WP16 – MMC Test Bench Demonstrator

Deliverable 16.1: Definition and Specification of Test Cases

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
Mail info@promotion-offshore.net
Web www.promotion-offshore.net

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CONTACT

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Task leader:	Philipp Ruffing	
WP Leader:	Philipp Ruffing	

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LIST OF CONTRIBUTORS

Work Package and deliverable 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.

PARTNER	NAME
DNV GL	Yin Sun, Yangtao Yang
KTH	Ilka Jahn, Staffan Norrga
DTU	Ömer Gösku, Nicolaos Cutululis
RWTH AACHEN	Philipp Ruffing, Markus Kaiser, Matthias Quester, Fisnik Loku, Cora Petino
UPV	Ramon Blasco-Gimenez, Soledad Bernal-Perez
ØRSTED	Lorenzo Zeni

EXECUTIVE SUMMARY

The objective of Work Package 16 of the PROMOTioN project is to demonstrate the operation and control of meshed HVDC system using Power Hardware in the Loop (PHiL) and Controller Hardware in the Loop (CHiL) through the use of real-time simulators (RTS) in order to increase the confidence in the feasibility of MTDC operation. Moreover, the technology readiness level of state-of-the-art HVDC controls for meshed networks shall be raised.

Within this deliverable, the test cases and scenarios that will be investigated in Work Package 16 are defined and specified. These test cases cover the topics of the c*ontrollability and interoperability*, *fault handling and AC grid support* by meshed offshore DC grids. Additionally, resonance phenomena due to the harmonic interaction of active components such as WPP and MMC and the grid will be studied in detail.

To ensure the link between the technical work packages – especially WP2, WP3 and WP4 – as well as the standardisation efforts (WP11) and deployment plan of PROMOTioN (WP12), the test cases were discussed with representatives of these work packages.

CONTENT

1 INTRODUCTION

Within the framework of modernisation of the European electricity grid, multi-terminal HVDC offshore grids evacuating several gigawatts of wind from the Northern Seas shall be integrated into AC transmission systems. Additionally, offshore MTDC systems might be used as interconnectors between large synchronous zone (e.g. ENTSO-E, UK and the Nordic Grid). Such MTDC systems lead to novel challenges for transmission grid operators, grid planners and manufacturers. Nevertheless, the experience regarding the operation of these systems as well as their interaction with the AC transmission system and the offshore Wind Power Plants (WPP) is limited.

Within Work Package 16 of the PROMOTioN project, the operation and control of meshed HVDC system will be investigated using Power Hardware in the Loop (PHiL) and Control Hardware in the Loop (CHiL) technology using real-time simulators (RTS) in order to increase the confidence in the feasibility of MTDC operation.

The so-called Test Bench system of WP16 consists of downscaled hardware power components, which represent a DC network using hardware equipment with reduced power ratings. The Test Bench is coupled with a real-time representation of 1000-2000 nodes of European AC grids and several full detailed type-4 wind turbines (WT) representing offshore WPPs. The hardware Test Bench includes modular multilevel converters (MMC) with submodules, phase arm reactors and converter transformers as well as hardware line models. The lab-scale converters are connected to AC system simulators via four-quadrant power amplifiers (PAs), which are designed for a wide frequency spectrum, to enable an adequate representation of AC networks. The PAs are controlled by the real-time simulation of the AC networks emulating their dynamic behaviour. A schematic setup of the system is presented in Figure 1.

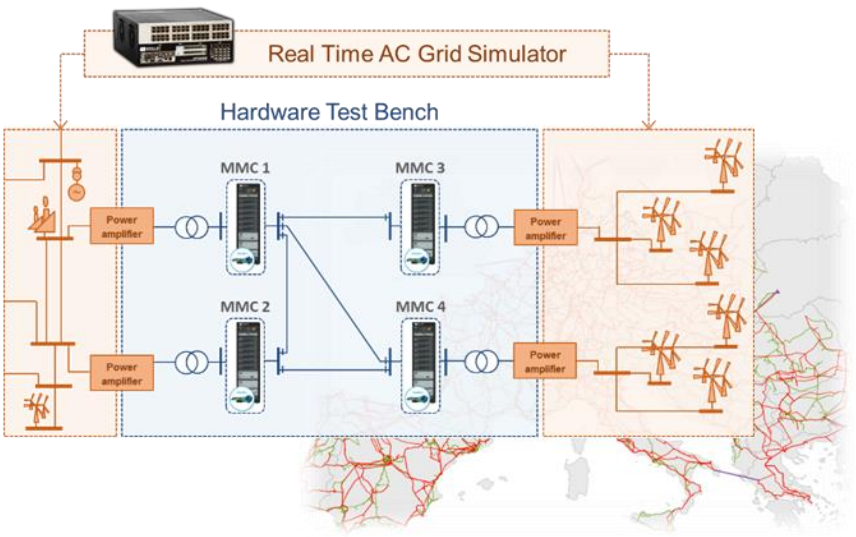

Figure 1: Scheme WP16

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A major advantage of the Test Bench system is its high flexibility. Thus, different control algorithms and protection schemes can be tested in various network configurations and for different converter types (half-bridge and full-bridge MMCs in monopolar or bipolar configuration). The system can also be used for the analysis of fault and post-fault disturbances and interactions with the AC networks (large onshore AC grid and WPP).

Based on this technology the major objectives of WP16 are:

- **Demonstration** of applicability of developed controls and simulation models of PROMOTioN
- **Technical and economical de-risking** for the deployment and continuous operation of meshed HVDC-systems
- **Improvement** of certainness for road mapping process and standardization efforts

Therefore, realistic circumstances in the transmission and offshore system, e.g. operative incidents, disturbances and faults will be investigated with the Test Bench system. The controllability of such a DC network will be investigated in different network configurations (monopolar and bipolar DC networks) and with different converter types (fault feeding and fault blocking converters). Moreover, the interoperability of different converter types within the same grid will be investigated.

Additionally, the protection IED (intelligent electronic device) from WP4 shall be integrated into WP16´s Test Bench. This protection IED will be pre-programmed to provide different protection algorithms (e.g. voltage derivative) and protection strategies (e.g. fully selective). Specific timings and thresholds can be configured via a MATLAB graphical user interface. To measure voltages and currents in the Test Bench, the IED´s hardware interface is done via pluggable I/O modules that will be adapted to the specific requirements of the Test Bench. The objective of the integration of the protection IED is the demonstration of the complete protection sequence in the PHiL system (Measurement → Detection → Communication to breaker or/and converter → Fault separation → Network recovery). Therefore, also a flexible small-scale breaker model based on solid-state switches and arresters will be developed in WP16. The switching behaviour of different DC circuit-breakers is to be emulated by controlling the switch. However, the breaker representation will not take into account possible transients that might be introduced into the grid by specific breakers. Additionally, chopper models, which will be relevant for the analysis of AC fault studies and pole re-balancing during DC faults, will be developed and integrated in the system. The will be relevant for the analysis of AC fault studies and pole re-balancing during DC faults.

The interaction between large grid areas and interconnecting HVDC systems with respect to system stability shall be studied in detail as well. The focus will be on the active power control and therefore on frequency control and power oscillation damping. The modified active power exchange between asynchronous AC networks as well as between OWPP and one AC network due to frequency supporting controllers or power oscillation damping controllers will be investigated.

Another important aspect of WP16 is the analysis of harmonic stability problems related to resonance phenomena. In the context of increasing renewable penetration in the power grid, network oscillations/incidents caused by the

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adverse interaction between voltage source converters (VSCs) and power network have caught the attention of transmission system operators (TSOs) worldwide. In Europe, harmonic oscillation between offshore wind turbine converter and HVDC platform has been reported to cause significant delays in the offshore wind farm development. For this reason, the leading offshore wind farm developers have already considered harmonic stability as part of their overall project risk management. In China, large scale onshore wind farm connected to the power grid via long transmission lines, in several occasions, also demonstrated the harmonic oscillation; both state grid and CEPRI (China Electrical Power Research Institute) concerns the origin and solution to such harmonic oscillation.
To address the issues related to the high penetration level of renewable integration worldwide, both CIGRE JWG C4/B4.38 and IEC 61400-21-3 already formulated task forces to address the relevant technical challenges related to the converter harmonic oscillations. The proposed research project under WP 16 of PROMOTioN aims to execute input admittance measurement of wind turbine converter from leading wind turbine manufacturer in the CHIL (Controller Hardware in the Loop) concepts. The derivation of linearized input admittance of unit VSC device is essential for the harmonic stability study, where multiple VSCs and passive grid components are interacting in complex manner. The test results will provide guidelines on the test procedures applicable to the MW industrial level applications and produce material/content for the future development of international standards and recommended practice. Therefore, the Flexible Power Grid Laboratory (FPGL) of DNV GL will be used in this project to enable innovative testing and model validation of DER equipment, such as wind turbine converter. The test facility is one of a few that allows testing of the correct functioning of distributed energy resource unit under realistic condition in a system. It verifies the hardware (power parts) and the control (ICT) simultaneously to validate that a DER unit is ready to be integrated into a larger system (e.g. the energy grid). The FPGL lab is the only facility able to test this combination on medium voltage level (up to 24 kV) and high-power level (up to 1 MVA). The main purpose of FPGL testing is to de-risk equipment and ensure flawless operation in a real grid. The FPGL includes a facility for HIL testing with RTS and power amplifier (0 – 200 KVA). The FPGL is part of the DER-LAB Network of Excellence and takes part in EU project on R&D infrastructures like DERLAB (FP6), DERRI (FP7) and EriGrid (H2020).

To demonstrate the operation of DRU-enabled wind turbine control systems in an HVDC grid the construction of a real-time prototype demonstrator with actual control (CHiL) and protection hardware will be done in WP16. The objective is to conduct behavioural tests according to the previously defined test cases (in WP2 and WP3) and to validate the applicability of different systemic/technological options. A key aspect is to test the fault handling in AC grid based on grid forming WTGs. Therefore, a commercial AC protection relay will be tested in a DRU connected AC network in the DRU CHiL system.

The overall goal of the WP is to increase the confidence in the control of meshed DC grid and to raise its technological readiness level. Thereby, the studies of WP16 will contribute to develop appropriate principles and operation strategies, which enable a smooth interoperability between different components and technologies of future meshed HVDC offshore grids.

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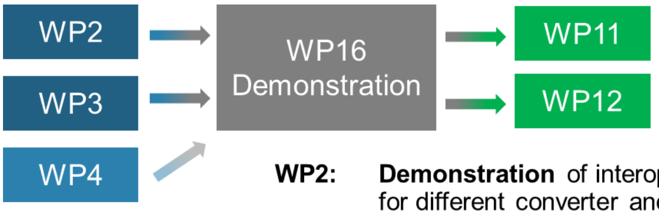
1.1 LINK TO OTHER PROMOTION WORK PACKAGES

An important aspect of WP16 is to demonstrate the knowledge gained in the technical work packages of PROMOTioN. This includes grid operation and control concepts for meshed and DRU connected DC networks from WP2, wind turbine and wind power plant control concepts and models from WP3 and protection strategies from WP4. Additionally, it is an objective of WP16 to integrate the protection IED developed in WP4 into the Test Bench System.



WP2: **Demonstration** of interoperability, controllability for different converter and grid configurations

WP3: **Demonstration** of applicability of WT and WPP control (with full detailed WT models)

WP4: **Demonstration** of different protection strategies
Integration of protection IED

WP11: **Recommendations** for standardisation

WP12: **Improvement** of certainness for road mapping process

Figure 2: Link to other PROMOTioN work packages

The findings of WP16 will be used as in input for WP11 and WP12, to contribute to the standardisation efforts and the elaboration of a roadmap for future meshed offshore DC networks.

1.2 OBJECTIVE OF THIS DELIVERABLE

The objective of this deliverable is to define and specify the test cases, which will be conducted in Work Package 16. Moreover, a high-level overview of the scenario variations for each test case is provided.

To ensure the link between the technical work packages – especially WP2, WP3 and WP4 – as well as the deployment plan of PROMOTioN (WP12) the test cases have been presented to the work packages. Based on the feedback from the other WPs the test cases were re-evaluated and finalised by the partners of WP16. Additionally, the origin of each test cases is described and a motivation is provided. Even though all defined test cases and all scenarios are worth to investigate, the significance of each test case is rated as "mandatory" or "optional", in order to provide the most relevant results for the given amount of time.

Since the investigations of WP16 will be conducted in three different laboratories – the MMC Test Bench at the RWTH Aachen, RTS and WT-Replica at DNV GL Arnhem and the DRU CHiL at the UPV – the location as well as the main responsibility is specified for each test case.

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1.3 OVERVIEW OF THE PLANNED TEST CASES

The Test Cases, which will be conducted in WP16 are categorised into four major topics:

- Controllability and Interoperability
- Fault Handling in Offshore Grids
- Resonance Phenomena
- AC Grid Support

An overview of the test cases is provided in Table I, whereas the detailed definition is presented in section 2.

Table I: Overview of the defined test cases of WP16

Controllability and Interoperability	**Fault Handling in Offshore Grids**	**Resonance Phenomena**	**AC Grid Support**
Controllability of a Meshed DC Offshore Grid	Fault Clearing in Meshed DC Grids	Unit MMC Turbine Converter Model Validation for Resonance Phenomena Studies	Frequency Support by a Meshed Offshore Grid
Black Start Capability of HVAC and DRU-Connected Offshore Wind Farms	Fault Handling with Grid Forming WTGs	Unit MMC Converter Model Validation for Resonance Phenomena Studies	Frequency Support and Power Oscillation Damping by OWPP Clusters
Demonstration of the Interoperability of Different Converters	Offshore Symmetrical and Asymmetrical Faults	Offshore Wind Park Harmonic Resonance Analysis with AC Cable Connection	
Cluster Control of Two/Three OWPPs Connected to the Same HVDC Converter	OWPP Response to DC Faults	Offshore Wind Park Harmonic Resonance Analysis with MMC-HVDC Connection	
Grid Forming OWPP Cluster (One or All Grid Forming)		Harmonic Impedance Analysis for DC Grids with DRU	

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2 DETAILED DEFINITION AND SPECIFICATION OF TEST CASES

2.1 CONTROLLABILITY AND INTEROPERABILITY

An important part of work package 16 is the demonstration of the general controllability of meshed offshore grids. Therefore, the generic control algorithms developed in WP2 will be transferred on the controllers of the test bench system and their functionally will be tested. These "normal operation" test cases will be the foundation for the other test cases, i.e. the fault studies. The test cases include the controllability of the DC grid and the offshore wind power plant. A special focus is given to the control of grid forming wind turbines.

2.1.1 CONTROLLABILITY OF A MESHED DC OFFSHORE GRID

<table>
<tr><th colspan="2">Test Case Motivation</th><th>Origin</th><th>Significance</th></tr>
<tr><td colspan="2">Within WP1 and WP2 different configurations and topologies for offshore grids are identified. These shall be investigated in WP16 in regard to the controllability of the DC system. Moreover, interaction with the offshore WPPs and the onshore AC grid shall be analysed.

A first goal of WP16 is the confirmation of proposed control strategies and thereby improve the TRL of common converter control principles.</td><td>WP1, WP2</td><td>Mandatory</td></tr>
<tr><th colspan="4">Test Case Definition</th></tr>
<tr><td colspan="4">The objectives of the investigations are:
Controllability demonstration of the converters (half-bridge and full-bridge) in a meshed grid connected to Wind Power Plants. Based on these, it is one objective of WP16 to point out the difference between the PHIL system and EMT simulation. Based on the lessons learned, recommendations for future simulation models will be provided.
Controllability demonstration of different converter configurations within one meshed HVDC grid
Controllability demonstration of different grid topologies (p2p, radial, meshed)</td></tr>
<tr><th colspan="3">Specification of the relevant scenarios</th><th>Significance</th></tr>
<tr><td colspan="3">Half-bridge and full-bridge converters
Monopolar DC System (WP2 Minimal Meshed Network)
Bipolar DC System (WP2 Minimal Meshed Network)
Change of power flow set-point changes
Change of wind infeed changes
Change of AC grid use-case (share of RES, Load) → From WP2
Network layout/extension</td><td>Mandatory
Mandatory
Mandatory
Mandatory
Mandatory
Optional
Optional</td></tr>
<tr><th>Physical location and the simulation environment</th><th colspan="3">Main Responsibility</th></tr>
<tr><td>Aachen – Test Bench System with RTS</td><td colspan="3">RWTH</td></tr>
</table>

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2.1.2 BLACK START CAPABILITY OF HVAC AND DRU-CONNECTED OFFSHORE WIND FARMS

Test Case Motivation	**Origin**	**Significance**
Developed grid forming controllers for DRU connection of offshore wind farms have been shown to have good performance during islanding operation and also when connecting and re-synchronising to a very weak HVAC-grid (umbilical). The feasibility of the extension of these controllers to black and brown start operation will be studied in this test case using a real-time CHiL set up.	*WP2, WP3*	*Mandatory*
Test Case Definition		
The objectives of the investigations are: • *Validation of strategies for offshore wind farm self-start operation using CHIL for the WTG controller and for the OWF controller and using detailed OWF models.* • *Validation of synchronization strategies to a weak on-shore ac-grid.*		
Specification of the relevant scenarios		**Significance**
• *Offshore wind farm self-start with limited energy storage.* • *Case a: HVAC export cable and HVAC transformer energisation and synchronisation to a weak grid (brown start) or to an unenergised grid (black start).* • *Case b: DRU transformers, filters and HVDC cable energisation and on-shore MMC converter connection to a weak grid (brown start) or to an unenergised grid (black start).*		*Mandatory* *Mandatory* *Mandatory*
Physical location and the simulation environment		**Main Responsibility**
Valencia – CHIL Prototype demonstrator		*UPV*

2.1.3 DEMONSTRATION OF THE INTEROPERABILITY OF DIFFERENT CONVERTERS

Test Case Motivation	**Origin**	**Significance**
In the future, different converters might be used in the same DC network. These are mainly classified as fault feeding and fault blocking converters. *A demonstration of the interoperability of these converter types and the controllability of such a DC network shall be conducted in WP16.*	*WP1, WP2, WP4*	*Optional*
Test Case Definition		
In WP16 the different converter types (fault feeding and fault blocking converters) will be represented using most established designs – half- and full-bridge Modular Multilevel Converters. *The objectives if this test case is the demonstration of the control interoperability of fault feeding and fault blocking converters. However, this normal operation test case is mainly the foundation for the interoperability investigations of different fault clearing strategies in test case 2.2.1 – scenario: Interoperability of fault clearing methods.* *The detailed scenarios for the interoperability of different converter types will be defined in collaboration with WP2 and WP4*		

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Specification of the relevant scenarios	Significance
• *Monopolar DC System (WP2 Minimal Meshed Network)* • *Bipolar DC System (WP2 Minimal Meshed Network)* • *Change of power flow set-point changes* • *Network layout/extension*	*Optional* *Optional* *Optional* *Optional*
Physical location and the simulation environment	**Main Responsibility**
Aachen – Test Bench System with RTS	*RWTH*

2.1.4 CLUSTER CONTROL OF TWO/THREE OWPPS CONNECTED TO THE SAME HVDC CONVERTER

Test Case Motivation	Origin	Significance
In WP3, test cases as "detailed models for multiple WPPs each with multiple wind turbines connected to the same HVDC converter" have been described. Today there are many installations of WPP clusters; however, grid codes for these clusters are not well-defined.	*WP3*	*Optional*
Test Case Definition		
The objectives of the investigations are: • *To demonstrate cluster and WPP level control solutions* • *To demonstrate compliance with the "new" grid codes (that will be recommended)*		
Specification of the relevant scenarios		
• *Set-Point Changes* • *Wind infeed changes* • *Disconnection of one of the WPPs*		*Optional* *Optional* *Optional*
Physical location and the simulation environment	**Main Responsibility**	
Aachen – Test Bench System with RTS	*DTU*	

2.1.5 GRID FORMING OWPP CLUSTER (ONE OR ALL GRID FORMING)

Test Case Motivation	Origin	Significance
Grid forming WT control strategies have been developed and tested in simulations mainly in WP3, where several wind power plants (hence wind turbine converters) are connected in parallel. However, the demonstration of these control strategies on real converters has not been performed in the project. The motivation is to demonstrate the grid forming capability of wind turbine converters when they are in parallel operation, whereas all or one of the wind power plants are in grid forming mode.	*WP3*	*Mandatory*
Test Case Definition		
The objectives of the investigations are:		

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• *To experimentally demonstrate synchronized operation of several wind turbine converters in grid forming mode* • *To experimentally demonstrate the stability of parallel connected OWPPs with different control strategies, grid forming and grid following*	
Specification of the relevant scenarios	**Significance**
• *Energization of the offshore AC network by the OWPP(s), i.e. grid forming wind turbine converters* • *Disconnection and re-connection of wind turbine converter(s) to the offshore AC network, formed by one or more grid forming wind turbines* • *The offshore MMC controlling active and reactive power towards the DC link (not offshore grid forming)*	*Mandatory* *Mandatory* *Mandatory*
Physical location and the simulation environment	**Main Responsibility**
Aachen – Test Bench System with RTS	*DTU*

2.2 FAULT HANDLING IN OFFSHORE GRIDS

Another important part of WP16 is the demonstration of protection in particular fault clearing methods. Although simplifications have to be made in a down-scaled laboratory testbench (pi-links instead of cables, converter with less number of cells), the functionality of protection chain (fault clearing) will be tested and analysed for several cases and scenarios. Therefore, the protection IED developed in WP4 will be modified and included in the Test Bench system. If possible, implications of fault handling on operation of HVDC offshore grids and wind power plants will be derived.

2.2.1 FAULT CLEARING IN MESHED DC GRIDS

Test Case Motivation	**Origin**	**Significance**
A set of relevant DC fault clearing strategies is defined and studied with regard to selectivity, speed, robustness, requirements on backup protection and requirements on post-fault restoration for VSC-based grids in WP4. *Moreover, these strategies and their impact on DC grid components as well as their impact on the AC grid and the WPPs are studied in WP2.* *In standard offline EMT simulation the level of detail of the onshore AC networks and the WPP is usually limited, due to long simulation times. A main advantage of the PHiL and RTS is the opportunity to analyse the combined AC and DC system behaviour (using detailed EMT models) in different cases. Therefore, the interaction between the systems will be studied within WP16.* *The findings from WP2 and WP4 shall be confirmed by the studies on the Test Bench system in WP16*	*WP2, WP4*	*Mandatory*
Test Case Definition		
In WP16, DC Fault Clearing Strategies defined by WP4 shall be investigated in the test bench system in combination with the real-time representation of the AC onshore grid and the offshore wind power plants. The AC models will have a higher level of detail compared to the models used in standard EMT simulations. The fault detection and discriminations as well as the breaker control will be represented by the protection IED developed in WP4. The main objective is to improve the TRL of the fault clearing strategies.		

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The objectives of the investigations are: • *Analysis of converter controllability during DC fault (internal energy management, STATCOM operation, reconnection/restart after temporary blocking for HB and FB MMCs)* • *Interaction analysis of fault clearing strategies with offshore WPPs (with a number of WTs modelled in full detail)* • *Interaction analysis of fault clearing strategies with onshore AC grid and AC grid stability (transient stability, frequency stability)* • *Analysis of the usability of the protection IED in the PHiL system. This include the influence of single-ended / double-ended protection methods.*

Specification of the relevant scenarios	**Significance**

• *Monopolar DC System (WP2 Minimal Meshed Network)*
• *Bipolar DC System (WP2 Minimal Meshed Network)*
• *Variety of different fault scenarios (Location, Type, Resistance)*
  ○ *AC Onshore Faults*
  ○ *DC Grid Fault*
  ○ *AC Offshore Grid Faults*
• *Ground schemes*
• *Network topology variations*
• *Load flow variations → Different use cases*
• *Fault detection algorithm (WP4 single-ended / double-ended)*
• *Breaker technology (fast, slow)*
• *IED busbar communication*
• *Interoperability of fault clearing methods (e.g. HB-MMC with DCCB and FB-MMC with HSS)*
	Mandatory
	Mandatory
	Mandatory
	
	Optional
	Optional
	Optional
	Mandatory
	Mandatory
	Optional
	Optional

Physical location and the simulation environment	**Main Responsibility**
Aachen – Test Bench System with RTS	*RWTH*

2.2.2 FAULT HANDLING WITH GRID-FORMING WTGS

Test Case Motivation	**Origin**	**Significance**
WTG controllers developed in WP3 for DRU use are all grid forming, as well as those used in WP16 test case 2.1.2 for basic black-start operation. However, fault handling with this kind of grid forming wind turbine controllers needs to be studied in realistic conditions.	*WP2, WP3*	*Mandatory*

Test Case Definition
The objectives of the investigations are: • *Demonstration of offshore ac grid fault clearing strategies in systems employing grid forming converters in islanded operation* • *Demonstration of offshore ac grid fault clearing strategies in systems employing grid forming converters with DRU-HVDC connection* • *Grid forming converter contribution to on-shore grid fault handling* *Therefore, different AC fault scenarios will be conducted and analysed.*

Specification of the relevant scenarios	**Significance**
• *Offshore grid faults (with variation of the fault type) with islanded grid-forming wind turbine generators*	*Mandatory*

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• *Offshore grid faults with DRU-HVDC connected grid forming WTGs* • *On-shore grid faults with HVAC connected grid forming WTGs* • *On-shore grid faults with DRU-HVDC connected grid forming WTGs*	*Mandatory* *Mandatory* *Mandatory*
Physical location and the simulation environment	**Main Responsibility**
Valencia – Prototype demonstrator	*UPV*

2.2.3 OFFSHORE SYMMETRICAL AND ASYMMETRICAL FAULTS

Test Case Motivation	**Origin**	**Significance**
The offshore symmetrical and asymmetrical faults are being studied in PROMOTioN and also by manufacturers. The grid codes for these faults are not mature enough. There is the need for detailed recommendations for grid code requirements (both for the HVDC and wind turbines). The demonstration of faults will decrease the risk of inaccurate requirements.	*WP2, WP3*	*Optional*
Test Case Definition		
The objectives of the investigations are: • *Analysis of offshore faults in a converter dominated offshore network* • *Demonstration of HVDC and WPP fault responses* • *Demonstration of recommended grid code requirements*		
Specification of the relevant scenarios		**Significance**
• *Only the HVDC converter is connected - securely cleared fault* • *Both the HVDC and WPP converter are connected - securely cleared fault* • *The WPP is securely disconnected due to failure of fault clearance*		*Mandatory* *Mandatory* *Mandatory*
Physical location and the simulation environment	**Main Responsibility**	
Aachen – Test Bench System with RTS	*DTU*	

2.2.4 OWPP RESPONSE TO DC FAULTS

Test Case Motivation	**Origin**	**Significance**
DC faults are mostly being investigated in terms of clearing strategies. The response of OWPP plays an important role as it will impact the eventual loss of infeed. For instance, if the OWPP can stay connected for "long" duration of DC faults, then the loss of infeed would be decreased.	*WP2, WP3, WP4*	*Mandatory*
Test Case Definition		
The objectives of the investigations are: • *Analysis of OWPP – HVDC converter interaction during DC faults* • *Analysis OWPP response as a function of DC fault clearing duration* • *Demonstration of OWPP robustness during DC faults* • *Demonstration of recommended requirements for OWPP DC fault response*		

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Specification of the relevant scenarios	Significance
• *Monopolar DC System (WP2 Minimal Meshed Network)* • *Bipolar DC System (WP2 Minimal Meshed Network)* • *Fault Blocking (Full-Bridge) Converter* • *Fault Feeding (Half-Bridge) Converter in combination with and without DC-CBs* • *Variety of different fault scenarios (Location, Type, Resistance)* • *Network topology variations* • *Load flow variations → Different use cases*	*Mandatory* *Mandatory* *Mandatory* *Mandatory* *Mandatory* *Optional* *Optional*
Physical location and the simulation environment	**Main Responsibility**
Aachen – Test Bench System with RTS	*DTU*

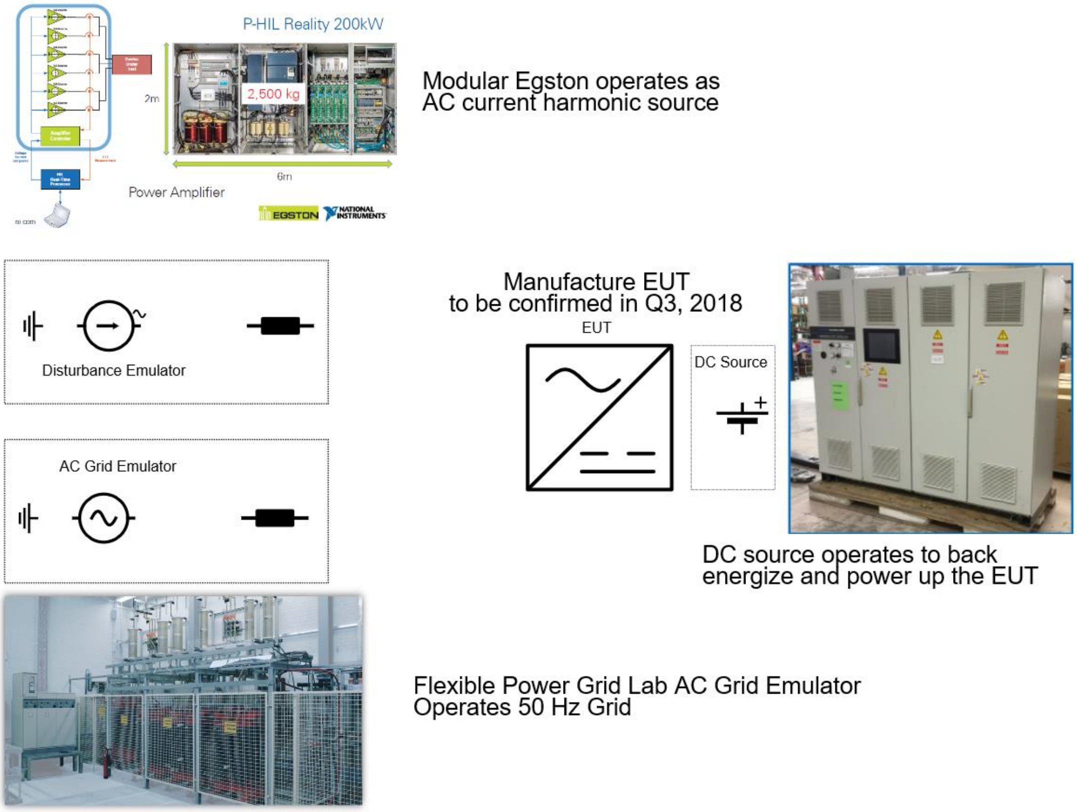
2.3 RESONANCE PHENOMENA STUDIES

Using the impedance based models, harmonic stability problems related to resonance phenomena can be predicted in the frequency domain. For this, the frequency response of the developed impedance models will be validated by means of comparisons with time domain simulations and laboratory results of the test bench system. Furthermore, the harmonic stability and potential interactions of active components and the passive grid will be studied by means of the developed models.

2.3.1 UNIT WIND TURBINE CONVERTER MODEL FOR RESONANCE PHENOMENA STUDIES

Test Case Motivation	Origin	Significance
The test case focuses on the development of a frequency domain converter model for wind turbines and verifies the frequency domain results with the time domain simulation/test results obtained from a unit wind turbine converter. The test case is intended to validate the derived analytical impedance model and the wind turbine converter model. A simple test circuit of wind turbine connected to the physical voltage source via the pre-defined grid impedance is planned.	*WP16*	*mandatory*
Test Case Definition		
Objective: *Extract the frequency behaviour of wind turbine converters using the test bench in Arnhem and compare it to the prediction of the analytical wind turbine converter model.*		

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



Specification of the relevant scenarios	**Significance**
• *Small signal perturbation test using the amplifier operated as voltage source (perturbation signal is directly injected to the amplifier input)*	*Mandatory*
• *Small signal perturbation test using the amplifier operated as current source parallel injection.*	*Mandatory*
• *Power Hardware in the loop test to be performed*	*Mandatory*

Physical location and the simulation environment	**Main Responsibility**
Arnhem – Flexible Power Grid Lab	*DNV GL*

2.3.2 UNIT MMC CONVERTER MODEL VALIDATION FOR RESONANCE PHENOMENA STUDIES

Test Case Motivation	**Origin**	**Significance**
The test case centres on the development of a frequency domain MMC converter model and verifies the frequency domain results with the time domain simulation/test results obtained from a single MMC testbench unit. A simple test circuit of one MMC testbench unit connected to the physical voltage source via the pre-defined grid impedance is planned.	*WP16*	*mandatory*
Test Case Definition		
Objective:		

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

Extract the frequency behaviour of an MMC converter using the test bench and compare it to the prediction of the analytical MMC model in the frequency domain. *For the validation, the scaled test bench will be used as rectifier in dc voltage control and connected to a load. As preliminary study, the real-time simulator can be used for the frequency response of a full-scaled MMC model.*	
Specification of the relevant scenarios	**Significance**
• *Small signal perturbation test using the amplifier operated as voltage source (perturbation signal is directly injected to the amplifier input)*	*Mandatory*
• *Unit MMC converter operated as STATCOM mode or inverter/rectifier mode of typical MMC-HVDC node*	*Mandatory*
Physical location and the simulation environment	**Main Responsibility**
Aachen – RTS	*DNV GL*

2.3.3 OFFSHORE WIND PARK HARMONIC RESONANCE ANALYSIS WITH AC CABLE CONNECTION

Test Case Motivation	**Origin**	**Significance**
Utilizing the frequency domain impedance based model of wind turbine unit (developed and validated in DNV GL Arnhem Test Lab with manufacture replica –test case 2.3.1) and MMC converter (developed and validated by test case 2.3.2), this test case investigates the system level harmonic resonance risk with respects to an AC cable connection. *The MMC testbench will be connected with time domain real-time RT-LAB model of wind turbine (via power amplifiers), and time domain real-time AC/DC grid model (via power amplifiers). The harmonic resonance prediction in the frequency domain will be verified against the time domain power hardware in the loop test results.*	*WP16*	*Optional*
Test Case Definition		
Objective: *Validate the harmonic resonance prediction using the impedance based stability criteria with time domain results concerning an offshore wind park connection via AC cable.*		

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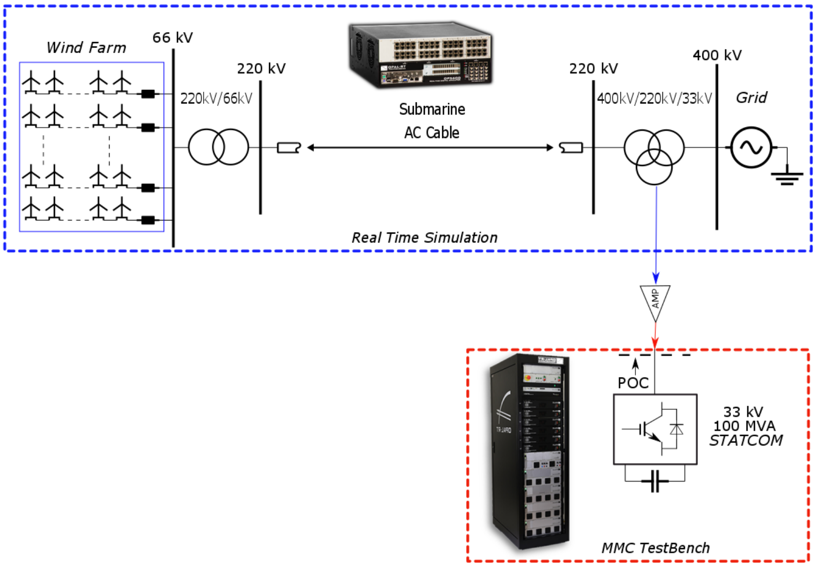


Specification of the relevant scenarios	**Significance**
• *Offshore wind park AC collection grid + Wind turbine + AC export cable will be represented in the RT-LAB real-time simulation environment and interface to the MMC testbench unit operated as STATCOM via a power amplifier. The onshore AC grid will be modelled in RT-LAB real-time simulation environment as well and interfaced to the same onshore node where STATCOM and export cable of wind-park are connected.* • *Wind farm start-up sequence (i.e. Stability of MMC STATCOM)* • *Wind farm normal operation stability assessment (i.e. Wind Turbine, STATCOM and Grid Interaction)*	*Optional* *Optional* *Optional*

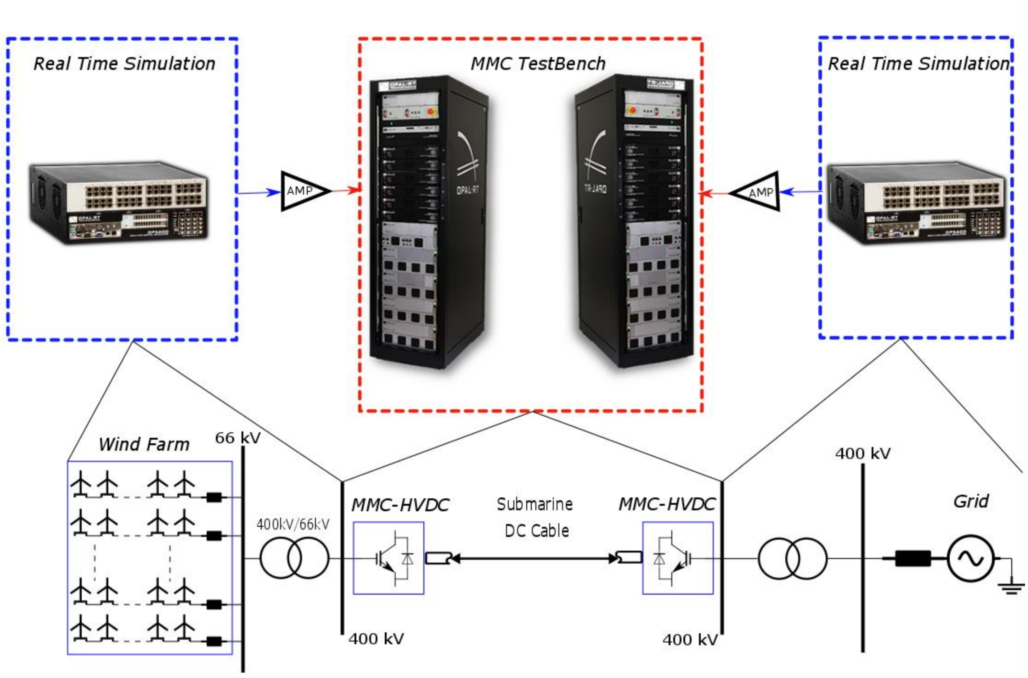
Physical location and the simulation environment	**Main Responsibility**
Aachen – RTS	*DNV GL*

2.3.4 OFFSHORE WIND PARK HARMONIC RESONANCE ANALYSIS WITH MMC-HVDC CONNECTION

Test Case Motivation	**Origin**	**Significance**
Utilizing the frequency domain impedance based model of a wind turbine unit (developed and validated in DNV GL Arnhem Test Lab with manufacture replica –test case 2.3.1) and MMC converter (developed and validated by test case 2.3.2, this test case investigates the system level harmonic resonance risk with respects to MMC-HVDC *The MMC testbench will be connected with the time domain real-time RT-LAB model of the wind turbine (via power amplifier), and the time domain real-time AC grid model (via power amplifier). The harmonic resonance prediction in the frequency domain will be verified against the time domain power hardware in the loop test results.*	*WP16*	*Mandatory*
Test Case Definition		
Objective:		

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

- *Comprehensive study regarding harmonic resonance with respect to different offshore grid states (e.g. number of connected wind turbines, different power in-feed). The study will be done by means of the impedance based stability criteria.*
- *Validate the harmonic resonance prediction by the impedance based stability criteria with time domain results concerning an offshore wind park connection via MMC-HVDC platform*



Specification of the relevant scenarios	Significance
• *Wind farm normal operation stability assessment (i.e. Wind Turbine, MMC-HVDC interaction)*	*Mandatory*
• *Offshore wind park AC collection grid + Wind turbine will be represented in the RT-LAB real-time simulation environment and interface to the MMC testbench unit operated as MMC-HVDC platform via power amplifier. The onshore AC grid will be modelled in RT-LAB real-time simulation environment as well and interfaced to the same onshore MMC-HVDC station represented by MMC testbench via power amplifier.*	*Optional*
• *Wind farm start-up sequence (i.e. MMC-HVDC and AC grid interaction)*	*Optional*

Physical location and the simulation environment	Main Responsibility
Aachen – RTS	*DNV GL*

2.3.5 HARMONIC IMPEDANCE ANALYSIS FOR DC GRIDS WITH DRU

Test Case Motivation	Origin	Significance
Grid forming WTGs are required for islanded operation, DRU operation, in some black-start strategies and also improves the characteristics of HVAC and MMC-HVDC connected wind farms.	*WP3*	*Mandatory*

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This test case aims at verifying the validity of frequency domain models for the harmonic stability of offshore wind power plants consisting of grid forming WTGs.		
Test Case Definition		
Objectives: • *Study the validity of existing frequency domain impedance techniques for harmonic stability analysis of grid forming offshore wind farms.* • *Validate in a real-time CHIL the frequency domain models obtained analytically.*		
Specification of the relevant scenarios		**Significance**
• *Harmonic resonance analysis of islanded WPPs with grid forming/mixed WTGs* • *Harmonic resonance analysis of HVAC connected WPPs with grid forming WTGs* • *Harmonic resonance analysis of DRU-HVDC connected WPPs with grid forming WTGs*		*Mandatory* *Mandatory* *Mandatory*
Physical location and the simulation environment	**Main Responsibility**	
Valencia – Prototype demonstrator	*UPV*	

2.4 AC GRID SUPPORT

The high controllability of multi-terminal HVDC systems opens up a wide variety of possibilities for ac network support. The question on how to use this potential is subject of many publications. The following test cases shall investigate the frequency support between asynchronous ac systems using multi-terminal HVDC systems as well as the frequency support of connected OWPP. Additionally, the potential of power oscillation damping using OWPP can be demonstrated.

2.4.1 FREQUENCY SUPPORT BY A MESHED OFFSHORE GRID

Test Case Motivation	**Origin**	**Significance**
Using the Test Bench System with RTS it can show, that the frequency support strategies investigated in WP2 are realistic and functional.	*WP1, WP2*	*Mandatory*
Test Case Definition		
In WP2 the possibilities of different control algorithms for frequency support are analysed. The results shall be compared to the results of a "lab scale" representation in combination with reduced AC grids by means of node numbers. The reduction of the adjacent AC grids is necessary because of the limited computing power of the test bench system. Nevertheless, the modelling of each ac node due to the used EMT models is more detailed compared to the simulations of WP2. 1. *Frequency support control by decentralized droop controllers using the dc voltage as communication medium.* 2. *Frequency support control by centralized ("master") control using optical fibre based communication* *The frequency deviations will be simulated based on the loss due to an n-1 fault.*		
Specification of the relevant scenarios		**Significance**

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The impact of different share of RES as well as different load situations shall be analysed in WP2. The associated scenarios in WP2 shall be transferred to the scenarios of WP16. • *DC Grid connected to one detailed synchronous zone (e.g. ENTSO-E) and one simplified synchronous zone (single bus network)* • *DC Grid connected to a different detailed synchronous zone (e.g.GB) and one simplified synchronous zone (single bus network)* • *DC Grid connected to two separate detailed synchronous zones (e.g. ENTSO-E and GB)* • *DC Grid connected to one detailed synchronous zone (e.g. ENTSO-E) and one offshore wind power plant (OWPP) (in collaboration with 2.4.2)*	*Mandatory* *Optional* *Optional* *Optional*
Physical location and the simulation environment	**Main Responsibility**
Aachen – Test Bench System with RTS	*RWTH*

2.4.2 FREQUENCY SUPPORT AND POWER OSCILLATION DAMPING BY OWPP CLUSTER

Test Case Motivation	**Origin**	**Significance**
In the ENTSO-E HVDC NC Article 39 (1); "a DC-connected power park module shall be capable of receiving a fast signal from a connection point in the synchronous area to which frequency response is being provided and be able to process this signal within 0.1 seconds from sending to completion of processing the signal for activation of the response. Frequency shall be measured at the connection point in the synchronous area to which frequency response is being provided". *Compliance with this requirement should be demonstrated.* *Additionally, "Article 39 Frequency stability requirements 2. (b) DC-connected power park modules connected via HVDC systems which connect with more than one control area shall be capable of delivering coordinated frequency control as specified by the relevant TSO"*	*WP1, WP2, WP3*	*Optional*
Test Case Definition		
The objectives of the investigations are: • *Demonstration of OWPP frequency support and POD capabilities to the onshore grid/s* • *Demonstration of cluster control functionalities mastering the OWPPs for frequency support and POD, provided to more than one onshore control area.*		
Specification of the relevant scenarios		**Significance**
The technical feasibility of impact of frequency support and POD by OWPP shall be investigated in the following scenarios: • *DC point-to-point connection between one detailed synchronous zone (e.g. ENTSO-E) and one offshore wind power plant (OWPP)* • *DC Grid connected to one detailed synchronous zone (e.g. ENTSO-E) and one offshore wind power plant (OWPP)* *The detailed scenario layout will be developed in close contact with test case 2.4.1 and WP2*		*Optional* *Optional*
Physical location and the simulation environment		**Main Responsibility**
Aachen – Test Bench System with RTS		*DTU*

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