European Network of
Transmission System Operators
for Electricity

Network Code for HVDC Connections and DC-connected Power Park Modules

Explanatory Note

30 April 2014

Disclaimer: This document is not legally binding. It only aims at clarifying the content of the Draft Network Code for HVDC Connections and DC-connected Power Park Modules. This document is not supplementing the final network code nor can be used as a substitute to it.

Content

1. INTRODUCTION

1.1. Aim of this document

The Network Codes (NCs) for grid connection establish required capabilities of performance defined at the connection points, but (as with all NCs) do not contain the motivation for the requirements. The NCs provide the "whats", but not the "whys". This Explanatory Note (EN) for HVDC is one of several supporting documents which together make up ENTSO-E's "whys" for this particular NC. The aim of this EN is to explain the challenges that are addressed by the NC HVDC. With this document ENTSO-E is also sharing feedback received from stakeholders.

This EN provides a summary of the NC HVDC supporting documents and endeavours to guide the readers to access other supporting documents for further in-depth information of specific interest. This EN is organised in sections which deal with the material in the following manner:

1. The aim of the NC HVDC, the broader task of the series of NCs with the context for their development and the application and challenges associated with HVDC technology;
2. Stakeholder interactions undertaken through public consultations, workshops and user group meetings;
3. How the proposed code is structured, what are the limits of its scope and classification of its requirements? The relation with various existing European practices is described, together with the justification for possible deviations and the associated cost implications;
4. The main considerations associated with the specific requirements related to frequency management, voltage management, robustness, control, protection, system restoration, DC-connected Power Park Modules, information exchange and compliance;
5. Conclusions;
6. References to relevant documents;
7. Abbreviations and aligned definitions used.

1.2. Why develop a NC HVDC?

The formal reason

The rapid increase of renewable energy sources (RES), the implementation of smart grids, and the efficient functioning of the internal electricity market while ensuring system security will all lead to massive changes to the electrical power system as we know it today. This will require a new framework to cope with these challenges and all participants of the energy market will have to face significant changes.

The connection Network Codes define the minimum performance capabilities in context of cross border implications for all classes of new grid connections. The capabilities contribute to the overall objective of maintaining the existing high level of security of electricity supply in Europe.

One of the changes is an expected rapid increase in HVDC applications. In this context, ENTSO-E elaborates the "Network Code for HVDC Connections and DC-Connected Power Park Modules". This Network Code is referred to as the "NC HVDC". The NC HVDC is based on ACER's Framework Guidelines on Electricity Grid Connections (FWGL) [1]. The NC HVDC is a key part of the ENTSO-E annual work programmes 2013 to 2014 [2] and responds to the EC's mandate to develop this Network Code for submission to ACER by 1 May 2014.

This planned NC HVDC [3] will be the third connection code in line with the FWGL [1]. The two connection codes preceding the NC HVDC are the "Requirements for Grid Connection Applicable to all

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Generators" (RfG) and "Network Code on Demand Connection" (DCC). A fourth network code on Connection Procedures, also founded guided by the same FWGL [1], may follow at a later date still.

Why HVDC?

Efficient and reliable power transmission grids are a prerequisite to support EU energy targets and to achieve the political goals of a low-carbon energy system. The way the power system is designed and operated must be consistent with these paramount targets. This poses new challenges for TSOs and all grid users. The future power system must:

- Facilitate the integration of RES, partially located far away from load centres (e.g. offshore wind parks)
- Manage greatly increased cross-border power flows in a strengthened European energy market.
- Achieve both targets with minimal impact on environment, at the lowest societal cost.

An efficient technology choice to achieve these targets is based on economic and technical performance. In general the choice is between AC and DC transmission. A comparison between these two technologies leads to the following areas of application for DC transmission:

- Crossing long distances: Long–distance, bulk power transmission is often more economic by HVDC technology.
- Meet environmental constraints: The corridor needed to transmit a certain amount of power is considerably less for HVDC compared to AC paths.
- Overhead line versus cable: The charging current of AC cables requires distributed reactive power compensation. .For long cables (e.g. subsea cables) AC may not be economic compared to a DC solution beyond a certain length.
- Asynchronous interconnection: AC systems operating at different frequencies or using independent frequency control systems can still be coupled by HVDC technology to allow for power transfer.
- Control and stabilization of power flows: HVDC systems in an integrated power system may through their excellent control capability enhance the overall system performance and system security.

In view of the above mentioned challenges and requirements for a future power system, DC transmission is expected to become increasingly prevalent. HVDC development including DC-connection of PPMs (mostly offshore) is considered of major importance for the future development of the European Network. European market integration is expected to be facilitated by major increases in numbers and capacity of HVDC interconnectors, of embedded HVDC links and of DC-connected PPMs. Section 3.4 gives the numbers of existing installations of these three use cases of HVDC technology, the level of activity expected by ENTSO-E's member TSOs by 2025 and again by 2035.

For a range of perspectives on the importance of HVDC in the future, see

- 8 March 2011 the European Commission issued "A Roadmap for moving to a competitive low carbon economy in 2050" [4].

- In March 2014 Greenpeace released the publication "powE[R]2030. A European grid for 3 / 4 renewable electricity by 2030". [5] This report advocates few, but very large (e.g. 10GW10 GW) HVDC corridors to link the main parts of the European power systems in a RES dominated vision of the future. In March 2014 Friends of the SuperGrid released the publication "Supergrid preparatory phase: review of existing studies and recommendations to move forwards", [6]

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- ENTSO-E's own Ten Year Network Development Plan, combining the expert views and detailed system knowledge of all European TSOs, indicated in its last report (2012) also an expectation of about 12.000km of additional HVDC lines planned for the coming years.

HVDC and its role for "smarter" transmission

Modern HVDC transmission systems offer advanced performance, which can include independent control of active and reactive power. The first HVDC connected wind farms in the North Sea demonstrate that present HVDC connections are able to control the frequency of islanded AC networks and to supply weak networks. If well planned and designed, these features offer remarkable flexibility:

- Future fast changes in power flows resulting from the change in generation pattern could be handled more securely by the operator.
- Additional reactive power (available inherently from VSC technology) would stabilise the voltage profile.
- The controllable active power flow can be used to minimise wider system losses and to overcome bottlenecks by distributing the power flow in an optimal way, making the fullest use of all circuits.
- In emergency situations, e.g. partial black outs or islanding of networks, the HVDC scheme could increase stability margins or reenergize or stabilize an island.

1.3. European Network Code Development

The proposed NC HVDC covers a specific area in a wider portfolio of network codes on electricity. The NC HVDC is the ninth code developed by ENTSO-E[1]. Key messages on the need for European wide network codes and an overview of how these interact, are linked with other European energy roadmaps, and benefit European energy consumers, are given in the ENTSO-E paper "European Network Code Development: The importance of network codes in delivering a secure, competitive and low carbon European electricity market" [7]. This section sketches some of the messages most relevant for the NC HVDC.

What are the network codes?

Network Codes are sets of rules which apply to one or more part of the electricity sector. The need for them was identified during the course of developing the Third legislative package and Regulation (EC) 714/2009 sets out the areas in which network codes will be developed and a process for developing them.

Europe's energy policy objectives

Europe's trio of energy policy goals – ensuring security of supply, promoting the decarbonisation of the energy sector and creating competitive, liquid markets which benefit consumers – is well known.

More interconnected networks and markets: The electricity system is becoming increasingly interconnected and the electricity market is becoming much more pan-European. This provides opportunities for generators to sell into different markets, based on price signals, and gives consumers a greater choice over who they buy energy from.

Increases in cross-border flows: A natural consequence of bigger markets and the siting of fluctuating generation further away from the consumption centres are much greater levels of cross-border and long-distance power flows. These flows require careful management by TSOs and require greater coordination

[1] https://www.entsoe.eu/major-projects/network-code-development/

between grid operators in planning infrastructure developments, in designing markets and in operating the system – given the significant influence such flows can have on the operation of the system in real time.

A changing role for network users: The changes in generation portfolio and operational challenges discussed above are creating a change in the role of network users. It is becoming increasingly important that all types of users (i.e. generation, demand, distribution networks, and interconnections) play an active role in providing the capabilities and services which are needed to maintain the security of the pan European transmission system.

Creating stronger, more robust and smarter networks: Without a robust transmission system, none of the trio of energy policy objectives will be achieved. Europe's networks will need to change significantly in the coming years, with much greater levels of interconnection and the probable extension of networks offshore, using a greater proportion of HVDC technology. They will also need to adapt to much more active distribution networks and to greater customer participation.

Ensuring closer cooperation between TSOs: TSOs are working more and more closely together (building on a tradition of doing so for over 60 years) to make better use of existing assets and build on the very high levels of security of supply enjoyed to date. More advanced and coordinated operational planning procedures are being implemented by many TSOs through multi TSO coordination initiatives (and through regional market coupling initiatives). TSOs are also developing systems for coordinating balancing and remedial actions where system issues exist and enhancing real time data exchange (e.g. via the ENTSO-E Awareness System).

The network codes under development: Investment decisions taken now will affect the power system for the next decades. The European energy system of 2020 is being built today and the foundations of the European energy system of 2050 are being conceived. As such, there is a need to make sure that all users are aware of the capabilities which their facilities will be required to provide – recognising both the need for all parties to make a contribution to security of supply and the high cost of imposing requirements retrospectively. The grid connection codes therefore seek to set proportionate connection requirements for all parties connecting to transmission networks (including generators, demand customers and HVDC connections). A stable set of connection rules also provides a framework within which operational and market rules can be developed.

The system operation network codes will provide a solid basis for coordinated and secure real time system operation across Europe while market related network codes aim at creating a relatively simple set of market rules which can promote effective competition, minimise risk for all parties (particularly renewable generators who will benefit from markets close to real time) and give incentives for market players to act in a way which is supportive to the efficient operation of the system and minimise costs. All of them need to be developed in light of the connection requirements established in connection related network codes:

HVDC	Sets requirements for HVDC connections and DC connected generation.
Load Frequency Control & Reserves	Provides for the coordination and technical specification of load frequency control processes and specifies the levels of reserves (back-up) which TSOs need to hold and specifies where they need to be held.
Balancing	Sets rules to define the roles and responsibilities of TSOs and market parties to procure and exchange balancing products to balance the system from day ahead to real time in the most efficient

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	way. It also includes financial principles for the payment of these services.
Requirements for Generators	Sets requirements which new generators connecting to the network (both distribution and transmission) – and existing generators (in very limited cases) - will need to meet, as well as responsibilities on TSOs and Distribution Network Operators.
Operational Security	Sets common rules for ensuring the operational security of the pan European power system.

The European electricity system is going through a period of unprecedented change. The generation mix is changing fundamentally, the potential for the demand side to become much more involved is vast and the market is becoming genuinely pan European. For Europe to achieve its trio of objectives of ensuring and enhancing security of supply; creating competitive markets; and facilitating the transition to a low carbon economy there will need to be a significant change in the role of network users, of Distribution System Operators and of Transmission System Operators.

With the growing share of electricity generation from intermittent renewable energy sources the difference between actual physical flows and the market exchanges can be very substantial. Remedial actions were identified by previous smart grid studies within European framework programs in operational risk assessment, flow control and operational flexibility measures for this area. At the same time an efficient and sustainable electricity system requires an efficient usage of existing and future transmission capacities to maximise transportation possibilities. New interconnections and devices for load flow control will be integrated in future transmission networks and will offer new operational options. Two major EC studies (iTesla [8] and Umbrella [9]) cover these aspects.

Network codes will impact on all parties active in the energy sector and will lead to considerable change in existing practices. ENTSO-E recognises the importance of engaging with a wide range of stakeholders to ensure that these impacts are understood and that as broad a range of views as possible are reflected in the network code development and is seeking to structure processes to allow this to occur.

Through a transparent approach, collaborative method of working and shared objectives we are confident that the network codes can deliver real benefits in realising each of Europe's energy goals.

1.4. Other Supporting Documents providing further depth

In addition to this Explanatory Note, the following supporting documents are available on the ENTSO-E website:

In addition to this Explanatory Note, the full package of NC HVDC supporting documents includes:

- Frequently Asked Questions (FAQs), including
  - Comparison of present practices with NC HVDC
  - General feedback from a manufacturers survey on cost impact
  - Considerations of allowing a lower grade option for radial HVDC connections of PPMs
- Requirement Outlines
- Evaluation of Comments: ENTSO-E's views on valuable feedback received in a written consultation on a draft of the NC HVDC

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Additional documentation of the consultation process includes:

- Presentations and minutes from Public Stakeholder Workshops
- Presentations and minutes of User Group Meetings
- Documents from bilateral stakeholder meetings
- Related Documents and Links

1.5. Challenges Ahead relevant to HVDC Requirements

Extended and more varied applications of HVDC

HVDC technology will increasingly be used in the coming years to develop interconnections between different synchronous areas and it is of the utmost importance for these new facilities to contribute to power system security. To supplement existing HVAC corridors, extensive developments of embedded HVDC systems (both within one or between several control areas) are also planned, in order to increase the flexibility and capacity of the entire system. The above contribute to market integration by supporting the development of cross-border exchange of energy and reserve. To that end, extensive active power controllability is needed. Automatic control modes are especially needed for exchange of frequency containment and restoration reserves. The NC HVDC defines the minimum standards and requirements needed for achieving these goals related to market integration.

The conventional task for HVDC is bulk transfer of large volumes of energy over long distances. Additionally, HVDC has been used like a firewall in its back-to-back connection of large AC transmission systems. These tasks will remain a focus, supplemented by the expected rapid growth of HVDC technology in the world of offshore power generation, predominantly associated with wind energy.

The HVDC technologies

The HVDC technology itself, in particular the branch of Voltage Sourced Converters (VSC), is developing rapidly. This was illustrated at a December 2012 International HVDC Conference (IET's ACDC2012) [10] with the statement that since the first VSC installation there had been a fundamental change of configuration for every second VSC project. In contrast with the emerging HVDC VSC technology and the potential for future associated HVDC Grids, the alternative HVDC technology using Line Commutated Converters (LCC) is a mature technology, applied with large capacity in relative low numbers. It is important that the NC HVDC facilitates the development of both technologies.

In this context CIGRE issued in December 2012 a WG report (WG B4-52) [11] concluding that DC Grids are feasible. Another CIGRE group (WG B4-56) is working on connection requirements for meshed DC Grids whose report is expected during 2014. CIGRE B4 has further set up a group to develop recommendations for standard DC voltages, similar to how 400kV is a standard voltage in Europe for AC. In a DC Grid it will eventually become possible to have a Connection Point directly at HVDC (with direct connection to a DC busbar).

A further variety of HVDC configuration is being demonstrated in 2014 by Skagerak 3 and 4 linking Norway and Denmark to combine VSC and LCC technologies in both ends in one HVDC system.

The system technical challenges ahead

As the proportion of electrical power transmitted by HVDC to the vicinity of major load centres increases, the characteristics of HVDC including its responses to fast system changes under disturbed conditions increases in importance in two ways. In the first place this relates to its own robustness to disturbances, the ability to continue to deliver the power. This is particularly important considering the size of most of the HVDC schemes. Secondly, and of similar importance, as HVDC displaces direct AC connection of generation, is the ability of the HVDC system to “pass on” quickly and in a controlled manner dynamic support from another system or from generation to deliver stable operation and hence security of supply.

The characteristics of the energy system are changing rapidly especially with the massive integration of RES (wind generators, PV installations) in the European electricity network. At a European level this is illustrated in the Ten Year Network Development Plan (TYNDP 2012) issued by ENTSO-E [12].

The likelihood for operation of a synchronous area or at least a control area with at times very high percentage Non-Synchronous Generation (NSG) increases. This was described for various countries in the Appendix (Section 7) of the NC HVDC Call for Stakeholder Input [13]. Ireland is the first synchronous area to experience 50% of generation from non-synchronous sources (predominantly converter-based). In the short term this condition is considered as a system technical limit, maintained when necessary by substitution [14]. Great Britain is expecting – under the “2013 Gone Green” scenario – to exceed 75% and even 90% for considerable durations under the most challenging operating conditions by 2030 [15]. The converter-domination of generation is further extended by HVDC converters under import conditions, but alleviated during HVDC export.

Operating conditions with the highest RES injection (typically in windy / sunny conditions with moderate demand) present major system challenges. One answer is to increase the controllability and the flexibility of all power system elements to deliver a power system which can react and cope better with the volatility of RES [16].

The three main new or expanded technical challenges ahead related to stable operation of the power systems are:

- Frequency management with reduced inertia in synchronous area or even in each control area;
- Voltage management in areas remote from main centres of RES installations during times of high RES production when conventional generation, which has traditionally provided this service, being displaced; and
- Fault level (system strength) management in context of rapid changes from high system strength during low RES production to extreme low system strength during high RES production, when synchronous generation is displaced (not operating).

In the extreme case the total demand may be covered by supply from converter based technology (PPM and HVDC connections). In general NSG results in both lower total system inertia as well as lower fault levels / short circuit ratios (or system strength). A family of challenges are related to operation with less system inertia and less system strength:

- Inadequate synchronising torque to retain stability.
- Potential commutation failures of LCC technology, the conventional type of HVDC. Traditionally LCC schemes required a fault level in MVA of at least 3 times the MVA rating of the HVDC link. Stability for the latest LCC systems can probably be extended down to 2 times the MVA rating.
- High harmonics: If minimum fault level (or short circuit ratio) in operation is much lower than the fault level used in the design, then unexpected high harmonics may appear. As a rough measure if the fault level is halved, the harmonic voltage distortion will double. High Negative Phase Sequence (or 3-phase unbalance) voltages: The synchronous generators as major sink for negative sequence currents are being displaced by non-synchronous generation which do not perform similarly as a sink, unless explicitly designed to do so.
- Larger voltage steps, e.g. when switching capacitors or reactors on the network in order to control the system voltage.
- New challenges for transmission protection Systems in which a distinction is to be made between fault currents and load current of similar magnitude.

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The technical requirements of HVDC systems may in future increasingly be designed to ameliorate some of the above problems by delivering a number of services, including:

- Synthetic Inertia (SI) to aid frequency management, [15]
- SMART use of SI contribution to deliver synchronising torque [14], [17]
- Very fast fault current contributions up to their current ratings. [18] This is still 2-3 times less than the initial fault current (sub-transient) contribution from the displaced synchronous generation would have been.

The motivation for developing and increasingly requiring these emerging services is to avoid or at least reduce in the most socio-economic manner the impact of one or more of the following alternatives:

- An upper limit on (local) development of RES;
- Large scale constraint of RES production (modest constraint or substitution for the most extreme conditions is still expected to be appropriate); or
- Jeopardising system security by no longer being able to maintain current system performance, having to accept a higher level of supply interruptions.

Starting point for the NC HVDC development

Security of the system cannot be ensured without considering the technical capabilities of all users. Historically large synchronous generation facilities have formed the backbone of providing technical capabilities.

The ENTSO-E TYNDP [12] shows that several countries have extensive HVDC activities and/or future plans. However, not many have detailed connection requirements already set in Grid Codes. A summary of existing current practices is to be found in section 3.4 and is further expanded on in FAQ 10. This demonstrates the importance and urgency need for a European NC HVDC, for network operators and developers.

Whereas the NC HVDC makes a start in the preparation to cope with the more extreme system challenges described above, it is likely that it will be necessary at a later stage to review and possibly add to 19 or extend the capabilities already included. The optimal time for this is expected to vary across Europe, with the smallest synchronous areas with the highest proportion of non-synchronous generation sources expected to meet these challenges first. Hence, the requirements already included (such as synthetic inertia and fast current injection during faults) are mostly optional (non-mandatory) and further left to be fully defined at national level (non-exhaustive).

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2. CONSULTATION

Interaction with interested and impacted industry organizations was facilitated by means of various workshops, two written consultations and the establishment of a dedicated NC HVDC User Group meeting.

Five User Group meetings have been held, with a first one before the formal development of the NC HVDC. These have been of great value to exchange views on the impact and benefit of the NC HVDC, both for ENTSO-E to explain its choices and its drafting and for users to explain their views and bring proposals for improvement of scope, code and interpretation. The material used in the presentations as well as the agreed minutes of the meetings are published on the ENTSO-E website.

A public written consultation of a full draft code was open during the period from 7 November 2013 through 7 January 2014. Various organisations from the industry, investors as well as academia submitted a total of nearly 2500 individual comments, which have all been assessed by ENTSO-E. The document "NC HVDC - Evaluation of Comments" provides ENTSO-E's evaluation of the comments organised into approximately 500 topics. For each topic ENTSO-E categorises its response to a proposed change as accepted, partially accepted or rejected and defines a motivation for each conclusion.

The material in "NC HVDC - Evaluation of Comments" is organised by Article number. The consultation has resulted in substantial improvements and a large number of changes. ENTSO-E appreciates the substantial effort made by many stakeholders in providing these contributions.

The input provided in this consultation covered both legal and technical aspects, either editorial or fundamental. Each suggestion has been assessed to further improve the NC HVDC. The major changes in the code can be summarised as follows for HVDC Systems:

- Definitions and scope have been enhanced for better clarity;
- Withstand capability in frequency have been reduced and made coherent with ranges resulting for national implementation of NC RfG and DCC;
- Admissible active power output reduction at frequency below 49 Hz has been introduced ;
- The Rate-of-Change-of-Frequency withstand capability is more clearly defined;
- Requirements for short-circuit contribution during fault has been kept non-mandatory and is now proposed in a more open manner, following agreement with the wind industry in recent NC RfG discussions where similar requirements are stated for PPMs;
- Requirements for Fault-Ride-Through capability in case of asymmetrical fault has been proposed in a more non-exhaustive formulation;
- An additional point is introduced in the FRT voltage-against-time curve to allow for a combination of a fast initial rise of voltage, but slower rise between 0.7 – 1 pu;
- Requirements for Reconnection Capability and Requirements for Isolated Network Operation have been removed since these capabilities are broadly covered by other NC HVDC requirements, and can in any case be further specified at national level.

The major changes in the code can be summarised as follows for DC-Connected Power Park Modules and Remote-end HVDC Converter Stations:

- Requirements for DC-connected PPMs and Remote-end HVDC converter stations are clearly distinguished in separate sections to improve clarity of which requirement applies to which element;
- Opportunities to use nominal frequencies other than 50Hz or frequency variable by design for the operation of the remote end are now explicitly addressed. This is subject to agreement with relevant TSOs to ensure that decisions are in line with long-term European network development plans;
- Ranges for frequency withstand capability are fully aligned with those of on-shore generation to ensure non-discrimination;

- Ranges of withstand capability in voltage are aligned more clearly with present best practice;
- Requirements for reactive power capability have been proposed to follow a progressive capability building depending on system need. Agreements shall ensure that reactive power capability is available when reactive power is needed for the power system;

The feedback received in the Call for Stakeholder Input, User Group meetings and public consultation provided crucial support in developing the code and its supporting documents, and more particularly to develop the code in context of offshore.

The requirements in NC HVDC have recognised that the possible largest cost component of reactive power should be selected from a defined range reflecting the relevant network development plans, as well as the option of optimization of DC link and offshore plant design. In particular, for DC connected PPM, flexibility has been introduced in the code in order to avoid unnecessary investments in reactive capabilities at the time of initial connection and commissioning. An agreement between the DC connected PPM owner, the HVDC owner and the relevant TSO can be obtained as soon as it is demonstrated that full reactive power capabilities can be delivered at a point in time defined by the Relevant TSO when theses capacities will be needed as a consequence of further network developments. For more details on this aspect, refer to FAQ 20.

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3. General Approach to NC HVDC

3.1 Structure of NC HVDC

The Network Code contains General Provisions, including Subject matter and scope, Definitions, Regulatory Aspects, Recovery of costs and Confidentiality obligations, before introducing the technical requirements. The Chapter on requirements for HVDC connections is followed by the Chapter on requirements for DC-connected Power Park Modules. To improve clarity this chapter has been further subdivided into the requirements for the Remote-end HVDC Converter and the requirements for PPMs. Further chapters cover Information exchange and coordination, Operational notification procedure for connection, Compliance, Derogations and Final provisions. The main requirement chapters are organised into sections covering a group of requirements. Each technical requirement is covered by a specific Article.

3.2 Applications to HVDC Connections and DC-connected Power Park Modules

According to ACER's FWGL, "*the network code will apply to grid connections for all types of significant grid users already, or to be, connected to the transmission network and other grid user, not deemed to be a significant grid user will not fall under the requirements of the network code*".

A major challenge of the HVDC code is consequently to answer to the central question "Who are the Significant Grid Users?" in order to define unambiguously the field of application of the code.

The FWGL gives a general definition of the Significant Grid Users as "*pre-existing grid users and new grid users which are deemed significant on the basis of their impact on the cross border system performance via influence on the control area's security of supply, including provision of ancillary services*".

For this specific NC HVDC ENTSO-E identifies the following HVDC configurations as Significant Grid Users:

- HVDC Systems connecting Synchronous Areas or Control Areas, including back to back schemes;
- HVDC Systems connecting Power Park Modules to the Network;
- HVDC Systems embedded within one Control Area and connected to the Transmission Network;
- HVDC Systems embedded within one Control Area and connected to the Distribution Network when a cross-border impact is demonstrated by the Relevant TSO and approved by the NRA; and
- All Power Park Modules that are AC collected and DC connected to a Synchronous Area at distribution or transmission level.

The following picture illustrates the above mentioned different ways HVDC is envisaged to be used as well as the location of the interface points where the NC HVDC requirements apply. Following consultation and following agreement with Stakeholder representatives at the 2nd User Group meeting ENTSO-E confirms that wherever possible, the performance requirements are defined for the HVDC system at the AC connection point. Motivation for this decision can be found in the document "NC HVDC – Frequently Asked Questions" (FAQ 16).

These connection points form the physical interface between the systems thus the performance requirements are usually defined related to this connection points. For DC connected PPMs, the remote (usually offshore) AC end of the HVDC converter may not always be a Connection Point, e.g. a national regime may turn it into a Connection Point late in the project development possibly with change of owner of one part. For such cases the term Interface Point is introduced in NC HVDC to identify the point at which NC HVDC capabilities are defined

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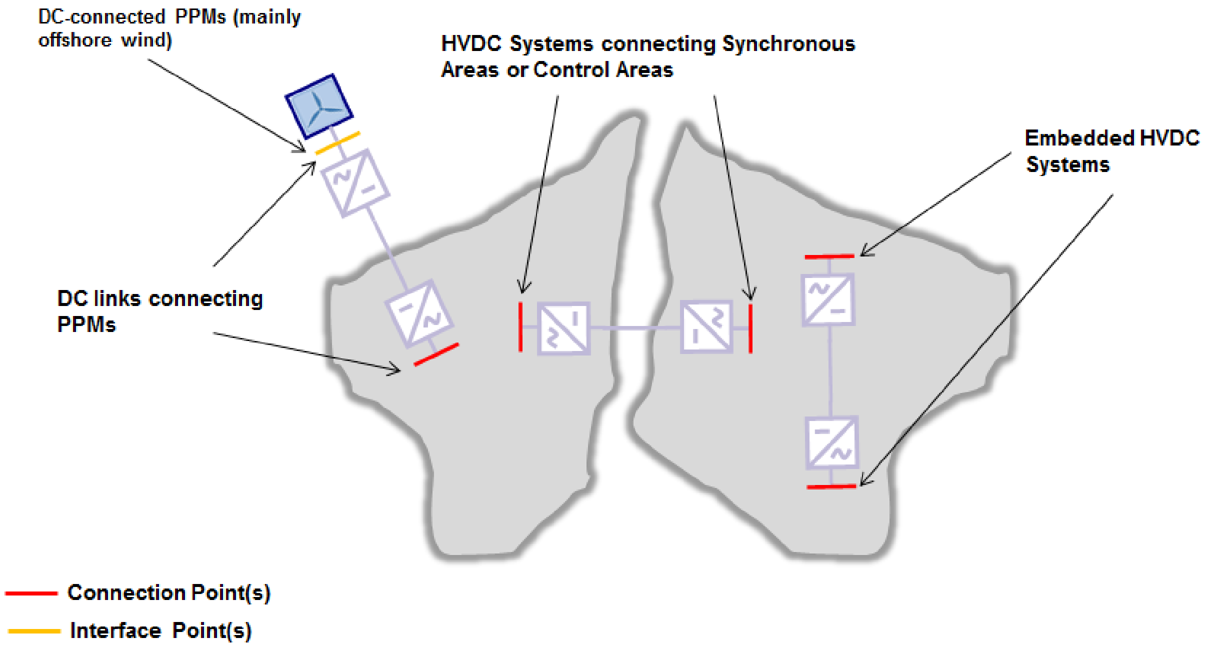
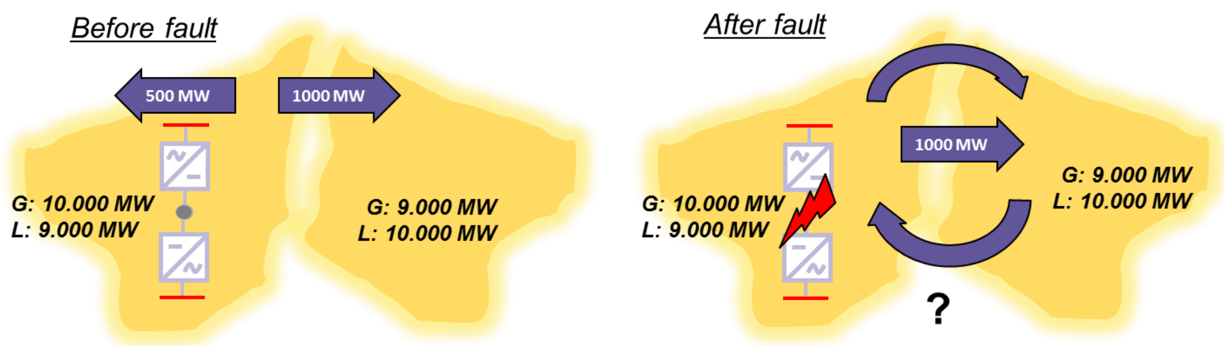


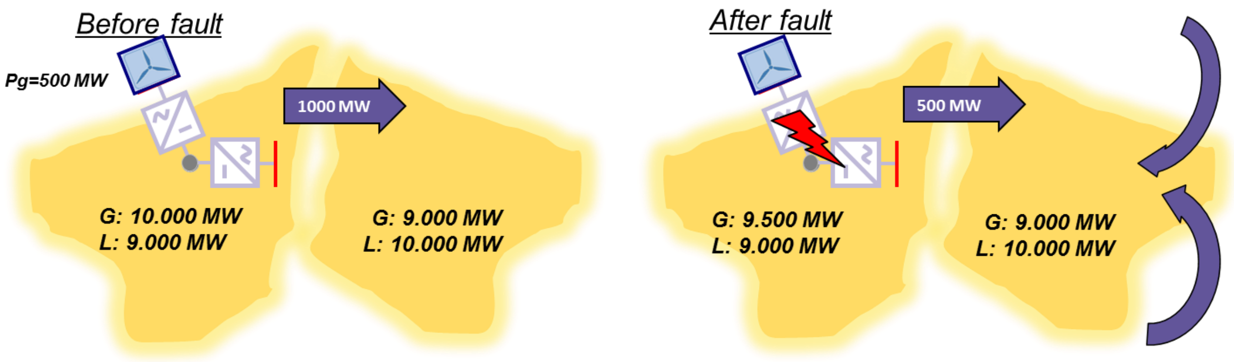
Example 1: HVDC transmission system across control areas

An HVDC system with AC/DC terminals across multiple synchronous areas or control areas, has a cross-border impact since a fault in the HVDC system causes a change of flows between control areas. Therefore these schemes are deemed to be Significant Grid Users.



Example 2: Embedded HVDC transmission system within single control area

Large HVDC connections embedded within one control area can also have significant cross-border impact. For instance, the loss of an internal HVDC link can modify the distribution of cross-border flows and consequently have impact on the power flow in neighbouring control areas. All HVDC connections embedded within one control area and connected at transmission level have such a potential impact on cross-border flows.



Example 3: HVDC generation collection system within one control area

A HVDC generation collection system, in which all the AC/DC terminals are connected within a single control area, has a cross border impact due to the fact that a fault on the HVDC system causes the change of flows between control areas. However it is important to recall that cross-border issues are not only based on active power exchange in tie lines but are also related to the technical capabilities of all the users playing a critical part in system security. Therefore the requirements will improve robustness to face disturbances, to help to prevent any large disturbance and to facilitate restoration of the system after a collapse. Moreover, harmonization of requirements and standards at a pan-European level (although not an objective in itself) is an important factor that contributes to supply-chain cost benefits and efficient markets for equipment, placing downwards pressure on the cost of the overall system.

Therefore, all requirements that contribute to maintaining, preserving and restoring system security in order to facilitate proper functioning of the internal electricity market within and between synchronous areas and to achieving cost efficiencies through technical standardisation shall be regarded as "cross-border network issues and market integration issues".

The option to apply the NC HVDC to most, if not all, HVDC links has the following advantages:

– The scenario that ownership of a HVDC link could be transferred to another party during its lifetime is realistic. The application of the code ensures that all links comply with the same appropriate minimum standards and requirements.
– All requirements apply when two entities connect to each other. In case a TSO develops a HVDC System within its own control area (so not covering the connection of two parties), the technical requirements still apply as described in Article 3(5) of the Code. In such case, an operational notification process or compliance test between grid user and network operator is not suitable. Requirements are expected to be covered in national planning standards or equivalent practices. Application of the NC HVDC to all HVDC System Owners ensures non-discrimination across Europe and contributes to the expressed objectives of this code.
– In case the HVDC link to AC collected and DC-connected Power Park Modules (e.g. offshore wind farms connected by HVDC) is owned by the TSO, application with the NC HVDC ensures a non-discriminatory approach towards these generating units in which the HVDC link is owned either by the Power Generating Facility Owner or by a third party.

In addition to point-to-point connections, multi-terminal schemes are also foreseen in future. In this regard the requirements shall ensure that multi-terminal schemes work together in a robust and safe way. For future connection points at DC substations, requirements are not provided in this issue of NC HVDC, but are expected to be added at a later revision when selective DC fault detection and HVDC switching technologies have emerged.

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Mixture of AC and DC transmission of power from offshore PPMs is also relevant. At present HVDC systems provide predominantly point to point power transfers. It is envisaged that DC grids (meshed DC systems) will gradually emerge for some applications, initially as a new emerging technology and eventually as a proven technology. One important step needed in this context for the TSO to further develop future HVDC systems is the interoperability of different vendors and the ability to integrate individual projects into the existing system. In this respect, the NC HVDC is expected in the future to play an important role [19]. Future revisions of the NC HVDC are expected to bring these aspects forward as the DC grid technology moves into implementation.

Relevance to Existing HVDC Systems

For existing users, previous connection codes (Requirement for Generators (RfG), Demand Connection Code (DCC)) provide an extensive but transparent and non-discriminatory process before the requirements could be considered applicable. A Cost-Benefit Analysis showing the socio-economic benefits and cost of the proposal has to be carried out and the report will be subject to a public consultation. Finally the TSO sends the proposal on the applicability of the requirement, including the outcome of the consultation, to the relevant National Regulatory Authority for approval. ENTSO-E considers that this approach is also relevant for the NC HVDC and therefore the same approach has been adopted. This may be expected for HVDC to be particularly relevant to facilitate low-cost software (control) changes with potentially large system security benefits.

3.3 Classification of the requirements

For each requirement, the NC HVDC provides a classification into exhaustive or non–exhaustive, and mandatory or non-mandatory requirements:

- **Non-mandatory** requirements leave a choice at national/regional level about including the specific requirements. This typically covers aspects which may not be essential everywhere.
- **Mandatory** requirements are to be implemented throughout Europe.
- **Non-exhaustive** requirements leave certain details of a requirement to be further specified at a national level. This is often focused on parameters. The national choice may be limited by a parameter range defined at European level within which the national parameter must be set.
- **Exhaustive** requirements define all details of a requirement.

These classifications are introduced to give an optimal balance of cross-border relevant functionalities that should be fully specified at European level and those where further specifications are best made locally to be fit for purpose at the lowest cost. The proposed classifications follow the same principle used in the network codes RfG and DCC.

Furthermore, network codes as referred to in Regulation (EC) 714/2009 only cover aspects with cross-border relevance and supporting market integration. Other capabilities relevant for efficient and cost-effective operation of the national power system still need to be defined in national regulation, standards, connection agreements or best practices.

Finally, when a requirement is defined as non-mandatory, its application will need to be judged in each national context. Where it can be demonstrated as justified and cost-effective, it will be included as a requirement. The framework of such national decisions is guided by national processes in accordance with the European Regulation. National Implementation Guidelines is also expected to be developed in order to support this process.

3.4 Level of deviation from existing European practices

ENTSO-E conducted a survey among its members to identify possible significant differences between the NC HVDC requirements and present practices.

- First of all it should be noted that a number of Member States at present do not have HVDC connections, nor are there plans for such connections in future. The following table gives an overview of the number of HVDC applications existing in operation end of 2014, further HVDC projects planned by 2025 and again by 2035.

	Interconnection	Embedded link	DC-connected PPM
Existing	37	4	4
Planned 2015-2025	32	15	38
Planned 2025-2035	14	15	29

The most significant difference between NC HVDC and existing national codes and specifications relates to offshore requirements for ranges for frequency, voltage and reactive power. This is an area largely still to be introduced into National Grid Codes. Nevertheless, in the only four existing applications of HVDC connecting 7 offshore PPMs physically in place by end of 2014 (projects referred to as "existing" in the table above), these offshore requirements are already broadly included, with only minor differences including even more challenging frequency ranges than specified in the NC HVDC.

The other noticeable aspect is the principle to ensure resilience of HVDC Systems to be equal to the highest national level of resilience (frequency & df/dt and offshore also for Voltage ranges) for generation. This inevitably therefore results in increased requirements in some countries, since the NC HVDC ensures these are introduced in all Member States.

For more detail, topic by topic, please look at FAQ 10 "Comparison of present practices with NC HVDC".

3.5 Input from HVDC converter manufacturers on cost implications

ENTSO-E is aware of the importance of potential cost implications, in particular to project developers. Specific emphasis on this aspect is also given by ACER when significant deviations from current standards and requirements are proposed in the NCs.

In its 7th May 2013 "Call for Stakeholder Input" consultation ENTSO-E requested information on this aspect, asking for the five requirements in the preliminary NC HVDC scope with the largest cost impact to be identified and also for any requirement with an impact greater than 0.1% of the total cost of the converter station. Unfortunately, this early public consultation did not result in any quantitative cost information related to the proposed scope items.

The commercial sensitivity of this aspect is well recognized. Following the two-month consultation and after further discussion with several HVDC equipment manufacturers, ENTSO-E sent a focused survey based on an NDA (Non-Disclosure Agreement) to the HVDC equipment manufacturers participating in the NC HVDC User Group, as well as the sector organizations of T&D Europe and EWEA. This NDA would limit ENTSO-E to only use high level information received from each manufacturer to ensure that only some high level conclusions, which are not attributable to any one manufacturer, are published.

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ENTSO-E appreciates the cooperation and significant effort made by manufacturers in responding to the survey. The high level conclusions of ENTSO-E are contained in FAQ 11 “Cost implications of significant new requirements in NC HVDC.”

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4. Requirements of NC HVDC

4.1. Requirements for Active Power Control and Frequency Support – Articles 7 to 15

For a secure operation of the power system, frequency needs to be stable both from a steady state and dynamic view point across a synchronous area and across all its voltage levels. Deviations of frequency from its nominal value indicate generation-load imbalances which have to be eliminated in order to guarantee a stable frequency across the electric system. The European TSOs are responsible for this frequency control and for maintaining frequency quality within pre-defined quality criteria. The Network Code on Load Frequency Control & Reserves will provide the coordination and technical specification of load-frequency control processes and specifies the levels for different classes of reserves which TSOs need to hold. The generating units, with their ability to vary their active power output when a frequency deviation occurs, as well as the other users connected to power system are required to contribute to frequency control or at least to frequency stabilisation. To that end, the connection codes set requirements for new facilities connected to the power systems.

Frequency ranges

HVDC converters should match a more stringent capability than that defined in the Network Code for Requirement for Generators in article 8(1)a), as well as that defined for DC-connected PPMs. This is in line with the principle of transmission assets being the most resilient elements of the power system. Nevertheless, it is important to note that this principle is applied with respect to withstand durations but not to the frequency ranges themselves.

Also, in case of rare network splitting, in which some isolated parts can experience large frequency deviations, system operation will be easier if TSOs can rely on the HVDC connections even though generation has partly or totally tripped.

Following the second stage of consultation (with the draft code), further refinement has been undertaken to retain above advantage, but noting the cost factors of duration and performance at the extreme frequencies, the durations have been reduced and a national option introduced to allow a reduced performance at extreme low frequency. The frequency duration reduction has also significantly softened the impact of the combined extreme frequency and voltage (e.g. low frequency and high voltage giving rise to possible over-fluxing). These changes have been made incurring only a limited loss of system resilience.

Rate of change of frequency withstand capability

HVDC converters as part of the core infrastructure are expected to have wider capability than that defined for generators (via Network Code for Requirement for Generators, Article 8(1)b) and for DC-connected PPMs). This is needed to maintain coordination of generators and HVDC systems and avoid sub-sequent unwanted tripping.

Active power controllability; control range and ramp rates

The management of variability and uncertainty is critical for the secure operation of a power system with high levels of variable generation and HVDC schemes. HVDC converters have the inherent capability to control active power within a few hundred milliseconds. In some cases, TSOs need fast active power control. For instance, in case of a nearby contingency that results in limited power transmission, the HVDC system shall be capable of decreasing its power output in order to solve overloads on the nearby network (‘fast run back’). On the other hand, in case of tripping of another parallel HVDC or AC circuit, the HVDC system shall be capable of increasing its power flow up to the nominal operation power in order to take over the net flow (‘fast run up’). This requirement is defined as non-exhaustive, giving the opportunity to add certain detailed requirements at a national or project level.

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TSOs require HVDC links to be capable to contribute to market integration by supporting the development of cross-border exchange of energy and reserve. To that end, extensive active power controllability is needed. Automatic control modes are especially needed for exchanging balancing energy resulting from the activation of cross-border frequency containment and restoration reserve. The prescribed control capabilities refer to the specific reserve exchange procedures detailed in the NC Load-Frequency Control & Reserves. This requirement is defined as non-exhaustive, giving the opportunity to add certain detailed requirements at a national level.

Ramp values for the active power control may be different and fixed or adjustable depending on power system needs, protection settings and topology, so as this value or a range of the values, when adjustable, should be agreed between TSO / facility owner and manufacturer. This requirement is proposed to be mandatory and non-exhaustive.

Frequency sensitivity and frequency control requirements

HVDC systems are required to be flexible in order to modify their active power flow during frequency excursions to maintain system frequency stability. Frequency deviations of a synchronous area can be reduced by a smooth reduction of the active power output of HVDC converters in case of high frequencies and by a smooth increase in case of low frequencies.

This requirement is included as mandatory and non-exhaustive to allow provisions for different ramp rates, gains, droop values, deadbands, static and dynamic reserve during operational time frames. Different values could be envisaged at national level depending on reserve requirement, generation, control structure and system characteristics at both ends of the HVDC connector. Schemes and settings of the different control devices of the HVDC system shall be coordinated and agreed between the relevant TSOs at both ends of the HVDC connector. In some cases those could be disabled to operate the HVDC system at fixed power.

The capability is mandatory. The capability is required by the TSO during normal or contingency situation such as system separation between two control areas or power restoration.

Synthetic inertia capability

System synchronous inertia fundamentally affects how fast and how far the frequency drops or increases during an energy imbalance, being the rate of change of frequency and the frequency turning point (lowest or highest). With high penetration of non-synchronous generation, power electronic devices and HVDC links connected to the grid, system inertia tends to reduce, resulting in larger frequency excursions and higher rate of change of frequency. This might trigger rate-of-change-of-frequency-type of loss of mains protection and some consider risks of transient stability issues (lack of synchronising torque). This will result in a fundamental change of behaviour under both steady state and transient condition for the power system.

Fast-acting response from HVDC converters can provide synthetic inertial capability if required by implementing the necessary controls. Reliable and useful measurement of rate of change of frequency is a substantial challenge, due to angular movement between generators when disturbed. Inertia emulation could therefore work against its intended purpose when not designed with great care. One method of implementing this capability (as well as other synchronous generator type capabilities) is given in [17], see also Section 2.5.

Furthermore, HVDC system linking two synchronous areas also needs to be able to transmit inertial support from one area to another. The NC HVDC requirement enables this.

The requirement for this capability is power system dependent and will change with the needs of each system and synchronous area as well as with the system development over time, i.e. substituting conventional, synchronous generation with non-synchronous generation. Therefore, this requirement is defined as non-mandatory and non-exhaustive.

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Maximum loss of Active Power

Given the technology potential for large capacity single DC links, the NC HVDC explicitly addresses the need for TSOs to give further specifications for the configuration of an HVDC System such that it does not result in unreasonable sizing of operational reserves with costs to be covered by all grid users.

4.2. Requirements for Power Control and Voltage Support – Articles 16 to 22

As part of the transmission system, the HVDC connections shall ensure the reliability of the power system, and in terms of voltage withstand capabilities shall have at least the same capability as generation and demand. This coordinated approach avoids subsequent undesired trips. The power system needs a stable and healthy voltage for its proper operation. As generation connected through power electronics is progressively displacing traditional synchronous generators, which are the traditional voltage control sources, voltage profiles are changing. For this reason voltage control must be required for new generation technologies as well as for the new equipment connected to the AC network, including HVDC technology.

Current injection profiles during faults are changing progressively in the AC network, while they are critical to both recover the voltage during faults and to inject enough current quickly enough for system protection schemes to operate reliably. For these reasons it is important that HVDC systems have extensive capabilities to support voltage and to provide voltage control to the AC network. While considering this family of requirements, the differences in capabilities and behaviour of the HVDC converter technologies arise. Some HVDC converter technologies are very flexible in terms of reactive power management as they can be managed independently from active power in such a way that the HVDC converter can provide voltage control during normal operation and voltage support during contingencies. Other HVDC converter technologies do not allow independent management of the reactive power, or they scarcely can do it, so that they can provide neither support nor control, unless shunt reactive compensation is added. To ensure that the full potential of all technologies can be used while no barriers should be created for future use of any of them, a balance in level of detail is pursued in requirements for reactive power and voltage support in the NC HVDC.

In this category and based on the above principles, the NC HVDC establishes requirements on voltage ranges, short circuit contribution during faults, reactive power capability, reactive power exchanged with the network, reactive power control mode, priority to active or reactive power contribution and power quality.

Voltage ranges

HVDC converters should at least match the same capability as defined in the Network Code for Requirement for Generators, Article 11(2). This is needed to maintain coordination among generators and HVDC systems and avoid subsequent unwanted trip. This requirement is intended to be mandatory and exhaustive otherwise voltage thresholds within a synchronous area may be applied in an inconsistent manner and potentially affect system security. Voltage range values may differ for each synchronous area.

Short-circuit contribution during faults

A certain minimum level of short circuit current during faults needs to be injected by HVDC converters in order to maintain the local short circuit current so that the voltage could recover properly. It is important here the time constant of reaction of the converter immediately after the short circuit to provide short circuit current. It is not the SCR or short circuit power level at which the HVDC connection must be able to operate because this is dealt with separately. In addition to support to voltage recovery, very fast short circuit contribution is needed to aid selective operation of transmission protection, particularly under high RES production [14]. This requirement is defined as non-mandatory and non-exhaustive, giving the opportunity to specify the details of the requirement at a national or project level depending on local system needs.

Reactive power capability

In order to maintain voltage stability, reactive power capability is required, independently from the technology of the converter. To ensure technology-neutrality and allow for local system specificities, this requirement is defined as non-exhaustive, allowing TSOs to adapt the specific requirements to local system needs.

Reactive power exchange with network

The NC HVDC defines the criteria needed to ensure voltage stability and voltage quality in steady-state and transient conditions. As the local systems need may differ, these requirements are defined as mandatory and non-exhaustive.

Reactive power control mode

Proper reactive power management is important for preserving system voltage stability. The most important source for voltage control and reactive power control were synchronous generators. However, increasing penetration of renewable energy sources will displace synchronous generators and reactive power control capability of HVDC converters in the power system needs to be utilized for the benefit of the power system.

Priority to active or reactive power contribution

The control of this balance can be of vital importance for the network security and voltage stability. The intention of this requirement is to ensure adequate balanced support from the HVDC converter station during AC network contingencies.

Power quality

HVDC converters shall not introduce harmonics that would breach power quality compliance and affect the optimum operability of the TSO(s). The requirement ensures that HVDC converters filter (at least) their own possible perturbations of the power quality.

4.3. Requirements for Fault-Ride-Through– Articles 23 to 25

Due to their importance for the future power transmission system HVDC systems must have a high availability in terms of active and reactive power exchange with the AC side. Fault ride through capability starts with the ability of a HVDC converter to remain transiently stable and connected to the system for a nearby fault or voltage dip

In case of DC side faults the admissible interruption times in particular depends on the realization of the DC transmission path connecting the converter stations. To interconnect adjacent synchronous systems often either a back to back HVDC station or underwater cables are utilized. For long distance onshore bulk power transmission the choice is between overhead lines, underground cables or a mixture of the two. Underground cables are considered the favoured alternative for environmentally sensitive areas. The increased difficulty in obtaining permits for new transmission overhead lines and routes leads to solutions attempting to enhance the transmission capability of existing lines. To this aim either a full or a partial conversion of AC lines to DC might be considered as an attractive approach.

The requirements that will be demanded from the HVDC system depend on the foreseen type of transmission path. Overhead lines are subject to atmospheric disturbances (lightning strikes; line swinging during windy weather conditions etc.) posing high requirements on the frequency and admissible duration of automatic reclosing sequences in case of DC link short circuits. To maintain the security of supply a high reliability and robustness comparable to today’s AC system performance must be ensured in this regard. In the case of parallel operation of AC and DC lines running on the same tower even higher requirements on the HVDC system result due to the probability of intersystem failures. On the other hand, if the transmission path is realized as underground cable, limited requirements to mitigate DC link short circuits might apply. In general a cable failure leads to time consuming repair times and fast recovery times for

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active power are not possible at all. Nevertheless there might be high demands with respect to reactive power support. Independent of system performance requirements the protection of the HVDC system against any kind of overloading must be assured for all specified fault scenarios.

Fault-ride-through capability

The type of fault, fault duration, fault condition and voltage dip is dependent upon local TSO system security criteria. The capability to ride through is to be determined by the local TSO who can specify system conditions that include minimum fault power/current at the connection point. Expected behaviour of the HVDC link in case of asymmetrical faults will depend on chosen approach to protect the local system. This requirement for asymmetrical faults is therefore defined as non-exhaustive. Further considerations related to fault-ride-through are given in [14].

Post fault active power recovery

The HVDC converter must be able to recover active power output following fault clearance for AC and transient DC faults or recovery from voltage dips. This ability shall help to restore frequency and voltage stability and shall reduce any consequential thermal overload. The speed and magnitude of recovery is to be determined by the local TSO.

4.4. Requirements for Control– Articles 26 to 31

HVDC transmission can be fitted more readily than AC to a gradual expansion plan for transfer of power. AC transmission often has to be built from the start with a high capacity to maintain stability, but DC can be tailored to discrete stages. Expansion of existing HVDC systems will naturally result in a more complex network with an increase in the number of multi-vendor converters in the same area. Therefore, requirements for cooperation and coordination of control systems designed and built by different vendors should be set up to allow expandability of network in the future.

HVDC systems provide great controllability and flexibility. Depending on the HVDC system technology, these devices can provide innumerable control functions to contribute to the overall system security and quality of supply. It is essential that this is made in a safe and coordinated manner. The NC HVDC establishes requirements to ensure the following:

- the control system is robust in case of a unexpected changes;
- the HVDC system does not interfere with other equipment connected to the AC network;
- the correct coordination between the protection systems of the HVDC system and the AC network; and
- the correct coordination of all the different control functions implemented within the HVDC system.

Also the NC HVDC will set the base for control functions that may be implemented if needed according to the AC network characteristics, e.g. power oscillations damping controller, sub synchronous torsional interaction damping controller and black start capability.

The interactions between AC and DC systems are quite complex and variable in nature. Taking the short circuit ratio value on the AC system is a simplified approach to evaluate these interactions. However, as non-synchronous generation becomes dominant, this concept may no longer hold entirely true, due to dominance of design based choices rather than machine characteristics [14]. The minimum short-circuit ratio at AC connection points is an important aspect for the functioning of the HVDC schemes. This is well established for LCC based HVDC schemes, but 11still considered by experts a major issue also for the performance of VSC type HVDC schemes.

The requirements related to the converter control could be classified into the following categories:

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Converter energisation and synchronisation

The HVDC links shall be capable of connecting and disconnecting without disturbances to the existing grid.

Interaction with the AC system / Control performance to enhance AC system performance

The requirements shall ensure that at first any adverse effect on the AC system or on any grid user is avoided (e.g. excitation of torsional stress on nearby generators). Further on the capabilities of HVDC converters to enhance the overall AC system performance and to contribute to its security shall be utilized, e.g. through Power Oscillation Damping contribution to the AC system dynamic stability (small signal). This will become more and more important in the future power system (e.g. due to reduction of conventional generation units otherwise providing ancillary services). The intention of this requirement is to avoid undesirable interaction of HVDC control system with offshore wind farm control or between nearby HVDC controls by proper and robust control design and control coordination.

Power oscillation damping capability

HVDC may enhance power system damping and contribute to the overall system stability. The intention of this requirement is to specify the performance of HVDC controllers with the purpose of damping low frequency oscillations, typically in the range from 0.1 – 2.0 Hz, in power systems caused by generator swing. The method of damping could be by active and/or reactive power modulating of the HVDC link or by active power modulation of the offshore PPMs or a combination of both.

Sub-synchronous torsional interaction damping capability

HVDC electrically close to power generating modules may contribute to instability in the sub-synchronous frequency range. The intention of this requirement is to ensure that under no conditions should one or more torsional modes of oscillation in the SSR range on a mechanical shaft of nearby power generating module(s) be negatively damped and destabilized by control interaction with the HVDC.

HVDC system robustness

The HVDC system has to be resilient for a prescribed list of system changes. Also tripping of the HVDC System itself should not result in unreasonable transients at the connection points based on further specifications given by the TSO.

4.5. Requirements for Protection Devices and Settings – Articles 32 to 34

It needs to be ensured that the HVDC links are designed in a way that the protection devices are discriminative and stable so as to minimise malfunction operations.

HVDC converters requirements should be in line with the capability as defined in the Network Code for Requirement for Generators, Article 9(5) b)

Due to the fact, that there are plenty of control and protection functions, a priority list has to be manifested by the TSOs operating an HVDC System. This requirement is necessary because the different control modes might interfere with each other and could lead to different control targets if not priority ranked. Hence, a clear list, what control modes are active and dominating together with the values is essential. Moreover, all TSOs operating at the same HVDC System have to know all priority lists.

The control schemes of the HVDC links connected together have to be able to work together during operation. The control schemes and settings, both at AC and DC side, have to be compatible with other remaining requirements, because response times, tripping times, reconnection time etc. depend on the control settings.

Any changes to the protection schemes relevant for the HVDC converters and the Network and to the setting relevant for the HVDC shall be agreed between the Network Operator and the HVDC converter owner and be concluded prior to the introduction of changes, as well as the procedure to carry out these changes, that sometimes will be motivated by the HVDC owner and other will be the TSO who will request them.

Additionally, the detailed internal set of parameters of the different control modes (such as gains, time constants, slopes, deadbands, references, etc…) as well as the protection settings that do not need to be operated remotely must be available so as to be modified if necessary (due to new network conditions, new more detailed studies, etc…) and not fixed in the control system. For example, a POD control could, with a set of parameters could be inefficient or even unstable if AC network conditions changes; in this case, the parameters must be settable and the TSO and the HVDC owner must arrive to an agreement in order to change them.

And finally, some control modes and their setpoint must be operable remotely if required by the Relevant TSO, and this should be specified in order to have the necessary communication system implemented.

4.6. Requirements for Power System Restoration – Article 35

Depending on local system needs, black start capability might be required from the HVDC system. For instance in case of a regional blackout the HVDC system could support the affected area via the converter station that is connected to the healthy part of the system. In this regard HVDC can play an important role to minimize down times and to energise the system as quickly as possible. Coordination is needed with other equipment in the affected area (protection, dispersed generation etc.), thus the necessary communication equipment has to be available even under disturbed conditions.

4.7. Requirements for DC-connected Power Park Modules and associated HVDC Converter Stations – Articles 36 to 48

These requirements mostly apply to offshore generation. Consideration is needed to match the requirement of the PPM and the offshore AC system with the requirements of the HVDC link. The requirements for the offshore PPM need to recognise the different characteristics of the offshore AC island system, having no system strength from synchronous generation. Thus, additional requirements become more relevant (e.g. harmonics…) whereas others (e.g. frequency ranges) have to be adapted in order to enable a safe and secure operation. Moreover, the definition of the requirements is aimed to enable the future enlargement of the islands. The communication from the main interconnected system to the offshore facility needs to be ensured. Communication within the installed equipment in the AC islands can be provided via system state variables, for example frequency, or via a separate communication channel.

More and more components in the European grid are connected by power electronic interfaces. Large offshore PPM clusters are developed and DC connected to the main (onshore) electricity system.

Currently these clusters are connected individually. However, as it is the case in e.g. Germany, the Offshore PPMs and the HVDC connections are developed and designed individually, i.e. when defining the design of the HVDC the Offshore PPMs are often not designed nor it is finally decided, which of the PPMs will be connected to the specific hub. Such a scheme can only be realized if both the Offshore PPM and the HVDC system are designed according to common rules and standards. Additionally, the potential wind harvest in an area cannot be transferred via a single HVDC line in an economically optimized way.

Therefore a number of HVDC systems will be installed next to each other when this is necessary due to the progress of installed PPMs. At this point of time it will be possible to interconnect the offshore HVDC stations by AC HV cable in order to enhance the availability and the security of supply – e.g. in case of maintenance of one of these offshore stations. This will not allow transferring the full amount of power; however, it will be possible to transfer a certain amount. Nevertheless these schemes do require a certain amount of common performance requirements in order to keep the system flexible.

In future these projects connected to one synchronous area may become DC or AC connected to another synchronous area. The grid behaviour is expected to be different from today. Bearing in mind that the PPMs and HVDC converter units installed today are built to operate for the coming 30 - 40 years, the requirements for designing this equipment needs to be specified now in order to allow a future stable, reliable and economically efficient operation of the system, even when operational or market rules would evolve further:

- AC connections may become DC and vice versa.
- A cluster of DC connected PPMs may become a node in the interconnection between synchronous areas.
- AC and DC circuits should be interchangeable.

Additionally, the specific performance indicators of power electronic dominated systems have to be taken into account:

- DC connected PPMs will have low inertia and be more volatile which impacts system operation.
- DC connected PPMs will be required to contribute system services into the network which they are providing power to.

Therefore, as a general principle the requirements for DC connected PPMs are closely aligned with the NC RfG, with possible variation in ranges and settings where needed. Similarly, remote end HVDC converters have to fulfil the requirements of the NC HVDC with possible variation in ranges and settings. DC connected PPMs and remote end HVDC converters together need to have economically efficient, consistent, coordinated requirements so as not to impair requirements at the AC onshore transmission connection point.

Further development of RES connections with non-synchronous generators as well as HVDC is gradually making the power system behaviour becoming dominated by converters. Converter interaction becomes a critical element in the system. Emulating several synchronous generation behaviours needs to be considered, leading to further requirements being defined in later versions of the NC HVDC.

Frequency and Active Power Control

The NC HVDC establishes economically efficient, consistent and coordinated requirements with regards to frequency and active power control for DC connected PPMs and remote end HVDC converter. With regards to frequency, PPMs and convertors must be resilient to reasonable frequency variations. DC connected PPMs shall be capable of staying connected to the network and operating within pre-defined frequency ranges and time periods compatible with AC connected. Given the nature of DC-connected PPMs, no split between Synchronous Areas is deemed reasonable for this requirements, resulting in a single frequency withstand capability for all of Europe. HVDC convertors as part of the network must be last to disconnect in case of severe system events, proposed consistent with any other convertor requirements, and do have as such longer duration times for this withstand capability.

The frequency withstand capabilities in context of offshore have also been clarified by differentiating requirements for DC connected PPM and remote end HVDC converter stations.

For DC connected PPM using 50 Hz nominal frequency, the frequency withstand capabilities have been strictly aligned to NC RfG while requirements for HVDC converter stations are based on the same frequency ranges as NC RfG and DCC but with longer times for operation in each range, ensuring that the network is more resilient to disturbance than generation or demand.

Greater flexibility has been added to allow for innovation particularly focused on reduction in the high offshore production costs, including allowing different choice of frequency, including

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- the 16 2/3 Hz design under consideration by some developers to allow AC applications to be used further from the shore with frequency converters located onshore
- variable frequency offshore, delivering the variable speed of the wind turbine for optimal energy capture with simpler and possibly more robust designs of the turbines.
- Although not explicitly covered, e.g. there is no block either on use of MVDC based generation with MVDC collection networks and MVDC/HVDC voltage conversion to link to an HVDC system.

Voltage withstand capability

Withstand capability of an HVDC link is mandatory over an acceptable set of operating voltage conditions. However, is order to be tuned to collection network needs, the ranges of withstand capability in voltage are defined as non-exhaustive form.

Reactive Power Control and Voltage Support

The NC HVDC establishes requirements for reactive power control and voltage support capability in order to allow a future stable, reliable and economic operation of the system. The proposed requirement is written to reach cost effective but secure capability building depending on system needs.

Fault Ride Through

The NC HVDC establishes requirements for FRT for all grid users within a DC connected AC collection grid in order to prevent large outages in case of failures within the AC collection grid. The entire DC connected AC collection system must be able to withstand disturbances in the AC transmission systems connected to. The expected behaviour of the DC connected Power Park Module in case of asymmetrical faults will depend on chosen approach to protect the local system. This requirement for asymmetrical faults is therefore defined as non-exhaustive.

4.8. Information exchange and coordination – Articles 49 to 52

The objective is to provide an adequate and coordinated information exchange between network operators and HVDC system and DC connected offshore PPM owners. These requirements enable the TSOs to operate the power system in an efficient and minimum cost manner.

The ENTSO-E NC HVDC drafting the requirements on information exchange and coordination reflect application of similar principles to those used in the other connection codes (generation, demand).

4.9. Compliance & derogation – Articles 65 to 75

The question whether the code is applied to existing HVDC link is a major one. In the previous connection codes (generation, demand), ENTSO-E has proposed an approach where a national TSO could initiate and carry out to its end a procedure of applicability. In that case, a Cost-Benefit Analysis showing the socio-economic benefits and cost of the proposal has to be carried out and the report will be subject to a public consultation. Finally, the TSO sends the proposal on the applicability of the requirement, including the outcome of the consultation, to the relevant national regulatory authority for approval.

ENTSO-E following initial consultation has incorporated this same approach to the NC HVDC.

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4.10. Comparison with existing regulatory practices

In order to secure the operation of the power system with the existing links or links expected in the near future, national grid codes or technical specifications are in place in 11 countries.

The NC HVDC is broadly in line with the requirements proposed in these existing documents. Application of the NC will therefore only result in minor or no deviation with regards to frequency ranges, voltage ranges, reactive power capability and power reduction at overfrequency.

Substantial changes have been made to earlier consultation version of the code, mainly related to the frequency/voltage withstand capabilities, maximum power reduction at under-frequency and reactive power requirements.

The most significant deviation from existing practices in national Grid Codes and specifications used relates to offshore requirements for ranges for frequency, voltage and reactive power. However, in the only four applications of HVDC connection of offshore PPMs physically in place by end of 2014 (these projects are here referred to as "existing") these offshore requirements are already broadly included, with only minor differences.

A more detailed evaluation of current practices can be found in FAQ 10.

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5. Conclusions

The energy system is changing rapidly especially with the massive integration of RES. This requires a new framework to cope with the challenges ahead. All participants of the energy market are faced with significant changes and the implementation of new processes and technologies. The NC HVDC is proposing to break new ground to help to accomplish this task at a European level. ENTSO-E acknowledges that significant changes to the existing framework are necessary.

To establish an optimal development of the network code, ENTSO-E conducted initially a "Call for Stakeholder Input" [13] focused on a draft scope and after having taken account of comments received developed the full code. In addition to the collaboration with various organizations via public workshops and meetings of a dedicated NC HVDC User Group, a two-month written consultation on a full draft code took place in Nov/Dec. 2013.

In ENTSO-E's view the NC HVDC contributes to the goals of ensuring secure system operation, enhancing market integration and supporting the integration of RES into the system now and in the years to come. As a consequence, not only today's situation that reflects the historical development was taken into account, but future development as given in European and national scenarios as well. As a result the requirements for the 3 main HVDC types of application are described, covering

- Interconnections of synchronous areas.
- Embedded HVDC links providing power corridors in parallel with HVAC.
- HVDC linking Power Park Modules to the larger Synchronous Areas.

ENTSO-E is confident that the NC HVDC is in line with ACER's FWGL, meets the needs for system operation for the European network for the foreseeable years and aligns with the key messages and opinions provided by stakeholders.

Capabilities should be established suitable for the lifetime of the assets. In NC HVDC it has been necessary to compromise with postponing some requirements in areas where the technology is not ready to deliver, such as direct DC connections to meshed DC systems. A similar position should be noted with regard to still emerging system needs (from system technical challenges) regarding operation with the most extreme RES domination (RES penetration much beyond 50% for a synchronous area). This approach should facilitate freedom for the technology to deliver the most optimal solutions practicable. These further aspects are expected to be covered in later versions of the NC HVDC.

On topics with potential for constraining innovation or for cutting costs particular care has been taken to fully explore options with manufacturers, project developers and other impacted parties and to find the right balance of equitable treatment and lowest cost for individual projects and society, in the interest of all energy consumers.

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7. Abbreviations and definitions

AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
CA	Control Area
CBA	cost-benefit analysis
CIGRE	International Council on Large Energy Systems
CP	Connection Point
DC	Direct Current
DCC	Demand Connection Code
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible AC Transmission Systems
FG	Framework Guidelines
H	system inertia constant
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronic Engineers
IET	Institution of Engineering & Technology
LCC	Line-commutated converter
NC	Network Code
NPS	Negative Phase Sequence
NSG	non-synchronous generation
PCC	power control characteristics
PPM	Power Park Module
PV	photovoltaic
RES	Renewable Energy Sources
RfG	Requirements for Generators (network code)
SA	Synchronous Area
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VSC	Voltage-sourced converter
WG	Working Group

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Active Power - is the real component of the Apparent Power at fundamental Frequency, expressed in watts or multiples thereof (e.g. kilowatts (kW) or megawatts (MW));

Active Power Frequency Response - is an automatic response of Active Power output from a Power Generating Module or a HVDC System, in response to a change in system Frequency from the nominal system Frequency;

Agency is The Agency for the Cooperation of Energy Regulators (ACER) as established by Regulation (EC) No 713/2009;

Apparent Power - is the product of Voltage and Current at fundamental Frequency, and the square root of three in case of three phase systems. It is usually expressed in kilovolt-amperes (kVA) or megavolt-amperes (MVA) and consists of a real component (Active Power) and an imaginary component (Reactive Power);

Black Start Capability - is the capability of recovery of a Power Generating Module from a total shutdown through a dedicated auxiliary power source without any electrical energy supply which is external to the Power Generating Facility or the capability of a HVDC Converter Station to energise a dead AC grid;

Compliance Monitoring - means the process of verification that, after starting operation, the technical capabilities of Power Generating Modules, Demand Facilities, Distribution Networks, Distribution Network Connections or HVDC Systems are maintained compliant with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009;

Compliance Simulation - means the process of verification that Power Generating Modules, Demand Facilities, Distribution Networks, Distribution Network Connections or HVDC Systems are compliant with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009. The process consists at least in reviewing the documentation, verifying the compliance with the requested capabilities by simulation studies and comparing against actual measurements;

Compliance Testing - means the process of verification that Power Generating Modules, Demand Facilities, Distribution Networks, Distribution Network Connections or HVDC Systems are compliant with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009. The process consists at least of reviewing the documentation, verifying the compliance with the requested capabilities by practical tests;

Connection Agreement - means a contract between the Relevant Network Operator and either the Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner, which includes the relevant site and technical specific requirements for the Power Generating Facility, Demand Facility, Distribution Network, Distribution Network Connection or HVDC System;

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Connection Point - is the interface point at which the Power Generating Module, Demand Facility, Distribution Network or HVDC System is connected to a Transmission Network, offshore Network, Distribution Network, or HVDC System, as identified in the Connection Agreement;

Cost-Benefit Analysis – is a process by which the expected costs of alternative actions aiming at the same objective are compared to the expected benefits in order to determine the alternative with the highest net socio-economic benefit. If applicable, the alternatives include network-based and market-based actions;

Current - unless stated otherwise, Current refers to the root-mean-square value of the phase Current, expressed in amps (A) or multiples thereof;

Derogation - means a time limited or indefinite (as specified) acceptance in writing of a non-compliance of a Power Generating Module, Demand Facility, Distribution Network or HVDC System with regard to identified requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009;

Distribution Network – means an electrical Network, including Closed Distribution Networks, for the distribution of electrical power from and to third party[s] connected to it, a Transmission or another Distribution Network;

Distribution Network Connection – means the electrical plant and equipment present at the Connection point, typically a substation, of either a new or existing Distribution Network to the Transmission Network;

Droop - is the ratio of the steady-state change of Frequency (referred to nominal Frequency) to the steady-state change in Active Power output (referred to Maximum Capacity) expressed in percentage terms;

Energisation Operational Notification (EON) - means a notification issued by the Relevant Network Operator to a Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner prior to energisation of its internal Network;

Equipment Certificate - means a document issued by an Authorised Certifier for equipment used by a Power Generating Module or a Demand Unit providing DSR connected to the Distribution Network, Transmission Connected Distribution Network, Transmission Connected Demand Facility or HVDC System confirming performance in respect of the relevant requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009. The Equipment Certificate defines the extent of its validity. This identifies its validity at a national or other level at which a specific value is selected from the range allowed at a European level. The Equipment Certificate can additionally include models confirmed against test results for the purpose of replacing specific parts of the compliance process. The Equipment Certificate will have a unique number allowing simple reference to it in the Installation Document, the Power Generating Module Document or the Demand Side Response Unit Document;

Fast Fault Current - means a current, measured in RMS value or as instantaneous value, to be injected by a Power Park Module or HVDC System during and after a system disturbance caused by an electrical fault with the purpose of identifying a fault by Network protection systems at the initial stage of the fault, supporting system Voltage retention at the later stage of the fault and system Voltage restoration after fault clearance;

Final Operational Notification (FON) - means a notification issued by the Relevant Network Operator to a Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner who complies with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009 to allow them to operate its respective Power Generating Module, Demand Facility, Distribution Network or HVDC System by using the grid connection;

Frequency - means the electric frequency of the system that can be measured in all parts of the Synchronous Area under the assumption of a coherent value for the system in the time frame of seconds, with only minor differences between different measurement locations, expressed in Hertz;

Frequency Control - is 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 Setpoint, in order to maintain stable system Frequency;

Frequency Response Deadband - is used intentionally to make the Frequency Control not responsive. In contrast to (in)sensitivity, deadband has an artificial nature and basically is adjustable;

Frequency Response Insensitivity - is the inherent feature of the control system defined as the minimum magnitude of the Frequency (input signal) which results in a change of output power (output signal);

Frequency Sensitive Mode (FSM) - is a Power Generating Module or HVDC System operating mode which will result in Active Power output changing, in response to a change in system Frequency, in a direction which assists in the recovery to target Frequency, by operating so as to provide Frequency Response;

Instruction - means any command given from a Network Operator to a Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner in order to perform an action, in so far as it is within the authority of the Network Operator to give that command;

Interim Operational Notification (ION) - means a notification issued by the Relevant Network Operator to a Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner to allow them to operate its respective Power Generating Module, Demand Facility, Distribution Network or HVDC System by using the grid connection for a limited period of time and to initiate compliance tests to ensure the compliance with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009;

Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) - is a Power Generating Module or HVDC System operating mode which will result in Active Power output reduction in response to a change in system Frequency above a certain value;

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Limited Frequency Sensitive Mode – Underfrequency (LFSM-U) - is a Power Generating Module or HVDC System operating mode which will result in Active Power output increase in response to a change in system Frequency below a certain value;

Limited Operational Notification (LON) - means a notification issued by the Relevant Network Operator to a Power Generating Facility Owner, Demand Facility Owner, Distribution Network Operator or HVDC System Owner who previously reached FON status but is temporarily subject to either a significant modification or loss of capability resulting in non-compliance with the relevant specifications and requirements of the Commission Regulations establishing Network Codes that have been adopted according to Article 6(11) of Regulation (EC) No 714/2009;

Network - is plant and apparatus connected together in order to transmit or distribute electrical power;

Network Operator – means an entity that operates a Network. This can be either a TSO, a DSO or CDSO;

Power Park Module (PPM) - is a unit or ensemble of units generating electricity, which is either connected to the Network non-synchronously or through power electronics, and also has a single Connection Point to a Transmission Network, Distribution Network , Closed Distribution Network, or HVDC System;

Reactive Power - is the imaginary component of the Apparent Power at fundamental Frequency, usually expressed in kilovar (kvar) or megavar (Mvar);

Relevant National Regulatory Authority - is the regulatory authority as referred to in Article 35(1) of Directive 2009/72/EC;

Relevant Network Operator - means the Network Operator to which a Power Generating Module, Demand Facility, Distribution Network or HVDC System is or will be connected;

Relevant TSO - means the TSO in whose Control Area a Power Generating Module, a Demand Facility, a Demand Unit, a Distribution Network or a HVDC System is or will be connected to the Network at any Voltage level;

Setpoint - is a target value for any parameter typically used in control schemes;

Synchronous Area - means an area covered by interconnected TSOs with a common system Frequency in a steady state such as the Synchronous Areas Continental Europe (CE), Great Britain (GB), Ireland (IRE), Northern Europe (NE) and the power systems of Lithuania, Latvia and Estonia (together referred as "Baltic") as a part of a Synchronous Area;

Synthetic Inertia - is a facility provided by a Power Park Module or HVDC System to replicate the effect of Inertia of a Synchronous Power Generating Module to a prescribed level of performance;

Transmission Network – means an electrical Network for the transmission of electrical power from and to third party[s] connected to it, including Demand Facilities, Distribution Networks or other Transmission Networks. The extent of this Network is defined at the national level;

Transmission System Operator (TSO) - is a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity;

U-Q/P_{max}-profile - is a profile representing the Reactive Power capability of a Power Generating Module or HVDC Converter Station in context of varying Voltage at the Connection Point;

Voltage - unless stated otherwise, Voltage refers to the root-mean-square value of the phase-to-phase voltage;

1 pu grid Voltage - for the 400 kV grid Voltage level (or alternatively commonly referred to as 380 kV level) the reference 1 pu value is 400 kV, for other grid Voltage levels the reference 1 pu Voltage may differ for each TSO in the same synchronous area i.e. the Voltage range in kV for all TSOs within a synchronous area may not be the same.

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