HV multi-terminal DC lines as the backbone of the energy transmission system – A research plan to tackle challenges

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Abstract. Transmission system reinforcement is an issue of great importance, in an effort to handle the increasing renewable power generation. Nevertheless, the upgrade of the transmission system (lines, substations, etc.) is not always attainable, due to techno-economical restrictions. To this context, High Voltage Direct Current (HVDC) grids or converting already existing AC lines to DC lines could offer an alternative solution, considering also the interconnection of offshore intermittent renewable generation resources, the connection of remote generation sources to load centers and the inter-continental transfer of large quantities of energy surpassingly an overlay grid. The current work presents a research plan for multi-terminal HVDC grids, in an effort to face technical challenges.

1 Introduction

Growth in renewable power generation results in new load flow patterns that may be difficult to be accommodated especially, in mature networks such as those in Europe and North America. This to be achieved, requires transmission system reinforcements. However, the permitting process for constructing new overhead lines is time-consuming or even impossible. High Voltage Direct Current (HVDC) grid, using underground cables for areas where overhead lines cannot be built, could offer an alternative due to higher transmission capacity. Another alternative could be converting existing AC lines to DC. Additionally, DC grids can be used extensively for interconnection of offshore intermittent renewable generation resources such as wave and wind, connection of remote generation sources to load centers, inter-continental transfer of large quantities of energy surpassingly an overlay grid. Multi-terminal HVDC grids could provide an adequate alternative to AC grids and contribute to the connection to the system of intermittent renewables. However, there are technical challenges to be investigated. These have been collected to a research plan, which is presented in the framework of this analysis. The research plan can be useful for TSOs, DSOs and producers, in order to achieve the optimum integration of the renewable energy sources and secure the efficient operation of the grids.

To this direction, it is important:

- to analyze the major technical challenges for the implementation of multi-terminal HVDC grid configurations, promoting DC networks for next generation transmission grids,

- to advance existing operational procedures of steady state analysis, dynamic and transient analysis, and,
- conclude with proving experimentally in the cloud-based virtual laboratory for representative HVDC network schemes.

Moreover, indicative DC topologies and offshore wind parks interconnection schemes have to be included, in an effort to advance the analysis, simulation and control strategies for multi-terminal HVDC schemes integration into existing AC transmission networks.

A virtual lab experimental setup and operational analysis of this HVDC overlay network could study the impact on the operating principles of the pan European transmission network, as these are expressed in the ENTSOe network codes: load-frequency control (primary, secondary and tertiary control), scheduling, operational security (N-1 criterion, voltage control and reactive power management, short circuit currents, angle stability).

The major contributions of this research plan are summarized as follows:

- development of efficient algorithms, tools and benchmark models on multi-terminal HVDC grids for steady-state, transient, short-circuit, grounding analyses and control, and,
- provision of the experimental testbed for RES integration and AC overlaid connection, with applicable requirements and procedures for the next generation pan European transmission network.

That is to say the research plan shall have the following objectives:

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- Propose detailed steady-state power flow modelling tools for multi-terminal DC grids that accommodate the requirements of different regions across the world.
- Provide a novel open-source hybrid AC/DC power system analysis platform for steady-state and dynamic / transient / contingency analysis.
- Design novel analytical dynamic cascaded converter control model.
- Analyse the influence of the power balancing after an outage on the AC grid stability.
- Provide contingency analysis tool for HVDC integration in the AC transmission network.
- Study multi-terminal HVDC grid interconnection of off-shore wind parks and advance recent research studies [1].
- Analyze the effects on the ENTSOe network codes by employing multi-terminal HVDC overlaid on the pan European interconnected transmission network.

2 Benefits of DC transmission and current installations

DC-transmission projects offer specific well-known advantages over AC transmission [2]. These advantages are also valid for multi-terminal DC transmission with Voltage Source Converters (VSC). VSC transmission seems to be particularly suited to the connection remote installations of the level of a few hundreds of MW of active power [3]. Main advantages of VSC are:

- the VSC does not require a commutation voltage from the network in order to operate satisfactorily
- the VSC can operate continuously at any power flow.
- the VSC does not suffer commutation failures.
- a VSC transmission converter station is much more compact than the equivalent Line Commutated Converter (LCC) HVDC converter station.
- a VSC transmission scheme will appear to the receiving network as a generator without inertia, but with less short circuit current contribution.

The VSC technology has been used for point-to-point HVDC transmission since the late 90s. This is still a developing technology unlike the LCC, which is mature and well-proven. The VSCs typically use IGBTs with antiparallel diodes. Due to the late development and relatively low available capacity, the deployment of VSC technology has been limited to only a small fraction of the overall HVDC installed capacity worldwide. However, there is enormous potential for VSC HVDC, especially for offshore applications. Similar to the conventional AC networks, the power reversal in a particular VSC HVDC link within a multi-terminal DC (MTDC) grid is achieved simply by reversing the current through that link while maintaining the voltage polarity at both ends. Thus, the VSC technology is the obvious and arguably the only choice for meshed DC grids [4].

Significant MTDC projects are already or up to be completed or designed in advanced stage worldwide:

a) Nan'ao island is in the southern part of the Guangdong province, China. The key objectives of the project were to incorporate the existing and future wind power generated on Nan'ao island into the regional power grid, both to safeguard future energy supply and to support the transition from coal towards renewable sources. This project implied the world's first multi-terminal VSC MTDC system, which was successfully commissioned on December 25th, 2013 [5]. The Nan'ao VSC MTDC system is an AC/DC parallel power transmission system, and each converter station is connected to the 110 kV AC system. The DC voltage of the entire project is 160 kV and the DC side of the converter employs the symmetric monopole configuration [5]. Each converter station consists of AC circuit breaker, converter transformer (110/166 kV), pre-charge resistor (to limit the current for converter charging), bypass switch, modular multilevel converter (MMC) and disconnectors at the DC side [6]. DC breaker technology is not mature and economical at present, so it was not used in this installation.

b) The Zhoushan archipelago is located in China's eastern coastal region, consisting of more than 1390 islands. Among the islands of the Zhoushan archipelago, the larger and more power-consuming islands include the main island of Zhoushan, followed by the islands of Daishan, Qushan, Yangshan and Sijiao. To meet the increasing demands of the construction of new areas and development of different islands, the power load capacity will need to increase constantly. The five converters rated at ± 200 kV in the Zhoushan DC grid are connected via modular multi-level voltage source converter (MMC-VSC) HVDC links to form a 5-terminal DC grid. The converter stations used in this system incorporate symmetric monopole main wiring mode and the cables connect the converters with a total length of 140 km [7-10]. A full-bridge cascaded new-type topology of the hybrid circuit breaker was designed for this project, which comprises three parallel branches including the main branch, transfer branch, and energy-consuming branch [7]. These HVDC circuit breakers have rated voltage 200 kV, rated current 2 kA, short-circuit current breaking capacity 15 kA, breaking time of 3 ms and transient voltage 300 kV [10].

c) Zhang-Bei is designed as a DC grid project to secure power supply to Beijing from a variety of clean sources, including wind, solar and hydro power. Four converter stations will be built for phase I, including 3 sending terminals (1500 MW/ ± 500 kV each) and one receiving terminal (3000 MW/ ± 500 kV). When completed in 2018, it will become the first and largest DC grid project in the world. Another two terminals have also been planned for phase II, with commissioning expected in 2021. The project adopts "Half Bridge MMC + DC Breaker" scheme [11]. In fact, the DC breaker developed in the Zhoushan project will also serve as a

pilot project for the DC breaker to be developed in the Zhangbei DC grid [12].

d) One of the oldest multi-terminal HVDC grid [13], which was commissioned in 1967, is SACOI (Sardinia-Corsica-Italy). A third terminal point at Sardinia, started operation at 1988 making the interconnection multi-terminal. The initial transfer capacity of the system was 200MW and the newer station was able to deliver 50MW.

e) India constructs its own multi-terminal HVDC system. It is the North-East Agra system to be operating at ± 800 kV with installed capacity of 6000 MW and total service line length of 1728 km [14]. For this system are foreseen three connection points at Biswanath Chariali, Alipurduar and Agra. The system will be developed in two stages. The first will include a bipolar system able to transfer 3000MW, which will be updated to two bipolar circuits and double its capacity.

f) Europe and North America have planned two major initiatives to increase the penetration of renewables and facilitate the transfer of energy from offshore plants. Specifically, these are the Atlantic Wind Connection project [15] and the North Sea Grid Initiative [3]. In both cases, there is major wind potential offshore, which is better to be absorbed by the system if multi-terminal HVDC are to be installed. It has to be mentioned that European industry was able to develop DC circuit breakers applicable to these projects [16].

Despite the fact multi-terminal HVDC grids have been a relatively old technology, several issues could be further investigated in order to improve performance, availability and stability of operation. These are described analytically below and proposed to be investigated in this research plan.

3 Research plan areas of contribution

3.1. Controllability

As with AC the power input and output at each DC terminal is quickly controlled to match the desired dispatch, as long as the power flows are within the capability of the converters and lines. With a VSC HVDC grid, each terminal can provide voltage support to the AC grid, within the power capability of the converter.

The operational situation of the grid changes in time. This is due to the intermittency of the energy production from renewables, the change of the load caused by consumers and consequently the need to adjust the production of the remaining sources in order to achieve the required energy balance. Having described the above, it is of paramount importance to perform load flow analysis in predefined time intervals. These are usually half an hour or hour intervals and span from a few months to a few years. An alternative could be to simulate the situation for a year or simply the worst-case scenario but in these cases the resolution to be achieved is inadequate to be able to produce safe conclusions.

Furthermore, multi-terminal HVDC grids for wind parks integration should be thoroughly studied, applying real wind production energy data derived from the National Centres for Environmental Prediction (NCEP) [18]. As far as the consumption is concerned, the consumption of the potential countries to be connected to a “European super grid” must be taken into account [3].

3.2 Fault clearance

The voltage drop at a DC side fault is spread out much wider in a DC grid than in an AC grid as the DC resistance of a line is much lower than the fundamental frequency impedance of an AC line. The DC breakers must be significantly faster than the AC breakers used today. With future high speed DC breakers, the fault clearing strategy must be the same for a DC grid as for an AC grid. Only the faulty equipment, line or converter, will be tripped, and the non-faulted parts of the system will remain in operation. Due to the fast disconnection of the DC side fault, the fault time and dips felt in the AC grid will be very short. Through the controllability of the DC grid it can quickly be re-dispatched to the desired power flow.

So, short circuit analysis for multi-terminal HVDC grids is also an issue of great interest. In this case, the Voltage Source Converters (VSC) connecting the DC side to the AC side isolate the two subsystems and a short circuit does not propagate to long circuit distances, thus there is not a need to apply an extensive network such as the one to be used for the steady state analysis. The most dangerous short-circuits for the operation of the multi-terminal HVDC are the ones appear at the DC side. Considering the complexity of the VSC and the fact that VSC appears to have different configurations that affect their short circuit performance, special attention must be given to model them in a proper way. The technical literature has to propose a variety of different network models [2, 20], however, this research plan intends to develop new ones tailored to meet next generation clean energy transmission grids.

Especially challenging for the implementation of multi-terminal grids is the simulation and experimentation difficulties caused by the lack of standardized advanced short circuit switches for the DC side [20]. As a matter of fact, the interruption capabilities of high current switches are limited comparatively to alternating current switches, thus presenting high installation and operation costs. For point-to-point HVDC the main proposed solution is to tackle short circuits through reducing the power of the power electronics connected to the terminals creating a stall of the system that in any case was not able to function properly due to the fault. However, in the case of multi-terminal high voltage direct current grids a short circuit that disables the whole system would substantially reduce its availability to an unacceptable level.

3.3 Islanding – Grid separation

This research plan proposes to implement the simulation and experimentation to understand in-depth the transient performance of a multi-terminal HVDC grid. In general, the transient stability and control studies will include simulations of transient fault currents, but on a large time scale of milliseconds to a few seconds and the simulations are usually based on simplified models for the DC lines with cascaded pi-sections. For the analysis of the fundamental fault current behaviour, simulations in the range of microseconds to milliseconds have to be performed and more accurate line models are required to represent the exact waveform of the fault surges. The literature review [21-27] has shown the lack of deeper understanding of the fundamental development of transient overcurrents and overvoltages and their influencing factors in a MTDC network. Methods for the simulation of transients exist for the AC transmission, but only a few approaches could be found for a MTDC grid, which are mostly based on very simple models. In this research plan, it is proposed the amplitude of overcurrents and overvoltages to be quantified for different fault scenarios and the influence of each element of a MTDC network on the transient behavior will be investigated. In order to be able to produce the appropriate models, different Voltage Source Converters will be tested using the developed virtual laboratory for extensive simulation.

The asynchronous nature of the HVDC interconnection can be of benefit to wind farms, particularly if the wind turbine generator does not comprise power electronics itself [28]. For example, a fault in the main AC network is not transferred to the wind farm grid, and the fault ride through capability of the wind farm may be improved. However, this requires appropriate measures to manage the surplus wind power that the HVDC link cannot export to the grid during the fault. This may involve special control features at the HVDC link and/or special control features at the wind generator if it comprises its own power electronic converters. Another benefit of faults not being transferred to the wind farm is that fewer faults and disturbances may be seen by the wind farm, which is of long term benefit, since mechanical stresses are caused within the wind farm during grid disturbances. HVDC converters can be used for power oscillation damping as proven in existing installations. This feature can be used to restore normal operation of the wind farm quickly and very smoothly and if necessary, to support the AC system for improving its transient stability.

3.4 AC/DC grids interconnection

These merits of DC grids shall be demonstrated through the indicative network schemes and extensive case studies of the experimental testbed. The above aspects are subject to converter rating limitations and to the availability of support from the AC networks, to which the DC grid is connected. The DC grid can connect asynchronous AC grids to make use of the spinning reserves in both systems. The dynamic interactions between the AC and DC grids will be further studied and generic and/or “black box”-models of the

VSC converter together with DC and AC will be developed and benchmarked.

4 The proposed research plan

Regarding the benefits of HVDC transmission, it is evident that deeper understanding of MTDC operation and effective network modelling will promote clean energy targets and transmission grid reinforcement. To begin with, this research plan deals with the steady state simulation of the multi-terminal DC grid. It includes load flow, N-1 contingency and weak point analysis for a number of nodes that adequately represent the range of a super grid, which may be on the level of thousand nodes [3]. Short circuit and transient analysis methodologies that provide deeper understanding of the fundamental characteristics of a MTDC network have to be elaborated. All the developed simulation tools must be based on proven industrial software tools; in this way, it will be easy to adapt with other research activities and study network topologies with significant complexity. In addition, network configurations of MTDC have to be examined in respect with conformity with the network codes of the panEuropean transmission system which describe controllability, islanding operation, stability margins.

In details, the basic steps of the proposed research plan (summarized in Fig. 1) are described as follows:

Step 1: The research plan shall initiate on a general classification of DC voltage control strategies, thereby addressing the steady-state working characteristics. The requirements for a DC grid voltage control must be systematically introduced and analysed. Standard two-terminal control principles, such as constant voltage, constant active power or current control and a voltage droop (intentional loss in output voltage from a device as it drives a load) shall be investigated. Also, it is proposed to be investigated the degree they can generally be combined to obtain more advanced control schemes, resulting in multi-terminal DC (MTDC) grids.

Fig. 1. Analysis of the research plan.

Step 2: An accurate steady-state model for VSC MTDC systems and cables is necessary to be developed. In the technical literature, a strong focus has been on two-terminal VSC HVDC systems and a general approach to VSC MTDC power flow calculations is missing. Contrary to earlier models, the proposed model shall include a detailed converter representation, defining the power and voltage set points with respect to the point of common coupling. The power flow model proposed to be developed must solve AC and DC systems sequentially and iterate between them, in order

to support DC overlay grids with existing AC grids. When solving the AC system, the DC grid variables will be kept constant and the converter interaction with the AC system will be modelled by means of standard PQ- and PV-buses. Similarly, AC grid quantities will be kept constant when solving the DC grid, in which the converters have been modeled as constant power buses or as a constant voltage bus, thereby implicitly extending the operational principles of two-terminal VSC HVDC schemes. An additional iteration is necessary to calculate the losses of the converter connected to the DC slack bus. As an alternative to the sequential power flow approach, all equations will be combined and solved in one single iteration. The sequential approach, however, has the advantage that it can straightforwardly be integrated with existing AC power flow software. Algorithms and respective simulation software have to be developed while benchmarking network topologies should be proposed to prove the superiority of the research work.

Step 3: A cascaded control scheme for MTDC systems that allows for voltage margin and voltage droop control and that current and voltage limits is essential be represented in detail, in order to allow additional internal limits and to be easily reconfigured to combine e.g., constant voltage control or constant power/current control with droop control. Alternative droop control schemes must be investigated from both a dynamic and a steady-state point of view. The general control strategies should be combined to obtain different droop-based control schemes including a constant power and current deadband or alternatively constant voltage characteristics to account for minor power variations in the DC grid. A secondary voltage control strategy should be also introduced, which mainly aims at restoring the voltage profile after a contingency.

Step 4: The influence of the converter power sharing after a contingency on the AC system transient stability must also be investigated by analyzing the input directions causing the smallest effect on the system outputs due to disturbances at the DC side.

Step 5: While “copper plate” approximation on the DC side, or a common voltage signal being used for the DC voltage control is common practices in HVDC control analysis, the DC grid topology influences the power sharing after an outage. This influence is critical to be studied analytically, both for power- and current-based droop control. These analytical expressions exactly hold for the current-based droop control. An optimization routine must be developed to achieve a trade-off when selecting the converter characteristics. On the one hand, the steady-state voltage deviations after a contingency have to be limited and kept within reasonable bounds. From a control perspective, on the other hand, the aim is to obtain an optimal power or current redistribution after a converter outage. Algorithms and respective simulation software have to be developed while benchmarking network topologies

will be proposed to prove the superiority of the research work.

Step 6: The development of a software package (platform) that can study complex MTDC grids with multiple nodes, overlaid with existing AC transmission network is essential. The software package shall be an open-source software tool to researchers and power engineers for studying the steady-state interactions in hybrid AC/DC systems. The mathematical modeling of the software must build on the sequential approach presented and extend the DC grid model to represent the droop-controlled converters previously presented. The converter models must be defined in a flexible manner and allow to include various converter topologies, either including or excluding the converter transformer and filters. The proposed software shall provide the functionality to investigate the effect of droop settings and contingencies such as converter outages. Efficient algorithms and software tools to be developed for steady-state and dynamic modelling, transient analysis and N-1 contingency analysis must also be integrated. Major efforts shall to be made to keep the tool as flexible as possible for the user, as well as to keep the source code easy to interpret and extend. The model has to be easily extendable to include user-defined models, such as current-based instead of power-based droop characteristics.

Step 7: Furthermore, extensive real-world scenarios are necessary to be studied for possible HVDC grids. HVDC grids are ideal for wind farm connections. According to the recent techno economic assessment “Offshore Electricity Grid Infrastructure”, HVDC wind farm connections generally become economically viable for distances above 50 km from shore, when the sum of installed capacity in a small area (~20 km) is relatively large, and standard available HVDC VSC systems can be used. Wind farms situated closer than 50 km to an onshore connection point are virtually always connected individually to shore. Based on the different HVDC topologies, indicative off-shore wind parks configurations could be studied and integrated in the pan European interconnected transmission system, considering the conformity of the case studies with the ENTSOe network codes and the overall performance of the AC/DC integration.

5 Conclusions

The current paper presents an analytical research plan for multi-terminal HVDC grids to tackle the arising technical challenges, in an effort to provide an alternative to AC grids and contribute to the connection to the system of renewable power sources that have intermittent generation. The objectives of the research plan, the contribution to solve existing problems and the basic steps to be implemented are analyzed in details. This proposed research plan covers the emerging issues of multi-terminal HVDC grids including steady state and

dynamic analysis giving emphasis to faults. Steady state analysis is to be based on European wide requirements as they are expressed by operator's needs. Dynamic analysis will include, except from issues of protection and fault clearance, the behavior of power electronics and DC/AC interconnection. The research plan can be valuable for Transmission and Distribution System Operators and producers, in order to ensure the best possible integration of the renewable energy sources and guarantee the effective and secure operation of the grids.

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