Deliverable 11.5 Best practice and recommendations for compliance evaluation

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Deliverable 11.5

Best practice and recommendations for compliance evaluation

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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LIST OF DEFINITIONS AND ABBREVIATIONS

DEFINITIONS

1. 'HVDC system' means an electrical power system which transfers energy in the form of high voltage direct current between two or more alternating current (AC) buses and comprises at least two HVDC converter stations with DC transmission lines or cables between the HVDC converter stations; [1]
2. 'DC connected power park module' means a power park module that is connected via one or more HVDC interface points to one or more HVDC systems; [1]
3. 'HVDC converter station' means part of the HVDC system which consists of one or more HVDC converter units installed in a single location together with buildings, reactors, filters, reactive power devices, control, monitoring, protective, measuring and auxiliary equipment; [1]
4. 'power park module' or 'PPM' means a unit or ensemble of units generating electricity, which is either non – synchronously connected to the network or connected through power electronics, and that also has a single connection point to a transmission system, distribution system including closed distribution system or HVDC system; [2]
5. 'offshore power park module' means a power park module located offshore with an offshore connection point; [2]
6. 'fault ride through' means the capability of electrical devices to be able to remain connected to the network and operate through periods of low voltage at the connection point caused by faults; [2]. Note that this definition does not locate the fault which in the case of HVDC systems can be in the onshore AC system, the offshore AC system and in the DC system.
7. 'synthetic inertia' means the facility provided by a power park module or HVDC system to replace the effect of inertia of a synchronous power – generating module to a prescribed level of performance; [2]
8. 'frequency control' means the capability of a power – generating module or HVDC system to adjust its active power output in response to a measured deviation of system frequency from a set point, in order to maintain stable system frequency; [2]. Note that this definition refers to AC connected power park modules, and that control of the offshore AC system frequency may differ significantly depending on the type of HVDC system.
9. 'frequency sensitive mode' or 'FSM' means the operating mode of a power – generating module or HVDC system in which the active power output changes in response to a change in system frequency, in such a way that it assists with the recovery to target frequency; [2]
10. 'black start capability' means the capability of recovery of a power – generating module from a total shutdown through a dedicated auxiliary power source without any electrical energy supply external to the power – generating facility;[2]
11. 'fast fault current' means a current injected by a power park module or HVDC system during and after a voltage deviation caused by an electrical fault with the aim of identifying a fault by network protection systems at the initial stage of the fault supporting system voltage retention at a later stage of the fault and system voltage restoration after fault clearance;[2]

12. ‘compliance testing’ means testing activities with the purpose of demonstrating the compliance with required specifications. [4]. Compliance testing also serves providing verification of the performance of the connections control and protection basis.
13. ‘compliance monitoring’ means monitoring activities with the purpose of demonstrating the continuous compliance with required specifications [4]. Compliance monitoring also supports verification of models against real time experience.
14. ‘compliance simulation’ means simulation activities with the purpose of demonstrating the compliance with required specifications, especially where testing is not applicable [4]. The simulation activities should include model validation
15. ‘grid code’ means a document that sets out the procedures and requirements relating to some or all of the activities of connection, management, planning, development and maintenance of the electrical transmission and distribution grid, as well as dispatching and metering etc. [4]
16. ‘grid code compliance’ means demonstration that the electrical behaviour of power plants satisfy specific technical requirements in grid codes given by power system operators. [4]

ABBREVIATIONS

Table 1 Abreviations used in the document

Term	Meaning
AC	Alternating Current
CR 2016/1447	European Network Code for the HVDC connections [1]
CR 2016/631	European Network Code for Requirements for grid connections of Generators [2]
CHIL	Controller Hardware In the Loop
DC	Direct Current
DR	Diode Rectifier
DRU	Diode Rectifier Unit
ENTSO-E	European Network of Transmission System Operators for Electricity
EMT	Electromagnetic transient
ESCR	Effective Short Circuit Ratio
ESO	Electricity System Operator
FACTS	Flexible AC Transmission Systems
FAT	Factory acceptance test
FEED	Front End Engineering Design
FON	Final Operational Notification
FRT	Fault Ride Through
FSM	Frequency Sensitive Mode
HIL	Hardware In the Loop
GB	Great Britain
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IP	Intellectual Property
MIIF	Multi Infeed Interaction Factor
MMC	Modular Multilevel Converter
MVDC	Medium Voltage Direct Current
OTS DUW	Offshore Transmission System - Development User Works
OWF	Offshore Wind Farm
PLL	Phase Locked Loop
PPM	Power Park Module
RMS	Root Mean Square
ROCOF	Rate Of Change Of Frequency
RTDS	Real time digital simulation
SCR	Short Circuit Ratio
SO	System Operator
SSTI	Sub-Synchronous Torsional Interaction
TO	Transmission Operator
TOV	Temporary over voltage
TSO	Transmission System Operator
VSC	Voltage Source Converter
VSM	Virtual Synchronous Machine
WPP	Wind Power Plant
WSCR	Weighted Short Circuit Ratio
WT	Wind Turbine
WTG	Wind Turbine Generator

CONTENT

EXECUTIVE SUMMARY

PROMOTioN project

The PROMOTioN project evaluates for the first time a series of technical challenges associated with how practically a meshed DC grid may be delivered. Networks must be delivered in a robust manner such that they are successfully integrated into the wider networks owned and operated by European TSOs. In order for this to be achieved there are questions surrounding the standards and processes that need to apply to that integration and how the performance of the DC grid is demonstrated in tests and in models provided not just to TSOs, but exchanged between the various manufacturers and developers interfacing or constructing the meshed DC grid to ensure that they in turn meet the needs of the onshore TSOs in connecting to their networks.

Offshore DC transmission comes with a number of unique challenges for standards, processes and compliance testing:

- The DC transmission method leads to de-coupled offshore AC infrastructure whose specification has a greater degree of freedom in comparison to HVAC WTG connection, but nevertheless needs to ensure the overall effect of the DC meshed network provides acceptable performance to the onshore system.
- Given the offshore AC system as a function of its decoupling across a DC meshed grid it has practically zero system inertia and limited short circuit level, requiring highly co-ordinated control solutions which challenge the scope and visibility of current data exchange and models in particular across parties.
- Because of the DC circuit decoupling, onshore disturbances are presented in different ways to the offshore WTG such that the suite of current data exchanges and tests may not prove sufficient.
- Design analysis for the DC circuit, testing of DC breakers and DC protection solutions introduce new paradigms of operation to support protection of the convertor, fault identification and limitation of impact from DC drive new areas of specification.

D11.5 method – what was done in this report and why

This report summarises the learning developed under previous work packages in the design, specification and testing of a meshed DC system. A further questionnaire to partners within the PROMOTioN project has also been used to further inform the recommendations that should be made in the above areas of challenge. These outcomes are summarised and discussed in the context of driving process recommendations.

Outcomes of work

The report concludes on the following areas for future compliance process that require proposals supporting efficient data exchange, design and testing activities;

- A coherent overall programme including milestones requiring a minimum level of data exchange to support tasks of composite design of the overall solution
- New test specification areas of the WTG to support differing requirements within DC meshed connections.

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- A recommended test programme for DC breakers and DC protection
- Clear processes of model exchange and support of RTD-HIL ahead of commissioning of such projects.

Key conclusions and recommendations.

- Model exchange of generic black boxed models in either RMS or EMT is insufficient to support effective delivery of meshed grids. Sufficiently open and complete models need to be available and synthesised together at key points in a projects design and commissioning
- There is a requirement to track the tuning and control settings being made across the delivery of a project and its subsequent operation and to maintain models which reflect these both to ensure the overall design remains robust and supports future expansion of the meshed grid efficiently.
- Model exchange should not be limited to a narrow range of onshore considerations. Models with sufficient detail to support consideration of DC circuit design and offshore operability need to be exchanged in formats supporting as a minimum EMT simulation in the detailed design phase and complemented with models suitable for real time analysis to require a range of TSO and meshed DC grid operator analysis between Factory Acceptance Testing and commissioning.
- Compliance testing should not just test plant, but also overall protection and control philosophies associated with the meshed DC grids. These philosophies should be clearly articulated and modelled in order to support meshed DC grid extension over the project lifetime.

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1 INTRODUCTION

1.1 OBJECTIVE OF D11.5

The objective of this report is to summarize and recommend best practice for compliance evaluation of meshed offshore grids including converter stations and wind power plants connected to the grid. The report summarises requirements to compliance evaluation in existing grid codes and standards, then supplements with findings in PROMOTioN, and finally identifies gaps.

Several parts of the work done in PROMOTioN contributes to this objective. This includes recommendations to requirements for meshed offshore grids, specific requirements to DRU connected wind power plants, and examples of compliance simulations. Those findings are supplemented with findings from a questionnaire survey made among PROMOTioN TSO and project development partners for the purpose of this report.

1.2 SCOPE OF COMPLIANCE EVALUATION

Compliance evaluation of a facility is the process of determining whether the electrical behaviour of the evaluated facility meets all relevant technical codes and standards. However, the study in this report focuses on compliance with the specific technical requirements in grid codes enforced by power system operators. The compliance evaluation methods can include simulations, testing and monitoring. The input to compliance assessment includes relevant supporting documents, testing results, validated simulation models and continuous monitoring data.

Key to the enforcement of compliance principles is the clarity with which the above principles are combined within the requirements of all relevant technical codes and standards; it is important that these are both clear, practical and complete. Within TSOs technical standards are often not within one but several documents and across these standards there can be scope for misinterpretation and/or inconsistent activity.

Increasingly, as networks become more complex in nature, and as a specific example as offshore designs become stages in the incremental development of integrated offshore solutions, it becomes important for compliance processes to provide a foundation for these future stages of work, as no TSO wishes to unduly limit innovation but nonetheless needs to be reassured that overall performance is acceptable and is being managed fairly and consistently across all technologies. The more complex the design, the more of its control and design concept may be hidden within the "black boxing" of simulation models provided, and the more relevant the changes to these designs (their tuning, their completeness) are to later stages of their construction. The risk exists that such individual design decisions may result in wider impacts not fully understood ahead of operation. In this respect, the relevance of the production and validation of models within the compliance process increases with there being a greater emphasis upon Hardware in the Loop (HIL) verification of overall designs. This is because the HIL environment represents the most complete analysis environment, and allows a wider range of test cases to be considered. HIL also provides a mechanism for confidential and complex devices to be fully represented in control and protection hardware, overcoming challenges of IP and confidentiality

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handling where many manufacturers are involved in a project. At earlier stages of the project and as validated against manufacturer tests, models should be integrated within real time simulation environments at the earliest possible stages to verify overall system performance of the collection of devices being delivered, together with their overall control and protection strategies.

The facility owner is responsible for ensuring that the facility as a whole (e.g. a wind power plant) complies with the relevant requirements. The wind power plant however may often be defined offshore and connected to several countries in multi terminal HVDC systems. In different countries, different arrangements and responsibilities exist for the high voltage infrastructure. The high voltage infrastructure is expected to increasingly be HVDC in technology. High voltage infrastructure is often not owned by the developer of the wind power plant but a separate network operator, or indeed the TSO of the onshore area.

The owner of the compliance evaluated facility has to inform the system operator of the planned test schedules and procedures to be followed for verifying compliance with the requirements of the relevant grid code prior to first operation. The relevant system operator shall approve in advance the planned test schedules and procedures. Where separate Network owners form part of the overall design, their roles and responsibilities also need to be defined within the compliance processes.

Test schedules and procedures can be carried out and assessed by third parties, e.g. testing institutes or certification bodies and their outputs integrated into the overall framework of compliance activities by the TSO.

1.3 STRUCTURE OF D11.5

Deliverable 11.5 “Best practice and recommendations for compliance evaluation” takes the findings of the earlier research areas of the PROMOTioN projects and focuses on relating these to the existing requirements on HVDC systems and DC connected wind power plants.

Section 2 of D11.5, examines the “state of the art” of current standards and guidelines in place and how these translate to future integrated offshore designs.

Section 3 summarises already published PROMOTioN findings and recommendations and provides an overview of the current processes and best practices applied to the compliance of offshore designs, synthesizing also the responses from project partners across the developer and TSO community on how offshore compliance testing, modelling and verification simulations are conducted across current project experience.

Section 4 provides a gap analysis of those areas where existing grid codes, standards and processes require complementing or adapting to respond to the findings of the earlier PROMOTioN work and to the emerging areas of best practice concerns being identified. Options for addressing these gaps are further evaluated.

Section 5 provides recommendations for future offshore compliance standards and processes.

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2 GRID CODES AND STANDARDS

2.1 GRID CODES

2.1.1 REQUIREMENTS FOR GRID CONNECTION OF HVDC SYSEMS AND DC CONNECTED WIND POWER PLANTS

The basic requirements on HVDC systems and on DC connected wind power plants are laid out in the European COMMISSION REGULATION CR 2016/1447 of 26 August 2016 [1], establishing a network code on requirements for grid connection of HVDC systems and DC connected power park modules. These are binding pan-European rules originally drafted by ENTSO-E in consultation with stakeholders (i.e. transmission system operators), with guidance from ACER (Agency for the Cooperation of Energy Regulators). Within the framework of the European network codes, these requirements are implemented and supplemented by more specific requirements in national grid codes or application rules.

Within the CR 2016/1447 framework there are different levels of requirement, ranging from some which are precisely defined within the flexibility of tolerances available to each TSO area to set them (for example frequency response) to others which are highly flexible (for example the specification of the offshore AC power island into which a power park module interfaces). Thus, some requirements are qualitatively settled, well defined and harmonized while quantitatively there remains some flexibility in determining the final parameters applied in each member state as the harmonization is done to the maximal extent possible but still considers tuning with respect to national specificities.

The compliance monitoring is considered within CR 2016/1447, hence it specifies to introduce appropriate compliance simulations and tests of grid compliance, and explicitly requires such tests and simulations for some specific requirements.

Another valuable contribution of CR 2016/1447 is the statement (Article 54) that system operator / TSO “may specify HVDC system owner to deliver simulation models which properly reflect the behaviour of the HVDC system in both steady state, dynamic simulations (fundamental frequency components) and EMT simulations” [1]. Still, current codes say very little on the modelling front. Modelling on its own is a limited benefit unless the models are validated against the real performance and up to the job of the sorts of simulations they are going to be used for. CR 2016/1447 recommends model validation against compliance tests.

CR 2016/1447 specifies requirements for compliance testing for (Articles 71-72) and compliance simulations (Articles 73-74). The explicitly mentioned requirements for compliance evaluation of HVDC systems are given in Table 2 and the explicitly mentioned requirements for compliance evaluation of DC connected power park modules are given in Table 3. It is not clear why the requirements for compliance evaluations are limited to the listed technical requirements.

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Table 2. CR 2016/1447 (Articles 71 and 73) requirments for compliance evaluation methods for HVDC connections (S = simulation, T = test)

CR 2016/1447 requirement	**Method**
Frequency sensitivity modes	T
Active power controllability, control range and ramping rate	TS
Reactive power capability	TS
Reactive power control mode	T
FRT capability	S
Short circuit contribution during faults	S
Post fault active power recovery	S
Power oscillation damping capability	S
Power system restoration – black start	T

Table 3. CR 2016/1447 (Articles 72 and 74) requirments for compliance evaluation methods for DC connected power park modules (S = simulation, T = test)

Requirement	**Method**
Active power control	T
Frequency response	T
Reactive power control	T
Reactive power capability	TS
Offshore AC FRT	S
Post fault recovery	S
Fast fault current during offshore faults	S
Power oscillation damping	S

2.1.2 REQUIREMENTS FOR AC GRID CONNECTION OF WIND POWER PLANTS

The basic requirements on power park modules like wind power plants are laid out in the European COMMISSION REGULATION CR 2016/631 [2] establishing a network code on requirements for grid connection of generators. CR 2016/631 specifies specific requirements for AC connected offshore power park modules (chapter 4) and compliance simulations (chapter 7) for a selection of

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requirements to offshore power park modules. Compliance simulations are required for the following requirements:

- Fast current injection during faults (Article 54.3)
- Post fault active power recovery (Article 54.5)
- Black start capability (Article 55.4)
- Synthetic inertia (Article 55.5)
- Power oscillation damping (Article 55.7)

It should be noted that the specified black start capability, synthetic inertia and power oscillation damping are not mandatory requirements without prejudice to the Member State's rights to introduce obligatory rules in order to ensure system security, and it makes no sense to require simulation of a non-mandatory requirement. Moreover the strategies for achieving these objectives for meshed DC grids may vary significantly to those associated with less complex connection designs. Many of these requirements await more precise definition of the onshore TSO performance requirement which will then necessarily inform the design of simulation requirements in the future.

2.2 STANDARDS AND TECHNICAL BROCHURES

2.2.1 WIND POWER TEST STANDARDS

IEC 61400-21-1 “Measurement and assessment of electrical characteristics - Wind turbines” [5] provides an internationally standardized methodology that ensures uniformity, consistency and accuracy in the testing and assessment of characteristics of grid connected wind turbines (WTs). The present edition of IEC 61400-21-1 is developed with AC connected wind turbines in mind, and does not yet include specific requirements for test of HVDC connected wind turbines.
IEC 61400-21-1 includes the following scope:

- 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.

The test and assessment methods specified in IEC 61400-21-1 are grouped into the following categories:

- Power quality aspects like flicker and harmonics.
- Steady state characteristics like maximum power, reactive power capability and unbalanced operation.
- Control performance including active power control, frequency control, reactive power control and voltage control.
- Dynamic fault ride through performance.
- Disconnection from grid including grid protection and reconnection tests.

It should be noted that the assessment methods described in IEC 61400-21-1 are only referring to the power quality aspects, and the idea is to specify how to use power quality characteristics, i.e.

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flicker and harmonics, measured during a single wind turbine type test to assess the power quality emission from a wind farm using this wind turbine type. It should also be noted that the assessment methods are moved to an informative annex in the latest edition of IEC 61400-21-1. It is generally accepted that the flicker evaluation methods have been proven reasonably accurate [6], the methods for assessing harmonic current emission are not considering important grid resonances and therefore have low accuracy. Better accuracy can be obtained using validated harmonic models, and this is why a technical report IEC 61400-21-3 [7] on wind turbine harmonic model and its application has been published simultaneously with IEC 61400-21-1.

It should also be noted that existing focus within IEC power quality standards are on the thermal implications associated with distortion, so called compatibility limits associated with averaged persistent behaviour over periods of 10 minutes or more which could potentially be considered to have impact upon conventional synchronous generation or motors or would have impacts upon conventional device performance. These standards are however beginning to consider the effects of harmonic burst distortion upon the withstand capabilities of power electronic devices and present recommendations in these areas.

2.2.2 COMPLIANCE EVALUATION OF WIND AND PV POWER PLANTS

Furthermore, at IEC subcommittee SC8A work on a document on “Grid code compliance assessment methods for grid connection of wind and PV power plants” (CD of IEC TS 63102 ED1) [4]. This document specifies recommended technical methods of grid code compliance assessment for grid connection of wind and PV power plants as the basic components of grid connection evaluation.

The electrical behaviour of wind and PV power plants in this technical specification includes

- active power production,
- reactive power capability,
- control performance,
- FRT capability,
- power quality and protection.

The technical specification recommends the following methods for compliance evaluation:

- Simulation and monitoring of operating areas (frequency range, voltage area and reactive power capability)
- CHIL testing, plant field testing and monitoring of control performance (active and reactive power)
- Simulation and monitoring of FRT (undervoltage and overvoltage, short circuit contribution)
- Plant field testing of power quality (harmonics, interharmonics and flicker)

2.2.3 MODELLING

IEC 61400-27-1 [8] specifies generic fundamental frequency models and a model validation procedure for wind turbine models based on tests performed in IEC 61400-21-1. Next edition of IEC 61400-27 will be in two parts and also include fundamental frequency models and validation

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procedures at the wind power plant level. IEC 61400-21-1 includes an informative annex about a generic software interface for use of models in different software environment, and this interface is mainly intended for EMT modes. However, there are no standards for generic EMT models or for method for validation of EMT models.

2.2.4 OTHER STANDARDIZATION AND HARMONIZATION BODIES

Furthermore, other standardization and harmonization bodies discuss and define requirements on HVDC systems, wind power plants and related equipment:
CIGRÉ:

- SC A3. High Voltage Equipment
- SC B4. HVDC and Power Electronics
- SC C1. Power System Development and Economics
- SC C2. Power System Operation and Control
- SC C4. Power System Technical Performance
- SC D1. Materials and Emerging Test Techniques

IEC:

- TC 8. System aspects of electrical energy supply
- TC 17. High-voltage switchgear and control gear
- TC 88. Wind energy generation systems
- TC 95. Measuring relays and protection equipment
- TC 115. High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV

CENELEC:

- TC 8X System aspects of electrical energy supply

A detailed description of the respective focus of these groups and of the relevant documents is given in D11.1 “Harmonization catalogue” [9]. In D11.1 also potential contributions from technical work packages to ongoing and future harmonization activities are described.

2.3 CERTIFICATION

Several countries include certification of electrical characteristics and electrical simulation models as part of wind turbine type approval. However, this is based on standards developed with AC connected wind turbines in mind and focuses on the electromechanical characteristics. Therefore, more information, especially on electromagnetic transients, is probably needed to assess compliance in HVDC system.

Unlike HVDC, which tend to each contain project specific control optimisations, wind turbine technologies have historically been founded upon a generic control structure where the tuning of that control is optimized closer to the time of deployment, which may in many cases be at the time of commissioning. As such it is common for TSOs to rely on generic certification processes which test the technology across the range of compliance areas, providing then a generic model which can be applied for each given project application. The tests performed by the manufacturer may support certification such that the tests demonstrate product robustness to a range of different TSO standards. As documents such as the requirements for grid connection in CR 2016/631 [2] are

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especially useful to manufacturers and the certification process is valuable to TSOs in focusing effort associated with compliance verification.

The German FGW technical guideline TR 3 [10] 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 TR 8 [11] specifies the assessment and certification of electrical characteristics of wind turbines and wind power plants.

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 [12].

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3 FINDINGS AND BEST PRACTICE EXPERIENCE

Section 3 summarises already published PROMOTioN findings and recommendations and provides an overview of the current processes and best practices applied to the compliance of offshore designs, synthesizing also the responses from project partners across the developer and TSO community on how offshore compliance testing, modelling and verification simulations are conducted across current project experience.

3.1 PROMOTION FINDINGS AND RECOMMENDATIONS

3.1.1 REQUIREMENTS FOR MESHED OFFSHORE GRIDS (D1.7)

PROMOTioN D1.7 [3] lists a qualitative and quantitative set of requirements for the meshed offshore grid based on the progress in the technical work packages during the first two years of the project. The deliverable includes requirements to the following areas:

- Functional system requirements to the meshed offshore grid including transmission capacity, interoperability, reliability, stability and controllability.
- General requirements to HVDC connections.
- Requirements to offshore generation connected to meshed offshore grids.
- Requirements to offshore consumption connected to meshed offshore grids.
- Operational requirements for the meshed offshore grid focusing on the DC side including operational ranges, fault behaviour, DC protection and SCADA communication.

The general requirements for HVDC connections in D1.7 refer to the AC side of the onshore HVDC converter station, which is also the case for the requirements to HVDC systems specified in CR 2016/1447 [1]. Those requirements are imposed by the onshore AC grid. The general requirements for HVDC connections are listed in Table 4 including references to relevant sections of D1.7 and CR 2016/1447

Table 4. General requirements for HVDC connections.

Requirement	**PROMOTioN D1.7**	**CR 2016/1447**
Frequency ranges	3.2.1.1	II.1.11
Rate-of-change-of-frequency withstand capability	3.2.1.2	II.1.12
Frequency sensitivity modes	3.2.1.3	II.1.15
Active power controllability, control range and ramping rate	3.2.1.4	II.1.13
Synthetic inertia	3.2.1.5	II.1.14
Maximum loss of active power	3.2.1.6	II.1.17
Voltage ranges	3.2.2.1	II.2.18
Reactive power capability	3.2.2.2	II.2.20

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Reactive power exchanged with the network	3.2.2.3	II.2.21
Reactive power control mode	3.2.2.4	II.2.22
Priority to active or reactive power contribution	3.2.2.5	II.2.23
Power quality	3.2.2.6	II.2.24
FRT capability	3.2.3.1	II.3.25
Short circuit contribution during faults	3.2.3.2	
Post fault active power recovery	3.2.3.3	II.3.26
Fast recovery from DC faults	3.2.3.4	II.3.27
Energisation and synchronisation of HVDC converter stations	3.2.4.1	II.4.28
Interaction between HVDC systems or other plants and equipment	3.2.4.2	II.4.29
Power oscillation damping capability	3.2.4.3	II.4.30
Subsynchronous torsional interaction damping capability	3.2.4.4	II.4.31
Network characteristics	3.2.4.5	II.4.32
Priority ranking of protection and control	3.2.5.1	II.5.35
Changes to protection and control schemes and settings	3.2.5.2	II.5.36
Power system restoration – black start	3.2.6	II.6.37
Information exchange and coordination	3.2.7	IV

Requirements to offshore generation connected to meshed offshore grids in PROMOTioN D1.7 refer to the AC side of the onshore HVDC converter station. However, the frequency response, synthetic inertia and power oscillation damping requirements refer to the AC side of the onshore HVDC converter station, assuming that onshore frequency and other relevant onshore measurements are communicated to the wind farm and the wind farm power is controlled accordingly. This is also the case for the requirements to DC connected power park modules specified in CR 2016/1447.

The general requirements for DC connected offshore wind farms are listed in Table 5. Several of those requirements also refer to CR 2016/631 [2]. For wind power plants connected to DRU terminals, a significant amount of the requirements to the remote-end converter are transferred to the offshore wind power plant. As a consequence, complexity in the offshore wind power plant regarding operation, control and communication will increase. The specific requirements to DRU connected wind power plants are discussed in 3.1.2.

Table 5. General requirements for DC connected offshore wind farms

Requirement	**PROMOTioN D1.7**	**CR 2016/1447**
Maximum power point tracking	4.1.1.1	
Operational frequency range	4.1.1.2	III.1.39
Operational rate of change of frequency	4.1.1.3	III.1.39
Active power independency of frequency	4.1.1.4	III.1.39

Active power control	4.1.1.5	III.1.39
Frequency response	4.1.1.6, 4.1.1.7, 4.1.1.8	III.1.39
Synthetic inertia	4.1.1.9	
DC voltage response	4.1.1.10	
Voltage range	4.1.3.1	III.1.40
Reactive power control	4.1.3.2	III.1.40
Reactive power capability		III.1.40
Offshore AC FRT	4.1.2.1	
Post fault recovery	4.1.2.2	
Fast fault current during offshore faults	4.1.2.3	
DC FRT	4.1.2.4	
Onshore AC FRT	4.1.2.5	
Power oscillation damping	4.1.4	
Offshore AC energization	4.1.5	
Auto-synchronous (grid forming) operation	4.1.6	
Power quality	4.1.7	III.1.44

The requirements for remote-end HVDC converter stations, i.e. the offshore HVDC converter station. Those requirements refer to the AC side of the offshore HVDC converter station. Note that (as stated in PROMOTioN D1.7), for some converter station technologies, some of those requirements will not be possible to meet without assistance of other technologies, and for those technologies some requirements will simply not be relevant. PROMOTioN D1.7 considers VSC based converter stations as well as Diode Rectifier (DRU) based converter stations. Since the DRU is a passive converter, it cannot contribute to the control.

The requirements for remote-end HVDC converter stations are listed in Table 6

Table 6. General requirements for remote-end HVDC converter stations

Requirement	**PROMOTioN D1.7**	**CR 2016/1447**
Voltage range	4.2.1.1	III.2.48
Frequency range	4.2.1.2	III.2.47
Rate of change of frequency range	4.2.1.3	III.2.47
Offshore active power range		II.1.13
Reactive power control		III.2.48
Reactive power capability		III.2.48
Robustness and stability of offshore AC	4.2.2	
Offshore short circuit FRT	4.2.3	II.3.25

Offshore AC energization coordinated with DC connected PPMs	4.2.4.1	
Offshore AC voltage control	4.2.4.2	
Offshore AC power quality	4.2.4.3	III.2.50

3.1.2 REQUIREMENTS RECOMMENDATIONS FOR DRU CONNECTED WIND POWER PLANTS (D3.8)

PROMOTioN D3.8 [13] provides a list of requirement recommendations to adapt and extend existing grid codes with the focus on the recommendations to cover the DRU concept, which has been studied in detail in WP3 of PROMOTioN. The deliverable provide the overview in Table 7 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 7: Overview of requirements considered for DRU connection in WP3 (Soirce: PROMOTioN D3.8)

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 FRT		X	X
2.11 DC FRT Requirements		X	X
2.12 Onshore AC FRT		X	X
2.13 Onshore Frequency Support Requirements	X		
2.14 Synthetic Inertia	X		
2.15 Onshore Oscillation Damping Requirements	X		

Recommendations on grid code extensions on requirements for grid connection of HVDC systems and DC connected power park modules are specified in D2.4 [17]. Those recommendations refer directly to CR 2016/1447 [1].

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3.1.3 COMPLIANCE SIMULATIONS FOR OFFSHORE WIND POWER PLANTS

3.1.3.1 GENERAL

In PROMOTioN D3.6 [14] “Report with the compliance test procedures for DR and VSC connected WPPs”, specifies requirements to simulation models and simulation-based validation procedures for HVDC connected wind power plants. Although this work focuses on DRU connected wind power plants, the specified compliance evaluation applies for VSC connected wind power plants as well for some of the specified functions.

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

- Wind turbine (WT) model
- Model of OWF Transformers
- Model of power cables within the OWF
- Models of active/passive compensation systems
- Model of DC-link and external grid to which the OWF is connected
- Model/documentation of OWF control

It should be stated that IEC 61400-27-1 [8] 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.

From TSO point of view, the principle should be that an EMT model should be provided as complete as possible in its inclusion of all AC system controls and protections present and includes all other relevant controls and protections expected to be engaged across the range of onshore AC offshore AC and DC circuit disturbances that performance will be reviewed. This EMT model should be sufficiently open that settings that may be modified over the lifecycle of the project and control and protection functions that can be engaged or removed over the lifecycle of the project are visible – not the detail of them necessarily but their presence within the EMT model.

The model should be available in a generic form at the beginning of the detailed design phase in order to inform TSO and manufacturer discussions surrounding the scope and any priority order to detailed design simulations. Ahead of FAT the model should be further made available in an updated form. Across FAT the performance of the intended system should be verified against code, and the EMT model also validated against the FAT. Across post FAT into commissioning phase, the EMT model should be maintained to represent and agree with tests and simulations subsequently conducted post FAT and post commissioning to align with in service experience. Besides the generic EMT model provided, its FAT validated update and its last update ahead of commissioning, the TSO should as a minimum also be provided with an RMS model to support its more general planning work.

Where the above obligations cannot be met within an EMT model alone, or where the EMT model contains an unacceptable level of limitations to its performance/ accuracy/ completeness, or where compliance and planning activities may be more efficiently conducted with it, the TSO should be able to require suitably specified replica control and protection hardware to be provided to support RTDS HIL analysis to complement other EMT models being made available. The same standards as

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above would pertain to the replica being provided and across the totality of EMT and replica made available all of the above criteria would need to be met.

The wind power plant functions included in the compliance simulations specified in PROMOTioN D3.6 are listed in Table 8. The table shows that all the functions are relevant for DRU connected wind power plants, and some of them also apply to VSC connected wind power plants. Some more details are given for the individual functions in the following.

Table 8: Overview of functions included in the compliance simulations specified in PROMOTioN D3.6

Wind power plant functions in PROMOTioN D3.6	**DRU connected**	**VSC connected**
4.1. Active Power control behaviour		
4.1.1 Active Power Production	X	X
4.1.2 Steady State Active Power Control	X	
4.1.3 Dynamic Active Power Control	X	X
4.1.4 Active Power Recovery	X	
4.1.5 Island Support (No HVDC or AC Connection)	X	
4.2. Harmonics		
4.2.1 Evaluation of Harmonics	X	X
4.3. System stability and ancillary services		
4.3.1 Frequency Envelope	X	
4.3.2 Steady State Frequency Control	X	
4.3.3 Dynamic Frequency Control	X	
4.3.4 Offshore Voltage / Reactive Power behaviour	X	X
4.4. Offshore AC Symmetrical / Asymmetrical Fault Requirements		
4.4.1 Offshore Fault Ride Through	X	X
4.4.2 Offshore AC Fault Current Injection	X	X
4.4.3 Offshore AC Fault Recovery	X	X
4.5. Onshore Grid Support Compliance Evaluation		
4.5.1 Frequency Response	X	X
4.5.2 Onshore Power Oscillation Damping Behaviour	X	X

3.1.3.2 ACTIVE POWER PRODUCTION

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. This is a simplification which makes sense if the purpose is to evaluate the maximum

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power point tracking of individual wind turbine. All credible points of power tracking should be considered for the range of operating points across which the meshed DC system is being operated to ensure there is no interaction between turbine and convertor complementary control in response to changes in the wind speed affecting the array of WTG being 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. The assumption is not specified in PROMOTioN D3.6, but the idea is to simulate the behaviour of the actual communication system taking into account the uncertainties in the communication time of the actual system.

3.1.3.3 STEADY STATE ACTIVE POWER CONTROL

For each one of the active power control 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.

The error of the optimal power tracking 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.

3.1.3.4 DYNAMIC ACTIVE POWER CONTROL

To evaluate the **dynamic active power control**, initially, the DRU connected wind power plants will be simulated as synchronized and transmitting active power to the on-shore AC grid via umbilical cable and via the DRU-HVDC link. VSC connected wind power plants will be simulated connected via the VSC HVDC. This is not stated in PROMTioN D3.6, but the simulation model shall include models of all wind farm components. Recognizing that changes in wind resource availability as they effect the array power output with manifest on the offshore AC grid as frequency disturbance, the dynamic active power control, its bandwidth limit and frequency range tolerance associated with the dynamic active power control should be specified based on the available response rates of WTG and HVDC controls.

3.1.3.5 ACTIVE POWER RECOVERY

To evaluate **active power recovery**, the following cases should be investigated:

- During **a close symmetrical fault with small short-circuit impedance**, the onshore 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. The offshore AC grid voltage will also require simultaneous regulation via the MMC in order to maintain it within limits. The fault ride through performance of the offshore WTG in this situation will be

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dependent upon its response to the simultaneous frequency and voltage disturbance imparted upon the offshore AC system rather than its ability to ride through a near zero voltage at its terminals. For a DRU based offshore design, the offshore WTG shall be required to support the additional challenges of commutation of the DRU during such conditions.

- 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. This in turn will represent a simultaneous high frequency and voltage disturbance to the offshore AC grid, of a lesser scale to that identified for the close fault above but with a longer duration of disturbance than the above event. It should be noted that the practical observed behaviour of remote fault clearance would normally involve differently timed circuit breaker openings in isolating faults such that more than one step improvement in voltage would be expected to be seen at the onshore AC terminals of the MMC, and replicated across proportionate power recovery against that recovered voltage.
- 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. For multiple MMC terminal designs that energy balancing may require actions extending across one or multiple offshore AC islands connected to the array and require a coordinated control strategy.

Compliance evaluation with regard to OWF capability to take part in island operation shall be conducted by means of simulations based on models of all relevant components (see section 3.1). CR 2016/631 [2] 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.

Within CR 2016/631 and HVDC codes, there is no specific criteria referenced for the withstand of the overall performance of the DC grid to repeated fault conditions. As such it should be assumed that there is no limit to the number of times an above event of the 3 types discussed above could occur.

It would be prudent for mesh HVDC systems design to study the repetition of fault conditions to assure that:

- For the range of typical conditions of Delayed Auto Reclose, and/or single phase auto-close operation of the TSOs network, the performance as required above can be delivered in full.
- Where, across repeated events, a fundamental limit is encountered to HVDC and/or WTG performance, the designer of the meshed DC system shares the analysis with the impacted TSO(s) and agrees a suitable overall design and control philosophy towards multiple FRT that satisfies their requirements and may be clearly documented, and sufficiently modelled and monitored across all parties.

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3.1.3.6 ISLAND SUPPORT (NO HVDC OR AC CONNECTION, OR LIMITED CONNECTION IN RESPONSE TO REMOTE ONSHORE FAULT CONDITIONS)

This function includes islanding operation as well as black start capability. Compliance Evaluation of OWF shall be conducted by means of simulations based on models of all wind farm components.

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

- 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.
- 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, D3.6 specifies more detailed simulation procedures for intentional islanding as well as re-synchronisation to external AC from island mode.

Compliance evaluation will follow **black start tests** specified in general in CR 2016/631 [2] and CR 2016/1447 [1]. A more detailed black start test procedure for generating units and stations is defined in the UK Grid code [18] .

3.1.3.7 EVALUATION OF HARMONICS

The compliance evaluation of harmonics described in PROMOTioN D3.6 refers to wind turbine compliance tests as well as wind power plant compliance simulations.

The wind turbine tests essentially refer to the test of harmonics, interharmonics and higher frequency components up to 9 kHz as specified in IEC 61400-4-7 [19], which is also applied in the wind turbine tests specified in IEC 61400-21-1 [5]. It may be noted that given the limited natural damping available within the offshore AC network, particular attention towards the burst harmonic voltage distortion in addition to compatibility limits may prove essential to the satisfactory specification of withstand of MMC and WTG components, and the specification of offshore harmonic filters and or relevant active controlled damping.

Using wind turbine IEC 61400-21-1 tests to evaluate compliance of wind farms has proven often to be very inaccurate, mainly because it does not consider the impact of resonances in the grid. Therefore, it is recommended to do compliance evaluation using detailed harmonic models.

PROMOTioN D3.6 recommends the use both of two simulation methods:

- Evaluation of harmonic distortion compliance: Simulation of normal operation, with the offshore wind farm producing energy. Analyses to be carried out include harmonic distortion studies using the Norton (or Thevenin) harmonic models of each element.
- Evaluation of small-signal stability: valuation will be carried out by computing the loop impedances as seen from relevant elements for the significant wind farm configurations. Particular consideration should be taken to capturing harmonic components via Harmonic

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State Space analysis techniques and capturing the loop impedances within the p-n frame as are including Negative Phase Sequence component effects of the convertor topology- the principle should be that the frequency of small signal behaviour should be reflective of that identified in EMT or RTDS study. Phase and gain margins will be calculated for each considered configuration and operating point of the design, including those that may exist across commissioning in addition to those present across ongoing operation and maintenance. For cases with the smallest phase and gain margin, EMT studies might be carried out to verify the results obtained by impedance analysis.

3.1.3.8 FREQUENCY ENVELOPE

This is referring to the offshore frequency envelope for DRU connected wind power plants. Compliance evaluation of **frequency envelope** requirements shall be conducted by means of EMT simulations based on models of all relevant components.

3.1.3.9 STEADY STATE FREQUENCY CONTROL

This refers to the offshore frequency control for DRU connected wind power plants. Compliance evaluation of steady state frequency control requirements shall be conducted by means of EMT simulations based on models of all relevant components.

3.1.3.10 DYNAMIC FREQUENCY CONTROL

This refers to the offshore frequency control for DRU connected wind power plants. Compliance evaluation of dynamic frequency control requirements shall be conducted by means of EMT simulations based on models of all relevant components.

3.1.3.11 OFFSHORE VOLTAGE / REACTIVE POWER BEHAVIOUR

CR 2016/631 [2] 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.

In order to evaluate the **reactive power/current capabilities** by simulations, a wide range of crucial test cases should be considered (see D3.6).

3.1.3.12 OFFSHORE FAULT RIDE THROUGH

PROMOTioN D3.6 specifies that **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. Different operating points (power at 5%, 50% and 100%) be tested and the fault ride through capability will be evaluated based on the simulations.

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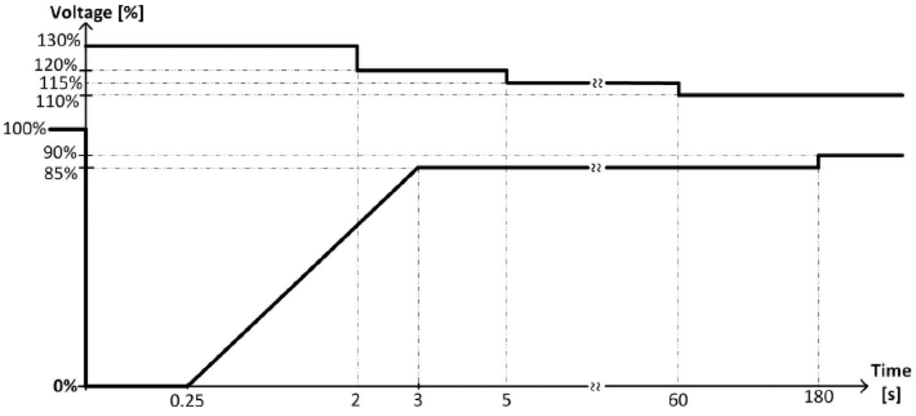

Figure 1. Voltage-time profile for offshore AC faults

3.1.3.13 OFFSHORE AC FAULT CURRENT INJECTION

Same simulation setup as for fault ride through, and the offshore AC fault current injection will be assessed.

3.1.3.14 OFFSHORE AC FAULT RECOVERY

Same simulation setup as for fault ride through, and the offshore AC fault recovery will be assessed.

3.1.3.15 FREQUENCY RESPONSE

This point refers to onshore AC frequency. Both for under-frequency and over-frequency cases, the OWF will be operated in curtailed mode, with 10% of the rated power reserved.
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.

3.1.3.16 ONSHORE POWER OSCILLATION DAMPING BEHAVIOUR

For the evaluation of power oscillation damping capabilities, various sets of sinusoidal active power references with magnitude of 0.1 pu and frequency of indicatively in the range 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 curtailed with up to 20%: 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. Subject to the TSO requirement, other damping requirements for example relating to SSTI or new local modes of invertor interaction- for example in the region of 10 Hz may be presented to the overall meshed DC connection to be satisfied either in active power control (which would require replication offshore within the WTG response) or reactive power control. The time for the damping to be initiated and to be effective across is also important- for example in GB the

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amplitude of oscillation should be possible to be attenuated with respect to a 12 seconds time constant as observed over at least 20 seconds as necessary.

3.1.4 QUESTIONNAIRE ON COMPLIANCE EVALUATION

In order to get inputs to TSO and developer best practices beyond what is described in standards and Cigré brochures, a questionnaire was prepared and distributed to the PROMOTioN project TSOs and developers. The purpose of this questionnaire is to collect information from PROMOTioN TSO and developer partners regarding the practice for compliance evaluation with special focus on HVDC systems and HVDC connected power park modules (offshore wind farms).

The questionnaire includes questions to the following topics:

1. Compliance evaluation purposes
2. Information, models and data exchange
3. Model types
4. EMT models
5. Sufficiency of understanding converter based (non-synchronous) designs
6. Project phases
7. Responsibilities
8. General requirements for HVDC connections
9. Requirements for DC connected power park modules
10. Requirements for remote-end HVDC converter stations
11. Compliance evaluation methods for HVDC connections
12. Compliance evaluation methods for power park modules
13. Compliance evaluation methods for remote-end HVDC converter stations
14. Basis for limiting compliance evaluation
15. Test methods
16. Complete system simulation and test

The complete questionnaire distributed to the TSOs is given in Annex A. The same questions were sent to the developers except question 2 and 5 which were directly targeted the TSOs.

In total, eight TSOs and developers replied to the questionnaire, but some of the responses were limited because of limited experience with HVDC connection of offshore wind power plants. The result of this questionnaire will be applied in the following sections.

3.2 PURPOSE OF COMPLIANCE EVALUATION

The scope of compliance evaluations was already described in 1.2 above. As a supplement, the answers of PROMOTioN partners to the questionnaire contributed with the following purpose of compliance evaluation:

- The purpose is demonstration of compliance first of all, e.g. of voltage, frequency control and FRT
- To see the HVDC/generator/load etc. model “in action”

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- Compliance evaluation is performed to ensure that connection requirements are met by connecting parties, and is an essential part of the quality chain; and because it is a legal obligation.
- Compliance evaluation aims at assessing
  - the adequacy of the HVDC system or HVDC connected power park modules with the needs and requirements as expressed to the suppliers in the specifications, and
  - the overall system security and stability in various situations (including the newly delivered HVDC system and other equipment in its vicinity).

3.3 GENERAL CHALLENGES OF COMPLIANCE EVALUATION

The questionnaire also asked the PROMOTioN partners to identify challenges of compliance evaluation. The following general challenges were reported:

- Some of the key challenges that would be addressed through compliance evaluation would be controller interactions, power quality and stability. The ability to test controller compliance and controller tuning is becoming more important with increased power electronics on the network.
- Follow-up on compliance after a completion certificate of overall compliance has been given – have seen cases where e.g. protection settings have been adjusted due to ad-hoc testing by the plant owner and not been set back to the as commission tested values. This may mean earlier tests and performance has been invalidated and highlights the importance of monitoring performance
- Grid codes which combine practical usability with strict and clear requirements are most welcome.
- Compliance evaluation processes are quite mature in EU markets. However, more focus in the future should be put on issues that are largely affected by generation being inverter-based rather than synchronous.
- There are no requirements available focusing the interoperability of power electronics equipment in an AC grid.
- Principally at present compliance is a mixture of self-certified demonstration of performance by the developer of the new devices, combined with modelled performance and data and model exchange as required against the relevant code of standard. These compliance processes focus on each individual commercial entity and apply ahead of the first connection. Subsequent compliance investigation may follow as a result of being informed of material modification or as a result of the experience of in-service behaviour which was unexpected at the time of connection. Without good monitoring and processes around each connection, it can become challenging to identify and enforce rectifying non-compliances when interactions are occurring.

3.4 INFORMATION, MODELS AND DATA EXCHANGE

The following specific model and data exchange challenges were reported to the questionnaire:

- Models are used for system studies, not only in the HVDC connection study.
- EU Commission Regulations are granting the TSO to state its own requirements in e.g. the HVDC regulation CR 2016/1447. Ideally, this would suffice, but there are included compromises based on experience from previous projects.

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- Vendors of HVDC, wind turbines etc. are using their own procedure in the development of the models, to which each procedure has its advantages. It is challenging to accommodate all methodologies in the NCs when stating the requirements. E.g. model can be compiled directly from source code for some vendors, whereas they have been (manually) adapted from another simulation platform from other vendors. As models are being developed from the hardware in different ways, it is not always clear how complete a model is in describing the performance of the hardware, or the limits for which that model may be used
- It is not pragmatic that individual TSOs state a specific method for the development, hence the specifics must be resolved in each project. This however has the challenge that approaches for studying individual projects may be inconsistent and may not be able to address interaction risks between projects
- Provision of an HVDC model to a third party is limited, but in response to this TSO is either having to develop their own good generic models or have gotten simplified EMT/RMS models from HVDC vendors that can be shared with third parties and may deliver limited insight into the control vulnerabilities that should be analysed within the context of the implementation of a project using that model.
- In the NCs, this TSO has stated that the protection system must be sufficiently represented. An ever-increasing need for such representation is observed, but it is a time consuming discussion with vendor during each project to actually have these included in the delivery. Protection systems are normally described by power system platforms as library generic models which are updated with relevant settings when the impact of protection is studied. This approach however is inadequate for modern digital protection approaches. This is because the physical protections algorithm for determining fault conditions is not sufficiently represented, and as such the library model and physical model will differ in their response to the fault current of power electronic devices which are not as predictable or sustained in nature as the synchronous fault injections that protection has been generally designed to detect. In general hardware in the loop integration is recommended in response to this challenge and it should be noted that in WP9 of PROMOTioN this approach has been taken. It may also be noted that WP9 of PROMOTioN was able to use this RTDS-HIL stage to develop and validate real time digital models of protection IEDs that provided good agreement with the hardware.
- For a TSO, as an owner and operator of the grid, models are a fundamental part of the system documentation and they are needed for various system studies. It is therefore necessary to make sure that models are delivered in projects as part of plant documentation. This can offer challenges as the models needed by the grid owner for overall system studies are not the same as those needed by the vendor for design studies. The current codes do not define the owners need clear enough. Both vendor and owner would probably benefit a lot from a well-defined and standardized procedure.
- It should be clearly stated in the grid code that the availability of models and data should be relevant “during the lifetime of the HVDC system”. This allows the TSO and the owners and developers to track the effect of changes to an increasingly more complex combination of active power-electronic devices, such as would occur within a meshed DC grid, but is relevant across other designs also. Across the lifetime of the HVDC system, minor changes to the HVDC control and settings could lead to significant adaptation of other control systems. It is not practical, given IP considerations to provide open models that would allow each party to understand this, but the regular updating of models to reflect changes being made allows the effect of change to be monitored and addressed pro-actively.

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- The existing grid code does not limit access to any specific type of model or data. It should be highlighted that models should be understood in its widest meaning, as some TSOs require digital models but also control replicas of the system for real time simulation.
- The only restriction comes from the suppliers' IP (Intellectual Property), which results in the provision of black boxed models and prevents from sharing any knowledge regarding the exact control implementation or internal parameters. For this reason, the relevant TSOs do not have access to internal details of the implementation of the HVDC-based system (but they have access to detailed models in black box models), and vendors cannot have access to detailed models (or replicas) of competitors' equipment (although this would be most beneficial for control tuning in case those installations are in close vicinity). Replicas enable simultaneously IP to be protected and yet control and protection not to be simplified, allowing a complete view of a device to be combined with other devices without breaching IP sensitivities. This is valuable not only to de-risk an overall project but inform the completeness of the models that more generally may be being used across parties and their accuracy.
- Those IP restrictions risk preventing the design of interoperable systems (that is, without any adverse interaction) from the design stage (ex ante). But on the other hand, it seems unlikely that such guarantee could be provided as it would limit the suppliers' IP and/or scope of delivery, which is naturally unacceptable for them. Hence, ex post adaptation of HVDC-based systems is the only applicable solution to date, as was demonstrated in a demonstration multi-vendor multi-terminal HVDC system [20]. Furthermore, this methodology also applies in multi-vendor HVDC links operating in close vicinity [21].
- The challenges to accommodate through exchange of models and data are, in the context of power electronics on the system, to carry out detailed dynamic studies. Thus the more detailed the model the more accurate a representation can be provided, with the most accurate being a replica of the hardware itself.
- To date the models exchanged have been 'black box'. This is the case from the manufacturer and TSO. The manufacturer will provide a black box to protect intellectual property, and the TSO cannot issue a detailed transmission models to manufacturers/ connecting parties without the revealing commercially sensitive data of parties connected to the transmission system.
- Additional information or data on controller operation or models would be valuable to enable the TSO to carry out more dynamic system studies.
- Unfortunately, a TSO does not expect to receive EMT and RMS models that can be shared with other manufacturers, which puts more risk at the TSOs because possible interactions cannot be properly studied by the newcomer.

3.5 PROJECT PHASES

As stated in Annex A. Questionnaire on compliance evaluation, CIGRÉ B38, CIGRÉ TB 563 and CENELEC define the following project phases

- Phase 1: Studies for planning
- Phase 2: Studies during bid process
- Phase 3: Post award – design studies
- Phase 4: Studies at the commissioning stage
- Phase 5: Studies over the operational life

In general, the TSOs and developers agree to this classification except for one developer who perform FEED studies, so there is no bid process involved. It is also stated that each project has its own life cycle and approach.

One TSO provided the following detailed information about the approach in each phase:

- Phase 1: Studies for planning
  Generic models are used at this stage, so no compliance needs to be assessed.
- Phase 2: Studies during bid process
  Simulation results may be expected from the manufacturers at this stage, but not models. Not strict compliance assessment is performed here (merely some high-level assessment that the manufacturer is able to deliver technology capable to suit our requirements).
- Phase 3: Post award – design studies
  As described in answer to Q4, different types of compliance analysis are performed:
    - Compliance of the system to the specifications: this is performed by the vendor and validated by the customer, through a series of simulations aiming to represent a variety of conditions and operation. The expected simulation variables and simulation scenarios are defined earlier in the specification document. Several iterations are required between the customer and the vendor before those compliance tests are finally validated.
    - Compliance of models delivered by the manufacturer: this is performed by the customer, by comparing the model behaviour with regards to the specifications, simulations obtained (and validated) during the FAT, and the control cubicles.
    - Compliance of the real time model and the HIL setup including control cubicles: similar to the model compliance.
- Phase 4: Studies at the commissioning stage:
  Compliance tests are mainly related to EMT models and the upgrade of the controls in the real time control replicas. This is performed by the customer.
- Phase 5: Studies over the operational life:
  Compliance tests are mainly related to EMT models and the upgrade of the controls in the real time control replicas. This is performed by the customer.

3.6 RESPONSIBILITIES

The main findings from the questionnaire are:

- The TSOs are responsible for the approval of compliance evaluation based on the inputs from the developer. The TSOs make their own simulations, see for instance -.
- The developer takes care of compliance analysis and tests. Analysis and tests could be passed on to suppliers and/or consultants depending on the scope, but responsibility eventually lies with the developer.
- Compliance is validated after commissioning, but not for all aspects, and the validation depends on the country
- In GB, Compliance evaluation responsibility sits with the National Grid Electricity System Operator in respect of Generator, HVDC and offshore connecting parties who develop their offshore networks (known as OTS DUW) must satisfy connection compliance against Grid Code. Compliance responsibility for internal HVDC connections and other supporting

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dynamic plant (not owned by those connecting) is with the relevant Transmission Owner (onshore or offshore), against the requirements of the National Electricity Transmission System Quality of Supply Standards.

- The relevant grid code CR 2016/1447 indicated that “all parties identified by the relevant TSO as relevant to each connection point, including the relevant TSO, shall contribute to the studies and shall provide all relevant data and models as reasonably required to meet the purposes of the studies. The relevant TSO shall collect this input and, where applicable, pass it on to the party responsible for the studies” (Art. 29). This wording is sufficient as it enables TSOs to have access to the relevant models for that purpose, and enables them to get support from other stakeholders if needed. In other words, it is not perceived as too bounding or restrictive for TSOs, which are responsible the overall AC and DC system stability. The nature of the studies, data and models is not detailed, which also is considered to be a safe approach as it is not restrictive.
- The compliance analysis would sit with either generator or system services (i.e. may relate to mandated areas of performance and /or those for which commercial arrangements exist)
- Compliance testing would be carried out by either generator or system services team. Dependent on each TSOs process and structure, certain tests are carried out and evaluated by system services team from the control room.
- Compliance simulations and tests are performed by the connecting party, compliance evaluation is performed by or on behalf of the TSO. The TSO monitors power quality levels in the transmission system. In GB the responsibility for power quality monitoring and specification sits primarily with the network owners.
- The developer takes care of compliance analysis and tests, while the evaluation approval lies with the system operator. Analysis and tests could be passed on to sub-suppliers and / or consultants depending on the scope, but responsibility eventually lies with the developer.
- The developer verifies compliance after commissioning but not for all aspects and it depends on the country.
- This developer does all the required analysis with the manufactures and in some cases involve consultants to verify the results provided by the manufactures.

3.7 MODEL CLASSIFICATION

CENELEC CLC/TS 50654-1:2018 distinguishes between 7 different types of models depending on the different applications. Those types are:

1. Load flow models
2. Short-circuit models
3. Protection system models
4. Insulation coordination related models
5. Electromechanical transient models
6. Electromagnetic transient models
7. Power quality models

All the questionnaires reply that this sub-division of models does not exactly reflect their models. For instance, Item 3 and 4 are normally provided as part of item 6, using full EMT model to study protection systems and insulation coordination. It is also replied that there are several types of EMT

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model as outlined in Cigré Technical Brochure 604, ‘Guide for the Development of Models for HVDC Converters in a HVDC Grid’ [22]. The level of detail in an EMT model can vary significantly and the simulation purpose could dictate the type of model used. These model types are not limited to HVDC converters.

Some TSOs are presently not using EMT models but expect that this will change in the future.

It is also noticed from one of the replies that stability models for the assessment of small-signal stability in the frequency domain are also going to be important in the future. These may be converter impedance models or more advanced models such as state-space. One TSO replies that they already request stationary harmonics models as well as harmonic stability and resonance models.

One TSO use a different classification of models, taking into account that some of the models are applicable for different types of studies, and some other types of studies are performed. From a practical point of view, the list of models which this TSO uses is:

- Load flow models
- Short-circuit and protection system models
- Electromechanical transient models (often denoted RMS models or fundamental frequency models)
- EMT models both for EMT studies and insulation coordination studies
- Models for harmonic / power quality studies

Real time models, used for HIL simulation with control cubicles provided by vendors. Those models are used for dynamic stability studies and harmonic interaction studies, to complement offline simulation performed with EMT models.

Within the GB similar models exist and have a history of use. Type 3 and type 6 models are provided for niche analysis areas and are not subject to specific frameworks of data exchange within GB.

Within the GB Grid Code, an umbrella clause in the Planning Code P.C.A.7 exists which supports the SO requesting any additional information in relation to a HVDC connection or issue to which HVDC contributes which it reasonably believes it requires additional information to support its analysis. These would be expected to be specified contractually with new connecting parties. In such cases there are challenges in supporting a changing requirement or a requirement which is not specific to a connecting user, but rather an issue affecting existing connecting parties also requiring their information, as in those cases the contractual options are less clear.

However, in addition to these areas, the TOs and ESO have also developed frequency scanning approaches to support SSTI analysis ahead of EMT assessment. The TO and ESO have also exploring enhanced RMS models, GB scale EMT models and a bridge between EMT and RMS stability assessment incorporating for example convertor PLL tracking responses
Across all of the above the current GB Grid Code currently requires that models provided need only be validated in respect of balanced 3ph behaviour; illustrating its synchronous generation heritage. Additional requirements for validation may be contractually required.

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Within GB recent work has highlighted, in agreement with other TSOs findings above that stability models for the assessment of small-signal stability in the frequency domain are also going to be important in the future, as are models incorporating protection, and the setting/ tuning of control and protection.

Suitably complete models sufficiently open to monitor the key changes ahead of commissioning and in service need to be delivered. The models supplied need to be suitable both for an EMT simulation environment and via the same or second submission an RTDS-HIL environment, enabling models/ hardware of suitable hardware to be combined effectively.

Models should be equally suitable for convertor interaction, network stability and protection function investigation. Where this drives an additional provision of replica control, obligations for the capability to update these models to maintain alignment with the installed hardware and support EMT model validation/ generate EMT models from them needs to be included in the obligation.

3.8 EMT MODELS

The questionnaire provided the following answers specifically regarding EMT models:

- EMT models are required (allowed to be provided as black box type). It is based on a compromise that the vendors will not provide the full open models that are including intellectual property right parts.
- In recent projects we are requesting not only a full (black box) model but also a “terminal” equivalent model that yields good comparison with the detailed model at the grid connection point. Such models we can e.g. share with relevant third parties.
- HVDC EMT detailed model is validated against HIL testing at the vendor’s site. Energinet is involved in the testing.
- Detailed EMT model is then used to evaluate the terminal EMT model as well as RMS model.
- Additional tests are done during the commissioning but are not critical for the model validation.
- EMT models are allowed to be black boxed, but verification of correct representation is required and shall be documented in a report. This verification shall be done before and as a preparation for factory test of control system
- There are limited processes in place to specify requirements of EMT models at present.
- We do not verify EMT models against HIL or replica controllers at present.
- The HVDC system owner shall verify the models against the results of compliance tests carried out according to CR2016/1447 [1] Title VI and a report of this verification shall be submitted to the relevant TSO. The EMT model can be validated by comparing the simulation results with EMT measurements from tests.
- EMT models for WTGs are validated against measurements on real equipment on the field. Verification against HIL or replica are valuable, but standards would be needed to define tests more clearly at a contractual level. Such standards should include a wider range of tests than those based on field measurements, taking advantage of the flexibility offered by the lab setup.
- For HVDC and FACTS, use of HIL is part of our process, but better standardization of these tests would be helpful for the industry.

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- In all projects, we acquire replica of the HVDC, MVDC, FACTS or WTGs.

One TSO provided a very detailed reply:

- As a customer, the TSO specify requirements such as the time step, the simulation software, the list of controls, expected variable outputs and interface etc. Those requirements are part of the whole specifications sent to the suppliers.
- Once the contract is awarded, the supplier in charge of design studies has to perform Factory Acceptance Tests (FAT) and deliver simulation results (including EMT simulation) for the customer to check the compliance with the specifications (especially regarding dynamic performance); this is based on a set of simulation scenarios and system conditions which are elaborated by the customer. It is very common to have several iterations between the manufacturer and the customer before actual compliance is achieved.
- Later on, once compliance of the design and control is assessed for all conditions and scenarios, the manufacturer has to deliver an EMT model which is detailed enough to reproduce the behaviour of the system under the various situations covered during the FAT. This model is black boxed, but provides access to the set of expected outputs defined in the specifications. This model is theoretically capable to reproduce identically all simulation results which have been approved during the system compliance tests (during the FAT). The customer should test a representative set of simulation scenarios to assess the performance of the EMT models and validate its compliance. This takes place no later than 6 months before the actual system commissioning.
- Control replicas are also delivered by the manufacturer 6 months before the commissioning. During that period before commercial operation, compliance tests are also performed both to check the controls hosted in the cubicles and the real time model needed for HIL simulation. Compliance is also assessed by comparing the results between HIL and EMT simulation.
- It should be highlighted that during the very last months before the commissioning and during the first year of operation, the actual system controls generally undergo a significant number of upgrades, especially based on field results and operation experience. Those changes are systematically applied to the control replicas without delay (the latter are also used to validate the control changes before that application on the actual HVDC system). However, the adaptation of detailed EMT models to match the updates takes a rather long time, and some updates may be skipped. As a consequence, the HIL setup is always the most reliable tool regarding compliance as it hosts the actual system controls with no delay. This already resulted in discrepancies between EMT simulation and real time simulation, where actual oscillations and field measurement could only be replicated with the latter [23].
- Compliance of both EMT and real time models is also assessed during the whole lifetime of the asset, as specific operation (e.g. energization and start-up sequences) and event (e.g. faults, power oscillations, harmonic interactions) experienced on-site and recorded with field measurement are compared with EMT and real time simulation.
- Finally, model compliance requires also special attention (both for EMT and real time models) during refurbishment operation, which result in either new controls, or new HV equipment (e.g. filters) or both.

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3.9 COMPLIANCE EVALUATION METHODS

In general, methods of project-based compliance assessment can be classified into three general categories [15]:

- Simulation
- Testing
- Monitoring

The benefits and of different testing methods should be taken into account:

- **Field testing** is particularly useful in checking expected settings and behaviours tested in the factory or illustrated in simulation occur in reality. Unless in one sense get lucky within the testing period and you monitor an actual real disturbance you were able to simulate, the field tests tend to be limited to open loop injections.
- The advantage of **CHIL closed loop** is that you get to see not just the first action of a control/ protection but how it evolves against an event. The problem however is that with all detailed modelling environments the process of setting up credible simulation conditions is time consuming and limits the range of conditions you can look at.
- **CHIL open loop** allows potentially a wide range of real events or simulations to be turned into control triggers but as discussed above doesn't then represent the subsequent behaviour accurately.

The right answer is to combine a blend of these methods for each of the tested performance areas, which across them cover the majority of material behaviours. If that is then teamed with good monitoring and event log capture, the compliance can be validated more broadly.

Normally, for each synchronous area, there is more than one compliance evaluation method. The selection of evaluation methods should take into consideration the following factors:

- The technology of the project,
- Experience with the particular generation technology,
- The connection point arrangement
- An assessment of the risk and costs of different testing methods,
- The availability of testing equipment and other necessary facilities.

3.10 COMPLIANCE EVALUATION OF HVDC CONNECTIONS

The general requirements to HVDC connections were listed in Table 4. From this list of requirements, the requirements for compliance evaluation of HVDC systems which are explicitly mentioned in CR 2016/1447 are listed in Table 2. To supplement this with a survey of best practices, the questionnaire asked relevant PROMOTioN partners which type of compliance evaluation you would apply for each requirement.

Four PROMOTioN partners replied to this part. Figure 2 summarizes the answers with respect to how many have answered to use compliance simulations and compliance tests for each requirement. The conclusion is that all the partners recommend to verify the vast majority of the

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requirements using compliance simulations whereas the partners tend less to verify requirements by tests than by simulations.

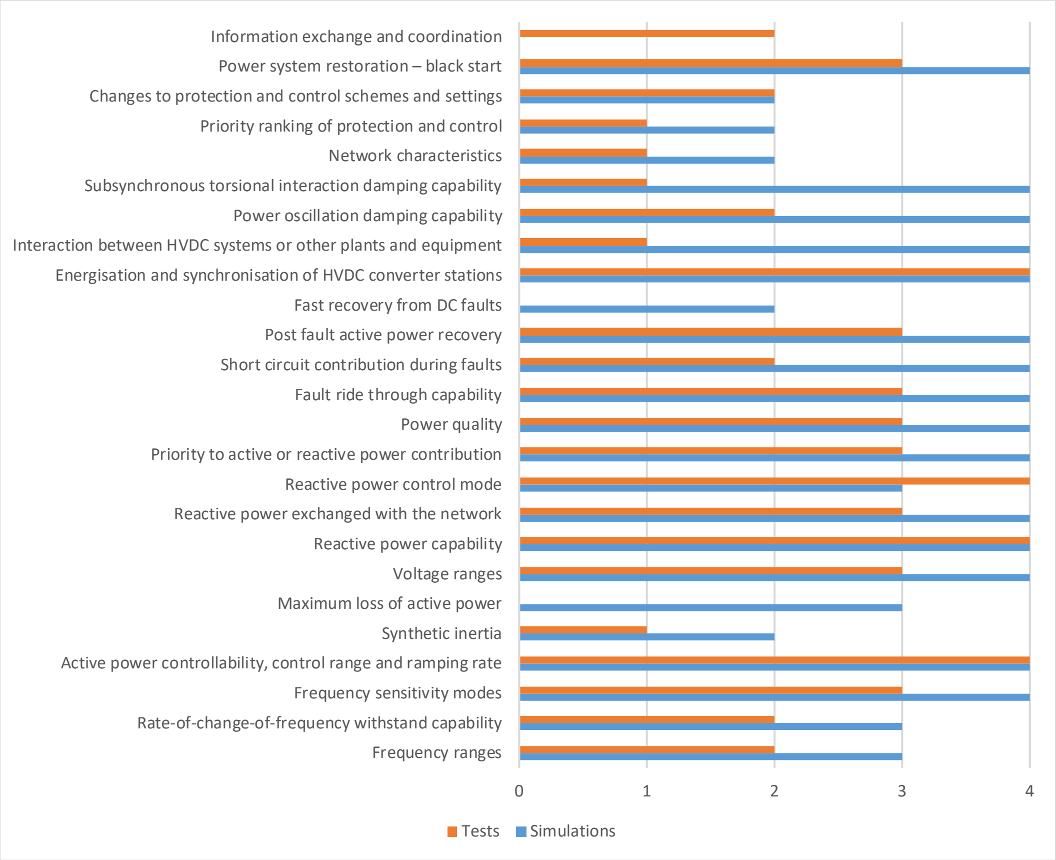

Figure 2. Number of partners (out of 4 replying) who are using compliance simulations or compliance tests for each requirement.

Figure 3 summarizes the answers with respect to distribution of simulations and tests respectively over the 5 phases. It is clear that the simulations are used most intensively in the early phases whereas tests for obvious reasons are applied post award or later.

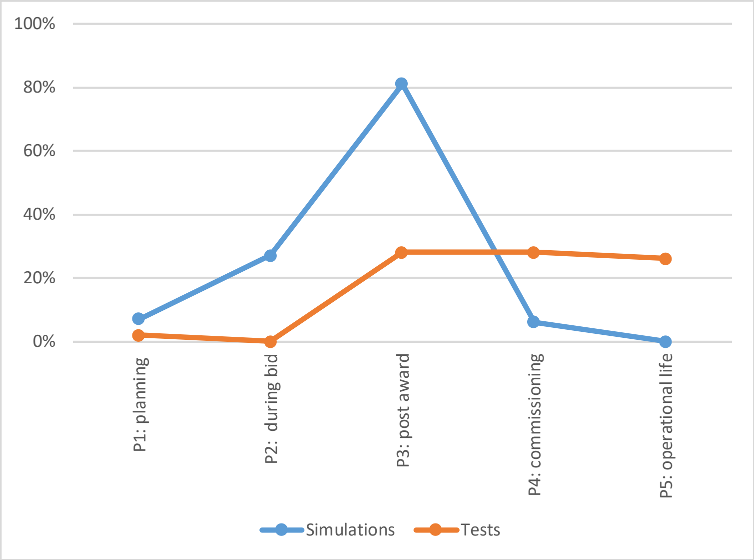

Figure 3. Fractions of requirements which are subject to compliance simulations or compliance tests during the 5 project phases

3.11 COMPLIANCE EVALUATION OF DC CONNECTED OFFSHORE WIND FARMS

Only one PROMOTioN partner provided feedback to the compliance evaluation of offshore wind farms. This partner performs compliance simulations for all the requirements and compliance tests for half of them.

Another PROMOTioN partner provided inputs about what they do for AC connected wind farms. This partner includes simulation of fault ride through test of active power control, frequency response, synthetic inertia, voltage range and reactive power control in the commissioning phase.

3.12 COMPLIANCE EVALUATION OF REMOTE-END (OFFSHORE) HVDC CONVERTER STATIONS

Because of limited experience with HVDC converter stations for connection of offshore wind power plants, only three PROMOTioN partners were able to fill in the sheet for mapping of compliance evaluation methods for the remote end HVDC stations.

Figure 4 summarizes the answers with respect to how many have answered to use compliance simulations and compliance tests for each requirement. As for the onshore HVDC connections in 3.10, the conclusion is that all the partners verify the vast majority of the requirements using compliance simulations and lesser requirements are tested.

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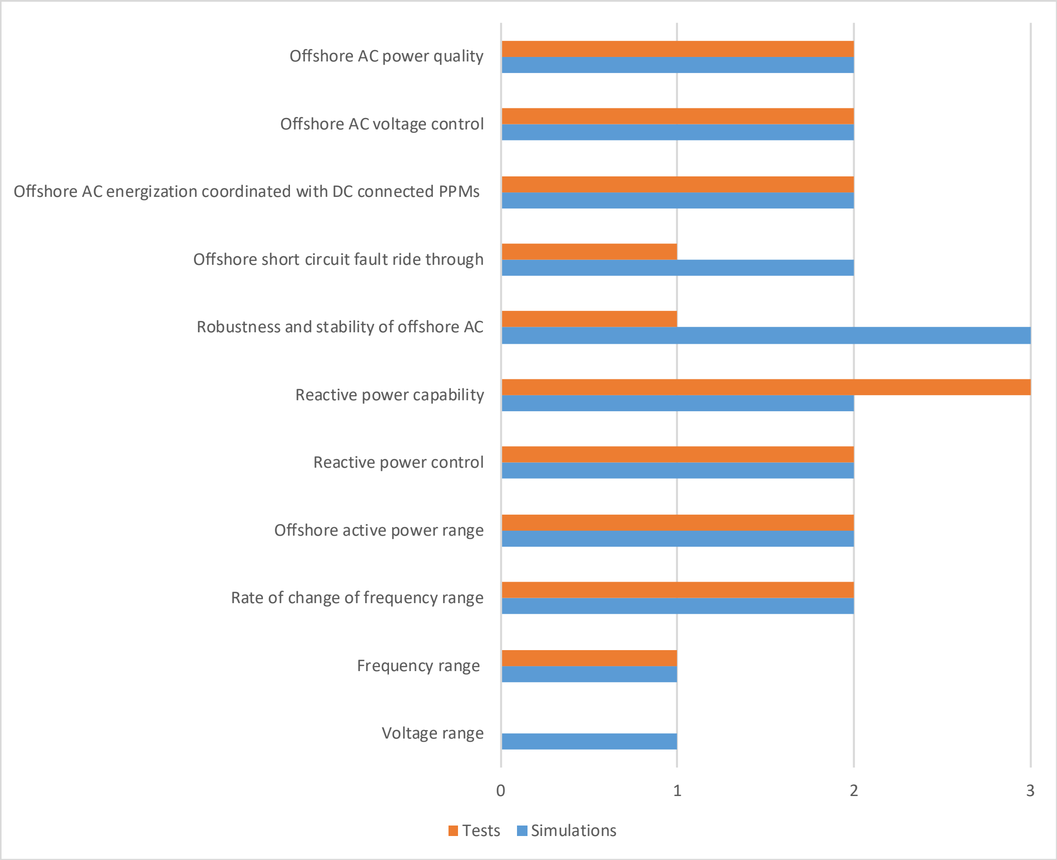

Figure 4. Number of partners (out of 3 replying) who are using compliance simulations or compliance tests for each requirement.

Figure 5 summarizes the answers with respect to distribution of simulations and tests respectively over the 5 phases. As for the onshore HVDC connections in 3.10, it is clear that the simulations are used most intensively in the early phases whereas tests are applied post award or later.

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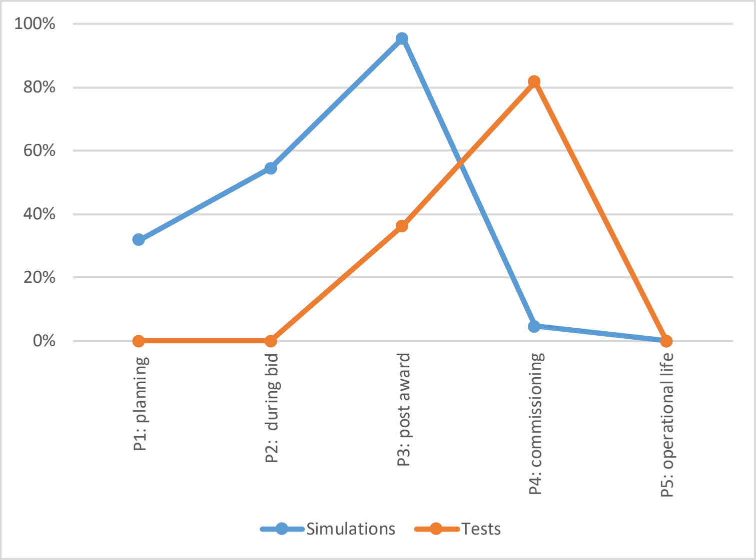

Figure 5. Fractions of requirements which are subject to compliance simulations or compliance tests during the 5 project phases.

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4 GAP ANALYSIS

Section 4 provides a gap analysis of those areas where existing grid codes, standards and processes require complementing or adapting to respond to the findings of the earlier PROMOTioN work and to the emerging areas of best practice concern being identified. Options for addressing these gaps are further evaluated.

4.1 INFORMATION, MODELS AND DATA EXCHANGE

Offshore a higher degree of co-ordination will be necessary as specifically defined relative to the control strategies adopted, requiring sharing of models of WTG and HVDC anticipated performance, settings and timings of control and protection actions, and monitoring supporting overall network control and network state.

As stated in 2.2.3, there are only IEC standards for wind power models, and those models are fundamental frequency models. However, as summarized in 3.7, several other model types like EMT models, harmonic models, real time models and controller replica are used, and it is recommended to harmonize those models in standards, not necessarily by specifying generic models as in IEC 61400-27-1 because it is not realistic to agree on such models. But it is recommended to initiate work on standard functional specifications for the models and standard procedures for validating the models.

As identified in 3.7, models for the assessment of small-signal stability in the frequency domain are also going to be important in the future. These may be converter impedance models or more advanced models such as state-space. Such models are an important source to understand interoperability between converters in the system. Cigré brochures and the technical report IEC 61400-21-3 should be the starting point for this, but it is recommended to initiate work in IEC on such small signal models. This work should include specifications for the models, as well as procedures for validation of EMT models. The existing standard test procedures for harmonics and interharmonics also need to be extended in order to provide useful inputs to harmonic model validation. This will also require new standard test methods which are intended to be used for model validation

4.2 SUFFICIENCY OF CURRENT GRID CODES AND STANDARDS

A number of gaps in current grid codes and standards have been identified through the questionnaire and other discussions:

- There are no requirements available focusing on the interoperability of power electronics equipment in an AC grid
- Compliance evaluation processes are quite mature in EU markets where we operate. However, more focus in the future should be put on issues that are largely affected by generation being inverter-based rather than synchronous.
- Grid codes which combine practical usability with strict and clear requirements are most welcome.

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- For an offshore synchronous area, the starting point may be to think about imposing the same frequency and frequency regulation requirements on the offshore system, but that may not be the most feasible and economic solution. Instead, the starting point should be that whatever the permitted frequency variation refers to the offshore frequency, this should not compromise frequency response or other capabilities such as resilience to faults of the whole HVDC system as it is observed onshore.
- A further area of robustness consideration exists as future multi terminal HVDC links may form and support “loop flows” across an onshore network. In this role, the specification of the HVDC connections themselves may be required to be more robust than that of the generation they support, such that – in the condition of an extreme event – their collective loss at the point in time where generation may begin to disconnect does not further exacerbate the effect of the extreme event.
- The term synthetic inertia sits in CR2016/1447 (HVDC) and CR 2016/631 (RfG) and other grid codes. However, there is no agreed definition of this concept which also makes it challenging to verify compliance.
- Whilst limited standardisation exists to define the nature of the design of the offshore AC island, its control strategies and specification. The existing onshore requirements have consequences that for progressively larger and more complex offshore design lead unavoidably towards particular areas of requirement which may benefit from future standardisation.

A number of respondents indicated that they did not believe the current standards are sufficient. There are a number of reasons for this:

- *Self-certification* where performance requires demonstration- it is not sufficient for this to simply be provided via a report or statement given that report or statement will be founded upon assumptions/ network conditions which are no longer stable over the life of the project.
- From a commercial confidentiality perspective, it is often not possible for one projects compliance statement to take into account the considerations of other connecting project or TSO or other network sourced infrastructure design existing or under development that may influence their performance.
- In addition to the analysis, statements which “tick box” compliance should be avoided. Sufficient model data exchange to allow that performance to be replicated in studies by the associated TSO and inform its broader analysis should form a basis for the future standards.
- The criteria for exchange of models may not purely be a matter or scale. Definitions for interaction this based on terms such as SCR ESCR/WSCR, or MIIF could be used in the future in addition to the bands of project scale as described within CR 2016/1447.
- The criteria being used to evaluate performance is currently based on a series of paradigms based on RMS modelling and a limited suite of power quality related measures and plant specific analysis such as insulation co-ordination related to transient aspects of network performance. The basis of current convertor technology is rather the performance of control systems influencing the system typically in the 0->200Hz bandwidth based on sub cycle scanning of the AC waveform informing control action. The nature of control instabilities are different, ranging from impacts on protection from the injected current responses of the convertor in angle and magnitude as measured across the fault and its clearance, super-positions of current control loop tracking of the convertors’ injection with classical instability phenomena, issues of direct control system compatibility and avoidance

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of conditions of instability and hunting, transient sensitivity to control approach based on limits built into the philosophy (e.g. instantaneous over/ under voltage and frequency, multiple faults etc.), and small signal instabilities of the convertors individually or in combination. The models to be exchanged need to support the management of these challenges, not just conventional synchronous generation & network considerations of the past.

- Modelled behaviour is frequently indicative, and can be based on generic illustrative models whose precise control tuning and control concept can vary significantly between point of outline design - conclusion of detailed design - conclusion of FAT- commissioning. Either the model, complete with total relevant protection and control for all purposes for which it is needed should be updated and validated against each stage, including in-service or physical hardware replication should also be provided at later stages of the project life cycle to support particular areas of study and project lifetime management, and/or allow the EMT models provided to concentrate on being accurate over a more limited scope of studies.
- Given the developing understanding of convertor related instabilities and other considerations, the approach of assuming that data provided is accurate and fit for purpose based on initial data exchanges up and until the point of connection is insufficient, the accuracy of the data exchange and the areas of data exchange need to be live throughout the whole project life cycle. In common to approaches commonly used for synchronous generation ahead of a manufacturer specific solution emerging, reference models should be agreed upon to define the envelopes of acceptable behaviour for the manufacturer specific design in such a manner that it does not compromise the challenges of manufacture IP.
- In managing manufacturer IP whilst it is acceptable for model structure and control to be black boxed, it is not acceptable for the impact of control tuning made across a solutions lifecycle to be black boxed. Control tuning whilst the province of the manufacturer to analyse and recommend- should be visible to the TSO such that the consequences of change can be understood. There are always trade-offs in efficiency and instability, which the TSOs may have specific needs in relation to.
- Rather than have a user inform a TSO as to whether a modification is considered material or not to trigger further investigation, there should be a general obligation to keep the TSO model up-to-date with the project. It is for the TSO then to inform the project of the materiality of that change as to whether it may trigger further work.

It is important to note that some requirements (in particular for fault contribution and reactive power control) should be aligned with the actual need of the offshore AC network as well as the onshore network- rather than transferred directly from those for onshore AC networks.

Recovery after faults is also important, as HVDC converters cannot be overloaded by possible power overshoots after fault clearance, and need to limit/mitigate TOV which can result.

Requirements for load-rejection following remote-end HVDC converter blocking should be developed. It should be noted GB has a minimum islanding criterion which can be used for this purpose. (Grid Code CP.A.3.6 (page 27 onwards of the CP)). This criterion assumes an inertia which needs to be substituted by intertripping, conditional convertor ramping and transient frequency deviation withstand tolerances offshore in the absence of offshore AC island inertia.

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Requirements for DC connected power park modules (the offshore wind farms) should be expanded:

- Active power control and frequency stability requirements
    - Maximum power point tracking
    - Operational frequency range
    - Operational rate of change of frequency/ conditional regulation to transient movement
    - Active power independency of frequency
    - Collective active power control in response to onshore frequency disturbance (i.e. either coordinated HVDC ramp to regulate offshore frequency during WTG response relative to a signal onshore- offshore or control of HVDC to drive sympathetic offshore WTG response either in response to frequency or voltage)
    - An offshore AC power island frequency regulation strategy relevant to fast ramping to support offshore WTG loss/ imbalance as well as regulating offshore frequency during periods of onshore FRT, frequency response, widespread voltage depression to a remote fault etc.
    - Frequency response
    - Inertia via VSM controls or fast ramping to limit extent of frequency deviation/ duration of frequency deviation
    - Controls on WTG capable of stabilizing voltage and associated control measurement across normal operation and operation across fault/ frequency response
    - DC voltage response
- Reactive power and voltage requirements
    - Dynamic U-Q control to onshore grid contradicts with above voltage control if offshore end is stiff voltage source in grid forming control mode- auxiliary devices may require consideration or an alternative fast staggered (step-wise) Mvar control in response to voltage deviation
    - Voltage range on and offshore
    - Mitigation and resilience to TOV on and offshore
    - Reactive power control – balance between WTG and HVDC and overall strategy stated and subject to robustness checks.
    - Reactive power capability
- Robustness and control during short circuit faults
    - Offshore AC FRT
    - Post fault recovery
    - Fast fault current during offshore faults
    - DC FRT
    - Onshore AC FRT
- Power oscillation damping
- SSTI if type 3 (doubly-fed) or type 1 (induction generator) variants are employed offshore (for completeness)
- Offshore AC energization coordinated with HVDC offshore converter
- Auto-synchronous (grid forming) operation
- Power quality- virtual resistance control may be required across WTG and/or HVDC link

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- Black start- a different control philosophy may be required against which the specific behaviours and performance needs to meet onshore grid code above are different to normal operation. This control approach will need to transition back to the normal one against some criteria at some stage (i.e. offshore HVDC end grid forming- that would need to come from WTG in this situation).

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5 RECOMMENDATIONS

A major takeaway from this study on compliance evaluation is that compliance evaluations relies on exchange of models and compliance test results between TSOs, project developers / owners and manufacturers of components including HVDC converter systems and wind turbines. With this in mind, the following recommendations are provided:

- **Model exchange.** At each stage of the project it should be possible to exchange a suitably complete EMT model of the components of the meshed DC grid. These models may not be wholly open, but should include relevant
  - Tuning parameters identified such that the sensitivity of any subsequent changes can be identified and understood.
  - Controls and protections which are relevant to the behaviour of the model.
  - A user guide describing the purpose and limitations of the model should be provided.
  - Any compiled or discrete code should be provided and maintained across updates to the EMT platform.
  - A suitably derived operating point dependant frequency dependent impedance model of the aspects of the AC system facing elements of the design should be provided to support small signal analysis and the informing of subsequent stages of EMT analysis.
  - Models in EMT should be of a common format (simulation format, version, range of compilers supported etc) as defined by the TSO.
  - The model provider should be obliged to maintain the model compliance with the TSOs analysis platform across the life of that model
  - EMT simulation models should be complemented from the point of FATs onwards with similarly maintained real time models against a format defined by the TO. The real time models should be wholly complete in protection and control function to both AC and DC facing analysis, and maintained across modification in real time and subsequent in-service operation, alternately where more practical and appropriate to do so, a physical replica control installed within an RTDS-HIL environment may substitute this requirement, and may offer additional advantages in the management of the DC grid and the training of the personnel associated with its operation.

- **Compliance tests** at each stage of the project, simulation / test should be additionally undertaken to:
  - Identify for a range of potential DC fault locations, that the DC protection is capable of suitably identifying the fault and discriminate its location & characteristic. This shall require a series of fault impedances being introduced into the DC fault study which encompasses suitable AC system models of the onshore DC system and the offshore WTG, together with a suitably detailed DC cable model and an accurate convertor model including associated internal topology and protection.
  - Additional WTG analysis examining the impact of a wider range of frequency variation, increased df/dt and response to transient over voltage. Additional consideration of harmonic burst conditions associated with the rapid ramping

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associated with the WTG and convertor may give rise to a requirement for virtual resistance controls to be developed within either the HVDC convertor and/or the WTG.

- Tests specific to the overall control concept of the DC meshed system for example in providing frequency response, power oscillation damping, and FRT upon the onshore system should be supported via a composite system testing environment supported by the TSO to ensure at key milestones of project delivery all salient aspects of the design work together cohesively to deliver these strategies. Standardisation of compliance tests presupposes that there are generally accepted and detailed functional requirements in grid codes. At this stage, the TSOs have limited experience with DC meshed grids, and naturally the meshed grids are not understood as deeply as the AC grids. However, on a project-by-project basis, the control concept should be clearly stated across all parties contributing to the meshed DC design and considered in their individual specification and testing. Following the evolution of meshed DC grids further opportunity should be taken to consider standardised control concepts and associated tests.

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Annex A. Questionnaire on compliance evaluation

A.1. Introduction

The purpose of this questionnaire is to collect information from PROMOTioN TSO partners regarding the practice for compliance evaluation with special focus on HVDC systems and HVDC connected power park modules (offshore wind farms). The answers will be referred to in the public deliverable D11.5 on compliance evaluation, but the individual TSO answers will be anonymized.

A.2. Questionnaire

This questionnaire includes 13 topics which are considered relevant for compliance evaluation. Each topic includes a question (Q) and a space for your answer (A).

1. Compliance evaluation purposes

Q: What are the challenges you aim to accommodate by compliance evaluation? Do you believe current codes are sufficient in compliance evaluation? Please identify the areas where you believe additional compliance evaluation would be valuable and why?

A:

2. Information, models and data exchange

Q: What are the challenges you aim to accommodate by exchange of models, data and other information? Which models and data are exchanged? Do you believe current codes are sufficient in model and data acquisition and exchange? Please identify the areas where you believe additional information, models and data exchange would be valuable and why?

A:

3. Model types

CENELEC CLC/TS 50654-1:2018 distinguishes between 7 different types of models depending on the different applications. Those types are:

1. Load flow models
2. Short-circuit models
3. Protection system models
4. Insulation coordination related models
5. Electromechanical transient models
6. Electromagnetic transient models
7. Power quality models

Q: Do you classify your models the same way or do you use lesser or more models for those 7 different applications?

A:

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4. EMT models

Q: To what extent are the requirements of EMT models captured in your processes? Do you allow such models to be black boxed? If so to what extent and why? To what extent are EMT models verified against hardware in the loop analysis and/or replica control behavior across your process?

A:

5. Sufficiency of understanding converter based (non-synchronous) designs

Q: Do you feel you have a complete understanding of the controls and protection present in non-synchronous designs that would potentially influence performance – if so, how is this achieved within your code? If not, how do you gain confidence that your code and processes sufficiently consider all material risks to onshore network performance?

A:

6. Project phases

CIGRÉ B38, CIGRÉ TB 563 and CENELEC define the following project phases

- Phase 1: Studies for planning
- Phase 2: Studies during bid process
- Phase 3: Post award – design studies
- Phase 4: Studies at the commissioning stage
- Phase 5: Studies over the operational life

Q: Please confirm if you would agree to these definitions, or if you would apply others or further compress the stages- please identify your definitions and why you use them.

A:

7. Responsibilities

Q: At each phase, who does what?

- Who does the compliance analysis?
- Who does the compliance tests?
- Who approves compliance evaluation?
- Do you verify compliance after commissioning?

A:

8. General requirements for HVDC connections

Q: Based on CR 2016/1447 and PROMOTioN D1.7, we have identified the general requirements for HVDC connections listed below. Those requirements refer to the AC side of the onshore HVDC converter station. Are those requirements appropriate, or is something missing or irrelevant?

A:

General requirements for HVDC connections:

- Requirements for active power control and frequency support
    - Frequency ranges
    - Rate-of-change-of-frequency withstand capability

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    - Frequency sensitivity modes
    - Active power controllability, control range and ramping rate
    - Synthetic inertia
    - Maximum loss of active power
- Requirements for reactive power control and voltage support
    - Voltage ranges
    - Reactive power capability
    - Reactive power exchanged with the network
    - Reactive power control mode
    - Priority to active or reactive power contribution
    - Power quality
- Requirements for fault ride through capability
    - Fault ride through capability
    - Short circuit contribution during faults
    - Post fault active power recovery
    - Fast recovery from DC faults
- Requirements for control
    - Energisation and 45ynchronization of HVDC converter stations
    - Interaction between HVDC systems or other plants and equipment
    - Power oscillation damping capability
    - Subsynchronous torsional interaction damping capability
    - Network characteristics
- Requirements for protection devices and settings
    - Priority ranking of protection and control
    - Changes to protection and control schemes and settings
- Requirements for power system restoration
    - Black start
- Information exchange and coordination
    - Operational requirements

9. Requirements for DC connected power park modules

Q: Based on CR 2016/1447 and PROMOTioN D1.7, we have identified the requirements for DC connected power park modules listed below. Note that the frequency response, synthetic inertia and power oscillation damping requirements refer to the AC side of the onshore HVDC converter station, assuming that onshore frequency and other relevant onshore measurements are communicated to the wind farm and the wind farm power is controlled accordingly. Are those requirements appropriate, or is something missing or irrelevant?

A:

Requirements for DC connected power park modules (the offshore wind farms):

- Active power control and frequency stability requirements
    - Maximum power point tracking
    - Operational frequency range
    - Operational rate of change of frequency
    - Active power independency of frequency
    - Active power control
    - Frequency response

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    - Synthetic inertia
    - DC voltage response
- Reactive power and voltage requirements
    - Voltage range
    - Reactive power control
    - Reactive power capability
- Robustness and control during short circuit faults
    - Offshore AC fault ride through
    - Post fault recovery
    - Fast fault current during offshore faults
    - DC fault ride through
    - Onshore AC fault ride through
- Power oscillation damping
- Offshore AC energization coordinated with HVDC offshore converter
- Auto-synchronous (grid forming) operation
- Power quality

10. Requirements for remote-end HVDC converter stations

Q: Based on CR 2016/1447 and PROMOTioN D1.7, we have identified the requirements for remote-end HVDC converter stations, i.e. the offshore HVDC converter station. Those requirements refer to the AC side of the offshore HVDC converter station. Are those requirements appropriate, or is something missing or irrelevant?

A:

Requirements for remote-end HVDC converter stations:

Note that (as stated in PROMOTioN D1.7), for some converter station technologies, some of those requirements will not be possible to meet without assistance of other technologies, and for some technologies some requirements will simply not be relevant. PROMOTioN D1.7 considers VSC based converter stations as well as Diode Rectifier (DRU) based converter stations. Since the DRU is a passive converter, it cannot contribute to the control.

- Operational ranges
    - Voltage range
    - Frequency range
    - Rate of change of frequency
    - Offshore active power
- Reactive power requirements
    - Reactive power control
    - Reactive power capability
- Robustness and stability of offshore AC
- Offshore short circuit fault ride through
- Offshore AC energization coordinated with DC connected PPMs
- Offshore AC voltage control
- Offshore AC power quality

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11. Compliance evaluation methods for HVDC connections

Q: Referring to the requirements for HVDC connections (at onshore HVDC converter station) from 8 above, *fill in the yellow fields* telling which type of compliance evaluation you would apply in each of the 5 project phases (see 6 above). Note that CR 2016/1447 specifies compliance tests (T) and compliance simulations (S) according to the second column. You can use the following abbreviations for compliance evaluation methods or define own:

- T: compliance test
- S: compliance simulation
- C: certification
- O: other
- blank: none

A:

Requirement	CR 2016/1447	P1: planning	P2: during bid	P3: post award	P4: commissioning	P5: operational life
Frequency ranges						
Rate-of-change-of-frequency withstand capability						
Frequency sensitivity modes	T					
Active power controllability, control range and ramping rate	TS					
Synthetic inertia						
Maximum loss of active power						
Voltage ranges						
Reactive power capability	TS					
Reactive power exchanged with the network						
Reactive power control mode	T					
Priority to active or reactive power contribution						
Power quality						
Fault ride through capability	S					
Short circuit contribution during faults	S					
Post fault active power recovery	S					
Fast recovery from DC faults						
Energisation and synchronisation of HVDC converter stations						
Interaction between HVDC systems or other plants and equipment						
Power oscillation damping capability	S					
Subsynchronous torsional interaction damping capability						
Network characteristics						
Priority ranking of protection and control						
Changes to protection and control schemes and settings						

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Power system restoration – black start	T					
Information exchange and coordination						

12. Compliance evaluation methods for power park modules

Q: Referring to the requirements for DC connected power park modules (the offshore wind farms) from 9 above, *fill in the yellow fields* telling which type of compliance evaluation you would apply in each of the 5 project phases (see 6 above). Note that CR 2016/1447 specifies compliance tests (T) and compliance simulations (S) according to the second column. You can use the following abbreviations for compliance evaluation methods or define own:

- T: compliance test
- S: compliance simulation
- C: certification
- O: other
- blank: none

A:

Requirement	CR 2016/1447	P1: planning	P2: during bid	P3: post award	P4: commissioning	P5: operational life
Maximum power point tracking						
Operational frequency range						
Operational rate of change of frequency						
Active power independency of frequency						
Active power control	T					
Frequency response	T					
Synthetic inertia						
DC voltage response						
Voltage range						
Reactive power control	T					
Reactive power capability	TS					
Offshore AC fault ride through	S					
Post fault recovery	S					
Fast fault current during offshore faults	S					
DC fault ride through						
Onshore AC fault ride through						
Power oscillation damping	S					
Offshore AC energization						
Auto-synchronous (grid forming) operation						

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Power quality		🟨	🟨	🟨	🟨	🟨

13. Compliance evaluation methods for remote-end HVDC converter stations

Q: Referring to the requirements for remote-end (offshore) HVDC converter stations from 10 above, *fill in the yellow fields* telling which type of compliance evaluation you would apply in each of the 5 project phases (see 6 above). Note that CR 2016/1447 specifies compliance tests (T) and compliance simulations (S) according to the second column. You can use the following abbreviations for compliance evaluation methods or define own:

- T: compliance test
- S: compliance simulation
- C: certification
- O: other
- blank: none

A:

Requirement	CR 2016/1447	P1: planning	P2: during bid	P3: post award	P4: commissioning	P5: operational life
Voltage range						
Frequency range						
Rate of change of frequency range						
Offshore active power range						
Reactive power control						
Reactive power capability	TS					
Robustness and stability of offshore AC						
Offshore short circuit fault ride through						
Offshore AC energization coordinated with DC connected PPMs						
Offshore AC voltage control						
Offshore AC power quality						

14. Basis for limiting compliance evaluation

Q: On what basis do you limit the tests, simulations and other compliance evaluation you do?

A:

15. Test methods

Q: What is the balance between full system tests, component tests, factory acceptance tests and hardware in the loop tests?

A:

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16. Complete system simulation and test

Q: Where composite dynamic devices are presented in a user's connection design (for example SVCs or STATCOMs together with offshore wind turbines within HVAC designs, or HVDC connected offshore wind designs), at what stages above is the complete performance of the overall solution simulated and tested, and why?

A:

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