



D3.8

List of requirement recommendations to adapt and extend existing grid codes

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks

Mail info@promotion-offshore.net
Web www.promotion-offshore.net

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	Name	Company
Validated by:		TenneT SHE Transmission
Task leader:	Ramon Blasco-Gimenez	UPV
WP Leader:	Ömer Göksu; Nicolaos Cutululis	DTU

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1. INTRODUCTION

This document provides a *List of requirement recommendations to adapt and extend existing grid codes* with the focus on the recommendations to cover the Diode Rectifier Unit (DRU) concept, which has been studied in detail in WP3 of PROMOTioN.

Within the course of the project, WP3 has identified and taken up three additional topics which are of high relevance for future offshore grid operation:

- Requirements for grid-forming Offshore Wind Power Plants (OWPPs), which are creating the offshore AC grid between the offshore HVDC converter (DRU or VSC) and the OWPP(s) and supplying loads at the offshore AC and/or HVDC substations,
- Fault response in 100% converter-based networks like the offshore AC grid with the OWPP(s) (with type 4 wind turbines (WTs)) and the offshore HVDC converter(s)
- Black start contribution from OWPPs and the VSC-HVDC converter, which is extensively handled in Deliverable 3.7 (being published in January 2020)

Today's OWPP connections are mostly based on HVAC connection, while a sizeable number of OWPPs are connected via HVDC. So far, the existing HVDC connections for the OWPPs are all based on Voltage Source Converters (VSC), e.g. Modular Multilevel Converters (MMC), which have grid forming capability to create the offshore AC grid voltage. The offshore WTs that are being connected to this type of converters are grid-following WTs relying on the HVDC converter's voltage to be energized and inject power.

However, the main focus of WP3 in PROMOTioN has been on the so-called Diode-Rectifier (DR) concept, which is also called as DRU [D3.1, D3.2]. The DRU is proposed to replace the offshore VSC-HVDC converter, while keeping the onshore VSC-HVDC as it is, i.e. controlling the HVDC link voltage in point-to-point connections. Figure 1.1 shows a simplified overview of the DRU connection studied in WP3.

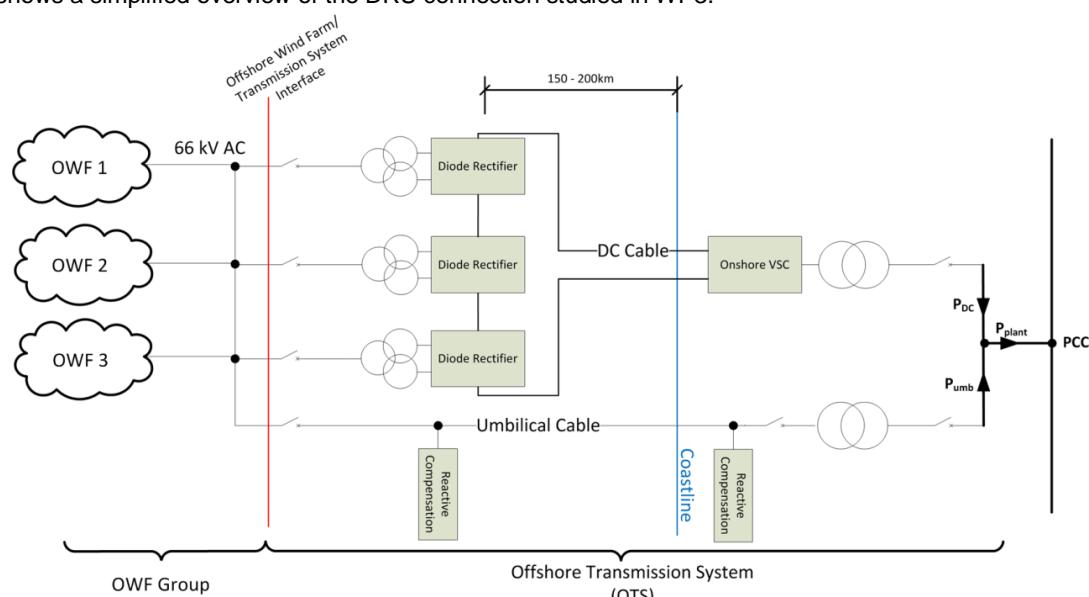


Figure 1.1 Simplified overview of OWPP group and offshore transmission system (OTS) [D3.1]



In case of DRU as the offshore HVDC converter, there is need for solutions to energize the offshore AC grid and the offshore WTs and forming (creating and controlling) the offshore AC grid voltage, because the DRU is a passive one-directional unit without any grid forming capability. The OWPP(s) and hence the WTs are considered to take the grid forming responsibility in the DRU-concept. As studied in detail in WP3, the WTs can create and control the offshore AC grid voltage such that wind power is transferred via the DRU, while keeping almost all OWPP capabilities (e.g. MPPT, active power control, FRT, frequency support to onshore grid) as in the VSC-HVDC case. In WP3, for initial energization (start-up) of the offshore AC grid and WTs, an AC umbilical cable has been considered, which is disconnected when the power flow from WTs over DRU starts. Therefore, the DRU-connected Wind Power Plant in Fig. 1.1 has to be able to operate in the following modes:

- Islanded mode (**ISL**): The WPP is neither connected to the DR station or to the HVAC umbilical cable
- HVAC connected mode (**SAC**), synchronised AC: The WPP is connected to a strong HVAC grid via the umbilical cable
- DRU connected mode (**DR**): The WPP is connected and delivering power through the DR station. This is the normal production mode of operation.
- Simultaneous DRU and HVAC connected mode (**DR-SAC**). The WPP is connected, at the same time to the DR station and to the HVAC grid. This mode of operation is used during power-up or power-down of the WPP. Usually, once the DR station is conducting, then the umbilical cable is disconnected. (N.B. a detailed description of the modes of operation and the transition between them is included in Deliverable D3.1).

In all cases, the WTGs should be grid forming. In line with today's available technology and implementations (VSC-HVDC), the existing grid codes (e.g. the ENTSO-E NC HVDC) are written from the perspective of VSC-HVDC such that the offshore HVDC converter is assumed to be grid forming and the WTs to be grid following. However, as described above, use of DRU would require a substantial paradigm change, requiring the OWPPs to be grid forming. D3.8 is aimed to provide some preliminary requirements for the OWPPs in order to be connected to the DRU.

Table 1 gives an overview of the considered and proposed requirements for DRU connection and indicates whether the requirements are equivalent to an existing grid code requirement, which can be fulfilled by DRU based systems, or if adaptions and/or extensions have been proposed to facilitate DRU integration.

Table 1: Overview of requirements considered for DRU connection in WP3

Requirements for DRU connection	Existing	Adapted	Extended
2.1 Dynamic Active Power Control	X		
2.2 Island Support (No HVDC or AC Connection)			X
2.3 Minimum Production Limit (DR mode)			X
2.4 Steady State Frequency Control (DR mode)		X	X
2.5 Optimized (Narrow) Frequency Range		X	X
2.6 Dynamic Frequency Control		X	X



2.7 Rate of Change of Frequency (ROCOF) Limits		X	X
2.8 Steady State Voltage/Reactive Power Control		X	X
2.9 Dynamic Voltage Control		X	X
2.10 Offshore Fault Ride Through		X	X
2.11 DC Fault Ride Through Requirements		X	X
2.12 Onshore AC Fault Ride Through		X	X
2.13 Onshore Frequency Support Requirements	X		
2.14 Synthetic Inertia	X		
2.15 Onshore Oscillation Damping Requirements	X		

As an extension to DRU capability, some of these requirements are also relevant for general grid forming capability of OWPP, which could be used for black-start. This is studied in more detail in task 3.4, which does include the simulative validation of offshore ac-grid forming wind turbine and wind power plant controllers. The corresponding deliverable D3.7 will include both the requirements and the compliance evaluation based on detailed simulations of such controllers.

Some important points to have in mind when reading D3.8 are listed in the following:

- D3.8 is providing “recommendations”, rather than specific grid code requirements. The objective of D3.8 is to give insight and a reference when the DRU or a similar concept is being deployed in the future.
- The set of grid code recommendations given in D3.8 are the outcome of the studies performed in WP3 and should not be considered as a complete set of requirements for DRU connection.
- Some of the requirements might be based on the specific structure(s) studied in WP3 (for instance the WTs are assumed as Type 4 – Full converter interfaced WTs). Hence, the requirements should be studied together with the previous Deliverables of WP3, especially D3.1 and D3.2. For the sake of brevity, the detailed structures are not provided here.
- The quantitative requirements in D3.8 are valid for the studied case(s) in WP3. Hence the values (e.g. voltage range) can change depending on the case/project.
- This document does not include a study on existing codes to identify existing requirements which indirectly assume grid following WTGs connected to VSC-HVDC rectifiers and might be incompatible with DRU use.
- The grid code recommendations and conclusions expressed in D3.8 are those of the authors and do not necessarily reflect those of the PROMOTioN partnering organizations.



2. REQUIREMENT RECOMMENDATIONS SPECIFIC FOR DRU CONNECTION

2.1. DYNAMIC ACTIVE POWER CONTROL

To support normal operation, the OWPP shall be capable of ramping active power from one set point to another (considering the wind related limitations) with a pre-determined rate.

2.2. ISLAND SUPPORT (NO HVDC OR AC CONNECTION)

Islanding requirement is defined in [ENTSO-E NC RfG 15-5- b- I as referred in ENTSO-E NC HVDC Article 38]. The OWPP shall support a temporary islanding of the offshore AC system for minimum 20 seconds, whenever there is sufficient energy available. Longer times might be required in order to allow for Delayed Auto Reclosure (DAR) of the on-shore network.

Note: Islanded operation is required for DRU operation, for a minimum amount of time, in order to keep the off-shore ac-grid energized during schedule or unscheduled events that lead to a temporary disruption of the HVDC link transmission capability. In some cases, islanding operation is also required during the OWPP and HVDC link power-up sequence.

It is understood that compulsory islanding operation is meant for either power-up sequence or for fast power recovery after an event. In these two cases, islanding operation only needs to be enforced if there is enough primary resource, as, otherwise, there is no power available to be transmitted through the HVDC link once its operation is resumed.

The 20 second requirement also allows for synchronisation and re-connection to the umbilical HVAC cable.

2.3. MINIMUM PRODUCTION LIMIT (DR MODE)

Due to the non-linear properties of the diode rectifiers, it is permissible to seize production from the OWPP at an agreed minimum production limit (e.g. 2.5%) when connected to a diode rectifier only (**DR** operational mode), in order to avoid discontinuous conduction. This limitation is not related to the OWPP; hence it should be understood as a transmission system limitation.

2.4. STEADY STATE FREQUENCY CONTROL (DR MODE)

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



2.5. OPTIMIZED (NARROW) FREQUENCY RANGE FOR THE OFFSHORE AC GRID (DR MODE)

The frequency ranges shown in Table 2 apply to the off-shore grid when the WPP active power is being transmitted only by the HVDC-DRU link (i.e. during normal **DR** mode of operation). This is a DRU solution specific requirement, not based on any grid code specification. The narrow frequency ranges are needed to allow optimal filter design and operation.

Therefore, these frequency ranges should not be understood as margins which, when exceeded, the WTGs are allowed to disconnect. On the contrary, in DR mode of operation, the off-shore grid frequency is controlled by the WTGs, therefore, there margins specify the maximum deviation allowed for the WTG based frequency controllers.

Table 2: Boundary between normal and abnormal frequency control range in operational mode DR.

Frequency Range	Time period for operation
49.000 – 51.000 Hz	<500 ms
49.500 – 50.500 Hz	<10 s
49.875 – 50.125 Hz	Steady state

When the umbilical HVAC cable is connected (usually only for start-up), the ranges corresponding to the on-shore HVAC grid would apply.

2.6. DYNAMIC FREQUENCY CONTROL FOR THE OFFSHORE AC GRID (DR MODE)

When the OWPP is connected to a diode rectifier only, the frequency shall be controlled to a new set point with a rise time of less than 3 s from the point where the set point is received by the OWPP.

Note this is a DRU solution specific requirement which applies only to the off-shore ac grid. Since the off-shore ac grid is entirely controlled by WTGs, this requirement is needed in order for the WPP to synchronize to the HVAC umbilical cable (i.e. it is not related to the inertial response of the off-shore ac grid).

2.7. RATE OF CHANGE OF FREQUENCY (ROCOF) LIMITS FOR THE OFFSHORE GRID (DR MODE)

The OWPP shall not introduce faster (offshore) frequency changes than +/- 2 Hz/s as part of normal operation (no HVDC blocking, no offshore LVRT etc.). This is a DRU solution specific requirement, not based on any grid code specification.

2.8. STEADY STATE VOLTAGE/REACTIVE POWER CONTROL FOR THE OFFSHORE GRID (ISL MODE).

When the OWPP is not connected via the HVDC (i.e. no HVDC power flow), it shall be possible to control the WTG output voltage/reactive power in such way to control the voltage magnitude at the interface between OWPP and HVDC.

Note: This aspect is relevant as, depending on specific regulations, connection points might be offshore (e.g. at one of the DRU input busbars). Also, OWPP might be connected through the HVAC umbilical cable, in this case steady-state voltage and reactive power control need to be used to control the voltage at the specified connection



point and to avoid overvoltages. This requirement is DRU specific, since it does not apply to the DR operation mode, as, in this case offshore AC grid voltage is determined by the HVDC voltage and the power to be transmitted and cannot be set to arbitrary values.

2.9. DYNAMIC VOLTAGE CONTROL FOR THE OFFSHORE GRID (ISL MODE).

When the OWPP is not connected via the HVDC (i.e. no HVDC power flow), it shall be possible to control the WTG output voltage/reactive power to a new set point with a rise time of 1 second from the point where the set point is received by the OWPP.

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

Dynamic voltage control, together with dynamic frequency control are required for synchronisation to the HVAC umbilical cable, i.e. in order to change from ISL mode to SAC mode of operation.

2.10. OFFSHORE FAULT RIDE THROUGH

OWPP shall be capable of staying connected to the network and continuing to operate stably after the (offshore) power system has been disturbed by faults on the offshore ac network. 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 2.1 is an example of the voltage-against-time profile and the exact values of the voltage-against-time profile are decided by the relevant TSOs. Each WT in the offshore grid should deliver its maximum available fault current until fault isolation.

Note: in a 100% power electronic converter system, fault currents are naturally limited by the converter. The requirement to keep the maximum available fault current during the fault implies that sufficient fault current will be seen by overcurrent relays during offshore array cable faults.

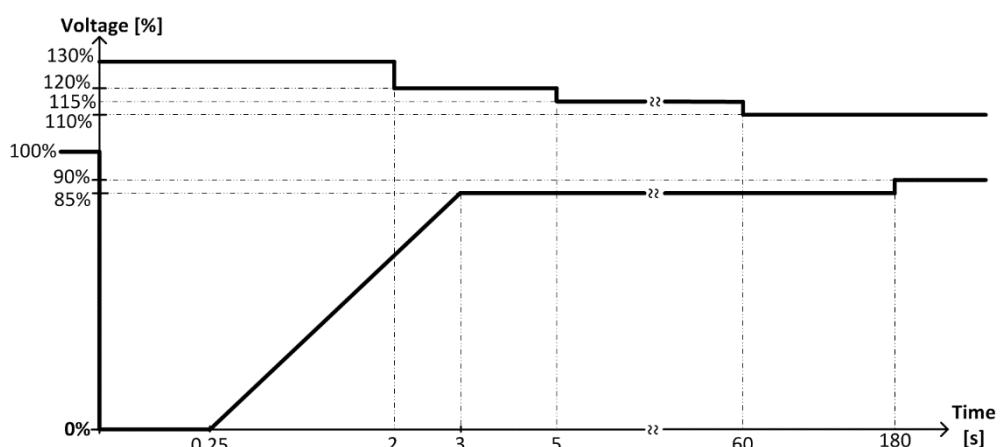


Figure 2.1 Example voltage-time profile for offshore AC faults [ENTSO-E NC RfG Article 16 (3) (a) (i)].



After offshore AC fault isolation, the OWPP should restore the offshore AC voltage and frequency to the pre-fault condition, without significant overvoltage or overcurrent. The OWPP shall be capable of restoring power transmission after isolation of offshore AC faults within 500 ms [National Grid NC] of the available active power. Active power oscillations shall be acceptable provided that:

- 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,
- The oscillations are adequately damped,
- Limitations of the transmission system are regarded.

Note: Reactive power should be shared among wind turbines during offshore AC fault recovery to avoid converter overcurrent.

2.11. DC FAULT RIDE THROUGH REQUIREMENTS

Depending on the detailed HVDC system structure, OWPP shall be securely turned off or perform fault ride-through operation:

- In case of a permanent loss of the DC connection, OWPP shall be capable of performing secure turn-off.
- In case of a DC connection with redundancy, OWPP shall be capable of performing fault ride through for securely cleared DC faults, same as the response to onshore AC faults. The OWPP shall be capable of returning the active power from a limited operating point to the pre-fault active power level within 500 ms.

OWPP shall be capable of staying connected to the network and continuing to operate stably after the AC collection network has been disturbed by secured DC 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 connection point during DC faults, as a function of time before, during and after DC faults. OWPP should autonomously provide fault currents during DC faults and limit the current amplitude to avoid overcurrent. The limited fault contribution from OWPP shall not expose HVDC station connected with the OWPP to overcurrents.

Note: It is expected that the DC fault will be observed by the OWPP to be similar to an offshore AC fault.



2.12. ONSHORE AC FAULT RIDE THROUGH

The onshore HVDC station shall remain connected and stable for onshore faults where the voltage remains on or above predefined the voltage-against-time profile. The AC currents should be properly controlled to avoid overcurrent. During remote symmetrical faults or asymmetrical faults, the onshore station shall be capable of partially transmitting active power to the onshore grid to alleviate the potential overvoltage of HVDC cables.

The OWPP shall automatically reduce the generated power to alleviate the overvoltage of HVDC cables during faults. The offshore AC grid voltage shall be properly control to avoid overvoltage.

After fault isolation, the onshore stations and OWPP shall automatically restore normal operation. During and after faults, overvoltage of HVDC cables needs to be avoided.

2.13. ONSHORE FREQUENCY SUPPORT REQUIREMENTS

Note: DRU connected OWPP should be able to provide the same ancillary services as VSC connected OWPP. In WP3 the provision of ancillary services via DRU connected OWPP was tested and found to be compliant with the following existing grid code requirements (section 2.13 - 2.15).

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

OWPP shall be capable of activating a power frequency response with an initial delay that is shorter than 0.5 s from receiving the signal (over- or under-frequency) and time for full activation shall be shorter than 30 s [ENTSO-E NC HVDC Article 39, ENTSO-E NC RfG Article 15 (2) (d) (iii)].

OWPP frequency response will take into account: ambient conditions (mainly wind speed) at the time of response triggering and the operating conditions of the OWPP, especially near the maximum capacity at low frequencies; such that OWPP cannot produce more than available (available wind and rotational kinetic energy), and taking into account the DR specific ROCOF limitations specified in 2.7.

OWPP should be capable of providing active power frequency response for minimum 15 min [ENTSO-E NC HVDC Article 39, ENTSO-E NC RfG Article 15 (2) (d) (v)], while taking the primary energy source of the power-generating module into account.

OWPP shall be able to respond based on the set of specified parameters, which allow for the calculation of the active power as a function of the frequency, as shown in Figure 2.2 below. The combination of choice of the parameters specified should take possible technology-dependent limitations into account.



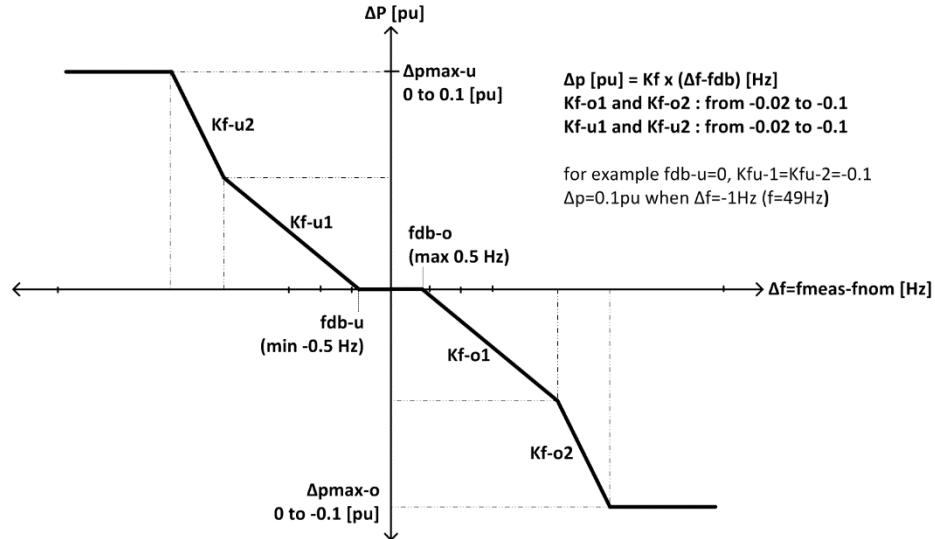


Figure 2.2 Frequency response capability of OWPP to onshore frequency changes [ENSO-E NC HVDC Article 39, ENSO-E NC RfG Article 15 (2) (d) (i)].

2.14. SYNTHETIC INERTIA

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

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

OWPP shall perform synthetic inertial response [ENSO-E NC HVDC Article 39, ENSO-E NC RfG Article 21 (2)]. OWPP shall perform synthetic inertial response of a conventional synchronous generator whose inertia (H) equals to 3.5 s. OWPP shall be able to provide at least 5% of the actual active power for about 10 s, when a large, short-duration frequency deviation occurs on the power system [Hydro Québec].

2.15. ONSHORE OSCILLATION DAMPING REQUIREMENTS

OWPP shall be capable of receiving Power Oscillation Damping (POD) signal (from the onshore synchronous area and sent by the OWPP Coordinator or system operator).

OWPP shall have the capability to modulate its active power output for a sinusoidal waveform in the frequency range of 0.3 Hz to 2 Hz [National Grid NC] with a given magnitude.



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LIST OF ABBREVIATIONS

Abbreviation	Meaning
DRU	Diode Rectifier Unit (DRU)
OWPP	Offshore Wind Power Plants (OWPPs)
VSC	Voltage source converter
HVDC	High voltage direct current
WT	Wind turbines
OTS	Offshore transmission system
MMC	Modular Multilevel Converters
MPPT	Maximum power point tracking
FRT	Fault ride through
ROCOF	Rate of Change of Frequency
LVRT	Low voltage ride through

