Transient Fault Studies in a Multi-Terminal VSC-HVDC Grid Utilizing Protection Means Through DC Circuit Breakers

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***Abstract*—Multi-terminal DC grids is a promising solution for integrating distant renewable energy sources and offshore wind farms into onshore AC networks. Protection of such networks is one of key factors ensuring their reliability and continuity of service. This paper addresses the dynamic behavior and sensitivity of a typical multi-terminal DC grid under faulty conditions, observing the severe impacts these could have on the entire hybrid AC-DC system. Protection measures will be introduced in the form of DC circuit breakers (CBs) to isolate the faults and recover system's normal operation. The study concludes the feasibility in using DC-CBs in a multi-terminal VSC-HVDC network serving as fault protection and stability recovery tool when the DC-CBs are located in an optimally distributed way. The simulation work depicting the various scenarios has been performed under DigSILENT PowerFactory environment.**

***Index Terms*--DC Circuit Breakers, DC Fault, DC Protection, MTDC, VSC-HVDC**

I. INTRODUCTION

High Voltage Direct Current (HVDC) technology has proved to be an efficient, cost effective and reliable way of transmitting electrical power over long distances as compared to the classic and traditional AC transmission [1]. Especially the use of Voltage Source Converter (VSC) based HVDC has provided a number of benefits compared to the classical Current Source Converter (CSC) HVDC, in terms of enhanced flexibility in independent control of active and reactive power [2].

Up to date, several installations of HVDC transmissions have been installed world-world [1], [3], utilizing both VSC and CSC technologies. However, the vast majority of them concerns point to point transmissions. A few years back, the first Multi-Terminal DC (MTDC) grid configurations started to come into light, and it mainly targeted the reinforcement of national networks [4], [5] and, less frequently, formed power sharing platforms between countries such as the Sardinia-Corsica-Italy (SACOI) connection [6].

Due to the significant economic and environmental benefits that MTDC grids have to offer, a constant interest started to grow towards the expansion of these networks aiming the integration of distant renewable energy sources, such as offshore wind farms to inland AC grids. Since then, a considerable amount of studies have been undertaken addressing technical issues regarding the operation and control of MTDC systems utilizing VSC technology. These were mostly focused for an economic and efficient importation of wind power into onshore power systems [7]-[12].

Protection measures however, securing the combined AC/DC systems from faults and disturbances forms an important issue, highly affecting the smooth and robust operation of the overall network. Some initial studies have been conducted concerning DC protection in MTDC grids [13]-[15]. The most recent ones concentrate on the location and isolation of DC faults relying on AC-CBs and fast DC switches [15]. However, this methodology requires temporal system unavailability since fault clearance heavily depends on functioning of AC-side circuit breakers, which sets the entire DC network out of service. This short gap in system's availability could have severe consequences on the overall network, as well as the interconnected sub-grids. This is especially true when large DC grids are considered interconnecting heavily loaded AC networks, such as the future European Supergrid [16], which will form the core of the power sharing platform of Europe.

Consequently, a selective and reliable protection scheme providing continuous and online security of MTDC networks against DC faults and disturbances is crucial, utilizing decent DC-CBs technologies [17] capable of instantly interrupting DC fault currents without affecting system's availability and performance.

In this work, a four-terminal VSC-MTDC grid is used to interconnect four individual AC power networks through bipolar connections. The system is equipped with DC-CBs distributed along every transmission line, ensuring that in the unfavorable event of a permanent DC fault on a line, that faulted line will be immediately selectively disconnected and system's stability will be re-established. This is a highly favorable scenario that will be seriously taken into account during future developments of offshore MTDC grids.

The purpose of this study is to gain an initial experience regarding the dynamic behavior of the AC/DC system under permanent (ac/dc) faults, observing how these affect the stability of the system. The second part of this work, introduces the application of DC-CBs used as protection measures tackling the faults (dc-side), and hence re-establishing stability. The study concludes by confirming the feasible use of DC-CBs in a VSC-MTDC grid, serving as a guard to fault events whereas at the same time contributing to fast recovery of system's stability.

The test system considered in this paper can realistically reflect the first stages of an evolutionary development of a multi-terminal (under-sea) DC network, such as in the area of North Sea, forming the core (also known as the critical point) of the European Supergrid.

II. TEST SYSTEM

Figure 1 illustrates a single-line diagram of the proposed system. Each tie-line represents a bipolar connection realizing power transmissions under positive and negative DC voltages.

A. *Power System Architecture*

The topology of the MTDC network comprises the properties of ring (Lines 1-4) and meshed (Line 5) connection, enabling the system to comply with a wide variety of DC network configurations. Transmission lines 1-5 have a total length of 100km, 50km, 100km, 50km and 120km respectively. These are typical values representing offshore wind power integration to onshore AC grids. Figure 1 also depicts the DC-Circuit Breakers (CBs) distributed along the network with appropriate labeling.

B. *Control Strategy*

Converter terminal VSC1 is set to ***Q-V**$_{dc}$* control mode. This serves into controlling the reactive power (***Q***) exchanged between external grid AC1 and the converter. Additionally it maintains the DC voltage (V_{dc}) of the network to a constant value. VSC1 acts as a slack bus to the system by balancing the power flows in the DC grid and adequately preserving a constant voltage level. The rest of the converters are all set to the ***P-Q*** control mode, establishing constant active power flows (***P***) in the grid, as well as regulating the reactive power (***Q***) exchanged between the AC grids and converter terminals.

C. *Power Sharing Plan*

The active power exchanged between the converter terminals (and hence the AC grids) is realized according to the following plan: Terminal VSC3 transmits a constant stream of 10MW to the DC grid, whereas terminals VSC2 and VSC4 each receive a constant amount of 10MW. Converter VSC1, acting as a slack bus to the system, compensates for the rest of active power needed including the power losses in the grid, by transmitting a total amount of 10.95MW. The reactive power transmissions, as controlled by each converter terminal, are all set to zero. The nominal voltage of the interconnected AC grids is set to 400kV (Line-Line) whereas the corresponding voltage of the DC grid is set to 320kV (Line-Ground).

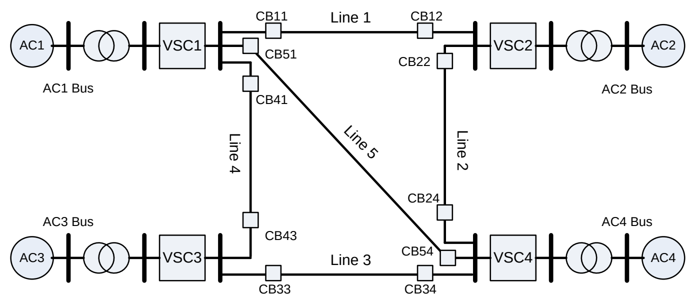

Figure 1. Single-line diagram of the mixed AC/DC test system

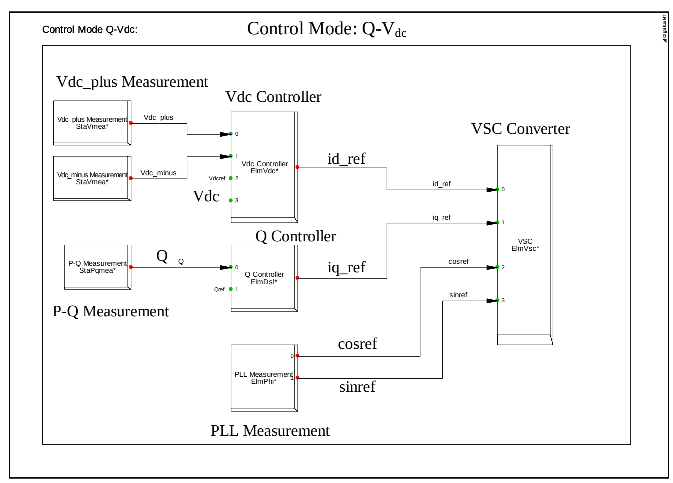

Figure 2. Control design of the converter terminal VSC1operating in V_{dc}-Q control mode and used to maintain a constant DC voltage level in the system

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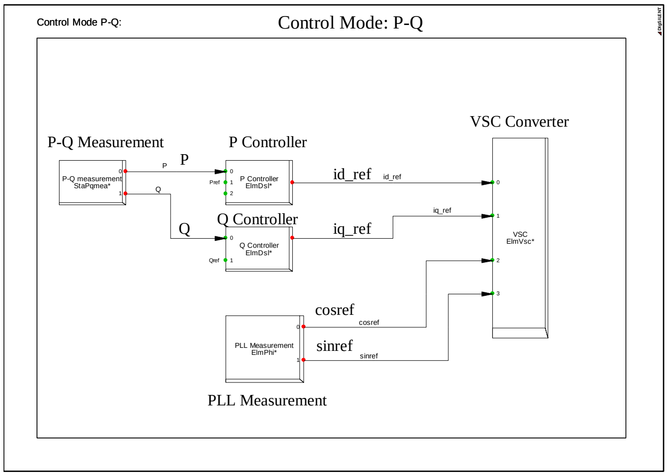

Figure 3. Control design of converter terminals VSC:2-4 operating in *P-Q* control mode which use to maintain constant active and reactive power streams in the system

III. SIMULATION STUDIES

In this section, two different scenarios will be considered. In the first scenario, a permanent AC/DC (short circuit) fault will be initiated on the given system presented in figure 1, aiming to record its natural response and to the extent to which it is affected following the disturbance. With respect to the second scenario, the primary focus will be on the DC-side disturbance and how this can be de-activated, since AC-side faults are widely known and well addressed so far. Here, protection measures in the form of DC circuit breakers will be applied on the system, targeting the isolation of the dc short circuit fault. This in turn will result in system's stability recovery. This part verifies the feasible application of DC-CB's on VSC-MTDC grids for system protection and stability issues.

A. *Case Study 1*

DC Fault

Here, a permanent DC fault of impedance 0+j0 Ohms is applied on the positive voltage (DC+) pole of line "Line 5", at the time instant of 2 seconds. The obtained results depicting the system's behavior are presented on figure 4 (a)-(b), where illustrate how the active powers (a), and DC voltage magnitudes (b), (as recorded on the positive terminal (DC+) of each converter), respond to the fault. It is important to note that identical results would have been obtained in the case where the fault would have simulated at the negative (DC-) pole of the transmission line while observing the negative terminals of each converter. Moreover, it is worthwhile making clear that the initial values of the active powers as shown on figure 4 (a) are half the magnitude provided in section II-Part C. This is expected since we only consider the positive (DC+) terminal of each converter here, keeping in mind that the total active power transmitted or absorbed by each converter is equally split between its positive and negative terminals.

It is evident from Figure 4, that the permanent existence of the DC fault on the positive pole of the transmission line will have severe impacts on the entire network, causing the active power flows and DC voltages on the positive terminals to collapse. This will further cause significant overloading effects on the negative terminals of the converters in response to the high disturbance, and finally resulting in the instability of the overall VSC-MTDC grid.

Consequently, this first part of case study 1 underlines the increased importance of a continuous online security system safeguarding against the occurrence of dc fault disturbances in a multi-terminal AC/DC grid. This should provide a fast and uninterrupted protection against DC faults, securing the system from undesired consequences of this kind.

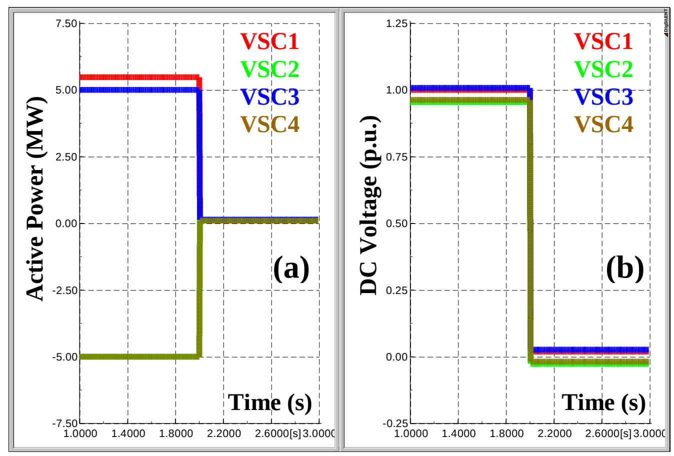

Figure 4. (a) Active power and (b) DC Voltage responses as recorded on the positive voltage terminals of each converter (VSC1-4) following a permanent DC fault disturbance

AC Fault

Lastly, case study 1 concludes by the investigation of a permanent bolted AC fault (impedance: 0+j0 Ohms) initiated on the AC side of our test system (bus AC1 Bus), at the time instant of 2 seconds. The purpose of this study is to observe how such a disturbance will propagate through the DC-side of the system and what consequences this could have on the entire network. The result of the study will determine whether control/protection actions, such as AC circuit breakers, are necessary for addressing such kinds of AC-side irregularities in a mixed AC/DC network. The simulation results realizing this scenario, are presented on Figure 5 (a)-(b), where likewise Figure 4 (a)-(b), the active powers and DC voltages are the chosen variables to reflect this condition.

According to Figure 5-(a), it is observed that at the instant of the fault the active power flowing through converter VSC1 is instantaneously reversed in direction, which is now flowing towards the fault and feeding the short circuit current (for just a fraction of a second), and immediately after drops to zero as expected. This loss of active power from converter VSC1 to the MTDC grid, has a direct consequence on the transmitted power by VSC3, which now increases to compensate for that loss. A part of it is injected into the DC network (which is then extracted by VSC2 & VSC4), while the rest of it is used to feed the short circuit current at AC1 Bus. Another impact of the zero power injection by VSC1 is the reduction of absorbed power by the converter VSC4. The reason behind this is because VSC4 was extracting active power from the grid directly from VSC1 and VSC3 (see Fig.1). A reduction in VSC1's transmitted power it will clearly be noticeable by VSC4's absorbed power. The less sensitive terminal to the AC disturbance, as Figure 5 suggests, is VSC2 which maintains its pre-fault power condition.

An analogous phenomenon is also depicted by the DC voltage profiles of the converters. As can be seen, the most highly affected voltage point in the DC grid is that of terminal's VSC1 which is the closest to the AC fault. This is reflected by a steep step decrease from its original value. The rest of the converter terminals also suffer a reduction in their voltage magnitudes, however the degree of that depends on their geometrical distance from the fault.

To summarise, an AC fault disturbance introduced in a multi-terminal VSC-HVDC network, has significant impacts on the DC-side of the system which can be represented by either the power or the voltage profiles of the system. In either way, it can be seen that the fault's effects are more pronounced closer to the affected AC network. However, it is important to note that a total black-out of powers and voltages was avoided, as compared to Figure 4, which shows that the DC grid merely takes shield actions. Despite that, continuity in service of the combined AC/DC network is an uncompromised priority and hence AC-side protection measures are necessary to establish this requirement.

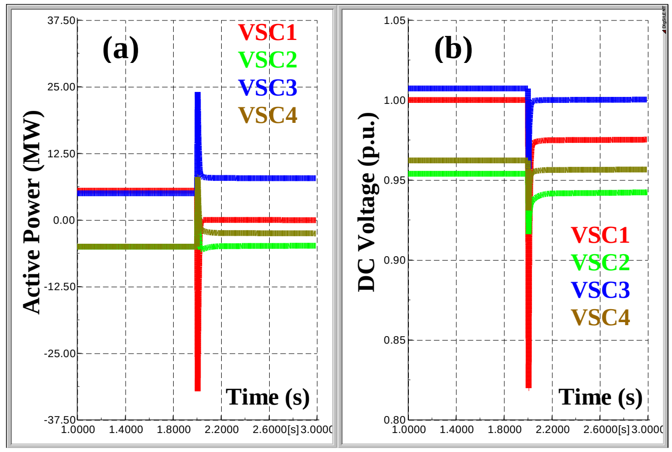

Figure 5. (a) Active power and (b) DC Voltage responses as recorded on the positive voltage terminals of each converter (VSC1-4) following a permanent AC fault disturbance

*B. Case Study 2 - **AC Fault Clearance***

In this second part of our simulation work, we examine how the VSC-MTDC grid recovers from faulty conditions and re-establishes stability and operational mode when appropriate control/protections actions are taken. These will take the form of AC and DC circuit breakers aiming to tackle the severe disturbances initiated on both the AC and DC sides of the system respectively.

Initially, we will begin by looking how the AC-CBs installed on network AC1 will operate at the location of AC1-Bus to clear/isolate the fault, and hence re-establish overall system stability. The installations of the AC-CBs however, are not marked on Figure 1 for reasons of simplicity, and bearing in mind that the focus of the paper is on DC-CBs. Tackling faults through AC-CBs in an AC grid is a well-known technology that has been extensively addressed in the field of electrical engineering. Consequently, a short description will be made here summarizing the post-fault behaviour of the system when the action of AC-CBs is introduced. This is shown on Figure 6 (a)-(b), which illustrates how the active powers and dc voltages of the converters evolve in time-domain following the fault. Here, the AC-CBs are triggered to isolate/clear the faulted sector of network AC1, 200ms after the fault is initiated (i.e. at 2.2 seconds).

As Figure 6 suggests, the introduction of CBs on AC1 works effectively as a shield to the AC disturbance, ensuring that the faulted sector is disconnected from the rest of the network, assisting into system's recovery to its pre-fault operational mode. This is confirmed by the active powers and dc voltages, both of which converge to their pre-disturbance equilibrium points as soon as the fault is cleared.

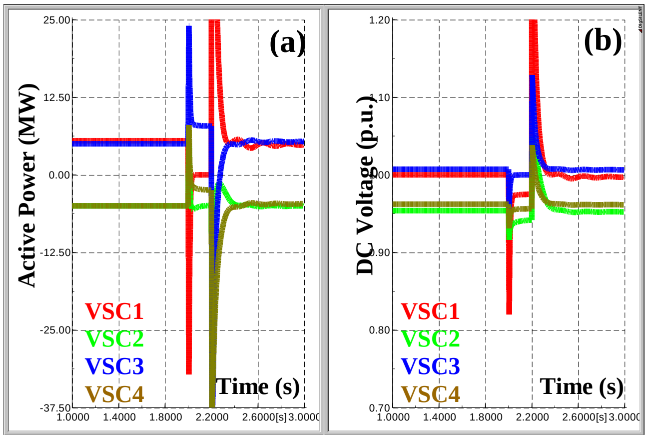

Figure 6. (a) Active power and (b) DC Voltage profiles of the four converters (as recorded on their positive voltage terminals) of the MTDC grid following an AC fault clearance through AC-CB's action

DC Fault Clearance

This last part of the simulation study, examines the feasibility in applying DC circuit breakers on the DC-side of the grid. This has a significant effect on the capability of these breakers in effectively interrupting DC fault currents (by tripping the appropriate faulted line), as well as providing support to the system to re-establish stability.

Here, the same (dc) fault scenario from Case study 1 – DC Fault is preserved, with the same characteristics and location. However now, the corresponding DC-circuit breakers (CB51 and CB54 – see Fig. 1) of the corresponding faulted line (Line 5) will be activated to clear the fault. This will be done by tripping the corresponding line out of operation 200ms after the fault event, i.e. at 2.2 seconds. The simulation results will determine whether the DC-CBs are capable of isolating/clearing such kinds of DC disturbances, while at same time preventing the system from losing stability. Figure 7 depicts this scenario, where the same variables (power, dc voltages) considered in the previous cases were chosen.

It can be seen from Figure 7 (a)-(b) that the use of the DC-CBs on the system efficiently tackle the DC disturbance (by clearing the fault in between 200ms), while at the same time assisting the network to return to its operational mode as soon as the fault is cleared.

With respect to active powers, it can be seen that up to 2.2 seconds a pattern similar to Figure 4-(a) can be seen. This indicates a stable power flow to/from the dc network and a sudden drop of zero power during the fault existence. However, immediately after the DC fault has been cleared by the DC-CB action, the active power flows quickly rise to their steady-state pre-fault values resuming the operational mode.

A similar scenario can also be observed from the voltage profiles. It is clear that during the fault all converters' voltages are severely affected by implementing significantly low values as compared to their initial (pre-fault) ones. Similarly here, once the fault has been resolved the voltages recover back to a stable mode.

Another important observation (besides the stability verification), is that the loss of a transmission line (through the operation of the tripping scheme) results in a reduction in overall capacity of the dc network as can be partially observed by Figure 7-(a). This has a direct consequence on the remaining "healthy" lines of the grid as they may overload and this may in turn result in an overvoltage effect on all terminals as can be observed by Figure 7-(b).

The impact of such phenomena however, could be dramatically decreased when larger/heavier VSC-MTDC grids are considered combining numerous assisting terminals interconnected with stronger AC networks. Additionally, it is also a matter of the novelty and sophistication of the control/protection algorithms adopted in the power system. Finally, it is also important a well-designed structure of the system (interconnections, complexity) providing enhanced robustness and flexibility.

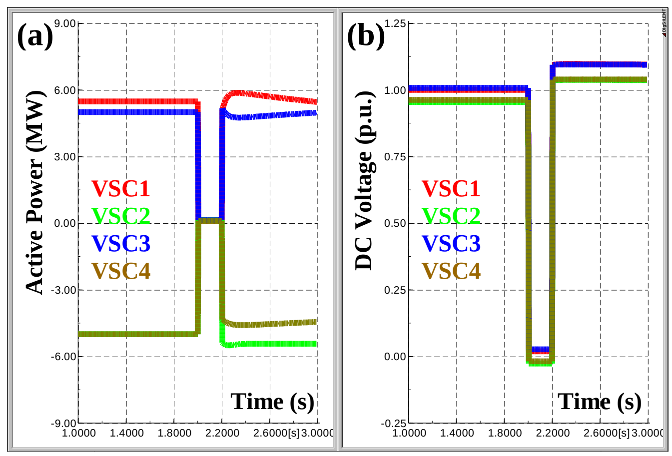

Figure 7. (a) Active power and (b) DC Voltage profiles of the four converters (as recorded on their positive voltage terminals) of the MTDC network following a DC fault clearance through the DC-CBs's action

IV. CONCLUSION

Summarizing the overall work, this study attempted to provide answers to some open questions regarding the behavior of VSC-MTDC grids under different types of disturbances (permanent/transient - AC/DC short circuit faults), and what impact these have on a part of or the entirety of the system depending on their location and nature.

Based on these, the study has been extended to include security/protection solutions providing isolation/clearance of the various faults based on the mature technology of AC CBs and the promising DC CBs.

Firstly, our results have shown that the initiation of a permanent DC fault on the system could have severe consequences on the entire VSC-MTDC network, resulting in total black outs. This was verified by both zero power injections and dramatically high voltage drops, both of which indicate the significance of a prompt protection action. On the other hand, an AC fault was shown to have considerable impact on the system which also needs mitigation strategies. However, total black outs were not observed, and it was shown that the severity of the fault was more pronounced closer to the fault (i.e. closer to the faulted AC network). This means, each of the four converter terminals of the network were affected to a degree analogous to their geometrical distance from the fault.

The second part of this study, attempted to tackle the AC/DC disturbance in the system as well as curbing propagation/distribution of these disturbances along the network, i.e. from AC to DC side and vice versa.

This was achieved by optimally spreading AC/DC circuit breaker devices along the network, covering both the AC and DC sides of the system. Once a fault is detected on a transmission line, the corresponding CBs of the faulted line open disconnecting the line from the rest of the network.

According to our simulation results, this method has proved very effective in successfully addressing the fault. In both fault cases (either of AC or DC nature), the corresponding CB devices (AC or DC respectively) were immediately triggered and isolated that fault in a time period of 200ms in both sides of the mixed AC/DC network. In addition to this, the termination of the short-circuit disturbance contributed in the recovery of system stability and hence the re-establishment of pre-fault operational mode.

Key outcome from this work, is the feasible use of an optimally combined protection scheme consisting of AC and DC circuit breaker technology applied into VSC-MTDC grid, which serves as an online guard securing the system from AC/DC fault events, while at the same time assisting the overall network regain stability and operation mode. This enhances the overall security and robustness of the transmission system to high disturbances such as instabilities and system paralysis, caused by short circuit phenomena.

It is a great advantage the fact that it is a relatively straight forward and robust protection solution, which can be directly applied to the offshore VSC-MTDC networks to be installed around the globe, forming the primary protection layer of the transmission medium.

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