# Principles and Calibration Work for HVDC Grids

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***Abstract- The main task of the paper is to gain a common understanding of basic operating and design principles of HVDC Grid Systems, and to make the ground for more detailed setting work. The HVDC systems are moving from the phase of point-to-point (PTP) connections to the stage of the transmission systems interrelating more than two stations and applying multi-terminal (MT), multi-vendor (MTMC) HVDC Voltage-Sourced-Converter (VSC) systems. The growth will be modular, e.g., in steps, starting with interrelating PTP connectors and founding three-pod, radial systems. Then, such modest systems may gradually be interrelated into circular and engaged HVDC-VSC systems including more HVDC lines and DC converter stations. This paper describes the thoughtful, requirement and setting of design and action principles of the HVDC grids seen as the first wanted steps towards such MTMV systems.***

## I. INTRODUCTION

At present, with very few exceptions, HVDC systems(i)
have been built as point-to-point (PTP) connectors(ii)
between AC transmission systems or being embedded
into one AC system. When such AC systems are(iii)
asynchronous, the HVDC technique is the only way to(iv)
establish a connection. Such PTP HVDC systems
utilize either Line-Commutated-Converter (LCC) or(v)
Voltage-Sourced-Converter (VSC) technologies.(vi)
Utilization of the LCC technology is restricted to connectors between or within AC systems with sufficiently high short-circuit capacities at both ends. The VSC technology is suitable even for connecting islanded systems like offshore wind power plants (OWPP) to the onshore AC systems over long distances. In 2010, the energy authorities of the ten countries of the North Sea region have enabled the North Seas Countries Offshore Grid Initiative (NSCOGI) to find out the best way of connecting the planned over 100 GW offshore wind power to the participating countries and establishing the offshore HVDC VSC transmission system.

The main goal is the Offshore Grid infrastructure design by 2030 bringing multi-terminal, multi-vendor HVDC VSC transmission in focus. The development towards such multi-terminal (MT) HVDC systems will be modular, e.g. in steps, The system development has begun with PTP connections and continues through simple, radial, MT systems. Such smaller systems will gradually be interconnected into larger radial and meshed HVDC-VSC systems comprising more DC terminals and HVDC links. Understanding, specification, and standardization of design and operation principles of HVDC grids are seen as the first necessary steps towards such multi-terminal, multi-vendor (MTMV) systems. Based on an initiative by the German Commission for Electrical, Electronic and Information Technologies, DKE, the European HVDC Grid Study Group has been founded in september 2010 to develop first HVDC Grids with the objectives:

Describing basic principles of HVDC grids with the focus on near-term applications.

Developing functional specifications of the main equipment and HVDC Grid Controllers.

Developing proposals to CENELEC EN/TS for starting standardization work.

The Study Group counts members from the TSO, standardization institutions, vendors, and universities: 50Hertz Transmission, ABB, ALSTOM, Amprion, DKE, Energinet.dk, ETH Zurich, National Grid U.K., Nexans, Prysmian, Siemens, SvenskElstandard, Tennet, TransnetBW, and TU Darmstadt. This paper presents the main results of elaborating typical applications and performance requirements of the HVDC grids. The paper treats also the topics of principles of DC load flow and control, short-circuit currents, short-circuit fault detection and clearing, and required ancillary services to the adjacent AC systems.

## II. TYPICAL APPLICATION FOR HVDC GRIDS

One of the first applications for MT HVDC VSC systems under discussion is the connection of large OWPP because the main advantages can be exploited here. The wind power production is subject to wind conditions, which implies that long and expensive PTP connectors are only fully utilized during relatively short periods. Fig. 1 illustrates this statement. The utilization of the connector can be increased if more than one AC system is connected as shown in Fig. 1.

During periods of low wind power generation, the connector could be used for trading electricity between the connected AC systems. The utilization can reach values close to 100% but depends on the particular situation of the two AC systems and the power capacities of the converter terminals and cable. In comparison to a topology with separate PTP connectors, so that two separate PTP connectors between the OWPP and AC System1 and between AC System1 and AC System 2, topology reduces the number of VSC stations, which also reduces the asset cost and maintenance.

## III. POWER SYSTEM PLANNING

An electrical transmission system, AC or HVDC, is built for the exchange of energy between its nodes representing energy consumption or production. The HVDC connectors have been interpreted as part of the AC system. ancillary services to the AC systems according to the Grid Codes (GC).

When the HVDC grids expand in terms of dimensions and power capacity, the design, operation and reliability of the HVDC grids will be based, similar procedures and criteria as, at present, for the AC systems. Future system expansions should be considered in an early stage of system planning because such aspects influence both the electrical design and interfaces towards the DC side of the VSC stations. Among the technical aspects is a selection of the nominal voltage and current as well as voltage and current control functions. In radial systems, the coordinated control of VSC stations can determine the power flow through the iradjacent DC lines. In meshed MT systems, power flow distribution between parallel lines is determined by equivalent resistances and control of the VSC stations. Under these conditions, controlling the power flow through an individual line requires additional series-connected power flow controllers as well as appropriate power flow monitoring and control coordination. From the power system planning perspective, it is possible to extend the system transmission capacity at a later stage bye stablishing additional HVDC connections. Systems that in the initial stages are built by a single manufacturer should be expandable later using equipment from other manufacturers, i.e. MTMV systems. Standardization of equipment functions, voltage levels, control, and communication (protocols) will be crucial for easy and cost-efficient grid expansion and planning. For example, the voltage level in a DC grid, once selected, can only be changed at very high costs .

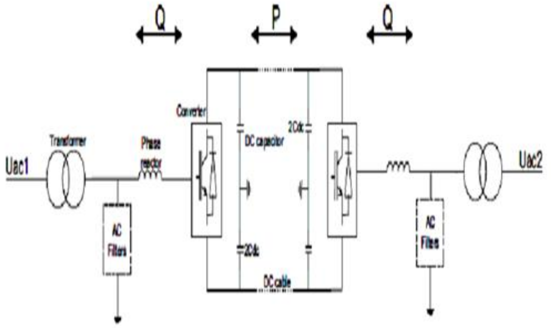

Fig 1. HVDC VSC connector configuration.

## IV. SECURITY OF SUPPLY

The grid expansion shall support agreed or predicted power and energy transmission needs and enable sufficiently high security of supply. The security of supply has a value guaranteed by the grid operator. It is determined as a product of system adequacy and system security. system security is the ability to maintain normal operation in cases of forced events such as faults, failures, and outages of grid components or generators. The system security is mostly analyzed for rare but severe events and stressed operation conditions, which represent the most critical situations, assigned from practical experience and expert evaluations. When defining the system topology, the grid operators decide how to achieve the required security of supply considering

i. HVDC circuit topology, e.g., monopole or bipole connection.
ii. Protection concept, including the topology of protection zones, the definition of the maximum fault clearing time, the establishment of a new power balance.
iii. Definition of critical operation balances and events in the HVDC and adjacent AC systems.
iv. static and dynamic stability of the HVDC and adjacent AC systems.
v. Possibility of fast energization and de-energization of the HVDC system, e.g., via the VSC stations.

## V. DC-LOAD FLOW PRINCIPLES AND CONTROLS

The primary objective of an HVDC grid is to transmit power amongst its converter stations, which import power from or export power into their AC systems. To change DC power transfer, the DC voltage has to be changed accordingly. At the same time, power import into the HVDC grid tends to increase, whereas power export from the HVDC grid decreases the DC voltage level. Transmitting power requires the DC voltage to be maintained within a certain range. Maintaining the DC voltage means balancing the power flow and power exchange with the adjacent AC systems. In most cases, any temporary mismatch between imported and exported power will be leveled out via the adjacent AC systems according to the control characteristics of the individual converter stations.

This action implies that the energy balance of each AC system is still fulfilled and the security of supply is not jeopardized. The AC systems can absorb such small, short-term power unbalance of both signs due to the system inertias. The short-term power unbalance with the AC systems is tolerable as far as it does not lead to their energy unbalance or affects negatively the frequency quality and security, e.g., due to a lack of inertia. In severe cases, the power surplus can be stored in energy storages, which at a present development stage are costly, or turned into heat using Dynamic Braking Devices, sometimes also referred to as DC Choppers.

## VI. VSC STATION CONTROLLERS

The VSC Station Controller handles the given VSC operation point, i.e. controlling the voltages and currents at the DC and AC terminals with the response time typically in a range of tens microseconds. The control objectives can be to keep a certain active power flow via the VSC station, AC system frequency, DC voltage, and can independently control reactive power exchange with the AC system, or AC voltage. In general, the VSC Station Controller does not rely on external communication. The control mode of a VSC station can be distinguished either by the direction of the active power flow, i.e. the rectifier or inverter mode, or by the type of control reference signal. When operated in “DC voltage control mode”, it has to adjust its active power exchange with the AC system to meet the given DC voltage reference value.

The active power exchange of this particular VSC station with the AC system is adjusted to balance the power in the DC system. Thus, this VSC station operates as the swing-bus of the DC system, e.g. absorbing any power unbalance of the HVDC system and exchanging the unbalance with the adjacent AC system. The response time to handle power unbalance and ability to maintain the DC voltage ranges shall be among the technical specifications to the HVDC systems, which include specifications to existing as well as planned for commissioning VSC stations . The response time range can be up to a few 100ms but depends on the DC capacitance of the HVDC system components, i.e. the DC voltage sensitivity, and on the control system constraints to power flow changes.

When a VSC station operates in “active power mode”, it adjusts its DC voltage to enable the active power transport to meet the active power reference value within the operational DC voltage limits. The VSC station will be required to participate in the primary frequency control of the adjacent AC system, which can either be a frequency-sensitive mode or a frequency-limiting mode [5].

The VSC station shall be commissioned to handle both frequency control modes, but activated one at a time. The requested frequency control mode activates and overrules the regular active power mode when frequency deviations exceed a normal-operation frequency range. The normal-operation frequency range, as well as the parameters of the frequency control modes, are defined by the TSO of the adjacent AC system, usually in the Grid Code. Since the HVDC system only transports but does not produce or store electric energy, activation of the frequency control of the VSC station in one of the adjacent AC systems may influence the frequency quality in other adjacent AC systems. Thus activation rules and parameters of the frequency control modes shall be agreed upon between the relevant TSOs. The characteristic response time is in a range from a few to tens of seconds. In practice, the active power reference value will comprise a contribution provided by a secondary control loop, i.e. controlling the AC frequency, which is added to the control signal of the primary control loop to produce the power reference value of the VSC station.

## VII. HVDC GRID CONTROLLER

The HVDC Grid Controller is a higher- level controller linked to each VSC Station Controller. Its main purpose is to provide the VSC Station Controllers with their control characteristics and reference values; this is illustrated in Fig. 2 for the case of a small, radial HVDC system. The HVDC Grid Controller is factored with the static, as-built information on the HVDC system topology and electric parameters, such as resistances and maximum ratings. Therefore, the HVDC Grid Controller shall also facilitate grid restoration when the grid has split up after the fault clearance. When all information is made available for the Controller, it performs the power-flow pre-calculation which is similar to the load-flow study for a conventional AC network.

The security-of-supply, i.e. the compliance to the (n-1) operation criterion, is assured using contingency analysis in a similar way as for AC networks. The calculations shall prove that the given voltage ranges will not be violated and the given current ratings (converters and lines/cables) will not be exceeded in normal operation as well as in (n-1) contingencies. Reliability of the HVDC system operation must also been sured if the HVDC Grid Controller fails; the failure is either due to outage or loss of communication to some or all grid-components. In the latter case, the affected VSC Station Controllers will act autonomously. It is not any longer possible or necessary to keep an optimized power flow, but the DC voltage must be kept within a required operating range. The HVDC system must remain stable until the normal operation of the HVDC Grid Controller is re-established.

## VIII. DC LOAD FLOW CONTROL CONCEPTS

The main target is that different concepts for the HVDC Grid Controllers and the VSC Station Controllers are applicable together within MTMV HVDC systems. The fact that converter controls are often considered intellectual property can make an exchange of information difficult. This apparent barrier towards MTMV HVDC systems can be overcome through the definition and standardization of the common control concepts and the common lists of parameters. Since the MT HVDC grid will be realized as a multi-vendor system, it must remain statically and dynamically stable regardless of which of the control concepts is applied to a certain station.

To demonstrate this requirement, benchmark simulations of the four-terminal system in Fig. 2 have been performed. In the described benchmark simulations, the stationary power ratings of the VSC stations are 800 MW, the nominal operating voltage is ±320 kV, and the VSC stations are connected via symmetric monopolar links comprising XLPE cables, 200 km length each. In the initial steady-state situation, VSC stations A and Bare rectifiers, i.e. importing 800 MW each into the HVDC system, whereas VSC stations C and D are inverters, i.e. exporting 775 MW at C and 800 MW at D. The total benchmark simulations comprise different power loss situations, i.e. outages of different VSC stations. The following example shows the case of a total load rejection, so that outage of the VSC station C. The outage leads to a surplus of 775 MW imported into the HVDC system. This condition is, first, handled by the local VSC Station Controllers which remain in-service, because the HVDC Grid Controller cannot react in such a short time frame. The three common control concepts, C1 to C3, have coped with this extreme situation and the post-event stationary power flow situation for all three common concepts after the transient shave decayed. In all three concepts, the power loss is compensated by an equal reduction of the power import via the VSC stations A and B.

The difference is that the final steady-state of the control concept C1 reaches the maximum voltage limit at the importing VSC stations and a final power flow of825 MW, and the lower voltage limit is reached for C3 at the VSC station D with the final power flow of only 784 MW. The simulation study has concluded that different control concepts of VSC Station Controllers should work together in a stable manner. The study has, however, applied generic-level models and parameters of the Controllers. The converters in general have non-linear voltage-current characteristics and principles of superposition should be used with great care only. Application of vendor-specific parameters and control concepts in a network with multiple concepts is recommended to study stability.

- Generally, it is recommended to design the system considering different levels of detail.
- In a high-level approach, dominant frequencies existing in the HVDC Grid shall be identified by simulations or measurements, if the system already exists. DC network harmonic impedances shall be calculated for all relevant network conditions.
- In a more detailed approach, time-domain simulations shall be carried out investigating possible interactions between the individual converters including their controls. Appropriate transient models of the existing converters shall be provided allowing measures to be taken to avoid control instabilities. Additionally, the interface between the HVDC Grid Controller and the local VSC Station Controllers influences the response of the entire HVDC system to a disturbance. The interface shall clearly define how fast and how exact the reference values sent to the VSC Station Controllers are met, i.e. whether an offset is permitted in the final response due to a dead band or a droop.

## IX. DC SHORT-CIRCUIT FAULTS AND PROTECTION

The protective clearance and removal of short-circuit faults have three important purposes:

- Minimizing hazard to personnel.
- Minimizing disturbance to system operation.
- Minimizing risks of equipment and buildings'

Converter station protections:
An asymmetrical VSC station willhave additional settings for the DC voltage unbalance [5]. Bipolarschemes are commonly designed with independent protectionsystems between the poles, so that as for two asymmetricmonopoles. The VSC station protections in Fig. 5 are grouped by the three main zones.

- DC-link over-current protection.
- DC differential protection detecting ground faults on the DC converter terminals or within the circuit up to the converter transformer.
- Bus-bar current differential protection detecting deviations between the sum of converter arm currents and the DC at positive and negative DC bus-bars.
- Asymmetry protection objecting to detect single-phase ground faults at the AC converter terminals.
- Converter/valve reactor over-current protection, i.e. in any of the six converter limbs.
- AC secondary / limb current differential protection objecting to detect faults between the limb reactors and the converter transformer.
- AC secondary under-voltage protection, i.e. at the AC converter terminals.
- Pre-insertion resistor over dissipation protection detecting excessive energy dissipation through the pre-insertion damage.

## X. DC SHORT-CIRCUIT CURRENT

The HVDC grid structure itself has a significant impact on the maximum possible amplitude of the DC short-circuit current, i.e. the fault current level.

## XI. HVDC FAULT DETECTION AND CLEARING

Since an HVDC Grid System comprises several converterstations, it requires more selectivity in the DC protection than conventional PTP HVDC transmission links with two converter stations. The selectivity shall allow both identification and subsequent removal of a faulty part and permit continued operation of the remainder of the HVDC Grid System. The protection system design shall acknowledge the following topics in detail.

i. The HVDC grid structure.
ii. Behavior of converters for earthing and short-circuit faults.
iii. Operational conditions before a fault.
iv. Fault types, i.e. converter faults, AC system faults, HVDC grid faults.
v. Utilization of HVDC breakers.
vi. Impact from communication.

The HVDC grid protection is dependent upon the specific needs on the detection, isolation, and selectivity of the grid following a short-circuit fault. The grid operator shall define whether fast dynamic isolation of a DC short-circuit fault is needed. Where there is no need for fast dynamic isolation, a temporary stop is accepted for manual control of reconfiguration of the HVDC Grid System after a fault. Such a temporary stop is acceptable for small HVDC systems and where it does not jeopardize the security of supply and stability of any of the adjacent AC systems. The VSC topology shall be taken into consideration for the evaluation of investment needs into fast isolation devices. The evaluation is based upon the requirement for the specific system to minimize the impact on the security of supply and stability of the entire AC and HVDC power systems.

For the VSC-based full-bridge converters, the fault current is suppressed by the converter control actions. Hence, high-speed switches can be utilized with such converters for interruption of the DC fault current. The use of high-speed switches will depend on the response time required to maintain the stable operation of the powersystem. This paper is based on the work conducted by the European HVDC Grid Study Group and presented some central items from the Study Group Report “Technical Guidelines for first HVDC Grids”. The work of the Study Group has determined important application and performance requirements to future multi-terminal, multi-vendor HVDC grids. Such multi-terminal, multi-vendor HVDC grids could be attractive solutions for connecting offshore wind power with onshore DC and AC systems in the future.. HVDC grid development and expansion are expected to be modular, i.e. stepwise development, from the present point-to-point or three-pod HVDC terminal configurations. Existing HVDC systems will gradually expand and become multi-terminal radial and meshed HVDC grids.

The planning and expansion of HVDC grids need to be in compliance with the design and operation criteria for the present AC transmission systems connected. The expansion design and planning shall secure both the right level of security-of-supply and facilitation of the HVDC grid with needed control principles.. For the successful expansion of a single-vendor system to a multi-vendor HVDC grid, several technical principles are found essential with the objective in mind: getting the HVDC Grid Controller and the local VSC Station Controllers to work right away as easily as if it were a-single-vendor, point-to-point HVDC connection.

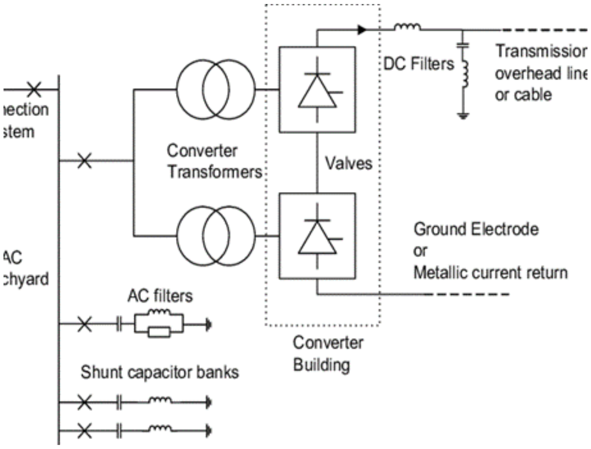

Fig :2: Common protection system for mono-polar HVDC system.

## XII. RESULTS AND DISCUSSION

The interface control principles and lists of required parameters shall be appropriately identified and standardized to achieve optimized power flow for each DC terminal added to the HVDC system. The study has identified the voltage-power droop together with a dead band (VPDDB), the voltage-current droop (VCD), and the voltage-power droop (VPD) as suitable common control concepts of the VSC Station Controllers. Furthermore, the selection of an HVDC Grid Controller is proposed for operating the individual VSC Station Controllers, each with different modes or concepts that will work together.

## CONCLUSION

The Study Group has also identified the need for standardization of short-circuit current calculation methods, earthing, and fault handling principles within HVDC grids. The short-circuit calculation methods and principles shall take the contributions from adjacent AC systems into account, which are not infinitely stiff AC systems.

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