Impact of DC Voltage Control Parameters on AC/DC System Dynamics Under Faulted Conditions

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***Abstract*— This paper discusses the influence of dynamics within a multi-terminal offshore DC grid (MTDC) on the onshore AC power system stability under faulted conditions. An AC-fault occurring at the HVDC converter station terminals may propagate via the offshore MTDC grid to the undisturbed asynchronously connected AC power system. This disturbance manifests itself as additional active power overshoot at the remotely connected converters. It is shown that the severity of this disturbance propagation is sensitive to the parameters of the DC voltage droop control employed for voltage regulation in the MTDC scheme. Furthermore, the effect of the MTDC grid topology on these dynamic interactions is illustrated by comparing a meshed with a radial topology. The analysis has been performed with phasor-mode time domain simulations, augmented with a user-defined state-space model for the MTDC grid. The AC system dynamics are based on available models of benchmark power systems in the stability simulation software PSS®E.**

***Index Terms*— multi-terminal HVDC transmission system, offshore grids, power system stability, offshore wind power plant.**

I. INTRODUCTION

An important share of offshore wind power plant modules, especially in the North Sea countries, will be located at large distances from shore where the conventional high voltage AC transmission technology becomes neither technically nor economically attractive. Consequently, grid connection of this bulk amount of wind generation will be mainly achieved by utilization of high voltage direct current (HVDC) transmission system technology. The new generation of HVDC transmission systems, termed as voltage source converter based HVDC (VSC-HVDC), offers attractive features in comparison to the classical current source converter (CSC) HVDC. The most important advantages are the capability to operate in isolated and weak (low short circuit power) networks, the capability to provide controlled voltage and frequency for the offshore collector system, decoupled active and reactive power control and the capability of fast power flow reversal.

Additionally, the increasing demand for transmission capacity in order to transport large amounts of offshore wind generation in combination with the need to increase interconnection capacity between North Sea countries has given rise to the idea of building an offshore HVDC grid. An offshore multi-terminal DC grid (MTDC) may represent a cost-effective solution to interconnect both offshore wind power plants modules as well as national power systems.

Many research activities have taken place in recent years to develop dynamic models for stability type simulations and to design the control schemes of such an MTDC grid both under normal and contingency situations [1]. Other studies dealt with various fault-ride-through (FRT) control strategies for AC side disturbances at the grid connection point [2]. However, many of these papers focus more on the response of the DC grid itself and less on the AC/DC system dynamic interactions under faulted conditions.

Our previous work in [3] has presented the FRT response of a “back-bone” MTDC grid connected to the Dutch power system which is part of the interconnected Central-Western European system model. In this work, it was shown that the presence of a MTDC in one control area may propagate the disturbance in a wider region. This disturbance manifests itself as additional active power overshoot at remotely connected VSC-HVDC stations and is triggered by the response of the droop controllers under the presence of DC over-voltages.

This paper is an extension of [3] by investigating the impact of both the DC voltage droop control scheme and DC grid topology on the dynamic interaction between two asynchronous power systems coupled by an offshore MTDC grid. Time domain simulations are performed on two power systems models, namely the IEEE 39-bus New England test system and a seven-generator benchmark test system that reproduces the inter-area modes of Great Britain system. The two systems are interconnected by a MTDC offshore grid. The results of this paper could be useful in the design of future grid codes for offshore MTDC transmission systems.

The paper is organized as follows. Section II discusses the MTDC grid modeling approach suitable for stability-type studies. Section III introduces the test system used in this

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paper while section IV discusses the simulation results. Conclusions and discussion is presented in section V.

II. MODEL OF THE VSC-BASED HVDC SYSTEM

A. *Model of the VSC-Based HVDC Converters*

The quasi-steady state approach developed in *dq* reference frame has been used to represent the dynamic behaviour of the VSC-HVDC station [3] [4]. In this approach the fast dynamics of the inner controller and phase reactor are neglected, hence *dq*-axis current set points are instantly reached by the converter. In fact, the inner controller response is infinitely fast with respect to AC system time constants and could be neglected in stability type studies. The DC side of the converter is modelled as a DC current source while the AC side by a Norton equivalent controllable AC current source.

B. *Model of the MTDC Grid*

The method followed to represent the dynamics of the MTDC grid cables in the time domain is by making use of state space equations. The necessity to represent DC cables with dynamic models appears as a need to model the dynamic response of the DC voltage. The later influences the control modules of the VSC-HVDC system, as it has been already discussed in the previous section [6].

Given the state space model of each cable section [5] it is possible to extend it to any DC grid topology by making use of the incidence matrix. The incidence matrix for a given MTDC grid with *n* number of nodes and *m* number of branches is defined as a mxn matrix. A graphical overview of the MTDC grid model and the detailed equations are introduced in [4].

Finally, in order to perform dynamic simulations for the MTDC grid, a DC grid power flow is used to calculate for a given operating point, the steady state voltages and currents of the DC grid and thus initialize accordingly all states associated with the converters in MTDC grid model. The detailed equations for this Newton-Raphson DC grid power flow are given in [1].

C. *FRT Control Strategy*

Grid connection requirements prohibit the disconnection of large generation units under faulted conditions. This is required in order to provide voltage support and short circuit current both during and under post fault conditions. Similarly onshore HVDC converters should not disconnect from the AC power system in the event of faults. Fault-ride-through (FRT) denotes the ability of the HVDC converter to remain synchronized with the grid during AC terminal faults while respecting the maximum current capability of the converters. Such an AC terminal fault would create a DC overvoltage in DC side (when power flows from DC to AC side).

In this paper, the FRT strategy used is the DC chopper method. DC choppers are installed at the onshore converters and can dissipate power maintaining power balance in the DC grid during the fault [2]. Each chopper is continuously controlled by a proportional controller which controls the dissipated power in the chopper resistors and in such a way maintains the DC voltage at controllable levels.

D. *Control of the DC Grid Voltage*

The control of the DC voltage is very important for the stable operation of the offshore DC grid. DC voltage variations are mainly related to power balance between onshore and offshore converters. There is no stable operation of an offshore DC grid unless at least one converter is assigned to balance the power in MTDC grid maintaining thus controllable DC voltage levels.

This burden of balancing the DC grid power could be mainly assigned to the onshore converter stations. The onshore converters will accordingly adjust their active power injection to the onshore power system keeping in such a way the DC voltage at normal operating levels. However, given the finite power capacity of the onshore converter, and in order to avoid a total DC voltage collapse as a result of converter outage, more than one or even all onshore converters could be assigned with the duty to balance the DC grid and control its DC voltage.

Two are the usual control strategies proposed so far in literature, the constant DC voltage control scheme (master slave) and the droop control method [5] [6]. In the droop method, the variations of DC voltage due to changes mainly in wind generation are mirrored to the active power variations of onshore converters. The droop control is considered as the most suitable candidate for MTDC grids. In this paper it is implemented by a proportional controller acting on the active current component (d-axis component when a synchronised with AC voltage rotating *dq* reference frame is used) of the VSC, as shown in figure 1(b).

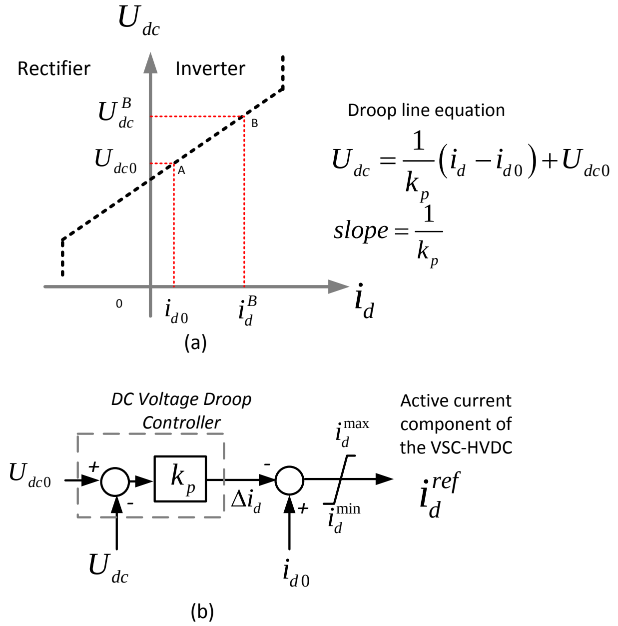

Figure 1. (A) Droop line characteristic of the onshore converter station (b) Controller for implementing this droop-line characteristic

Under this control scheme, the DC voltage at the DC node of each onshore VSC is compared with the given DC voltage set-point U_{dc0}, given from the DC grid power flow. The droop controller will relate the variations of the DC voltage from the given set-point, to variations of the active current, which in per unit equals the active power injection at the AC side. For example, let assume that the converter operates at point A and the DC voltage increases (let say due to additional wind generation) from the initial value U_{dc0}. The droop controller will increase the d-axis current component following the droop line characteristic, shown in figure 1 (a) and the new operating point will be point B where the power balance is achieved. The converter will reach this new operating point with higher DC voltage and higher active power injection.

Up to date, different studies have been investigating DC voltage control strategies but not many have been dealing with the effect of the droop control gains on the AC/DC system dynamics under short circuit conditions. In [6] the authors argue that the values of droop constants determine the degree of impact that the DC voltage drop will have on the sharing of balancing under both normal and contingency operation. Towards this direction, as soon as all converters onshore are sharing the responsibility of balancing the DC grid, the question which will be stressed out in this paper is how DC voltage droop influences the dynamic response of the remote converters under faulted conditions.

III. TEST SYSTEM

A modified version of the IEEE 39-bus (New England) system has been used for the purpose of this study, including both onshore and DC-connected offshore wind power plants. Two onshore wind power plants each of 800MW have been added at bus 25 and 21 respectively (see figure 2). Each onshore wind power plant is modelled by an aggregate full converter direct drive wind turbine using standard dynamic models. In addition, the IEEE 39-bus system is connected via a MTDC offshore grid to a seven-generator benchmark power system with 60 GW generation installed capacity [7]. The MTDC grid connects two offshore wind power plants with a total generation of 1200 MW. The two converters connected at IEEE 39-bus system inject a total of 800MW generation. The third converter is connected to the other asynchronous system as shown in figure 3. This second benchmark system was first used in [7] to represent the inter-area mode of 0.5 Hz of the Great Britain power system. All network parameters and dynamic parameters used for generators and their controls are taken from [7]. In order to match generation and load, the generator at bus 32 of the IEEE 39-bus test system is set offline. The total generation becomes 7.6 GW (with a share of 21% onshore, 10.5% offshore wind, and 68% conventional generation). Finally, the total load is scaled to 7.47 GW in this modified New England test system.

For this paper analysis a symmetrical bipolar MTDC grid is considered and the AC system is assumed balanced (also during faults). Hence, under these assumptions we can assume mono-polar representation of the DC infrastructure. Two MTDC grid topologies will be studied: a radial and a meshed MTDC grid as given by the dotted lines in figure 3. All onshore converters in both cases are in DC voltage droop control mode. The comparison of these two DC grid topologies will be performed for AC terminal disturbances at the converter stations onshore. The focus will be placed on how different MTDC grid layouts may influence the FRT response and AC/DC system dynamics. Furthermore, it will be shown how an AC fault in one system is propagated to the non-faulted power system, and the influence of DC voltage droop control gains on that dynamic response.

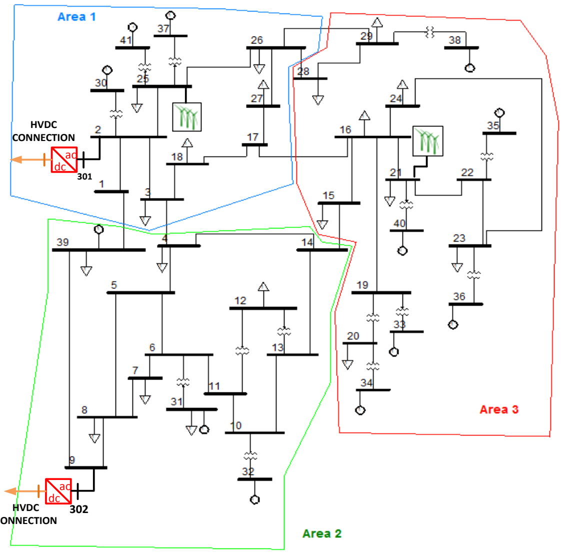

Figure 2. One-line diagram of the New England or IEEE 39-bus system

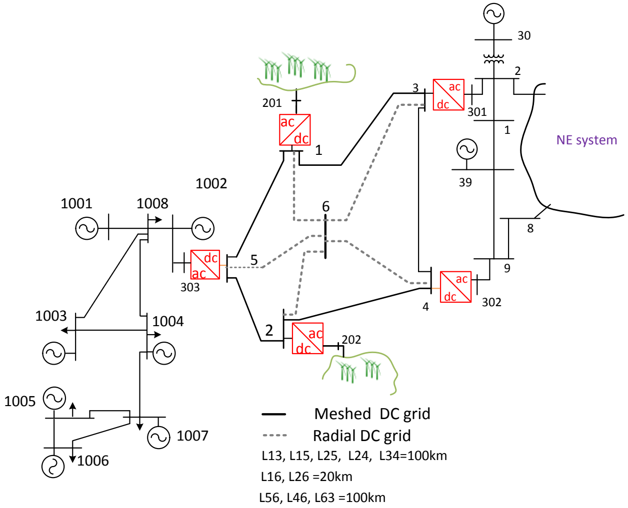

Figure 3. Coupling of the IEEE 39-bus test system with a Great Britain equivalent system model by (a) radial (b) meshed MTDC grid

IV. SIMULATION RESULTS

A. *AC Fault Propagation between Two AC Power Systems*

Initially, a 100 ms self-cleared symmetrical fault is applied at the AC terminal of the HVDC converter connected at bus 301. Figure 4 introduces the AC voltage profiles in the IEEE 39-bus system, the DC terminal voltage profiles in the MTDC grid, the active power response of the onshore converters, the power dissipated in the DC choppers as a result of the fault ride-through scheme and the rotor angles response of selected New England system generators for the given disturbance.

From the simulation results, it can be observed that as soon the fault is applied at bus 301 of the IEEE 39-bus system, the active power of the onshore converter drops to zero. The offshore wind power plant will continue injecting power to the DC grid during the fault. This creates a DC overvoltage at all DC terminals, as shown in figure 4. As soon as the DC voltage reaches the 1.1 p.u threshold, the chopper at the onshore terminal will dissipate this additional power and the DC voltage will eventually ascend at a certain level. This higher level of DC voltage during fault period will create an active power overshoot at the remote and un-faulted power system as it can be seen in the active power profile of converter 303, which connects to the remote AC system.

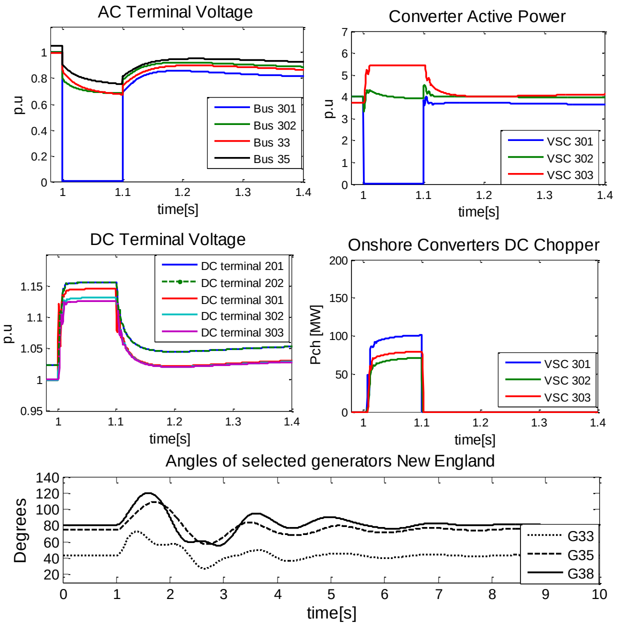

Figure 4. Dynamic Response of the radial MTDC grid for a symmetrical fault applied at bus 301 in IEEE 39-bus system (S_b=100MVA)

B. *Impact of the MTDC Grid Topology on Disturbance Propagation*

In order to further understand AC/DC systems' dynamic response, we will first compare a radial with a meshed MTDC grid for the same disturbance. Figure 3 shows the two MTDC topologies. In both cases the active power set-points for the offshore and onshore converters are kept similar. The same applies for all control parameters. The slight difference in the initial steady state value of the active power of converter 301 is due to the different losses between the radial and meshed topology.

As it can be observed from figure 5, there is very little sensitivity of the onshore converters active power response to the MTDC topology. The differences are more observable during the first ms after the fault is applied and immediately after it is cleared. These very fast transients are mainly related to the MTDC grid cables. With regard to the additional active power overshoot of converter 303, in both cases it is following the variation in DC terminal voltage and it can be only limited by the maximum current capability of the converter. In general converter, 303 will try to inject as much active power as possible following the droop line characteristic of its DC voltage controller.

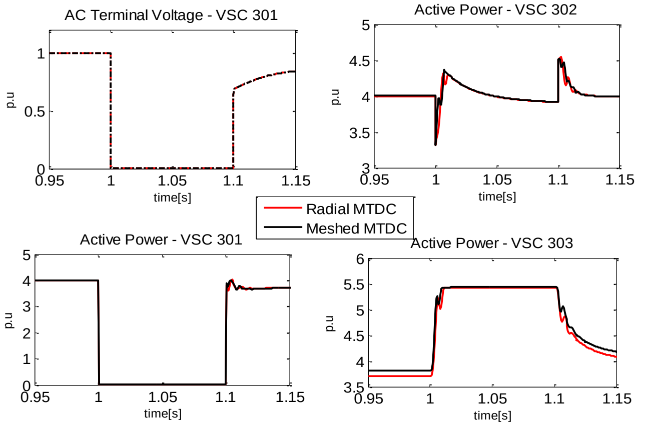

Figure 5. Active power response for the radial versus meshed DC grid topologies (power in 100MVA base)

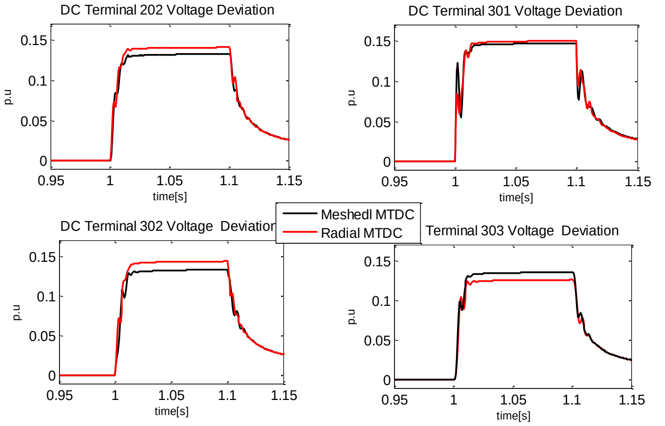

Figure 6. DC terminal voltage deviations from steady state value (U_b=320kV)

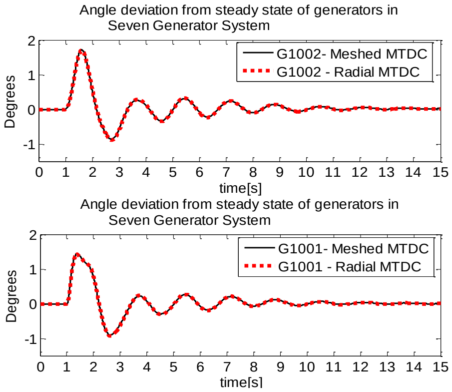

Figure 7. Deviations from steady value for the given disturbance of the active of selected generators in the Seven-Generator system

The effect of this additional active power overshoot on the dynamic response of the second benchmark system is shown in figure 7. As it can be seen, even though the second system is a very strong one, such a disturbance is triggering power system oscillations. The damping and the amplitude of these oscillations is mainly related to the power system itself and to the generator control modules. For both MTDC topologies it can be observed that there is almost no sensitivity between radial and the meshed MTDC grid on the response of rotor angles.

C. Impact of Droop Controller on Active Power Overshoot

In this section the effect of the DC voltage droop control gain on this additional active power overshoot at converter 303 will be shown. For two selected parameters of the proportional controller gains, the metrics of the MTDC grid and the power system are shown in figure 8.

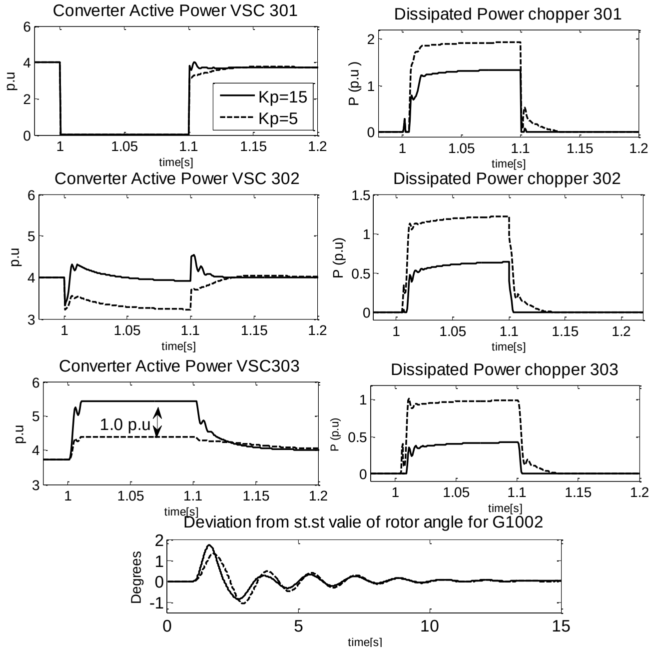

Figure 8. Sensitivity of AC and DC system response to droop control gain parameters (S_b=100MVA)

In general, a high proportional gain at the droop controller of figure 1(b) translates into a less steep droop line characteristic, as defined in figure 1(a). This will create a higher change in active power of the VSC for the same change in DC voltage, which amplifies the disturbance propagation between the two asynchronous power systems. On the other hand a small proportional gain means steeper droop line and smaller change in active power for the same change in DC voltage. Also with respect to the DC voltage response in figure 9, a higher gain means slightly lower over-voltage and faster post fault recovery to pre-fault values. Finally, it is worth of noticing the impact of droop gain selection on the dissipated power on the DC choppers and the DC terminals voltage response. A higher droop proportional gain means higher change in active power at remote converters and thus less power dissipated in the DC choppers.

V. CONCLUSIONS

In this paper the dynamic interactions between two asynchronous power systems coupled by a MTDC grid have been discussed. The work highlighted the way that faults in one AC system influence the dynamic response of generators in the second system. It has been shown, for this case study, that under AC side disturbances it is more the DC voltage droop control parameters which influence the AC/DC system interactions and less the topology of the MTDC grid itself. The converters in the remote and MTDC connected asynchronous system will respond to the DC overvoltage by additional active power injection to the AC system, which will disturb the second system generators. The higher is the proportional gain of the DC voltage droop controller the bigger the active power overshoot that appears and thus the disturbance added to the asynchronously HVDC connected power system.

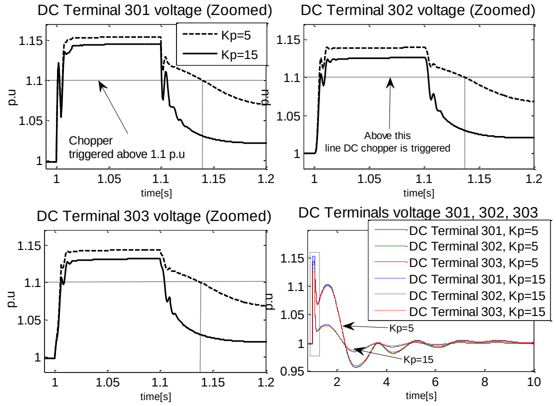

Figure 9. Sensitivity of DC voltage response of the onshore converters to droop control gain parameters (U_b=320kV)

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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