Influence of Frequency-Droop Supplementary Control on Disturbance Propagation through VSC HVDC Links

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Abstract—**The construction of the European Super Grid is a valuable solution to deal with the growth of electricity demand and the increasing penetration of renewable energies. Key feature is the introduction of large capacity High Voltage Direct Current (HVDC) links between countries bordering the North Sea. This paper investigates the level of coupling of two AC grids connected via HVDC links. Two reduced dynamic equivalent transmission systems resembling Great Britain are developed in DIgSILENT PowerFactory. Two balanced monopolar HVDC links equipped with two-level Voltage Source Converter (VSC) are used to connect the two grids. A frequency droop control that modulates the power transfer along the DC link has been designed for the converters to provide frequency support between the grids. A variety of disturbances were applied to the AC grids to test the extent to which faults in one grid propagate to the other. It was found that the presence of frequency droop control increases significantly the degree of coupling between the two grids.**

Keywords— **Droop control, frequency response, HVDC, HVDC control, VSC**

I. Introduction

The rapid increase of energy demand in combination with the significant penetration of renewable energy sources and the European carbon reduction targets [1] are forcing existing electricity networks to work closer to their operational limits. Consequently, the reinforcement of the existing power systems is becoming urgent. The European Super Grid, a vast AC/DC system capable of delivering power at a continental scale, represents a valuable solution. HVDC is regarded as the optimal technology for the realisation of interconnections between weak AC systems already working in stressed conditions since it creates benefits in terms of system stability, power flow control, and protection from disturbances [2].

In order to accommodate the increase in electricity generation and to deal with the significant penetration of renewable energy, the British Transmission System Operator (TSO) suggests increasing the power in-feed loss limit to 1.8GW. In [3] it is stated that "the level of loss of power in-feed risk is covered by frequency response to avoid a deviation of system frequency outside the range 49.5Hz to 50.5Hz. In 2014 this passes from 1320MW to 1800MW". In order to satisfy the security and quality requirements from [3], transient frequency deviations outside the limits should occur only in case of infrequent events. However, the rise in the level of loss of power in-feed (to 1.8GW) increases the risk of the system frequency of falling to an unacceptable level before frequency control can mitigate the situation [4] . In fact an event occurred in the Great Britain (GB) transmission network in 2008 that showed a frequency drop down to 49.2Hz for a loss of in-feed of 1.8GW [5]. To reduce the frequency deviations outside the acceptable range, a frequency-droop control strategy has been considered in this paper as a supplementary control for HVDC links.

Two balanced-monopole VSC HVDC links transferring 2GW each have been used to connect two full-scale dynamic equivalents national transmission grids [6]. Since the rating of VSC HVDC links is expected to increase significantly in the future, the rating of the link has been chosen to be 2GW. The VSCs are equipped with frequency-droop control on the rectifier end in order to increase the converter participation in disturbance mitigation. The control strategy is designed to regulate the power across the HVDC corridors in response to frequency deviations in the system.

The ability of the HVDC link to prevent the effects of faults originating in one grid from passing to the other is examined. Unlike [6], the implementation of frequency-droop control in the VSCs is expected to create interactions and increases the degree of coupling between the grids. In case of disturbances in one system, the other system intervenes to support the first thereby preventing the system frequency from reaching unacceptable values. This concept of mutual assistance will enhance the overall stability of the system in the perspective of the European Super Grid, where the number of interconnections between national power grids will be significantly higher than at present.

The reduced Great Britain (GB) transmission system developed in [6] in DIgSILENT PowerFactory is used here. Further improvements concerning the dynamics are presented to increase the fidelity of the model compared to the real transmission system.

The paper consists of five further sections. First a detailed explanation of the improvements made in the GB dynamic equivalent model is provided. Secondly the VSC HVDC links and the droop frequency control strategy applied to the converters are illustrated. The case study, describing the platform used to investigate the performance of the DC links, is outlined in Section IV. Time-domain simulations are presented and the outcomes explained in the successive section. Finally, some conclusions are drawn.

II. Great Britain Dynamic Equivalent Model

This section describes the dynamic equivalent model of the Great Britain (GB) transmission network developed in

DIgSILENT PowerFactory. A description of the model (both steady-state and dynamic controls) can be obtained from [6]. The network data (steady-state) is based on [7], [8] while [6] presents the network with dynamic models. The generators represent a mix of synchronous as well as non-synchronous generation, which are based on Fully Rated Converter (FRC) and Decoupled Fed Induction Generator (DFIG) turbines. This paper presents a set of further refinements to [6] which include the addition of dead-bands to governors to regulate their participation in frequency response, the implementation of several automatic voltage regulators and governors' types, and modifications of generators inertia constants

Unlike [6], the synchronous units (with their respective controls) have been represented as either hydro, steam or gas power plants [2]. A variety of Automatic Voltage Regulators have been selected following the IEEE practice standards [9]. These include Alternate Current and Static type AVRs.

The generator's inertia constant, denoted as H [MWs/MVA] is chosen according to [2]. The steam turbines inertia, including those of coal and nuclear power stations, varies in the range between 4 to 10 [MWs/MVA]. The inertia constant for hydro units ranges between 2 and 4 [MWs/MVA]; whereas H for gas turbines is 2.5 to 6 [MWs/MVA].

In order to examine the dynamic behaviour of the model, several tests have been performed. The disturbances include the loss of a generator (to observe the frequency response) and an impulse applied at a large generator unit (to trigger a power system oscillation) as shown in Figures 1 and 2 respectively. Figure 1 shows the deviation of system frequency in response to a 1.8GW loss of generation (at G19 in Figure 4). This situation simulated the event occurred in UK in 2008 [5]. Initially the frequency drops because of the mismatch between generation and load. Thanks to action of governors increasing the generated power, the frequency recovers promptly to a new steady-state operating point. The absence of Automatic Generation Control (AGC) means that the frequency stabilises but does not regain its nominal value and it settles at a new equilibrium point of 49.26 Hz. In order to achieve this result, dead-band limits have been applied to governors. This test is in close agreement with observations in [5].

The model has been further analysed by considering its dynamic response to a step-change of AVR reference in comparison with the expected response of the system. The AVR voltage set-point of G18 was increased by 0.05 p.u. for 0.5s before returning to its nominal value. Figure 2 shows the resulting tie-line flow in line 8-10, one of the main transmission corridors between Scotland to England. The dynamic response observed is in good agreement with the expected natural frequency and damping of the GB network. After performing modal analysis it was found that the system exhibited an inter-area mode of 0.53 Hz. The inter-area mode exhibits a poor damping and it settles in around 70-80 s. The power system stabilizers (PSSs) are assumed to be out of service for this study.

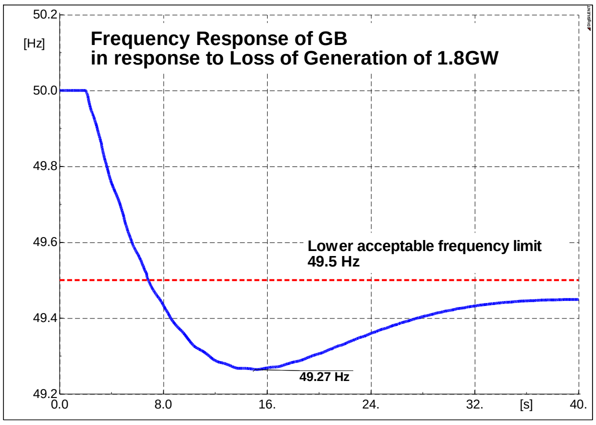

Figure 1: Frequency response of the system after a 1.8GW loss of generation (at G19).

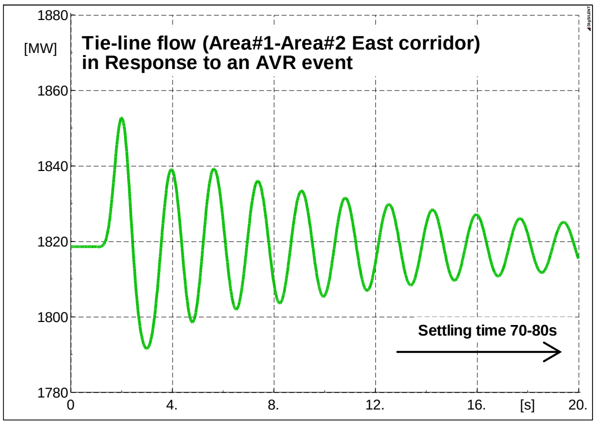

Figure 2: Tie-line flow in Line 8-10 in response to an AVR step change event applied at G18.

III. VSC HVDC Link and Frequency-Droop Control

This section describes the VSC HVDC link that was implemented for connecting two AC grids. The VSC converters have been equipped with frequency-droop control in order to provide support to the systems in case of disturbances.

A. *VSC HVDC Link*

An HVDC link employing 2-level VSCs in a balanced monopole configuration has been modelled [10]. The balanced monopole scheme is regarded to be the optimal configuration for VSC converters. PWM is considered for the control of the VSC HVDC system and the converters are represented by their averaged model in DIgSILENT PowerFactory. The DC lines have been represented by a lumped parameter model; they are modelled as underground cables, each line is represented with two parallel circuits and rated at 300kV, 2kA. A decoupled current control strategy in the synchronous reference frame (d-q) and standard PI controllers are implemented [11]. The rectifier operates in P-Q control mode, while the inverter operates in V_{dc}-Q control mode, keeping constant DC bus voltage and unity power factor on the point of common coupling [12]. The VSC HVDC is rated to transfer

2 GW across the DC cable. Table I summarizes the principal features of the converters.

TABLE I VSC PROPERTIES

	VSC GB1	VSC GB2
Vac [kV]	110	110
V_{dc}[kV]	600	600
S_{rating} [MVA]	2400	2400
Control Mode	P-Q	V_{dc}-Q
Set-point	2000 MW	0.97 p.u.

B. Frequency-Droop Control

In order to fully exploit the capability of the HVDC link, the VSCs have been equipped with droop control to provide frequency support to the AC networks in case of disturbances. The implementation of frequency-droop supplementary control is expected increases the degree of coupling between the two systems.

The principle of the frequency controller relies on the "active power-frequency" characteristic [13]. The active power across the DC-link is regulated according to the variations of frequency in the AC grid. The variation in power for a given variation in frequency is known as the droop of the system and it described by [13]:

$$f_{meas} - f_{nom} = -R_{droop}\,(P - P_{set}) \qquad (1)$$

The droop control loop, shown in Figure 3, is applied to the rectifier end. The measured grid frequency f_{meas} is compared with the nominal frequency f_{nom} (50Hz). If any deviations larger than the dead-band limit (±0.026 Hz) are detected, the DC line power order, P is modified considering the power set-point, P_{set} and in accordance with a look-up table defining the droop characteristics R_{droop} . In accordance with (1), it is sufficient to apply a proportional control to regulate the power.

The HVDC link is set to transfer 2 GW in steady-state operation. In the case of a loss of generation in the sending end AC grid, the frequency drops and the power transfer is reduced. This allows a faster restoration of the frequency within the nominal values in GB1.

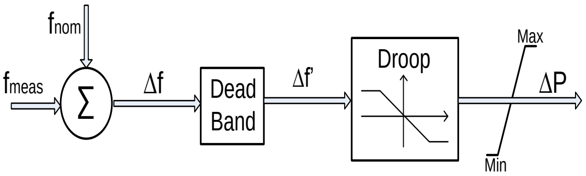

Figure 3: Droop control loop for the rectifier HVDC converter

IV. CASE STUDY ON THE GB EQUIVALENT SYSTEM

The full-scale GB transmission network has been duplicated and the systems, whose characteristics in terms of generation and load are shown in Table II, have been called GB1 and GB2. The second system has been created relying on the data and the models used for the GB transmission system; it may represent any transmission grid and it is, as GB1, a full-scale dynamic equivalent network model. In order to investigate the performance of HVDC corridors, two monopole schemes, featuring identical characteristics and modelled as described in section III, have been used to connect the two AC grids. The two links have been equipped with the same converters, but the length of the underground cables varies. The DC cable is 150km long for the north link (HVDC Link1) and 250 km long for the lower link (HVDC Link2). Figure 4 illustrates the final system where GB1 and GB2 are connected through two HVDC links. The second HVDC link has been implemented in order to increase the power transfer between the two networks; GB1 transmits 4GW to GB2 through the two DC corridors. This causes a stronger coupling between the two systems, and it makes GB2 significantly dependent on GB1 to satisfy its energy demand.

TABLE II GENERATION AND LOAD QUANTITIES IN GB1 AND GB2

		GB1	GB2
Generation	MW	64,300	56,700
	MVAr	15,800	17,300
Load	MW	59,850	59,800
	MVAr	40,407	40,407
Losses	MW	460	540
Spinning reserves	MW	15,290	10,650

HVDC Link1 has been placed between Area#1 of each grid, and HVDC Link 2 between Area#2 of each grid. The location of the links has been selected according to the generation characteristics of the Great Britain transmission network. The first link connects B2 in GB1, where large wind farm sites are located, to B5 in GB2; while the second link joins B15 in GB1, which is the site of one of the biggest power plants in UK, with B11 in GB2 (as shown in Figure 4). The position in Area#1 and Area#2 may affect the performance of the droop control, as the operations of the two controllers may enter in conflict.

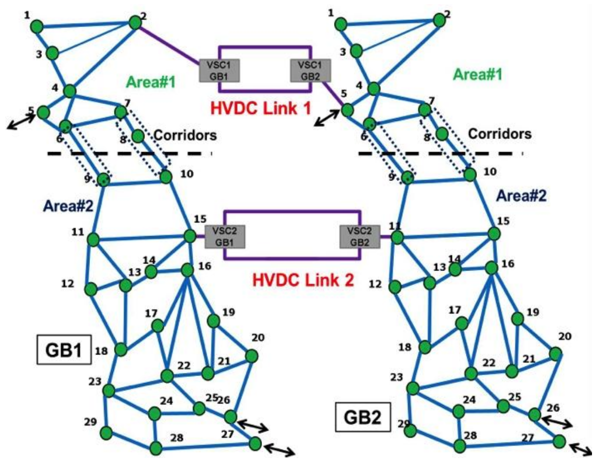

Figure 4: GB1 and GB2 connected through two VSC HVDC links.

V. SIMULATIONS AND RESULTS

This section offers a representative set of time-domain simulations conducted in DIgSILENT PowerFactory to explore the degree of coupling between the two AC grids with and without the frequency droop control. Once the two grids have been connected through the VSC HVDC links, a steady-state simulation was performed to validate the operations of the model in normal conditions. The dynamic performance of the system has been analysed for several scenarios. The case studies presented here include:

- Loss of Generation of 1.8 GW in G15 in GB1 with Power Export from GB1 to GB2.
- Loss of Generation of 1.8 GW in G15 in GB1 with Power Import from GB2 to GB1.

The disturbance is assumed to occur in GB1. The scenarios have been set to represent complementary situations; the import and export cases have been examined to assess the effectiveness of incorporating droop control with power flowing in either direction across the DC link.

A. Loss of generation in G15 in GB1 in Power Export scenario

A loss of generation of 1.8GW has been applied to G15 in GB1. The location of the fault is regarded to be quite severe since G15 is one of the biggest generating units in Area#2 and it is directly connected with the rectifier end of HVDC Link2. In this scenario a power transfer of 4GW, equally shared between HVDC Link1 and HVDC Link2, from GB1 to GB2 is considered. The dynamic performance of the system is observed with and without the application of frequency droop control.

Figure 5 (a) depicts the loss of generation occurring at G15 in GB1. The power transfer through HVDC Link1 is illustrated in Figure 5 (b). The two HVDC links have identical properties with similar transfer levels and therefore not shown in the plots. Figures 5 (c) and 5 (d) show the frequency response of GB1 and GB2 respectively. The green traces in Figures 5 (b), (c) and (d) represent the case when frequency droop control is not applied, whereas the blue traces show the system performance with droop control.

The conclusions from [6] have been confirmed here: in absence of supplementary control in the VSCs, the HVDC links act as firewall in case of faults; it prevents the propagation of disturbances originating in one system to the other, in spite of the very high power transfer between the two grids. The loss of generation causes the frequency to drop to 49.2Hz in GB1, but the frequency in GB2 is unaffected (Figure 5 (c) and (d)), the power transfer across the DC links in kept at 4GW (considering HVDC Link2, which has not been shown) as it is illustrated in Figure 5 (b).

With supplementary frequency-droop control applied, the level of coupling between the two AC grids increases. The frequency controller regulates the power across the DC links after detecting a frequency deviation due to the loss of generation event. For a loss of generation of 1.8GW, the DC power transfer is reduced to 1.45GW in each HVDC link; the regulation of the frequency droop control can vary according to the operational requirements. The reduction of the power exported from GB1 to GB2 prevents the frequency in GB1 from achieving unacceptable values outside the frequency range [3]. Indeed, Figure 5(c) shows that with droop control, the frequency drops to 49.7 Hz, while without droop it drops to 49.27 Hz which is outside the acceptable limits [3]. As a consequence of the variation in export power, the frequency in GB2 is now affected. It drops to 49.7Hz, which is still acceptable, and then it reaches a new steady-state equilibrium within 25s re-establishing normal conditions.

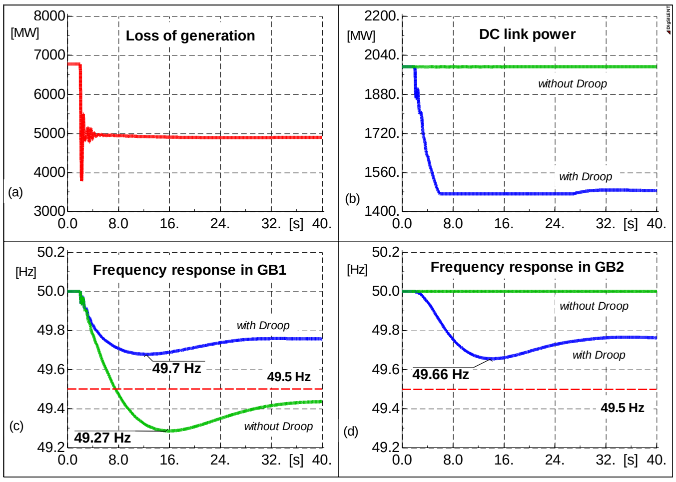

Figure 5: Dynamic performance of the system under a loss of generation event at G15 in GB1. (a) Power flow in G15 in GB1. (b) DC link power in HVDC Link1. (c) Frequency response in GB1. (d) Frequency response in GB2.

B. Loss of generation in G15 in GB1 in Power Import scenario

In this scenario the same disturbance, a loss of generation of 1.8GW at generator G15 in GB1, has been considered. In this case the DC power is reversed, hence 4GW is imported to GB1 from GB2. In order to realise this, the control modes in the converters have been inverted: the East converters act as rectifiers and are regulated in P-Q mode, whilst the West converters work as inverters and are controlled in V_{dc}-Q. Several modifications have been made to the generation and demand side of both grids in order to make the power import to GB1 possible.

Figure 6 (a) depicts the loss of generation occurring at G15 in GB1. The power across HVDC Link1 is illustrated in Figure 6 (b). Figures 6 (c) and 6 (d) show the frequency response of GB1 and GB2 respectively. The green plots in Figures 6 (b), (c) and (d) show the system response without droop control, whilst the blue plots depict the system performance with the droop.

The absence of droop control causes the HVDC link to act as firewall in case of disturbances, the frequency in GB2 is not affected by the loss of generation occurring in GB1 (Figure 6 (c) and (d)) and the power transfer along the link is kept to a constant value (Figure 6 (b)).

With the introduction of the droop control, the degree of coupling between the two AC grids increases. The frequency-droop control has been applied to the rectifier end, the frequency deviation occurring in GB1is transmitted to the frequency controller in GB2 through a communication link. The imported power flow is re-dispatched depending on the level of frequency deviations. The loss of generation causes the frequency to drop in GB1, therefore the import power is increased in order to re-establish normal operations. The frequency recovery in GB1 is not significantly different comparing the case with and without droop control, this is because in pre-fault conditions the DC link is rated near full-capacity with only around 150MW of headroom available. This scenario assesses the ability of the HVDC link to work in reversed operations. The two AC grids are coupled to a smaller extent; a different level of the droop control can be set to increase the coupling without compromising the performances in the export scenario.

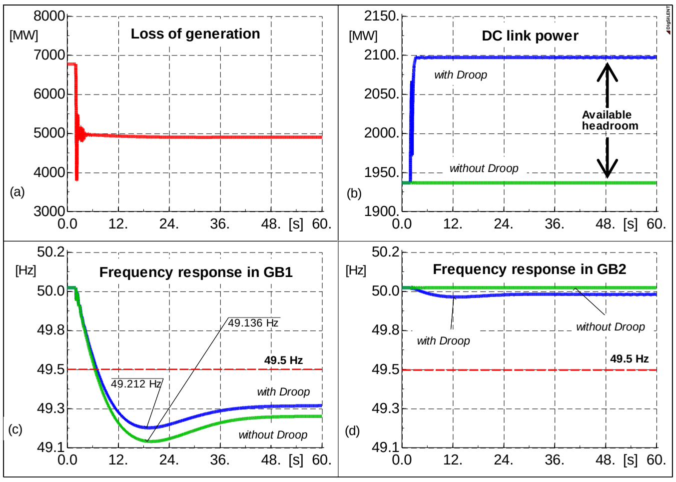

Figure 6: Dynamic performance of the system under a loss of generation event at G15 in GB1. (a) Power flow in G15 in GB1. (b) DC link power in HVDC Link1. (c) Frequency response in GB1. (d) Frequency response in GB2.

VI. Conclusions

The level of coupling of two national transmission systems connected through 2 VSC HVDC links has been examined through time-domain dynamic simulations. The action of frequency-droop supplementary control implemented in the rectifier end of the VSCs has the desired effect of helping a system that suffers a generation loss to recover its frequency but at the cost of coupling the event into the other system and causing a frequency disturbance there also.To facilitate the testing of the coupling, a model was created in DIgSILENT PowerFactory as an approximate representation of the Great Britain transmission system; the dynamics have been further validated through a loss of generation event and an AVR event. Prevention of the propagation of the disturbances originating in one system from passing to the other is of particular importance for a proper understanding of the performance of HVDC corridors among different countries in the prospective of the European Super Grid. This paper is part of a wider research project, where concepts such as the implementation of power oscillation damping control in the VSCs and multi-terminal HVDC schemes will be soon contemplated.

Acknowledgment

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