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Technical guidelines for first HVDC grids - A European study group based on an initiative of the German commission for electrical, electronic & information technologies

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SUMMARY

The envisaged decarbonisation of the society imposes new challenges for electric power transmission networks. Excellent bulk power long distance transmission capabilities, low transmission losses and precise power flow control make HVDC the key transmission technology for renewable energy. Specifically, the HVDC technology becomes relevant for connection of offshore wind farms to the onshore transmission systems.

While the power system enforcement is already underway by a number of new point-to-point HVDC interconnections, the advantages of multiterminal HVDC systems become more and more attractive. Examples are grid access projects connecting various wind parks or combining wind parks with point-to-point transmission, e.g. in the North and Baltic Seas. Multiterminal projects are already to be executed and there is planning for pan-European HVDC grids.

To become reality, HVDC grids need, besides the necessary political framework, competitive supply chains of equipment capable of operating together as an integrated system. This marks a significant change in the HVDC technology market. While - with very few exceptions – a today's HVDC system has been provided by a single manufacturer, future HVDC grids will be composed of systems 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 grids is seen as a first step towards multi vendor systems. It will help the development for the next round of

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European multiterminal projects, like Kriegers Flak in the Baltic Sea, that are in the planning stage. Furthermore, it will prepare the ground for more detailed standardization work.

Based on an initiative by the German Commission for Electrical, Electronic & Information Technologies, DKE, 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 standardisation 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 organisations have been actively contributing to the results of the Study Group achieved so far: 50Hertz Transmission, ABB, ALSTOM, Amprion, DKE, EnBW, 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 grids. This information guides to elaborating the basic principles of HVDC networks which will be described in a technical report. The information will be summarized in four main chapters, which are described in the present paper:

- "Typical Applications for HVDC Grids"
- "Principles of DC Load Flow"
- "Short Circuit Currents and Earthing"
- "Principles of Fault Detection and Fault Clearing"

From the technical principles described, functional specifications for the main equipment of HVDC networks will be derived. By end of 2011, work has started with elaborating the specifications for AC/DC converter stations. Further equipment planned to be described includes: DC Cables, DC Overhead Lines, DC Chopper, Charging Resistors, DC Circuit Breakers and communication for network control and protection.

Serving the near term applications, the study group decided to focus its scope of work on radial HVDC network structures as well as pure Voltage Sourced Converter (VSC) based solutions first. To achieve timely results, further specialisation might be required with respect to certain variants of HVDC networks.

This paper summarizes the selected results of work available by the end of 2011 and describes the next steps towards preparing the ground for standardization of HVDC multiterminal systems and HVDC grids.

KEYWORDS

VSC – HVDC – Multiterminal – Grid – Load Flow – Fault Current – Earthing – Protection – Standardization – Reliability

1 TYPICAL APPLICATIONS FOR HVDC GRIDS

The demand for power is the driving force for transmission system planning and development. It defines the performance and security requirements like losses or reliability which then transform into specific technical solutions like network topologies, converter technologies or fault clearing strategies.

Typical HVDC transmission tasks have been interconnecting asynchronous AC networks, long cable links connecting offshore wind farms to shore, connecting remote islanded loads or strengthening the existing AC networks. These tasks can be achieved by a corresponding number of individual point-to-point HVDC links, which could be interconnected via AC nodes calling for establishment and utilization of a large number of HVDC converter stations. This extensive approach is feasible, but not necessarily the most beneficial one due to significant power losses, investment and maintenance cost of such converter stations, especially when located offshore. Reducing the number of converter stations makes interconnection through multi-terminal DC systems more and more attractive.

The Study Group has been elaborating in detail the following aspects of system planning for HVDC grids:

- Reliability, system adequacy, security of supply, system planning and operation aspects
- Start/Stop requirements for individual converter stations including
  - House-load capability (auxiliaries)
  - Islanded operation capability (regarding AC and DC systems)
  - Black Start capability of AC systems
  - Black Start capability of DC systems
- Network behaviour during DC faults
  - Without fast selective fault clearing
  - With fast selective fault clearing
- Recovery after fault clearing
- DC-AC Interface Requirements
  - Ancillary services provided to the AC system

Each of these aspects can largely influence the technological solution chosen for an HVDC system in the planning stage. The limited size of the present paper unfortunately does not allow addressing all points individually. Therefore, the aspect of reliability shall be described as an example. A full description will be published together with the Study Group's technical report.

A sufficient grid is developed in a way that safe and reliable operational management with a correspondingly high security of supply is enabled. In present AC systems, the security of supply comprises two major terms: the system adequacy and the system security. The system adequacy is indexed from 0 (the lowest grade) to 100 (the highest grade). The system adequacy can be measured as percentage of energy supply without interruptions, in amount and duration, over a year. The system adequacy is considered high when it approaches 100%, but it can never reach 100%. The system security evaluation is done according to the n-D criteria, where D is a region-dependent number greater or equal to 1. The number D is influenced by the possibilities that allow securing power and energy supply in cases of component outages. For transmission systems being islanded or having weak interconnections to neighbouring systems, the dimensioning of the grid resources shall comply with D being larger than 1.

Countries and grid operators have defined targets for what to consider a sufficiently high system security.

There are basically two applications for HVDC systems leading to fundamentally different reliability requirements:

- HVDC systems can operate inside an AC system enhancing its performance.
- HVDC systems can serve the purpose of connecting a power plant, e.g. a wind farm.

When operating inside an AC system, the AC/DC converter stations should provide ancillary services to the AC system such as voltage or reactive power support, frequency control, active power flow control or contribution to short circuit power. Services like these will reduce the risks of AC system instability or blackouts and are treated according to the n-D criteria of the AC system. Connecting generation or interconnecting countries, the reliability requirements of the HVDC system correspond to those of a power plant. There are applications, however, that combine both types leading to the reliability requirements being combined accordingly.

The reliability requirements can lead to DC systems designed so that not every AC/DC converter station or DC line are loaded up to an 100% operating grade, but has a scheduled capacity margin to handle extra energy transport due to redistribution of power flows. Another possibility could be defining temporary overload ratings (in means of static and dynamic thermal limits) for AC/DC converters.

Already in the initial design phase, the system operators must make decisions to achieve the required or guaranteed system adequacy and security of supply under the edge conditions within the DC system. The edge conditions may introduce the needs to reduce the power transport through critical DC lines or jeopardize the guaranteed system adequacy and security of supply. The following edge conditions have been identified:

- topology (monopole or bipole) meeting best the adequacy and security of supply
- protection concept
- number of protection zones needed
- definition of protective schemes minimizing needs of power reduction via critical DC grid components during the DC system preparation to the next possible (n-1) event
- protection schemes securing the guaranteed system adequacy and security of supply
- cascade tripping of the AC/DC converters has to be excluded
- definition of the maximum fault clearing time (establish the new load balance after “x” amount of time)
- whether DC Breakers are needed
- faults and outages on the AC-side as well on the DC-side have to be investigated regarding temporary and permanent loss of components, at every reasonable situation with respect to the selected grid dimensioning criterion, e.g. the n-1, n-1-1 or n-D
- securing static and dynamic stability of the DC and AC systems in severe operation conditions combined with faults and risks of post-sequent multiple outages by investigations, equipment specifications and tests
- at every situation relevant, the possibility of energization and de-energization of the AC and DC systems has to be specified and secured

2 PRINCIPLES OF DC LOAD FLOW

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.

Any power surplus either needs to be stored in energy storages or turned into heat using discharging devices, like so-called DC choppers. Energy storages would also have to compensate any power deficit. If a DC network does not contain energy storages or DC choppers, power export and import have to be balanced all time by the converter stations, requiring proper controls. The control functions can be differentiated with respect to their dynamics into Converter Station Controller and HVDC Grid Controller.

2.1 Converter Station Controller

The Converter Station Controller handles the operating point of its converter controlling the voltages and currents at the converter DC and AC terminals with response times typically in the range of microseconds to some milliseconds. Control targets may be:

- a certain active power on the AC or DC terminals of the converter
- a certain AC system frequency
- a certain DC voltage
- a certain AC voltage.

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 can be achieved by pre-determined characteristics, such as fix reference values or droop characteristics.

The highly dynamic control allows keeping the energy storages inside the converters small for economical reasons (converter cost, space requirements, etc.). The Converter Station Controller sends status and measuring signals to the HVDC Grid Controller.

Traditionally the operational status of a converter station is distinguished into "rectifier" and "inverter" operation depending on the direction of active power flow. With respect to HVDC grids, other criteria can be added distinguishing converter stations operated in "DC voltage control mode - U_{DC}" or as an "active power station - P_{DC}". If the active power is controlled by an AC system frequency controller, such station is operated in "frequency control mode - f". The operating mode on the DC side has consequences on the AC side:

- A DC voltage controlling station adjusts its active power exchange to meet the DC voltage reference value, the AC system has to accommodate for the power needed.
- An active power station maintains the active power reference or frequency reference respectively and adjusts its DC voltage accordingly; the DC voltage has to be kept within limits by the other stations in the DC circuit maintaining the system stability.

Both DC voltage and active power control must maintain the voltage and current operating limits of a station. Therefore, DC voltage or power reference values may be bound to specific limits, or various droop characteristics may be applied.

2.2 HVDC Grid Controller

The HVDC Grid Controller serves the purpose of providing the individual Converter Station Controllers with their control characteristics and reference values. It uses the status and measuring signals to optimize the power flow within the network according to pre-defined rules, such as pre-calculated load flows in the DC circuit. Therefore, comprehensive information on the DC network topology and network components is needed, as there is: transmission line data, breaker and disconnector status, status and operating limits of converter stations, status and operating limits of energy storages or DC coppers, contingencies and relevant scenarios etc.

2.3 Concepts of Load Flow Control

The Study Group identified three different concepts to achieve the desired DC load flow:

- Voltage-power droop together with dead band
- Voltage-current droop
- Voltage-power droop

Each concept will be described in detail in the technical report of the Study Group.

The Study Group has evaluated the concepts using the following performance requirements:

- Fulfil P or Udc reference points
- Calculate well defined operating points (P, Udc, respecting known system restrictions)
- Continue operation at a stable operating point after a large disturbance, e.g. after a sudden loss of power at a station for any reason or after loosing a DC line
- Keep the DC voltage within acceptable limits
- Schedule optimal power flow (keep DC voltage at the rectifier as high as possible)
- Handle fluctuating loads and generation
- Be flexible with respect to combinations of Uac/f, P/Q and Udc control
- Handle restrictions and limitations in the DC and AC networks, e.g. islanded AC networks, thermal and stability limitations, power oscillation damping
- Prevention of overload of any DC grid component (cables, overhead lines, etc.)
- Provide autonomous control during temporary loss of communication
- Be robust against non-ideal conditions (e.g. tolerances of equipment)
- Interoperability

The evaluation has lead to the conclusion, that all three concepts represent technical solutions. Moreover, the concepts appear interoperable, provided that there is an appropriate information interface between the HVDC Grid Controller and the Converter Station Controller.

Investigating the individual properties of the concepts further, each manufacturer within the Study Group carried out benchmark simulations using the control system he has proposed based on an agreed network model setup as well as agreed study cases. The simulation results have proven the feasibility of the three control concepts and it was decided to further analyse the concepts with respect to various applications. The analysis of the control concepts will be carried out by a university that by end of 2011 has started reproducing the results of the manufacturers using self-made models. In a next step, the three different concepts will be applied to a common DC circuit investigating interoperability.

The network models considered so far have converter stations connected to strong AC networks. Simulating the realistic dynamic behaviour of the AC systems will require more detailed models of the converter stations, especially with respect to balancing the energy absorption or injection of the converter itself. Such investigations require proper models being available from the converter station manufacturers.

3 SHORT-CIRCUIT CURRENTS AND EARTHING

The investigations of the short circuit currents are important for the design of the equipment and the system behavior with respect to faults. The Study Group aims at identifying any measures recommended to achieve a certain fault performance or certain short circuit current parameters. The conditions after the initiation of short-circuit will be largely influenced by:

- The ability of a converter station to control fault currents.
  Line Commutated Converter (LCC) stations as well as Voltage Sourced Converter (VSC) Full Bridge (FB) stations can control or even break fault currents, while a VSC Half Bridge (HB) needs support from the AC side breaker to extinguish fault currents. A VSC HB combined with fast AC or DC side circuit breakers can behave similar to the VSC VB.
- Discharge of passive components of the DC network.
  The damping of the discharge current is influenced by the resistance of the short-circuit path and the resistance depends on the frequency of the oscillation.
- The earthing of the DC circuit in case of line to ground faults.
  Converter stations can be isolated forming a so-called Symmetric Monopole or solidly earthed forming an Asymmetric Monopole or a Bipole. The earthing concepts are in principle shown in Figure 3.1.

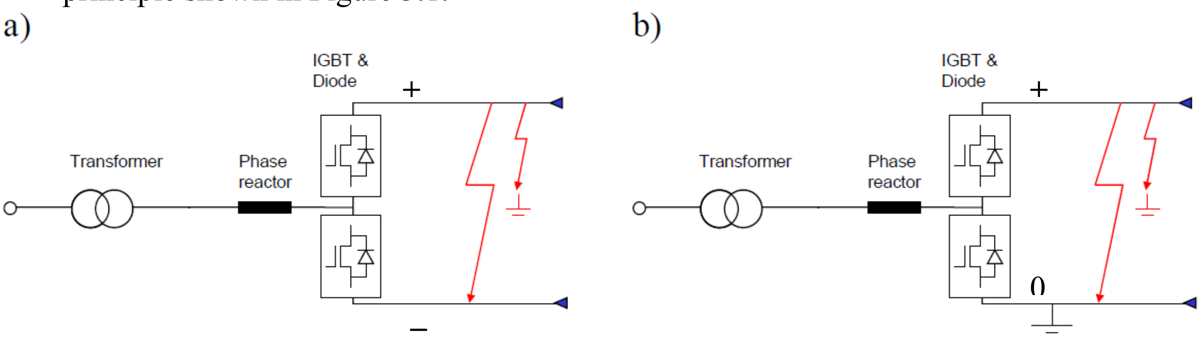


Figure 3.1: Grounding of the DC circuit at the Modular Multilevel Converter Stations
a) symmetric monopole b) asymmetric monopole

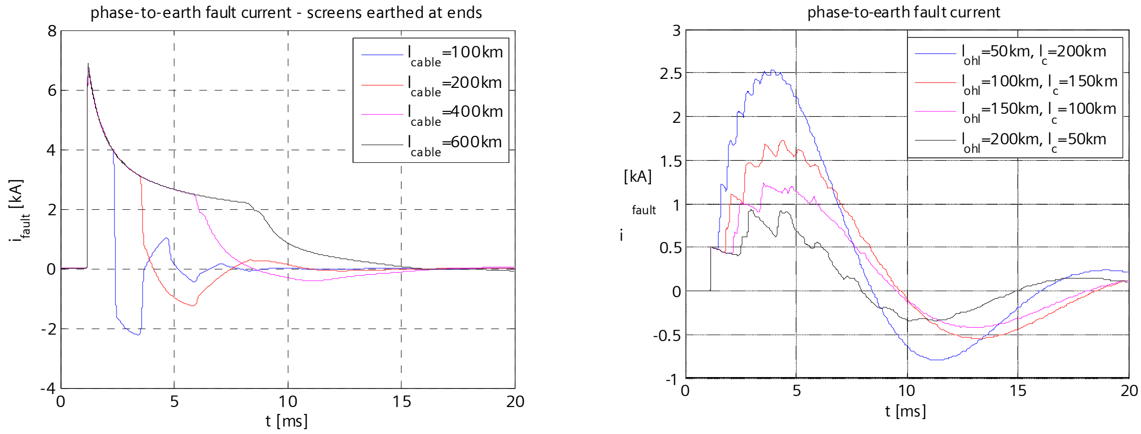
Line-to-line short circuits will lead to high short circuit currents irrespective of the earthing method. With the midpoint of the converter isolated (Figure 3.1a), line-to-earth faults will result in high temporary overvoltages but only small short circuit currents driven by the converters. If DC capacitors or filters are earthed, line-to-earth faults will lead to high transient currents caused by the voltage displacement. In case of asymmetric monopoles and bipoles high short-circuit currents will be obtained (Figure 3.1b).

The highest short-circuit currents are expected in case of solidly grounded systems. As a starting point, the Study Group has investigated the contributions of the converters and the passive DC circuit separately. The behavior of the passive components in DC circuits does not differ from those used in AC systems but the challenges associated with fault clearing draw special attention to the individual voltage and current wave shapes.

3.1 Influence of line discharge

Figure 3.2 shows the short-circuit current in case of line-to-earth faults for different overhead lines or cable length respectively.

The initial peak current in Figure 3.2a can be estimated by using the surge impedance of the overhead line or cable respectively and the current return path (earth and cable shield). For relatively short distances, the influence of the reflected wave is obvious. Overhead lines would show the same behavior in principle but having smaller peak currents and higher propagation speed than cables. The first peak of the discharge current occurs immediately after fault occurrence. A DC link consisting of a combination of cable and overhead line sections results in special current wave shapes depending on the exact configuration. If faults occur on the cable, the discharge current coming from the overhead line behaves similar to the case where the cable is open-ended. In the opposite case however, the reflection factor at the overhead line/cable interface is positive and relatively high, resulting in a short-circuit current that builds up with every reflection. The effect is stronger as the over head line section between the fault and the cable is shorter. This is illustrated in Figure 3.2b.



a) Short-circuit current in case of a earthed cable shield, exemplary

b) Short-circuit current in case of a combined overhead line/cable connection (earthed cable shield), exemplary

Figure 3.2: Typical wave shapes of the short circuit current in case of line-to-earth faults

The following circumstances have to be taken into consideration influencing the amplitude and the shape of the short-circuit currents:

- The line length influences the frequency of the discharge.
- The resistance of the short-circuit path is influenced by the frequency and in consequence, the amplitude of the current is reduced and the oscillation is damped.
- The current return has to be considered depending on the fault type, e.g. via earth in case of an overhead line or cable shield and earth in case of a cable system respectively.

3.2 Contribution of the converter stations

With focus on the first multiterminal HVDC projects in Europe, the Study Group has been focusing on VSC solutions first. The behavior of VSC FB and VSC HB will be described in the Report of the Study Group.

Both, the discharge of the passive components as well as the contribution from the converter stations have to be considered for the design of the network components. The Study Group will therefore discuss possible measures reducing the fault current magnitudes as well as the switching duties of short circuit current breaking devices, like DC circuit breakers.

4 PRINCIPLES OF FAULT DETECTION AND FAULT CLEARING

The Study Group has been focusing on fault detection and fault clearing on overhead lines and cables, especially in the context of HVDC multiterminal systems and HVDC grids.

All protection systems need to be selective and trigger on a fault within a protective zone as well as not trigger for faults outside this zone. The protection system is dependant upon the configuration, including earthing principles and the need for separation.
With the purpose of proposing protection systems multiterminal systems and HVDC grids the Study Group considers the following points in detail:

- Typical DC systems (layout), including earthing, overhead lines and cables.
- Converter behavior for the typical faults.
- Operating conditions of DC systems (voltage, current, power flow).
- Definition of fault types (converter faults, AC faults or DC system faults).
- Benefits of DC circuit breakers for fault clearing
- Impact from communication

The HVDC system has to be designed to meet the operational requirements with respect to fault clearing. Means for DC side fault clearing can be located on different places:

- On the AC side of converters (AC side converter circuit breakers)
- Within the converters (Full Bridge Voltage Sourced Converters – FB VSC)
- On the DC side of converters (DC side converter circuit breakers)
- On each feeder of a node in the DC network (DC feeder circuit beaker).

The different locations of the fault clearing equipment result in different control and protection concepts, fault clearing performance and investment cost. Depending on the location of the fault clearing device, different concepts of fault clearing can be applied resulting in different functions of the AC and DC side circuit breakers. These aspects will be elaborated further by the Study Group.

The DC protections are dependant upon the specific requirements on the isolation and selectivity of the system following a fault. The following requirements can be defined:

- No requirements on fast dynamic isolation
- With requirements on fast dynamic isolation

A method to categorize the requirement on fast dynamic isolation following DC side faults is to analyze the acceptable outage times, i.e. the time from fault to recovery of power transfer as shown in Table 5.1.

Table 5.1: Outage time and related breaking device requirements

Outage time	Breaking device type needed
< few ms	Fast dynamic isolation is needed.
< 100 ms	Mechanical DC breakers to extinguish small residual fault currents are needed to support disconnectors.
< few sec	Conventional AC breakers are needed.
Minutes	Conventional disconnectors can be used.
Manual	Conventional disconnectors can be used.

4.1 HVDC Converter

The requirements on the converter and its control and protection system can be summarized as follows:

- The converter protections shall be able to distinguish between internal faults and DC grid including other converter faults.

- The converter shall be self protected i.e. not rely on the DC grid protections with the exception of DC ground faults.
- A converter isolation failure scheme shall be set up.
- Not generate more fault current than the DC grid can accept.
- Not drain more power than the DC grid can provide.
- Not provide more power than the dc grid can absorb.

With the exception of the isolation failure scheme, which is a backup, the above shall be independent on communication with the dc grid or other converters.

4.2 DC system w/o fast dynamic isolation
Systems without fast dynamic isolation will allow a temporary shut-down of the link in case of a fault. VSC HB will be blocked immediately after detecting the fault leaving the diodes feeding the fault from the AC system until an AC side circuit breaker opens. After opening the AC side circuit breaker, there will still be a trapped DC fault current decaying according to the damping of the converter, the DC circuit and the fault itself. After the fault current has become small enough, the faulty part of the DC circuit can be isolated and restart of the remaining sound part of the DC grid can take place. Restarting the remaining system could take minutes if conventional disconnectors are used or could be below a few seconds if fast disconnectors, e.g. AC breakers are used. The restart sequences and associated inrush currents are on the agenda for future discussions within the Study Group.

4.3 DC system with fast dynamic isolation
Fast dynamic isolation should have the capability to isolate the faulty section without interrupting operation of the healthy DC system. That requires fast DC breakers with operating times of a few Milliseconds. Operating times as short as that require communication faster than what has been considered for AC systems so far. Alternatively, new methods of providing selectivity without communication need to be developed. However, if the DC system is connected in one physical location, i.e. a star connection, selectivity can be provided by conventional DC protections.

Besides the principles described above, the study group will investigate the following aspects:

- Sequences for emergency and normal shut down of the DC circuit or parts thereof
- Selective fault clearing of pole-to-earth faults in systems with isolated DC circuit
- Selective fault clearing of pole-to-pole faults with and without earth connection in solidly grounded DC circuits
- Clearance of a converter side AC phase-to-earth faults

SUMMARY

HVDC Grids become more and more attractive for solving today's challenges in power transmission, including the utilization of renewable energy sources like offshore wind. Future HVDC systems require a new level of standardization of technical solutions to assure competitive supply chains for the equipment. The HVDC Grid Study Group was founded in 2010 to elaborate "Technical Concepts for first HVDC Grids". With focus on the first applications of HVDC grids in Europe the Study Group describes basic principles of DC load flow, short circuit currents and earthing as well as fault detection and fault clearing. The concepts developed will be used to create functional specifications for the network components. The work will lead to New Work Item Proposals to be offered to CENELEC for starting standardization work.