 40th order.

Consequently, no spectral line of a DFT spectrum is counted twice, as happens in the IEC 61000-4-7:2002 'harmonics' and 'inter-harmonics' grouping.

Centre frequency of the spectral lines grouped in 200 Hz blocks from the 40th harmonic order up to 9 kHz compliant with the definition in IEC 61000-4-7:2002 from the 'Assessment of volt-age harmonic subgroups' chapter are the quadratic sums of the root mean squares of the DFT spectral lines relative to the rated value.

Here, the centre frequencies are referred to as the higher frequency components. The number of spectral lines varies with the bandwidth of the spectral lines. The first centre frequency in the 50 Hz grid is 2100 Hz and encompasses the range > 2000 Hz up to and including 2200 Hz.

The arithmetic average is formed over the 10-minute record for each harmonic, inter-harmonic and higher frequency component of the current.

In addition, the associated total distortions are determined from the current and voltage harmonic subgroups. Here, the total distortion of the current harmonics (TDC) is determined.

Documentation

The test report must contain the following details:

- Measurement period
- Conditions during testing
    - Voltage range
    - voltage unbalance
    - Voltage TDD
    - Grid frequency range, where applicable

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- Number of measurement intervals per power bin
- Reactive power fed in (if deviating from cos φ =1):

All determined harmonic values refer to the PGU's rated current in percent, rounded to two decimal places and giving the measurement uncertainty.

The width of the window from which the spectral components are acquired must be documented.

The harmonics, inter-harmonics and higher frequency components of the current shall be given in the test report as the maximum values of all 10-minute mean values of the records in the respective active power bins.

The total voltage distortion (TDD) and total current distortion (TDC) must be given in the test report.

Compliance Evaluation using detailed simulations

The previously described compliance evaluation method cannot be applied to systems in the design or planning phase. In these cases, compliance Evaluation of OWF shall be conducted by means of simulations using the harmonic models (Thevenin/Norton equivalents) of all the relevant system elements.

It should be stated if the Thevenin/Norton equivalents have been obtained from EMT simulations or by analytical means (or both).

Simulations:

Evaluation of harmonic distortion compliance – DR operation

Simulation of normal operation, with the OWF producing energy and the diode rectifier unit conducting (DR operation mode). Analyses to be carried out include harmonic distortion studies using the Norton (or Thevenin) harmonic models of each element.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.6.

For the harmonic distortion analysis, at the off-shore PCC (DRU ring bus), the voltage harmonic amplitude, as well as the voltage THD will be tabulated. These results will be compared to the requirements set in deliverable D3.1.

Evaluation of harmonic distortion compliance – SAC, DRSAC operation

Possible harmonic overvoltages at the off-shore grid when the umbilical cable is connected will be evaluated. It is assumed that HVDC cable harmonics have a negligible effect on ac-side harmonics. Analyses to be carried out include harmonic distortion studies using the Norton (or Thevenin) harmonic models of each element.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.6.

For the harmonic distortion analysis, at the off-shore PCC (DRU ring bus), the voltage harmonic amplitude, as well as the voltage THD will be tabulated. These results will be compared to the requirements set in deliverable D3.1.

Evaluation of small-signal stability (DR operation)

This project has received funding from the European
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programme under grant agreement No 691714.

Evaluation will be carried out by computing the loop impedances as seen from relevant elements for the significant wind farm configurations. Phase and gain margins will be calculated for each considered configuration. For cases with the smallest phase and gain margin, EMT studies might be carried out to verify the results obtained by impedance analysis.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.6.

Simulation of normal operation, with the OWF producing energy and the diode rectifier unit conducting (DR operation mode) off-shore AC grid shall remain stable regardless of number of connected WT.

Sensitivity analysis will include studies considering the complete OWF and by reducing the number of connected strings until the minimum number of WTs for DR operation is reached.

For each case, there will be analysis of a representative set of different power levels.

The gain and phase margin of each considered case will be obtained to ensure adequate phase and gain margins (PM>30deg and GM>3dB).

Evaluation of small-signal stability (SAC, DRSAC operation)

Small stability studies will be carried out by computing the loop impedances as seen from relevant elements for the significant wind farm configurations. Phase and gain margins will be calculated for each considered configuration. For cases with the smallest phase and gain margin, EMT studies might be carried out to verify the results obtained by impedance analysis.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.6.

SAC and **DRSAC** configuration are evaluated. In both cases, the auxiliary supply cable is connected.

DRSAC: Sensitivity analysis will include studies considering the complete OWF and by reducing the number of connected strings until the minimum number of WTs for DR operation is reached.

SAC: Sensitivity analysis will include cases considering WTs operating as STATCOM and also WTs controlling active power through the auxiliary supply.

For each case, an analysis of a representative set of different power levels will be made.

4.3. SYSTEM STABILITY AND ANCILLARY SERVICES

4.3.1 FREQUENCY ENVELOPE

Aim:

Evaluation of frequency envelope requirements

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of EMT simulations based on models of all relevant components.

This project has received funding from the European
Union's Horizon 2020 research and innovation
programme under grant agreement No 691714.

Simulations:

Simulations as described in sections 2.1.2 (Steady state active power control) and 2.1.3 (Dynamic active power control) of this document will be performed and evaluated against frequency related requirements.

4.3.2 STEADY STATE FREQUENCY CONTROL

Aim:

Evaluation of steady state frequency control requirements

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components.

Simulations:

Simulations as described in sections 2.1.2 (Steady state active power control) and 2.1.3 (Dynamic active power control) of this document will be performed and evaluated against frequency related requirements.

4.3.3 DYNAMIC FREQUENCY CONTROL

Aim:

Evaluation of frequency control requirements

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components.

Simulations:

Simulations as described in sections 2.1.2 (Steady state active power control) and 2.1.3 (Dynamic active power control) of this document will be performed and evaluated against frequency related requirements.

4.3.4 OFFSHORE VOLTAGE-/REACTIVE POWER BEHAVIOUR

VOLTAGE ENVELOPE

Aim:

Evaluation of OWF voltage

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of EMT simulations based on models of all relevant components. RMS voltage values would be calculated considering a 10-cycle window.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Simulations:

Simulations as described in sections 2.1.5 (Island support) of this document will be performed and evaluated against voltage envelope related requirements.

REACTIVE POWER/CURRENT CAPABILITIES

Aim:

Evaluation of reactive Power/Current capabilities

Compliance Evaluation

ENTSO-E RFG specifies compliance testing (chapter 4) and compliance simulations (chapter 7) for offshore power park modules also considering reactive power capabilities. Instead of tests or simulations, equipment certificates may be used in order to demonstrate compliance with requirements.

Simulations

In order to evaluate the reactive power/current capabilities by simulations, a wide range of crucial test cases should be considered:

(1) HVDC link and off-shore AC-grid start-up operation

The start-up procedure is carried out. The complete system will be completely dis-energised and at the end of the procedure, the OWFs will be delivering their active power set-point through the DRU, with the auxiliary AC supply (umbilical) disconnected.

(2) HVDC link and off-shore AC-grid disconnection operation

The system will be completely energised, OWF working on their power tracking point and umbilical cable disconnected. At the end of the procedure, the off-shore system will remain energized through umbilical cable and all WTs disconnected waiting for available wind power.

(3) Reactive power sharing command with DR configuration

OWF shall support reactive power required to control the voltage within their range. Also, OWF shall be able to share reactive power demand between WT considering their capability.

(4) Reactive power sharing command in ISL configuration

OWF shall support reactive power required to maintain the voltage within their range when active power is not being transmitted. Besides, OWF shall be able to share reactive power between WTs according to WT in operation and its limitations.

(5) Operation with reduced number of DRUs

The system should be able to operate within normal ranges with a reduced number of DRUs. The system is supposed to have already manoeuvred and isolated the pertinent DRU and is waiting to recover power flow. It will start in island mode and receive the order from OTS to begin power generation. At the end, each WT should be transmitting via the two remaining DRUs the maximum power available, with its correspondent limitations.

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Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, sections 4.2.1., 4.2.2, 4.2.7 and 4.2.10.

STEADY STATE VOLTAGE/REACTIVE POWER CONTROL

Aim:

Evaluation of Steady State Voltage/Reactive Power Control capabilities

Compliance Evaluation

ENTSO-E RFG specifies compliance testing (chapter 4) and compliance simulations (chapter 7) for offshore power park modules also considering voltage/reactive power control capabilities. Instead of tests or simulations, equipment certificates may be used in order to demonstrate compliance with requirements.

Simulations

In order to evaluate the voltage/reactive power control capabilities by simulations, the following crucial test cases should be considered:

(1) Reactive power sharing command with DR configuration
    OWF shall support reactive power required to control the voltage within their range. Also, OWF shall be able to share reactive power demand between WT considering their capability.

(2) Reactive power sharing command in ISL configuration
    OWF shall support reactive power required to maintain the voltage within their range when active power is not being transmitted. Besides, OWF shall be able to share reactive power between WTs according to WT in operation and its limitations.

Detailed information on the required aggregation level of simulations and on the test cases necessary for a sensitivity analysis are given in D3.2, section 4.2.7.

4.4. OFFSHORE AC SYMMETRICAL / ASYMMETRICAL FAULT REQUIREMENTS

4.4.1 OFFSHORE FAULT-RIDE-THROUGH

Aim:

Evaluation of Fault-Ride-Through capabilities

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components as previously described.

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Simulations:

DR operation

Symmetrical (3-phase to ground) and asymmetrical (1-phase to ground fault, phase-phase, phase-phase to ground) AC offshore faults are applied in the offshore AC network. Offshore AC protection devices will be configured to provide adequate voltage profiles similar to that outlined in Figure 1 though as previously stated it is unlikely same voltage profile can be reproduced. Different operating points (power at 5%, 50% and 100%) as previously outlined will be tested.

Detailed response of both the OWF and the DRU HVDC connection will be examined to evaluate the compliance of the system.

SAC, DRSAC operation

Symmetrical (3-phase to ground) and asymmetrical (1-phase to ground fault, phase-phase, phase-phase to ground) AC offshore faults are applied in the offshore AC network. Offshore AC protection devices and the AC system to which the umbilical cables are connected to will be configured to provide adequate voltage profiles similar to that outlined in Figure 1. However, again it is unlikely same voltage profile can be reproduced. Different operating points Different operating points (power at 5%, 50% and 100%) as previously outlined will be tested.

Detailed response of both the OWF and the DRU HVDC connection will be examined to evaluate the compliance of the system.

4.4.2 OFFSHORE AC FAULT CURRENT INJECTION

Aim:

Evaluation of Fault Current Injection capabilities

Compliance Evaluation

Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components as previously described.

Simulations:

For DR, SAC and DRSAC operations

Symmetrical (3-phase to ground) AC offshore faults are applied in the offshore AC network. Different fault impedances will be tested to provide different terminal AC voltages at the OWF terminal (i.e. zero voltage, 20% voltage, and 50% voltage). Both the initial fault current providing capability and delivering additional reactive current capability will be tested. Different operating points (power at 5%, 50% and 100%) as previously outlined will be tested.

Detailed response of both the OWF will be examined to evaluate the compliance of the system.

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4.4.3 OFFSHORE AC FAULT RECOVERY

Aim:
Evaluation of AC Fault recovery capabilities

Compliance Evaluation
Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all relevant components as previously described.

Simulations:
DR and DRSAC operation
Symmetrical (3-phase to ground) and asymmetrical (1-phase to ground fault, phase-phase, phase-phase to ground) AC offshore faults are applied in the offshore AC network. Different operating points (50% and 100%) will be tested.
Detailed response of the complete system with power measured at the OWF, onshore MMC AC terminal, and umbilical cable terminal) will be examined to evaluate the compliance of the system.

SAC operation
Symmetrical (3-phase to ground) and asymmetrical (1-phase to ground fault, phase-phase, phase-phase to ground) AC offshore faults are applied in the offshore AC network. Different operating points (50% and 100%) will be tested.
Detailed response of the OWF will be examined to evaluate the compliance of the system.

4.5. ONSHORE GRID SUPPORT COMPLIANCE EVALUATION

4.5.1 FREQUENCY RESPONSE

Aim:
Evaluation of Frequency Response Capabilities

Compliance Evaluation
Both for under-frequency and over-frequency cases, the OWF will be operated in curtailed mode, with 10% of the rated power reserved.
The compliance will be evaluated for the operating point of the OWF as below;

- Available power 100% (i.e. rated power), operating at 90%
- Available power 70%, operating at 60%
- Available power 30%, operating at 20%

Artificial step changes (up and down) will be applied to the onshore frequency signal communicated to the OWF, so as to imitate frequency changes in the onshore grid. A measurement delay will be considered (only for the onshore frequency signal inputted onto the OWF. Delays due to voltage measurement, frequency calculation or communication from the onshore grid to the OWF will not be considered.

This step is a per unit value defined as Δf [pu]= $(f_{max}-f_{threshold})/f_{nominal}$, whereas f_{max}= 51.5 Hz, $f_{nominal}$= 50 Hz, and $f_{threshold}$ is chosen as 50.5 Hz. Hence the step response is taken as 0.02 pu.

$T_{measure}$ is the measurement delay, which can be taken as one period, i.e. 20 ms.

The compliance value for response time: $t_{95\%} \leq 1.38$ s [10].

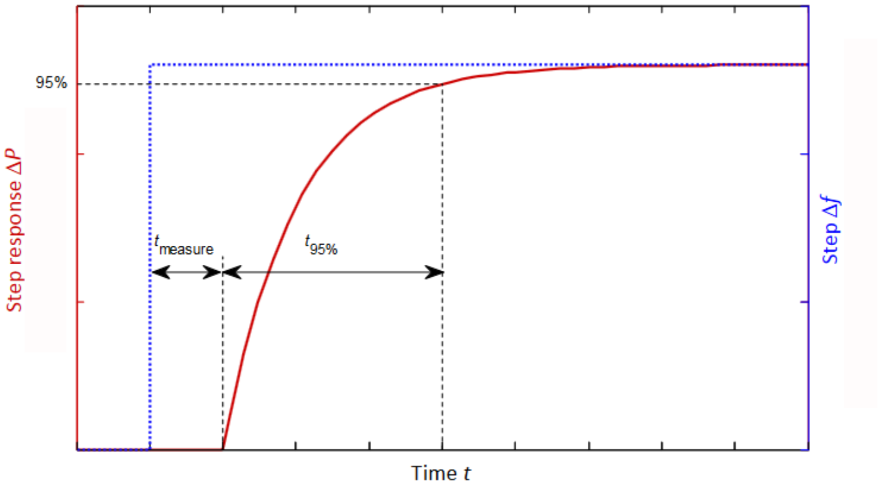

Figure 2 Required time behaviour for frequency support [10]

4.5.2 ONSHORE POWER OSCILLATION DAMPING BEHAVIOUR

Aim:

Evaluation of Power Oscillation Damping Capabilities. Here the purpose is to evaluate that the OWF is able to modulate its active power output with respect to a sinusoidal reference signal (in reality with decaying magnitude). The idea is that the OWF will be utilized as an actuator in an outer POD function, which will measure (or observe) onshore power system voltage and frequency and process it to damp oscillations using the OWF active power output. The necessary damping functions e.g., wash-out filters, lead-lag compensation filters, closed loops, will be part of the outer POD function.

Compliance Evaluation

Various sets of sinusoidal active power references with magnitude of 0.1 pu (i.e. rail to rail maximum active power variation as 0.2pu) and frequency of 0.3 to 2 Hz will be given to the OWF at a time (i.e. the magnitude and frequency of the reference signal will be kept constant during each test; not decaying) while the OWF will be set to have available power as below. Before the POD signal is applied, the OWF will be curtailed with 20%:

- Available power 100% (i.e. rated power) operating at 80%
- Available power 70% operating at 50%
- Available power 30% operating at 10%

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The active power response of the OWF shall be observed. Independent of the operating level and sinusoidal reference magnitude and frequency, the response to varying sinusoidal reference frequency shall be identified.

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programme under grant agreement No 691714.

5. CONCLUSION

This deliverable stands as an open guideline for compliance test procedures of DRU-connected OWFs, with some procedures also applicable for VSC-connected OWFs. The test compliance evaluation based on this deliverable will provide input for Task 3.4 “Compliance evaluations based on detailed numerical simulations” and D3.8 “List of requirement recommendations to adapt and extent existing grid codes”.

The compliance evaluation test procedures have been proposed to match the requirements identified in D3.1 “Detailed functional requirements to WPPs” as shown in the table below.

Compliance Evaluation procedures (D3.6)	**Requirements: D3.1, no.**
4.1.1 ACTIVE POWER PRODUCTION	3.4.1
4.1.2 STEADY STATE ACTIVE POWER CONTROL	3.4.2
4.1.3 DYNAMIC ACTIVE POWER CONTROL	3.4.3
4.1.4 ACTIVE POWER RECOVERY	3.4.4.
4.1.5 ISLAND SUPPORT (NO HVDC OR AC CONNECTION)	3.4.5
4.1.5 A ISLAND OPERATION	
4.1.5 B BLACK START CAPABILITY	
4.2.1 EVALUATION OF HARMONICS	3.5
4.3.1 FREQUENCY ENVELOPE	4.2.1
4.3.2 STEADY STATE FREQUENCY CONTROL	4.2.2
4.3.3 DYNAMIC FREQUENCY CONTROL	4.2.3
4.3.4 OFFSHORE VOLTAGE-/REACTIVE POWER BEHAVIOUR	4.3
4.4.1 OFFSHORE FAULT-RIDE-THROUGH	4.4.1
4.4.2 OFFSHORE AC FAULT CURRENT INJECTION	4.4.2
4.4.3 OFFSHORE AC FAULT RECOVERY	4.4.3
4.5.1 FREQUENCY RESPONSE	4.7
4.5.2 ONSHORE POWER OSCILLATION DAMPING BEHAVIOUR	4.8

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

6. BIBLIOGRAPHY

1. **PROMOTioN, "Deliverable 3.1: Detailed Functional Requirements to WFs", Project Deliverable, Dec. 2016.**
2. **PROMOTioN, "Deliverable 3.2: Specifications of the control strategies and the simulation test cases", Project Deliverable, Mar. 2017.**
3. **PROMOTioN, "Deliverable 3.4: Operation of WPPs connected to DR- HVDC", Project Deliverable, Dec. 2017.**
4. **PROMOTioN, "Deliverable 3.5: Performance of ancillary services provision from WPPs connected to DR-HVDC", Project Deliverable, Dec. 2017.**
5. **FGW TR 4, available at:** https://wind-fgw.de/produkt/demands-on-modelling-and-validating-simulation-models-of-the-electrical-characteristics-of-power-generating-units-and-systems/?lang=en#2
6. **FGW TR 3, available at:** https://wind-fgw.de/produkt/determination-of-the/?lang=en
7. **FGW TR 8available at:** https://wind-fgw.de/produkt/certification-of-the-electrical-characteristics-of-power-generating-units-and-systems-in-low-medium-high-and-extra-high-voltage-grids/?lang=en
8. **ENTSO-E RFG, available at:** https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2016_112_R_0001
9. **ENTSO-E HVDC, avaliable at:** https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1447
10. **ENTSO-E "Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe" avaliable at:** https://docstore.entsoe.eu/Documents/SOC%20documents/RGCE_SPD_frequency_stability_criteria_v10.pdf

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