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Technical Guidelines for Radial HVDC Networks

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Technical Guidelines for Radial HVDC Networks

Directives techniques pour les réseaux
HVDC radiaux

Technischer Leitfaden für radiale HGÜ-
Netze

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CENELEC

European Committee for Electrotechnical Standardization
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Contents

Page

Foreword	7
0 Introduction	8
0.1 The European HVDC Grid Study Group	8
0.2 Technology	9
0.2.1 Converters	9
0.2.2 DC Circuit	9
0.2.3 Technological Focus of the European HVDC Grid Study Group	10
1 Scope.....	12
2 Terminology and abbreviations.....	12
2.1 General	12
2.2 Terminology and abbreviations for HVDC Grid Systems used in this report	12
2.3 Proposed Terminology by the Study Group	13
3 Typical Applications of HVDC Grids	14
3.1 The Development of HVDC Grid Systems.....	14
3.2 Planning Criteria for Topologies.....	15
3.2.1 General.....	15
3.2.2 Power Transfer Requirements.....	16
3.2.3 Reliability.....	17
3.2.4 Losses.....	19
3.2.5 Future Expansions.....	21
3.3 Technical Requirements	21
3.3.1 General.....	21
3.3.2 Converter Functionality	22

3.3.3	Start/stop Behaviour of Individual Converter Stations	23
3.3.4	Network Behaviour during Faults	24
3.3.5	DC-AC Interface Requirements	25
3.3.6	The Role of Communication	26
3.4	Typical Applications – Relevant Topologies	27
3.4.1	General.....	27
3.4.2	Radial Topology	27
3.4.3	Meshed Topology	29
3.4.4	HVDC Grid Systems Connecting Offshore Wind Power Plants	29
3.4.5	Connection of a wind power plant to an existing HVDC VSC link	30
4	Principles of DC Load Flow.....	31
4.1	General	31
4.2	Structure of Load Flow Controls	31
4.2.1	General.....	31
4.2.2	Converter Station Controller	31
4.2.3	HVDC Grid Controller	32
4.3	Converter Station Control Functions	34
4.3.1	General.....	34
4.3.2	DC Voltage (U_{DC}) Stations	34
4.3.3	Active Power (P_{DC}) and Frequency (f) Controlling Stations	34
4.4	Paralleling Transmission Systems	35
4.4.1	General.....	35
4.4.2	Paralleling on AC and DC side	35
4.4.3	Paralleling on the AC side	35
4.4.4	Steady-State Loadflow in Hybrid AC/DC Networks	36

4.5	Load Flow Control	38
4.5.1	DC Voltage Operating Range.....	38
4.5.2	Static and Dynamic System Stability.....	39
4.5.3	Step response	39
4.6	HVDC Grid Control Concepts.....	40
4.6.1	General.....	40
4.6.2	Voltage-Power Droop Together with Dead Band.....	45
4.6.3	Voltage-Current Droop	48
4.6.4	Voltage-Power Droop — Control of the HVDC Grid Voltage	54
4.7	Benchmark Simulations of Control Concepts.....	57
4.7.1	Case Study	57
4.7.2	Results	58
4.7.3	Conclusions	60
4.7.4	Interoperability	61
5	Short-Circuit Currents and Earthing	61
5.1	General	61
5.2	Calculation of Short-Circuit Currents in HVDC Grid Systems.....	61
5.3	Network Topologies and their Influence on Short-Circuit Currents	63
5.3.1	Influence of DC Network Structure	63
5.3.2	Influence of Line Discharge.....	66
5.3.3	Influence of Capacitors	67
5.3.4	Contribution of Converter Stations.....	69
5.3.5	Methods of Earthing	72
5.4	Secondary Conditions for Calculating the Maximum/Minimum Short-Circuit Current.....	73
5.5	Calculation of the Total Short-Circuit Current (Super Position Method).....	74

5.6	Reduction of Short-Circuit Currents	75
6	Principles of HVDC Grid Protection	76
6.1	General	76
6.2	HVDC Grid System	77
6.3	AC/DC Converter	78
6.3.1	General.....	78
6.3.2	DC System	79
6.3.3	HVDC Switchyard.....	80
6.3.4	HVDC System without Fast Dynamic Isolation.....	80
6.3.5	HVDC System with Fast Dynamic Isolation	80
6.4	DC Protection.....	81
6.4.1	General.....	81
6.4.2	DC Converter Protections	81
6.4.3	Protective Shut Down of a Converter	83
6.4.4	DC System Protections	84
6.4.5	DC Equipment Protections	84
6.5	Clearance of Earth Faults	84
6.5.1	Clearance of a DC Pole-to-Earth Fault.....	84
6.5.2	Clearance of a Pole-to Pole Short Circuit	85
6.5.3	Clearance of a Converter side AC Phase-to-Earth Fault	85
7	Functional Specifications.....	85
7.1	General	85
7.2	AC/DC Converter Stations	86
7.2.1	DC System Characteristics.....	86
7.2.2	Operational Modes.....	89
7.2.3	Testing and Commissioning.....	95

7.3	HVDC breaker	96
7.3.1	System Requirements	96
7.3.2	System Functions	96
7.3.3	Interfaces and Overall Architecture	96
7.3.4	Service Requirements	96
7.3.5	Technical System Requirements	96
Annex A	(informative) HVDC – Grid Control Study	99
Annex B	(informative) Fault Behaviour of Full Bridge Type MMC	106
B.1	Introduction	106
B.2	Test Results	106
B.3	DC to DC Terminal Faults	106
B.4	DC Terminal to Ground Faults	107
B.5	Conclusion	107
Bibliography		119

Foreword

This document (CLC/TR 50609:2014) has been prepared by CLC/TC 8X “System aspects of electrical energy supply”.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CENELEC by the European Commission and the European Free Trade Association.

This document was already sent out within CLC/TC 8X for comments and the comments received were discussed within CLC/TC 8X/WG 06 and were incorporated in the current document as far as appropriate.

0 Introduction

0.1 The European HVDC Grid Study Group

Existing power systems in Europe have been developing for more than 100 years to transmit the power, generated mainly by fossil and nuclear power plants to the loads. Climate change, limited fossil resources and concerns over the security of nuclear power are drivers for an increased utilization of renewable sources, such as wind and solar, to realize a sustainable energy supply. According to the geological conditions, the location of large scale renewable energy sources is different to the location of existing conventional power plants and imposes new challenges for the electric power transmission networks, such as extended transmission capacity requirements over long distances, load flow control and system stability. The excellent bulk power long distance transmission capabilities, low transmission losses and precise power flow control make High Voltage Direct Current (HVDC) the key transmission technology for mastering these challenges, in particular for connection of offshore wind power plants to the onshore transmission systems.

While the power system reinforcement is already underway by a number of new point-to-point HVDC interconnections, the advantages offered by multiterminal HVDC systems and HVDC grids become more and more attractive. Examples are grid access projects connecting various wind power plants or combining wind plants with point-to-point transmission, e.g. in the North and Baltic Seas. Multiterminal projects are already in execution and there is planning for pan-European HVDC grids. In this document, multiterminal HVDC systems and HVDC grids are referred to as HVDC Grid Systems.

To become reality, HVDC Grid Systems need, in addition to the necessary political framework for cross country system design, construction and operation, competitive supply chains of equipment capable of operating together as an integrated system. This marks a significant change in the HVDC technology market. While today - with very few exceptions – a HVDC transmission system has been provided by a single manufacturer, future HVDC Grid Systems will be built step by step composed of converters and HVDC substations supplied by different manufacturers. Interoperability will thus become a fundamental requirement for future HVDC technology.

Common understanding of basic operating and design principles of HVDC Grid Systems is seen as a first step towards multi vendor systems, as it will help the development for the next round of European multiterminal projects. Furthermore, it will prepare the ground for more detailed standardization work.

Based on an initiative by the DKE German Commission for Electrical, Electronic and Information Technologies, the European HVDC Grid Study Group has been founded in September 2010 to develop “Technical Guidelines for first HVDC Grids”. The Study Group has the following objectives:

- to describe basic principles of HVDC grids with the focus on near term applications;
- to develop functional specifications of the main equipment and HVDC grid controllers;
- to develop “New Work Item Proposals” to be offered to CENELEC for starting standardization work.

CIGRÉ SC B4, CENELEC TC8x and ENTSO-E and “Friends of the Supergrid” are involved at an informative level with the results of the work.

Members affiliated with the following companies and organizations have been actively contributing to the results of the Study Group achieved so far: 50 Hz Transmission, ABB, ALSTOM, Amprion, DKE,

TransnetBW, Energinet.dk, ETH Zurich, National Grid, Nexans, Prysmian, SEK, Siemens, TenneT and TU Darmstadt.

As a starting point the Study Group has been investigating typical applications and performance requirements of HVDC Grid Systems. This information helps elaborating the basic principles of HVDC networks, which are described in the following clauses:

- Clause 3, Typical Applications of HVDC Grids;
- Clause 4, Principles of DC Load Flow;
- Clause 5, Short-Circuit Currents and Earthing;
- Clause 6, Principles of HVDC Grid Protection.

From the technical principles described, functional specifications for the main equipment of HVDC networks are derived and summarized in Clause 7.

0.2 Technology

0.2.1 Converters

HVDC transmission started more than 60 years ago. Today, the installed HVDC transmission capacity exceeds 200 GW worldwide. The vast majority of the existing HVDC links are based on so-called Line-Commutated-Converters (LCC). LCC today are built from Thyristors. The power exchange of such converters is determined by controlling the point-on-wave of valve turn-on, while the turn-off occurs due to the natural zero crossing of valve current forced by the AC network voltage. That is why LCC rely on relatively strong AC systems to provide conversion from AC to DC and vice versa.

With so-called Voltage Sourced Converters (VSC), a different type of converters has been introduced to HVDC transmission slightly more than a decade ago. VSCs today utilize Insulated Gate Bipolar Transistors (IGBT) as the main switching elements. IGBTs have controlled turn-on as well as turn-off capability making the VSCs capable of operating under weak AC system conditions or supplying power systems where there is no other voltage source, also referred to as passive networks.

The evolution of VSC transmission was started with so-called Two-Level converters at the end of the 1990s and has commenced to Three Level Converters and further to Modular Multilevel Converters (MMC) which have made their break-through in the mid to late 2000s. All MMC type converters apply the same principle of connecting a number of identical converter building blocks in series. However, at the present time there are basically two types of such building blocks: referred to as Half-Bridge (HB) and Full-Bridge (FB) modules.

Other converter equipment which have been proposed for HVDC Grid applications, such as DC/DC converters, load flow controllers, etc. are not discussed in this document.

0.2.2 DC Circuit

Similar to AC networks, HVDC transmission systems can be distinguished by their network topologies as radial and/or meshed networks and with respect to earthing in effectively grounded and isolated systems. Both aspects influence the design criteria and the behaviour of the HVDC system.

– Radial and Meshed Topologies:

In radial systems, there is not more than one connection between two arbitrary nodes of the network. The DC voltages of the converter stations connected to each end of a line solely determine the power flow through that line, for example in Figure 1-1, station C is radially connected with station D.

In meshed systems, at least two converter stations have more than one connecting path. Without any additional measures the current through a line will then be determined by the DC voltages of the converter stations as well as the resistances of the parallel connections. In Figure 1-1, the DC circuit connecting stations A, B and C forms a meshed system while C and D is a radial connection. A HVDC Grid System having a meshed topology can be operated as a radial system if parallel connections are opened by disconnectors or breakers.

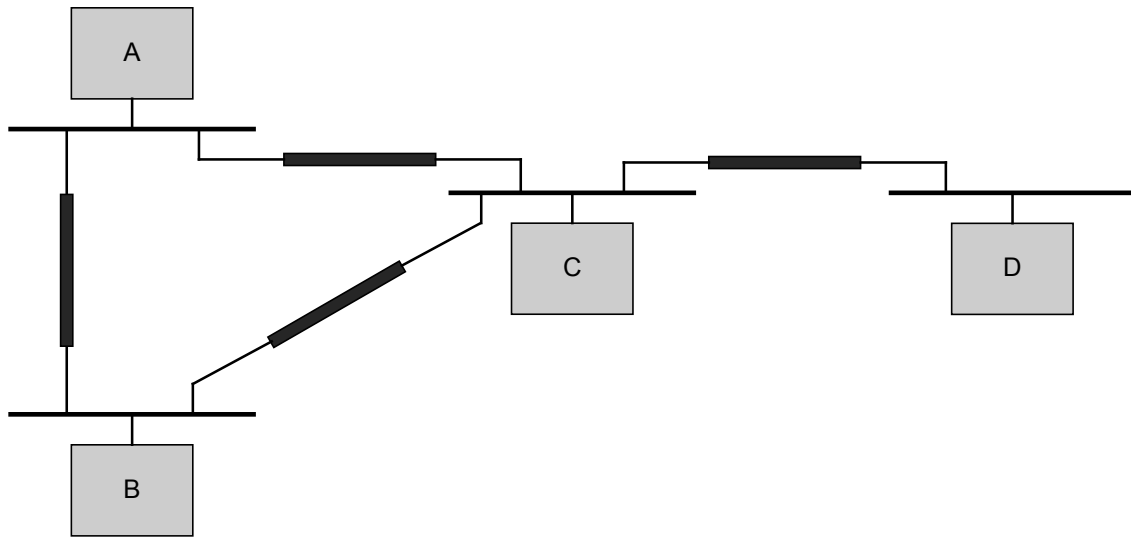


Figure 1-1 — Example of an HVDC Grid System having a meshed and radial structure

– Earthing:

DC circuits can be effectively grounded if one DC pole is connected to earth through a low ohmic branch. Such systems are also referred to as asymmetrical Monopoles or just “Monopoles”. Two Monopoles of opposite DC voltage polarity are often combined into so-called bipolar systems or just “Bipoles”.

Isolated DC circuits do not have a low ohmic connection to ground on the DC side. These configurations are also referred to as “Symmetrical Monopoles”.

0.2.3 Technological Focus of the European HVDC Grid Study Group

Various technologies are available for building HVDC Grid Systems. Some of them have already been used in commercial projects; others are in the demonstration phase or are in an early stage of discussion. This applies to the converter technology as well as the topologies of connecting them into a HVDC Grid System.

Serving the near term applications, the Study Group decided to focus its scope of work on radial HVDC network structures as well as pure VSC based solutions. Both grounded and ungrounded DC circuits are considered.

The integration of HVDC Grid Systems is seen as an important part of developing future electric power systems. The Study Group bases its work on typical requirements applied to state of the art HVDC converter stations today and investigates aspects that are specifically related to the design and operation of converter stations and DC circuits. The requirements from the AC systems as known today are included. Secondary effects associated with changing the AC systems, e.g. the replacement of rotating machines by power electronic devices, are not within the scope of the Study Group.

The Study Group report summarizes the selected results of work and gives recommendations for the next steps towards preparing the ground for standardization of HVDC multiterminal systems and HVDC Grid Systems.

The interface requirements and functional specifications given in this document are intended to support the specification and purchase of multi vendor multiterminal HVDC Grid Systems.

1 Scope

This Technical Report applies to HVDC Systems having more than two converter stations connected to a common DC network, also referred to as HVDC Grid Systems. Serving the near term applications, this report describes radial HVDC network structures as well as pure VSC based solutions. Both grounded and ungrounded DC circuits are considered.

Based on typical requirements applied to state of the art HVDC converter stations today this report addresses aspects that are specifically related to the design and operation of converter stations and DC circuits in HVDC Grid Systems. The requirements from the AC systems as known today are included. Secondary effects associated with changing the AC systems, e.g. the replacement of rotating machines by power electronic devices, are not within the scope of the present report.

The report summarizes applications and concepts of HVDC Grid Systems with the purpose of preparing the ground for standardization of such systems.

The interface requirements and functional specifications given in this document are intended to support the specification and purchase of multi-vendor multiterminal HVDC Grid Systems.

2 Terminology and abbreviations

2.1 General

In the work undertaken here it has been identified that a common list of terminology and abbreviations used specifically to describe HVDC Grids should be established.

The International Electrotechnical Commission (IEC) standard EN 60633 [1] describes General Terminology for HVDC Transmission and is the reference for common terms and abbreviations. Furthermore EN 62501 [2] describes electrical testing of VSC. A new proposed work item in IEC is to develop terminology for VSC HVDC systems. In addition CIGRÉ has published a brochure 269 on basic operational principles of VSC-HVDC [3]. Specific terms required for components and methods for multiterminal HVDC Transmission, e.g. HVDC breakers and control modes, are described here.

The Study Group has established information exchange established with the ongoing CIGRÉ B4.52 feasibility study on DC Grids. Also in the CIGRÉ work, new terms used to describe phenomena and components in DC grids are used. The terminology used in this report corresponds to the terminology used in the CIGRÉ working group.

2.2 Terminology and abbreviations for HVDC Grid Systems used in this report

AC	Alternating Current
DC	Direct Current
ENTSO-E	European Network of Transmission System Operators for Electricity
FB	Full Bridge
GW	Giga Watts

HB	Half Bridge
HSS	High Speed Switch
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LCC	Line Commutated Converter
MMC	Modular Multilevel Converter
OHL	Overhead transmission line
PCC AC	Point of common coupling (ac side)
PCC DC	Point of common coupling (dc side)
TRV	Transient Recovery Voltage
TSO	Transmission System Operator
VCD•	Voltage-current droop
VPD•	Voltage-power droop
VPDDB•	Voltage-power droop together with dead band
VSC	Voltage Sourced Converter

2.3 Proposed Terminology by the Study Group

- Converter Station Controller A controller determining the voltages and currents at DC and AC terminals of its converter station.
4.2.2, Converter Station Controller
- Dynamic Braking Device A controllable branch absorbing energy from the DC circuit.
7.2.2.2, Energy absorption capability (Dynamic Braking Device)
- HVDC Grid Controller A high level controller linked to each individual Converter Station Controller
4.2.3, HVDC Grid Controller

3 Typical Applications of HVDC Grids

3.1 The Development of HVDC Grid Systems

Today power transmission systems are largely based on AC. AC is beneficial in most applications for a number of reasons:

- easy to generate from mechanical energy in rotating machines or to convert back;
- easy to transform to higher voltage levels reducing power transmission losses;
- current zero crossings allow simple principles for load current switching and fault clearing.

However, there are applications where AC cannot be used or where DC technology is more economical than AC. Examples are:

- connecting asynchronous AC systems;
- long distance Overhead Line (OHL) or cable transmission;
- power flow control in large integrated AC systems (improving system stability).

Since its introduction in the middle of the 20th century, High Voltage Direct Current (HVDC) transmission has become a fundamental part of many electric power transmission systems worldwide. With a few exceptions, HVDC transmission systems are built so far as point-to-point links.

The requirements for point-to-point links have been specified by the Transmission System Operators (TSOs) involved according to the functionality needed as well as the respective AC network operating conditions. When HVDC technology is considered for multi-terminal systems or HVDC grids, more TSOs are involved with system planning and operation. At the same time the functional requirements and variety of AC system conditions to be covered increases. This requires establishing efficient coordination of design, operation, control and regulation between the connected AC and DC systems. Agreement contracts on physical and regulatory boundaries, responsibilities and utilization of the AC/DC converter stations as well as harmonization of technical regulations for the AC and DC systems are necessary prerequisites for the cooperation between the involved operators.

Multi-terminal Systems and HVDC Grids will further on be referred to in this report as “HVDC Grid Systems”.

Similar to the evolution of AC transmission systems, HVDC Grid Systems should have the ability to grow according to demand. It should be possible to interconnect several smaller HVDC systems into larger integrated systems.

Some of the future HVDC Grid Systems may be financed and operated by independent HVDC Grid System companies. To ensure the required level of interoperability, the system design and operation requirements for the individual HVDC systems need to be harmonized in corresponding Grid Codes.

The development of HVDC Grid Systems is likely to start in small scale radial configurations, like with DC connections between existing AC systems. The Kriegers Flak Combined Grid Solution (CGS) project in the Baltic Sea may be amongst the first pilot projects of such future HVDC Grid Systems. If commissioned

as the CGS, the offshore based HVDC Grid System will connect the expected 600 MW wind power at the Danish area of Kriegers Flak and approx. 400 MW at the Baltic 1 and Baltic 2 German wind power plants to the onshore AC transmission systems of Denmark and Germany and provide a connection between the AC systems of these two countries. The commissioning period of the HVDC-based CGS is expected between 2018 and 2020. The Kriegers Flak CGS shall be specified, commissioned and operated by the Danish TSO Energinet.dk and the German TSO 50 Hz Transmission GmbH. The Kriegers Flak CGS project has been granted European Union funding from the European Energy Programme for Recovery (EEPR).

The present clause describes important system operation and design criteria for HVDC Grid Systems that are intended to become integral part of the European electric power transmission systems. This work gives guidance to the elaboration of the functional requirements for HVDC grid components and systems within the European HVDC Grid Study Group. It intends also provide a contribution to the development of a common Grid Code for European HVDC Grid Systems.

3.2 Planning Criteria for Topologies

3.2.1 General

The starting point and a governing factor when evaluating and deciding on the system topology is the geography with the primary consumers, producers, and load flow exporters and importers. The first choice for this system topology will be the most obvious, easiest and immediately the cheapest way to connect the consumers and producers with each other.

The normal operational flow direction is defined from production to consumption centres. For example, in the case of a wind power plant, bi-directional power flow may be required: In normal operation the wind turbines produce energy that is transferred from the offshore platform to the onshore substation. Occasionally it will also be necessary to transfer energy from the onshore substation to the offshore platform converter when there is no wind, when the electrical equipment on the platform has to be maintained or the wind turbines are starting up, e.g. energizing the offshore platform converter and the offshore medium voltage (MV) and HV networks.

When choosing the system topology, the AC grid connection-point candidates are evaluated. The evaluation comprises, but is not limited to, benchmarking of the connection-point candidates from technical, environmental, cost-benefit and socioeconomic criteria. The benchmarking process shall also consider if the topology and connection-point candidates are dependent on each other; e. g. alternative topologies evolve from alternative connection-points and vice versa.

The needs and ability for the topology to expand in the future is difficult to predict. Therefore there is a risk of “built-in” overcapacity within the selected topology to cover possible, but not necessarily provable, future expansion. At present, the national AC grid operators apply similar, but area- and country-specific, procedures including technical, cost-benefit and socioeconomic evaluation criteria for future grid capacity and topology. The differences between such area- and country-specific procedures are due to different grid design and operation practice, regulations and definition of security of supply. The common goal should be that the AC and, in future, DC grid operators establish standard, European-level procedures. The standard procedures should be established for decisions on the overcapacity financing model including technical, regulatory, cost-benefit and socioeconomic evaluations of risks, benefits and disadvantages of the topology from present and future perspectives. The future perspective should be evaluated for mid term, i.e. for between 5 and 10 years perspective, and long term, i.e. over 10 years perspective, from the commissioning date.

Depending on the specific topologies, there can be various constraints for system operation, as there are:

- operation conditions (grid revision plans);
- disturbances (faults and outages);
- controllability restrictions;
- limitation of maximum short circuit currents;
- load flows congestions.

Operational constraints can be present both in the DC and AC transmission systems due to limitations of the system components. By careful selection of the system topology, adequate system capacity and sufficient controllability and redundancy the consequences of system constraints can be minimized.

For relatively short distances and small energy flows, AC cable transmission systems are economically competitive and advantageous to DC transmission systems. The competitive elements of DC transmission may include the cost-benefit evaluations of the AC versus DC system components, technical and commissioning aspects, arrangements for required ancillary services, maintenance, reliability, losses minimization, commercial availability and experience from earlier projects etc. The evaluation shall be performed for the (expected) lifetime period of the system. The advantages gained with a DC system should outweigh the cost.

3.2.2 Power Transfer Requirements

The main purpose of an electrical transmission system is the exchange of energy between its sub-stations representing energy consumption or energy production.

AC transmission systems are built for operation at high voltage levels, e.g. above 110 kV AC, whereas distribution systems belong to medium-voltage (MV) and low-voltage (LV) levels. At present, AC dominates the transmission systems whereas DC technology is present as part of the AC systems, for instance, in point-to-point connectors between two AC systems. AC is also the standard for distribution level systems.

Both HVAC and HVDC systems are utilized to transport significant amounts of power and energy over great geographical distances. HVDC transmission has advantages if costs associated with the distances and amounts of the power to be transmitted are lower than the costs for an appropriate HVAC transmission. Typical break-even distances of HVAC versus HVDC transmission utilizations are in the range of 50-110 km for cable connections, and in the range of 500-600 km for connections via overhead transmission lines. The ranges are dependent on several technical factors such as the nominal voltage, nominal power, losses, but also non-technical factors like rights of way. When two asynchronous HVAC areas are interconnected, HVDC is chosen for technical reasons.

HVDC transmission is also used in parallel, with HVAC connections; this is referred to as “embedded HVDC” systems. In addition to its main function of power transport, embedded HVDC systems are used for stabilization and power flow control of the corresponding HVAC connections. For example, HVDC systems in parallel with HVAC lines may be used for damping of inter area oscillations. [4], [5], [6] Furthermore, within their design capabilities, HVDC converter stations can support the HVAC transmission systems by providing reactive-power, AC voltage and frequency control.

Until today, the main focus of HVDC transmission has been mainly on design, operation and reliability of the AC system. The AC/DC converter stations have been interpreted as generator-like units and assigned to the grid code requirements of the AC system operators [7]. When the HVDC Grid System expands in terms of system dimensions and power capacity, the HVDC Grid System is expected to require ancillary services from the adjacent AC systems. This may lead to the DC system design, operation and reliability being based on similar procedures and criteria as applied to AC systems today. For example, similar to the concept of HVDC Grid Systems complementing AC systems, an islanded AC system can also be used to interconnect various HVDC links. At the same time the islanded AC system can provide connection for local generation (or load) such as offshore wind power plants (or oil and gas platforms) [8].

3.2.3 Reliability

The reliability requirements of the HVDC grid will impact upon the redundancy and maintainability of the individual components. Hence the reliability and security-of-supply aspects will have great influence on the final system topology. While reliability is a well-known criterion for AC system planning, its application to HVDC Grid Systems still needs to be defined.

a) AC System Reliability:

The expansion of an AC grid is always targeted to the agreed or predicted power and energy transmission needs. An AC grid is developed so that safe and reliable operational management with a sufficiently high security of supply is achieved. The security of supply has two major terms: the system adequacy and the system security. For further use in this document, those terms are explained below.

The system adequacy is based on probabilistic analysis combining availability of transmission lines and components, energy production and capacity as well as energy demand. The system adequacy is measured in terms of not-delivered energy by amount and time. Periods of not-delivered energy are defined as the time, when some consumption centres do not get all the required energy due to system constraints, lack of energy production or lack of energy capacity. The system adequacy is evaluated for a system in normal operation and in contingencies. The system adequacy is indexed from 0 (the lowest grade) to 100 (the highest grade). When the system is able to deliver all the required energy to all consumption centres at any time, with no constraints or interruptions, then the system adequacy is 100. Here not-delivered energy over a year is zero. When the system is not able to deliver energy to the consumption centres at all, the system adequacy is 0.

The system security is defined as the ability to maintain normal operation in case of forced events such as failures and outages of components or production units. The system security is analysed for rare, but severe and often the most critical, situations determined from practical experience and expert evaluations. However, not all critical situations are possible to predict and analyse. While some unreasonable and unrealistic situations are excluded from such analysis, other plausible severe situations might be overlooked. This means that short-term interruptions of energy delivery to consumption centres may occur and are deemed acceptable in extremely severe and unpredicted operational conditions. The system security can be measured as percentage of energy supply without interruptions, in amount and duration, over a year. Each country and each grid operator have defined targets for what to consider as a sufficiently high system security.

Investments increasing the AC system security of supply should be justified from technical, cost-benefit and socioeconomic evaluations including cooperation with neighbouring system operators. Such cooperation often relies on common rules and grid codes, which the participating members shall comply with. Today, the compliance of each member contributes to efficient operation and security of supply of

the entire interconnected system. However, each grid operator remains responsible for the security of supply within his own system.

With increasing European interconnections and the utilization of HVDC Grid Systems in particular, bodies coordinating the individual TSOs on an European level become more and more important

As the first step to a possible grid expansion, the dimensioning of the grid resources is evaluated with respect to the system adequacy. The common rule for the system adequacy evaluation is n-1 criteria [9], but it can be extended to comply with specific needs of individual grids [10].

The n-1 criterion is fulfilled, if after an outage of a component of the transmission system (overhead line, cable, interconnector, transformer, compensation devices or production units) the following effects are excluded [11], [12]:

- 1) permanent off-limit conditions of nominal operating data and conditions that lead to a significant hazard to reliable operational management or to the damage of electrical equipment;
- 2) interruption of supply despite all available redundancies;
- 3) cascade tripping of protection devices of not direct influenced electrical equipment;
- 4) loss of stability (static and dynamic).

When evaluating the impact of an individual HVDC link on the AC system security, both the function of active power transmission and the ancillary services like reactive power and voltage control should be considered. With respect to active power, individual HVDC links can be divided into the following groups:

- 5) systems connecting wind parks or interconnectors to a different TSO; HVDC systems belonging to this group are considered like controllable generators. Generators are normally built n-0 secure as long as their ratings do not exceed the tolerance imposed by the primary reserve.
- 6) HVDC systems that are embedded into an AC system; HVDC systems belonging to this group are considered like a transmission line. The whole system including the HVDC normally has to fulfil the n-1 criterion. The HVDC system itself is often considered for 100 % operating utilization.

b) HVDC Grid System Reliability:

The HVDC Grid System needs to be considered together with the HVAC grid system as part of the same transmission grid. The rules to be applied should be analogue to the reliability and security-of-supply aspects of existing HVAC transmission systems: The security of supply of the entire system can be divided into the system adequacy and the system security.

Similar to the practice for AC systems, system adequacy evaluation can be based on the n-1 criterion taking into account technical and socioeconomic factors, cost benefits as well as practical experience and regulations. The transmission system operator(s) can define and approve a required (guaranteed) level of the HVDC Grid System performance.

The selected criterion would have to be fulfilled for the combined HVDC/HVAC systems in a similar way as the system adequacy is applied for dimensioning the AC system resources and securing the desired (guaranteed) level of the system adequacy. This means that redundancy, normal-operation and possible

overload conditions of the DC-connections would have to be already addressed and considered in the design stage of the HVDC Grid System. This could require:

- 1) Dimensioning the HVDC Grid System resources so that, in a case of an outage of any single component (e.g. a HVDC line or a HVDC converter station), the scheduled or predicted energy transport requirements can be fulfilled within the required level of the system adequacy. This may require some HVDC converter stations or HVDC lines to be designed to include extra margin (temporary or permanent) for utilization resulting in a capacity margin to handle extra energy transport due to redistribution of power flows within the HVDC Grid System.
- 2) Fast system reconfiguration providing alternative connections to transmit power.

When defining the system topology, the system operators decide how to achieve the required security of supply considering:

- 3) HVDC circuit topology (monopole or bipole connection);
- 4) protection concept;
- 5) topology of protection zones;
- 6) definition of the maximum fault clearing time (establish the new load balance after a predetermined time period);
- 7) relevant faults and outages on the AC system as well on the HVDC grid system;
- 8) static and dynamic stability of the HVDC Grid System and AC systems;
- 9) possibility of energization and de-energization of the HVDC Grid System and AC systems.

3.2.4 Losses

Power transmission is associated with power losses. Within certain limits, the power losses can be influenced by the design of the network components, e. g. cables, converter station or transformers. Typically, the losses at a component behave in an inverse proportion to the investment cost, i.e. a requirement for lower losses results in higher equipment cost. Important reasons for this behaviour are that an increased amount of material may be needed to enlarge conductor cross sections, more expensive materials required or more advanced and precise monitoring and control equipment to be implemented and maintained. An overall economic solution can be achieved based on a realistic assessment of the value of power losses versus equipment cost.

One of the important benefits of HVDC power transmission is its efficiency in terms of losses over long distance transmission in comparison to HVAC power transmission. However it is also important to consider the losses for the total combined AC and DC system as a HVDC transmission link in parallel to an AC transmission system may reduce the losses in the AC transmission system. The no load losses of both HVAC and HVDC power transmissions should also be considered.

One advantage of a multi-terminal scheme instead of separated HVDC links is that a multi-terminal scheme reduces the number of power conversion from AC to DC and vice versa. Each additional conversion will give both greater losses and higher investment cost.

Operating losses are largely influenced by the selection of the nominal DC transmission voltage for the HVDC overhead lines or HVDC cables. An increase of the nominal transmission voltage will reduce the transmission losses due to the lower current, but at the same time likely increases the size and weight of the AC/DC converter stations and its platforms to meet insulation requirements. The cost of equipment would be increased accordingly as are the cost of the transmission lines. Optimization between operation costs and investment costs, taking into account possible future expansion is therefore recommended.

Both in point-to-point HVDC connections and in HVDC Grid System, typical operational power profiles could be used in the loss evaluation. No-load losses in HVDC Grid Systems can be treated by the same evaluation procedure as in point-to-point HVDC connections.

IEC has published standard procedures to calculate the losses in the main components in AC grids. Corresponding loss calculation standards are recommended for all components in a HVDC Grid System. Some of the standards exist and others are under development.

The value of the losses can be calculated with a typical socioeconomic value of e.g. 6 Eurocent/kWh; however the typical support regime value is higher in the North Sea area (the Netherlands, Germany, UK, and Denmark).

At present, the value of losses is often linked to the market value for electricity, disregarding that the factual cost of producing and transporting electricity offshore is higher than onshore. The calculation procedure for present and future (accumulated) value of losses is recommended to be harmonized. The harmonization process should take place within an IEC/CENELEC framework with participation of technical experts from research institutions, industry and grid operators. The harmonized procedure should account for the socioeconomic discounting percent rate and the economic interest rate of the company, e.g. owning and operating the grid. The harmonized procedure should also account for variations of the economic interest rate in time and limits of the support regime, for example a warranty limit of 15 years.

Typically the value of losses is expressed by a loss evaluation formula. The following equation is just one example. It may differ according to the specific conditions of an application.

$$K_P = K_0 * P_0 + \sum_n K_n * P_n \quad (3-1)$$

where

K_P is the total cost of losses;

K_0 is the cost of no-load losses;

K_n is the cost of load losses at a defined operating point or average value of load losses for a defined operating range;

P_0 is the no-load losses (not depending on the operating point);

P_n is the load losses at a defined operating point or for a defined operating range.

Such formula allows the manufacturer to design his equipment to an optimum of investment cost and cost of power losses during operation.

3.2.5 Future Expansions

Whilst consideration of the benefits of possible future expansion is recommended, this should be balanced with the early investment in additional equipment

Future system expansions should be considered in an early stage of system planning as such aspects are likely to influence both the electrical design and the interfaces at the DC side of the AC/DC converter stations with respect to selection of the nominal DC voltage and DC current as well as the control functions.

In radial network topologies, the coordinated control of AC/DC converter stations can determine the power flow through their adjacent cable or overhead line, respectively. In case of meshed multi-terminal topologies, load flow distribution between parallel paths is determined by equivalent path resistances and power flow control of the converter stations. In principle, small series DC voltage injections could be used to control the power flow, but this would require the provision of the corresponding type of equipment, power flow monitoring systems and an advanced control coordination.

From a system planning perspective, it is possible to extend the system transmission capacity at a later stage by adding parallel HVDC connections.

In addition to the design considerations for future grid expansion, an open market for equipment based on the same regulatory rules is an important prerequisite for reliable system planning. Systems that may be built in its initial phase by a single manufacturer should be expandable later using systems from other manufacturers, i.e. multi-vendor systems. Standardization of the principles of equipment function, system operation, control and communication (protocols) will make expansion easier.

At present, the market for AC transmission equipment and systems can be considered a role model for future DC transmission. In modern AC systems standardization gives detailed rules for specifying equipment dedicated to specific tasks. This applies to single components like switchgear or transformers as well as to complex systems like power plants or Static VAR Compensators (SVC). The equipment specified and manufactured according to standardized rules can be selected from different manufacturers and once it is added to the AC system, it becomes an integral part of it.

The development of multi-terminal, multi-vendor HVDC systems and HVDC grids will be simplified by standardized interface requirements of HVDC terminals. Moreover, other types of equipment should be considered, for example HVDC breakers.

3.3 Technical Requirements

3.3.1 General

Functional requirements for a HVDC Grid System can be described by a number of criteria, such as rated power, rated voltage, frequency, losses, reliability, availability and maintenance as well as the weight and dimensions. In addition the technical regulations (grid code) of the system operators need consideration.

The following section introduces important aspects which are relevant for reliable and stable operation of the AC and DC transmission systems.

3.3.2 Converter Functionality

The main functional requirements for the converters connected to a HVDC Grid System are:

- the power reversal of a single station shall not lead to DC transmission system voltage instabilities.
- disturbance in the AC system in one converter should not result in collapse of the DC grid voltage.

Two fundamentally different HVDC technologies are commercially available and, with some restrictions, are potential candidates for the DC transmission systems. The technologies are: the Line Commutated Converter (LCC) technology and the Voltage Sourced Converter (VSC) technology. The LCC technology is a tried-and-proven technology used in numerous point-to-point connection projects worldwide.

a) Power reversal:

The LCC technology utilizes thyristor based converter stations and as the thyristors can carry current in one direction only, the DC current direction is fixed. To change the power direction, the DC voltage polarity has to be changed.

VSC technology utilizes IGBT devices with bi-directional conduction and allows changing the DC current direction, so that the DC voltage polarity can be fixed. This concept is applied to VSCs based on so-called Half-Bridge (HB) building blocks (Half Bridge type Modular Multilevel Converters - MMC HB). VSCs based on so-called Full Bridge (FB) building blocks feature both changing the DC current direction as well as changing the DC voltage polarity (Full Bridge type Modular Multilevel Converter - MMC FB). Both types of converters are referred to in more detail in 5.3.4, Contribution of Converter Stations, and [17].

b) Disturbance:

The use of thyristor based converter stations requires access to relatively strong AC systems at all stations. That is, the AC systems have to have sufficient levels of short-circuit capacities at the point of interconnection. The system strength is often described by the Short-Circuit Ratio (SCR) as defined by Formula (3-2):

$$SCR = \frac{S_{sc}}{P_{dn}} \quad (3-2)$$

where

S_{sc} is the actual short circuit power level of the AC system;

P_{dn} is the nominal DC power of the converter station.

Subtracting total reactive power of filters and capacitor banks from actual short circuit power level in Formula (3-2) yields the Effective Short Circuit Ratio (ESCR). Based on ESCR's value, AC system strength is classified by Cigré as follows, considering a reactive power compensation of 50 % of the nominal DC power [13] [14]:

- strong ac system (high levels): $SCR \geq 3$, i.e. $ESCR \geq 2,5$

- weak ac system (low levels): $3 > SCR \geq 2$, i.e. $2,5 > ESCR \geq 1,5$
- very weak ac system (very low levels): $SCR < 2$, i.e. $ESCR < 1,5$

Furthermore, pre-established AC voltages within defined operating ranges are amongst the prerequisites for a LCC converter station to start operation. Thyristors can be turned on but cannot turn off and therefore rely on the ac system voltage to commute the current from one device to another. Consequently AC system disturbances may cause LCC to have commutation failures leading to large DC voltage disturbances.

The VSC technology is based on semiconductor devices with controlled turn off capability such as the IGBT. The use of VSC based converter stations allows independent control of the active and reactive current within the power rating of the station and does not require established ac voltages for turn off and do not experience commutation failures, hence, the short-circuit ratio of the AC system can be low. The VSC converter stations can also control and black-start islanded AC systems.

At present, VSC offer many advantages for HVDC Grid Systems. There is one project (Skagerrak 4) combining LCC and VSC technology in a bipolar arrangement with the purpose of expanding the existing LCC capacity.

In this document, the terms referring to AC/DC converter stations and HVDC Grid Systems imply pure VSC transmission, i.e. VSC HVDC converter stations and transmission systems.

3.3.3 Start/stop Behaviour of Individual Converter Stations

The converter station may stop for the following reasons:

- as part of normal operation;
- due to scheduled maintenance periods;
- in situations where protective action is needed.

When the HVDC Grid System shall go back to normal operation conditions the AC/DC converter station shall energize and re-start.

The time for a start/stop sequences depends on the specific operating requirements of the AC/DC converter station and the HVDC Grid System.

In case of a DC fault, the start/stop sequence of the AC/DC converter system(s) and the faulted part of the DC system should be fast. Typical timings are:

- stop and clear the DC fault within a few cycles of the fundamental AC system frequency;
- reconfigure, energize and re-start the affected converter station(s) as needed within some tens of milliseconds to a few seconds.

In case of a scheduled revision, there is no need for fast start/stop sequences. The time specification of the start/stop sequence should follow the common safety rules of the AC and DC transmission system operator(s) owning / operating the AC/DC converter station(s) and relevant part of the HVDC Grid System.

The term Black Start is used in conjunction with the start-up of a power system, i.e. going from a de-energized condition to an operation condition, and starting power delivery. Black Start includes start-up of house-load and islanded operation capabilities for the respective AC system and HVDC Grid System. The house-load, islanded-operation and black-start capabilities of the AC/DC converter stations should be specified by the respective system operators.

The following sequence can be applied for the Black-Start of a power system:

- 1) An AC source is needed to energize the DC Grid System through one HVDC converter.
- 2) Thereafter, other HVDC converters can be energized from their DC side or AC side (if energized). This will require the HVDC converter station to be designed for start-up from the relevant source (for example by charging resistors).
- 3) Energizing an islanded AC system via an HVDC converter. The converter should control the voltage and frequency in the islanded AC network.

3.3.4 Network Behaviour during Faults

Short-circuit faults can be distinguished in faults in the AC network, inside a converter station and on the DC network. Faults inside a converter station can be further differentiated in to faults on the converter AC side and faults on the converter DC side.

The fault behaviour of AC systems is well defined by existing AC Grid Codes [7]. Recommended requirements for the other types of faults are described in the following paragraphs.

– AC Side Converter Station Faults:

Faults that are on the network side of the station transformer require the station transformer to stay operational as per the requirement in ENTSO-E, ref [9].

Faults of the converter station transformer or inside the converter station are allowed to lead to an emergency disconnection sequence of the respective converter station. The system has to be designed in a way that the emergency switch off does not result in unacceptable conditions for other equipment in the AC or DC networks.

– DC Side Converter Station Faults:

Faults that are inside the converter station can lead to an emergency disconnection sequence of that respective converter station. Disconnection on the DC side may involve a temporary shutdown of the DC circuit, reconfiguration, and restart of the remaining DC network without the faulty station. The system has to be designed in a way that the emergency switch off does not result in unacceptable conditions for other equipment in the AC or DC networks.

– DC Network Faults:

Ground faults within a HVDC Grid System have a different behaviour to that from the condition known from AC networks. Without any countermeasures, the lack of significant short circuit impedance inside the DC circuit will cause the rapid collapse of the DC voltage throughout the DC network. Consequently, any ground fault inside the DC network will affect all interconnected AC/DC converter stations and influence

the adjacent AC systems accordingly. From the perspective of the adjacent AC systems, a DC network short circuit fault will be seen as a temporary three-phase voltage drop at different locations simultaneously.

The DC fault behaviour can be described as follows:

- As soon as a fault on the DC feeder occurs, the energy that is stored in the capacitance of the DC system (cables, overhead lines and DC-side capacitors of the converter stations if any) is discharged into the fault. This produces an over-current with similar shape as a classical RC-discharge.
- The fault behaviour of the converter station depends on the type of converter, i.e. whether or not the converter has a fault current control capability. The converters with fault current control capability can interrupt fault current with appropriate control of converter valves (additional fault isolation reconfiguration is needed). The converters without fault current control capability need AC or DC circuit breakers to interrupt the fault current. HVDC breakers are under development and may become standardized in the future.

Depending on possible interruption methods of a DC fault current, two different reactions are to be distinguished:

- Fast clearing, without temporary stop will have minimum impact on operation and stability of the DC and adjacent AC systems and would be required in a system where the n-1 requirement applies also for the DC system. This would only allow stopping the affected part of the DC system. A fast fault recovery for the healthy part of the system is required where the power loss due to the DC system shutdown is not acceptable for security of supply. The tolerable interruption time of power flow through the DC circuit should be studied considering the adequacy requirements of both the AC and DC power systems.
- Fast clearing with temporary stop of the affected DC system will allow more time for system reconfiguration and restart. A typical example of this is fault clearing by the AC side converter station circuit breaker, where the corresponding DC circuit is temporarily discharged, reconfigured if necessary, re-energized and transmission re-started.

In either case, fast fault detection and localization will be required as a pre-requisite for appropriate system reconfiguration.

The difference in the allowed actions regarding the DC fault clearing also influences the requirements for the AC/DC converter stations as well as delivery of ancillary services to the AC systems.

Fast clearing and isolation is a likely requirement when overhead lines are part of the HVDC Grid System as they are prone to suffer faults due to their exposure to environment phenomena such as thunderstorms.

3.3.5 DC-AC Interface Requirements

AC/DC converter stations have to comply with a set of requirements formulated by the AC system operators. For example ref. [7] provides common technical regulations for all generator types connected to the ENTSO-E HVAC system.

From the AC system operation and stability perspective, common requirements may comprise, but are not necessarily limited to, the following categories:

- definition of interfaces between DC and AC;
- operation ranges and ancillary services in normal operation of the AC system;
- operation ranges and ancillary services at over- / under- frequency and voltage in the AC system;
- low-voltage fault-ride-through and support to the grid in AC short-circuit faults;
- high-voltage fault-ride-through as consequence of grid disturbances (separation from the main AC grid);
- power Quality, e.g. allowed harmonic emission ranges;
- tests and documentation requirements;
- model delivery and validation.

It is recommended that similar categories are defined for the DC side.

3.3.6 The Role of Communication

The HVDC Grid System should be designed to operate without interruption and in a safe way even in the event of loss of communication. The converter station protection should be operating locally and not rely on communication.

Nevertheless, communication will play an important role for HVDC Grid Systems in order to simplify and optimize coordination of DC grid operation modes, such as:

- power control;
- power flow control;
- mode control of individual converter station, e.g. start/stop sequences, emergency power control, DC voltage control, Frequency control, etc.
- reactive power control.

The HVDC Grid System operation will be governed by a HVDC Grid Controller which is linked to each individual converter station controller via the communication system. Communication between the HVDC Grid Controller and a Converter Station Controller should allow:

- coordinating the operation modes of the converter stations, i.e. assigning power or DC-voltage control mode and reference values;
- optimizing the power flow in the HVDC Grid System, e.g. assigning the DC voltage references and specific control parameters, such as droops, selecting operation regimes minimizing power losses etc.; specific description to this control coordination part is given in Clause 3;

- status information and switching orders to and from each HVDC station.

Communication with the TSO's operation control centres informs the system operators of the status, capacity and power flow of a converter station, and enable them to operate the HVDC Grid system efficiently. In general, communication functions that are essential for operating the HVDC Grid system should be implemented as redundant systems.

3.4 Typical Applications – Relevant Topologies

3.4.1 General

This section makes a connection between theoretical, feasible requirements which a HVDC Grid System should comply with, and practical realistic application cases for the near future. In general, the HVDC Grid system topologies distinguish in:

- radial applications;
- meshed applications.

The HVDC Grid System topologies can also be combined with the AC system islands and AC lines.

3.4.2 Radial Topology

In radial topologies, each of the converter stations is connected by a single line at any time. Typical radial topologies radial topologies are illustrated in Figure 3-1.

The case present in Figure 3-1 a) shows AC/DC converter stations that are connected via the DC line/cable.

In the case present in Figure 3-1 b), the two converter stations are connected to the DC line/cable at a common DC bus bar.

As an example in offshore HVDC Grid Systems, the AC/DC converter stations utilizing the radial topology may be:

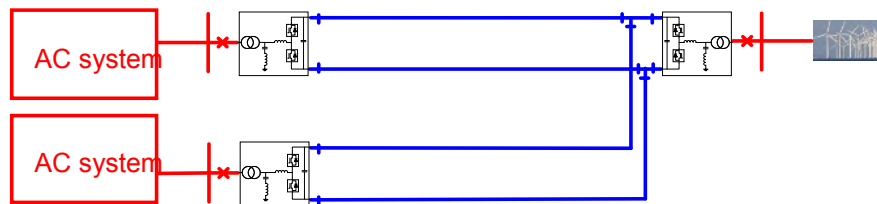
- wind power plants, when considering generation units;
- large oil platforms, when considering consumption units.

In Figure 3-1 a), the two AC/DC converter stations feeding into the AC systems can represent the DC connection between two separate and asynchronous AC systems which could be many, possibly hundreds of kilometres, apart. Offshore, there could be two (or more) wind power plants that are connected into the main DC line.

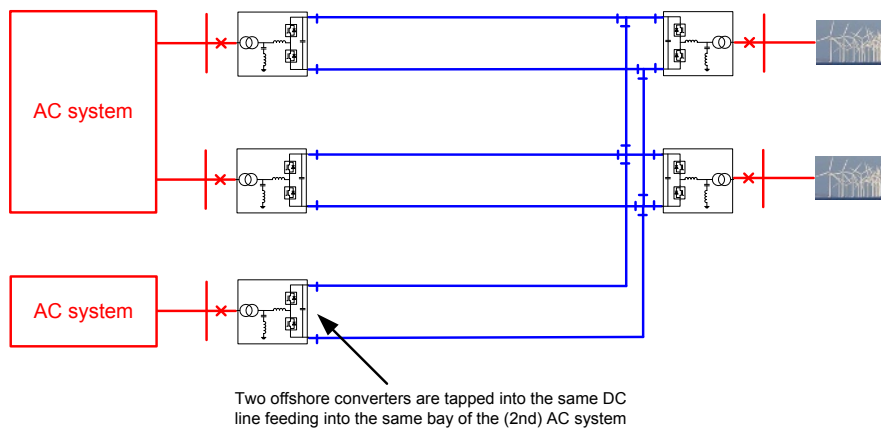
An example of the topology shown in Figure 3-1 a) is the HVDC VSC part of the Kriegers Flak Combined Grid Solution, which is presented in 3.1. The Development of HVDC Grid Systems. The topology of Figure 3-1 b) illustrates the Kriegers Flak CGS expansion to Sweden, and additional offshore wind power plant are connected to the main DC line.

Figure 3-1 c) illustrates a parallel system where there are two AC terminals offshore and one AC terminal onshore. The shown DC system has a crossover DC line between the two parallel DC lines. By disconnecting and crossing the respective DC lines, one AC/DC converter station can use the other AC/DC converter station's parallel DC line for the power transport. Such power transport rearrangement is useful if one of the DC lines is out of service.

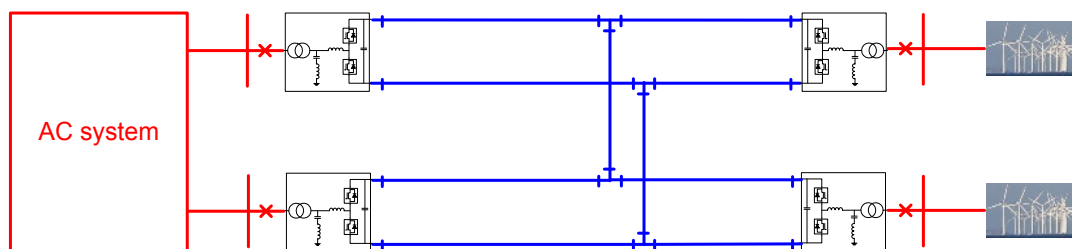
In HVDC Grid Systems having a radial topology the current through each DC line is controllable through the AC/DC converter stations coordinated by the HVDC Grid Controller.



a) One offshore wind power plant with connection to two (non-synchronized) AC systems



b) Two offshore wind power plants with connections to two AC systems



c) Two offshore wind power plants with cross connected parallel DC sea cables connected to one AC systems

Figure 3-1 — Radial HVDC VSC system topologies illustrating possible configurations of the Kriegers Flak Combined Grid Solution

3.4.3 Meshed Topology

In case of meshed topologies, at least two converter stations are connected by more than one transmission line forming parallel paths for the power flow. This will allow some redundancy of power transmission capability, within the limits of power and current ratings of the DC lines and AC/DC converter stations respectively. The value of the redundancy for the overall system should be justified by cost-benefit analysis. That is, the additional cost of redundancy is justified in comparison to the benefits of continuing power transport and retaining the agreed level of security of supply. Figure 3-2 illustrates the use of a meshed HVDC Grid System with redundancy by means of two DC connectors. The DC system shown can be operated in two ways: with or without connections between the DC lines during normal operation.

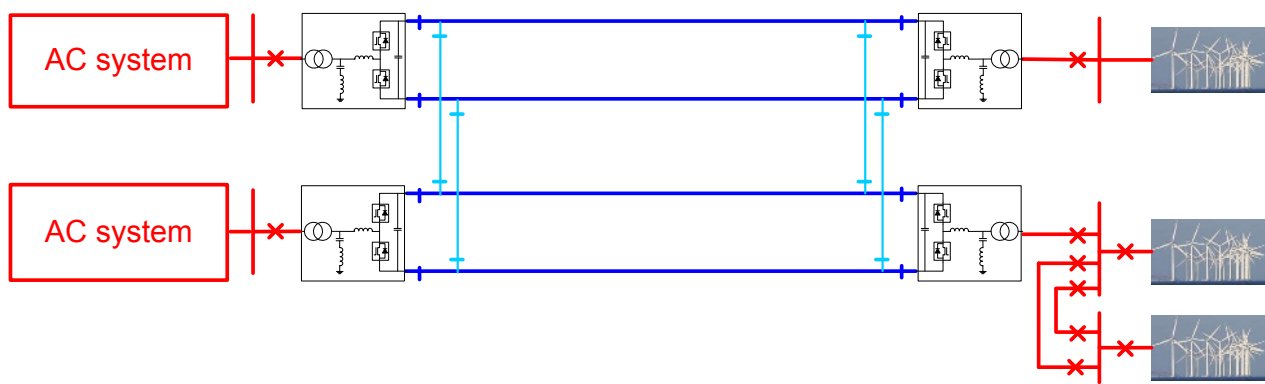


Figure 3-2 — Meshed HVDC Grid System topology with redundancy by means of DC connectors

Operating the system without connection between the DC lines, results in two independent DC circuits. If an outage of one of the DC lines occurs, both AC/DC converter stations could be connected to the remaining healthy DC line. This will require appropriate switching equipment on the DC side of the AC/DC converter stations. System reconfiguration may require the temporary interruption of transmission on the healthy system. The required switching equipment can include HVDC breakers, HVDC disconnectors or manual connectors. The type of switchgear should be selected according to the speed of system reconfiguration needed. In this configuration the DC switching equipment is not required to break fault currents. However, when specifying the switchgear the charging current for the DC lines as well as the remote converter stations should be considered.

It may be necessary to take both main DC lines out of operation when changing the configuration on the DC side.

Operating the system with connection between the DC lines may be advantageous if fast fault clearing and isolation technologies are used. The technology of fast fault clearing and isolation should be carefully analysed and selected to minimize the possibility of outage of both DC lines due to DC faults which will affect all of the dc converters simultaneously.

3.4.4 HVDC Grid Systems Connecting Offshore Wind Power Plants

An important application of HVDC Grid Systems will be the connection of large offshore wind power plants to the adjacent, onshore AC transmission systems. Referring to 3.1, The Development of HVDC Grid

Systems, the Kriegers Flak CGS is one example for the establishment of such offshore HVDC Grid Systems, shown as a draft in Figure 3-3.

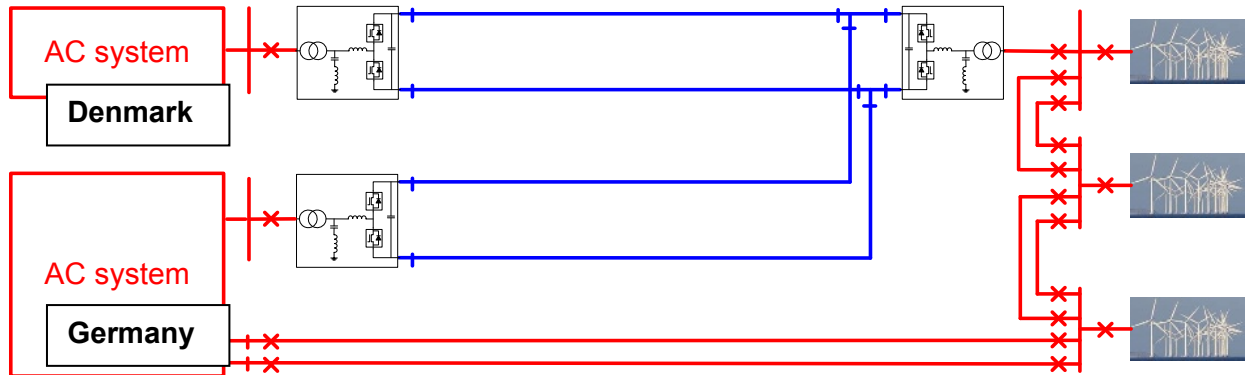


Figure 3-3 — Possible grid-connection topology of approximately 1 000 MW offshore wind power at Kriegers Flak to two onshore not-synchronized AC systems of Denmark-East and Germany

At present, the DC part does not require fast fault clearing and isolation technologies as in the event of a DC system outage, some power from the offshore wind power plants can still be transported through the AC lines. In case of an outage of the AC lines, the wind power is collected at the offshore AC/DC converter station and transported through the HVDC system to the onshore AC systems. Hence, the connection between the wind power plants provides a redundant path for power transmission. The value of this redundancy is to be justified by cost-benefit analysis.

3.4.5 Connection of a wind power plant to an existing HVDC VSC link

Figure 3-4 illustrates the case, where a new offshore wind power plant is connected to an existing HVDC Grid System (e.g. between two AC systems).

The existing DC cables are extended to reach the offshore platform. It would be possible to remove a faulty section of the DC cable and keep the rest of the DC system in operation. Appropriate DC switchgear would be an advantage in order to achieve a rapid system reconfiguration and thus minimize the outage period for the remaining healthy parts of the dc system.

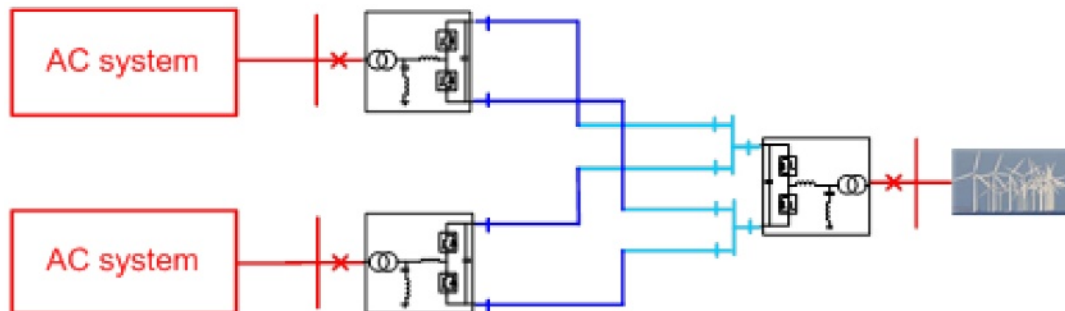


Figure 3-4 — Connection arrangements of a new offshore wind power plant to an existing HVDC Grid System

4 Principles of DC Load Flow

4.1 General

This clause discusses the principles of steady-state and dynamic load flow control for a HVDC Grid System. The primary objective of the control system is to achieve reliable and stable power flow over all operating conditions including unplanned or unscheduled power flows caused by outages and fault conditions.

4.2 Structure of Load Flow Controls

4.2.1 General

The primary objective of an HVDC Grid System is to transmit power between its converter stations. Depending on the transmission task, some converter stations import power into the DC circuit, others export power. Power import tends to increase the DC voltage level of the network; power export tends to decrease the DC voltage. Transmitting power requires the DC voltage to be maintained within certain limits.

Maintaining the DC voltage within acceptable limits means that any power surplus either needs to be stored in appropriate energy storage devices or dissipated as heat using dedicated discharging devices, usually referred to as Dynamic Braking Devices. Energy storage will also have to compensate any power deficit to keep the DC voltage reasonably constant. If a DC network does not contain energy storages or Dynamic Braking Devices, power export and import have to be balanced at all times by the proper control of the converter stations.

The control functions of a DC Grid can be differentiated, with respect to their dynamics, into Converter Station Controls and HVDC Grid Controls.

4.2.2 Converter Station Controller

The Converter Station Controller determines the operating point of its converter. It controls the voltages and currents at the converter DC and AC terminals with response times typically in the range of a few milliseconds. Control objectives may be:

- active power flow through the converter;
- AC system frequency;
- DC voltage;
- reactive power exchange with the AC network;
- AC voltage.

In general the Converter Station Controller obtains measuring signals from its own converter station or receives status signals from external controllers that may influence the control strategy. The Converter Station Controller does not rely on external communication. Coordination with the DC and AC networks is achieved by pre-determined characteristics, such as fix reference values or droop characteristics.

The dynamic operation of the control system has a direct influence on the rating of the internal DC capacitors of the converter. This in turn has a significant impact of the cost and space requirements of the converter.

The Converter Station Controller sends local status and measured signals to the HVDC Grid Controller.

4.2.3 HVDC Grid Controller

4.2.3.1 General

The HVDC Grid Controller provides the individual Converter Station Controllers with their control characteristics and reference values. It uses the status and measured signals to optimize the power flow within the network according to pre-defined rules. It provides the interface to the system operators. The HVDC Grid Controller relies on communication.

If the telecommunication between the HVDC Grid Controller and any station is out of service, the loading of this station has to be an estimate based on information from other stations or manually entered by the operator.

When an HVDC Grid System is separated into two parts, e.g. following a permanent fault on a transmission line, each part requires an HVDC Grid Controller to continue operation.

To ensure control of the HVDC Grid System in event of major losses of equipment, there should be a “back-up” HVDC Grid Controller. The back-up HVDC Grid Controller should be located at a different location.

4.2.3.2 Steady State Load Flow Control

HVDC Grid Controller aims to compensate mismatches in the grid dispatched power by increasing or decreasing the overall voltage level. This can be used to handle small power variations as they occur for example at wind farms. However, such variations have to allow sufficient margin in the permitted voltage bands. Under steady-state conditions the utilized voltage bands shall be smaller than the maximum allowable value. To achieve this, the HVDC Grid Controller pre-calculates the load flow in the DC circuit to determine the reference values for all individual Converter Station Controllers. Therefore information on the DC Network Topology and network components is required, for example:

a) Switchgear (Disconnectors and Circuit Breakers (if any)):

- 1) present status (open, closed);

b) Load Flow:

- 1) dispatch patterns;
- 2) contingency conditions and strategies;
- 3) loading of all converters;
- 4) loading of all DC power lines;

- 5) DC voltages in all stations;
- c) Converter Station:
 - 1) present status (blocked, de-blocked);
 - 2) maximum and minimum voltages;
 - 3) maximum currents;
 - 4) control mode (U_{dc} or active power);
- d) Lines and Cables:
 - 1) resistances;
 - 2) maximum temporary and steady-state current ratings;
- e) Energy Storages and Dynamic Braking Devices (if any):
 - 1) present status;
 - 2) maximum and minimum voltages;
 - 3) maximum currents;
 - 4) energy absorption/supply capability.

Once all information has been factored into a load flow model, the study procedure will be similar to that of a conventional AC network steady-state load flow study. For any combination of dispatch patterns and contingency conditions the load flow will be solved and shown that the given voltage bands will not be violated and the given current ratings (converters and lines/cables) will not be exceeded. In case of an initial network planning stage, necessary voltage and current ratings can be determined.

4.2.3.3 Dynamic Load Flow Control

For major disturbances of the load flow, such as load rejections of complete converter stations or tripping of lines, the resulting voltage variations will be large. Therefore converter stations injecting active power into the DC grid should limit overvoltages by reducing power import. On the other hand any station exporting power should limit undervoltages by reducing power export.

A dynamic model of the DC system has to include, in addition to that required for the steady-state load flow study, data on network reactance and dynamic limitation functions. A time-domain based calculation will provide the dynamic over-voltages and currents to be expected as well as show the dynamic system stability.

Appropriate strategies have to ensure, that the capabilities of the AC systems connected to the individual converter stations are taken into account. This may require high level coordination between the AC and DC network operations.

4.3 Converter Station Control Functions

4.3.1 General

Traditionally the operational status of a converter station is distinguished into “rectifier” and “inverter” operation depending on the direction of active power flow. Especially with the respect to multiterminal HVDC systems, another way to categorize the behaviour of an individual converter station has become more important. Regardless of the actual direction of active power flow (from AC to DC or vice versa), a converter station can be operated in “DC voltage control mode” or as an “active power station”. In the special case, where an active power station is controlled by an AC system frequency controller, the active power station is operated in “frequency control mode”. In either case the converter stations have to stay within their voltage and current operating limits. As a consequence the power rating of these stations has to be coordinated with the worst case scenario to be considered for loss of load or generation in the DC system.

The following sections describe these options and give indications on the constraints for the connected AC networks.

4.3.2 DC Voltage (U_{DC}) Stations

A converter station operating in DC voltage control mode adjusts its active power exchange to meet the DC voltage reference value. As a consequence, the active power of this particular station is determined to balance power in the DC circuit.

In principle the voltage reference value can be kept constant within certain power limits or it can follow a droop characteristic, meaning that a given DC voltage results in a defined power exchange. With respect to DC system stability, controlling the DC voltage requires the AC system connected to a DC voltage controlling station to accommodate the active power export or import determined by the HVDC Grid System. It is recommended that dynamic network simulations are undertaken to assess the stability of combined AC and DC systems to identify the limitations to operation.

4.3.3 Active Power (P_{DC}) and Frequency (f) Controlling Stations

A converter station operating in active power mode adjusts its DC voltage to meet the active power reference value.

This control mode can be used to balance active power in the adjacent AC network. In that case, the power reference value could be provided by a secondary control loop controlling the frequency in the AC system, making the station a Frequency Controlling Station. Frequency control will be required for isolated AC grids, like offshore wind parks or oil and gas platforms.

In principle the active power reference value can be kept constant within certain DC voltage limits or it can follow a given droop characteristic, meaning that the given active power results in a defined DC voltage.

With respect to DC system stability, controlling the active power or frequency control requires the DC system to accommodate the active power export or import determined by the connected AC grid. This has to be achieved maintaining voltage and current limits of all converter stations in the network. Temporary overvoltages in the DC system may have to be limited, e.g. by appropriate power run-back functions or Dynamic Braking Devices. Similarly, temporary undervoltages may have to be limited by appropriate power run-up functions. Dynamic network simulations taking into account the actual capabilities of the DC

system are recommended investigating the system stability of the DC network together with its AC system environment as well as identifying proper measures.

Active power or frequency control is recommended for weak AC grids. In case of strong AC systems, the station can be used for constant DC power operation.

4.4 Paralleling Transmission Systems

4.4.1 General

Special considerations have to be made in case that two (or more) converters are connected in parallel at one sub-station. The paralleling may take place on their AC sides or on their DC terminals (or both).

4.4.2 Paralleling on AC and DC side

Converters that are connected commonly to the same nodes on the AC and DC side appear like one converter in the system. A typical situation is shown in Figure 4-1 at Sub-Station A, when the dashed connection on the DC side is in place. Applications include extending existing stations or converter stations having power ratings exceeding the capabilities of a single converter.

When converters are connected in parallel each converter control system has to ensure that its converter contributes a predetermined fraction of the active and reactive power of the overall converter station at all times. In particular, situations where one station increasingly feeds power while another one counteracts are to be avoided. Such situations are also referred to as “hunting” and result in uncontrolled loop-flows and unstable operation. Hunting may be avoided by implementing a station master controller that provides each converter control with exact reference values. Alternatively, applying droop characteristics to the appropriate control modes, e.g. DC voltage, active power, AC voltage, Reactive power. Droop characteristics require the dynamic behaviour of the individual converters to be studied in order to avoid hunting.

4.4.3 Paralleling on the AC side

Figure 4-1 shows an example at Sub-Station A with two converters connected in parallel on the AC side assuming the dashed connection on the DC side does not exist. One example for such a configuration can be islanded AC networks connecting wind parks with different HVDC stations. The HVDC converters may via DC networks be connected to:

- 1) different AC systems if the AC connections between Sub-Stations A, B and C do not exist, or
- 2) the same AC system but at different nodes (at least partly) if the connection between Sub-Stations B and C or A and C exist.

In case 1), the active power requirements as well as the active power capabilities of the DC systems DC_1 and DC_2 will often be different. The DC systems may even require different control modes, such as U_{DC} control for VSC_1 and P_{DC} control for VSC_2 . These conditions will result in different reference values for P_1 and P_2 . The Sum of P_1 and P_2 has to be provided or absorbed by the system AC_3 .

In case VSC_1 and VSC_2 share frequency control in the system AC_3 , the capabilities of the systems DC_1 and DC_2 can be taken into account when defining the power-frequency droop characteristics applied to VSC_1 and VSC_2 .

In Case 2) the same conditions can apply as described in Case 1. However, the additional connection between the systems DC_1 and DC_2 opens up the possibility of power loop flows between VSC_1 and VSC_2 via the AC systems AC_1 and AC_2 . Such power loop flows are further described in 4.4.4, Steady-State Loadflow in Hybrid AC/DC Networks. Load flow studies investigating all relevant operating conditions are required to identify appropriate strategies for the AC and DC system dispatch controls (see 4.5, Load Flow Control for more details).

The AC connection between systems AC_3 and AC_2 allows power loop flow and this situation applies to all HVDC links embedded into integrated AC systems. The possibility of power loop flow occurring should be considered when determining the P_1 and P_2 reference values.

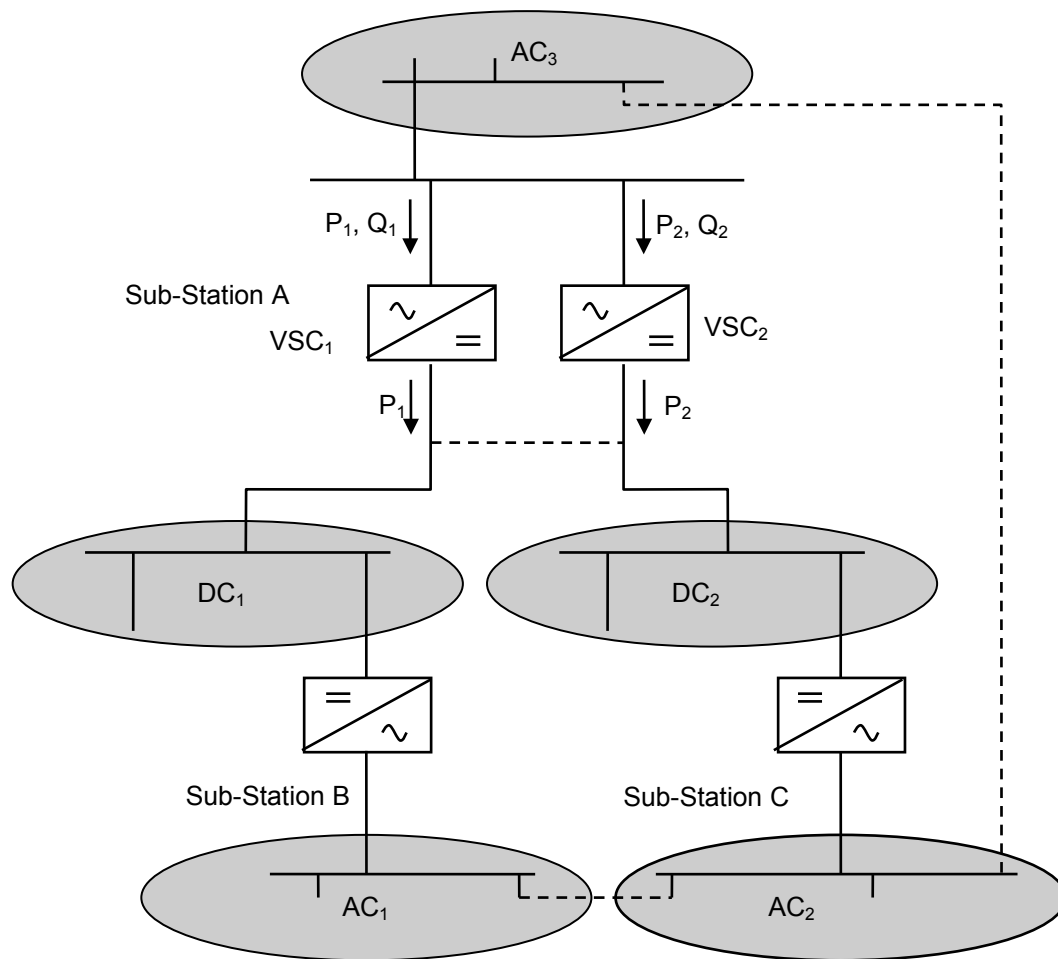


Figure 4-1 — Network showing parallel operation of converters in various configurations (example)

4.4.4 Steady-State Loadflow in Hybrid AC/DC Networks

Figure 4-2 shows the simplified DC and AC connection between two nodes of a large DC grid and the associated AC system. The DC grid superimposed on an AC grid can provide an alternative path to transfer bulk power across a large geographical area, potentially providing lower transmission loss and