Operation and Control of hybrid AC/DC transmission grids

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***Abstract*—This paper describes challenges and possibilities related to operation and control of hybrid AC/DC power transmission grids. The aim is to discuss topics that transmission system operators and regulators must assess in order to develop technical standards, grid codes, market regulations and operational procedures for multi-terminal DC grids that connect different synchronous AC systems. The topics include control and operation in a fully integrated power market, solutions for exchange of reserves and possible adverse interactions and consequences of interconnecting AC grids on power system stability. It is shown that there is stronger interaction between AC systems when voltage droop control is applied in converter control, and when inertia support and exchange of primary reserves are provided through the DC grid. With coordinated design and well-tuned controllers, we have found no evidence of adverse interactions. We conclude that in relation to dynamic responses and power flows, it is possible to design control schemes that makes interconnected AC/DC grids behave almost like one AC grid. This property can be exploited in design of future primary and secondary control services, as well as to preferred schemes for market integration.**

Keywords—HVDC, control, reserves, interaction, stability

I. Introduction

High voltage direct current (HVDC) transmission is the preferred solution, from a technical and economic point of view, when power transmission distances are very long, or when interconnecting different synchronous power grids. The increasing number of HVDC connections around the world contributes to more exchange of power and energy and creates closer integration between different synchronously interconnected AC grids. Decisions to build HVDC links are mostly driven by economic opportunities in the power markets, exploiting price differences between grid areas and market zones. The power markets are greatly influenced by the green shift. Development of renewable energy sources and decommissioning of fossil fuel and nuclear energy-based power plants contribute to higher price differences and more volatility in future power markets. It is therefore expected that the many existing and new HVDC projects connecting the Nordic, Central European and UK synchronous zones across the Baltic and North Seas will create economic and environmental benefits to the European society.

The use of HVDC systems is particularly interesting in relation to development of offshore wind energy. The fact that most new HVDC links are based on voltage source converters (VSCs) creates opportunities and motivation for investigating multi-terminal and possibly also meshed HVDC grids. With this technology and a growing offshore demand, it is likely that true hybrid AC/DC interconnected power systems will be realized.

The variability and complexity of the future power system create new challenges for secure operation and control. HVDC links have long been designed to provide some system services, like under-frequency and under-voltage emergency control. Now, there is also increasing focus on the potential of HVDC connections to enable exchange of reserves on a more regular basis, and with this enabling integration of balancing markets across synchronous interconnections.

This paper deals with operational and control issues that transmission system operators and regulators will need to assess in order to develop technical standards, grid codes, market regulations and operational procedures. That is, we will focus on challenges and possibilities related to operation and control of HVDC connections, and specifically on multi-terminal HVDC (MT-HVDC) grids. The main topics discussed are:

- Methods and analysis related to control and operation of a MT-HVDC grid in an integrated power market perspective.
- Control solutions enabling exchange of reserves.
- Analysis to identify possible adverse interactions and consequences of interconnecting AC grids on power system stability

There is a lot of research ongoing in this field, and the list of references included in the paper is far from exhaustive. The analyses described are mainly taken from our own research and further discussed with reference to other relevant research.

Hybrid AC/DC transmission grids have been investigated in the context of deregulated markets, such as in [1] and [2], where nodal pricing methods have been proposed to increase the effective transmission capacity and improve the utilization of renewable generation. Research on security-constrained unit commitment for the hybrid grid architecture of interest has recently been carried out in [3], [4]. In all transmission planning and power market analysis the knowledge of power flows and grid constraints is essential. For this purpose, power flow algorithms including the hybrid

AC/DC nature of the transmission have been developed. An early contribution is described in [1], but various alternative methods have been proposed in the literature. In [6] the authors propose a method to compute power flows for both asynchronous grids and for synchronous AC grids with embedded VSC-based MT-HVDC. The contribution in [7] extends the optimal power flow for hybrid systems including wind power integration.

Stable and secure operation of hybrid AC/DC transmission systems demand flexible power control strategies, including options to deliver ancillary services. A control strategy for exchanging automatic frequency-controlled reserves is described in [8], but different technical solutions have been proposed. These may be completely decentralized, where only the local frequency measurement is used [9], or rely on communication to provide the frequency measurement from all asynchronous AC grids to the converter stations of the MT-HVDC grid. The choice of solution will have different impacts on robustness and performances, as discussed in [10], [11]. Control schemes for hybrid AC/DC grids have also been adapted and analysed for wind power integration applications [12], and extended to include more realistic operational limits [13].

The remainder of the paper is organized as follows: Chapter II discusses the basics of controlling a MT-HVDC grid with respect to steady state power flows, market aspects and security considerations. In chapter III we introduce the dynamic control challenges and discuss ways of exchanging reserves through a DC grid. The possibility of interconnecting several synchronous AC grids through DC networks raises the question about stability and possible adverse interactions. This is discussed to some extent in Chapter IV. Finally, based on the conclusions we discuss the possibilities and challenges for future developments in Chapter V.

II. Control and Operation of Multi-Terminal HVDC

A. Power Control Priciples

Our definition of a hybrid AC/DC transmission grid is main grid infrastructure of a power system that consists of more than one AC synchronous area and one or more HVDC links or DC grids that connect the AC grids (Fig. 1).

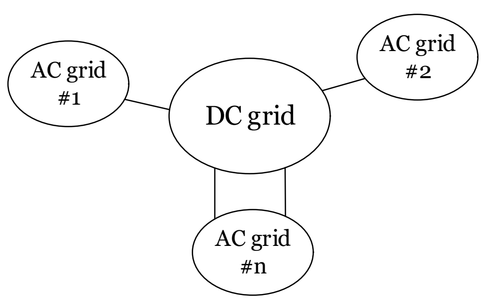

Fig. 1. Structure of a hybrid AC/DC power system

Most of the synchronous areas in Europe are already interconnected to a neighbouring grid by point-to-point HVDC links. Such links have been around for several decades, and hence, the principles for control and operation are very well established. However, when more and more interconnections are built, there will be much higher transmission capacity between AC grids. There will be more converter stations and terminals for HVDC links within each grid area, and not least significant, the preference of choosing voltage source converters in new projects opens the potential for multi-terminal HVDC links as well as meshed HVDC grids. In this scenario, several new possibilities and challenges arise regarding operation, control and protection.

Although it is of crucial importance for the development of meshed DC grids, we will not discuss protection in this paper. On the power control side, care must be taken to avoid that power flows on HVDC connections become critical limitations concerning power system security. Common practice today is that a fault leading to an outage of a HVDC link is regarded as a single contingency on each side and treated separately in security assessments within the separate areas. However, when the interconnections become tighter, and eventually with a meshed multi-terminal DC grid, this is no longer sufficient; it may result in too conservative or too relaxed capacity limits depending on the control and protection of the MT-HVDC grid.

One of the important factors for secure operation is how the automatic control of power balance and power flows within the DC grid is implemented. If voltage droop control is chosen for all converters, the grid can be made more robust towards DC line or converter outages. The principles behind voltage droop control and impact on power flows is analysed in [15] and further discussed in chapter III.

B. Power market integration

With the ongoing efforts to integrate the European electricity markets [14], it is crucial that the HVDC connections are utilized in a most optimal way. A main advantage with HVDC is that power flows can be controlled more precisely than in a meshed AC grid [15]. Power injections through HVDC converters are fully controllable within their operational limits, and this can be exploited e.g. when day-ahead markets are cleared. With implementation of flow-based market coupling in Europe (or nodal pricing elsewhere) the power injections can be treated as control variables in the optimization algorithm that determines the prices and power transfers between areas. A model to illustrate the principle was developed and described in [2]. The basic idea is that power transfer through converter terminals on the AC side are treated as injections (generators or demand) with zero marginal costs. The power balance within the DC grid, including enforcement of power transfer capacity limits, is obtained by including the DC grid power flow model as part of the constraints.

Furthermore, if using a simple method for DC grid power flow computation, for example as described in [15] and [16], one may explicitly model the effect of primary voltage droop control. In this way, adjusted set-points for the converters are obtained simultaneously, accounting for the losses and voltage drops in the DC grid. The possibility of including transmission losses in the market clearing process may be very important when considering the actual cost benefit of exchanging reserves and energy over very long distances.

III. Exchange of Reserves and Dynamic Analysis

A. On MT-HVDC converter controls

MT-HVDC grids can operate in various types of active power and/or DC voltage control modes such as master-slave, voltage margin, DC voltage droop and dead-band droop control modes [8], [9], [17]. Fig. 2 shows a block diagram of an outer loop of an MT-HVDC converter controller with DC voltage droop on active power control. In the figure, the superscript * indicates reference signals, and V_{dc}, P_g, and i_d are

DC voltage, active power and d-axis AC current component, respectively. DC voltage droop control is a distributed type of control where more than one terminal participate in control of active power and DC voltage. In this control mode, the DC voltage droop parameter, ρ_{dc} (Fig. 2), determines the desired (linear) relationship between the power flow and the local DC voltage.

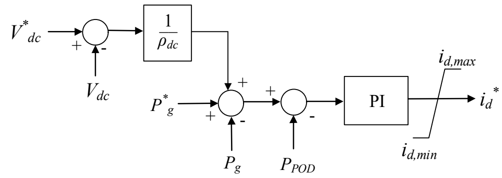

Fig. 2. Controller structure for active power control in DC voltage droop mode, also indicating input signal for a power system stabilizer (POD) function.

P_{POD} is output of an optional POD (power oscillation damper) controller. DC voltage droop control in MT-HVDC neither requires communication nor is it dependent on a single terminal to maintain power balance. For these reasons, it is considered the most appropriate type of control mode for MT-HVDC grid operation.

B. Exchange of frequency containment reserves

The converters forming the MT-HVDC grid naturally decouple the AC and DC grids in terms of power, frequency and voltage fluctuations. This natural decoupling also suggests that the primary frequency response characteristic of one particular AC grid---connected to a DC terminal of the MT-HVDC system---is not automatically transferred to other terminals; and in turn, to other asynchronous AC grids. Indeed, this prevents any possibility of exchanging primary reserves between distant asynchronous AC grids via the multiple HVDC links [8], [18]. Interestingly, this missing coupling between AC and DC grids can be artificially created via control action. One possible and simple solution was proposed in [9] consisting in including a standard frequency droop control formulation for AC grids in the converter DC voltage droop control---see Fig. 3.

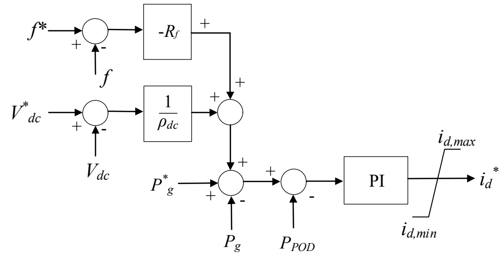

Fig. 3. Control structure for for an auxiliary AC frequency droop function enabling exchange of primary reserves.

This modification to the converter droop characteristic was shown to make the different asynchronous AC grids interact with one another through the MT-HVDC, responding to variations of power imbalances, reflected by voltage deviations on the DC side and frequency deviations on the AC side. Moreover, it was proven in [18] that the same control method can be extended to AC terminals connecting offshore wind farms, where the frequency would be completely unassociated to the power flow---due to the lack of direct connection of rotational machines---if it were not for the artificial coupling created by the droop control strategy discussed above.

A case study was presented in [8] with the purpose to illustrate how frequency containment reserves could be exchanged across the synchronous areas around the North Sea. This was done with a simple model of a hypothetical meshed North Sea MT-HVDC grid, and by simulating outages of an offshore wind farm producing 250 MW. Fig. 4 shows one result where, by applying the combined frequency and voltage droop control method, the frequency dip is significantly reduced in the area where the wind farm is connected.

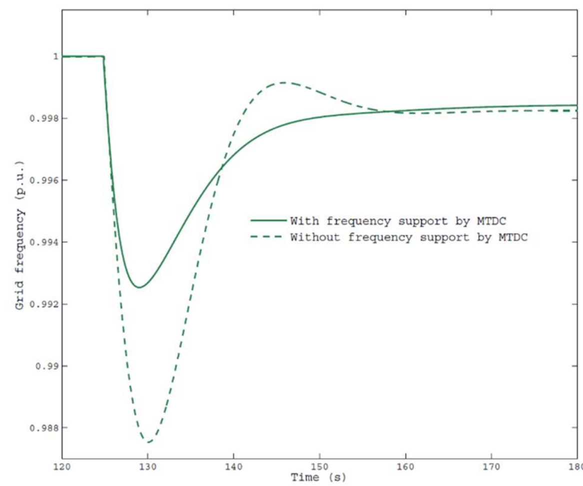

Fig. 4. Frequency dip resulting from an outage of 250 MW wind power - as investigated in [18] – with and without frequency containment reserves received through the offshore MT-HVDC grid.

Finally, the amount of expected frequency and/or DC voltage deviations can be adjusted with good enough accuracy by careful tuning of the droop coefficients, as shown by the sensitivity analysis in [19].

C. Provision of reserves from offshore wind farms

The approach to control of HVDC converters, as discussed in the previous section, enables the possibility of providing frequency containment reserves from offshore wind farms. This is achieved, for example as explained above, by adding a frequency droop signal to the active power control of the converter connected to the AC grid that receives the frequency support. Further, the scheme must be coordinated with proper control at the offshore end to make the offshore wind farm respond as desired. It was proposed in [11] to include direct communication, such that frequency support contribution of the offshore wind farm could be maximized. The proposed coordinated control structure is sketched in Fig. 5, where it can be observed that the offshore terminal of the MT-HVDC is receiving the frequency measurement of the onshore grid converter in addition to its own local frequency and DC voltage measurements.

The investigation carried out in [11] showed that the proposed method improves the overall performance of the system. The simulation example used a model of a three terminal HVDC system, with onshore terminals #1 and #2 connected to separate AC grids, and terminal #3 connected to an offshore wind farm---see Fig. 11 in Appendix. The two cases presented in Fig. 6 show responses to loss of load in the AC grid connected to terminal #1. The offshore wind farm was simulated with and without the direct communication link (respectively, blue and red curves in Fig. 6).

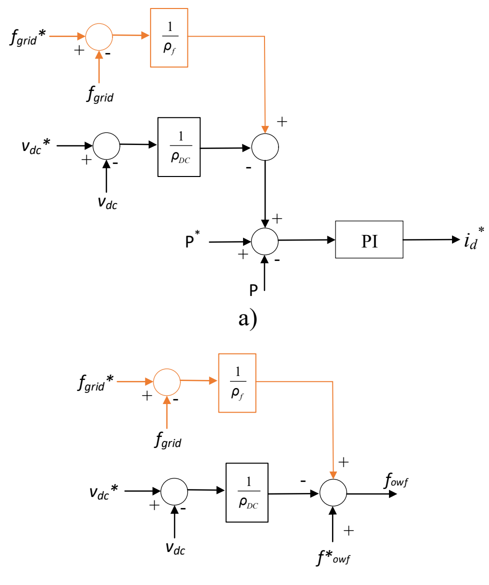

Fig. 5. Auxiliary MT-HVDC converter controller on a) the onshore grid terminal, and b) the offshore wind farm terminal that also receives the communication signal "f_{grid}" from the onshore terminal.

From these results, one may conclude that the case with a direct communication (blue curves) has a better performance compared to the other case, which relies solely on local voltage and frequency droop control. This is particularly clear from the onshore terminal #2, where the frequency is almost unperturbed, although more down-regulation has been achieved to compensate for the loss of load. However, this is not necessarily a robust solution: consider the case when the disturbance occurs in the other AC grid (terminal #2) and the offshore wind farm responds (partly) to the frequency signal communicated from terminal #1. The unwanted response in that case, combined with the complexity of the solution, suggest that the simpler solution without direct communication, although not optimal in every case, is still preferable.

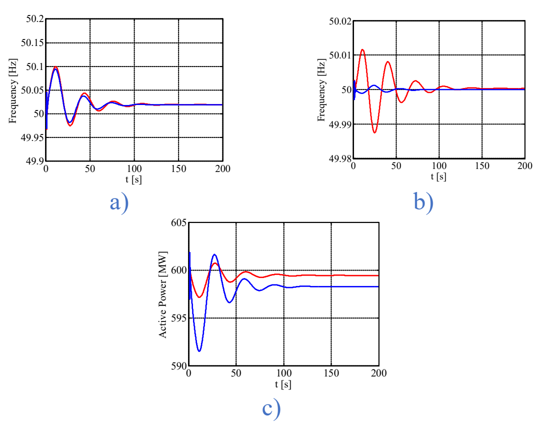

Fig. 6. Frequency in the a) onshore grid connected to terminal #1 and b) onshore grid at terminal #2; c) active power delivered from the offshore wind farm. Red curves: Case with frequency and voltage droop control but without communication. Blue curve: with direct communication of frequency deviation at terminal #1 to wind farm.

IV. Interaction and Stability Analysis

A. Modal analysis study

The studies referred to above on the possibilities and potential pitfalls in operation and control of hybrid AC/DC systems have motivated a more thorough analysis of stability and robustness associated with control of multi-terminal HVDC grids. In [17] a control system design study was performed based on computation and analysis of relative gain arrays (RGAs). In an earlier study [20], the main objective was to assess interactions between the subsystems in hybrid AC/DC grids using dynamic analyses:

- Are there significant dynamic couplings between the asynchronous areas?
- Will they affect positively or negatively the stability of a subsystems?
- Which factors are influencing the level of interactions?

The power system model used in this study (Fig. 7) consists of a four converter DC grid that is connected to three different AC grids.

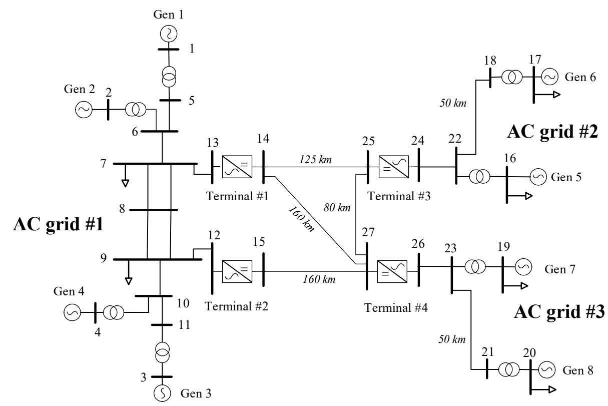

Fig. 7. Hybrid AC/DC test system for interaction analysis.

The methods applied are modal analysis (mode shapes of eigenvalues and participation factors) and time domain simulations. A main finding is that the modes in a hybrid AC/DC power system can be considered a mere combination of the modes in the separate AC grids, plus the additional modes related to the DC grid and converter controls. However, some of the eigenvalues associated with an AC grid are seen to move (or change value) when the grids are interconnected. By studying the mode shapes, i.e. the observability factors of these eigenvalues, it is possible to identify dynamic interaction between the different synchronous grids.

Inter-area oscillations are normally understood as the phenomenon where groups of generators in one area oscillates against groups of generators in another area of the same AC grid. Results from modal analysis show that there were one significant inter-area mode associated with each grid: λ_A in grid #1, λ_B in grid #2 and λ_C in grid #3. Table I lists magnitude of mode shapes of speed state variables for these three inter-area modes in the hybrid AC/DC test system. It shows that the electromechanical modes are mostly confined to their respective AC grids. For example, eigenvalues λ_A is most observable in speed state variables of Gen3, followed by the three other generators in AC grid #1. But albeit low magnitude, the mode is also observable in generators 5 to 8. This indicates that there exists a weak dynamic coupling between the asynchronous AC grids due to the interconnection via a DC grid.

TABLE I. Magnitude of mode shapes of generator speed states for the electromechanical modes in the hybrid AC/DC system.

	State (speed)	AC grid	λ_A	λ_B	λ_C
Gen1:	$\Delta\omega_{A1}$	#1	0.172	0.002	0.002
Gen2:	$\Delta\omega_{A2}$	#1	0.079	0.001	0
Gen3:	$\Delta\omega_{A3}$	#1	1	0.002	0.002
Gen4:	$\Delta\omega_{A4}$	#1	0.982	0.001	0
Gen5:	$\Delta\omega_{B5}$	#2	0.009	0.971	0.001
Gen6:	$\Delta\omega_{B6}$	#2	0.013	1	0.006
Gen7:	$\Delta\omega_{B7}$	#3	0.008	0.005	0.84
Gen8:	$\Delta\omega_{B8}$	#3	0.016	0.002	1

Time domain simulations support the results from modal analysis. However, when one of the AC grids were exposed to a larger disturbance, the main observation was that it is the critical modes in each area that become significantly excited. The main conclusions can be summarised as follows:

- Generators located in asynchronous grids interconnected through an MT-HVDC can be seen to oscillate against each other.
- This can be explained from linear analysis that shows poorly damped electro-mechanical modes of one area being observable in other areas that are linked through an MT-HVDC.
- The interaction arises from the shared control of DC voltage when operating under DC voltage droop control.
- The level of the interactions is mostly affected by the choice of control mode for the converters and the tuning of the controllers.

B. Need for coordinated controller design

The future power grids face a number of new challenges due to more generation variability, more interconnections and more power electronics. With less inertia and fewer power plants directly connected with synchronous machines, many of the operational challenges must be solved through control. Power electronics, including HVDC converters, play a crucial role, partly as the source of problems but also providing the solutions. For example, to compensate for less natural inertia, the provision of fast frequency control and virtual inertia through coordinated control of MT-HVDC converters appears as an interesting solution.

The aim of the study in [21] was to illustrate the possibility of exchanging fast frequency reserves between two AC grids (A and B) through an HVDC link, while at the same time investigating possible adverse effects. Examples of results are shown in Fig. 8 and 9 where a loss of load in Grid B was simulated. Three different control scenarios for the HVDC link were analysed and compared through simulations:

- "No droop": Constant power control (as a base case)
- "20% droop": Grid B receives support through frequency droop control
- "20% droop with inertia support": Grid B receives both frequency and inertia support (through a proportional +derivative -type of controller)

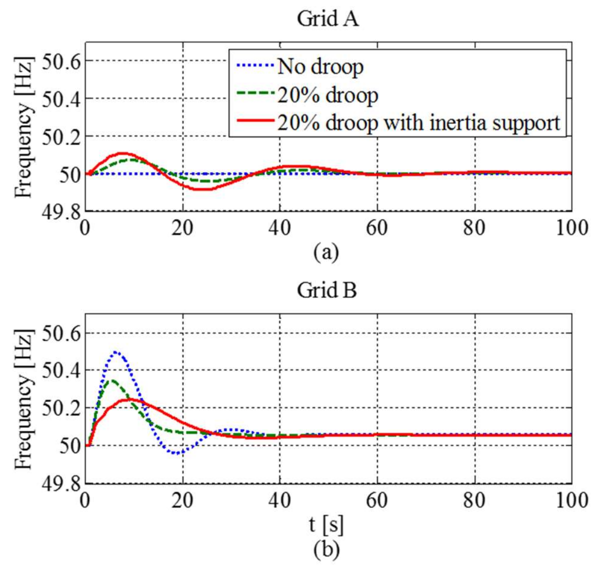

Fig. 8. Simulated responses to loss of load in Grid B focusing on system frequency in the two AC grids. (a) shows responses in Grid A and (b) responses in Grid B for the three

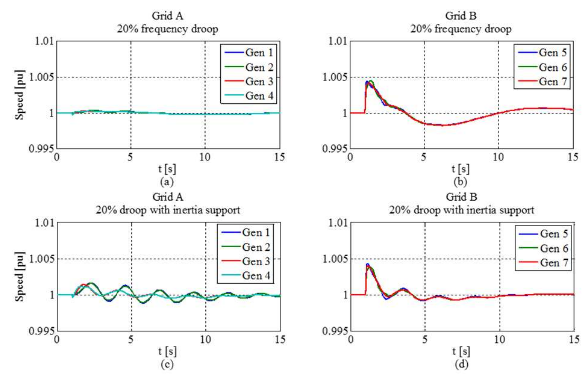

Fig. 9. Simulated responses to loss of load in Grid B focusing on electro-mechanical modes visible in the generator speeds. (a) and (b) show responses in Grid A and Grid B, respectively, for the "20% frequency droop case", (c) and (d) show the same responses in Grid A and Grid B, respectively, when "inertia support" is added.

The results from the simulation study serve to illustrate another interaction phenomenon. When first focusing on system frequency (Fig. 8), we see that the case providing inertia support is indeed successful in the sense that the frequency peak in Grid B is reduced - while there is no significant change in Grid A. However, if we look closer at other variables and focus on the electro-mechanical modes, it can be seen (in Fig. 9) that damping of the main inter-area mode has been reduced. In general, whether the inter-area modes will be destabilised, depend on several factors, but most important is that due care is taken in design and tuning of the controllers. One way of mitigating this problem is to apply an auxiliary power oscillation damper (POD), but clearly that also adds to the complexity in tuning of the controllers. A resulting converter control structure for active power could then be as shown in Fig. 3 and Fig. 10.

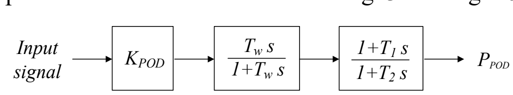

Fig. 10. Possible structure for an auxiliary POD function on HVDC converter controls.

V. DISCUSSION AND CONCLUDING REMARKS

In this paper we have summarised some of the challenges and possibilities that result from tighter interconnection of power systems into hybrid AC/ DC transmission grids. We have discussed normal operation issues, including angle stability, primary control of power balance to market considerations. Other important issues to be resolved, such as protection of DC grids, standardisation and regulatory aspects have not been addressed.

The main conclusion that can be drawn from the research we refer to is that regarding response to changes in generation, loads or power flows, it is possible to design control schemes that makes interconnected AC/DC transmission grids behave "almost" like one AC grid. This property can be exploited in design of future primary and secondary control services, as well as to preferred schemes for market integration.

The "almost" refers to the fact that in a hybrid AC/DC system there is not only one system frequency, and therefore extra care must be taken when defining the control strategy. This is because most of the interactions between the grid areas, whether desired or adverse, depend on controls.

It is shown that there is stronger interaction between AC systems when voltage droop control is applied in the DC grid, and when inertia support and exchange of primary reserves are provided through the DC grid. Mostly, this represent desired interactions, but there may be other adverse effects. One example is when fast frequency control is enabled through the DC grid, this may unintentionally destabilize electromechanical modes in one or more AC grids. However, with coordinated design and well-tuned controllers we have found no evidence of adverse interactions that would be showstoppers for further developments.

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APPENDIX

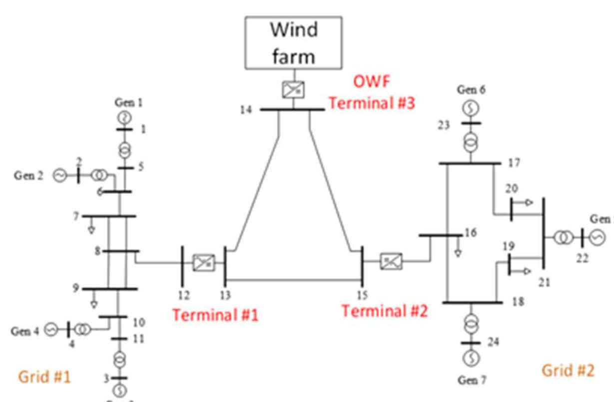

Fig. 11. Three-terminal, three area system model used to study provision of reserves from offshore wind farms in [11].