On Control Interaction Studies of HVDC-connected OWFs – Carbon Trust OWA Project

Viktor Rudan, Hani Saad, Daniel Yates, Arsim Ahmedi, Marina Oluic, Sarath Wijesinghe

***Abstract*-- The rising renewable energy in-feed in power systems entails wider presence of power electronic devices (PEDs). Consequently, adverse dynamic phenomena can be observed in power systems, as a result of the interaction between different controllers or between controllers and existing power grid equipment in the close vicinity.**

This paper aims to outline the key contributing factors of controller interactions with focus on HVDC-connected offshore wind farms (OWF) by proposing a comprehensive methodology to identify system topologies and conditions that can instigate interactions in the onshore system. In this regard, a benchmark model has been developed in an EMT-type tool comprising three generic HVDC-connected OWFs, a fourth OWF connected through an AC cable and a STATCOM. Moreover, two different versions of the control system of the HVDC links were developed to study interactions between controllers from different manufacturers. Parametric EMT-type simulations were performed for various system conditions and topologies to provide a wider view on the risk of interaction between multi-infeed HVDC links and OWF systems. Harmonic stability is also studied to illustrate the risk of resonance between two HVDC links connected in the network.

***Keywords*: Control Interaction Study, Dynamic studies, EMT-type, HVDC multi-infeed, offshore wind farm.**

I. Introduction

The rapid increase of the integration of renewable energy sources in power grids through power electronic devices (PEDs) has raised concern of interactions between the different controllers present in the network. Recent reports on field events of controller interactions involving OWFs and HVDC systems from different stakeholders are confirming the necessity of better understanding of these phenomena [1]-[3]. It is understood that converter-based devices have a much wider control bandwidth if compared to traditional components that result in potential resonances in a larger spectrum of frequencies. As such, there is a potential risk that these phenomena are not properly addressed, or at least not properly taken care of, by conventional studies.

The presented work was realized within the Offshore Wind Accelerator program, launched by Carbon Trust, and including nine European offshore wind developers. The project was entirely funded by Carbon Trust.

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Additionally, it is evident from previous events and experiences that manufacturers of wind turbines and HVDC converter stations should be seen as key providers of technical solutions to existing and future challenges. Thus, the development of study scopes as well as proposals for modification of grid performance requirements should be aligned with their trends and technology developments. A review of the solutions proposed by wind developers to deal with controller interaction risks in HVDC connected OWF projects is, therefore, much needed.

The analysis of potential controller interactions in power networks from today's perspective is a challenging task given the large number of PEDs in the network that could contribute to certain adverse phenomena. Several screening methods to identify interactions have been used in the industry, such as EMT studies, impedance scan, small signal analysis, etc., nevertheless, [4] classifies EMT-type study tools as the main tool that covers all interaction studies. Therefore, an effective approach in tackling all types of controller interactions in such complex networks is through extensive EMT studies, i.e., by simulating a large number of scenarios and network events in different network configurations using an EMT-type software.

In that direction, Carbon Trust has launched an industry-driven research project within their program Offshore Wind Accelerator, along with a consortium of nine European wind developers to study interactions between multiple PEDs installed in the same AC network. The project was contracted to the consortium composed of RTE international and The National HVDC Centre aiming to define a framework to study controller interactions. Additionally, the defined methodology and analysis provide an insight into study requirements related to control interactions in different grid codes.

This paper summarizes the defined interaction study methodology and verifies the approach through illustrations of such observed phenomena in the conducted interaction studies. The study process consists of comparing the behavior of converters in multi-infeed scenario with a base case – the standalone scenario, in various grid conditions and dynamic events. The studies were performed in an EMT-type tool using generic models of the HVDC links and the wind turbine generators (WTGs). Moreover, two versions of the HVDC links with different control were defined in order to consider multi-vendor scenarios.

II. Interaction studies

Due to their fast control, PEDs can cause interactions in the grid, both expected and unexpected. It is, however, important to differentiate between interactions that might have a positive impact on the network stability and those that push the system operating points outside of the stability margin, thus leading to an unfavorable grid condition and tripping of some elements

[5]. The interaction phenomena that can be observed between different PEDs and the surrounding network can be defined in three categories, as seen in Fig. 1.

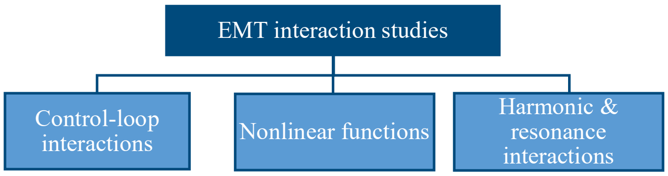


Fig. 1. Interaction phenomena [4].

- Interactions between the control loops of different converters: This type of interaction is a direct result of the existence of several control loops within the same system. Consequently, the stability margin of the whole system comprising several controllers is affected.
- Interactions caused by the presence of nonlinear functions implemented in the control systems: Examples of such functions are limiters in the control, activation of protection, transformer saturation, fault ride-through strategies etc., therefore, they are mainly activated at big disturbances or transients, such as AC or DC faults, overvoltages in the AC network, connection and disconnection of big loads or lines. Two HVDC links connected to the same onshore bus in proximity of each other can improve the dynamic behavior of the system by enhancing the performance of the control systems **Error! Reference source not found.**. However, the presence of nonlinear functions in the control could still give rise to negative interactions.
- High-frequency interactions are a result of harmonics generated by different converters present in the same network and the resonances that might be excited as a result. These types of interactions refer to adverse phenomena that are attributed with high frequencies which can potentially happen between HVDC links and the AC grid, which if not properly limited, may spread throughout the entire network.

The introduced interaction phenomena are the subject of study in this paper. The EMT-type models of the network components have been appropriately developed in order to create scenarios in which interactions can be observed.

III. Benchmark Model

Interactions between multiple controllers in the network are not always observable and do not necessarily manifest under any circumstances, therefore, initiation of such phenomena requires appropriate development of an EMT model. In order to study interactions and potential adverse behavior of the converters, numerous test cases were simulated in a benchmark study network shown in Fig. 2. The system was modelled in PSCAD. The benchmark network model has been developed based on publicly available data representative of a realistic UK power system network data where several HVDC-OWF systems are under construction. It comprises two 400 kV AC networks separated by two long 200 km-long lines, three 1.2 GW HVDC-connected OWFs, one 600 MW OWF connected through an AC cable and a STATCOM with a rated power of 200 MVA and two 900MW/50Mvar loads. Two of the HVDC-connected OWFs are coupled at the same onshore bus.

Depending on the conducted study, the two 400 kV onshore networks are modelled either as Thevenin equivalents (in order to reduce complexity and time needed to run the simulations); or as multi-mass synchronous machine (SM) models, for a proper representation of the dynamics in the studies that require so, such as the SSTI studies. The synchronous machine models also include generic governor/turbine and exciter models.

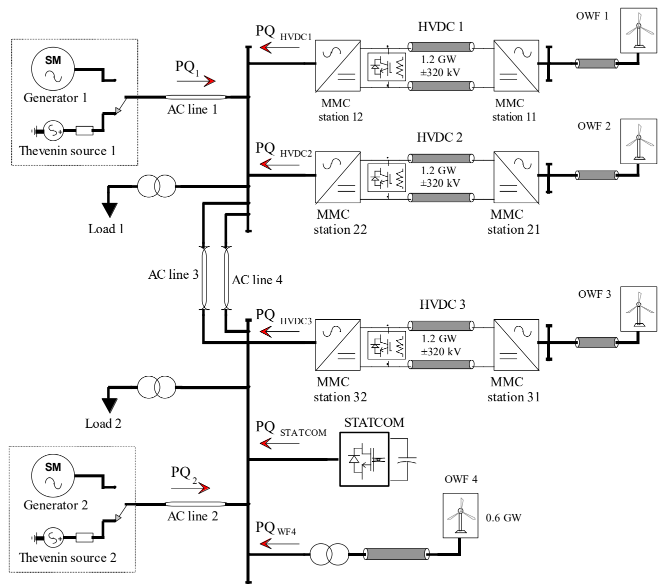


Fig. 2. Benchmark network for control interaction studies.

The benchmark model provides a reasonable compromise between being sufficiently detailed, to perform the requested interaction studies, and sufficiently simple, to provide clear understanding and illustration of the studied phenomena. It should be noted that all HVDC systems are initially developed with generic models and include the main protection functions, such as DC overvoltage and DC overcurrent protection.

Additionally, in order to investigate interactions in a multi-vendor scenario, two versions of control system were developed. The objective of this approach is to give rise to possible interactions caused by the differing control system settings of converters produced by different manufacturers that operate in close vicinity of each other. The two versions are referred to as “HVDC vendor A” and “HVDC vendor B”. To derive the two versions of the control system, the models underwent modifications based on an iterative approach until the two were deemed appropriate to represent realistic dynamic behavior in a standalone scenario. Firstly, in steady state, the two models should exhibit stable performance individually. Furthermore, the dynamic behavior of the two versions should be different aiming to potentially incite interactions between the controllers under the simulated network events. More precisely, the control schemes of the onshore and offshore converters of the two versions are identical, while changing the parameters of the outer and inner control loops, PLL gains, filter parameters etc. Additionally, the two variations have different negative-sequence current injection strategies. The two variants also have different arm reactance values and different converter transformer parameters.

A generic model of the STATCOM was derived from the HVDC and WTG generic models which means that the STATCOM model is very similar to the onshore HVDC converter station used in the studies (it includes the same control loops). This way, the STATCOM model has a similar level of detail and analogous dynamics.

The Bergeron model was used for all lines in the system.

All generic EMT models employed in this paper (that of the WTG, HVDC and STATCOM) comply with CIGRE recommendations with the level of detail needed for the control interaction study [6].

IV. Interaction Study Process

This section highlights the process used to conduct the control interaction study.

A. Methodology

The general methodology of identifying interactions was to compare results from the same dynamic events simulated in two scenarios: 1) standalone scenario with only one HVDC-connected OWF, which is the focus of the study and 2) multi-infeed network scenario with the consideration of at least two HVDC-connected OWFs. The same quantities from the two scenarios are compared by superposing them in the same plot, as illustrated in Fig. 3. The measurements correspond to the point of common coupling (PCC) of the first HVDC-connected OWF, i.e., PQ_{HVDC} in Fig. 2, thus showing the impact of additional HVDC links on the examined link HVDC1. Several signals can be traced to identify potential interactions. At the converter station, the observed signals include the injected active and reactive power by the converter onshore, instantaneous, RMS values and positive- and negative-sequences of the voltages and currents at the PCC onshore, d and q components of the current (onshore converter), DC voltage and current, frequency, capacitor voltages, energy dissipated in the dynamic braking system (DBS).

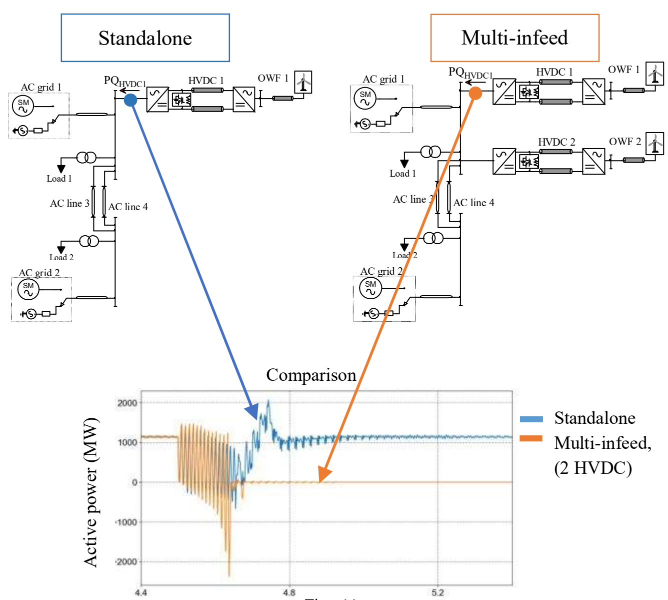


Fig. 3. Presentation of results in the interaction studies.

B. Scenarios

Various network topologies were considered in terms of number of HVDC-connected OWFs included, as well as different vendors of the HVDC converters, and thus different control schemes. The different topologies for which all test cases are simulated is summarized in Fig. 4.

In Fig. 4, the prefix “S” in the notations SA and SB stands for standalone scenario, i.e., the case where only one HVDC link is present in the network. Therefore, the notation SA indicates that the considered network has only one HVDC link with the control that corresponds to the vendor A, and SB with that of vendor B. The prefix M indicated a multi-infeed scenario where at least two HVDC links are present in the studied network. Furthermore, the order of the letters corresponds to the top-to-bottom order of the HVDC links presented in Fig. 2. The letter “O” refers to cases with the AC cable-connected OWF with STATCOM.

The stepwise analysis is categorized into three control interaction (CI) studies: the first (CI1), where the standalone scenarios (SA and SB) are compared with the multi-infeed scenarios with two HVDC-OWFs (MAA, MAB, MBB and MBA); the second one, CI2, where the standalone scenarios are compared to the multi-infeed scenario with three HVDC-OWFs (MAAA, MABB, MBBB and MBAA) and the third (CI3), where the multi-infeed scenarios with three HVDC-connected OWFs and one AC line connected OWF with STATCOM are compared to the corresponding standalone case. Moreover, all network configurations can be studied in scenarios where the AC network is represented by either a Thevenin equivalent or synchronous machines.

First, for all test network topologies, the performance of the system in steady state is examined in order to evaluate the impact of the number of PEDs on the stability of the system and then the dynamic test cases were simulated to identify interactions among different converters.

	SA		SB	
CI1	MAA	MAB	MBB	MBA
CI2	MAAA	MABB	MBBB	MBAA
CI3	MAAAO	MABBO	MBBBO	MBAAO

Fig. 4. Network topologies simulated in different cases.

C. Test cases

The methodology consists of simulating the same events in different network topologies, with each event corresponding to one of the 30 test cases defined in TABLE I.

TABLE I
List of Dynamic Test Cases

Group	#	Description
Steady state	1.1	UQ diagram at *Pmax*
	1.2	UQ diagram at *Phalf*
Step change converter control	2.1	Step change of -5% during 1 s on VDC control
	2.2	Step change of +5% during 1 s on VDC control
	2.3	Step change of -10% during 1 s on Vac control
	2.4	Step change of +10% during 1 s on Vac control
	2.5	Step change of +10% on Id ref
	2.6	Step change of +10% on Iq ref
	3.1	Onshore 1LG solid fault for 150 ms

AC and DC fault	3.2	Onshore 2LG solid fault for 150 ms
	3.3	Onshore 2L solid fault for 150 ms
	3.4	Onshore 3LG solid fault for 150 ms
	3.5	Onshore 3LG fault, residual voltage 10% for 150 ms
	3.6	Onshore 3LG fault, residual voltage 30% for 150 ms
	3.7	Onshore 3LG fault, residual voltage 50% for 150 ms
	3.8	Onshore 3LG fault, residual voltage 70% for 150 ms
	3.9	Offshore 1LG fault for 150 ms
	3.10	Offshore 2LG fault for 150 ms
	3.11	Offshore 2L fault for 150 ms
	3.12	Offshore 3LG fault for 150 ms
	3.13	Permanent DC pole-to-ground fault on DC cable
TOV AC network	4.1	Temporary overvoltage (TOV) of 1.35 pu in the AC network for 100 ms
Frequency dynamics	5.1	AC load outage
	5.2	Frequency step change of 200 mHz for 1 second simulated in the Thevenin source
	5.3	Linear increase of frequency from 50 Hz to 50.5 Hz within 1 s simulated in the Thevenin source
	5.4	Long-duration onshore 3LG fault
Other AC network events	6.1	Disconnection and energization of a long AC line connecting the two AC systems
	6.2	1LG temporary fault at the long line and single-phase opening of the breaker followed by successful breaker reclosing
	6.3	3LG temporary fault followed by three-phase opening of the breaker
Control stability	7.1	Frequency response between 100 and 5000 Hz

For instance, firstly, one standalone HVDC-connected OWF is subjected to an event, and then the same event is simulated in a multi-infeed scenario, i.e., with multiple HVDC links connected. Considering all dynamic test cases in all network topologies in Fig. 4 yields a total of 518 simulations.

To run all these simulations in a timely manner, an automated script was used. This process has been proven very effective for conducting a large number of parallel simulations. It also decreases the simulation time and ensure a robust and systematic approach each time a new iteration is performed.

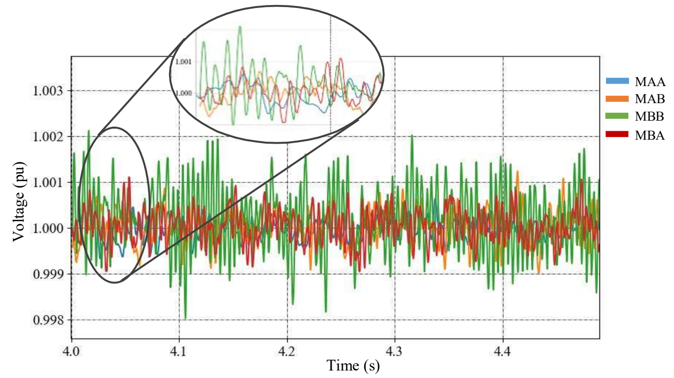
V. Results from the Interaction Studies

The objective of the performed studies is to investigate interactions between PEDs by simulating various network events or converter control changes in different network topologies. This process is, however, not straightforward and requires repetitive modifications of the grid conditions. This paper will present only the notable results of the three interaction studies.

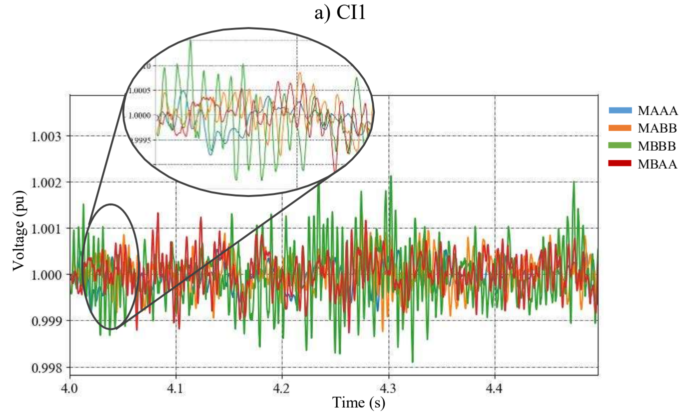
In order to spot interactions in the three interaction studies (Fig. 4), firstly, the behavior of HVDC1 in presence of other HVDC links in steady-state operation is evaluated. After evaluating the performance of the studied systems in steady state, the dynamic test cases were simulated.

A. Steady-state performance

One example of the results in steady state in CI1 and CI2 is shown in Fig. 5. The figure presents the RMS voltage at the PCC of HVDC1. All four network configurations display stable voltages and similar behavior in steady state in both interaction studies CI1 and CI2; however, slightly higher amplitude of oscillations can be observed in the cases where all HVDC links come from vendor B (MBB and MBBB). These oscillations of around 200 Hz are due to the different arm reactance values in the HVDC vendors A and B.



a) CI1



b) CI2

Fig. 5. RMS voltages in steady state in first (a) and second (b) interaction studies.

Conversely, an obvious instance of differences in the steady-state results among the four studied network topologies can be seen in the CI3. Fig. 6 shows prominent oscillations of 9 Hz in the RMS measurements of the onshore voltage in two of the four studied network configurations. It can be observed that the oscillations are only seen in the cases where HVDC2 and HVDC3 are from vendor B, which implies the possibility that the interactions arise from the connection of the AC-connected OWF (OWF4+STATCOM) and the MMC from vendor B (HVDC3) connected to the same bus. Further investigation revealed that the connection of the HVDC link from vendor B and the AC cable-connected OWF to the same bus onshore is the root of this oscillation. It is worth noting that this oscillation has an amplitude of 0.075 pu, which could seriously impact the behavior of the system in different simulated test cases.

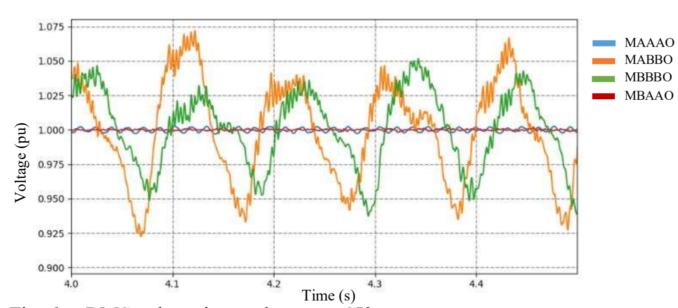


Fig. 6. RMS voltage in steady state - CI3.

B. *Results from dynamic test cases*

After assessing the steady-state performance of the system under different network configurations, the dynamic test cases from TABLE I were simulated. The purpose of this analysis is to identify adverse behavior of certain network configurations in the studied test cases, therefore identifying possible patterns in the interactions. Possible observed adverse effects include protection activation of the controllers, pronounced resonances, etc.

One notable test case is the onshore phase-to-phase solid fault (test case 3.3 in TABLE I), where the impact of the number of converters and network configurations can be seen distinctly. The fault is simulated in the standalone and all multi-infeed scenarios where all HVDCs are from vendor A. As seen in Fig. 7 the fault causes tripping of the HVDC link in all multi-infeed scenarios. The observed difference in the multi-infeed topologies is a result of interactions between the converters as they display stable standalone operation. Further inspection of the problem revealed that the DC overvoltage protection in the multi-infeed scenarios has been triggered after the voltage has exceeded the threshold value of 1.3 pu.

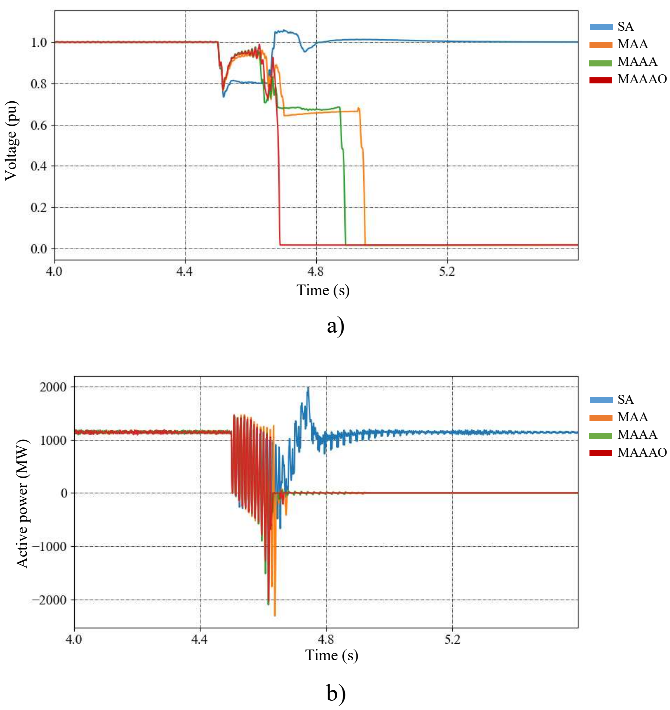


Fig. 7. RMS voltage (a) and active power (b) during phase-to-phase fault in different network configurations.

Another conclusion can be drawn from the analysis of the same event (onshore phase-to-phase solid fault) in a scenario where different vendors are present in the network. For instance, Fig. 8 reveals that in the multi-infeed scenario with two OWFs connected through different vendors, the studied HVDC link does not trip as was the case with two identical vendors. This implies that the different control, hence different dynamics during fault conditions of the second link (in this case from vendor A), can come in support to the first HVDC link (in this case from vendor B) and improve the overall reliability of the system.

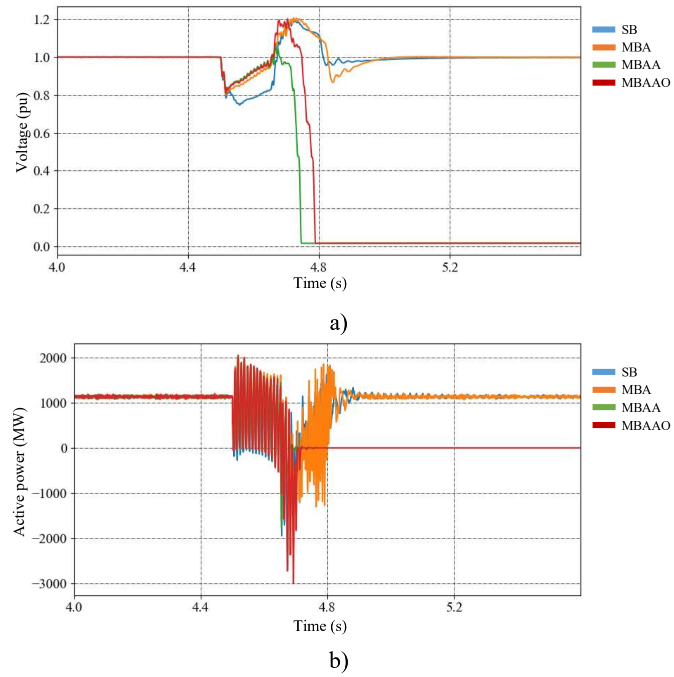


Fig. 8. RMS voltages (a) and active power (b) during phase-to-phase fault in different network configurations.

This case of phase-to-phase fault can be used to analyze the impact of the different network configurations on the stability of the system. Table II summarizes the results of the simulated test case of L-L fault in all network configurations for the three interaction studies. The configurations marked in green indicate that the studied HVDC1 recovers successfully after the fault, whereas red indicates tripping of the HVDC1 during or after fault. The configurations marked in blue represent the cases where pronounced oscillations are present in steady state, as was shown in Fig. 6. Several observations can be made from this table. Primarily, it can be observed that the higher number of HVDC-connected OWFs in the network, increases the risk of tripping of the HVDC converters in fault scenarios. In the studied fault it can also be observed that the presence of converters with different control settings can be favorable as the contributions from two converters complement each other and render the system less prone to disturbances.

TABLE II
PHASE-TO-PHASE FAULT SIMULATED IN DIFFERENT NETWORK CONFIGURATIONS

SA		SB	
MAA	MAB	MBB	MBA
MAAA	MABB	MBBB	MBBA
MAAAO	MABBO	MBBBO	MBBAO

HVDC1 trips
HVDC1 recovers after fault
Oscillations in steady state

The impact of higher number of PEDs in the network can be seen from the comparative analysis of the maximum AC and DC voltages measured during the fault test cases (from 3.1 to 3.8 in TABLE I). As can be seen in Fig. 9, there is an obvious rising trend of the overvoltages with higher number of PEDs in the network. On the other hand, the maximum DC voltages measured in all fault test cases shown in Fig. 10 show that the highest overvoltages are comparable among all compared network topologies for the same event, except in the case of a phase-to-phase fault (3.3 of TABLE I) where voltages tend to reach much higher values. Since on the secondary side of the onshore converter transformer, the tendency for increasing maximum overvoltages with higher number of converters in the network can be observed, having the highest DC voltages comparable, implies that the modulation index of the onshore converter is increased (i.e., lower voltage margin) when more HVDC links are connected in the network. Consequently, the security margin of the converter becomes narrower.

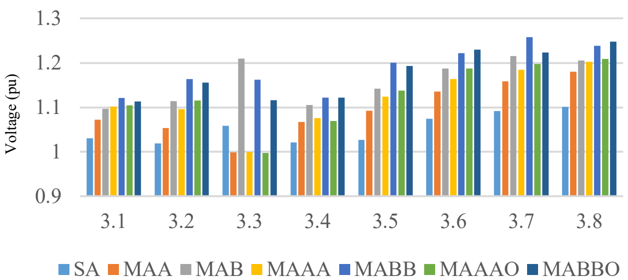


Fig. 9. Maximum onshore RMS voltages obtained in the fault cases for different topologies.

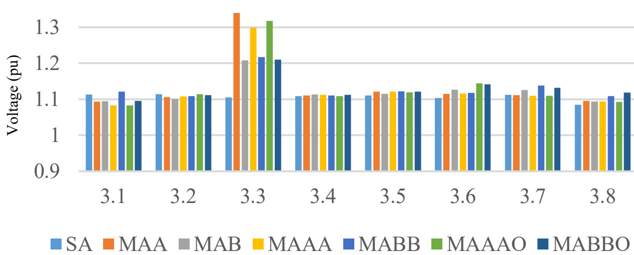


Fig. 10. Maximum DC voltages obtained in the fault cases for different topologies.

As has already been discussed, several test cases were simulated in the system with the two 400 kV networks modelled as two large synchronous generators. As such, the offshore frequency dynamics of the system is displayed realistically.

One example, a temporary three-phase to ground fault (test case 6.3 from TABLE I), whose elimination results in separation of the two AC networks has been studied to evaluate the impact of the different network topologies. The fault is simulated at the end of the AC line 3 in Fig. 2, with AC line 4 disconnected. The fault is simulated at t=60 s and is eliminated by opening the AC line 3 three cycles later, which is followed by an attempt to re-energize the line after 1.5 seconds. The onshore voltage measurements in the four different network topologies are shown in Fig. 11. It can be observed that higher number of HVDC-connected OWFs connected in the system decreases the damping of the post-fault oscillations significantly. On the other hand, it can also be concluded that the connection of the fourth AC cable-connected OWF+STATCOM contributes to decrease the amplitude of the oscillations following the line re-energization. Nevertheless, it can also be concluded that the damping of the post-disturbance oscillations in that case is the lowest out of the four compared cases.

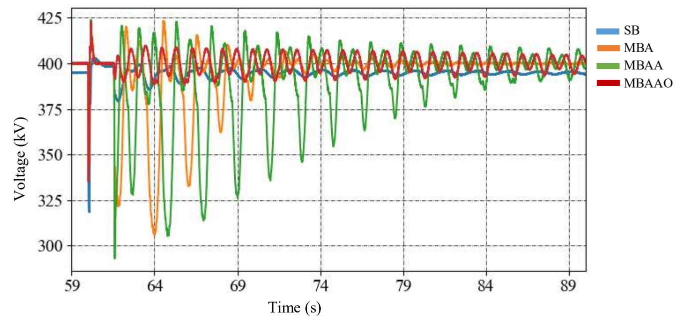


Fig. 11. Reactive power during three-phase-to-ground fault and after network separation.

C. Harmonic instability between two HVDC vendors

Additional interaction test cases were performed in order to study the potential harmonic instabilities between the different converters in the network. More precisely, high-frequency oscillations of around 1300 Hz were observed at the PCC of one of the HVDC link upon disconnection of one big load of 1 GW. The scenario is shown in Fig. 12. The two HVDC links come from a different vendor (vendor A and vendor B) and are connected to a different onshore busbar. The mentioned high-frequency oscillations are observed after disconnection of the load 1 (1 GW) by opening the breaker BRK1.

The two links in standalone operation are stable before and after disconnection of the load. However, when the two are connected in the network, the mentioned high-frequency oscillations are observed after disconnection of the load 1 (1 GW) by opening the breaker BRK1. The oscillations in the active power and voltage measured at the two PCCs before and after the load disconnection are shown in Fig. 13. The bottom plot shows the zoomed-in voltage waveforms.

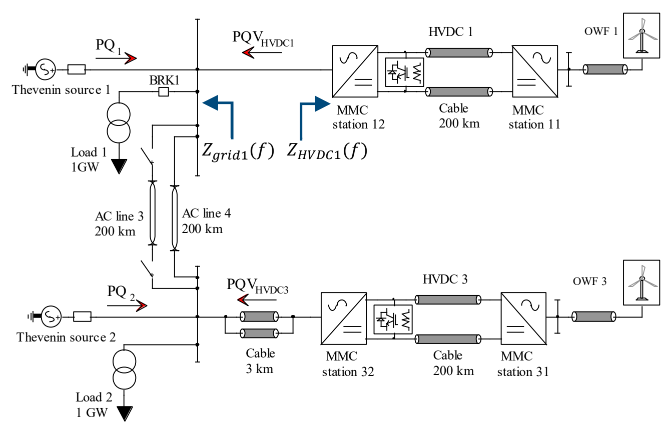


Fig. 12. Simulated network in the resonance study case.

In order to identify the root cause of the resonance, the impedance stability criterion was applied [7]. The frequency responses of HVDC1 and the grid, with and without the load, were determined and plotted in the frequency range from 100-2500 Hz. The results are shown in Fig. 14. As can be concluded from the plots, the grid impedance magnitude and the converter impedance intersect at 1305 Hz for which the phase margin is larger than 180º, implying the risk of instabilities.

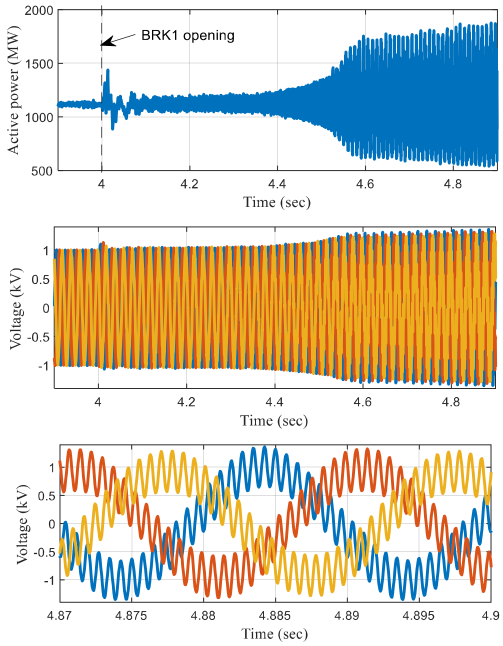


Fig. 13. Oscillations at the PCC of HVDC1 after opening of BRK1.

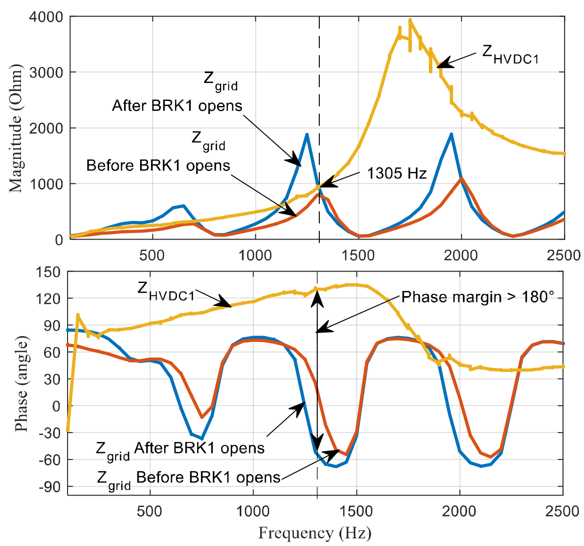


Fig. 14. Frequency response of HVDC1 converter station and grid impedance before and after opening of BRK1.

VI. CONCLUSION

This paper summarizes relevant findings from the investigation of control interactions between multiple power electronics-based devices in the network. The studies were performed as part of the project "HVDC-connected OWFs: Controller interactions" within the program Offshore Wind Accelerator.

This paper aims to provide the methodology of interaction studies in a network with multiple HVDC-connected OWFs in a multi-vendor scenario. The proposed approach consists of sequential interaction studies with increasing number of OWFs connected to the network (multi-infeed scenarios) and considering identical or different control systems. In each interaction study, steady state and dynamic events were simulated and the interactions were identified by comparing them to the standalone cases. All PEDs (i.e., OWFs, HVDC links and STATCOM) display stable and realistic behavior in a standalone scenario. In the stepwise interaction study procedure, three types of interactions were observed: interactions between different control loops of the converters, interactions due to the nonlinear nature of the control and harmonic resonance interactions.

A few conclusions can be drawn from the conducted simulations. Firstly, it has been shown that there is a tendency for more prominent interactions when the number of PEDs in the network increases. Also, there is no pattern in terms of presence of different vendors that renders better performance of the system under different phenomena. In other words, both cases, i.e., the cases where the converters are from the same vendor, as well as the cases with different vendors, can be shown more prone to interactions in different simulated scenarios. This attests for the intricacy of identifying interactions in systems with many PEDs due to their non-linear nature. Therefore, it is important to conduct project-specific interaction studies to identify and avoid adverse interactions.

Additionally, a high-frequency resonance case when two converters from different vendors are connected in the network has been shown.

The presented work provides insights into potential guidelines for future grid code development: further requirements should be included to both (i) take into account faster dynamics originating from larger number of PEDs in the system and (ii) incorporate their potential interactions.

VII. ACKNOWLEDGEMENT

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