Barriers and solutions for AC low voltage fault ride-through on Multi-terminal HVDC grids

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***Abstract*—This work analysis the multi-terminal DC grids dynamics under AC mainland grid fault events envisioning to assess the feasibility of fault ride-through provision. The major bottleneck related with the operation under AC fault consists on the DC side power imbalance that takes place due to the HVDC converter current limits and consequent incapability of delivering all the generated power to the grid. It was also verified that the power imbalance leads to a DC overvoltage occurrence. The mechanism of including chopper devices at the onshore converters DC terminals has been studied as a mean of power equilibrium promotion. Simulations comparing the both cases were performed and the comparison and the effectiveness of the adopted approach are also presented.**

Keywords- Chopper resistor; Fault Ride-through; HVDC; Multi-terminal DC grids; Offshore wind power; Voltage Source Converter

I. INTRODUCTION

The wind power generation plans in Europe is moving towards a large-scale implantation of offshore wind farms [1, 2]. The interconnection of such massive amount of power together with the need of having extensive offshore interconnection cable circuits presents technical challenges for electricity transmission. Nevertheless, the power transmission in HVDC technology is an high potential emerging solution that can handle the physical limitations of offshore AC systems which is also being currently presented as the pathway for large scale offshore wind power transmission and for the creation of complementary corridors for continental areas interconnections [3].

Nowadays, due to power electronic developments', there are two HVDC technologies in the market; the LCC (Line Commutated Convertor) and the VSC (Voltage Source Converter). The VSC presents several characteristics such as black-start capability, independent control of active and reactive power, fault ride-through capability and capability of forming Multi-terminal DC (MTDC) grids. Some research works and prospects point towards the adoption of MTDC grids [2]. In fact, the idea on connecting several offshore Wind Farms to several onshore AC systems through a shared DC grid infrastructure seems very promising from the economical and reliability point of view.

The adoption of massive wind energy generation brought some concerns for the operation of AC systems. One of the major concerns was related to the loss of huge amount of wind power due to Wind Farm (WF) undervoltage tripping in case of AC network faults [4]. European grid codes [5] started requiring wind generators to remain connected to the grid during fault occurrence avoiding the loss of large amount of power that could lead network to dynamic instability. It is expected that offshore HVDC connected wind farms comply with grid codes providing Fault Ride-Through (FRT) capability. The work conducted in [6] and [7] evaluated the possibility of offshore WF connected through a DC point-to-point connection to provide FRT capability. The existence of DC power imbalance and thus DC overvoltages during AC fault occurrence was identified. Authors proposed methods to promote power balance by reducing or dissipating the exceed incoming power from the WF. In [6], three methodologies for the promotion of DC power equilibrium were studied: de-loading the offshore WF, dissipating the incoming power in a DC chopper and short-circuiting the offshore converter .

A fully operational MTDC system for the integration of large offshore WF requires the specification and development of a reference architecture model regarding the implementation of advanced control functionalities aiming to support its operation in close coordination with offshore wind farms and Transmission System Operators (TSO) control centres. Given the key role MTDC grids will play in the future, its contribution for the provision of ancillary services to TSO needs to be envisioned, similarly to key requirements specified in different grid codes for the connection of wind generators, such as the participation on primary frequency regulation or the provision of Fault Ride Through (FRT) in case of mainland AC grid faults [2].

In order to identify the most appropriate control strategies to provide FRT capability from MTDC grids it is required a deep understanding of the main dynamic phenomena that characterizes its behavior and the resulting

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interaction with mainland AC grids. As pointed, in [6] the DC power balance must be promoted very quickly in order to avoid overvoltage occurrence (10-30 mili-seconds). This critical time was also estimated for the MTDC grid case and led to conclude that communication infrastructures and the consequent centralized controller to send/receive setpoints from the intervenient may not be able to cope with desired operation times.

The approach proposed in this paper in order to provide FRT capability consists on adopting DC chopper devices at onshore converter DC terminal to avoid overvoltage occurrence. To assess the impacts and establish comparison, a first study case with no power dissipation mechanisms was simulated. Comparison between the results is also presented in the paper in order to demonstrate its feasibility

II. Modelling, Operation and Control of MTDC grid

A MTDC grid is a DC cable infrastructure that mainly aims on interconnecting offshore WF to onshore grid collection points. Additionally, this grid also promote inter AC-area connection (via its DC infrastructure) allowing to have power exchange among the interconnected AC areas. In this section each MTDC grid component model is explained.

A. Multi-terminal HVDC Grid

The MTDC grid was assumed to be bipolar (two cables with symmetrical DC voltages – nominal voltage $\pm V_n$). The connections within the DC grid are assured by the cable circuit which was modeled by concentrated parameter (cable resistance and inductance) according with the approach introduced in [8]. The MTDC grid is then modeled by the corresponding algebraic and state equations according to the Kirchoff's law.

B. HVDC Converters

Both onshore and offshore converters are Voltage Source Converter (VSC) technology. The converters were modeled using an RMS dynamic control models, which is a good representation of its behavior independently of its internal topology. So, fast switching transients, harmonics and inverter losses are neglected similarly to the approaches followed in [9] [10]. The differences between the converters (onshore and offshore) were focused on its control strategy and are presented next.

1) Onshore VSC: The onshore converter is responsible for controlling the voltage of the DC-side converter capacitors'bank (see *Figure 1*). The converter dynamics were modelled by proportional-integral (PI) controllers. Since VSC allow independent control of active and reactive power, two indenpendent control loops were implemented. The converters model were inplemented in *d-q* synchronous reference frame following the approches suggested on [10]. According to the scheme presented on *Figure 1*, the error between the Vq_{ref} and Vq (the reference and the actual value, respectively) generates the iq_{ref} current reference. Then, the error between the iq_{ref} and the actual iq value generates the *Vq'* output. The analougus process is adopted to obtain the *Vd'* voltage reference. However, a slight difference exists in the way to attain the id_{ref} current reference (see *Figure 1*). In fact, the id_{ref} current is given by the error between the actual VSC DC-side voltage (V_{DC}) and a reference DC voltage value (V_{DCref}) after passing through a PI controller as depicted in the same figure.

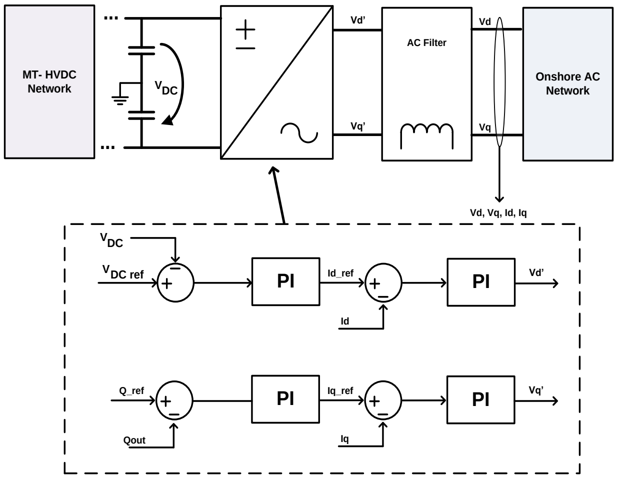

Figure 1: Onshore VSC control-loops

2) Offshore VSC: The offshore converter interfaces the offshore AC grid with the DC cable circuit. It is responsible by imposing the AC-side voltage and frequency and delivers all the offshore WF generated power to the DC grid [11]. The control scheme for the offshore VSC is represented in *Figure 2*. Once again, PI controllers were adopted. The *Vd* and *Vq* errors generate the id_{ref} and iq_{ref} references that are compared with the existing value in the so-called inner current loop, generating the *Vd'* and *Vq'* voltage output.

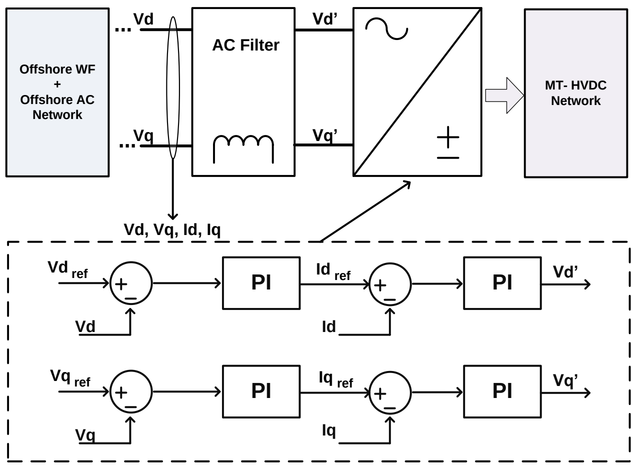

Figure 2: Offshore VSC control-loops

C. Operation and Control of the MTDC grid

The onshore converter is responsible for imposing the voltage profile at its DC-side terminals. On the other side, offshore converters are responsible for delivering all the generated offshore WF power to the DC-grid. So, it must be guaranteed that proper DC voltage values are within the DC grid terminals to allow power sharing among onshore converters in order to accommodate eventual power variations from the wind farms. A droop control was then adopted on each onshore VSC in order to assure that the delivered AC power was performed according to the DC voltage profile variation as suggested in [11]. The control rule can be expressed by the following equation:

$$V_{DC} = V_{DC\,\text{set}} + k_{pv} \times P_{out} \qquad (1)$$

Where V_{DC} and k_{pv} are configurable values that can be parameterized in each onshore VSC according to the specific operation of the AC grid. Basically, this relation dictates that the voltage at onshore VSC will depend on the power amount delivered to the AC grid. The parameter $V_{DC\,\text{set}}$ can be remotely adjusted to act as a dispatch variable.

D. *Wind Generator Model*

The offshore wind generators are interconnected to the offshore converter by AC submarine cable circuit. From the modeling perspective offshore generators are similar to onshore. Without loss of generality, a Permanent Magnet Synchronous Generator (PMSG) interfaced by a full AC/DC/AC converter has been considered. The mechanical, aerodynamic and electrical models were implemented according to the suggested in [12].

III. MTDC GRID BEHAVIOR UNDER AC ONSHORE FAULT

The previous simulation models were used to test the dynamic behavior of the MTDC grid under AC onshore fault events. To perform this assessment, current limits were included in the previously presented onshore VSC control loops. The active and reactive current limits are presented on Figure **3**. Additionally, the i_q control loop was set to control AC voltage instead of imposing a fixed reactive power set point (as previously presented in Figure 1). This modification was performed to ensure that the reactive current injection will impact on leveraging AC voltage profile.

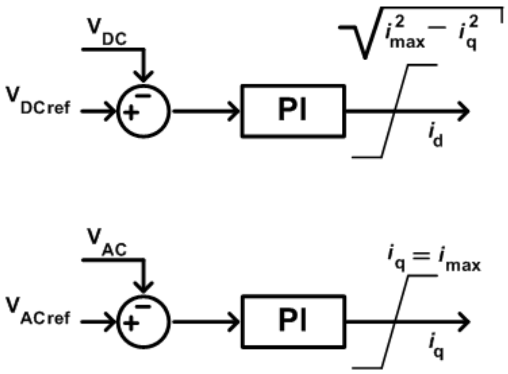

Figure 3: Current limits modifications for onshore VSC

The current i_q is the reactive current, i_d is the active current and i_{rat} is the converter maximum rated current which was considered to be 40% above the nominal converter current.

In order to assess the MTDC response for AC fault events, after enhancing the onshore converters with the aforementioned current limits, a three phase fault was simulated near Area #1 onshore converter AC terminals (see Figure **4**). As depicted in Figure **4**, the MTDC network consists on a H topology DC grid connecting two 200MW offshore WF (each) to two onshore AC grids.

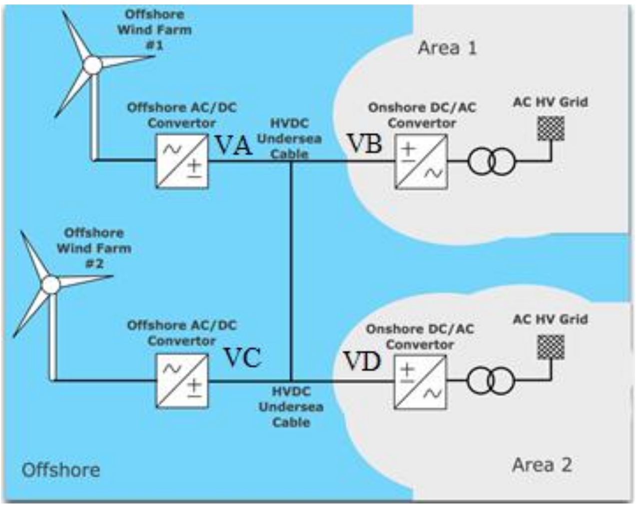

Figure 4: Multi-terminal DC grid infrastructure

From the results depicted in Figure **5** it is possible to verify that the 3-phase fault reduces the active power delivery capability of the onshore HVDC converter station connected to the faulted area. During fault event the AC voltage is significantly reduced. Thus, to inject the same amount of power, the onshore VSC will increase the active current injection. However, its value is limited due to the converter current limits, which leads to the reduction of the active power injection.

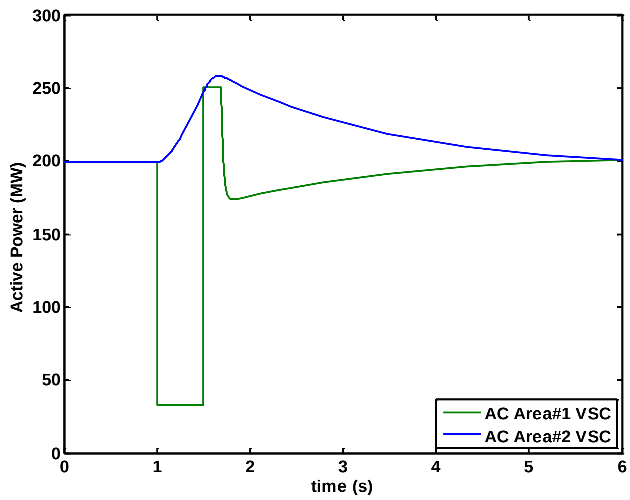

Figure 5: Active power delivered by onshore VSC

On the opposite MTDC grid side, offshore wind farms will continue injecting the pre-fault active power into the MTDC grid since the DC grid decouples AC-DC voltage and frequency variations disabling the offshore WF to notice the AC-side fault occurrence. It is possible to verify that the Area #2 onshore VSC will increase the amount of power injection on AC Area #2. However, the maximum current amount will be also limited, constraining the maximum power delivery to the onshore AC grids. It is possible to notice that healthy onshore converter (Area#2) tries to promote the power sharing delivering some of the non-delivered power by the Area#1 VSC. However, system dynamics provokes a power imbalance within the DC grid. As identified in [6] (for a point-to-point connection) the power imbalance impacts on the DC voltage by increasing it. Figure **6** depicts the DC voltages on the MTDC grid terminals'. The expected overvoltage takes place leading a voltage peak of about 1.55 p.u.

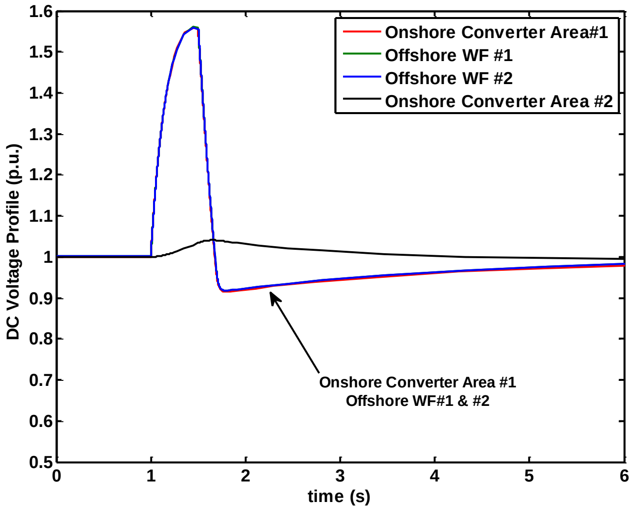

Figure 6: DC voltages at MTDC grid terminals

The over-voltage occurrence is dangerous for the VSC power electronic devices as well as for the DC cable circuit insulation thus it must be limited or avoided. This phenomenon is related with the power imbalance described by:

$$v_{dc} \times C \frac{\partial v_{dc}}{\partial t} = P_{Gen} - P_{Grid} \quad (1)$$

During fault event, P_{Grid} (the active power delivered to the AC grid) is reduced. Since the Generated power (P_{Gen}) remains constant the DC voltage profile (v_{dc}) will vary according to the equivalent DC network capacitance (C). For the case of P_{Grid} reduction, an overvoltage will take place. The time to promote the power equilibrium within the DC grid can be computed based on the equivalent capacitance of DC grid and admitting that the voltage can assume a maximum value (maximum admissible voltage). For the presented case the power equilibrium for a fault leading to 200MW of AC power delivery (similar to the loss of the affected converter) must be performed in a time no longer than 30 mili-seconds assuming that the voltage can rise to 1.2 p.u., at maximum. The fastest way to promote power equilibrium is to adopt chopper devices [6, 7]. A chopper is a load resistor controlled by power electronics and is normally used to promote power equilibrium to avoid overvoltage occurrence. The amount of power to be dissipated is controlled by the power electronic interface and is usually proportional to the overvoltage magnitude.

IV. ONSHORE AC FAULT WITH DC CHOPPER INCLUSION

As aforementioned, the inclusion of DC chopper should promote the power equilibrium within the DC grid during fault events. Choppers resistors interfaced by power electronic converters were modeled and included on each onshore VSC DC terminal aiming on assessing whether this technique is able to meet the time requirements for power equilibrium promotion.

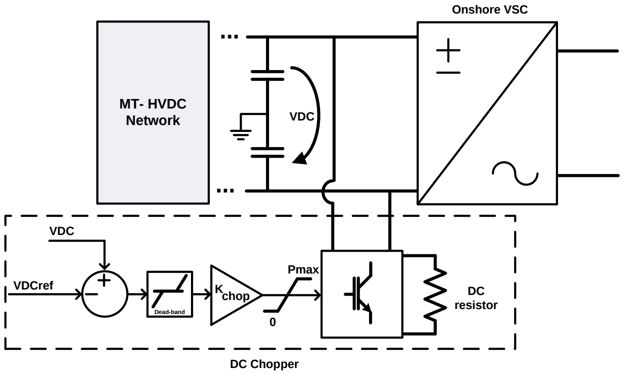

Figure 7: Chopper connection and control scheme

The scheme presented Figure **7** depicts the chopper configuration and control. The DC voltage error passes through a dead-band to ensure that small voltage fluctuations will not lead to power dissipation. Then a droop relating the voltage variation and the power to be dissipated is applied. A limiter ensuring that the chopper does not exceed the maximum power is intercalated before the power control signal reach the electronic converter that interfaces the DC resistor bank and the DC onshore VSC terminal.

To establish a comparison basis, the same fault was applied to onshore Area #1 AC grid (near onshore VSC). The powers delivered by each onshore VSC and dissipated at each chopper device are depicted in Figure **8**. It is possible to remark that onshore VSC #1 reduces the delivered power to the AC grid Area #1 from 200 to about 30 MW, similarly to the previous case. However to establish the power equilibrium on DC grid, the chopper installed at VSC #1 DC terminals dissipates about 135 mega-watt while the VSC #2 dissipates about 6 mega-watt. The discrepancy between the dissipated power amounts among the DC choppers can be justified by the DC voltage profile depicted in Figure **9**.

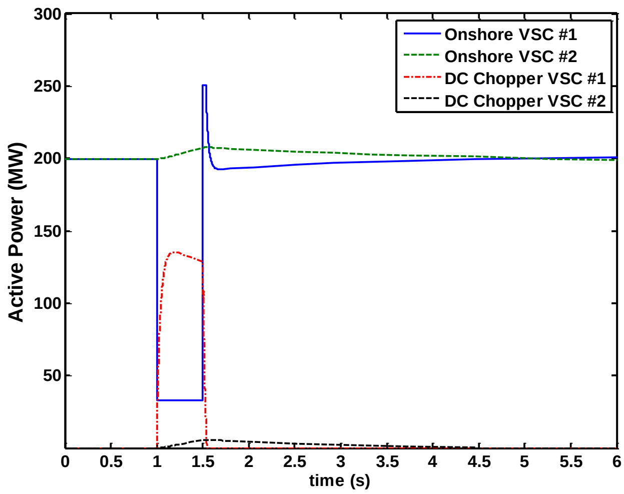

Figure 8: Active power delivered by onshore VSC and dissipated at DC choppers

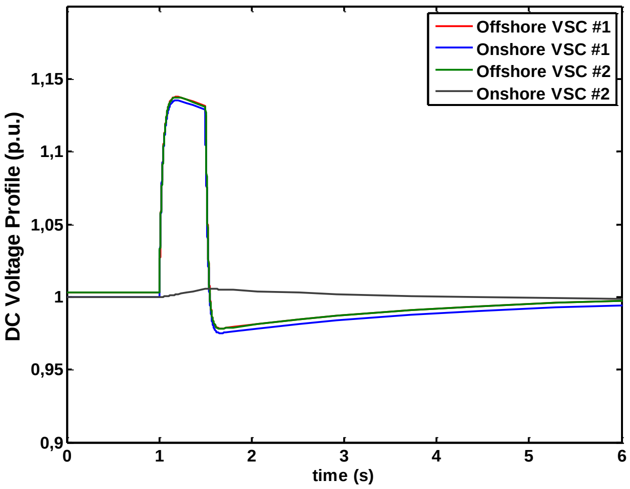

Figure 9: DC voltages at MTDC grid terminals

In fact, the voltage increase is originated by the VSC #1 (due to the current delivery constraint) and is induced in the MTDC grid terminals excepting the onshore VSC #2 terminal. Indeed, as explained on section II, each onshore VSC is responsible by setting its DC-side voltage and extract active power accordingly. It is possible to verify that the DC voltage profile at Area#2 VSC slightly increase leading to power dissipation at the associated DC chopper and to an small increase on the power delivery from the DC grid to the AC Area #2 network.

Summarizing, the power delivery and power dissipation amounts, does not totals the Area #1 VSC non-delivered power failing to accommodate about 25 MW. This power surplus mismatch is responsible for the DC voltage raise. However, in this case its value is admissible (being under the maximum admissible value of 1.2 p.u.) and also is significantly smaller than the no-chopper case depicted on Figure **6**.

V. CONCLUSION

Fault events on the AC mainland grids can reduce or even block the power injection coming from HVDC-VSC. Since the adoption of DC decouples the AC voltage between the interconnected AC areas, offshore WF are not able to directly sense the fault event (voltage drop) on the opposite side of the DC link, keeping the constant power injection. Thus, an overvoltage takes place provoked by the positive power imbalance.

It was verified that the same behavior occur for a multi-terminal DC grid. Thus, it has been identified the need to avoid overvoltage during AC-side fault events. The proposed approach consisted in adopting DC chopper devices to be installed at the onshore VSC. On contrary to what could be expected, the contribution of healthy onshore VSC to accommodate the power surplus is not very effective on what regards the overvoltage occurrence. It was verified that the VSC dynamics is slow to deal with fast power accommodation within the interval for overvoltage avoidance.

Since no communications were adopted (due to the tight time-frame to perform power dissipation), the offshore wind turbines (WT) were not able to dissipate some power on their internal chopper devices. A further analysis for future work should consist on evaluating the feasibility of endowing HVDC-VSC with a cascading control scheme (similar to the proposed in [13]) to promote power balance at WT level. This alternative will exploit power control at the wind turbine level in coordination with the reaction at the VSC level.

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